Microlensing Event Modeling for the Roman Galactic Exoplanet Survey (RGES)

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RGES Event Modeling Efforts

RGES modeling goals to be achieved by three modeling efforts:

1. Microlensing Science Operation System (MSOS) – See Etienne Bachelet’s talk (3:00pm)
   - Direct Project funded to meet level-1 science requirements
   - Supported by PIT with modeling algorithms, realistic light curve simulations needed (including all higher order effects (microlensing parallax, orbital motion, additional lens masses and sources)
   - Modeling effort is somewhat more complicated than anticipated by the previous science team
2. RGES PIT modeling effort
   - Major contributions from Valerio Bozza
   - Needed to attain our main science goals – well beyond the level-1 science requirements
   - New code developments are needed, including a different strategy for higher order effects
3. MExoFAST = MuLensModel + ExoFAST (Jennifer Yee, Radek Poleski and Jason Eastman)
   - Easy to use, but highly capable code for the astronomy public
   - To enable broad participation in Roman’s exoplanet microlensing survey data.
   - Project code will be public, but has no funding to make it easy to use

Level-1 Science Requirements and a Gap

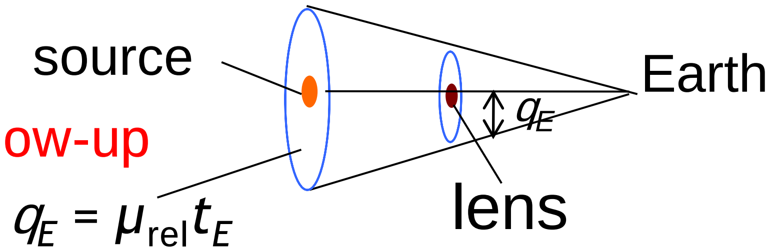
- EML 2.0.1: RST shall be capable of measuring the mass function of exoplanets with masses in the range $1M_\oplus < m < 30M_{\mathrm{Jupiter}}$ and orbital semi-major axes ≥ 1 au to better than 15% per decade in mass.
- EML 2.0.2: RST shall be capable of measuring the frequency of bound exoplanets with masses in the range $0.1M_\oplus < m < 0.3M_\oplus$ to better than 25%.

Not Verified!

- EML 2.0.3: RST shall be capable of determining the masses of, and distances to, host stars of 40% of the detected planets with a precision of 20% or better.
- EML 2.0.4: RST shall be capable of measuring the frequency of free floating planetary- mass objects in the Galaxy from Mars to 10 Jupiter masses. If there is $1M_\oplus$ free-floating planet per star, measure this frequency to better than 25%.
- EML 2.0.5: RST shall be capable of estimating $\eta_\oplus$ (the frequency of planets orbiting FGK stars with mass ratio and estimated projected semimajor axis within 20% of the Earth-Sun system) to a precision of 0.2 dex via extrapolation from larger and longer-period planets

No star-planet separation requirements – since they don’t affect hardware (much)

2 of 3 Mass-Distance Relations

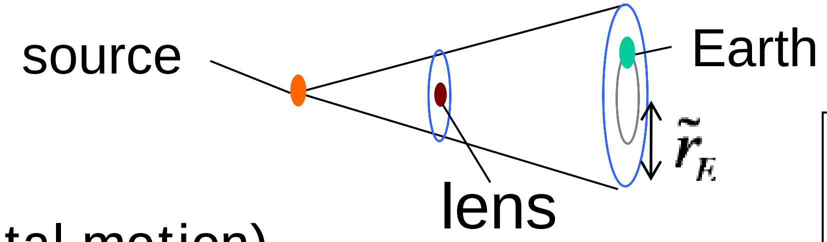


§ μ_{rel} - finite source or follow-up

Angular Einstein radius $q_E = \mu_{\mathrm{rel}} t_E$

$\mu_{\mathrm{rel}} = q_* / t_*$ q_* = source star angular radius

D_L and D_S are the lens and source distances



§ Microlensing Parallax

(Effect of Earth's orbital motion)

Einstein radius projected to Observer

$$\tilde{r}_E = \frac{\mathrm{AU}}{\pi_E}$$

OR

§ One of above ✚

Lens brightness & color(AO,HST)

mass-distance relation è D_L

➡

$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

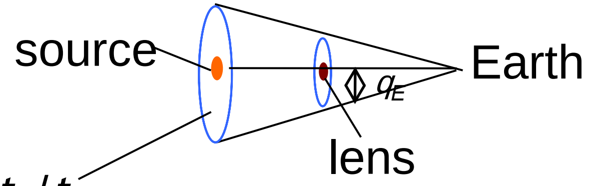
✖

$$M_L = \frac{c^2}{4G}\left(\frac{\mathrm{AU}}{\pi_E}\right)^2 \frac{D_S - D_L}{D_S D_L}$$

⬇

$$M_L = \frac{c^2 \mathrm{AU}}{4G}\frac{\theta_E}{\pi_E}$$

A 3rd Mass-Distance Relation

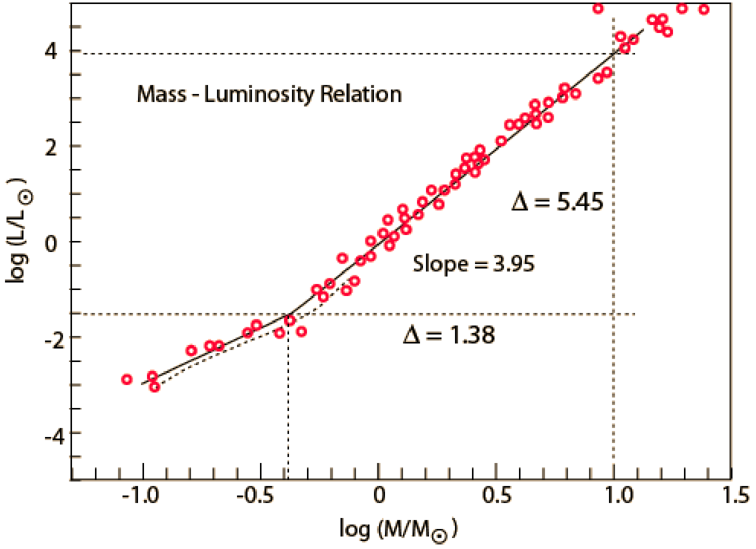


- Finite source effect
  or lens-source proper motion:
  - Angular Einstein radius $q_E = q_* t_E / t_*$
  - q_* = source star angular radius
  - D_L and D_S are the lens and source distances

$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

+

Keck Key Strategic Mission Support program for WFIRST

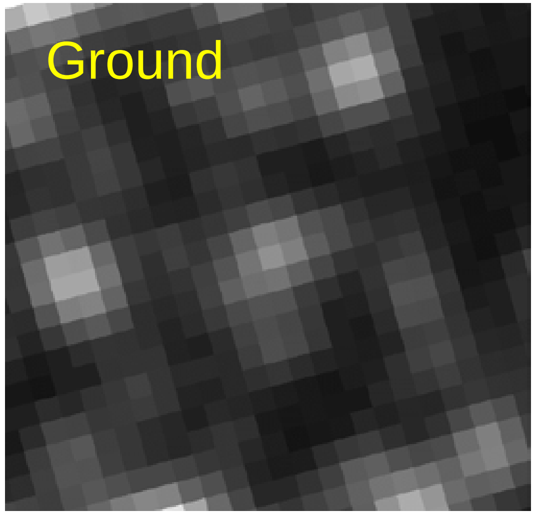


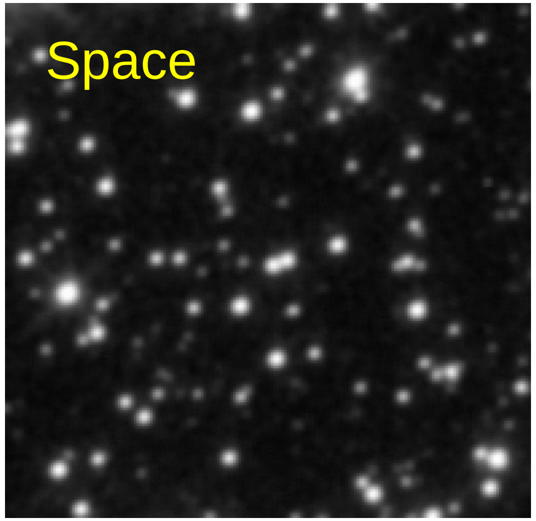
- **Lens brightness from high resolution image used in Mass-Luminosity relation**
  - mass-distance relation è D_L , M_L

- Lens-source relative proper motion is key to lens star identification

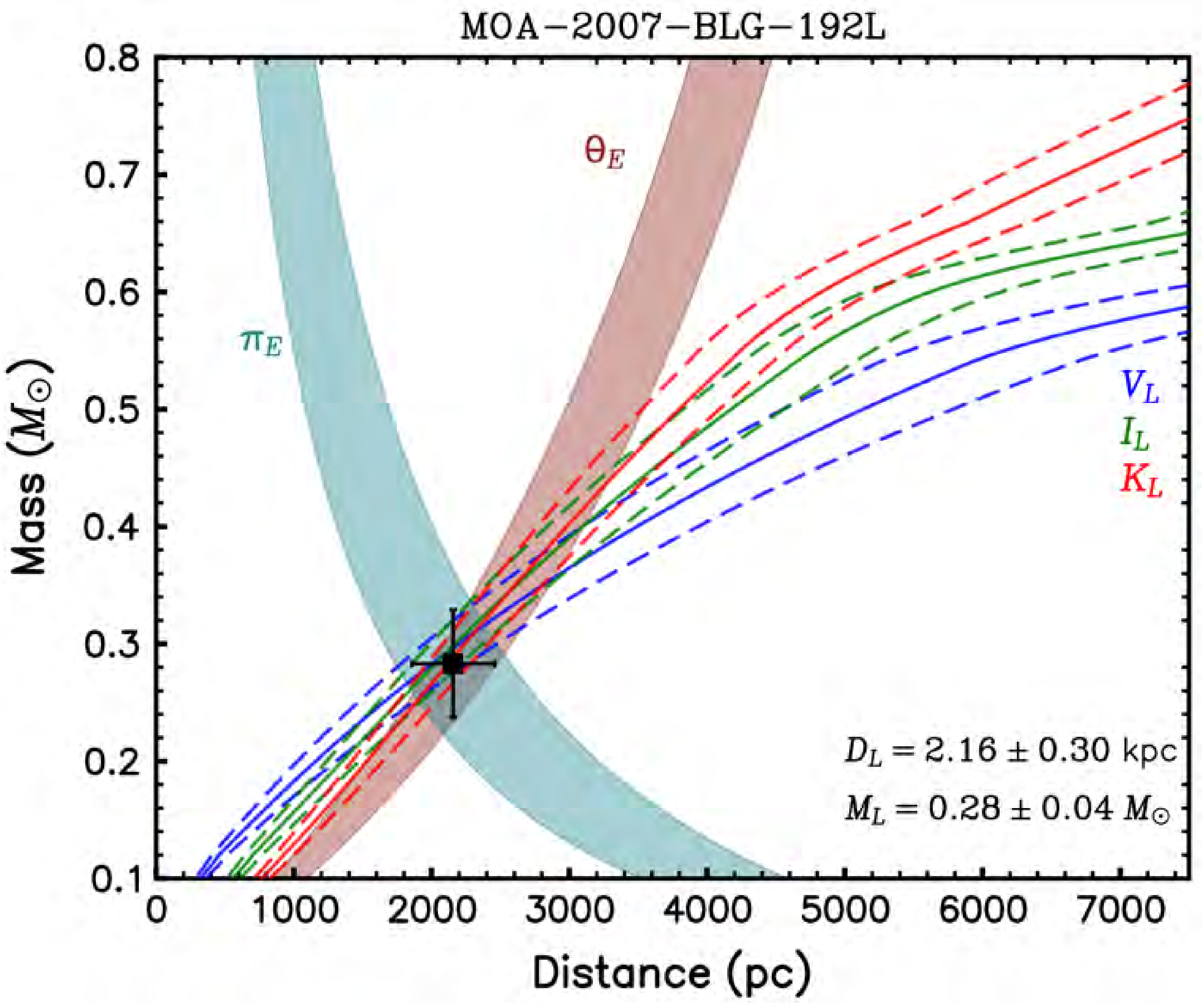
- Independent measurement in every passband

- Seeing limited image don’t help





Mass & Distance Measurement Example



MOA-2007-BLG-192L

- HST V_L, I_L measurements
- Keck K_L measurements
- π_E from light curve and Keck + HST $\mu_{\mathrm{rel,H}}$ observations
- θ_E from light curve and Keck + HST $\mu_{\mathrm{rel,H}}$ observations

see Sean Terry’s talk, Friday 9:15am

Higher Order Light Curve Effects

& Why We Need Them (w/ examples from Suzuki+16)

- Microlensing Parallax, $\boldsymbol{\pi}_{\rm E}$ (always present)
  - Yields lens masses when combined with $\theta_{\rm E}$ (ob06109, mb09266, ob110265) or lens magnitude
  - 1-d $\boldsymbol{\pi}_{\rm E}$ lens masses when combined with $\theta_{\rm E}$ and $\boldsymbol{\mu}_{\rm rel,H}$ (ob05071, ob120950)
    - 1-d $\boldsymbol{\pi}_{\rm E}$ likely to be common for RGES
  - Always present and can effect other parameters like $t_{\rm E}$ and source magnitude (mb08379)
- Lens orbital motion (always present)
  - Does not affect host star parameters, but could affect mass ratio, q
  - Can interfere with $\boldsymbol{\pi}_{\rm E}$ measurements (ob05071, ob06109, mb09266, mb09387, mb10328, mb10477, ob110265 – but not compared to no orbital motion in some cases)
  - Sometimes needed to fit the data (ob06109, mb10328)
- Source companion (not always present)
  - xallarap and 2nd magnified star can interfere with $\boldsymbol{\pi}_{\rm E}$ measurements (ob07368, mb10328, ob161195)
  - Early lens-flux analysis will reveal excess flux at location of the source, which will limit the total lens+companion magnitude – multiple colors could help separate lens and companion magnitudes
  - Faint companions (white dwarfs, late M-dwarfs, and brown dwarfs) may yield only xallarap signals
- Additional lens masses → frequently present, but often not detectable

RGES Requires a New Modeling Strategy

Old Strategy

- Only include higher order effects as needed to fit the data
- High angular resolution follow-up imaging, is a problem for someone else, many years from now

Roman Galactic Exoplanet Survey modeling strategy

- Higher order effects must be included if they influence the uncertainties of other measurable parameters
  - Parallax ($\boldsymbol{\pi}_{\mathrm{E}}$)is always present and can influence t_{E}, orbital motion can influence $\boldsymbol{\pi}_{\mathrm{E}}$.
  - Galactic priors can be used to exclude very unlikely $\boldsymbol{\pi}_{\mathrm{E}}$ and orbital motion parameters.
  - Source companions at separations of < 10 AU can yield xallarap and additional magnified sources
- Roman's high angular resolution imaging will be available for all events, and image-constrained modeling simplifies the analysis
  - Hints of source companions are available immediately.
  - Relative proper motion, $\boldsymbol{\mu}_{\mathrm{rel}}$, measurements available toward the end of the survey and can yield accurate $\boldsymbol{\pi}_{\mathrm{E}}$ and θ_{E} measurements

Image Constrained Modeling Makes Analysis Easier

- Use constraints from high angular resolution imaging and Galactic models on the modeling of light curve data.
- Initially, we don’t have $\boldsymbol{\mu}_{\mathrm{rel,H}}$ measurements, but we can constrain the following:
  - Lens + Source(s) magnitudes. Since there could be unrelated stars blended with the source and lens, we might just use upper limits on the Lens + Source(s) brightness
  - Priors based on Galactic models and orbital distributions for $\boldsymbol{\pi}_{\mathrm{E}}$ and orbital motion
    - These allow reasonable uncertainties to be obtained for $\boldsymbol{\pi}_{\mathrm{E}}$ and orbital motion when the data are not sufficient to measure these parameters.
- When $\boldsymbol{\mu}_{\mathrm{rel,H}}$ is measured, the constraints are much stronger
  - Source and lens systems are separated, so that we can constrain the magnitudes independently
    - We also constrain the lens-source magnitude difference, as it may be known more precisely
  - $\boldsymbol{\mu}_{\mathrm{rel,H}}$ allows the direction of $\boldsymbol{\pi}_{\mathrm{E}}$ to be constrained
    - Which allows 1-d $\boldsymbol{\pi}_{\mathrm{E}}$ to be converted to full 2-d $\boldsymbol{\pi}_{\mathrm{E}}$ measurements
    - This requires a conversion from $\boldsymbol{\mu}_{\mathrm{rel,H}}$ to $\boldsymbol{\mu}_{\mathrm{rel,G}}$ which depends on the source distance, so D_S is included as a fit parameter (with a prior)
- Imaging constraints significantly reduce the range of acceptable models for faster modeling
- Coding is relatively simple.

Mass Measurement Complications

- Analysis of 15 Suzuki+16 sample events (out of 29 planets in 28 events):
  - OGLE-2005-BLG-071 – 1-d π_E
  - OGLE-2005-BLG-169 – OK
  - OGLE-2006-BLG-109 – triple lens (2 planets) w/ orbital motion 1-d π_E resolved by terrestrial π_E
  - MOA-2007-BLG-192 – π_E contaminated by color-dependent atmospheric refraction
  - MOA-2007-BLG-400 – OK
  - OGLE-2007-BLG-349 – triple lens w/ circumbinary planet favored over 2-planet model by lens flux
  - MOA-2008-BLG-379 – source magnitude 27σ too bright
  - MOA-2009-BLG-266 – OK (some improvement of π_E with orbital motion)
  - MOA-2009-BLG-319 – weak triple lens w/ degenerate circumbinary and 2-planet models
  - MOA-2010-BLG-117 – binary lens, binary source with π_E measurement
  - MOA-2010-BLG-328 – π_E + orbit vs xallarap investigated, both are needed along with 2nd lensed source
  - OGLE-2011-BLG-0265 – degenerate π_E models w/ different masses
  - OGLE-2011-BLG-0950 – planet – stellar binary degeneracy, planet χ^2 is better, but rejected by Keck data
  - OGLE-2012-BLG-0563 – systematic error in t_* and therefore θ_E
  - OGLE-2012-BLG-0950 – 1-d π_E

Failure due to higher order effect not modeled

Systematic photometry error

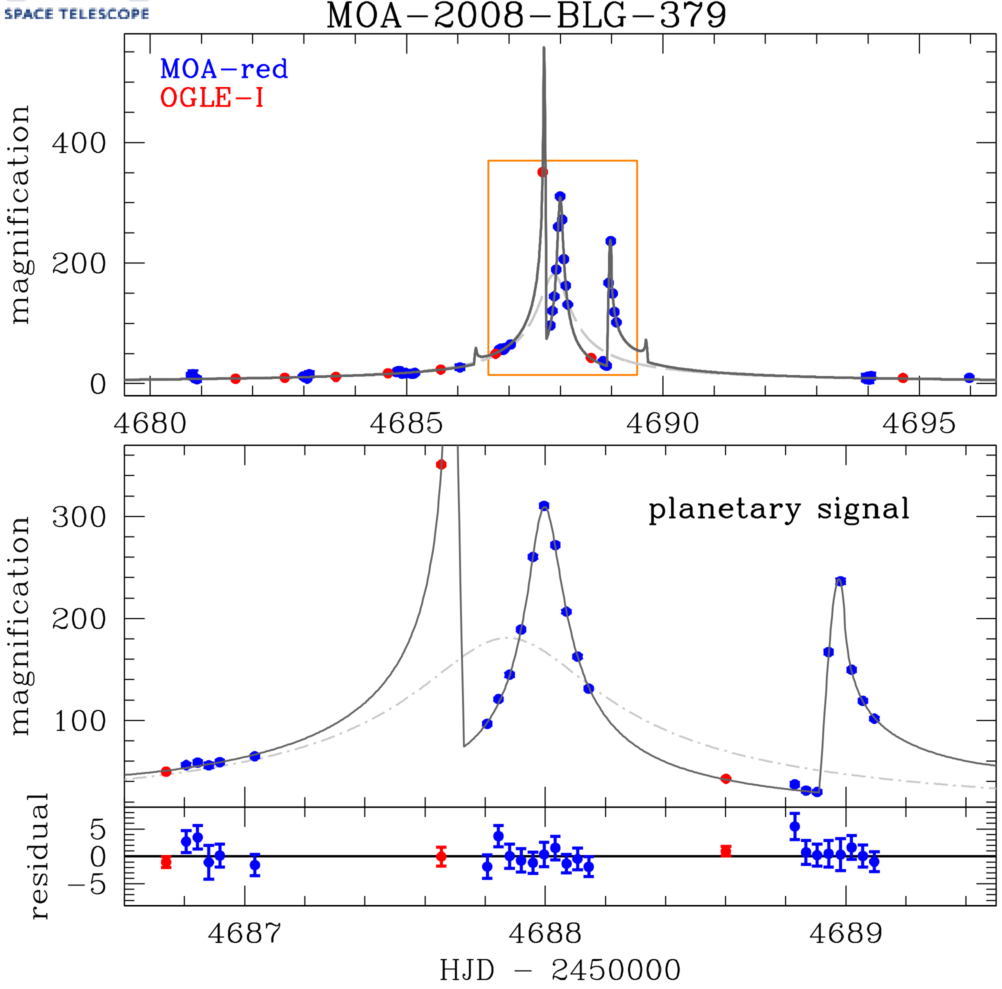
3L1S or 2L2S model needed

1-d π_E

Model degeneracy with different implied masses

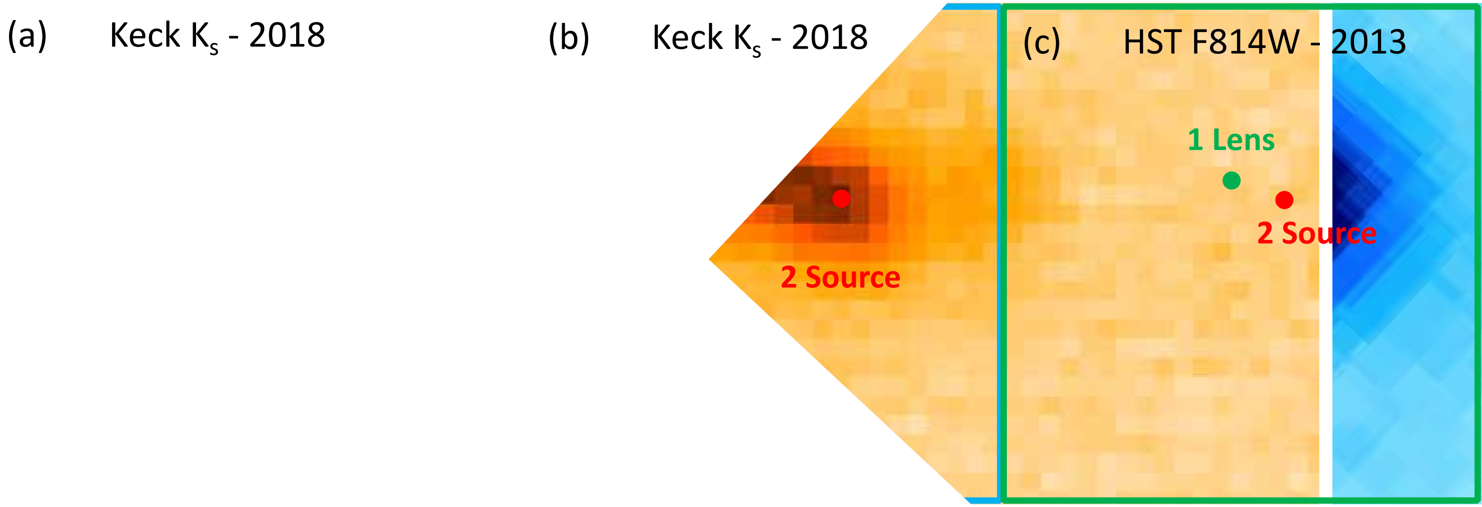
Only 3 out of these 15 events give clear mass measurements with simple and fast modeling

MOA-2008-BLG-379: Source Mag. & t_E Errors



Suzuki+14: I_{source} = 21.30 ± 0.03

t_E = 42.5 ± 0.5 days



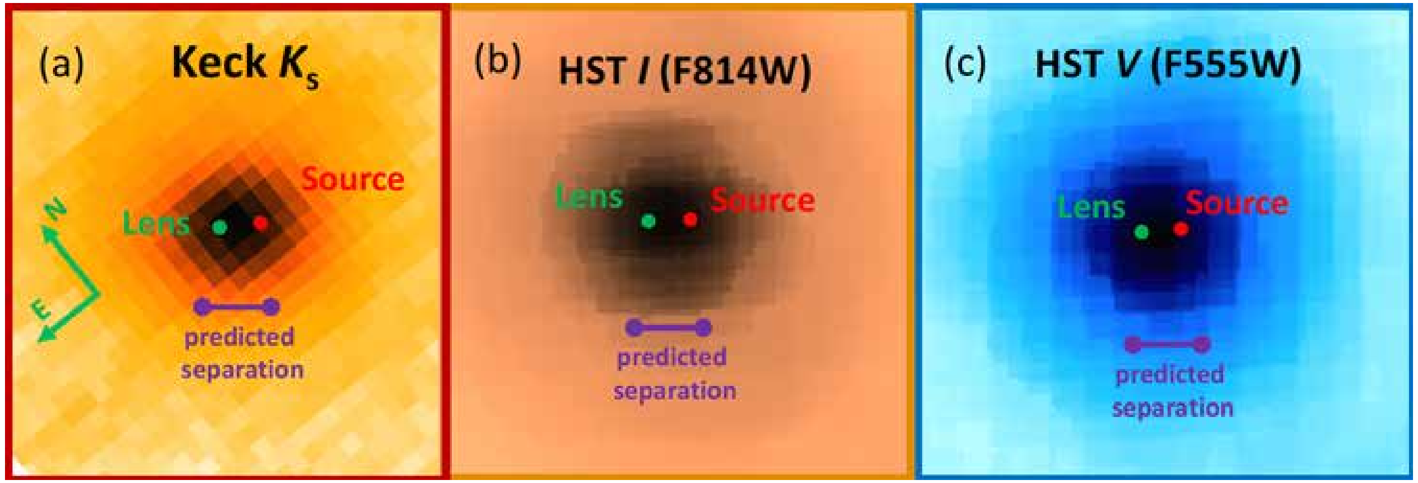
Bennett+23 with Keck, HST constraints:
I_{source} = 21.56 ± 0.15, K_{source} = 18.87 ± 0.06
t_E = 55.8 ± 5.5 days

Central t_E is 27σ larger than the Suzuki+14 value.

But, the Suzuki+14 model had $\boldsymbol{\pi}_E$ º 0.
With $\boldsymbol{\pi}_E$ ` 0, we have t_E = 45.0 ± 6.2 days
New t_E is 1.7σ larger than this value
Modeling $\boldsymbol{\pi}_E$ is needed for reliable error bars!

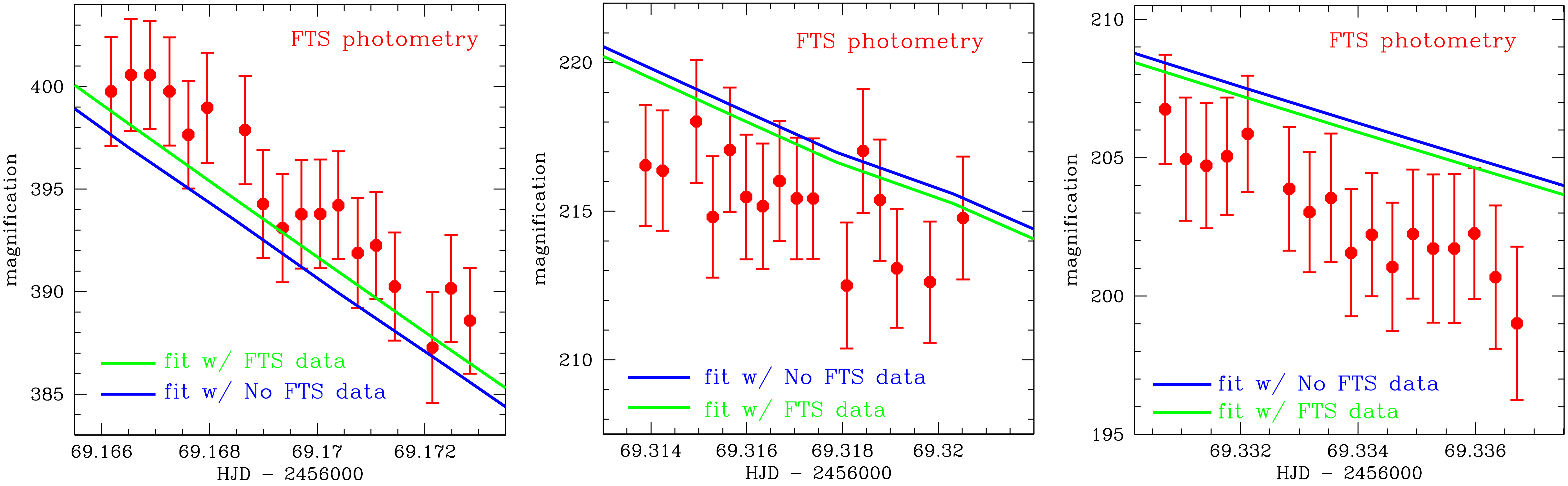
Detection of Systematic Photometry Error

- 3-color Keck (*K*) and HST (*V*, *I*) observations find $\boldsymbol{\mu}_{\mathrm{rel}}$ to be 0.6 x Fukui+15 $\boldsymbol{\mu}_{\mathrm{rel}}$ value
- image constrained modeling reveals systematic error in FTS Observations
  - OGLE favors the *V*, *I*, *K* measured $\boldsymbol{\mu}_{\mathrm{rel}}$ value
- ρ measurement seems unlikely at ρ e $2u_0$
- $M_{\mathrm{host}} = \xcancel{0.34^{+0.12}_{-0.20} M_\odot}$ now $M_{\mathrm{host}} = 0.81 \pm 0.03\ M_\odot$



(Bhattacharya+23,
Bennett+23 in preparation)
talk Friday at 10:00am

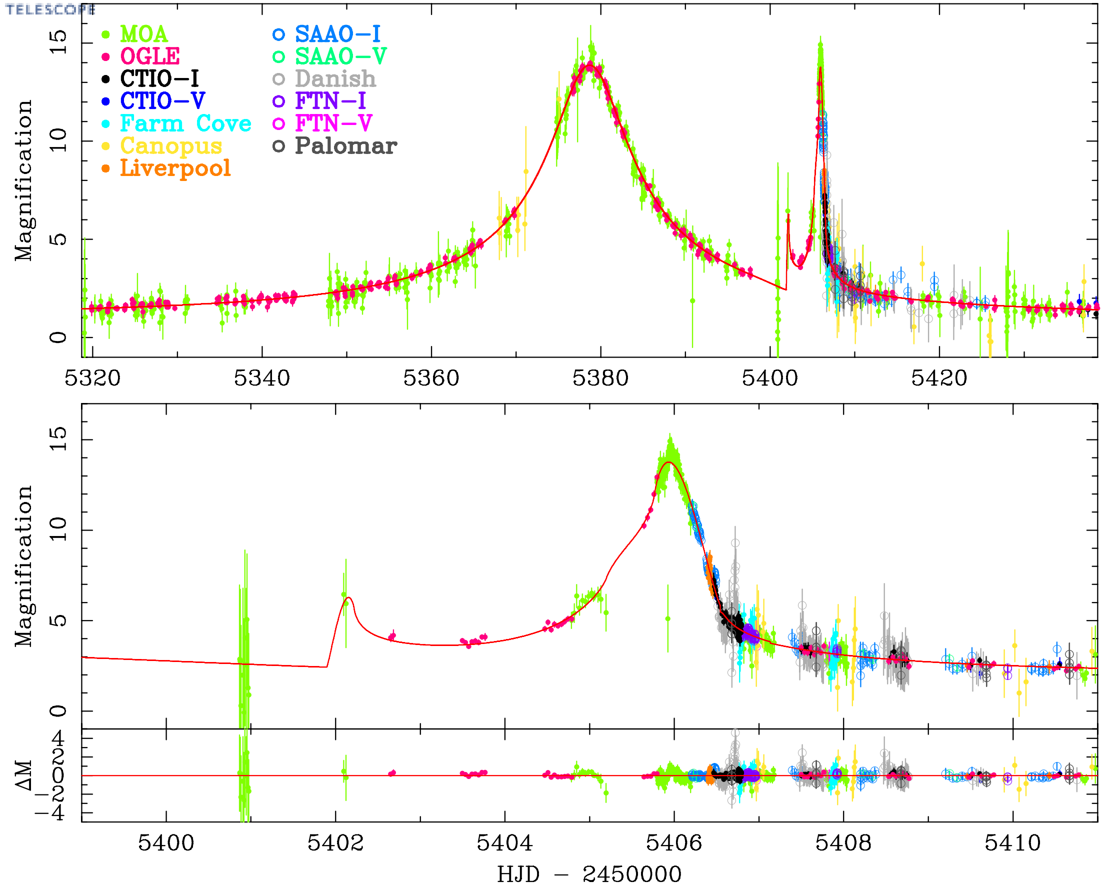
FTS Photometry for OGLE-2012-BLG-063



FTS data drives small t_* (or ρ) value (green curve), but fit without FTS data (blue curve) is consistent with the $\boldsymbol{\mu}_{\mathrm{rel}}$ to values measured by Keck and HST

See Aparna Bhattacharya's talk: Friday at 10:00am

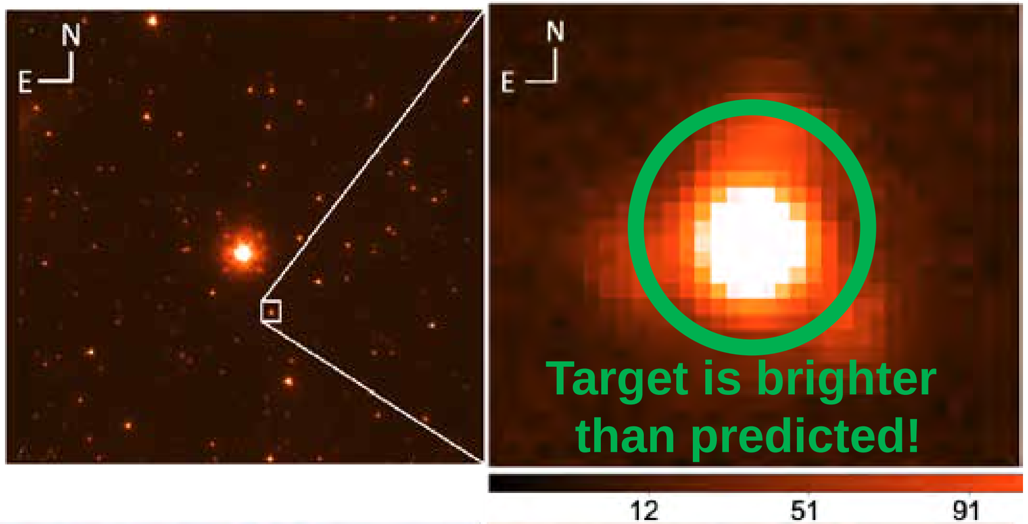
MOA-2010-BLG-328: Parallax or Xallarap?



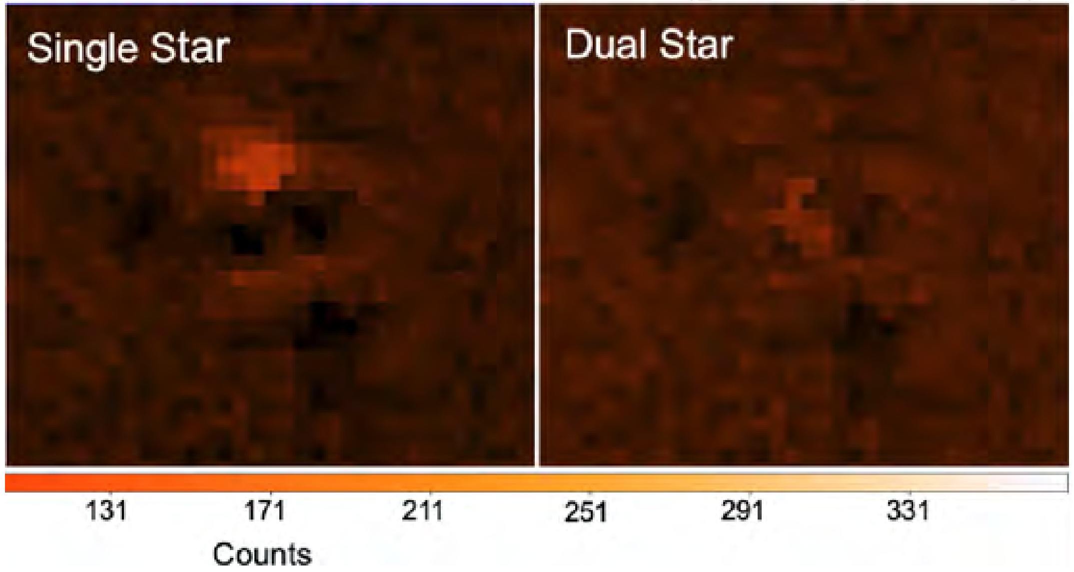
Furusawa+13 found competing solutions:

- microlensing parallax + orbital motion or
- xallarap models

Which is right?



Target is brighter than predicted!

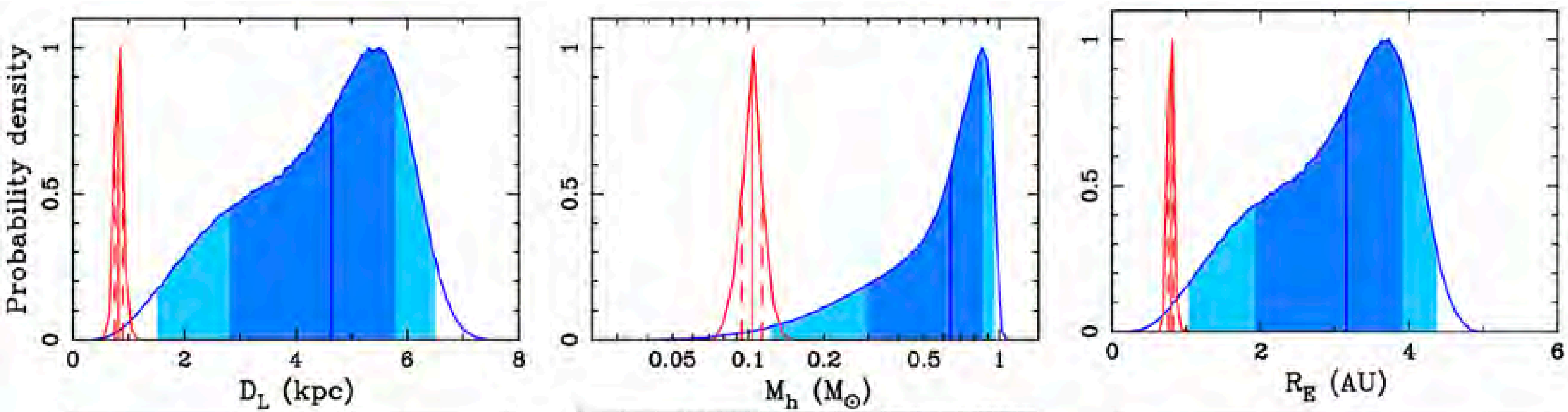


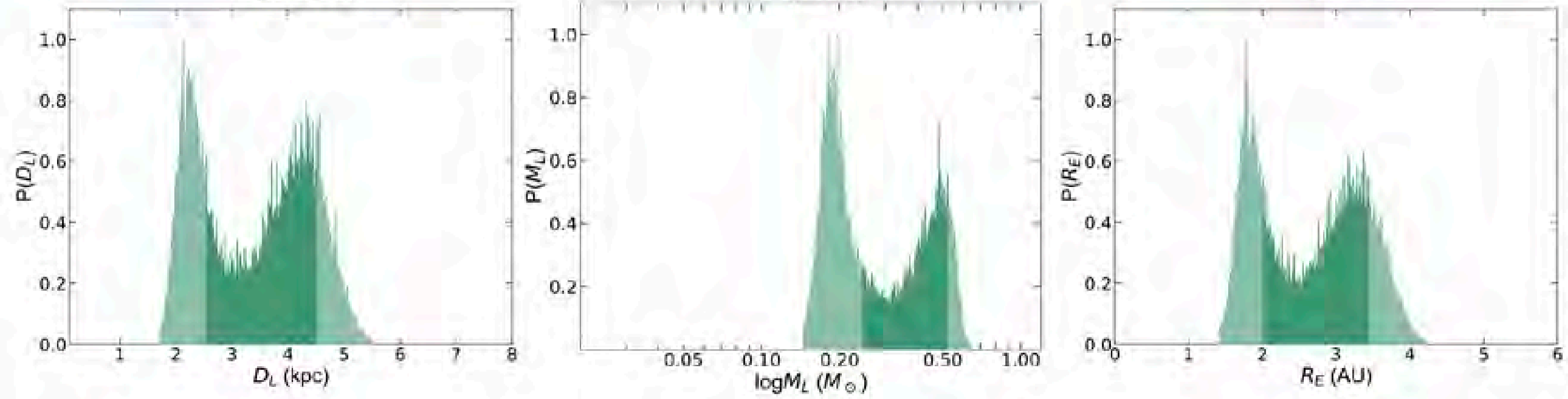
Excess flux suggests xallarap from a source companion, but every event has microlensing parallax

MOA-2010-BLG-328:
$\boldsymbol{\pi}_{\mathrm{E}}$, orbital motion, xallarap, and 2$^{\mathrm{nd}}$ magnified source

See Katie Vandorou’s talk, Friday at 9:45am

Furusawa+13 model results: parallax in red and xallarap in blue





Vandorou+24 results in preparation have 2 peaks, dominated by parallax and xallarap, but both effects are important (along with lens orbital motion and 2$^{\mathrm{nd}}$ source magnification