Fast Two-Star Modeling of High-Resolution Images toward Joint Light-Curve and Image Fitting of Microlensing Events

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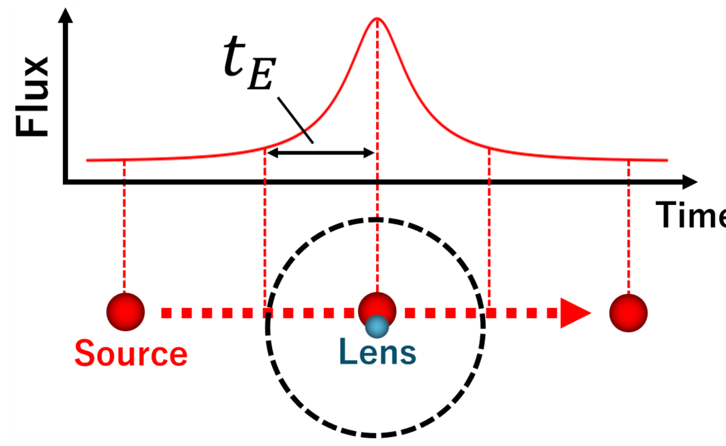
Background & Motivation

Why High-Resolution Imaging?

Microlensing Light Curves

Microlensing light curves typically constrain the event timescale, t_E.

$$t_\mathrm{E} \propto \frac{\sqrt{M_\mathrm{L}\left(D_\mathrm{L}^{-1} - D_\mathrm{S}^{-1}\right)}}{\mu_\mathrm{rel}}$$



t_E depends on a degenerate combination of the lens mass M_L, lens distance D_L, source distance D_S, and lens-source relative proper motion μ_{rel}

High-Resolution Imaging

High-resolution images obtained several years (Δt) after the event can constrain:

- Lens−Source separation vector $\boldsymbol{\Delta\theta}$ $\Rightarrow$ $\boldsymbol{\mu_{rel}} = \frac{\boldsymbol{\Delta\theta}}{\Delta t}$
- Lens Flux F_L provides information on M_L and D_L

Combining these measurements with the light curve helps break the degeneracy among the lens mass, distance, and relative proper motion.

Toward Joint Light-Curve and High-Resolution Image Fitting

Many Roman microlensing lenses are expected to be faint, low-mass stars such as M dwarfs, leaving some lens–source pairs unresolved or the lens undetected during the mission. In these cases, lens flux and separation are strongly correlated, limiting constraints from imaging alone.

Joint fitting of the light curve and high-resolution image can incorporate constraints on the source flux, relative proper motion, and microlens parallax derived from the light-curve analysis, thereby reducing this degeneracy and enabling lens characterization before the lens and source are fully resolved.

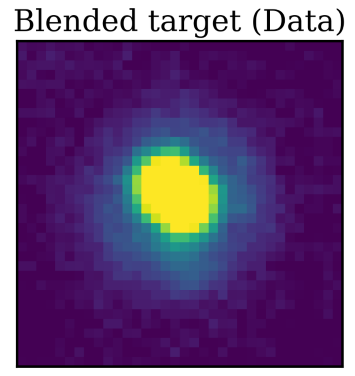
However, applying joint fitting to large Roman samples requires repeated evaluation of the image likelihood during MCMC sampling, motivating a fast framework for high-resolution two-star image fitting.

Method

1. DAOPHOT-Based Two-Star Image Model

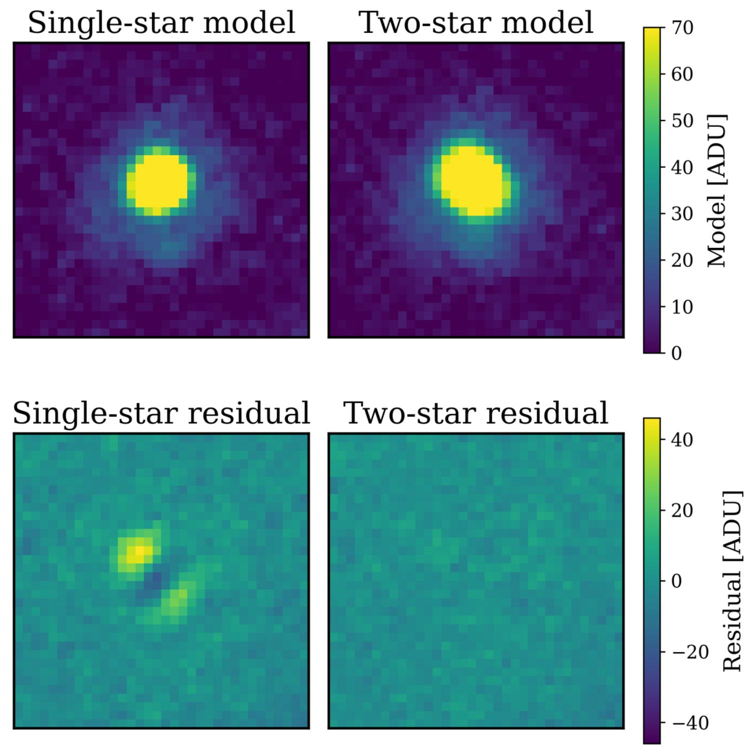
As a proof of concept, we tested two-star fitting on a visually elongated stellar target in a Keck adaptive-optics image. An empirical PSF was constructed from isolated stars using the standard DAOPHOT procedure (Stetson 1987). The target was modeled as two shifted and scaled PSFs:

$$M_{i,j} = F_1 P(i - x_1, j - y_1) + F_2 P[i - (x_1{+}\Delta x), j - (y_1{+}\Delta y)]$$



Here, F_1 and F_2 are the component fluxes and $(\Delta x, \Delta y)$ is their pixel separation. DAOPHOT interpolation enables subpixel centroid measurements.

The example at right shows that the two-star model reduces the structured residuals left by the single-star fit.



Because the component positions and fluxes are correlated, we use MCMC to sample their joint posterior distribution, $(x_1, y_1, \Delta x, \Delta y, F_1, F_2)$ and propagate their uncertainties. The posterior pixel separation is converted into an angular separation using the astrometric calibration.

2. Accelerating PSF Evaluation with JAX

The DAOPHOT algorithm evaluates the PSF pixel by pixel. A direct Python implementation therefore requires nested loops, making repeated likelihood evaluations during MCMC computationally expensive.

To remove this bottleneck, we replaced the pixel-wise loops with **vectorized** array operations and compiled the image-likelihood function using **JAX just-in-time (JIT)** compilation. This eliminates Python-level nested loops and accelerates repeated likelihood evaluations during MCMC sampling.

Results & Outlook

Faster Likelihood Evaluation

We compared the Python nested-loop and vectorized JAX JIT implementations using the same posterior-chain inputs in 32-walker batches.

Implementation	Likelihood-evaluation time per 32-walker batch
Python nested loops	4.91 s
Vectorized JAX + JIT	2.39 ms

2,054× faster

※Median of five repeats over the same 100 posterior-chain batches; JIT compilation time is excluded.

Future Work

Joint Light-Curve and Image Fitting

We have developed a joint-fitting framework that combines the microlensing light-curve likelihood with the fast two-star image likelihood developed in this work. We will apply it to events followed up with Keck and other facilities in which the lens and source remain unresolved, testing whether joint fitting can constrain the lens flux and relative proper motion before full separation

Extension to Roman Imaging

The current implementation uses a DAOPHOT-based empirical PSF derived from Keck AO data. Applying the framework to Roman WFI images will require a Roman-specific effective PSF that accounts for undersampling and spatial variation across the field. We will replace the PSF-evaluation module while retaining the vectorized, JAX-compatible two-star likelihood framework.

References

Stetson, P. B. 1987, PASP, 99, 191