

Building a lookup table for strongly lensed transients and prospects for **FiNK**

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James Nightingale



CBPF

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Fink-Brazil Workshop @ CBPF - RIO



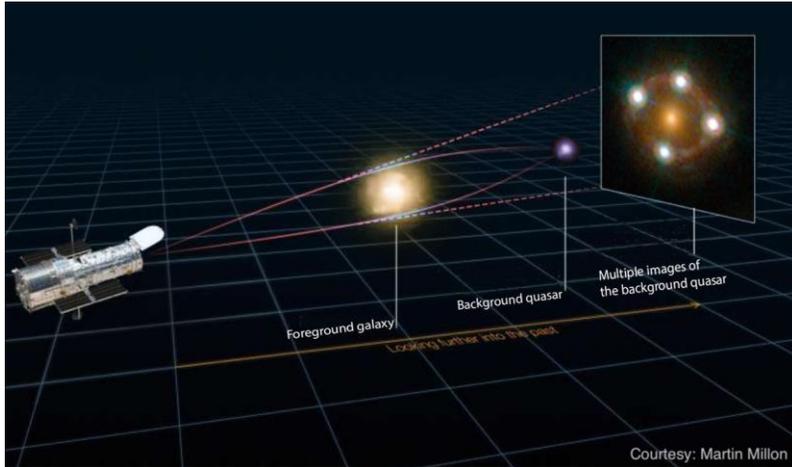
Credit: HSC, SuGOHi-X¹ & LaStBeRu

Outline of this talk

- Strong lensing and the H_0 parameter
- The LaStBeRu
 - Sample
 - (Vetting and) Tagging SL candidate systems
- SL modeling
 - Point-source and Extended modeling
 - Modeling a comprehensive sample
- ZTF crossmatches with LaStBeRu SL candidate systems
 - J043814.8-121714.0 & J043814.8-121714.0 Light curve and modeling results
 - Time-delay predictions
- Summary

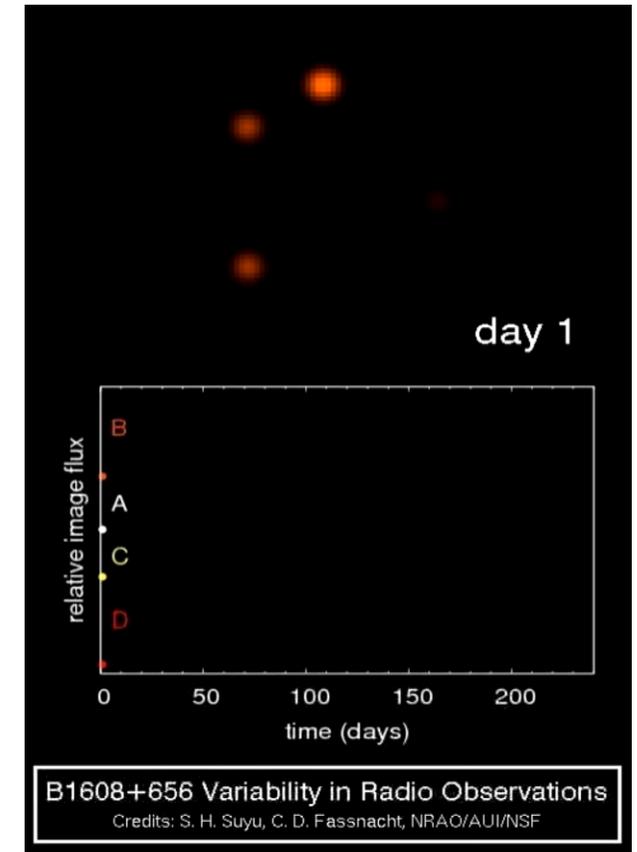
Measuring H_0 with Strong Lensing (SL)

Time-delay cosmography



- If source is variable, there is a time-delay between multiple images
- Allows to probe absolute distances of source-lens-observer configuration
- Direct measure of H_0

Radio observations of J1608+656
10.1086/309557, Snellen+ 95



Credit: S. Suyu, C. Fassnacht

$$t(\theta, \beta) = \frac{1}{c} \frac{D_d D_s}{D_{ds}} (1 + z_d) \phi \left[\frac{(\theta - \beta)^2}{2} - \psi(\theta) \right]$$

$$D_{\Delta t} \propto \frac{1}{H_0}$$

Time-delay distance

Relative time-delay
between pairs of images

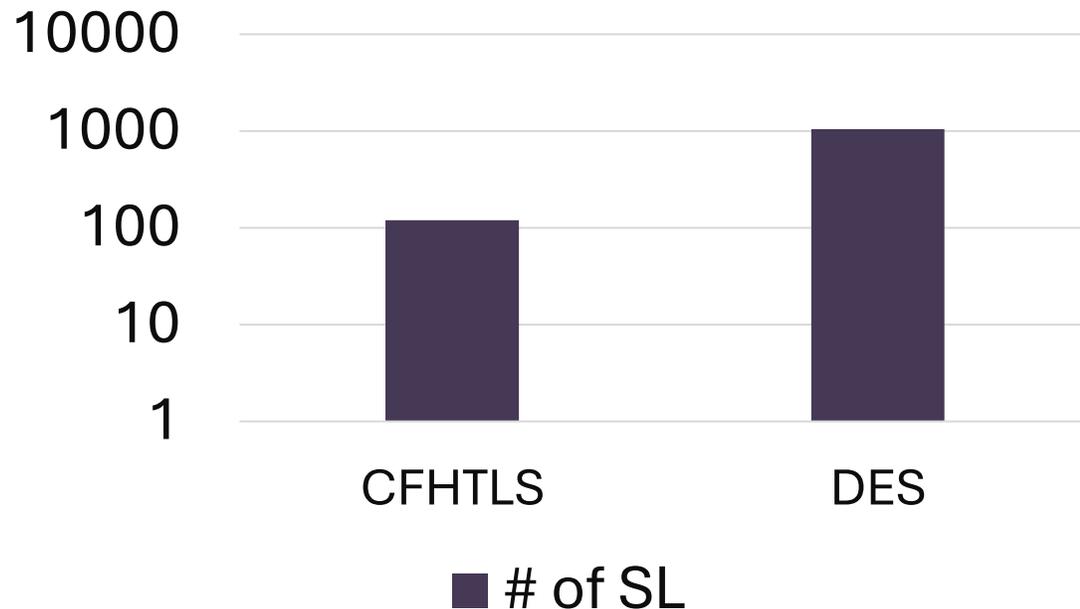
$$\Delta\tau = \frac{1}{c} D_{\Delta t} \Delta\phi$$

Monitoring → ← Modeling

The Last Stand Before Rubin (LaStBeRu)

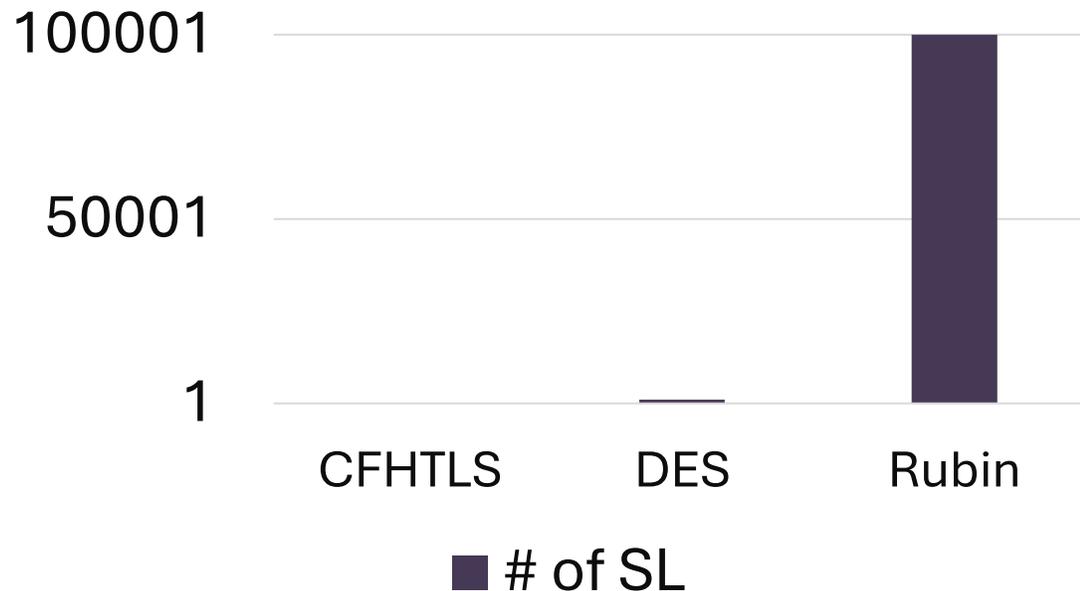
Rubin Observatory

- 15 TB/night for 10 years
- Covers 18000 deg ² (40% sky)
- **thousands of lensed quasars** and **hundreds of lensed SNe** in the 10-year LSST survey [Oguri & Marshall 2010; Goldstein et al. 2017; Wojtak et al. 2019]



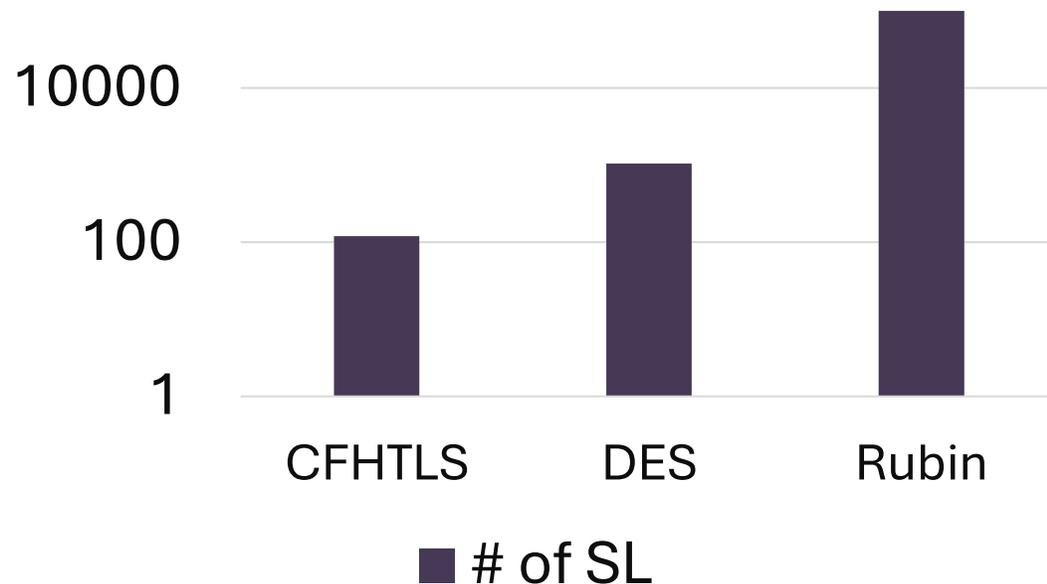
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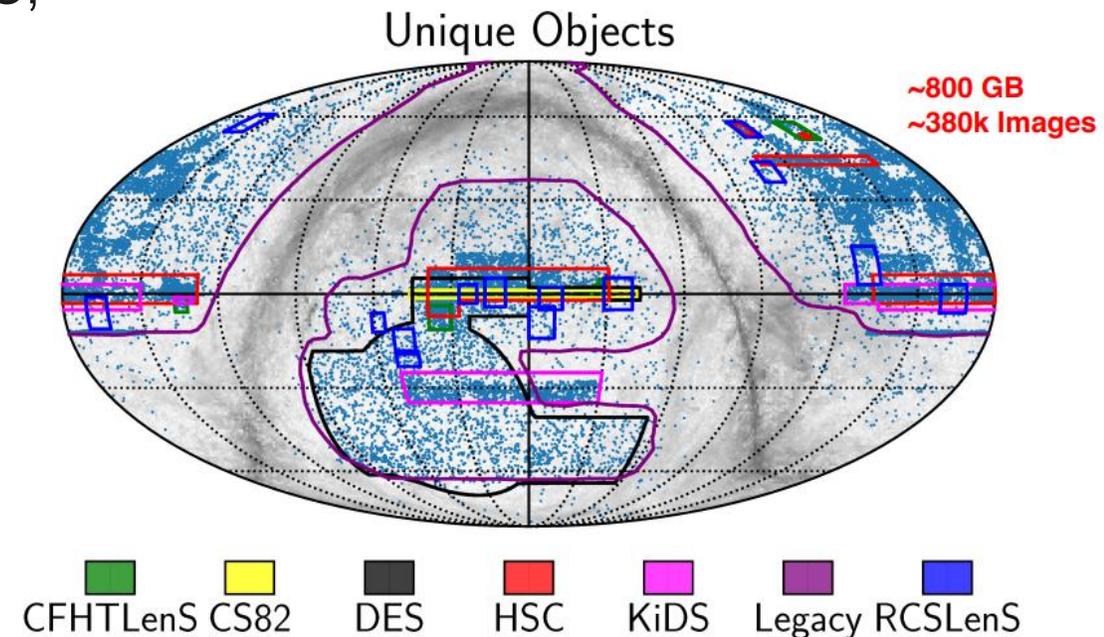
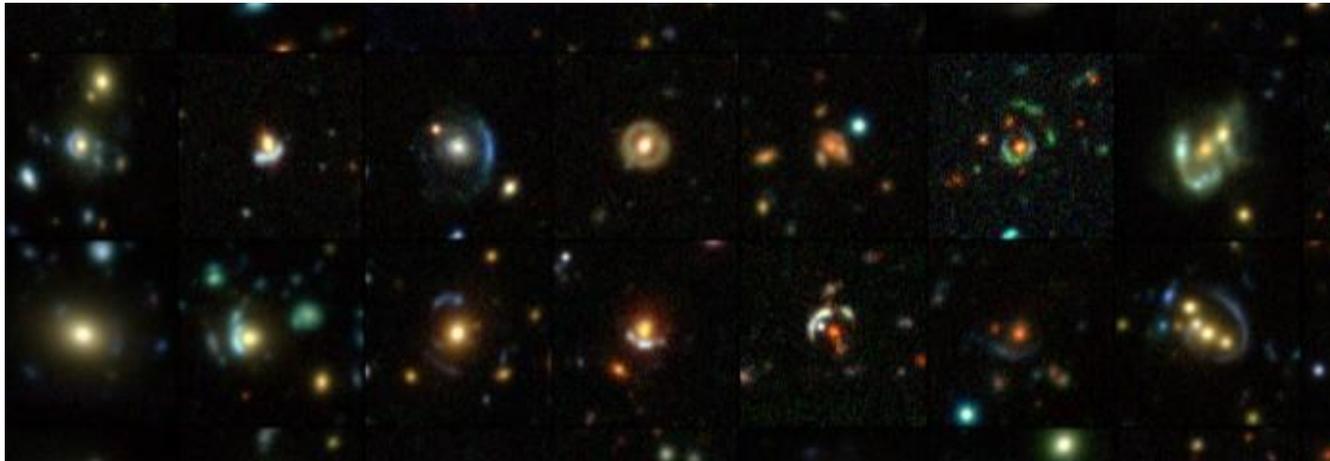


the Last Stand Before Rubin (LaStBeRu)



Renan Oliveira

- A compilation of SL **candidate systems** from various catalogs (mostly from wide-field surveys and spectroscopic surveys) in a single database
- **Cutouts/postage-stamps** of the systems (sizes 4' x 4' and 20" x 20") + **RGB color composites** in DES, HSC, KiDS (+RCSLenS, CFHTLenS, CS82)
- Crossmatch with **photometric** and **spectroscopic surveys**



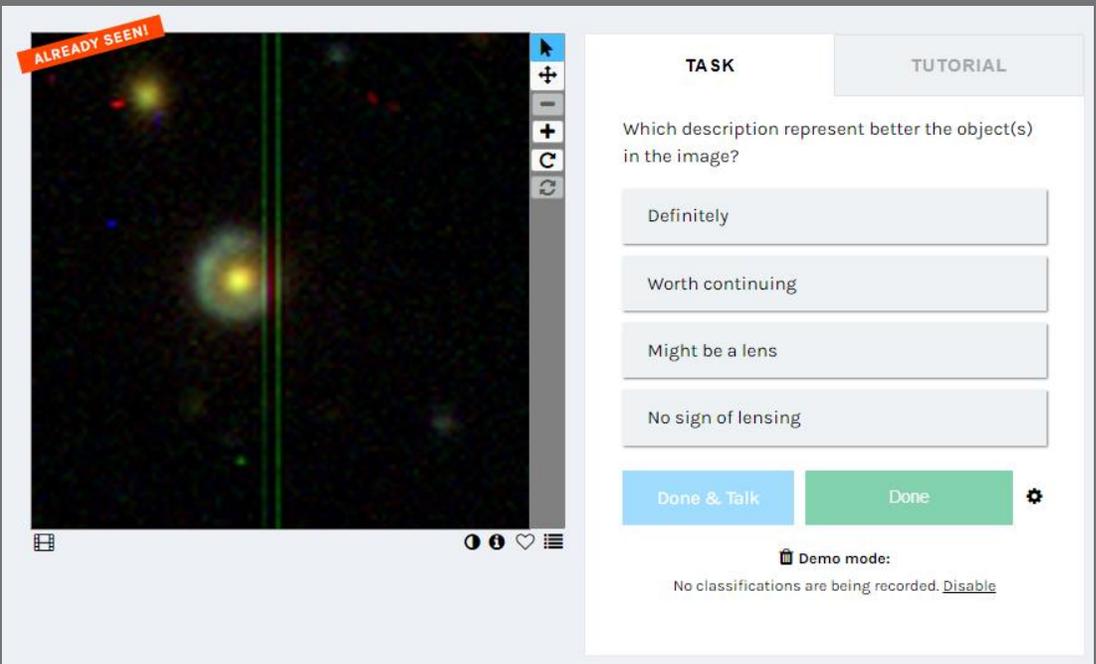
Oliveira and Makler, in Prep.

Classifying candidate SL systems in ground-based images

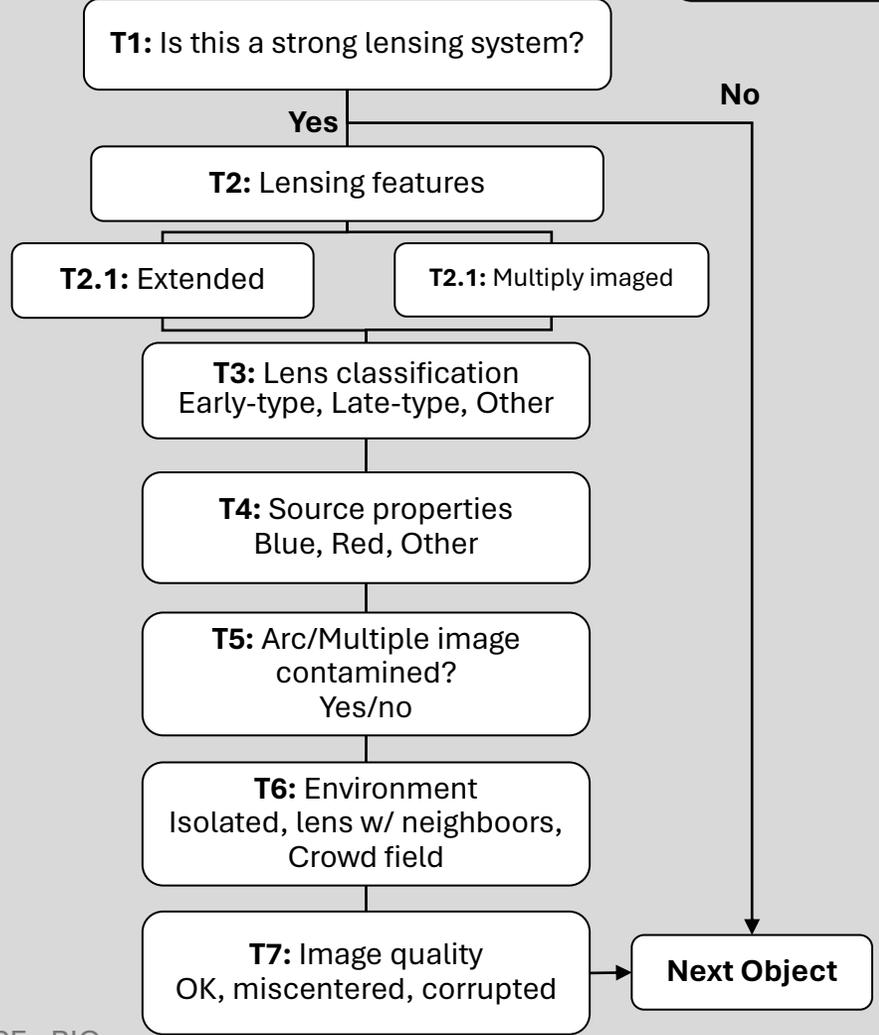
Vetting

Tagging

T1: Quality of the system as a possible SL



- Survey-independent classification**
- CFTHLenS
 - CS82
 - RCSTLenS
 - KiDS
 - HSC
 - DES
 - Legacy



Classifying candidate SL systems in ground-based images



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NOTIFICATIONS MESSAGES JOAOFRANCA ▾

Classifying strong lensing system candidates in ground-based images

EXPLORE PROJECT ▾

Learn more

<https://www.zooniverse.org/projects/joaofranca/classifying-strong-lensing-system-candidates-in-ground-based-images>

Inverse modeling

Point-source modeling

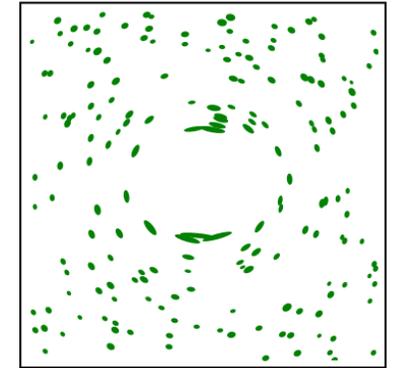
Elliptical Power-Law (EPL) projected mass density

$$k_\alpha(x, y) = \frac{\Sigma(\xi)}{\Sigma_{\text{crit}}} = \frac{3 - \alpha}{1 + q} \left(\frac{b}{\xi} \right)^{\alpha - 1}$$

External shear

$$\gamma_1 = \frac{1}{2} \left(\frac{\partial^2 \psi}{\partial \theta_1^2} - \frac{\partial^2 \psi}{\partial \theta_2^2} \right)$$

$$\gamma_2 = \frac{\partial^2 \psi}{\partial \theta_1 \partial \theta_2}$$



https://en.wikipedia.org/wiki/Weak_gravitational_lensing

Using multiply images to determine the lensing potential

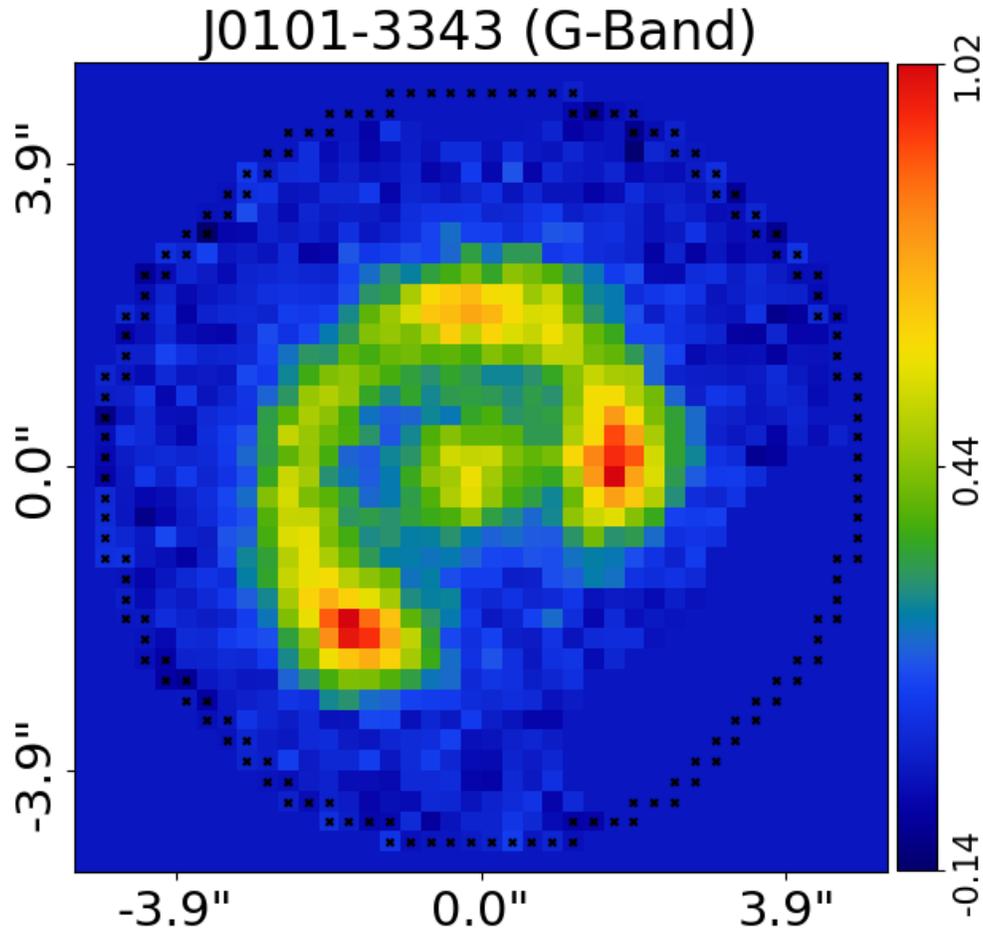
(q, mass(b), etc)

$$\chi_{\text{lente}}^2 := \sum_i \left(\frac{\vec{\theta}_i^{\text{obs}} - \vec{\theta}^{\text{mod}}(\vec{\beta}, \vec{\Pi})}{\sigma_i^{\text{obs}}} \right)^2$$

Multiple image positions

Error on image positions

$\vec{\Pi}$: parameters of the mass distribution and cosmological parameters



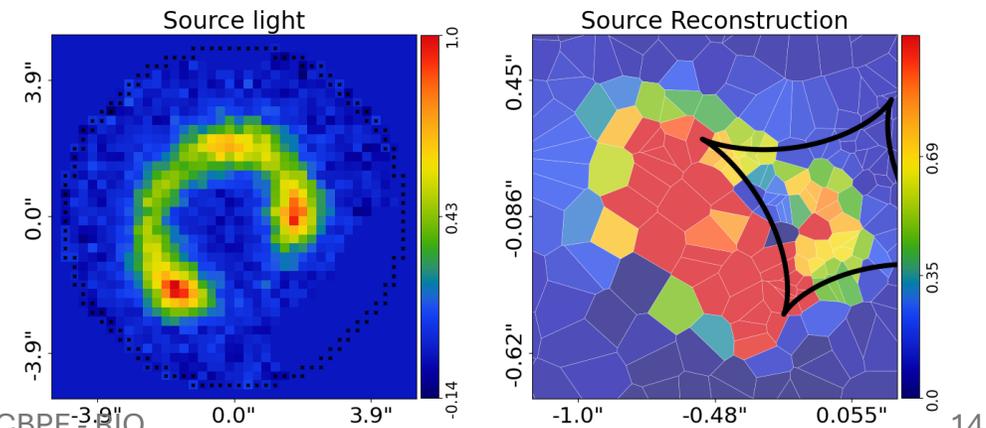
Extended sources and adaptive pixelization

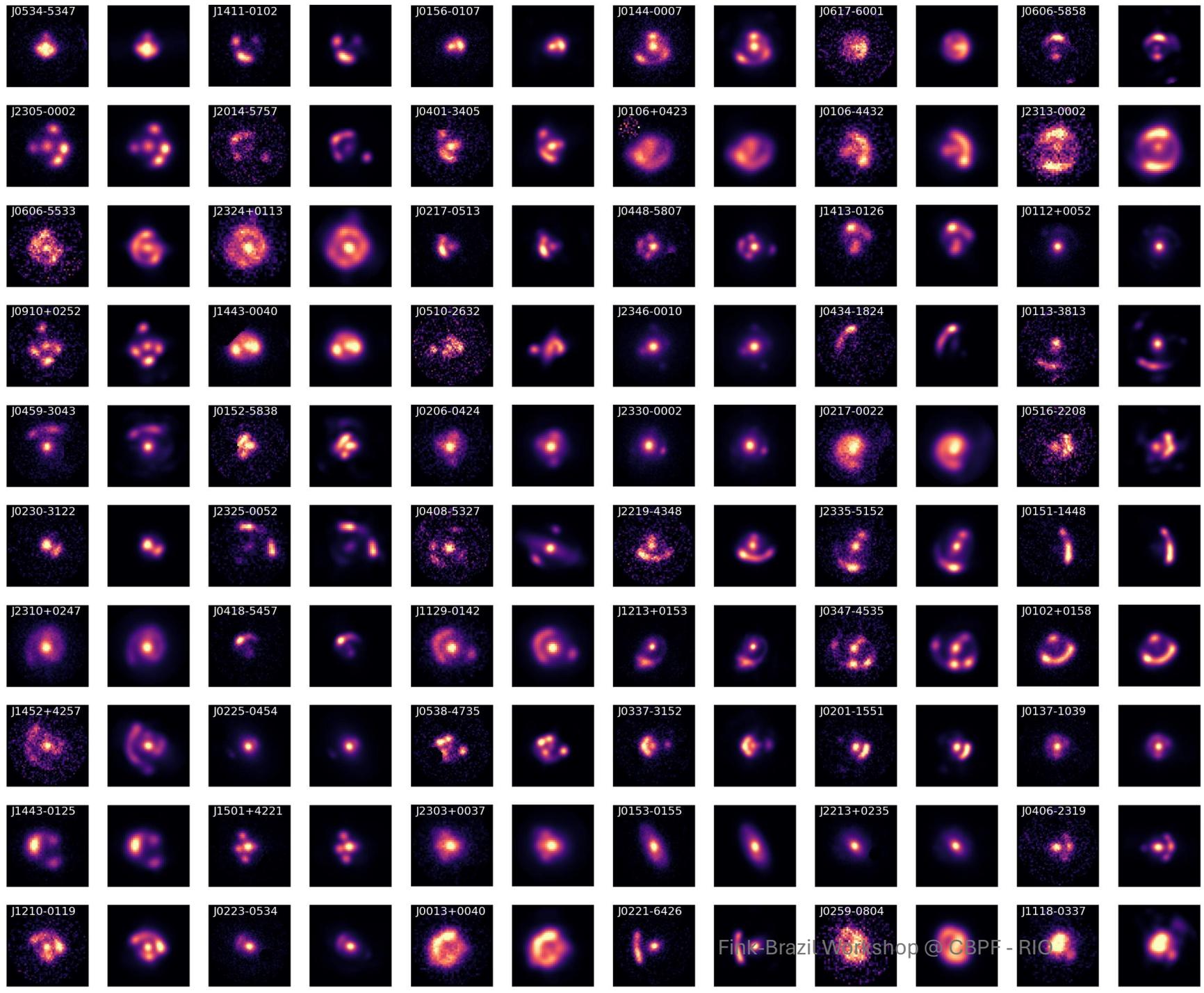
Source Lens and Mass (SLaM) pipelines
In PyAutoLens
(<https://pyautolens.readthedocs.io>)

Session	Phase	Component	Model	Prior info
Source Parametric	SP	Lens mass	SIE+Shear	-
		Lens light	MGE	-
		Source light	MGE	-
Source Pixelized	SPix1	Lens mass	SIE+Shear	SP
		Lens light	MGE	SP
		Source light	MPR	-
	SPix2	Lens mass	SIE+Shear	SPix1
		Lens light	MGE	SP
		Source light	BPR	-
Light	L	Lens mass	SIE+Shear	SPix1
		Lens light	MGE	SP
		Source light	BPR	SPix2
Mass	M	Lens mass	EPL+Shear	SPix1
		Lens light	MGE	SP
		Source light	BPR	SPix2

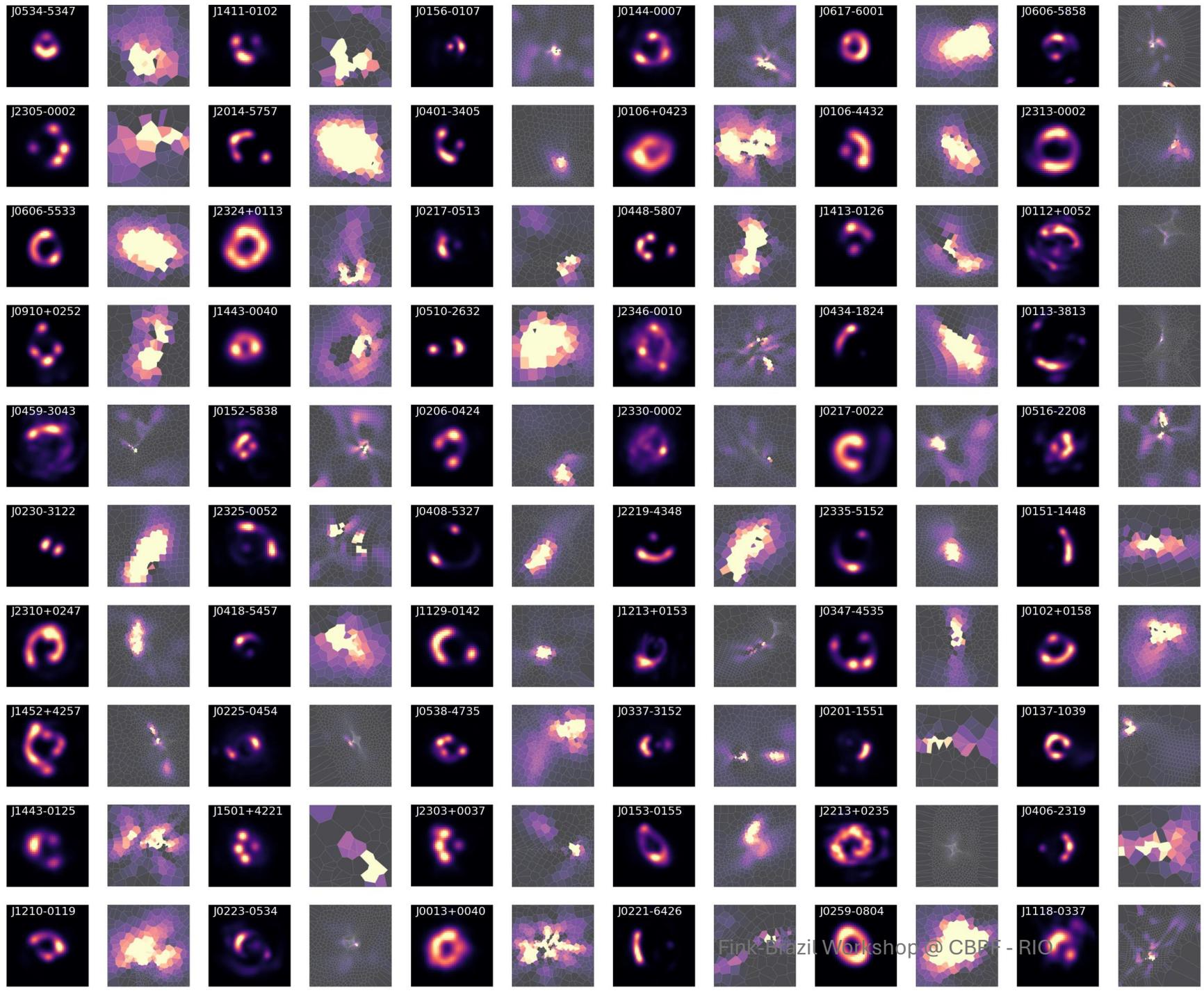
- Lens model initialization with MGE+SIE+Shear (Multi-Gaussian Expansion & Isothermal profiles) in **SP**
- Source reconstruction in a Voronoi mesh grid (**Spix1** & **Spix2**)
- Lens light is refitted (**L**)
- Elliptical Power-law mass profile in **M**

Source reconstruction of J0101-3343
in DES Imaging data





- ~150 SL candidate systems uniformly modeled with SLaM (same product methods, models & priors)
- Tested in HSC, KiDS, DES, Legacy, CS82 imaging data
- Feed LaStBeRu database with classifications and modeling reconstructions



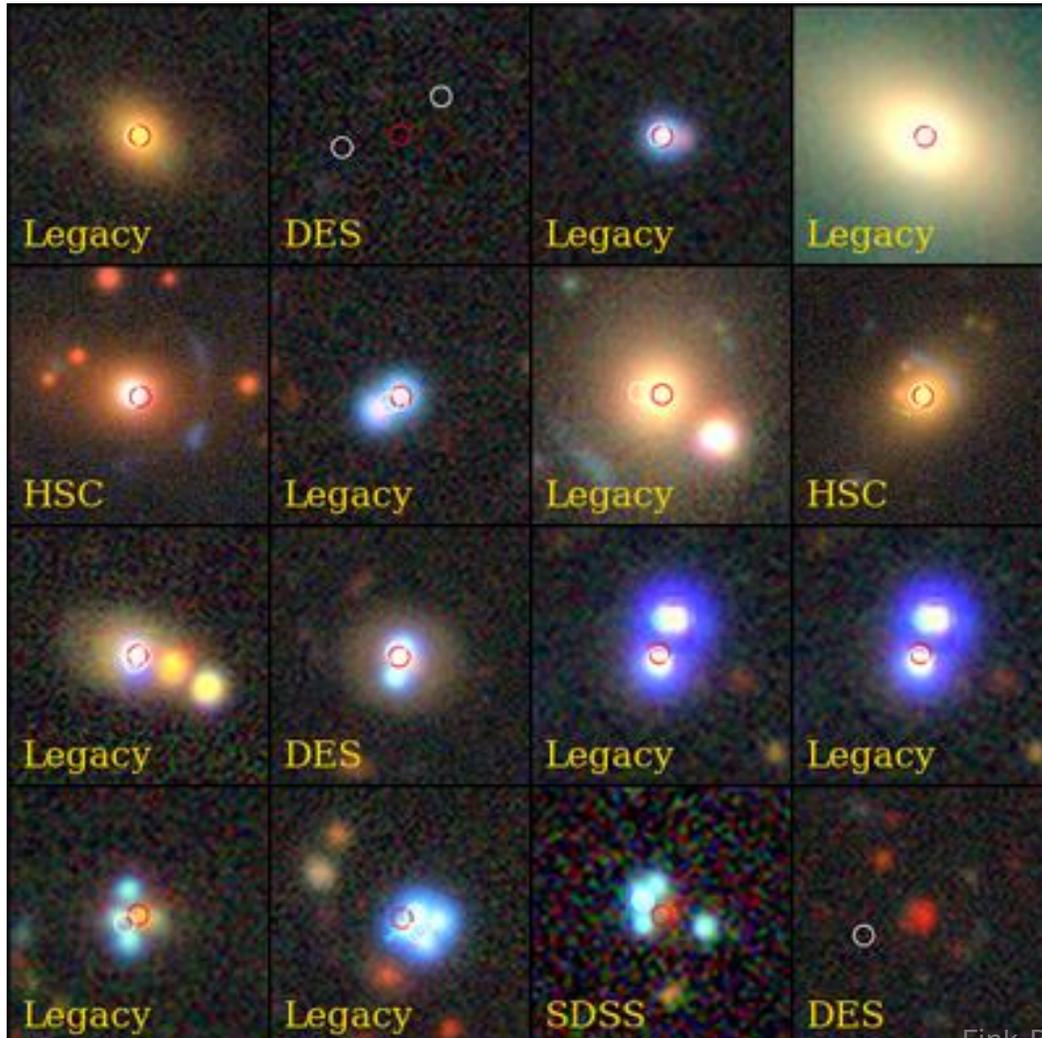
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Crossmatch between FINK ZTF SN candidates and LaStBeRu SL candidates

ZTF and LaStBeRu crossmatches

330 crossmatches within 5arcsec & 5500+ crossmatches within 60arcsec!

Some 20 arcsec-sq cutouts from the crossmatch:

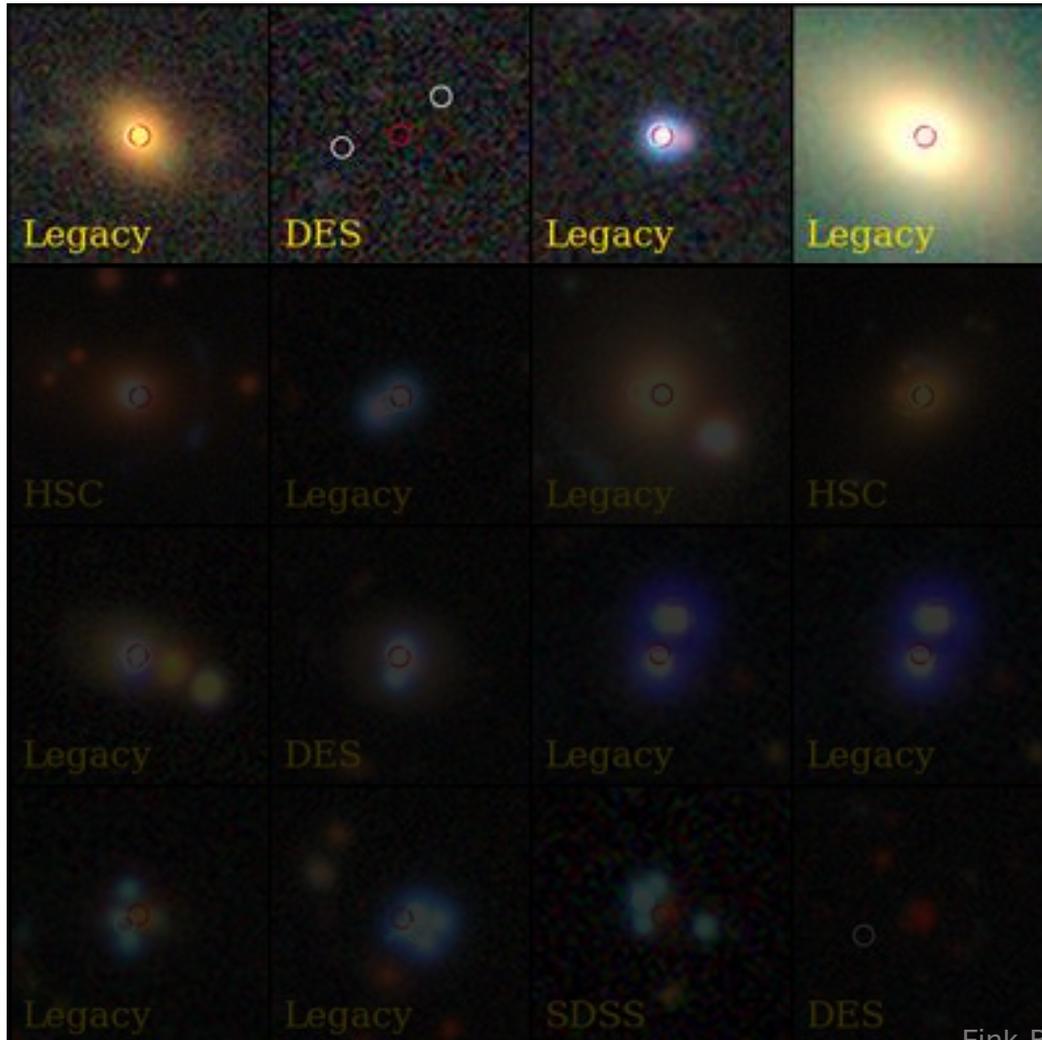


- **LaStBeRu** SL candidates in the footprint of ground-based images and **ZTF alerts**
- Crossmatches within
 - **5 arcsec** (search for **galaxy**-scale strongly lensed transients)
 - **60 arcsec** (search for **cluster**-scale strongly lensed transients)

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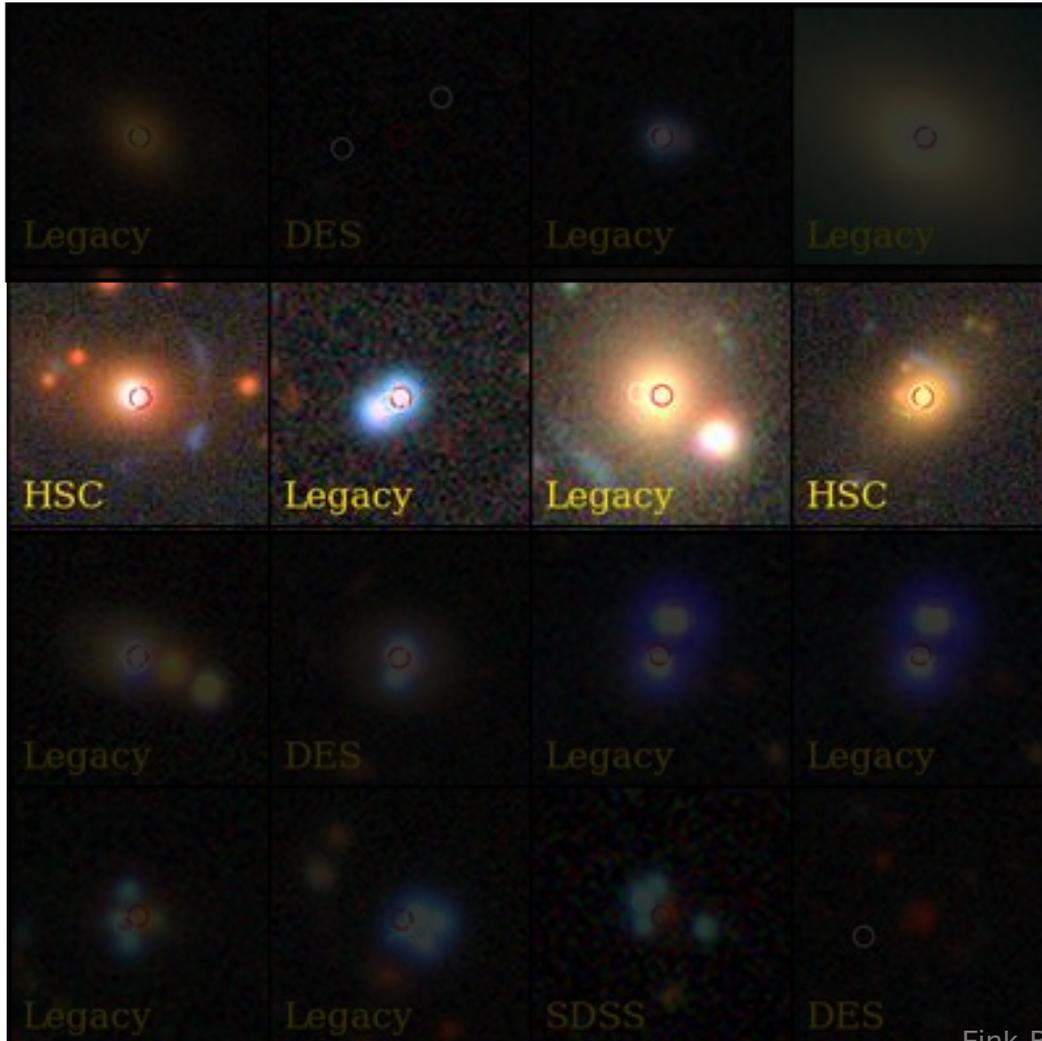


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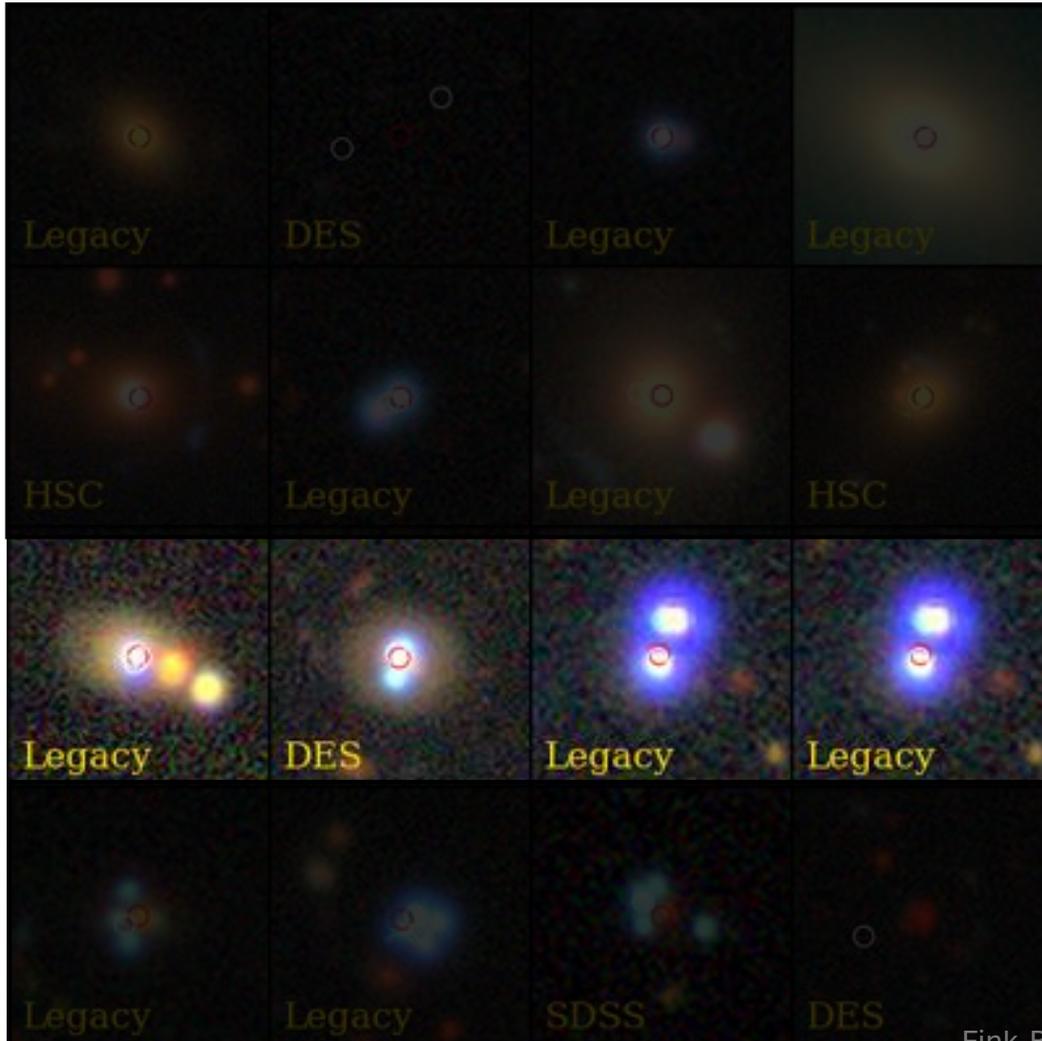


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 - **5 arcsec** (search for **galaxy**-scale strongly lensed transients)
 - **60 arcsec** (search for **cluster**-scale strongly lensed transients)
- **No sign of lensing** from ground-based images
- Candidates matching with the **host galaxy**
 - Allow us for mass estimation of SN host galaxies with SL modeling

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Some 20 arcsec-sq cutouts from the crossmatch:

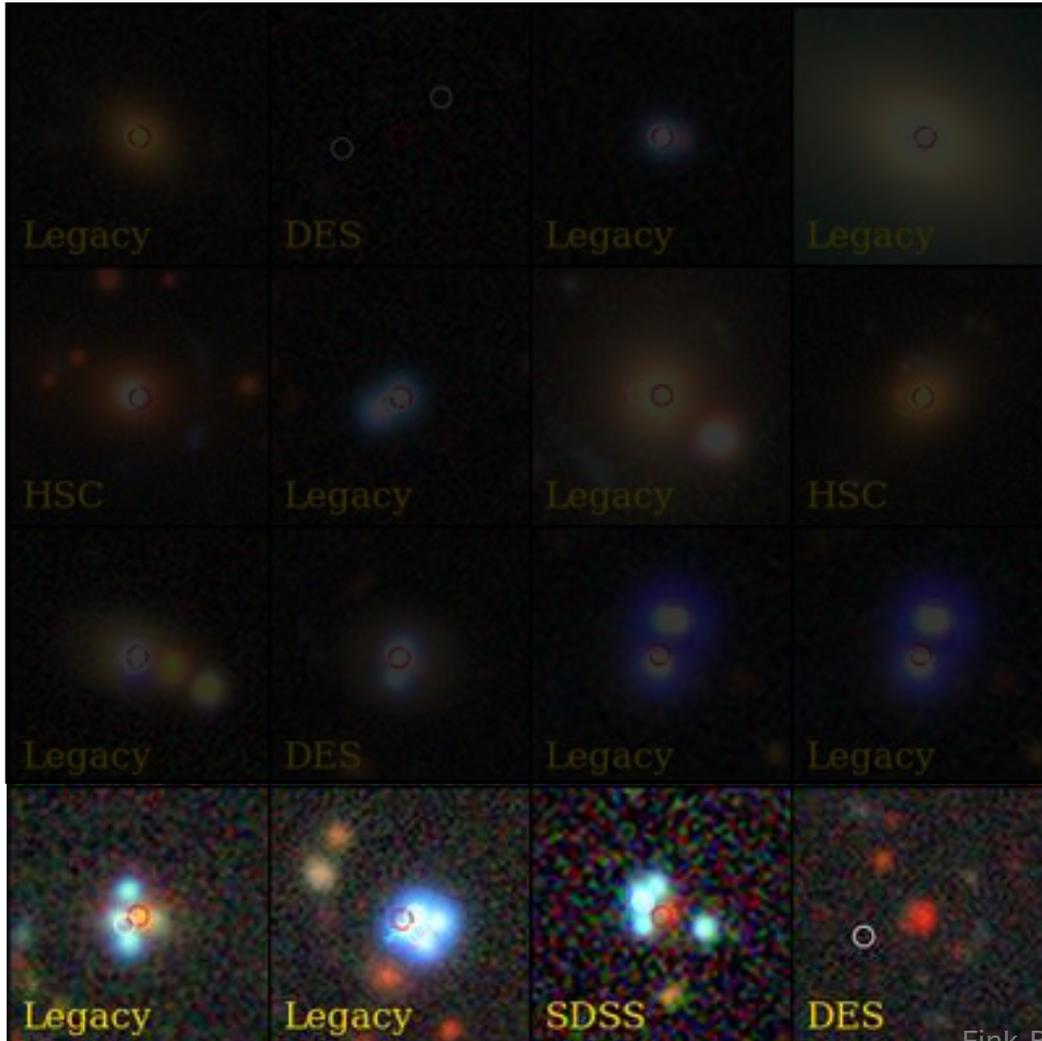


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- **No sign of lensing** from ground-based images
- Candidates matching with the **host galaxy**
- candidates matching with **sources** (candidate **doublets**: two images from SL)
Poor constraints on lens mass distribution from SL modeling

ZTF and LaStBeRu crossmatches

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Some 20 arcsec-sq cutouts from the crossmatch:

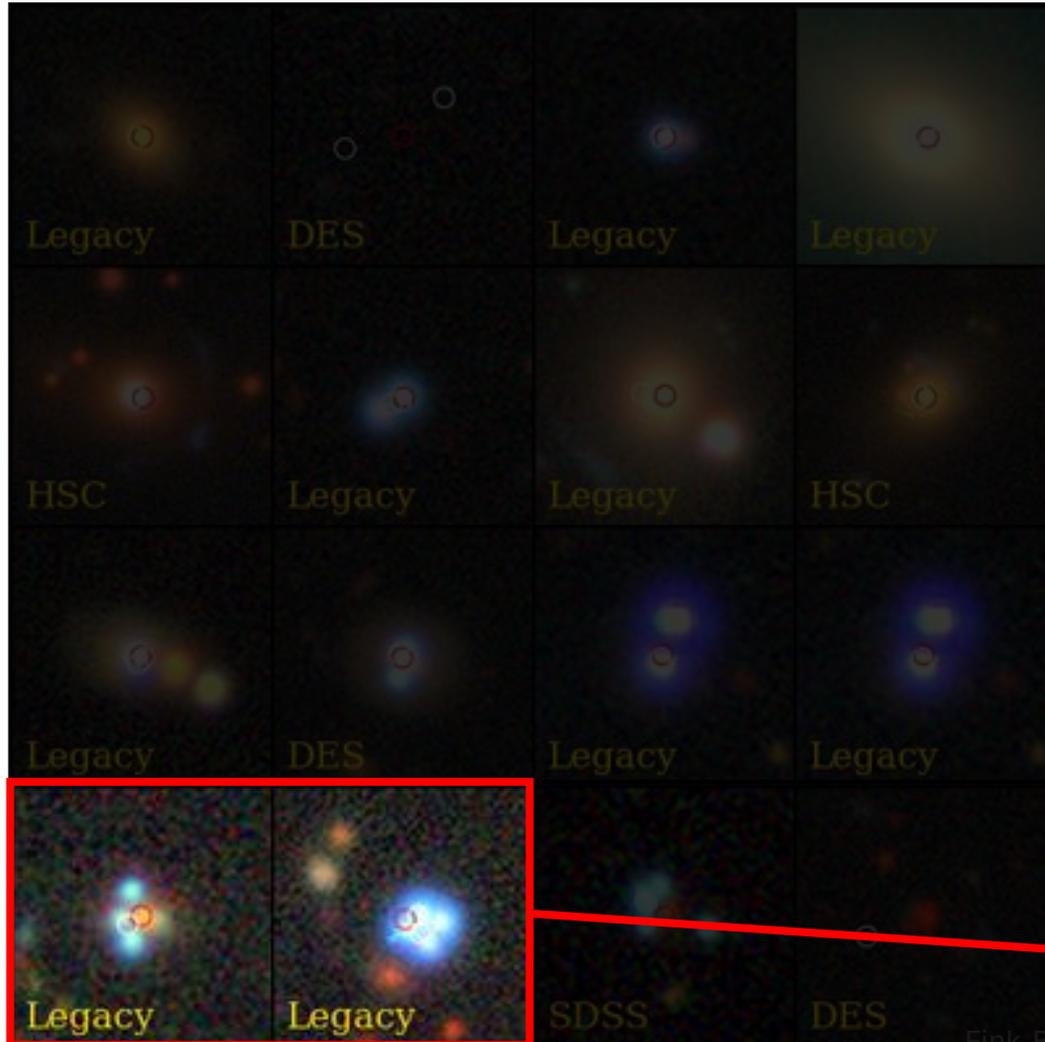


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- **No sign of lensing** from ground-based images
- Candidates matching with the **host galaxy**
- candidates matching with **sources** (candidate **quads**: Einstein crosses)
Best candidates for SL modeling (time-delays) and follow-ups

ZTF and LaStBeRu crossmatches

330 crossmatches within 5arcsec & 5500+ crossmatches within 60arcsec!

Some 20 arcsec-sq cutouts from the crossmatch:



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- Candidates matching with the **host galaxy**
- candidates matching with **sources**

Will be focusing on **J143322.9+600715.2**
and **J043814.8-121714.0**

J043814.8-121714.0

ZTF light curves



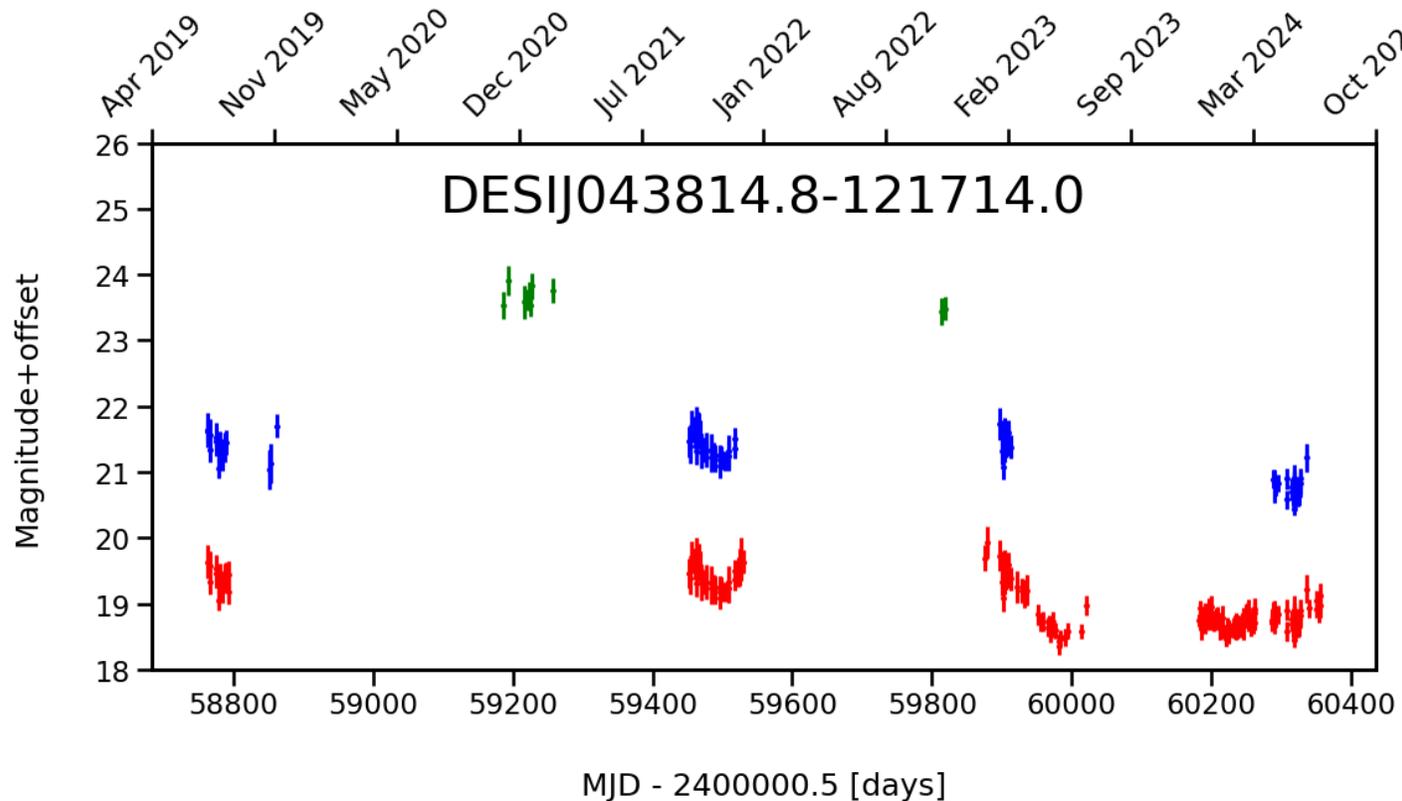
1.2-meter telescope
@ California

Classification:

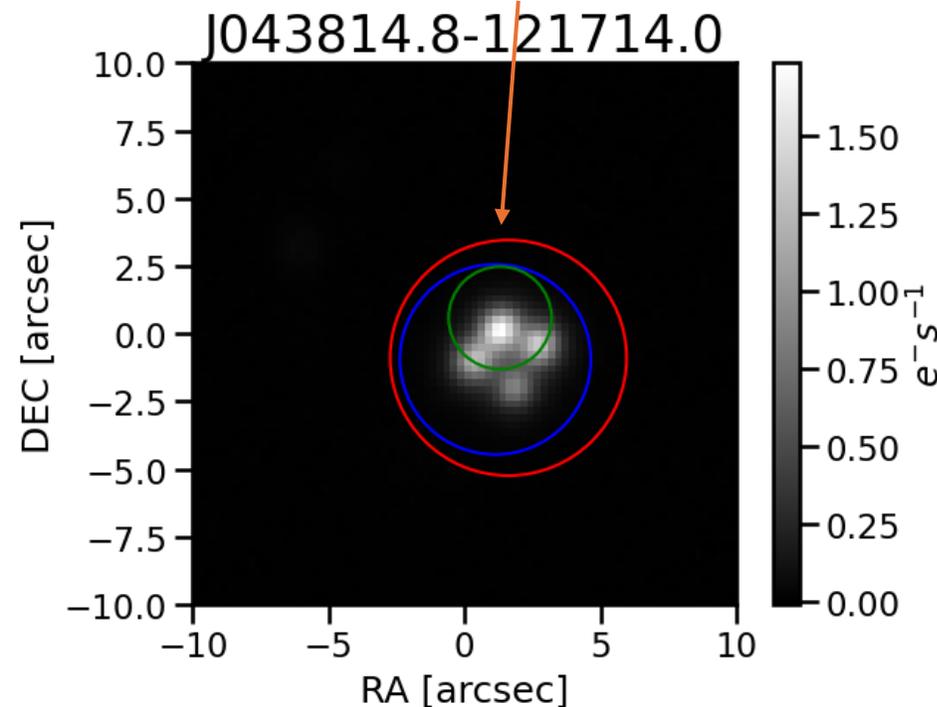
LensedQ: 86%, Unknown: 14%

Unknown: 53%, LensedQ: 5%, QSO: 42%

Unknown: 60%, QSO: 40%



mean PSF of individual alerts:
($\sim 4.3 \pm 0.1$) [arcsec]

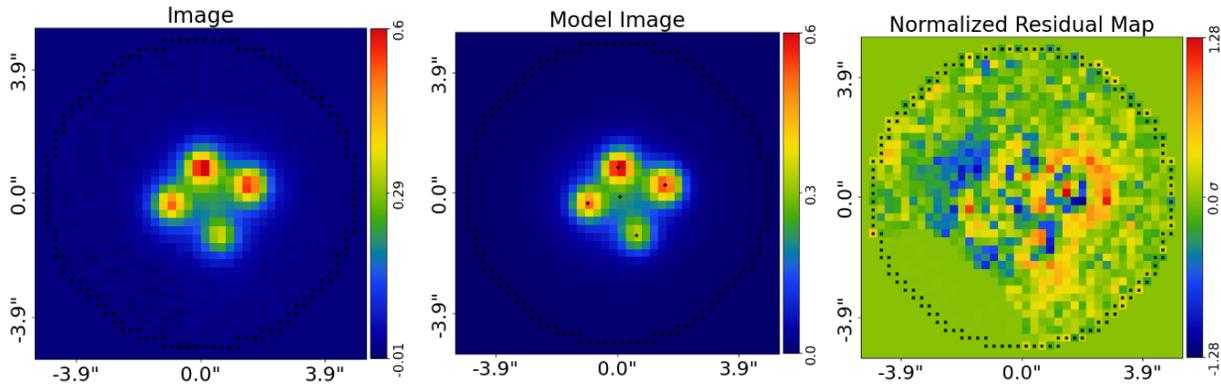


J043814.8-121714.0

Modeling

Point-source subtraction and sub-pixel precision modeling
(Dynesty optimization)

PyAutolens



With multiple image sub-pixel precision and assuming a lens mass model of EPL+Shear:

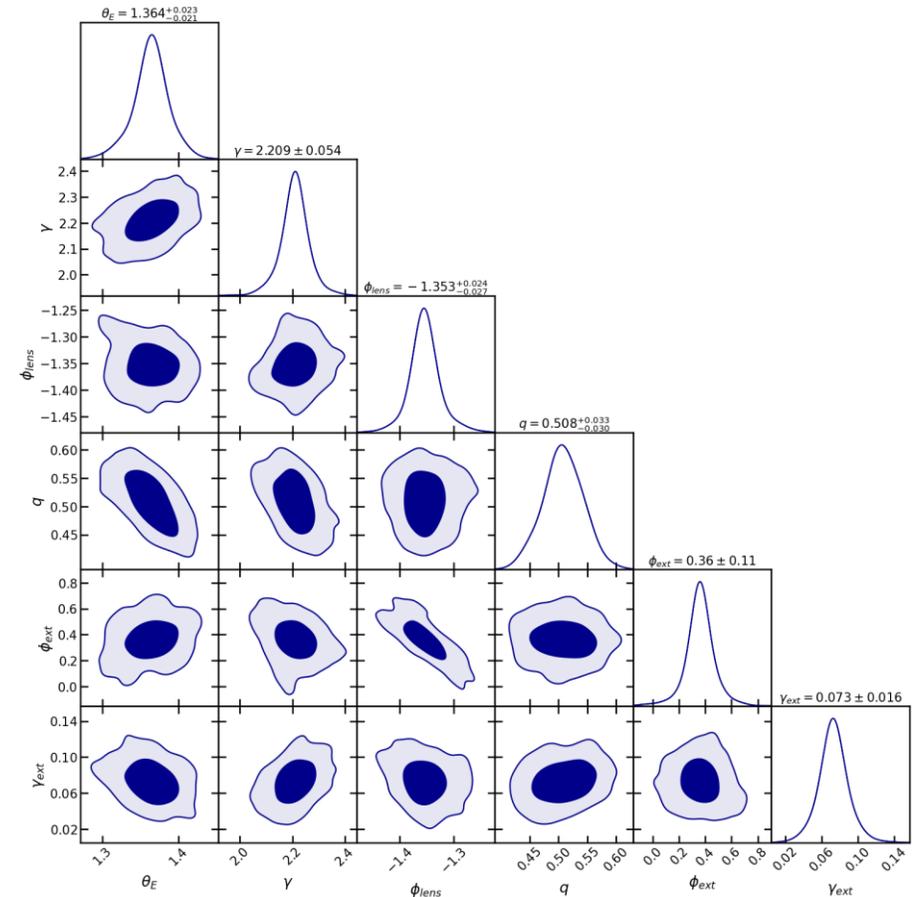
$$k_\alpha(x, y) = \frac{\Sigma(\xi)}{\Sigma_{\text{crit}}} = \frac{3 - \alpha}{1 + q} \left(\frac{b}{\xi} \right)^{\alpha-1}$$

$$\gamma_1 = \frac{1}{2} \left(\frac{\partial^2 \psi}{\partial \theta_1^2} - \frac{\partial^2 \psi}{\partial \theta_2^2} \right) \quad \gamma_2 = \frac{\partial^2 \psi}{\partial \theta_1 \partial \theta_2}$$

we applied a point-source modeling

PDF on lens-parameters
(PSO for optimization+MCMC)

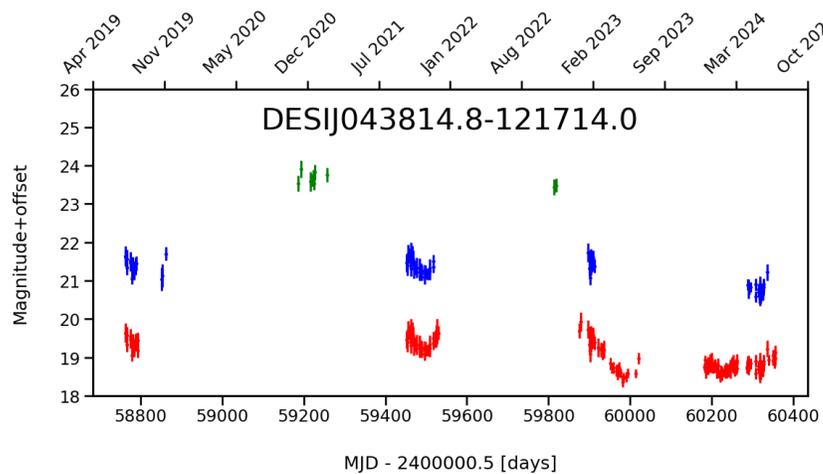
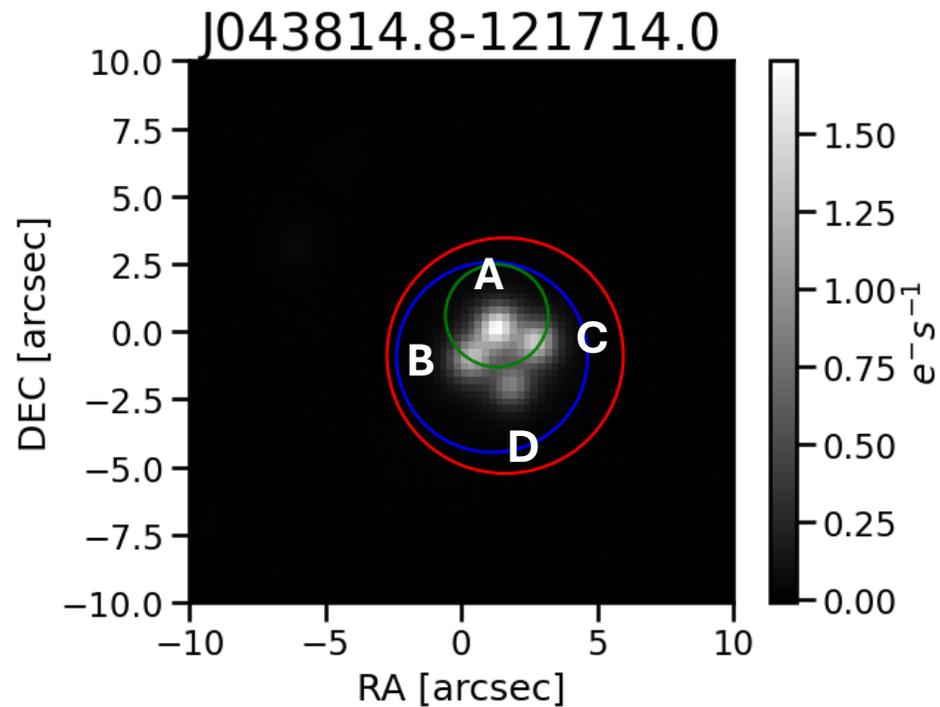
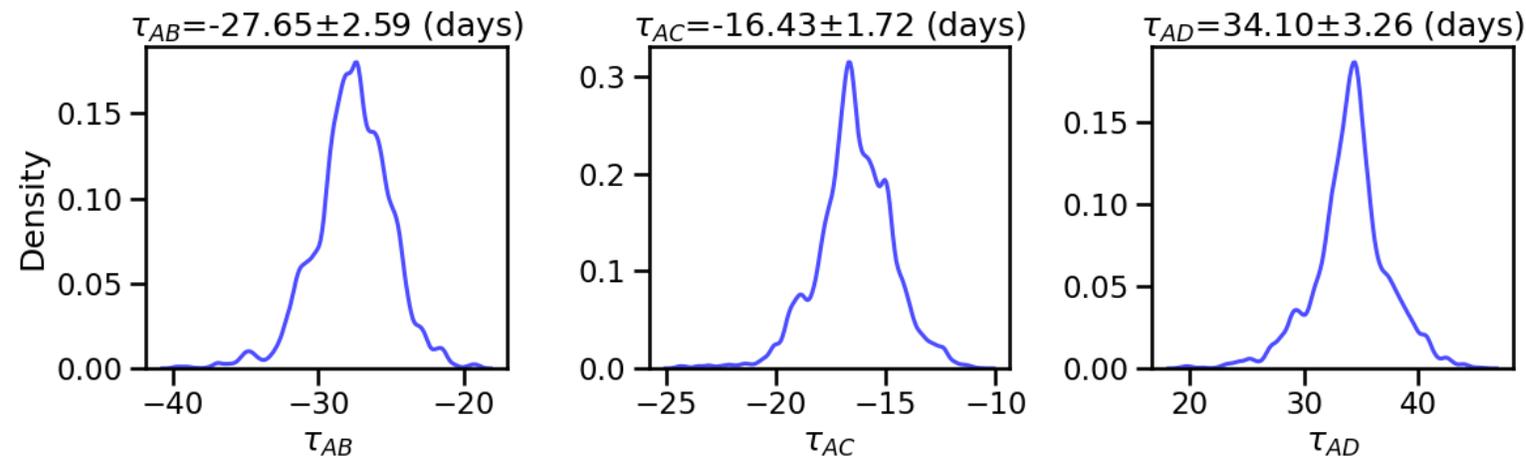
Lenstronomy



J043814.8-121714.0

Modeling

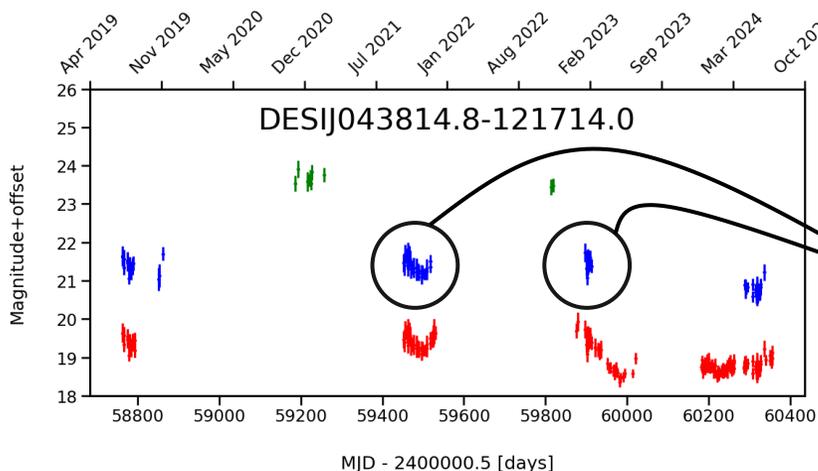
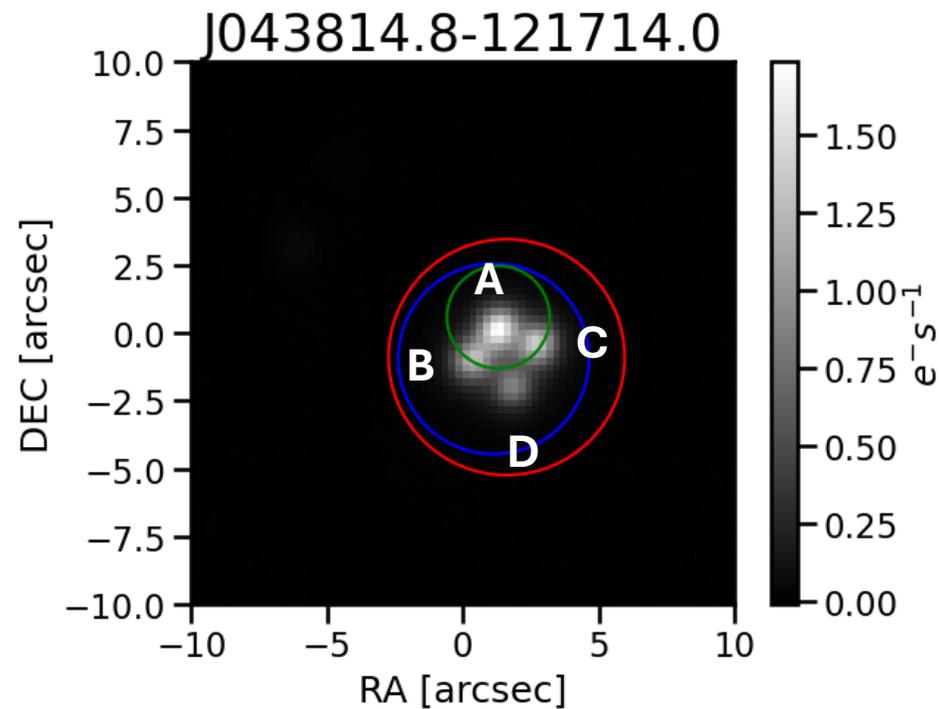
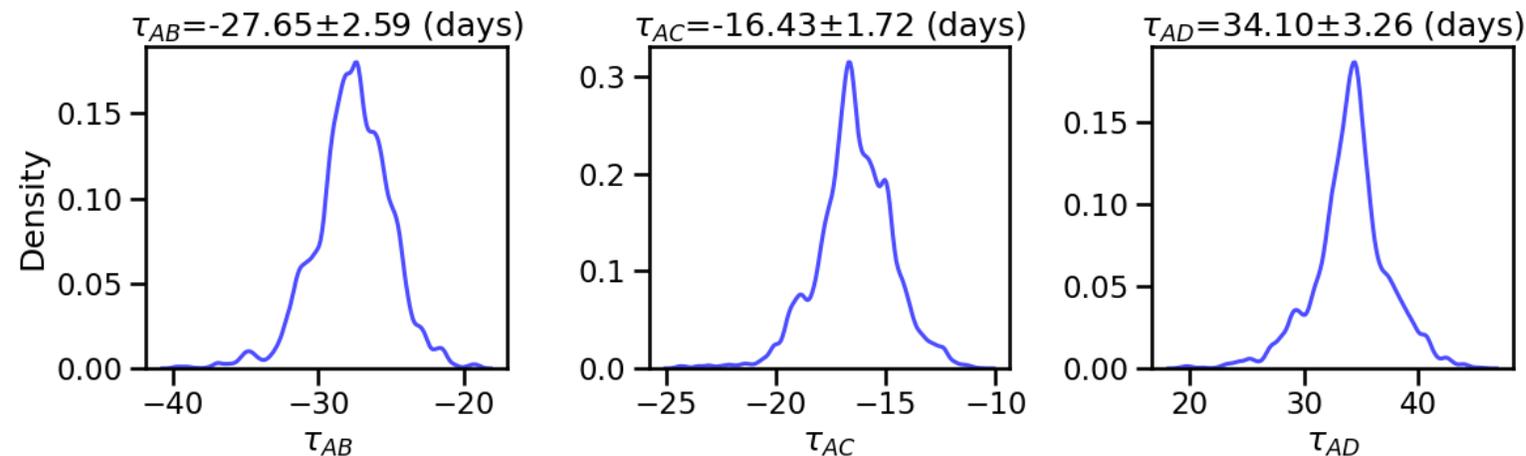
Relative time-delay predictions



J043814.8-121714.0

Modeling

Relative time-delay predictions



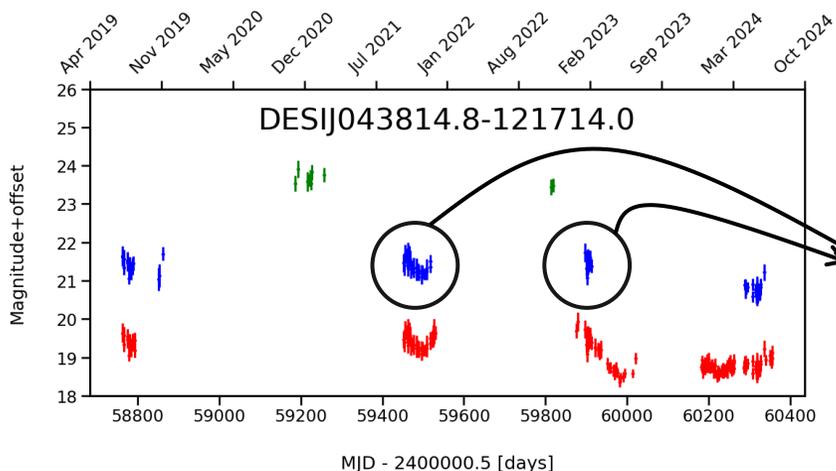
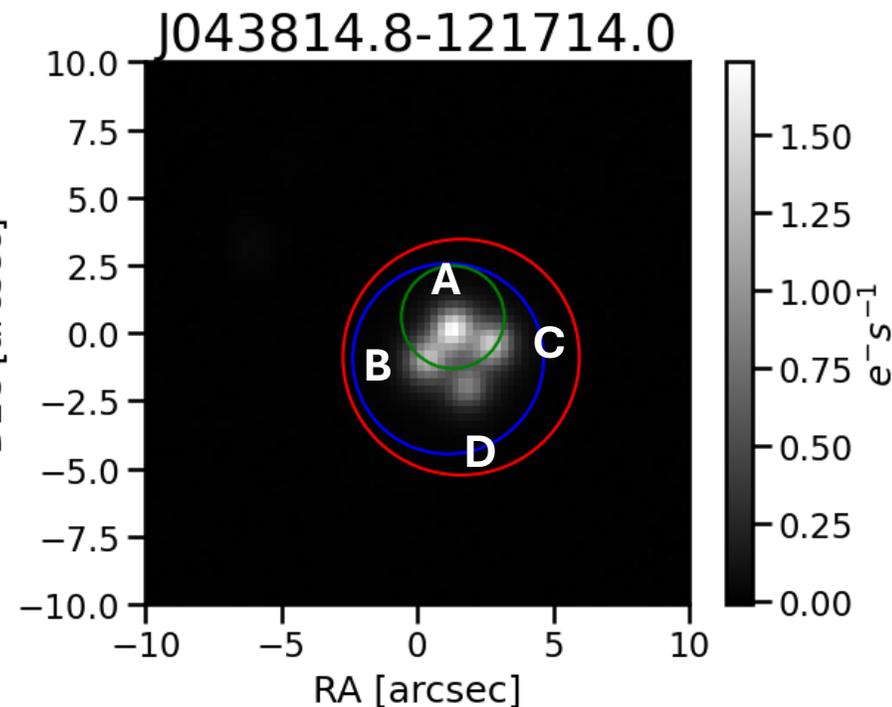
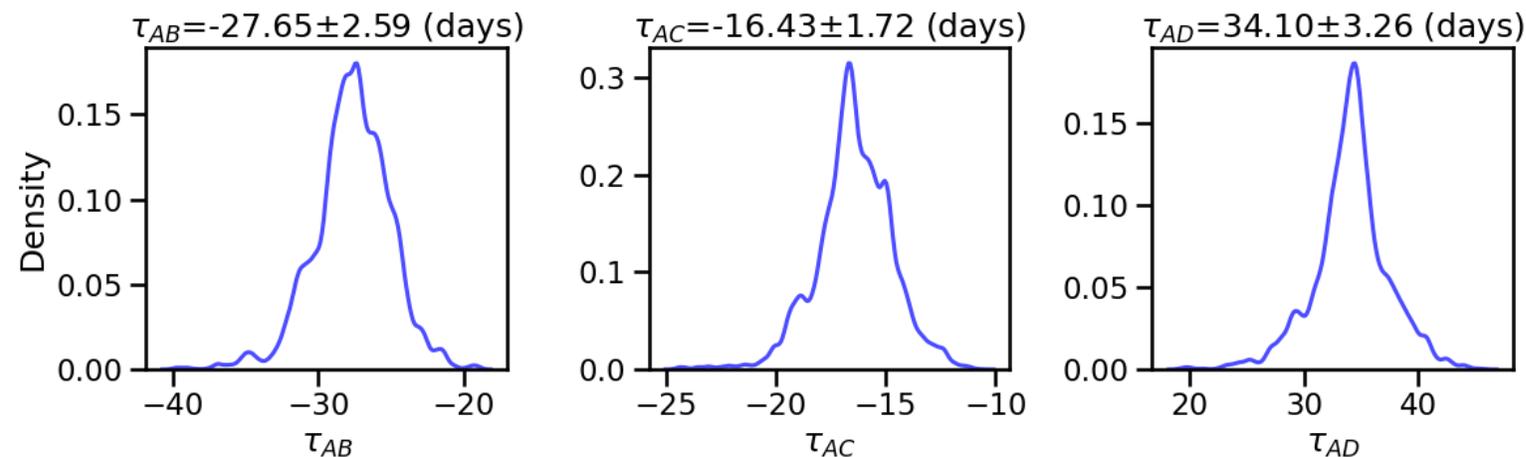
Open questions:

- How could we determine which event belongs to which multiple images given high PSF values?
- Same transient?

J043814.8-121714.0

Modeling

Relative time-delay predictions



Open questions:

- How could we determine which event belongs to which multiple images given high PSF values?
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Nevertheless, excellent system for a follow-up!

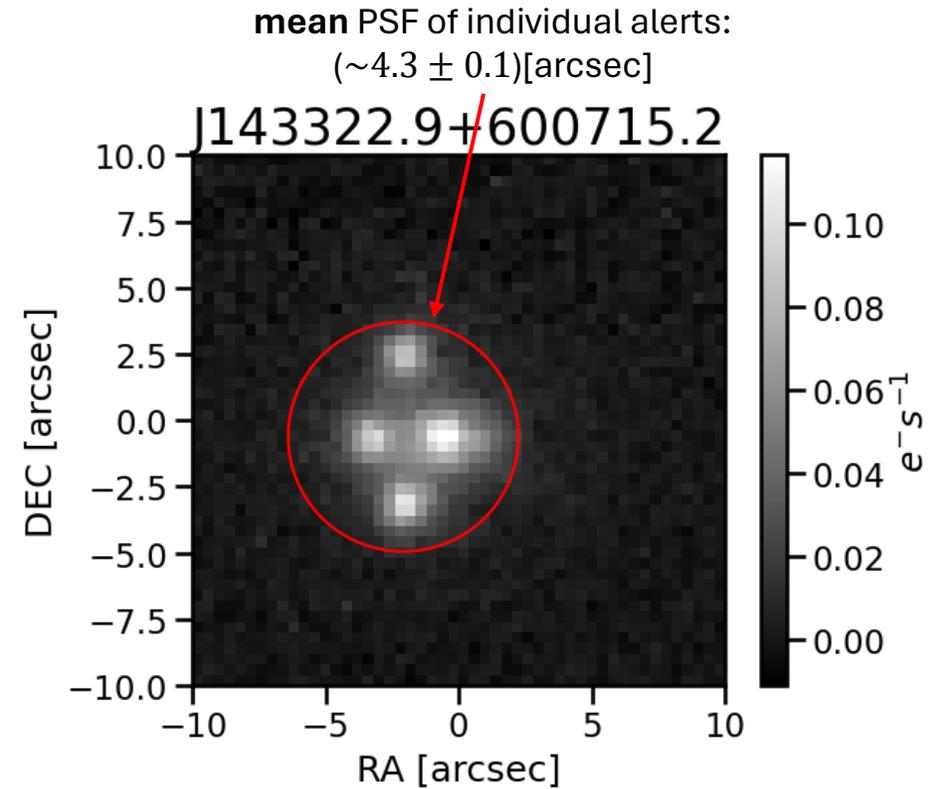
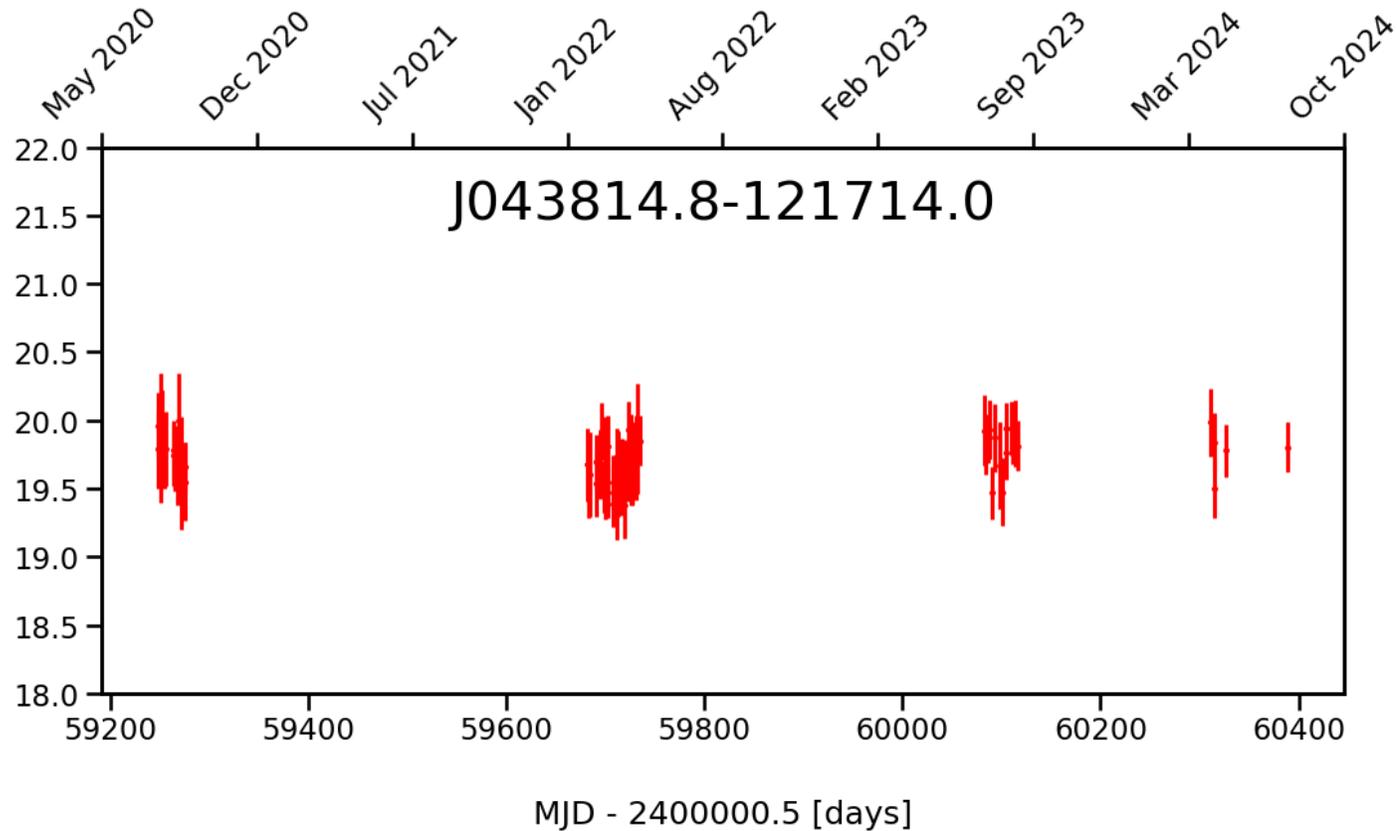
J143322.9+600715.2

ZTF light curves



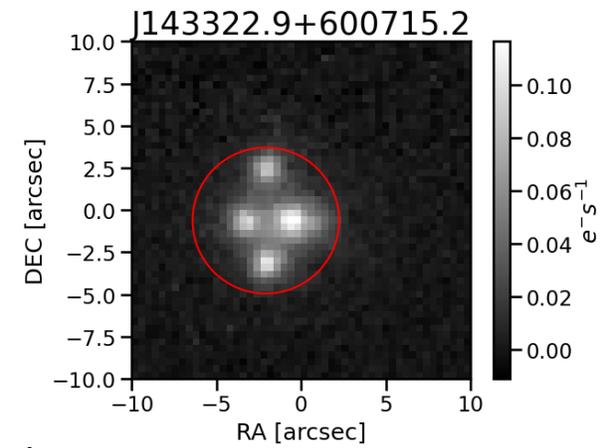
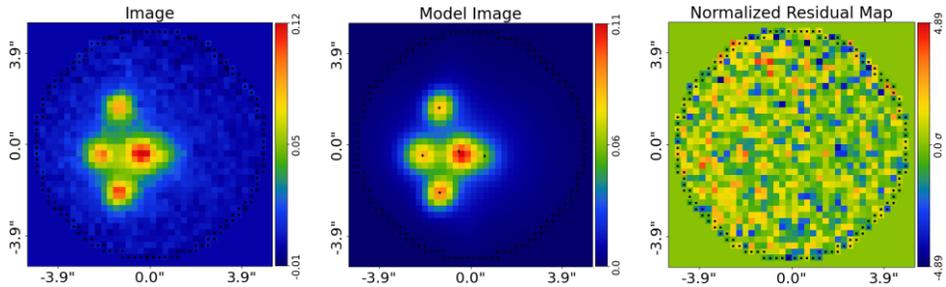
1.2-meter telescope
@ California

ZTF classifications:
LensedQ: 100%

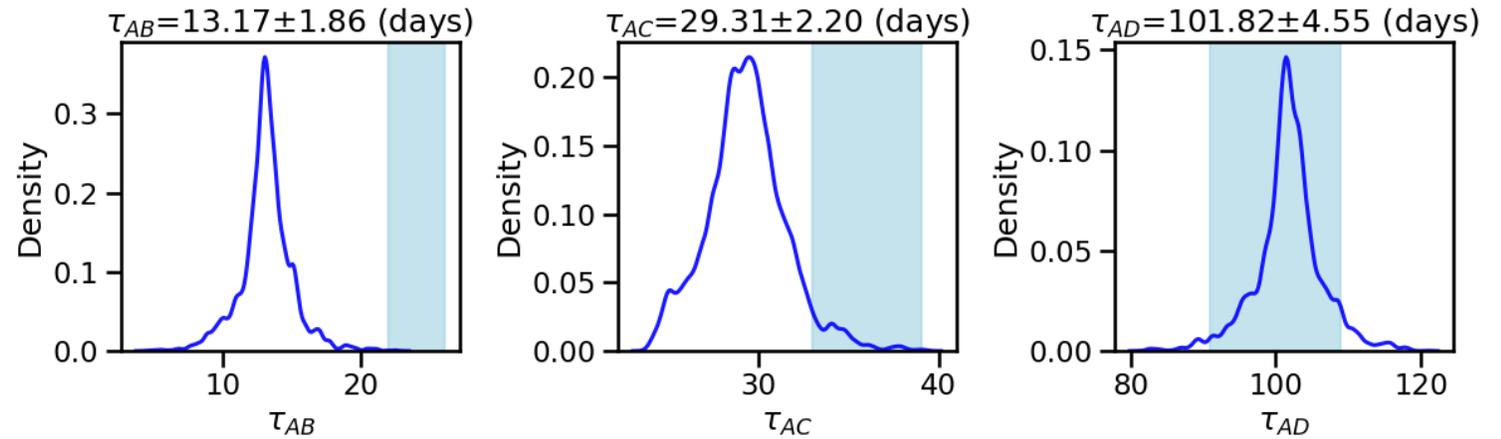


J143322.9+600715.2 Modeling

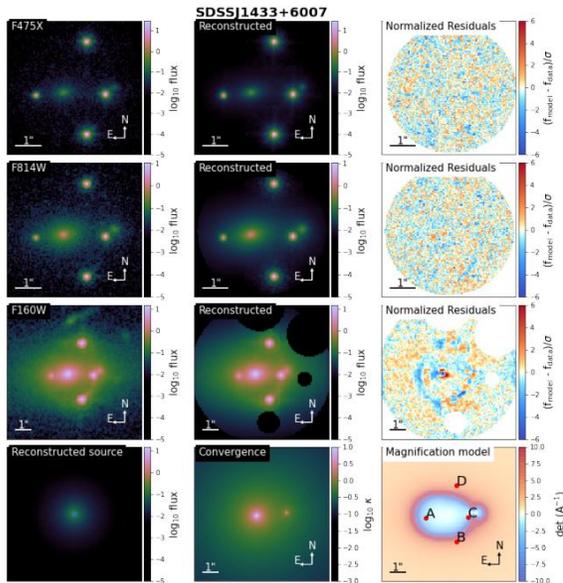
Same analysis: point-source subtraction + Modeling



Relative time-delay predictions:



Available modeling reconstruction on space-based (HST) data

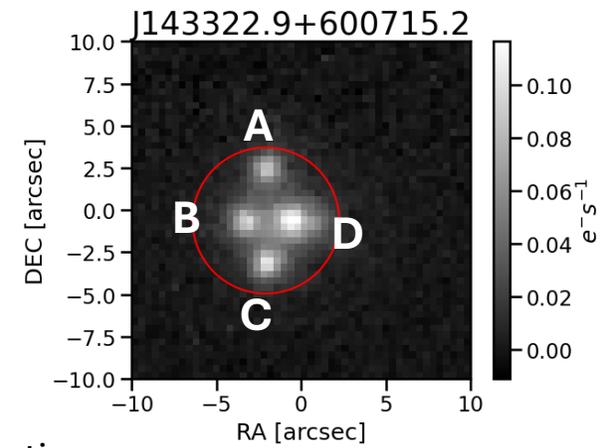
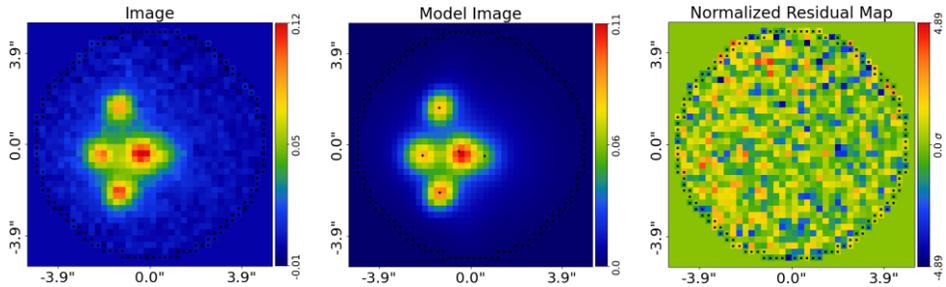


- Light blue regions are constraints on τ_{IJ} from [Shajib+, 2020](#)
- **Width** of predicted time-delays are **roughly similar** on ground and space-based
- Unaccounted satellite object near **B** on ground-based modeling

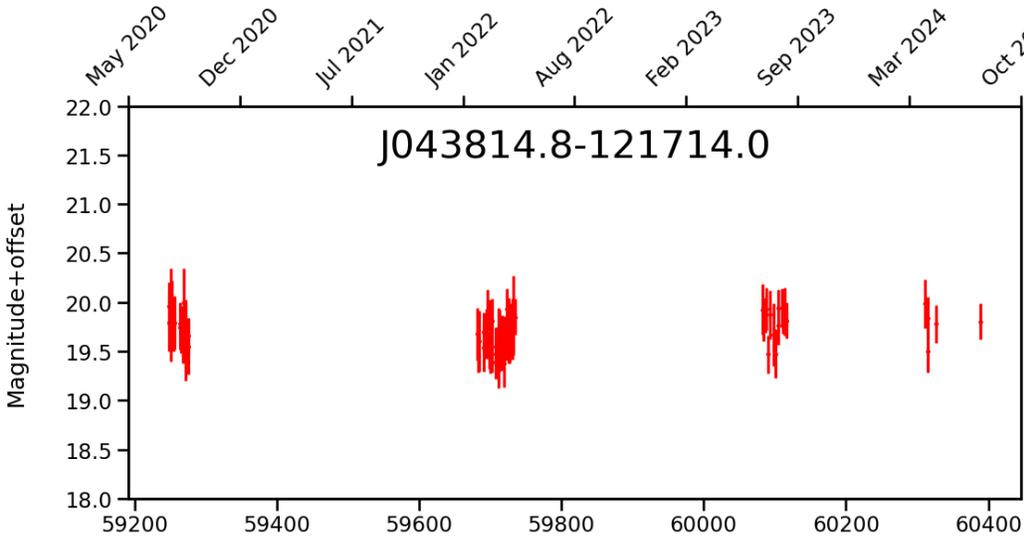
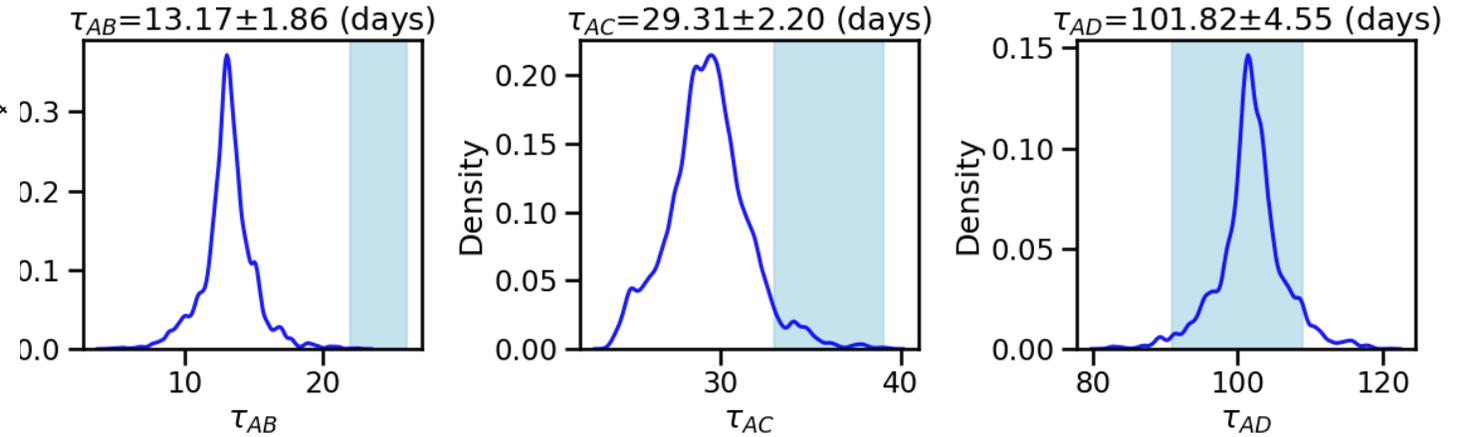
J143322.9+600715.2

Modeling

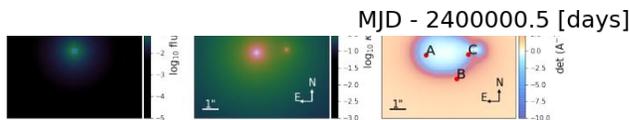
Same analysis: point-source subtraction + Modeling



Relative time-delay predictions:



- Light blue regions are constraints on τ_{IJ} from [Shajib+, 2020](#)
- **Width** of predicted time-delays are **roughly similar** on ground and space-based
- Unaccounted satellite object near **B** on ground-based modeling
- Why only one light curve? Check if the instrument was operating during time-delay prediction windows



Summary and what's next?

Summary

- Strong lensing as an independent and powerful probe of cosmology
- (LaStBeRu) Compilation from a large set of catalogs, including images from the main wide-field imaging surveys conducted from the ground, and cross-matching with photometric and spectroscopic catalogs
- Visual inspection and tagging of strong lensing candidate systems
- Semi-automated modeling of the best systems using ground-based data

Future work

- Address open questions
- Estimate time-delays from ZTF light curves
- Compare predicted and observed time-delays (Follow-up for best models)
- Improve FINN/ZTF+ LaStBeRu analysis for real-time alerts (better imaging data and light-curves for time-delays)