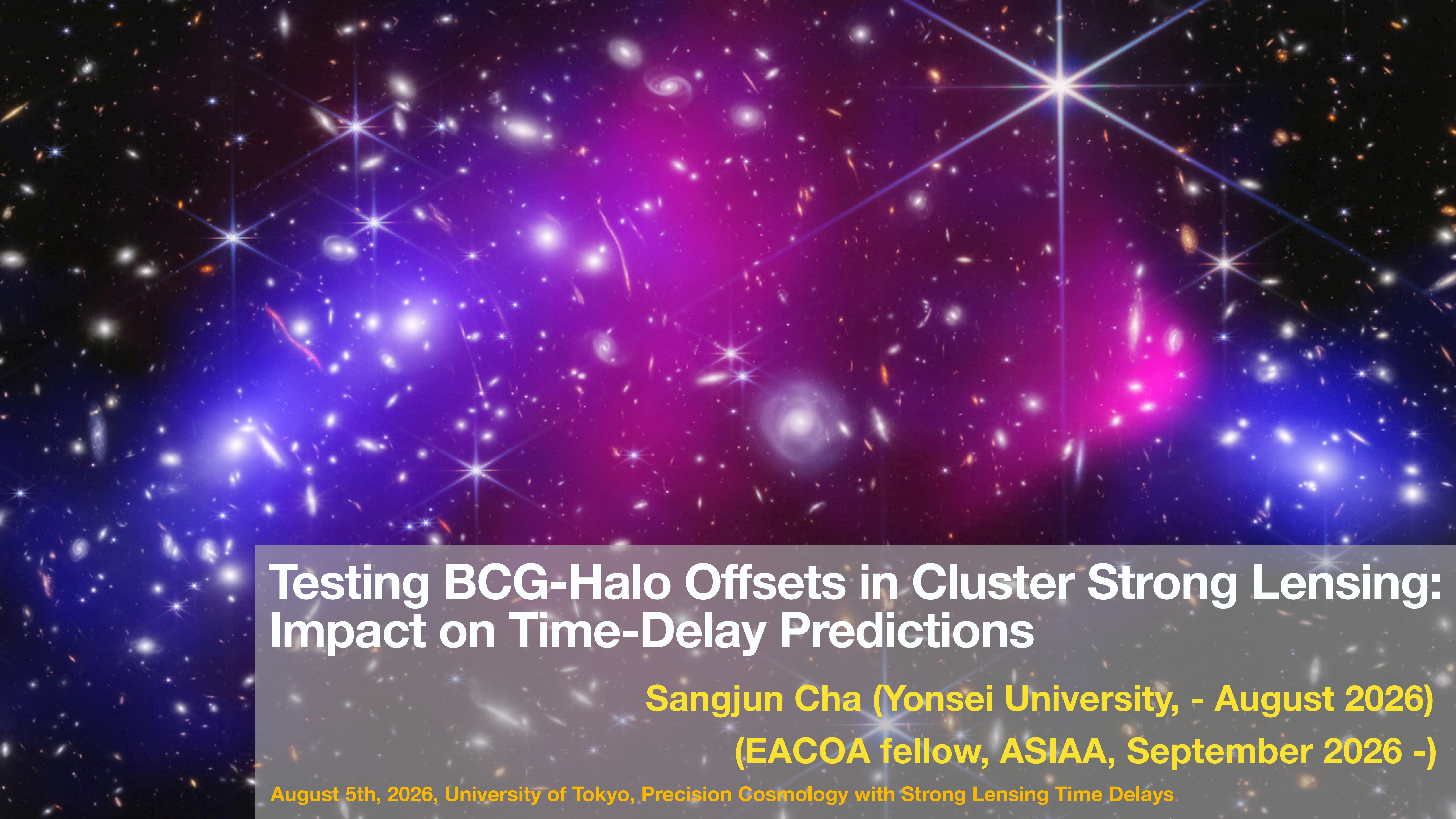


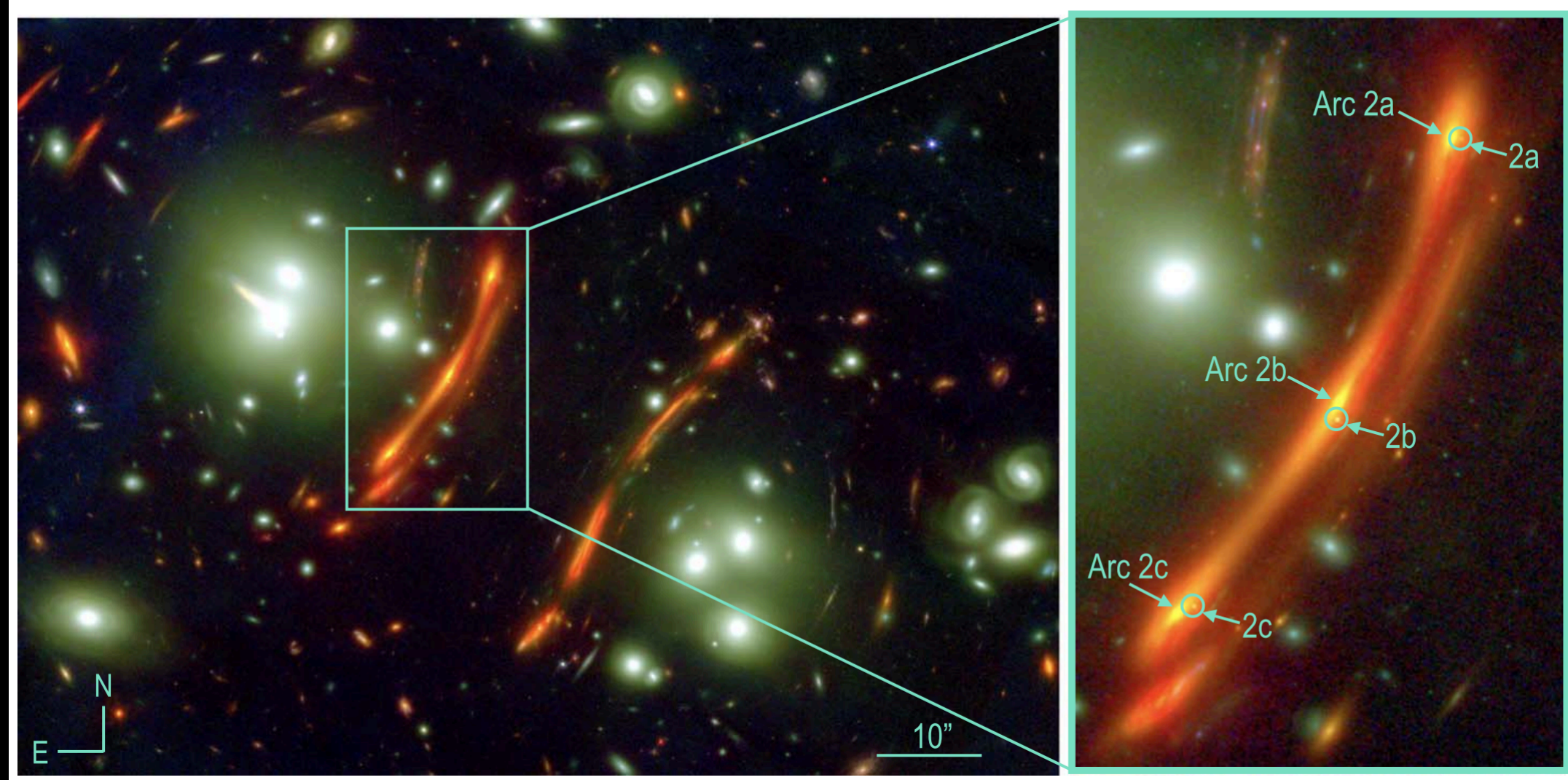
A cosmic background image featuring a dense field of galaxies in various colors (blue, purple, orange) against a dark space. A grid of thin blue lines is overlaid on the image, with a prominent star-like bright spot at the top right intersection.

Testing BCG-Halo Offsets in Cluster Strong Lensing: Impact on Time-Delay Predictions

Sangjun Cha (Yonsei University, - August 2026)
(EACOA fellow, ASIAA, September 2026 -)

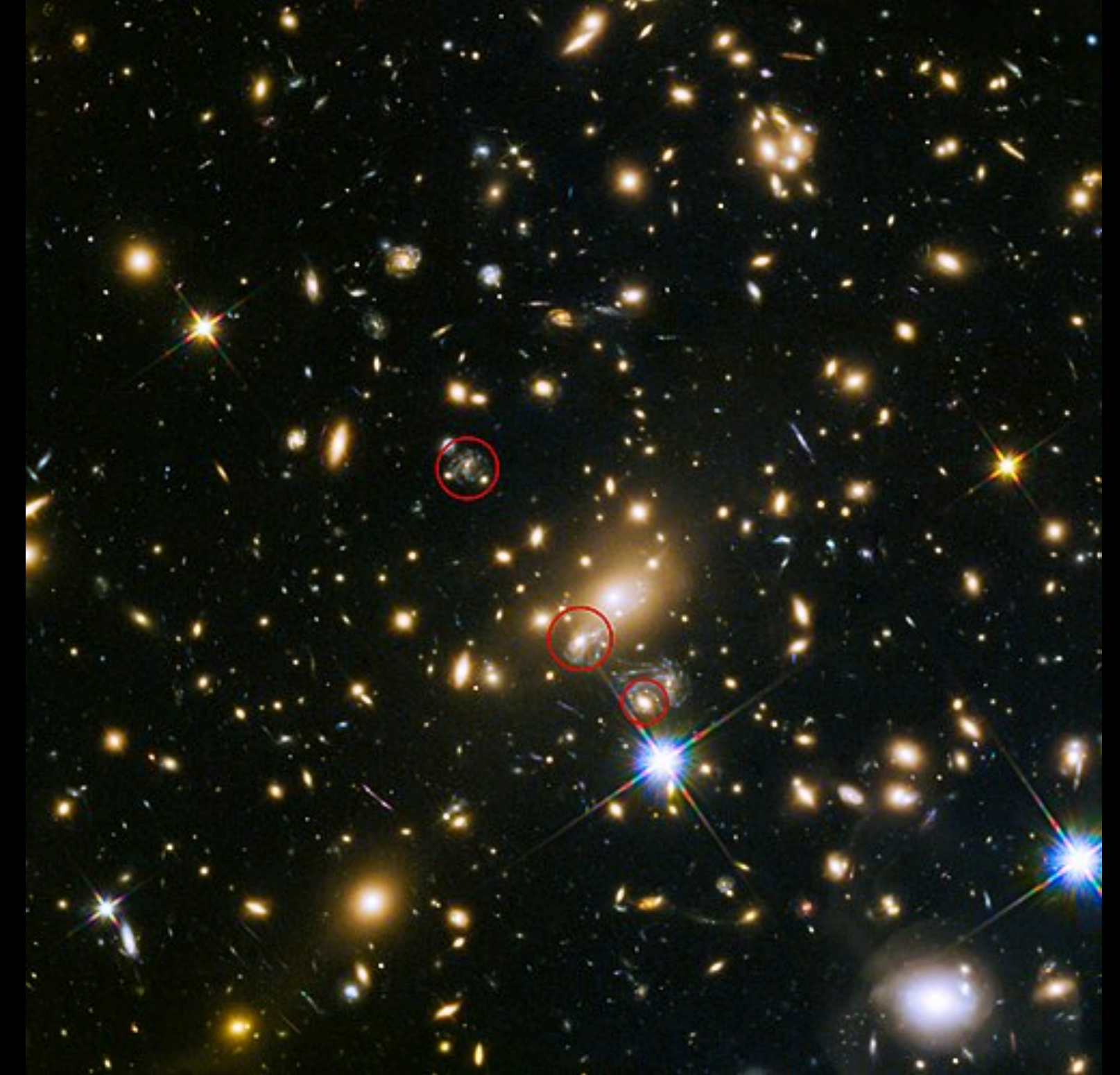
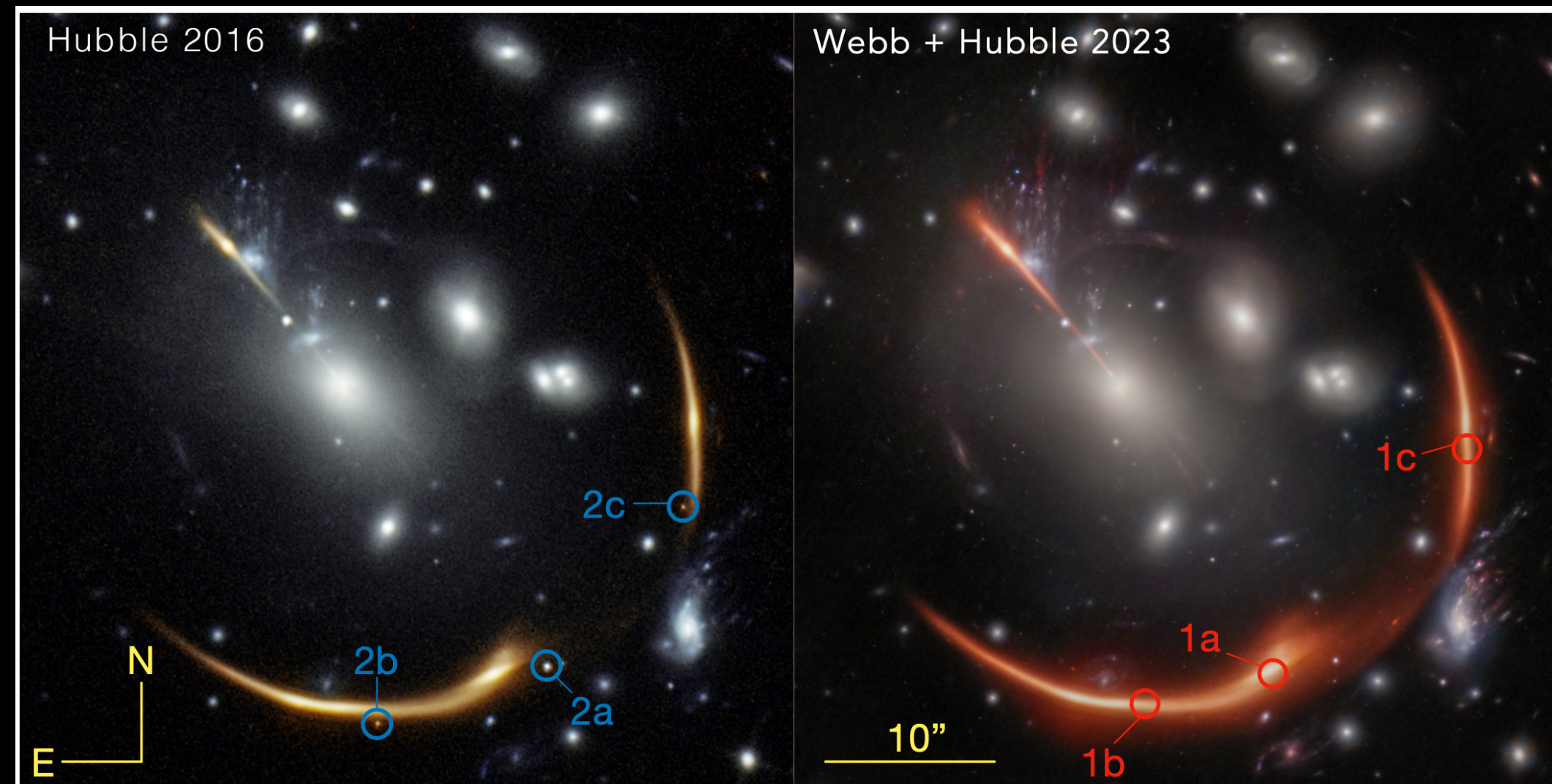
August 5th, 2026, University of Tokyo, Precision Cosmology with Strong Lensing Time Delays

Strong Lensing in Galaxy Clusters



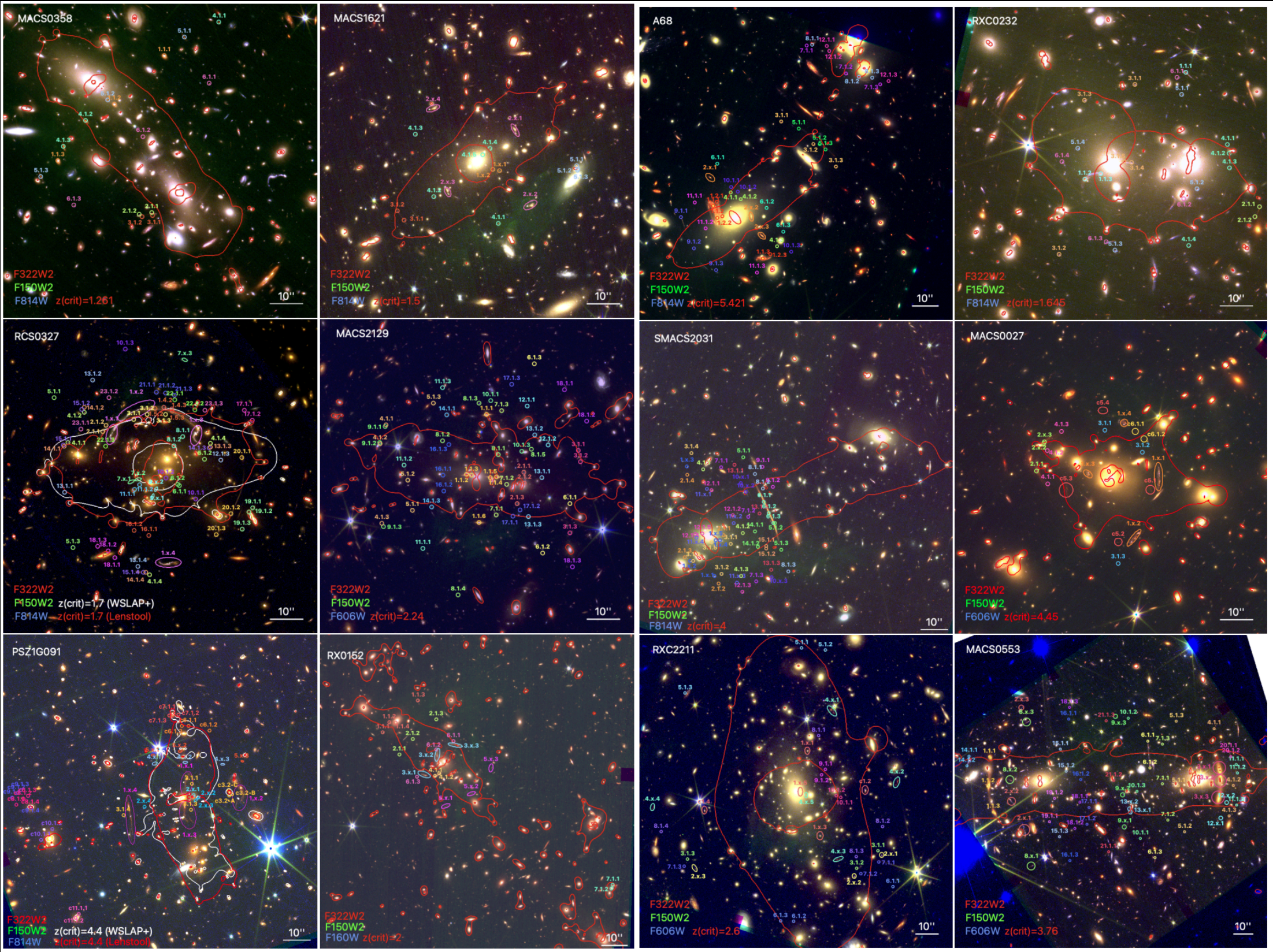
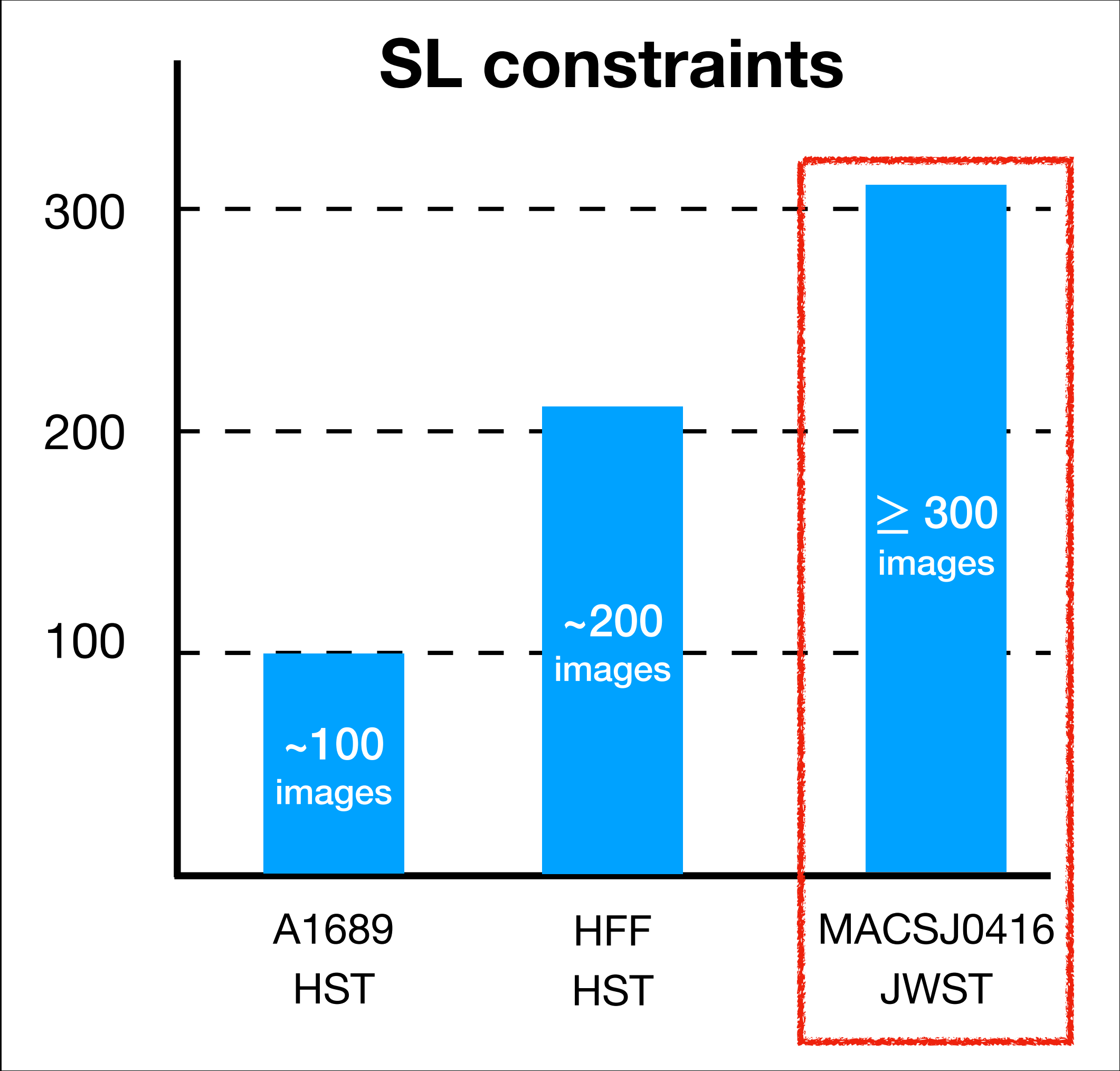
Frye et al. (2024)
 Pierel et al. (2024)
 Pascale et al. (2025)

Suyu et al. (2025)
 Pierel et al. (2024, 2025)



Grillo et al. (2016, 2018, 2024)
 Kelly et al. (2016, 2023)

Strong Lensing in JWST Era



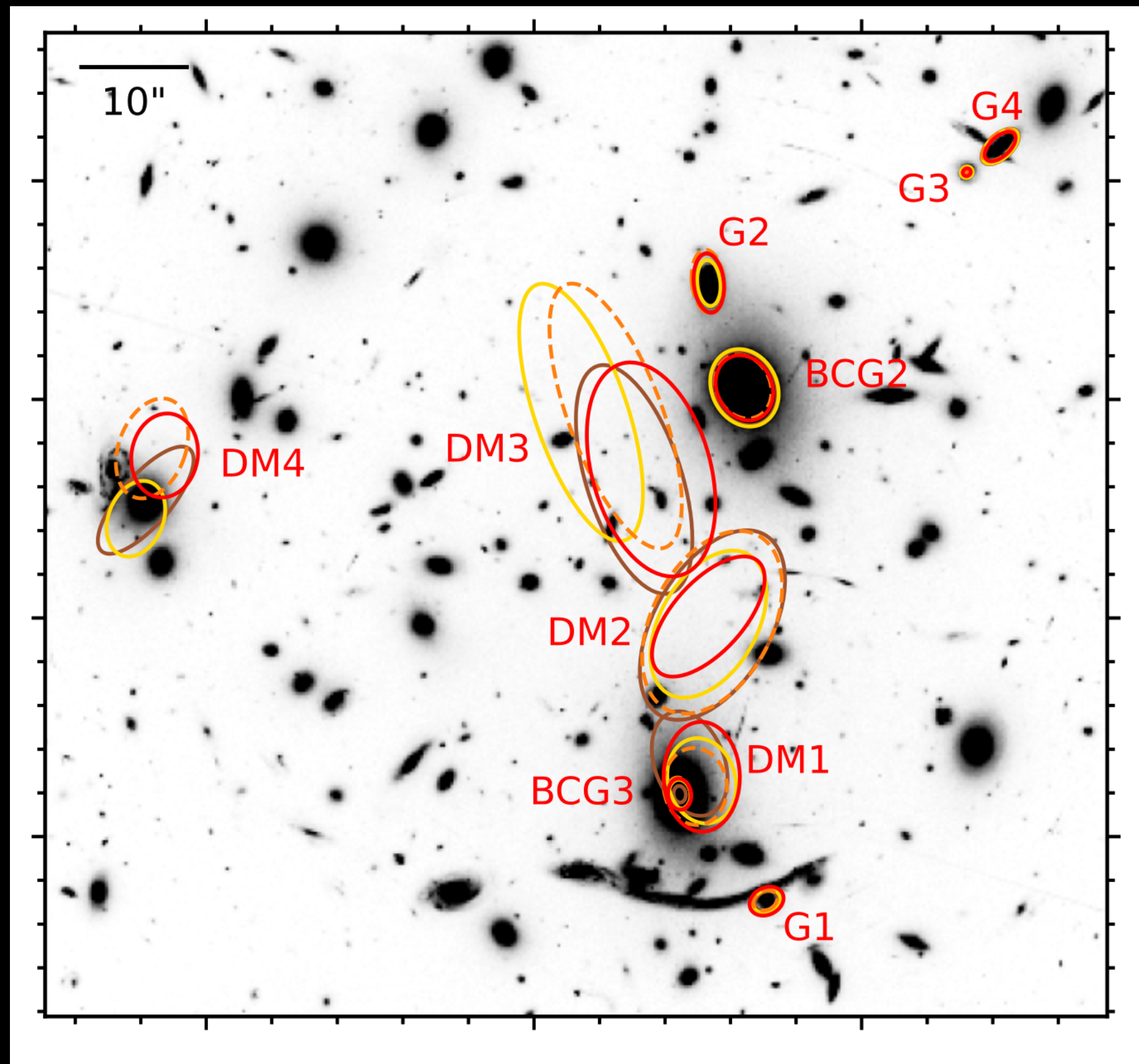
Cerny et al. (2025)

- More SL multiple images
- More SL galaxy clusters

BCG-halo Offsets in Lens Models

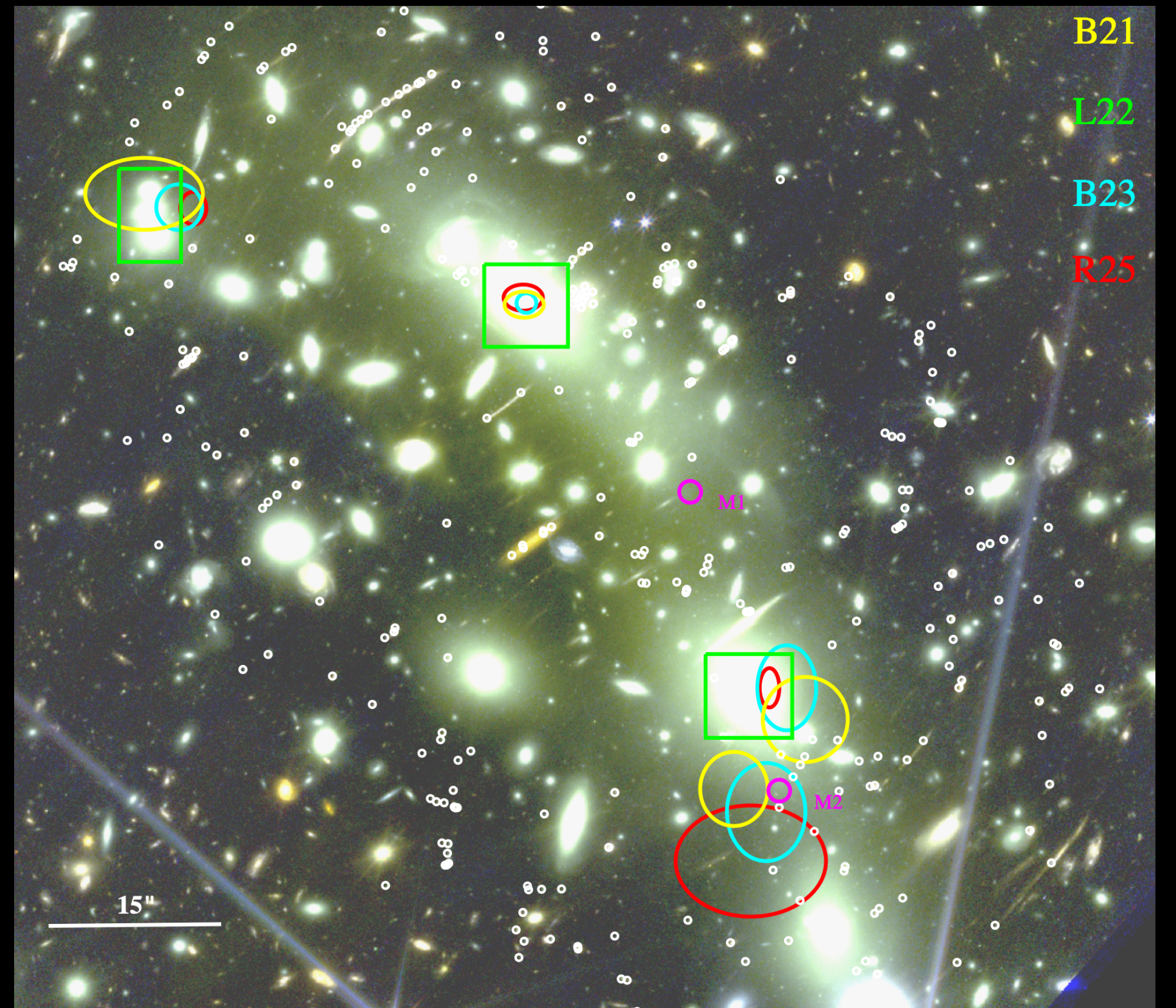
Offsets or without optical counterpart

Abell 370



Niemiec et al. (2023)

MACS J0416.1-2403

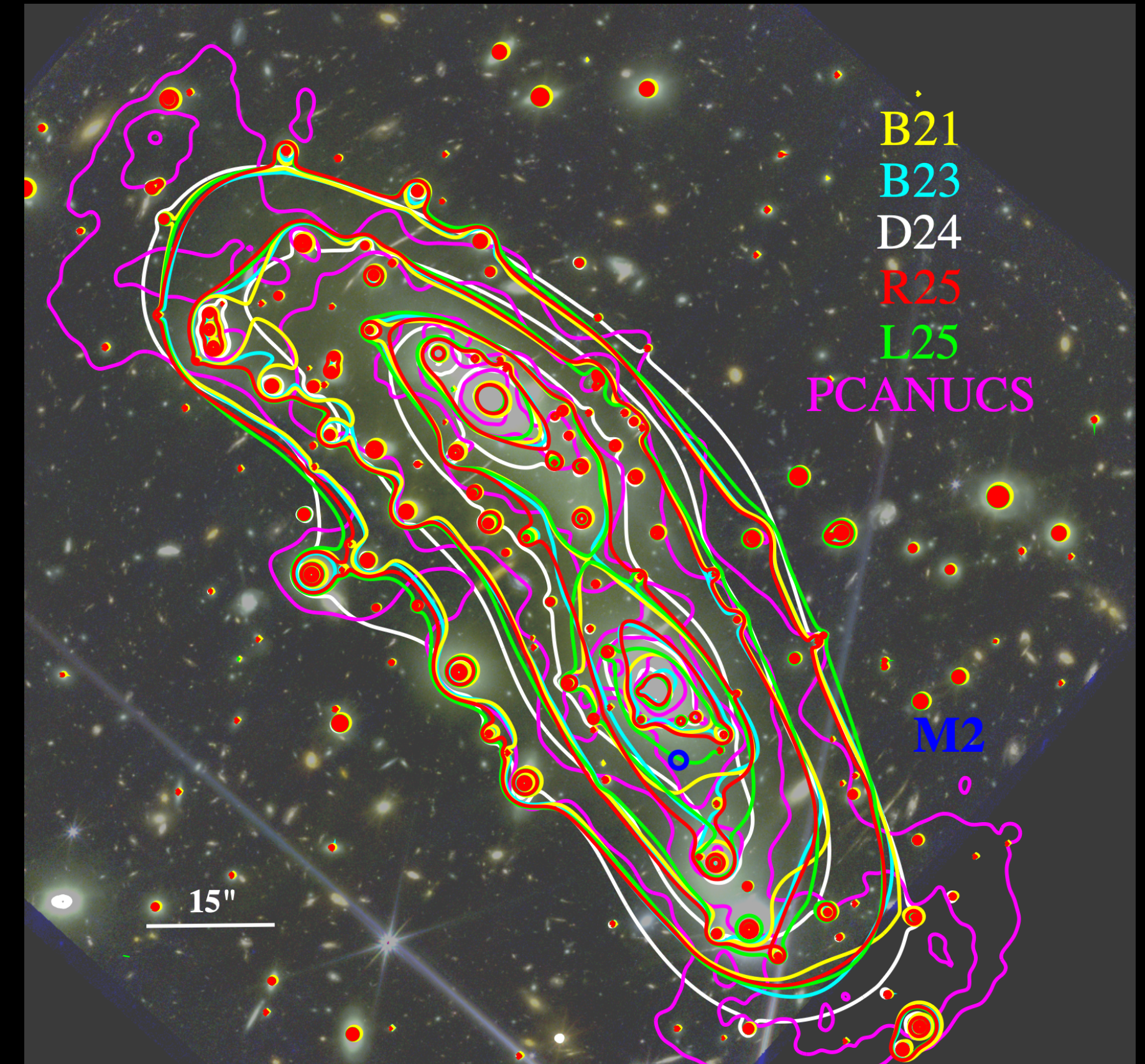
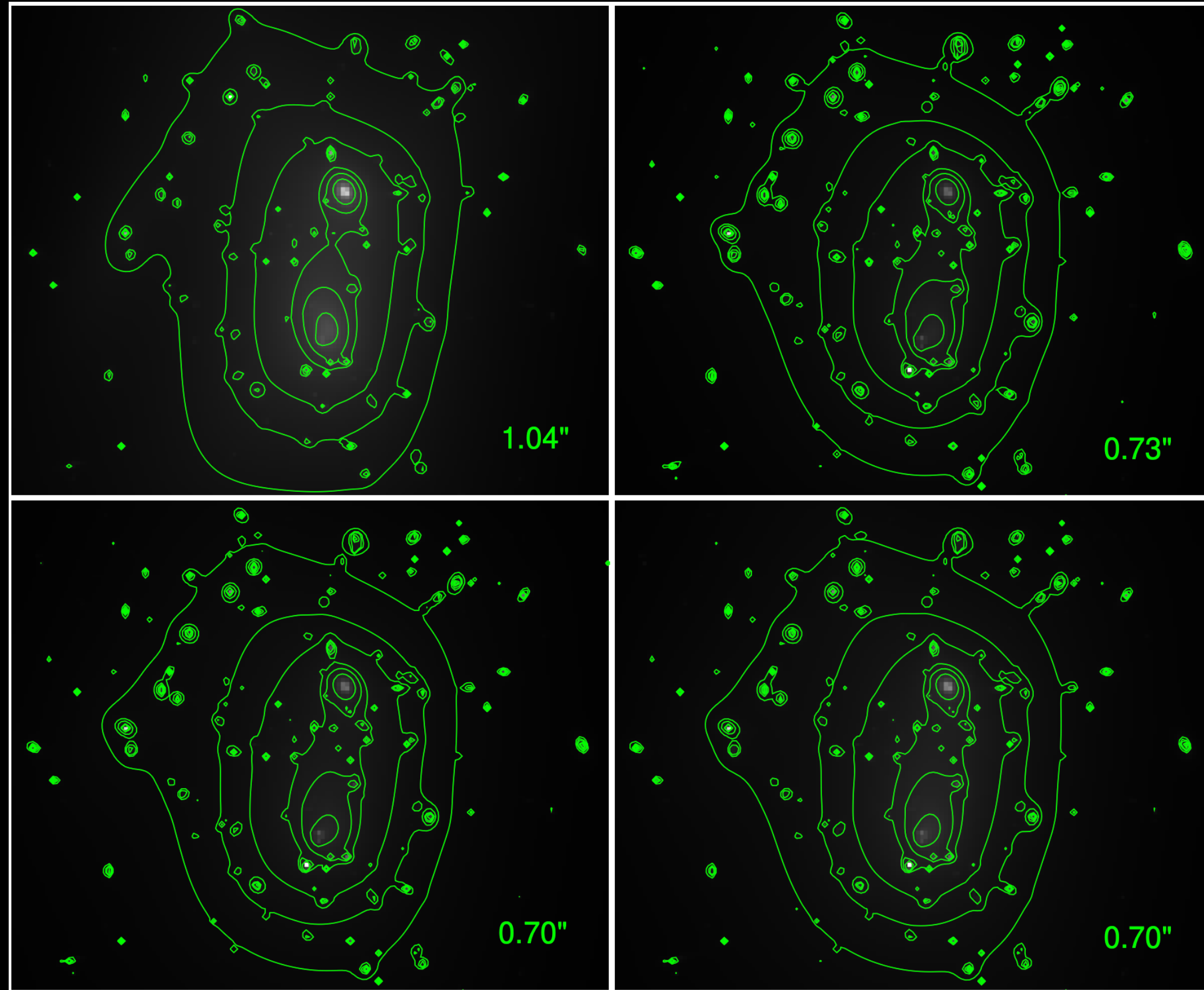


Limousin et al. (2025)

Could These Offsets Be Physical?

- These offsets may be physically possible, but only under specific conditions, such as a large SIDM cross section.
- DM halos without optical counterpart could indicate the existence of dark core.
- Since these offsets can be interpreted as physical, it is crucial to evaluate the necessity of these offsets.
- If these offsets are not required by data, these unnecessary offsets could affect the lensing outputs, such as time delays or magnifications.

Are These Offsets Uniquely Required by SL Data?



- Previous studies assessed whether anomalous components were needed through their effect on the image plane rms.

In Previous Studies...

1. Purely parametric or free-form methods

- ➡ Parametric models restrict the allowed mass structure, whereas free-form models do not explicitly separate the BCG and cluster-scale halo components.

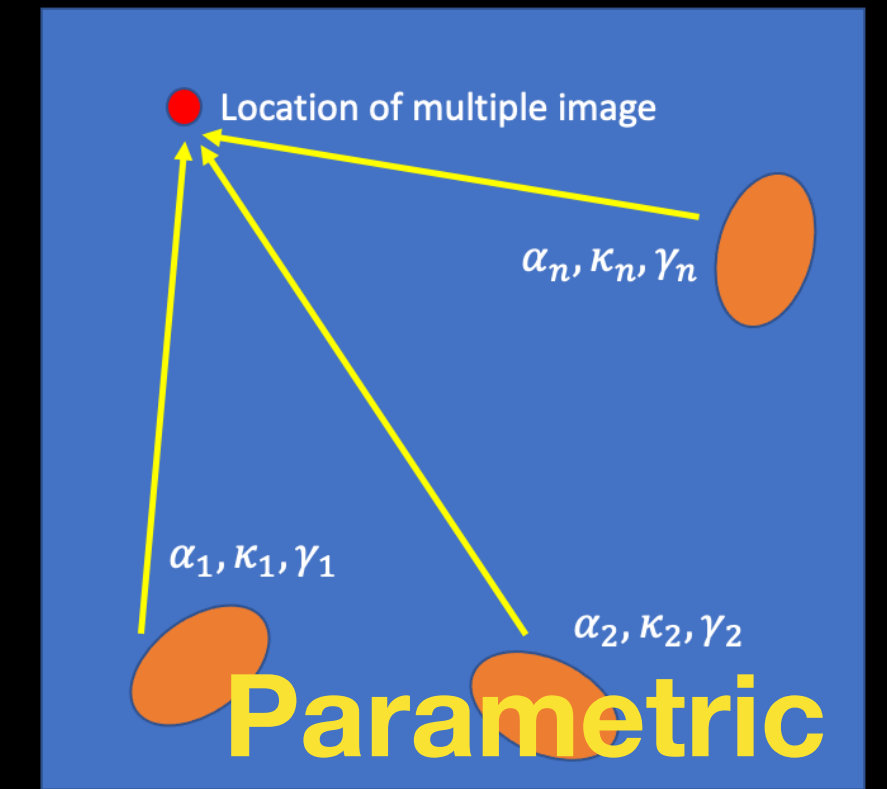
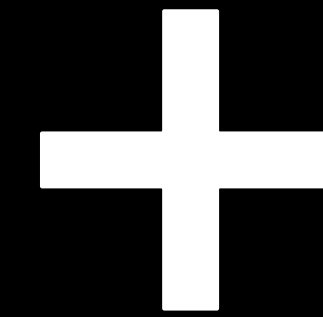
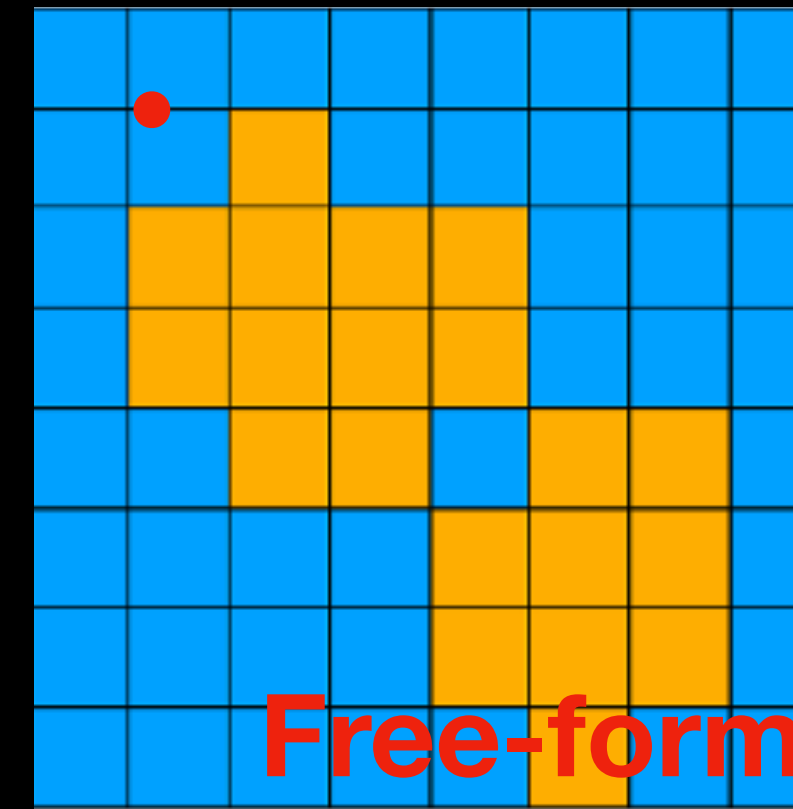
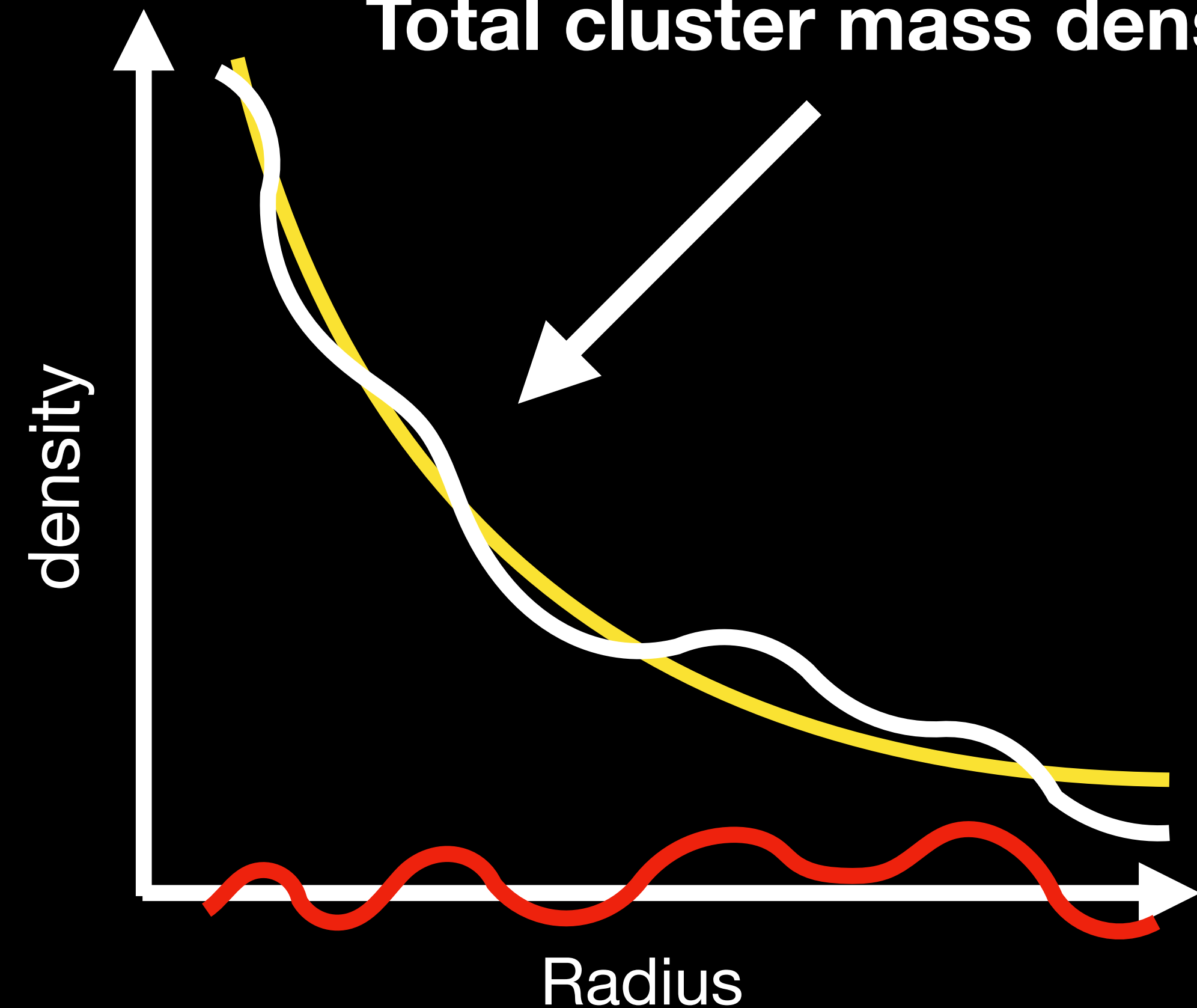
2. Image plane rms

- ➡ The image-plane RMS can only show how precisely a model reproduces the multiple images used in the reconstruction, and not how accurately it predicts unused systems.
- ➡ Halo position freedom can compensate for limited model flexibility and reduce the rms values even when such freedom is not required by the SL constraints.

MrMARTIAN: Hybrid Lens Reconstruction Method

$$f = \chi_{SL}^2 + rR$$

Total cluster mass density profile =



- MARTIAN reconstructs **global profiles using analytic halos** and **local fluctuations based on a grid**.
- Our hybrid model is flexible enough to reproduce the overall mass distribution well.
- This allows us to compare fixed and free halo positions while the grid captures residual mass structure.

Jackknife Test

Beyond mass distribution & rms

- A low rms only shows that a model can reproduce the images used in the reconstruction (precision).
- Source exclusion jackknife tests whether the lens model can predict a multiple image system that is not used (accuracy).
- Therefore, a lower jackknife rms indicates that the model better predicts SL systems beyond those used to construct it.

rect based on the accuracy i.e., the predictive power. If the model has high predictive power, the model is considered correct. If the model has low predictive power, the model is considered incorrect.

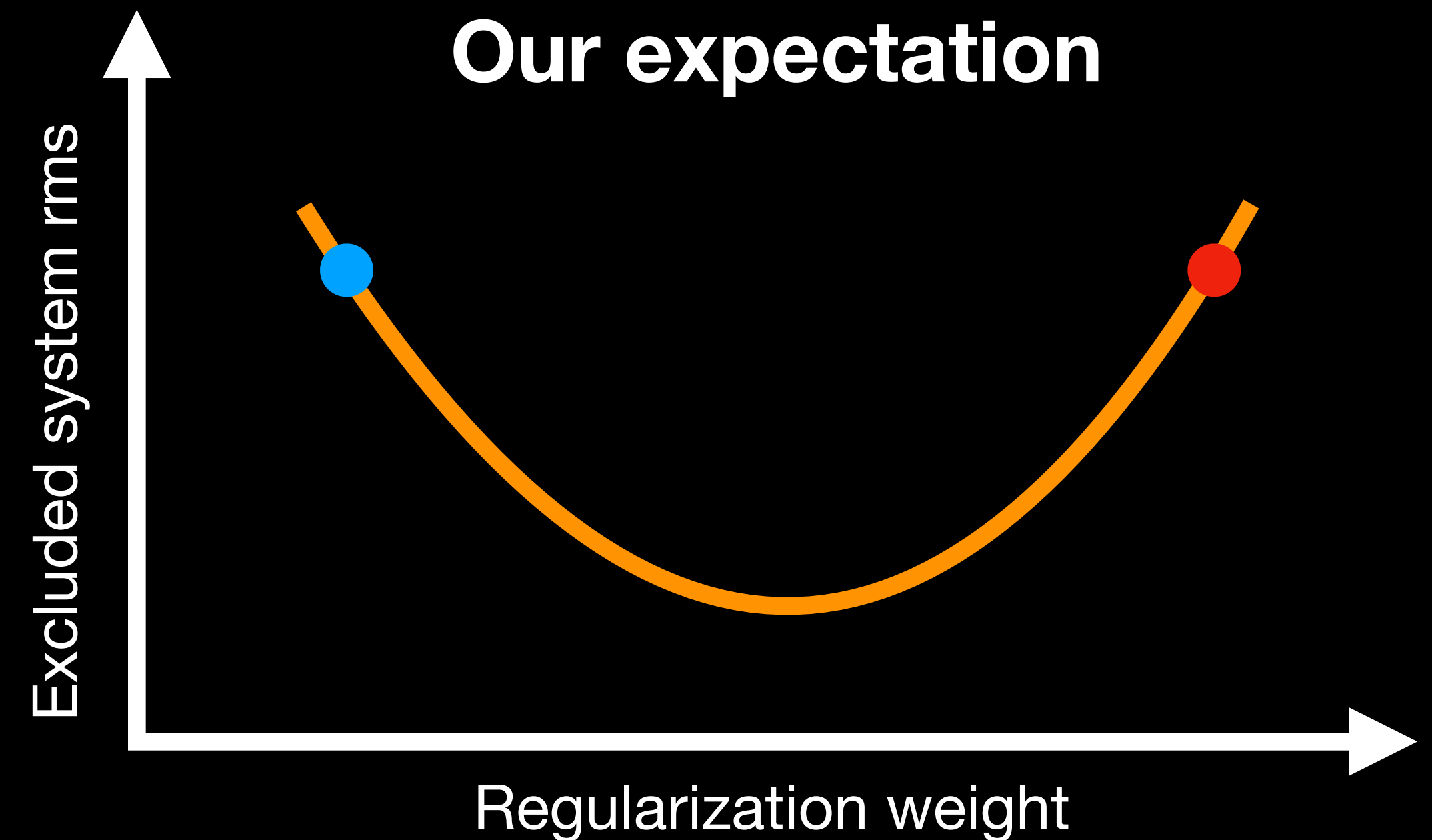
In this paper, we use the Jackknife method to quantify the predictive power of the mass model. This method evaluates how well a mass model can predict positions of multiple images that are excluded from the fit. The spe-

Nishida et al. (2025)

Jackknife Test

Data-driven Weight for MrMARTIAN

- Because each cluster has a different mass distribution, line of sight structure, and set of multiple images, different regularization weights are required.
- We adopt the regularization weight that minimizes the mean rms of the excluded source systems.



- Too small reg weight: the model becomes overfit, and the residuals of the excluded image systems will increase.
- Too large reg weight: the model becomes overly smooth, its predictive power weakens, and the residuals of the excluded image systems again increase.

Jackknife Test

Jackknife test with different reg weights

Step 1.

Set multiple regularization weights: $r = r_1, r_2, \dots, r_n$ (Here, we tested $r=25, 50, 100, 250, 500$)

Step 2.

Perform the Jackknife test for each weight

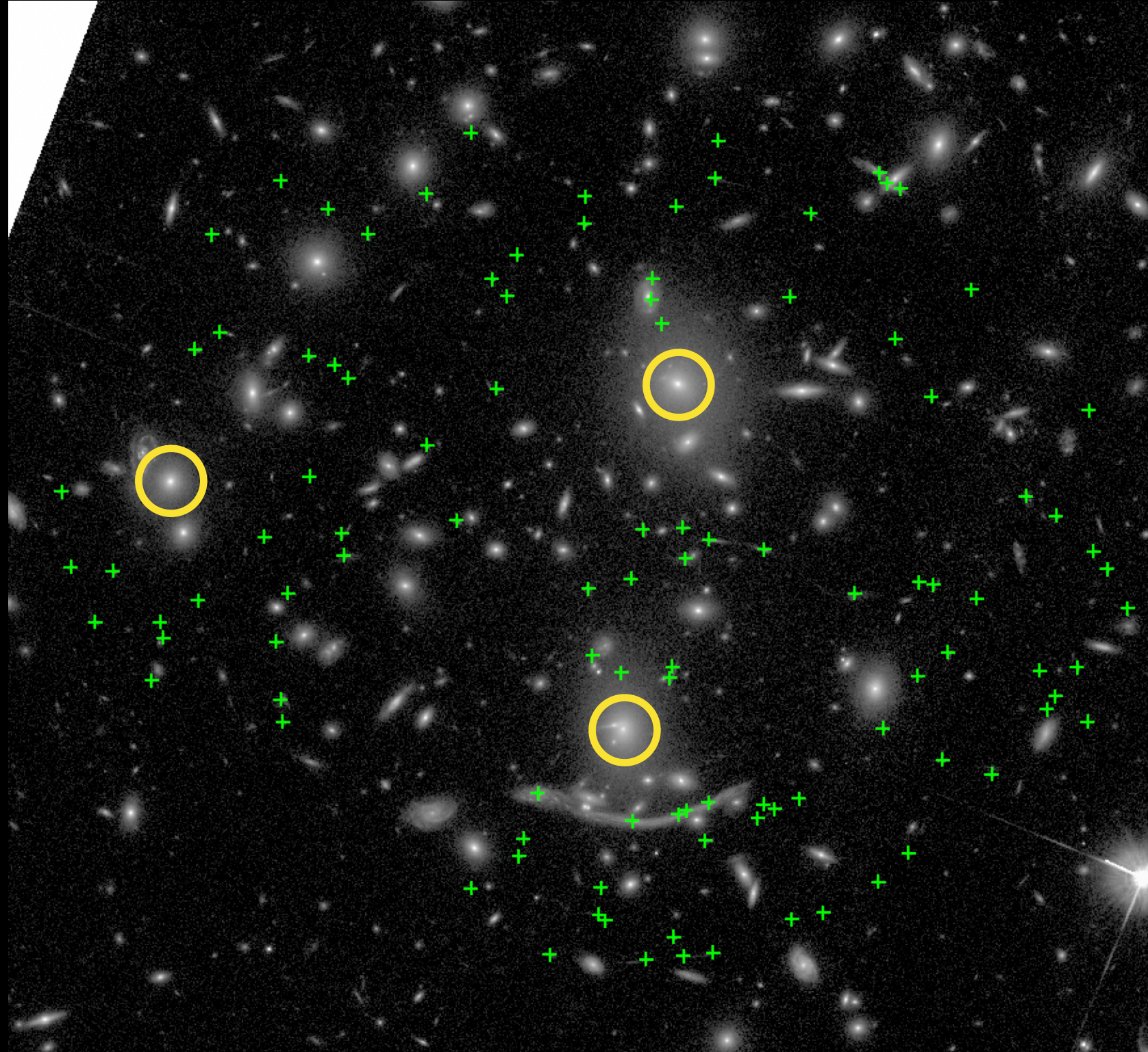
- Exclude source 1 $\Rightarrow$ reconstruct lens model $\Rightarrow$ compute the image plane rms of source 1
- Exclude source 2 $\Rightarrow$ reconstruct lens model $\Rightarrow$ compute the image plane rms of source 2
- ...
- Exclude source m $\Rightarrow$ reconstruct lens model $\Rightarrow$ compute the image plane rms of source m

Step 3.

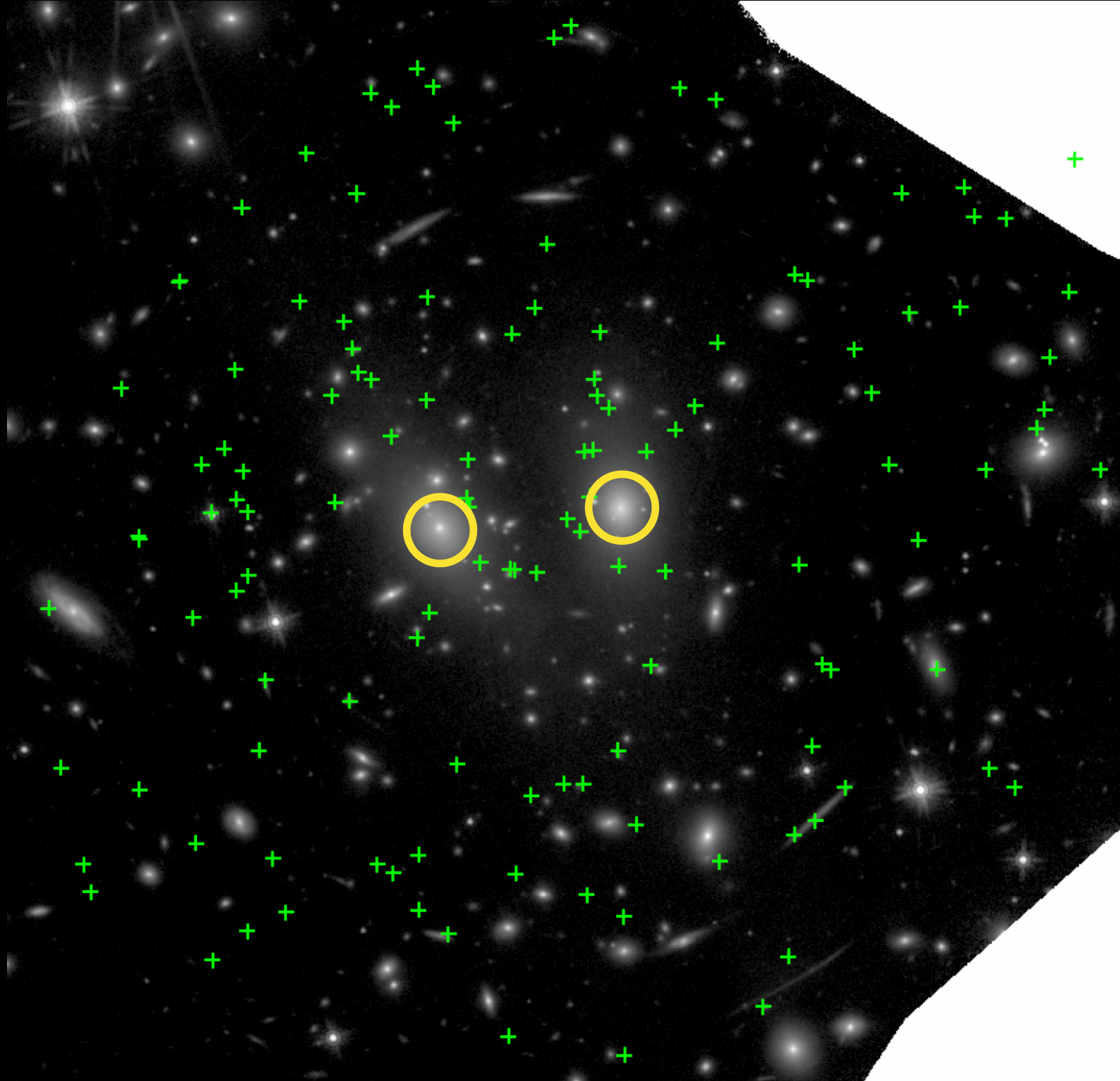
Select the regularization weight that minimizes the system mean rms.

Lens Modeling Setup

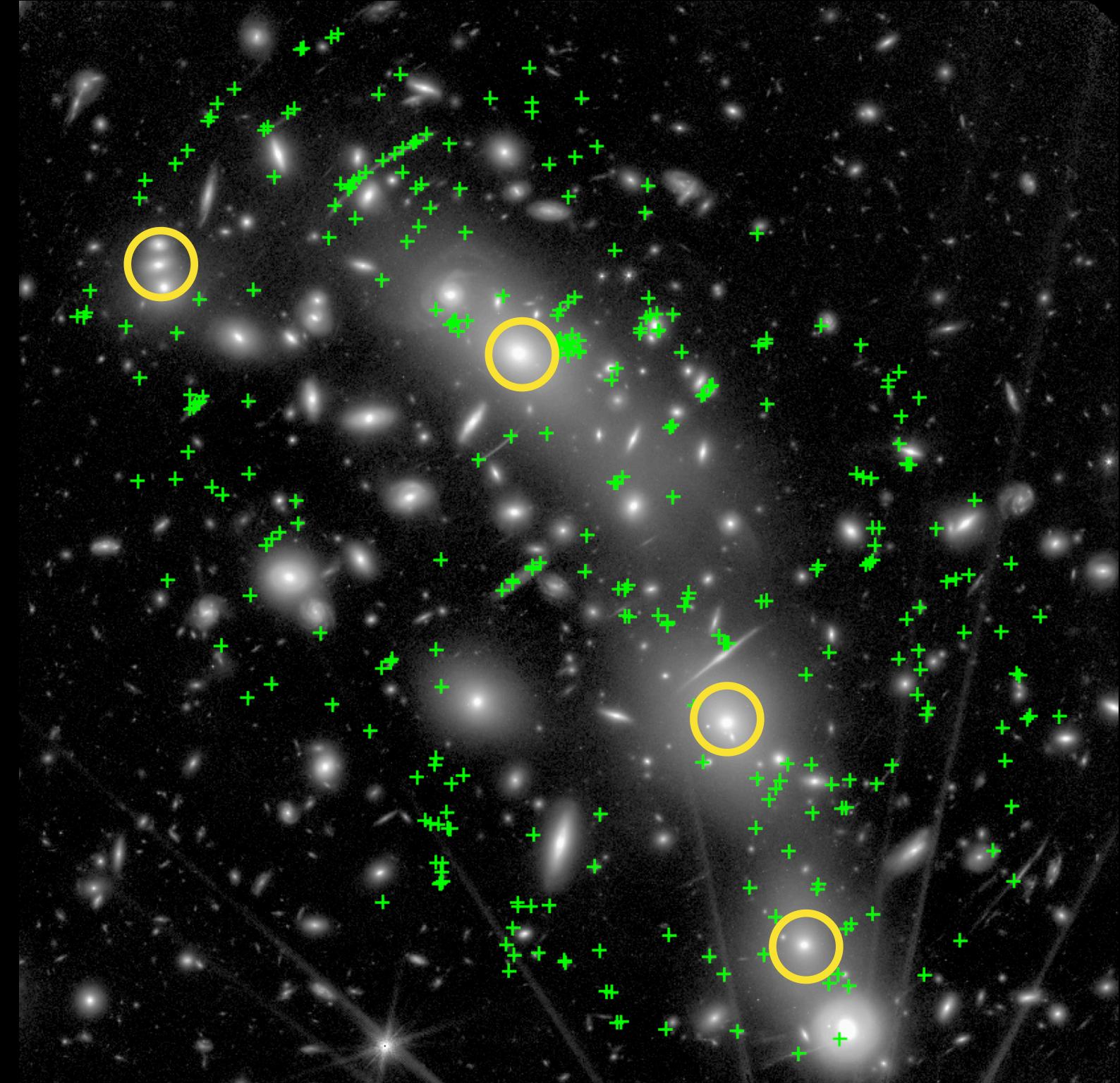
Abell 370 ($z=0.375$)



RX J1347.5-1145 ($z=0.451$)



MACS J0416.1-2403 ($z=0.396$)

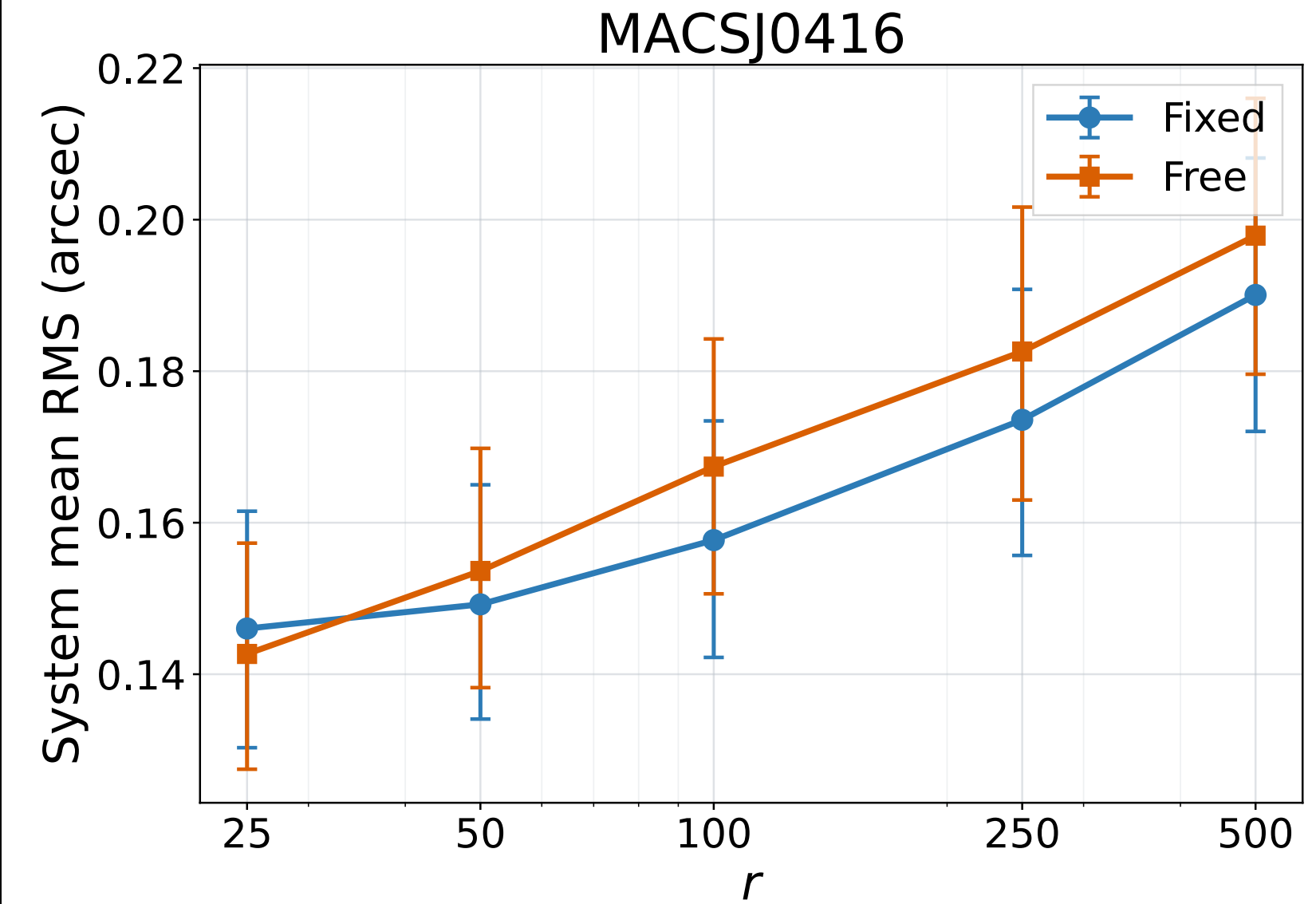
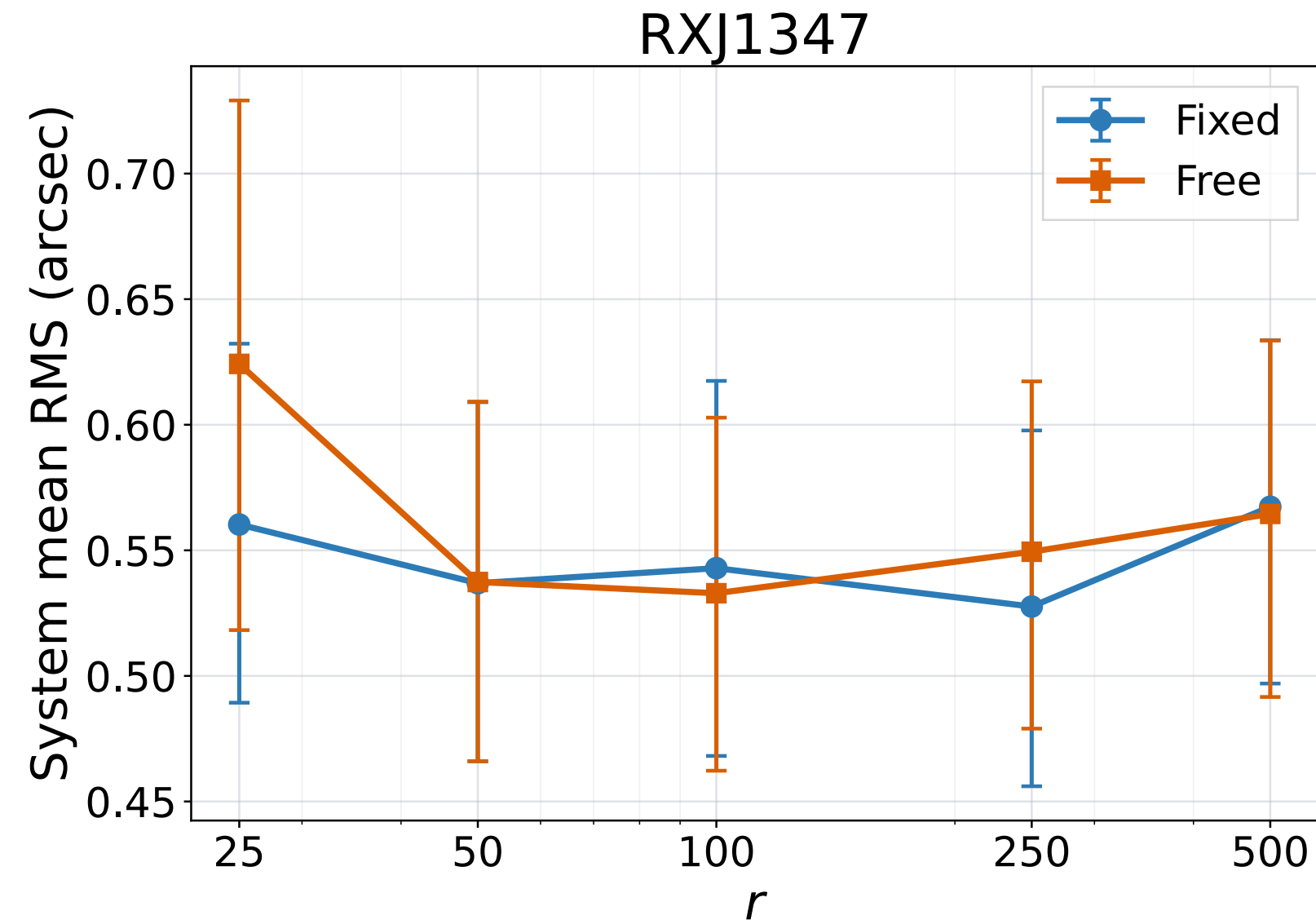
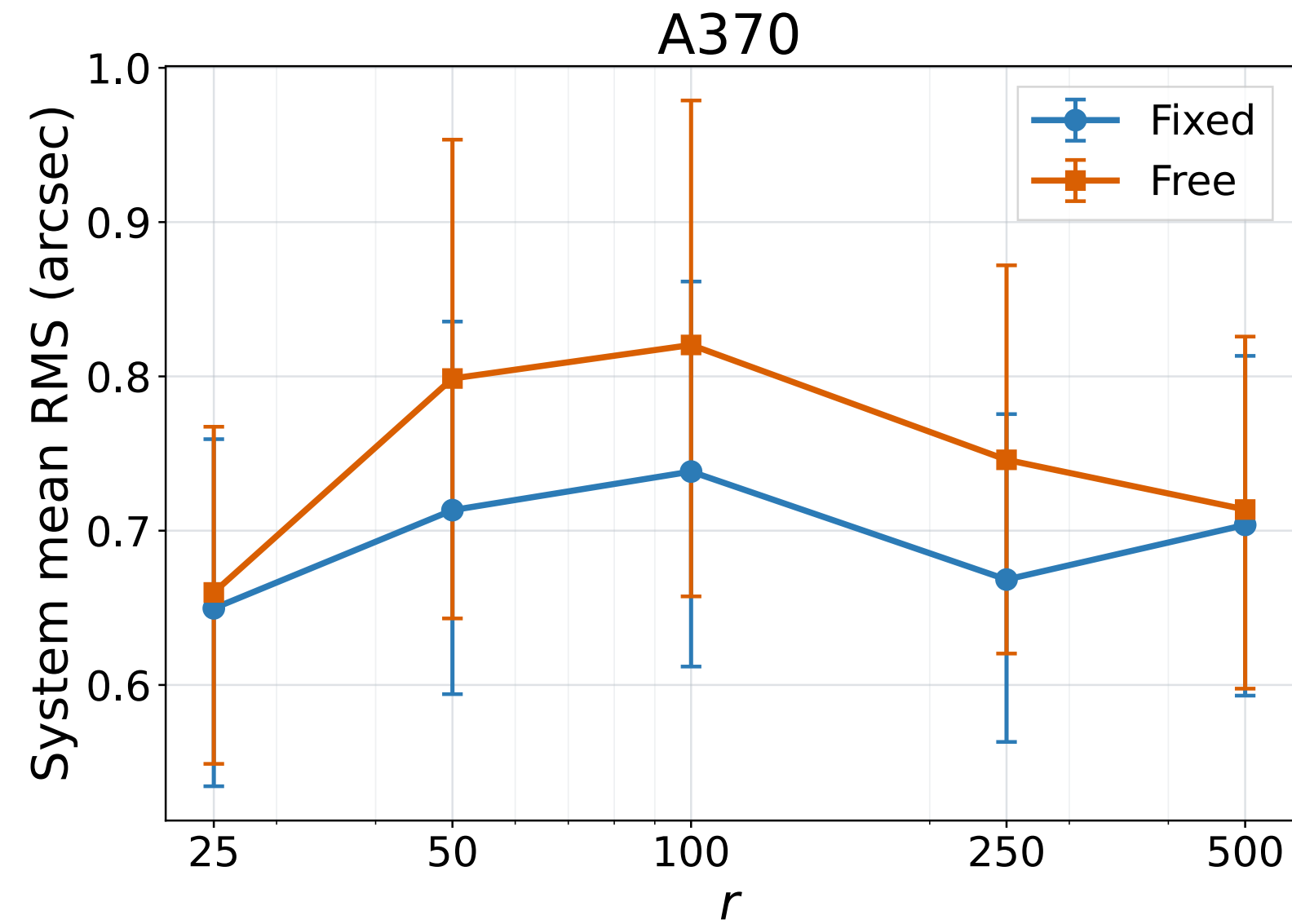


	Abell 370	RXJ1347	MACSJ0416
# of multiple images	105	125	303
# of cluster halos	3	2	4
# of member galaxies	126	139	213
# of total parameters	4924	4918	4926

Lens Modeling Setup

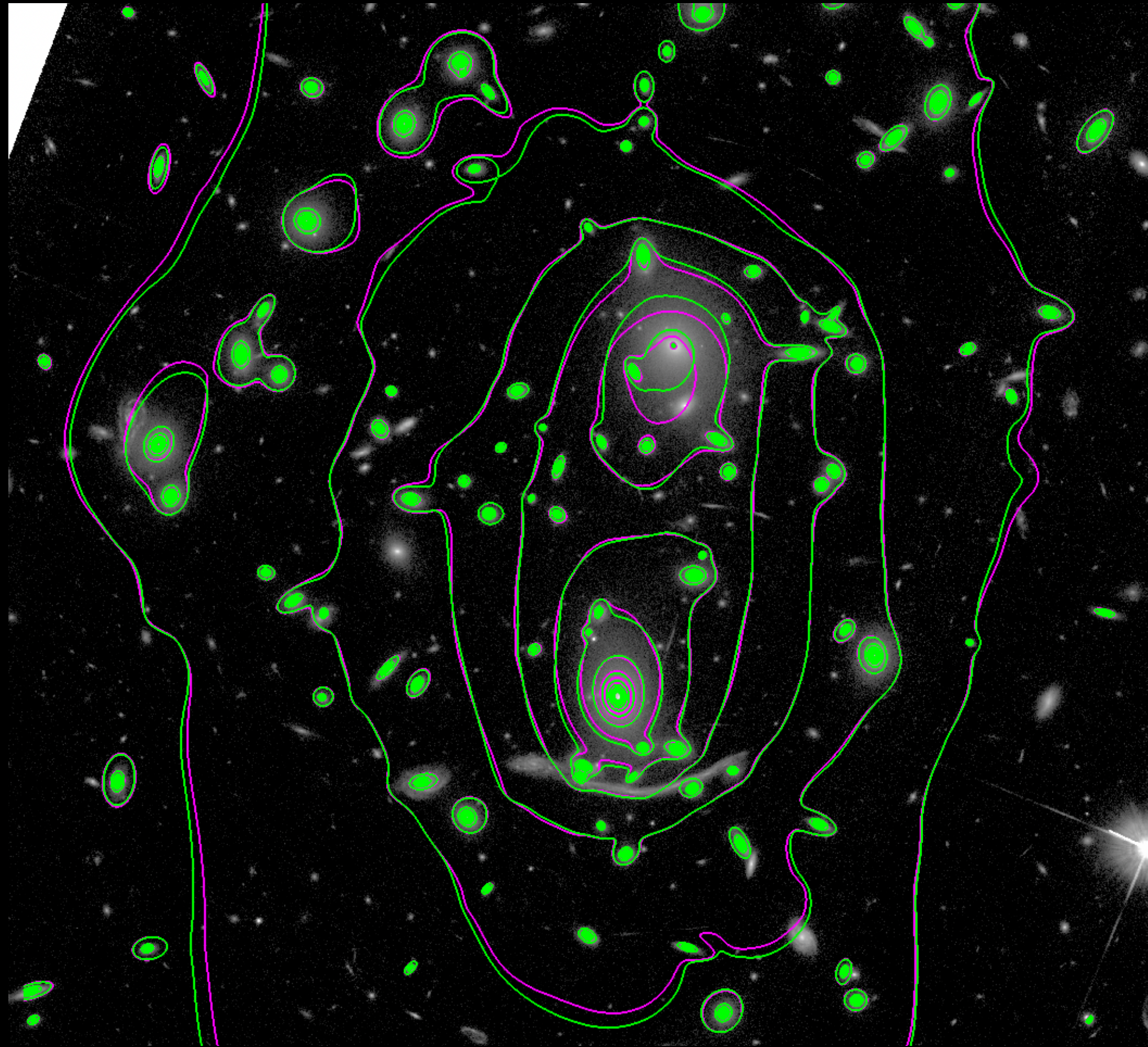
- For a grid part, we use 50x50 grids (4900 parameters including marginal region).
- We use PIEMD profiles (cluster-scale halo) and dPIE profiles (cluster member galaxies).
- A prior range for PIEMD is $[-15'', 15'']$ around each BCG for the free halo position models.
- We use the scaling relation to constrain the member galaxies, with $\alpha = 0.25$, $\beta = 0.5$ for A370 and RXJ1347, $\alpha = 0.3$, $\beta = 0.6$ for MACSJ0416.
- All multiple images have spectroscopic redshifts.

Jackknife System Mean RMS

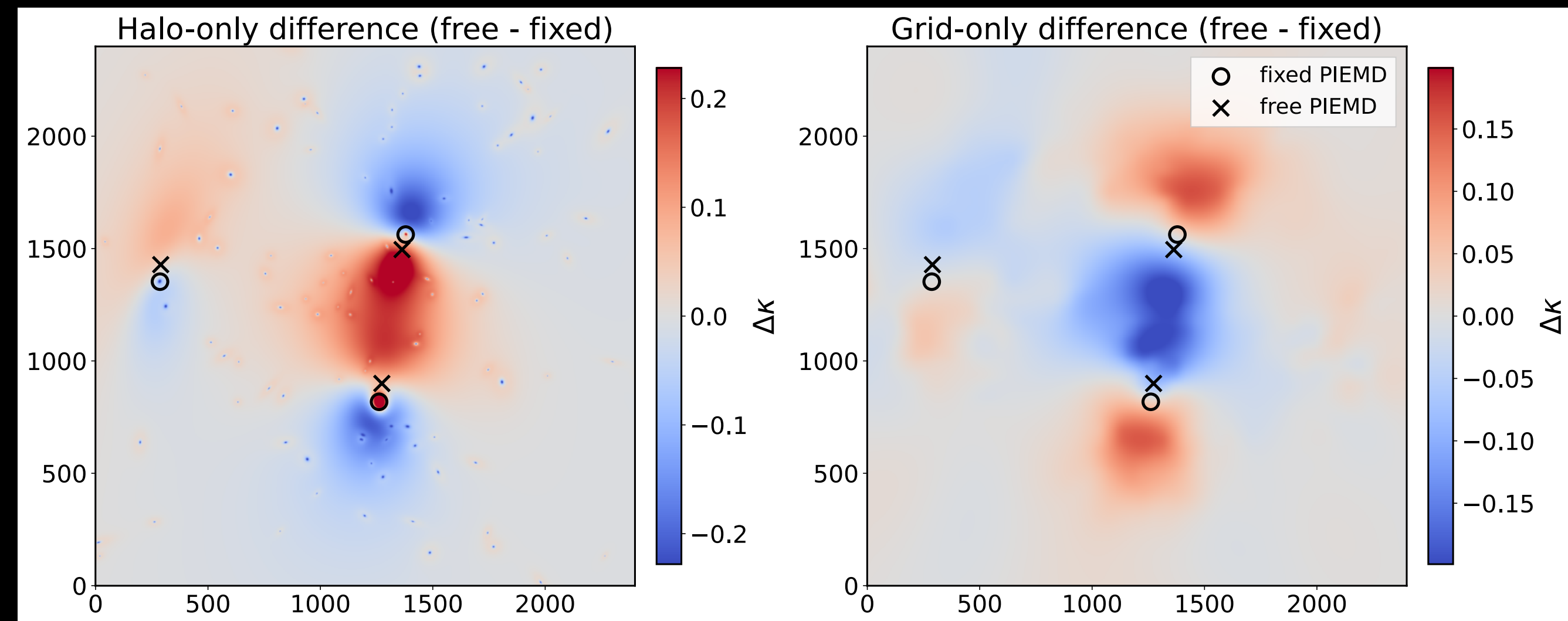
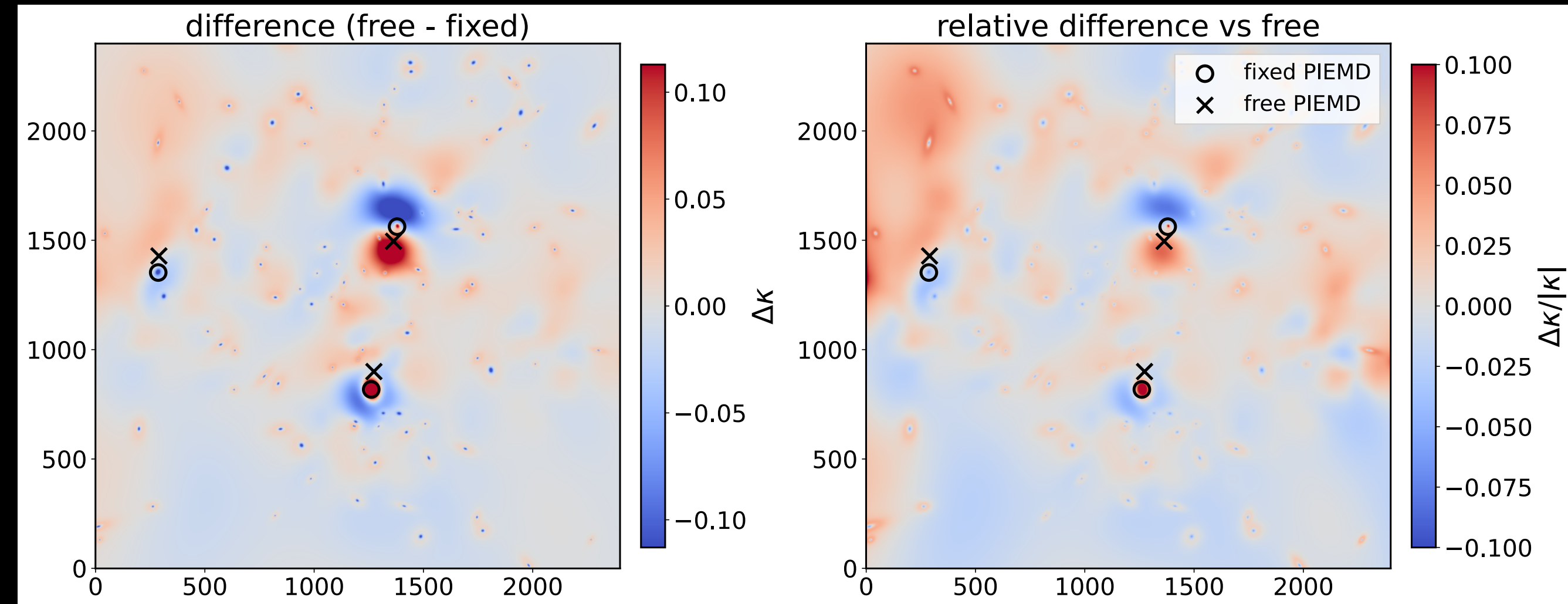


- Errors were estimated from 10000 bootstrap resamples of the held-out systems.
- For each cluster and positional assumption, we adopt the fiducial regularization weight that minimizes the mean rms of the excluded source systems.

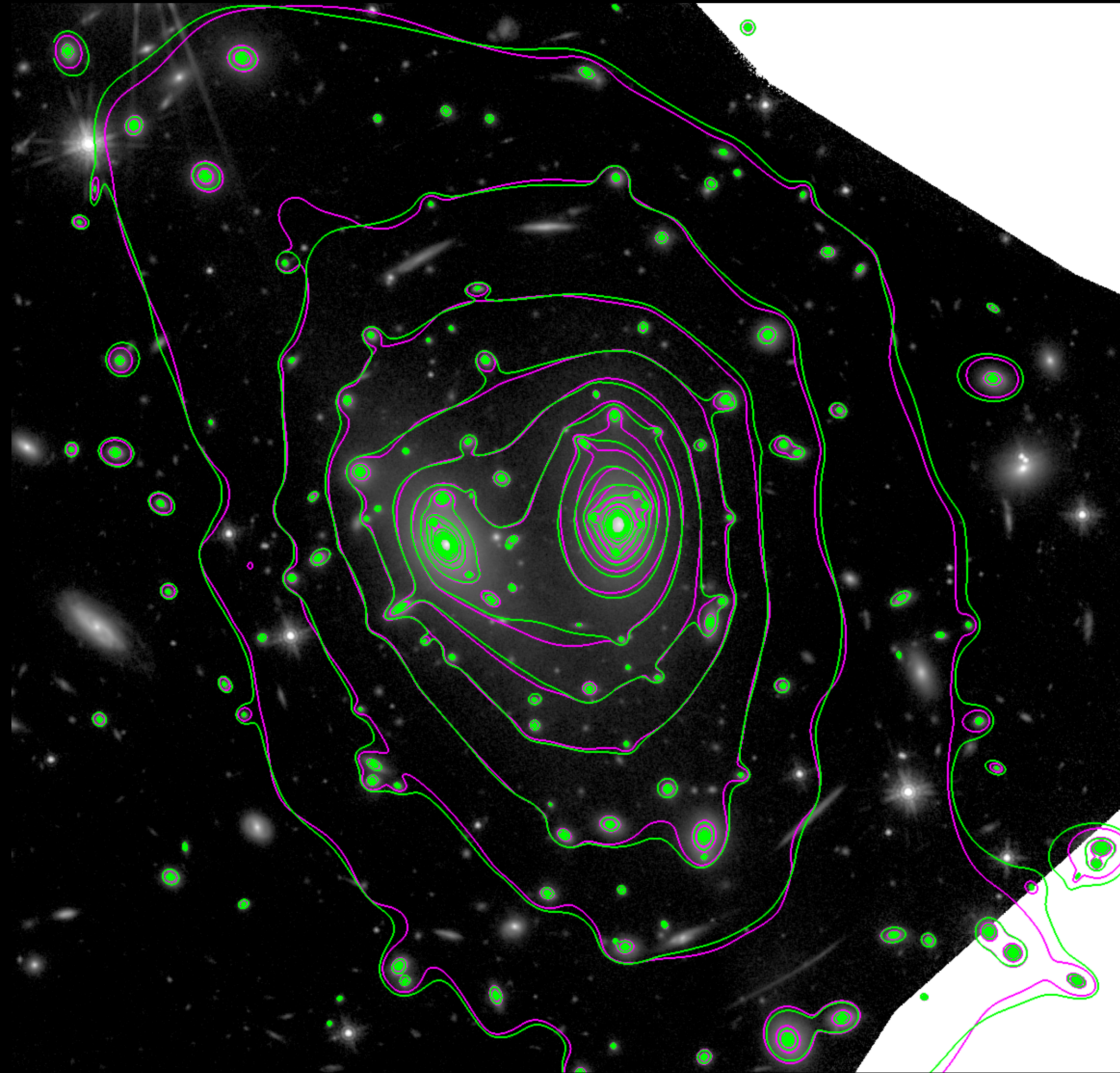
Fixed vs. Free Model Comparison - A370



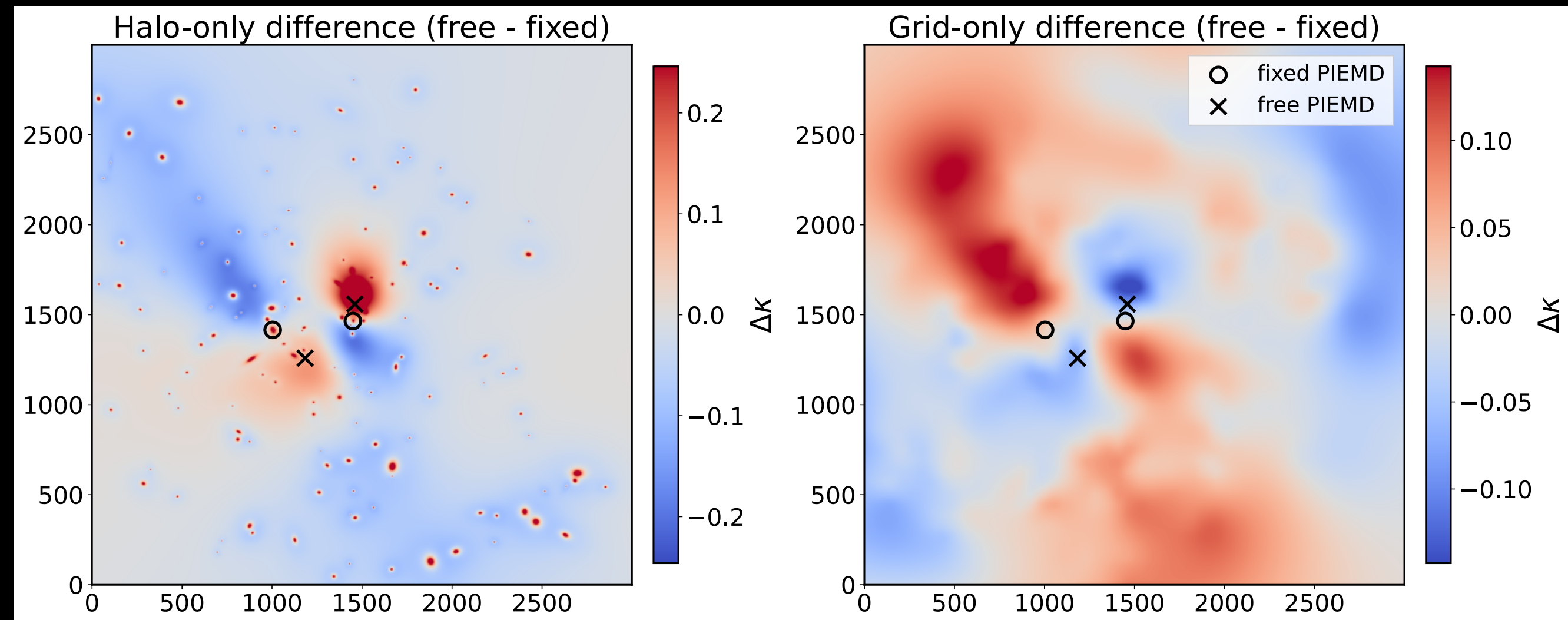
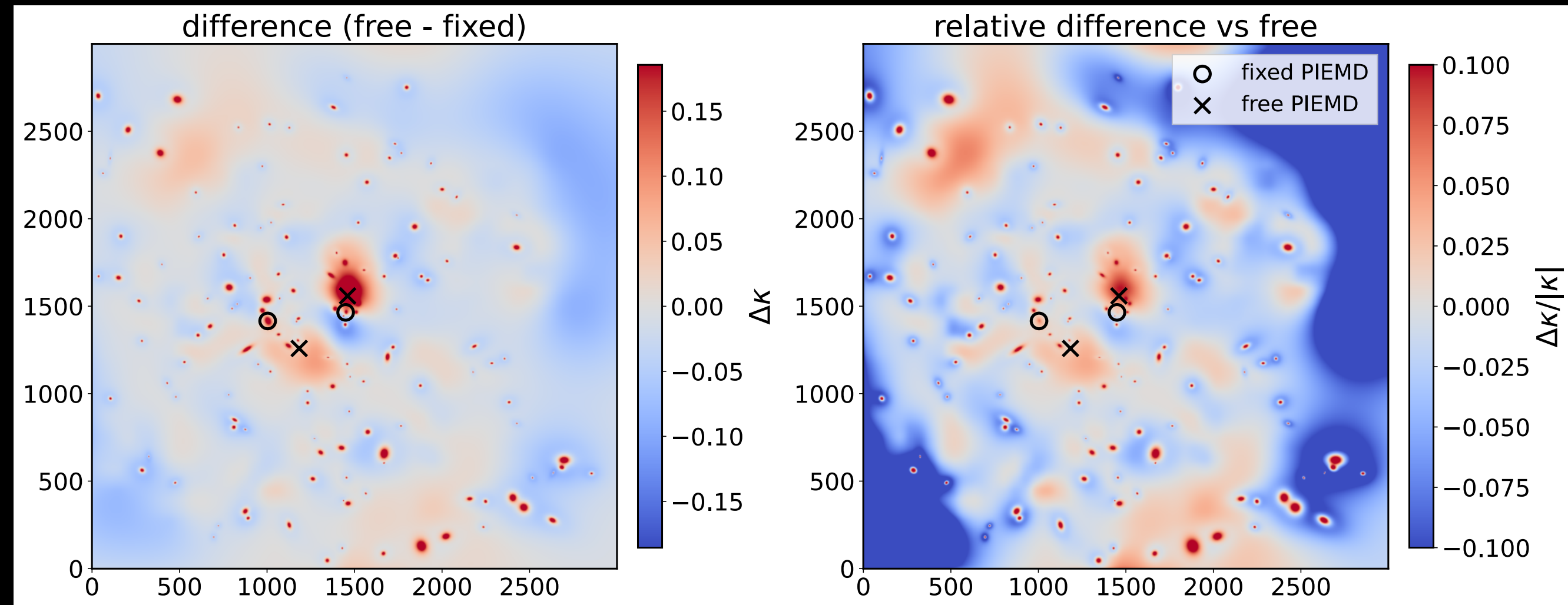
Green: fixed position
Magenta: free position



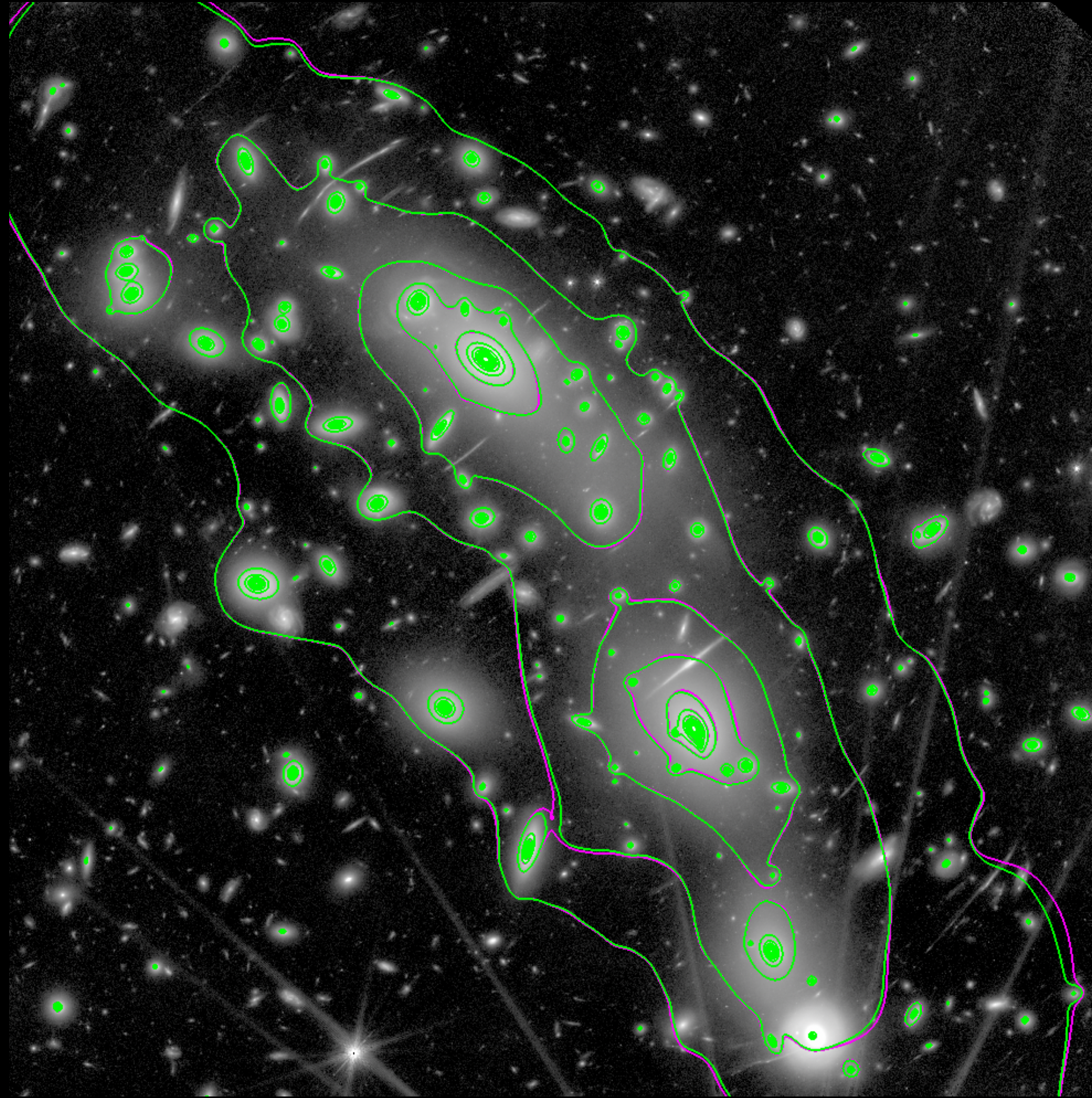
Fixed vs. Free Model Comparison - RXJ1347



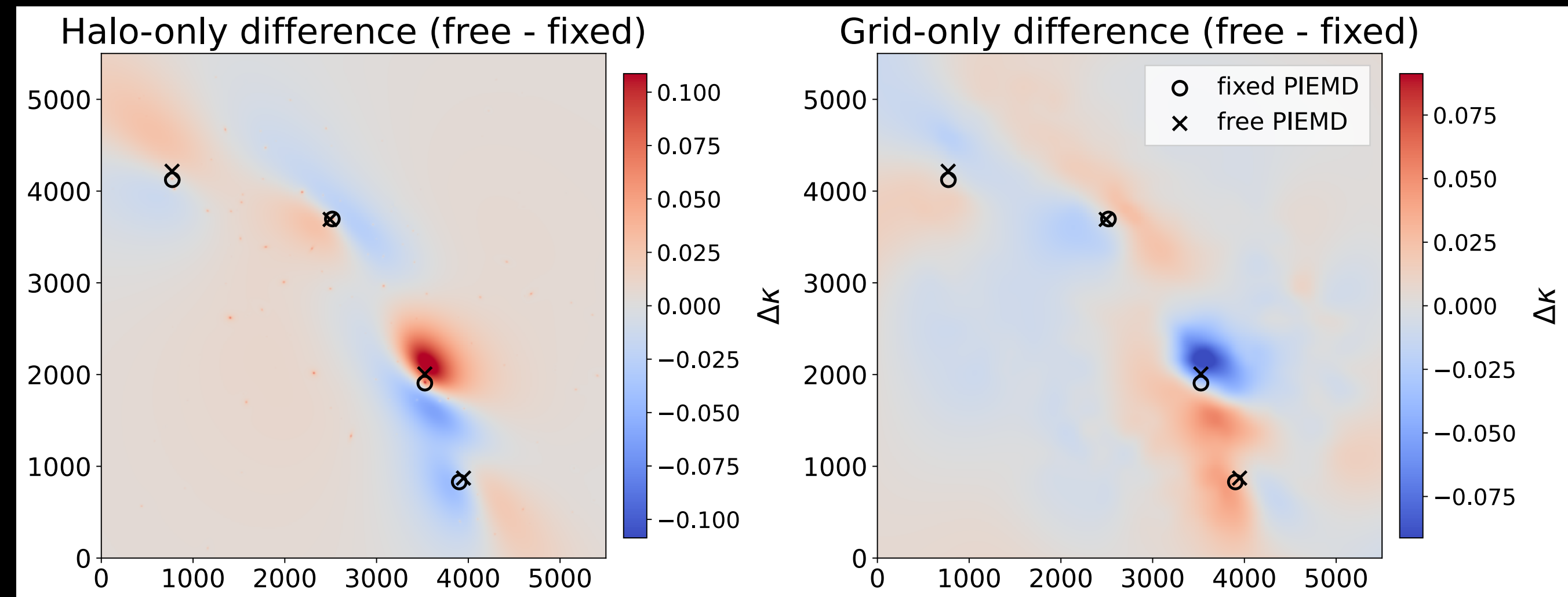
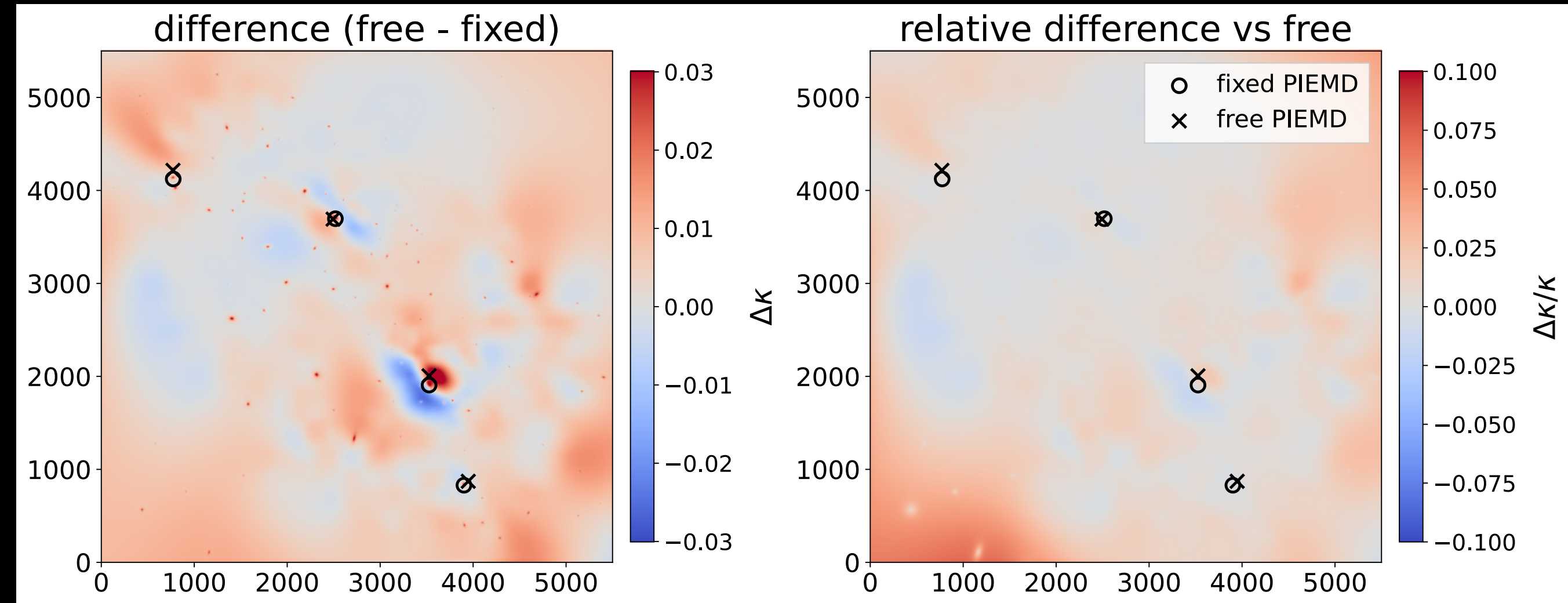
Green: fixed position
Magenta: free position



Fixed vs. Free Model Comparison - MACSJ0416

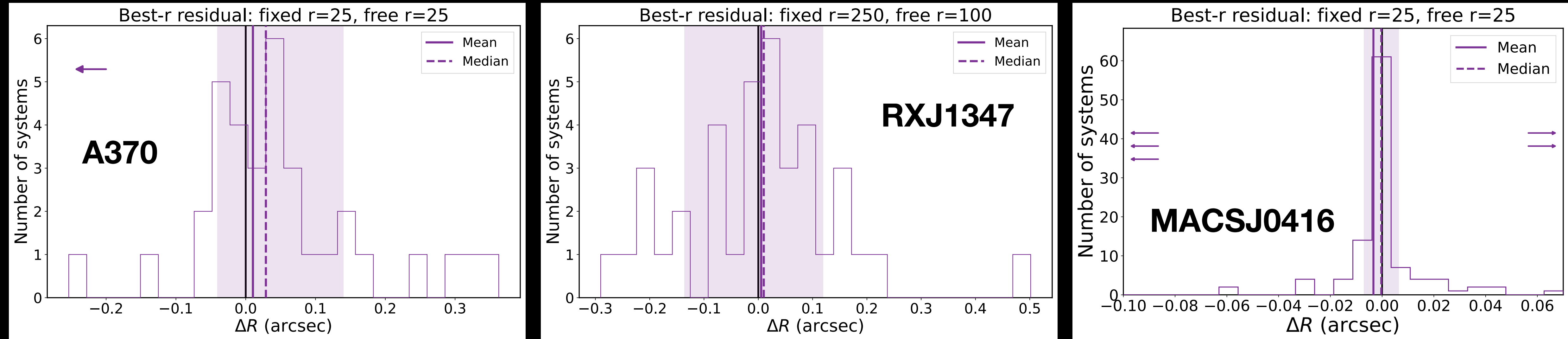


Green: fixed position
Cyan: free position



Are These Offsets Uniquely Required by SL Data?

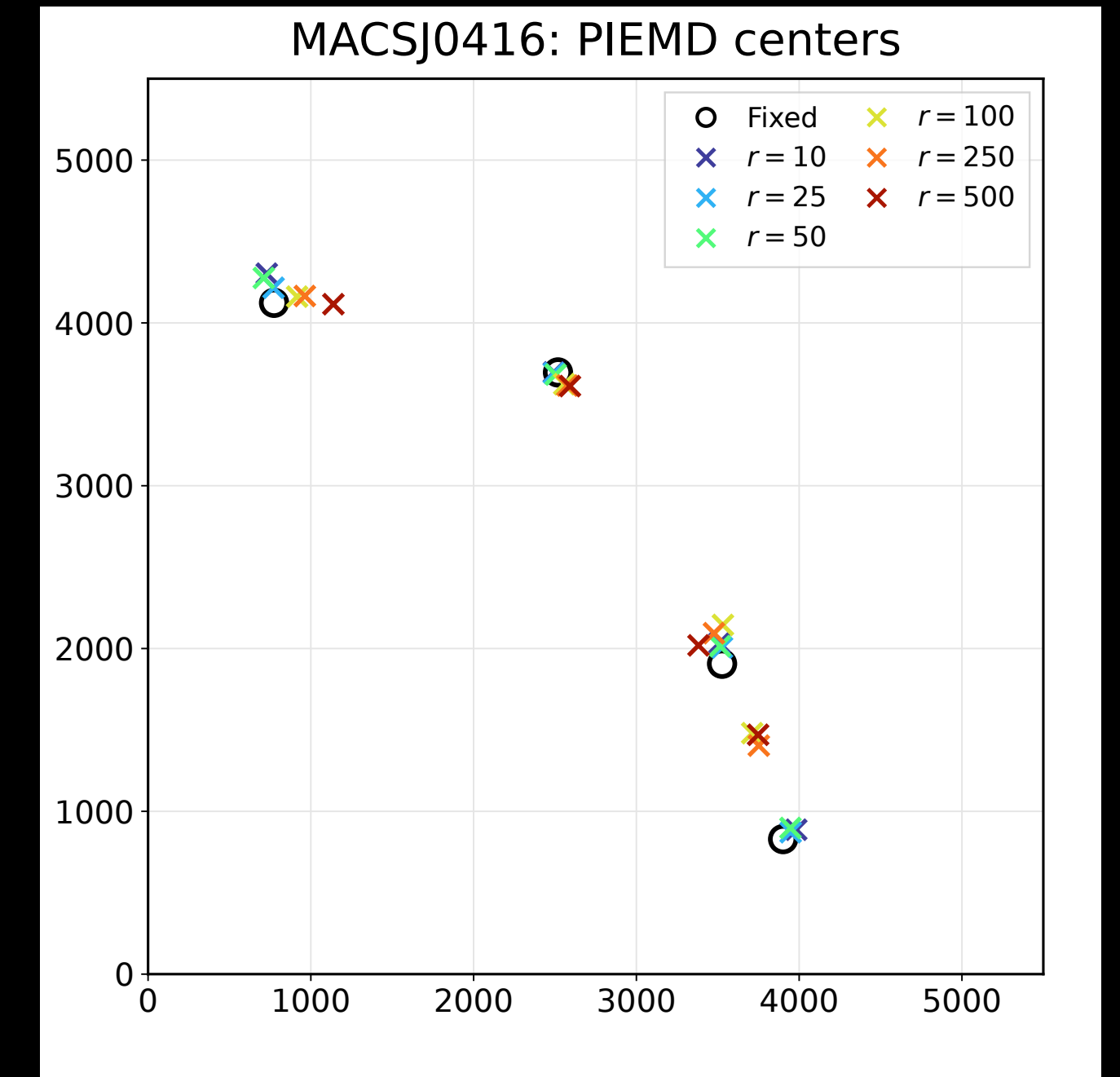
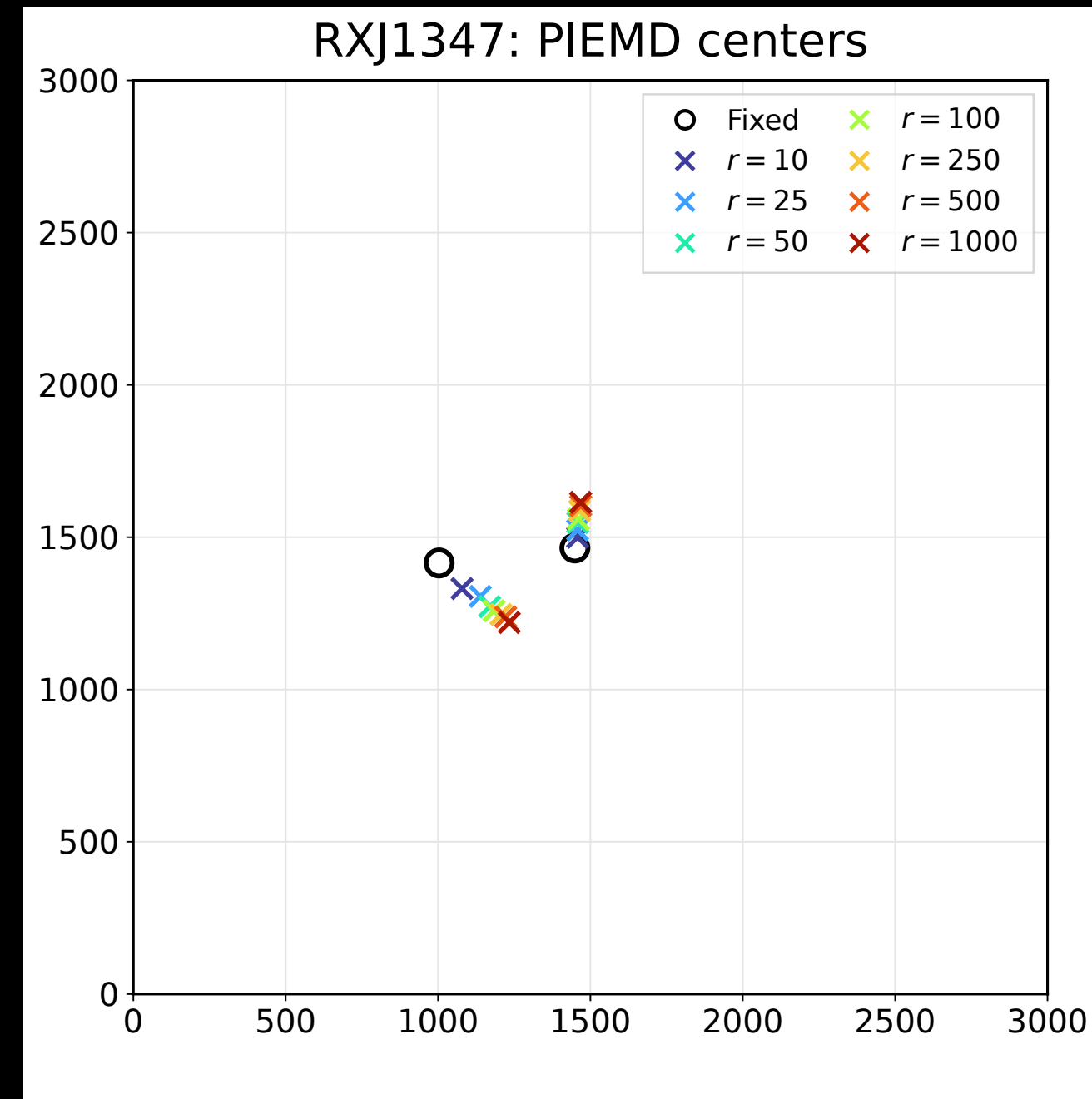
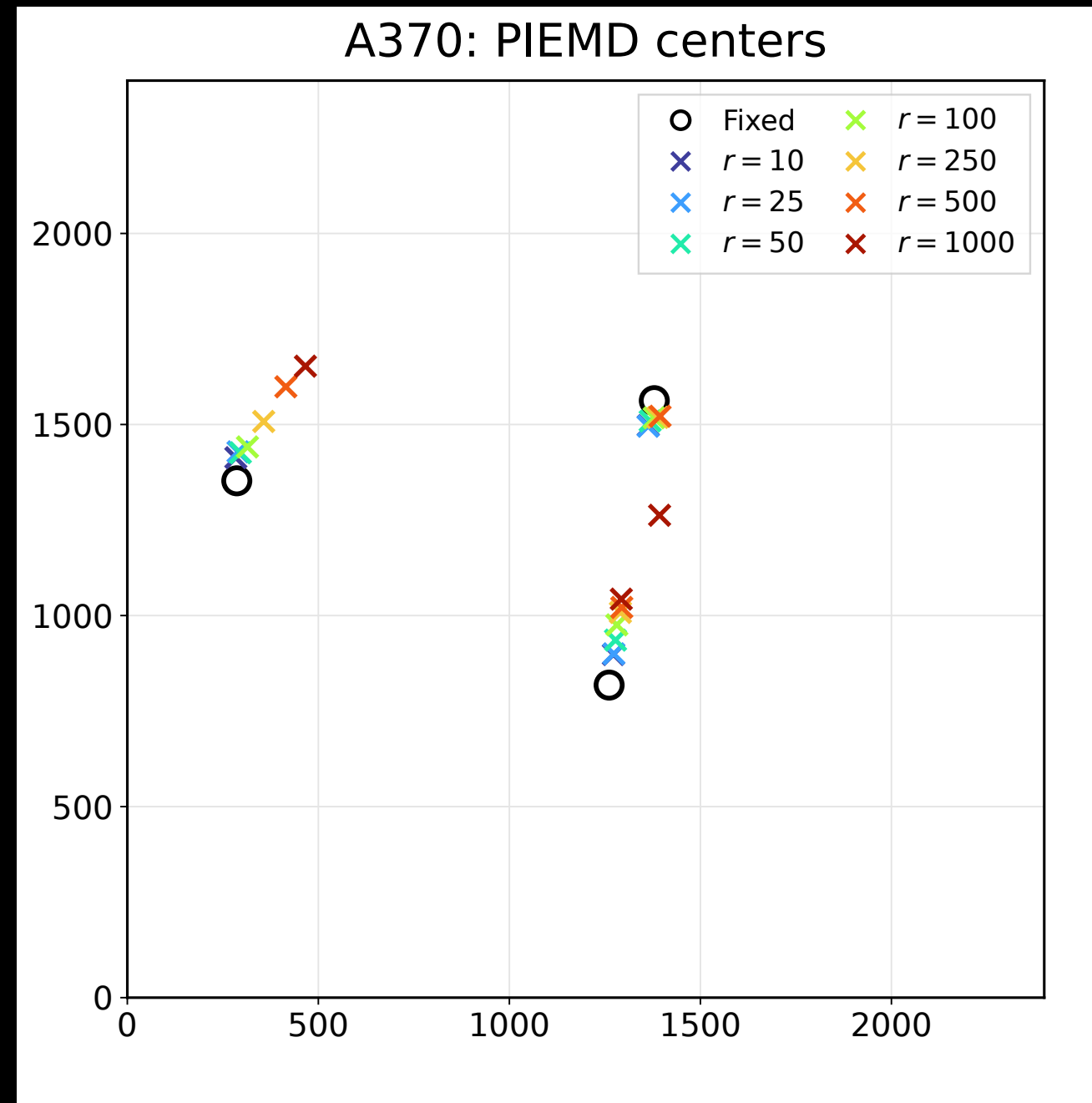
- We compute rms residuals, $\Delta R_{\text{sys}} = R_{\text{free}} - R_{\text{fixed}}$, for each excluded multiple image system.



- At the jackknife-selected regularization weights, halo position freedom does not clearly improve the prediction power for the excluded systems.
- The inferred halo offsets are one of the possible solutions, but not uniquely required by the tested SL constraints.

Are These Offsets Uniquely Required by SL Data?

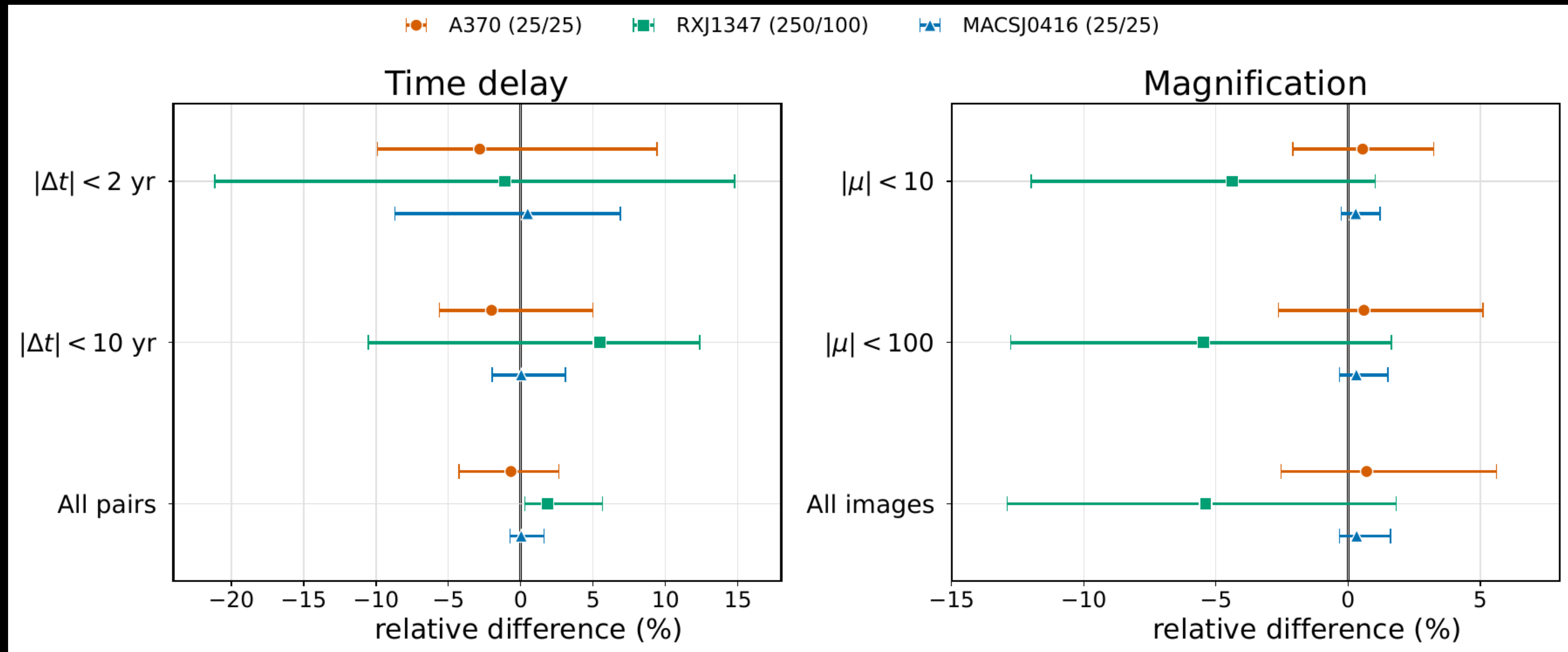
Halo Positions vs. Regularization Weight



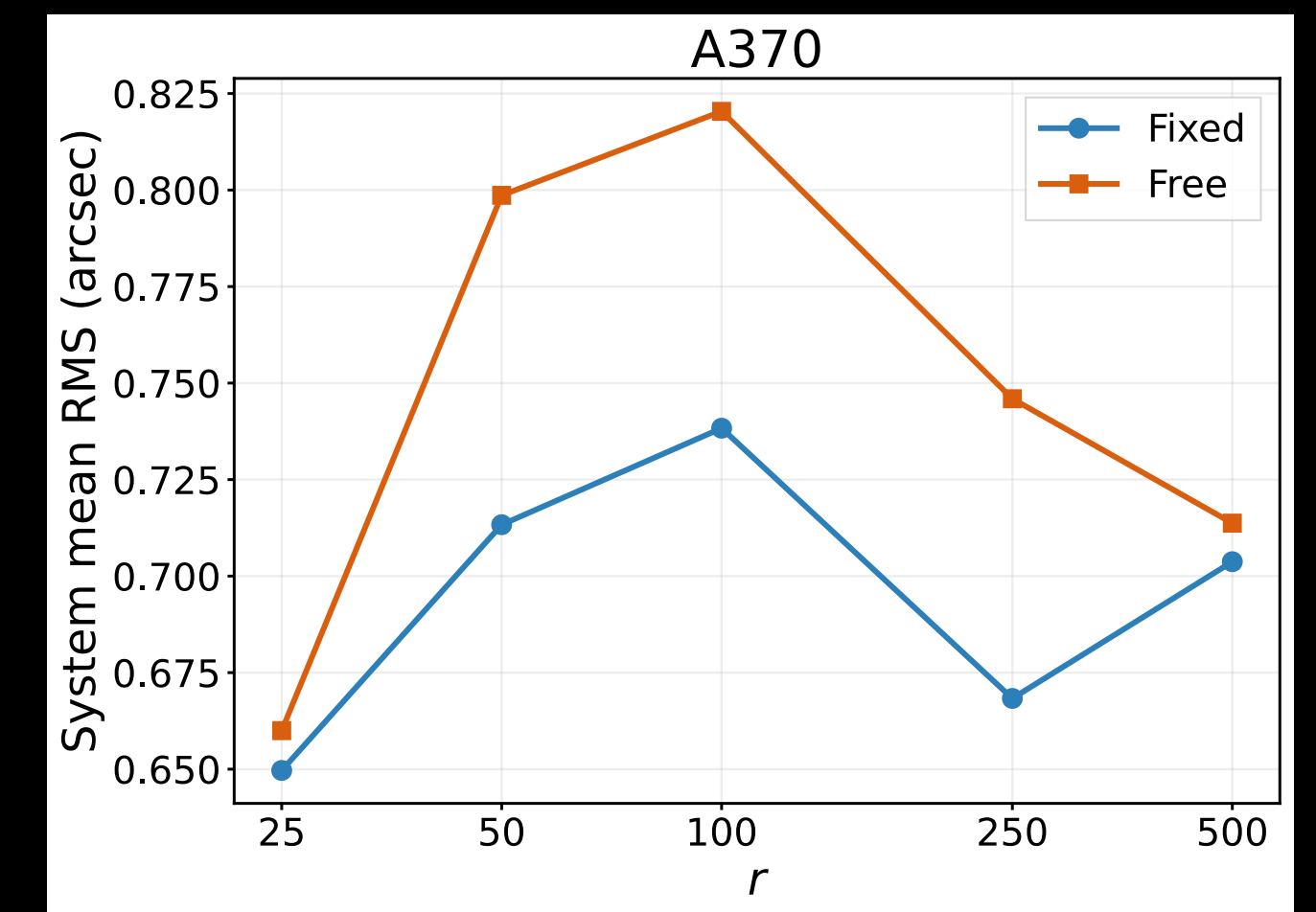
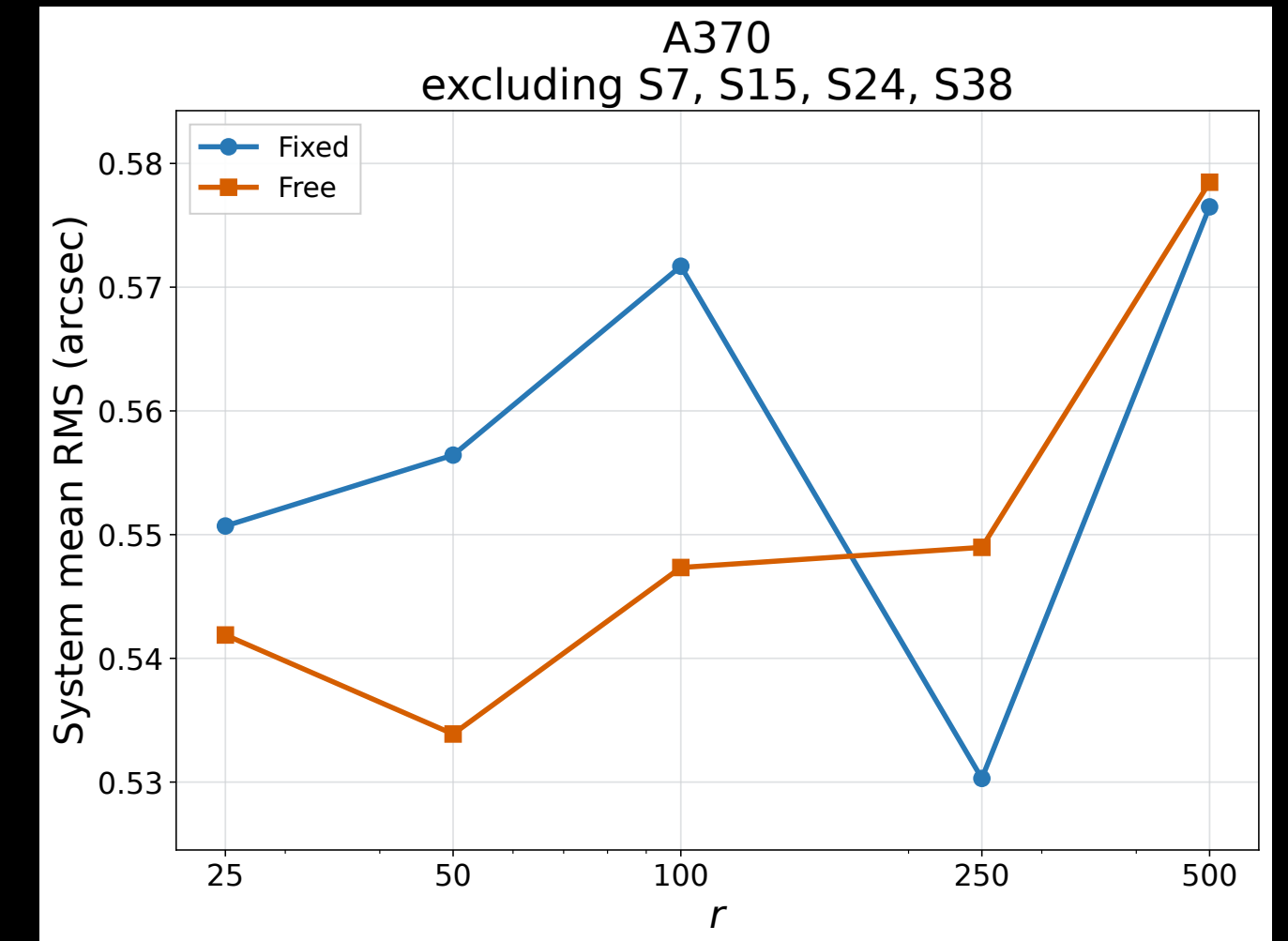
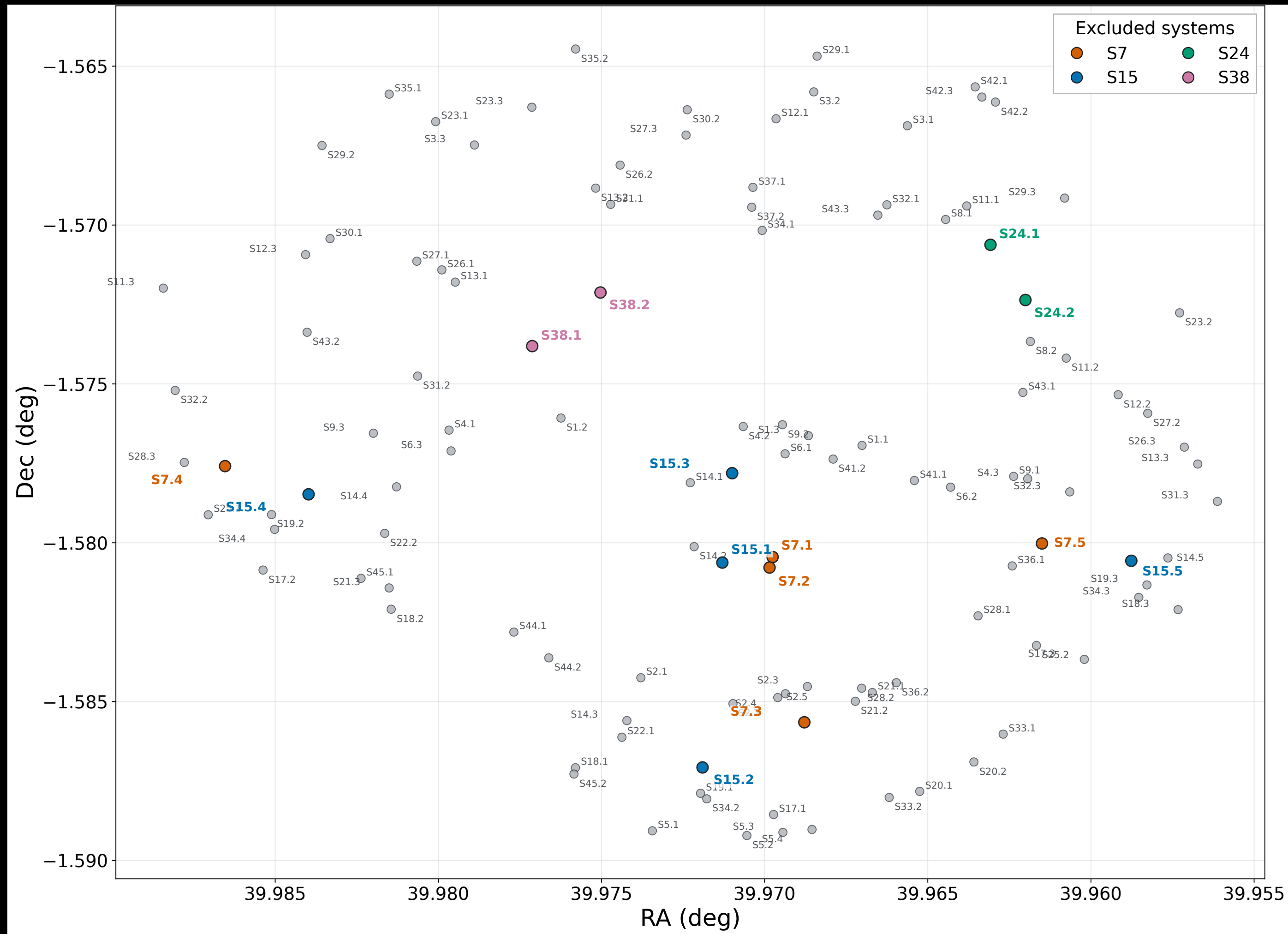
- Stronger regularization suppresses contrast in the grid and causes residual mass structure to be absorbed by shifts of the analytic halo centers.
- The offsets change with regularization, while the system mean rms remains broadly similar.
- This indicates that the separation of residual mass between the grid and halo shifts is not uniquely determined.

Time Delay & Magnification Differences

At the jackknife selected regularization weights



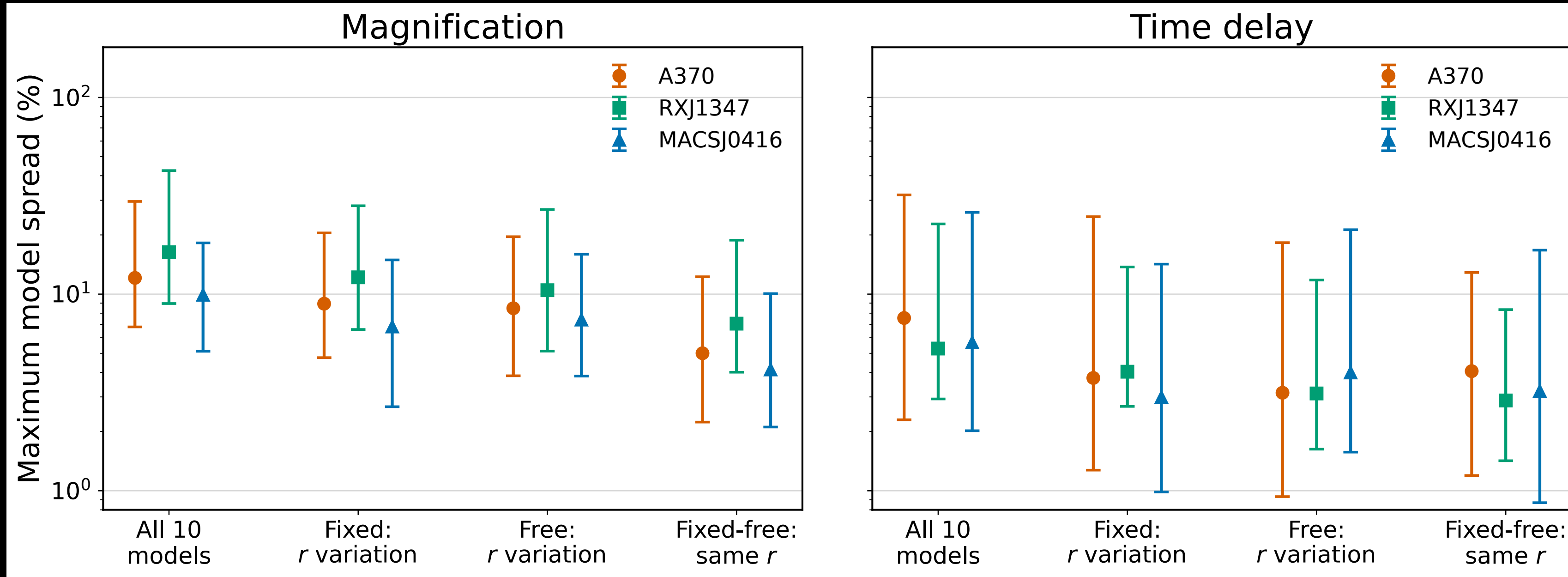
Limitations of the Jackknife Test



- Multiple-image systems are neither uniformly distributed nor equally informative, so a few high-leverage systems can dominate the jackknife rms.

Time Delays and Magnification

For all 10 models



$$D_{\max} = \max_{a,b \in M} \left[100 \frac{|a - b|}{(|a| + |b|)/2} \right],$$

$$M = \{r = 25, 50, 100, 250, 500\} \\ \times \{\text{fixed}, \text{free}\}.$$

- For a conservative analysis, we check the maximum differences among all 5 regularization weights and halo positional freedom assumptions.
- Across all 10 models for each cluster, the $D_{\max}$ is ~10% for magnification and ~5% for time delay.

Summary

- In cluster SL modeling, some lens models show large offsets between the cluster-scale halo and BCG.
- Using a jackknife test, we try to examine whether halo position freedom is required by SL multiple images.
- Allowing the halo positions to vary provides no clear improvement in predictive power, which indicates that the offsets are one of the possible solutions but not uniquely required.
- The inferred halo positions change with regularization, indicating that residual mass structure is not uniquely decomposed between the grid and halo-center shifts.
- The positional freedom and different regularization weights produce around 5-10% differences in TD and magnification.

Thank you!