Challenges in Roman Microlensing

Light Curve Modeling

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ROMAN GALACTIC EXOPLANET SURVEY
Project Infrastructure Team

History of Planetary Microlensing Event Modeling

- First planetary microlensing event, OGLE-2003-BLG-235 (Bond+2004)
  - models confirmed by members of both groups
- Most planetary events modeled by several independent groups
  - Modeling confirmations often came in real time with semi-public alert event data.
- First 2-planet microlensing event, OGLE-2006-BLG-109 (Gaudi+2008, Bennett+2010)
  - hierarchical method: “single lens model ⇒ binary lens model ⇒ triple lens model” seems to work for virtually all 2-planet, triple lens events (but this event requires lens orbital motion to be included)
- First binary host star system plus planet event, OGLE-2013-BLG-0341 (Gould+2014)
  - But there doesn’t seem to be a general method to model such events
  - Possible confusion between 3L1S (3 lens, 1 source) and 2L2S (2 lens, 2 source) events
  - OGLE-2016-BLG-0613 published as a binary host system plus a planet, but MOA data contradicts the model and no viable model has been found
- By ~2020, it seemed that modeling triple lens events could be difficult, but

~~Binary lens modeling is a solved problem!~~

says “Not So Fast”

Planetary Microlensing is Modeling More Complicated for Roman Data

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- Realistic simulations from the Roman Galactic Exoplanet Survey (RGES) simulations group group!
- Roman light curve modeling differs from ground-based light curve modeling:
  - the magnification patterns of RGES events have higher density features because
    - RGES is sensitive to fainter source stars with smaller angular radii
    - RGES is sensitive to lower mass planets which magnify a smaller sky area
- The GBTDS observing seasons occur at the time of maximum gravitational acceleration perpendicular to the line-of-sight
  - This causes a maximum deviation from the nominal constant Telescope velocity assumption, and so maximizes the microlensing parallax, π_{E}, signals.
- Roman's high angular resolution removes excess noise from stellar blends, enabling much higher precision photometry at low magnification
  - Roman's continuous high cadence maximizes the number of low magnification images
  - This increases sensitivity longer duration features like π_{E} and orbital motion

Planetary Microlensing is Modeling More Complicated for Roman Data

- Thanks to Roman Galactic Exoplanet Survey (RGES) simulations and data challenge group groups!

Matthew Penny

Farzaneh Zohrabi

Alison Crisp

Amber Malpas

Jon Hulberg

Arjun Murlidhar

Macy Huston

RTModel & VBMicroLensing

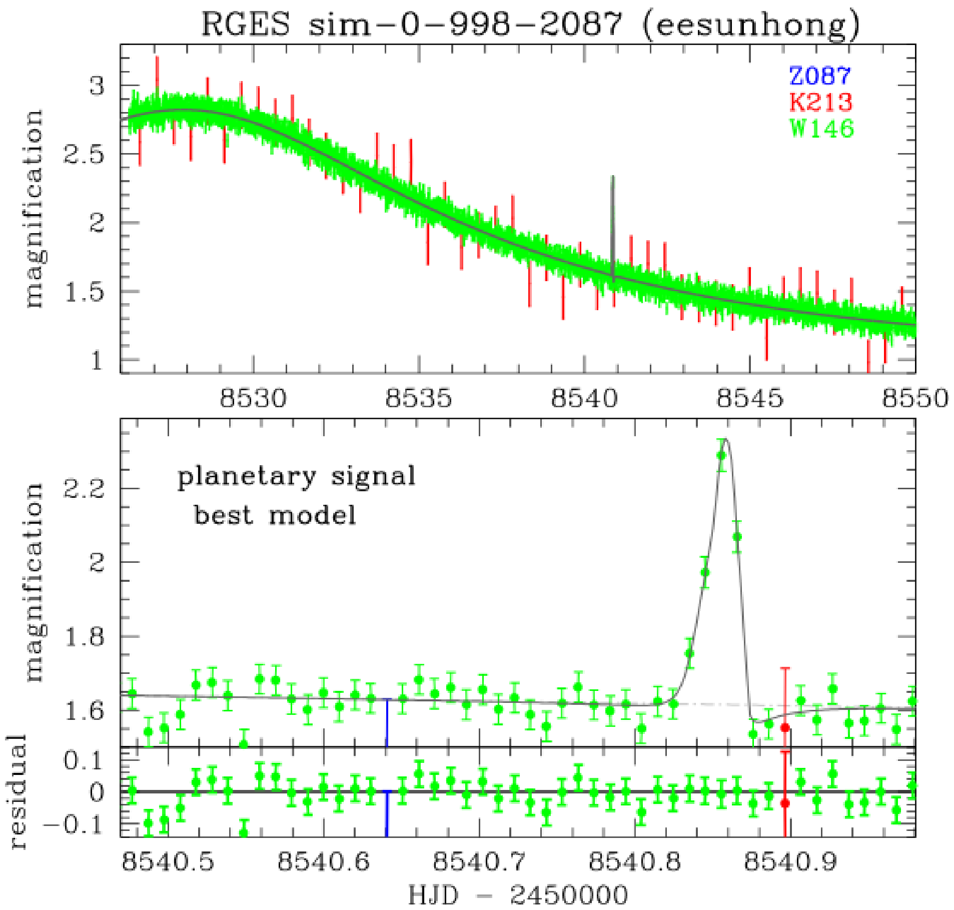
- Obvious choice as basis for the Microlensing Science Operations System (MSOS) pipeline due to fast VBMicroLensing magnification calculations and automation.
- Written by Valerio Bozza (U of Salerno)
- RTModel stands for Real Time Model, and is fully automated.
- Uses fast and efficient VBMicroLensing code to calculate microlensing magnification
  - Contour integration method
  - astrometric microlensing now included
- Selects initial conditions for binary microlensing events from a catalog of light curve types
- Very good for planetary microlensing events with ground-based data
  - Some difficulties for planetary events that are dominated by the signal from a widely separated planetary caustics, but these are not common.
- **Well optimized for ground-based data**

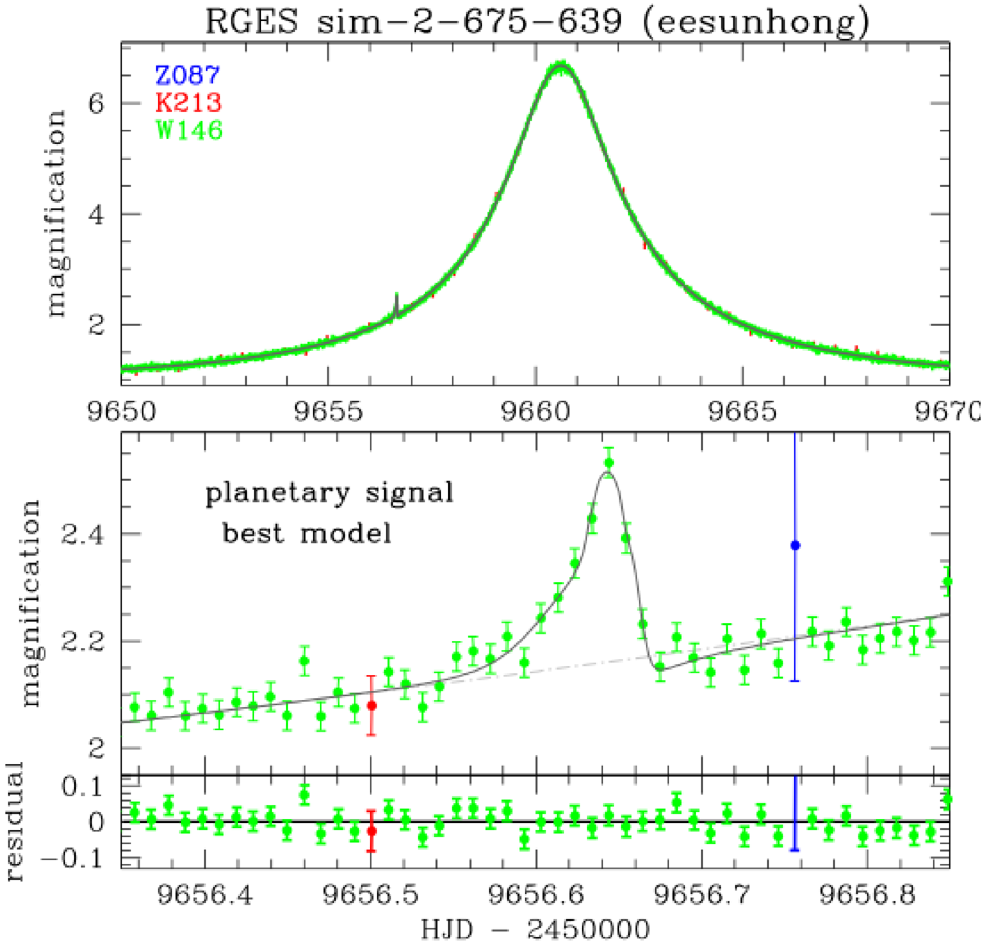
Tests Done with 2371 “Representative Sample”of Simulated Events from RGES PIT

- New “Experienced” Data Challenge and machine learning training simulation are now available and will be used for future tests.
- ~10% of these events may have too low S/N to be detectable, so sample may be ~1.5× larger than the real sample.
- RTModel runs on simulated data done by

  Stela Ishitani Silva (MSOS staff) and Jon Hulberg (Goddard NPP Postdoc in August

RTModel v2.4, v3.1 and v3.2 strugle with low mass ratio planets: 2 events not solved by RTM





Event 0_998_2087 has q = 1.64×10^{-7}

Event 2_675_639 has q = 8.49×10^{-7}

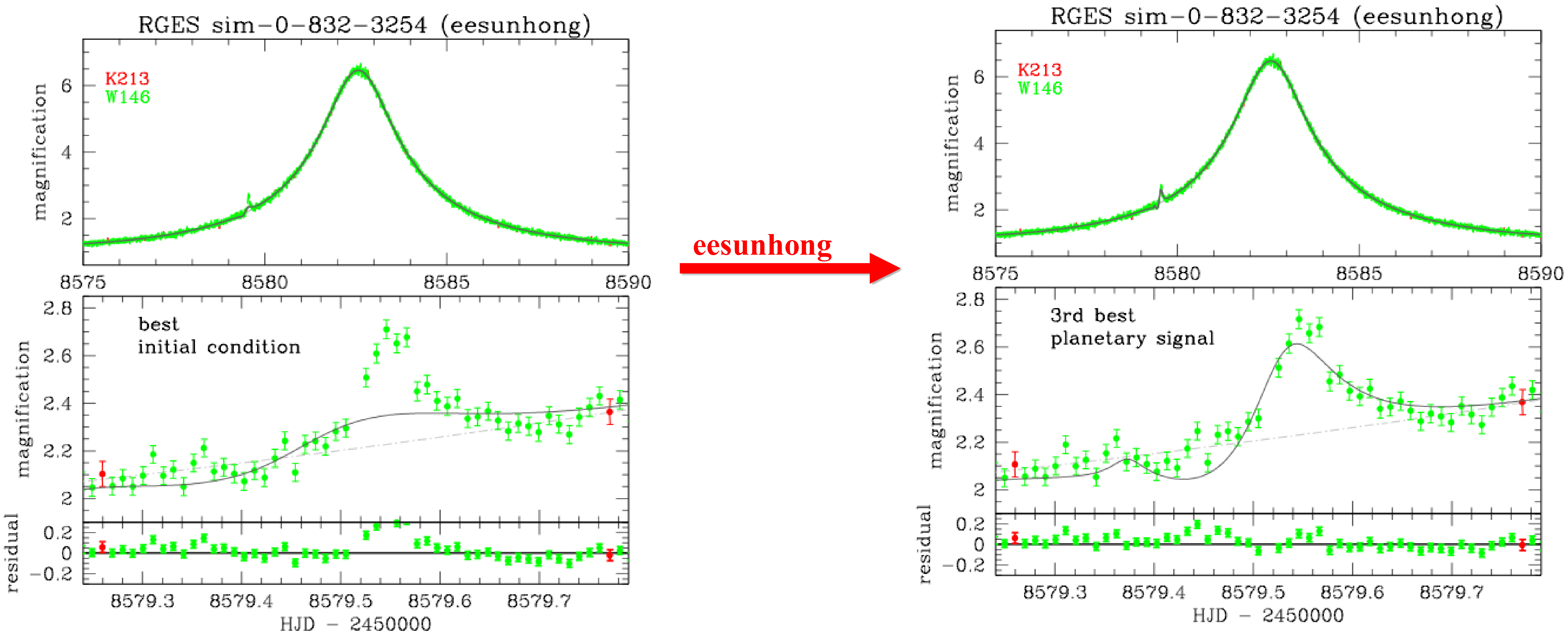
Low mass planets are challenging, due to short duration signal and smaller source angular radii

Eesunhong's Initial Condition Grid Search Method – designed for low q planets

Sun Hong Rhie
= 이선홍
Ee Sun Hong
in Korean

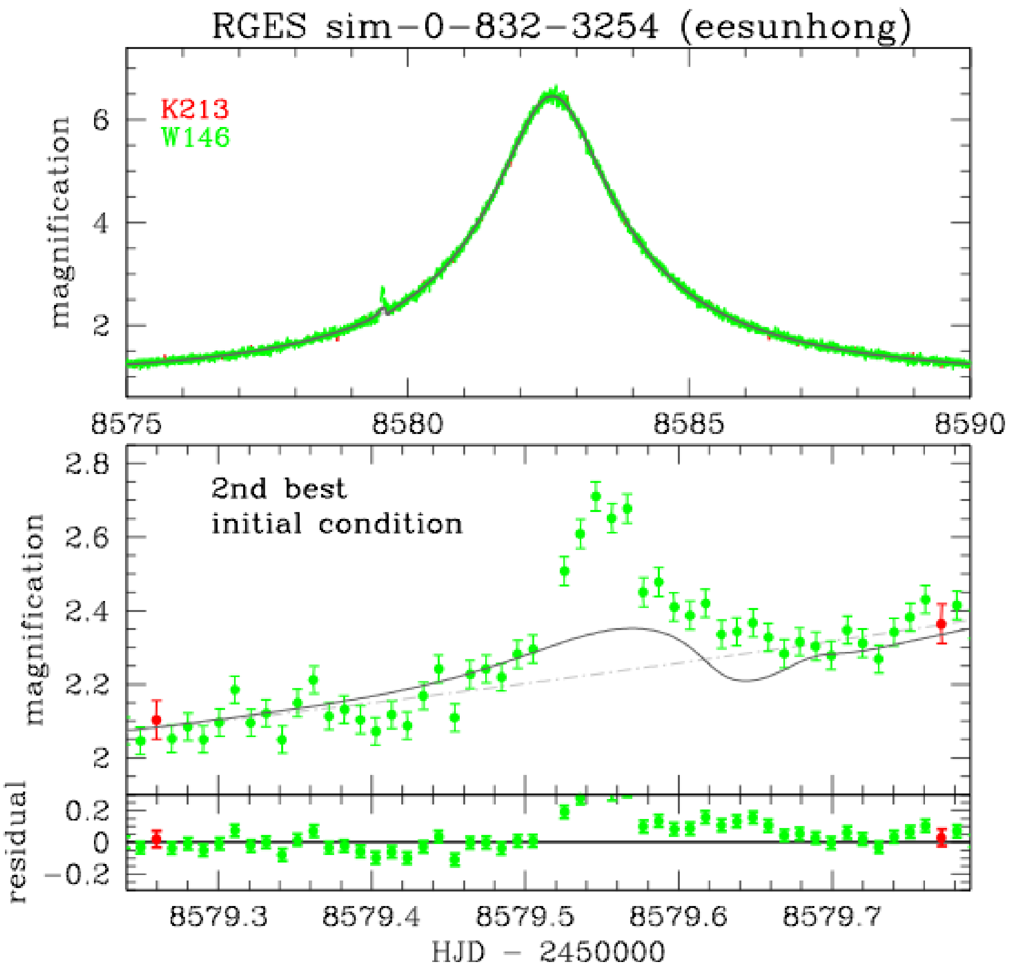
1. Bennett & Rhie (1996) and Bennett (2010)
2. Fit light curve with single lens model
   a) Use finite source for high mag events
   b) Possibly remove data with obvious planetary signa (not used for GBTDS simulation analysis)
3. Fix single lens parameters, t_0, u_0, t_E, t_* [perhaps different t_* values based on source mag]
4. Grid parameters for eesunhong analysis of RGES simulations:
   a) $\varepsilon = q/(1+q) = 3.16 \times 10^{-7}, 10^{-6}, 3.16 \times 10^{-6}, 10^{-5}, 3.16 \times 10^{-5}, 10^{-4}, 3.16 \times 10^{-4}, 10^{-3}, 3.16 \times 10^{-3}, 10^{-2}, 0.0316$
   b) s = 0.36, 0.38, 0.40, 0.42, 0.44, 0.46, 0.48, 0.50, 0.52, 0.54, 0.56, 0.58, 0.60, 0.62, 0.64, 0.66, 0.68, 0.70, 0.72, 0.74, 0.76, 0.78, 0.80, 0.82, 0.84, 0.86, 0.88, 0.90, 0.92, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 1.00, 1.01, 1.02, 1.03, 1.04, 1.055, 1.07, 1.09, 1.11, 1.13, 1.15, 1.17, 1.19, 1.21, 1.24, 1.27, 1.30, 1.33, 1.36, 1.39, 1.42, 1.45, 1.48, 1.52, 1.56, 1.60, 1.65, 1.70, 1.75, 1.80, 1.85, 1.90, 1.96, 2.08, 2.02, 2.14, 2.2, 2.3, 2.4, 2.5, 2.62, 2.75, 2.8, 2.9
      - note higher density near $s = 1$
   c) α = 946 values from -3.15 to 3.15
5. Pick ~20 initial conditions with best χ^2 values and different (ε, s) pairs (best α per pair)
   - use (q,s) for RTM

ICGS Example: best initial Condition for 0_832_3254

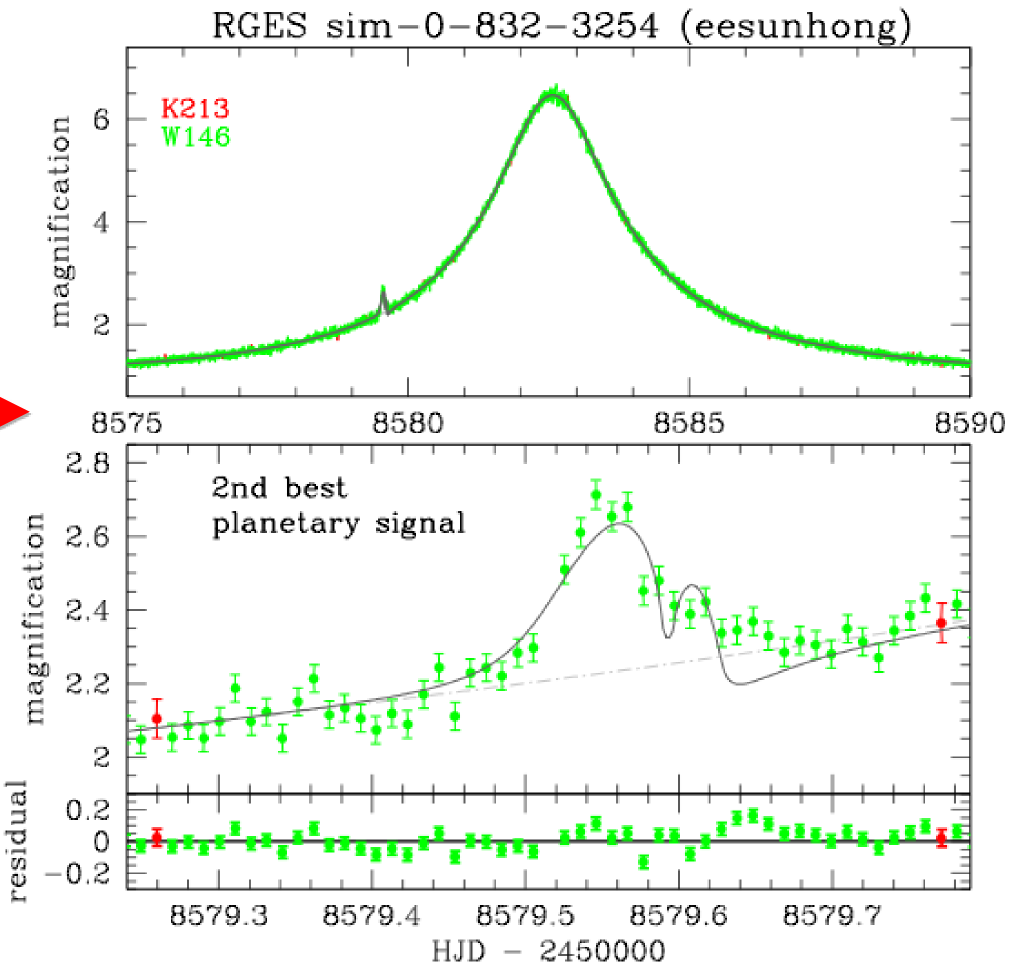


$q_{\mathrm{true}} = 5.21725 \times 10^{-6}$ $s_{\mathrm{true}} = 1.27043$

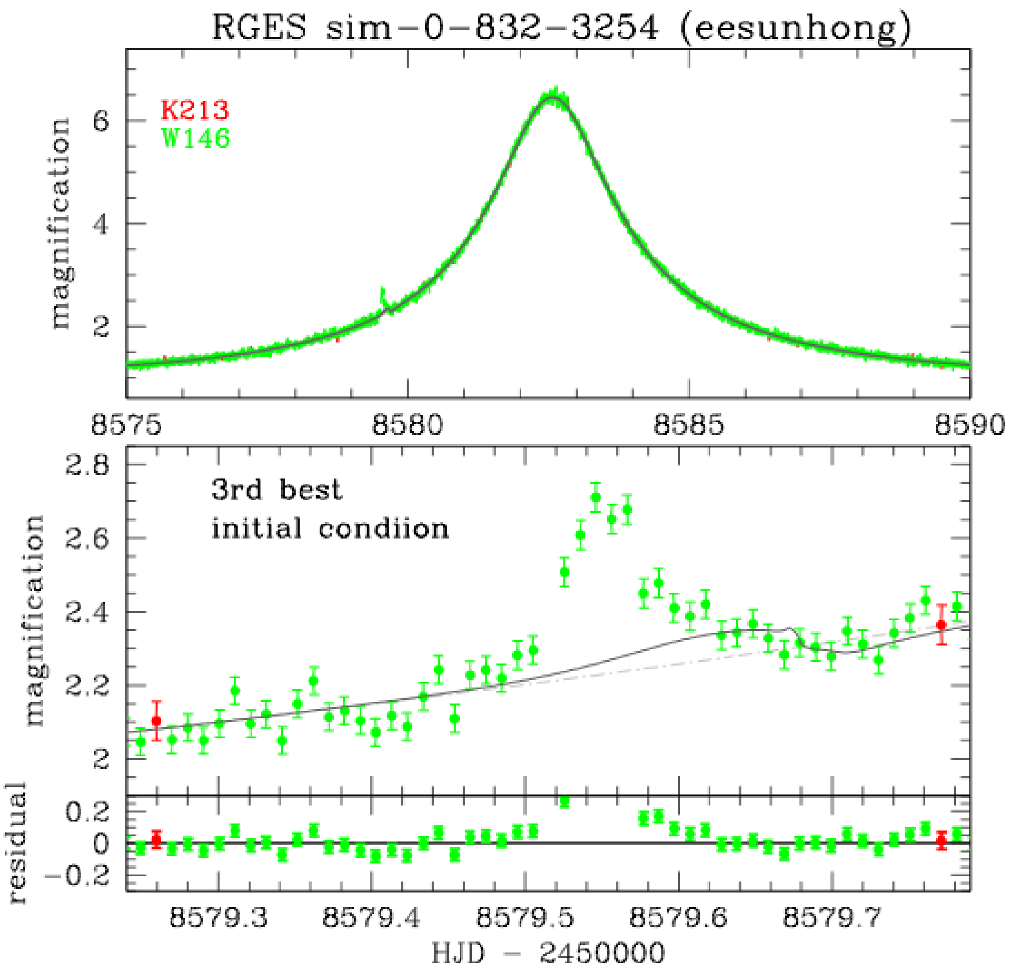
ICGS Example: 2nd best initial Condition (0_832_3254)



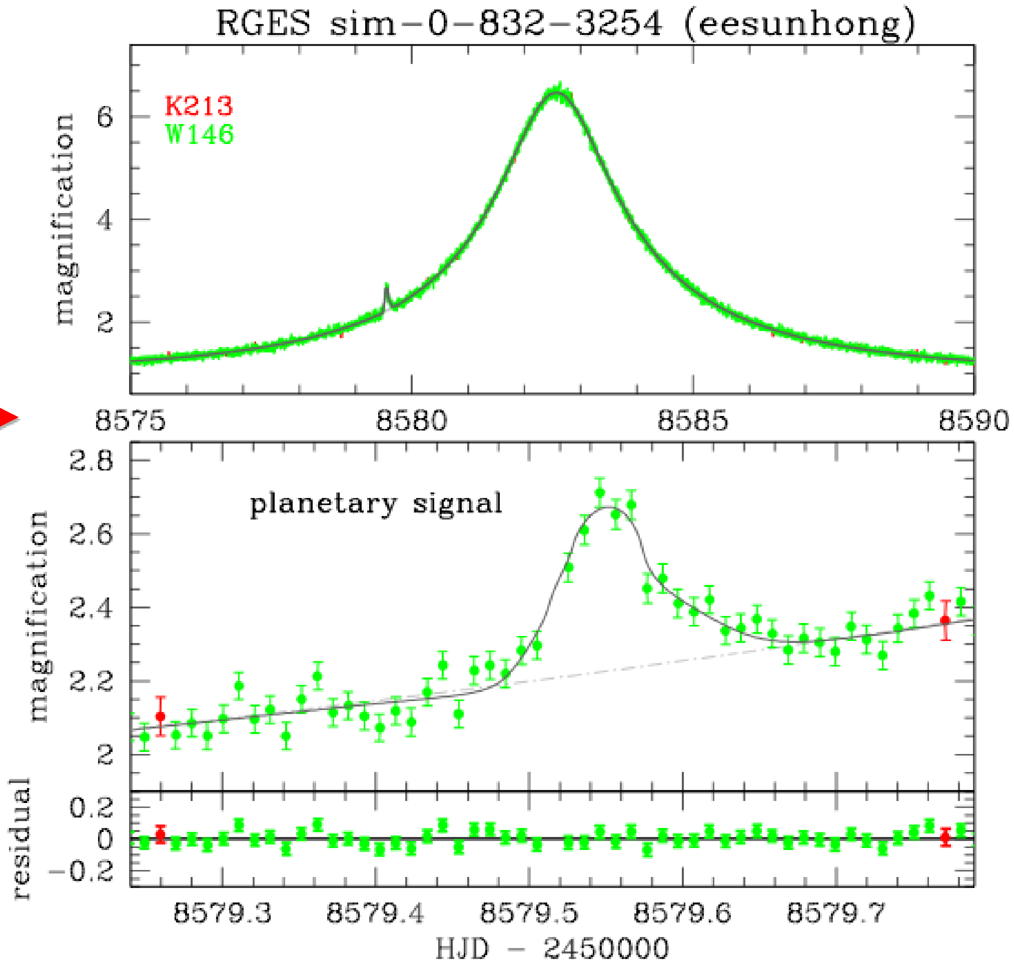
eesunhong



3^{rd} best initial Condition yields best model



eesunhong



$$q_{\rm true} = 5.2172 \times 10^{-6} \qquad s_{\rm true} = 1.2704$$

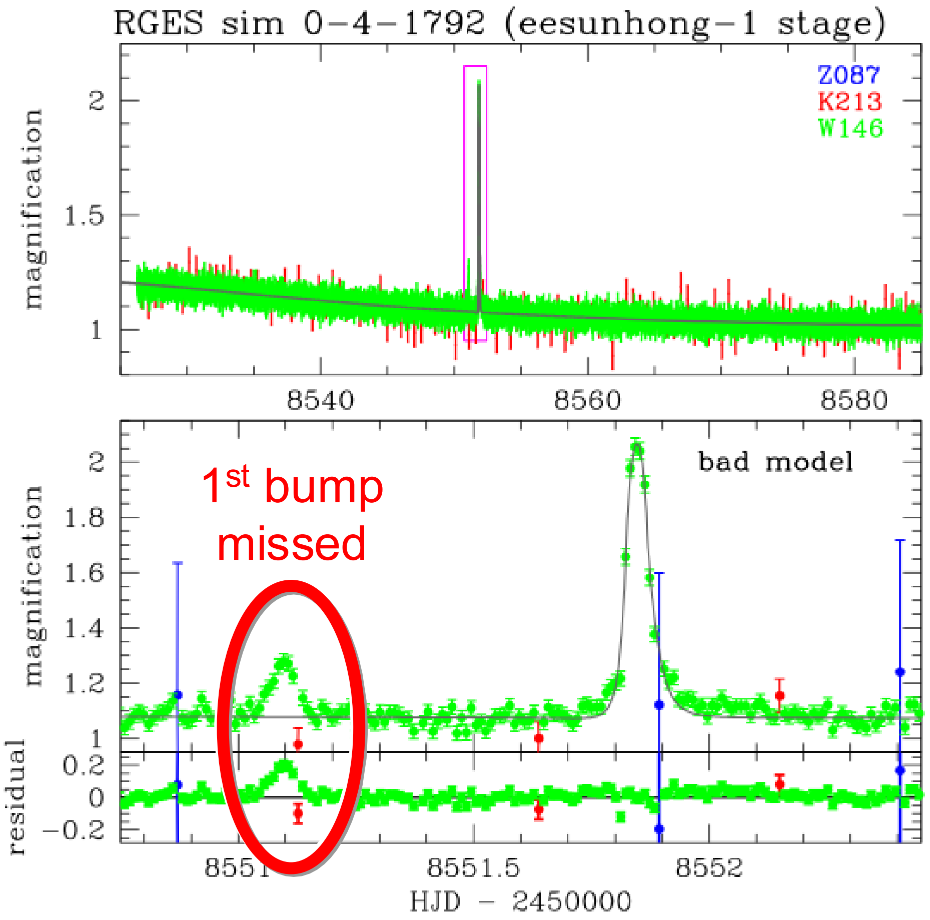
$$q_{\rm esh} = 5.6874 \times 10^{-6} \qquad s_{\rm esh} = 1.2740$$

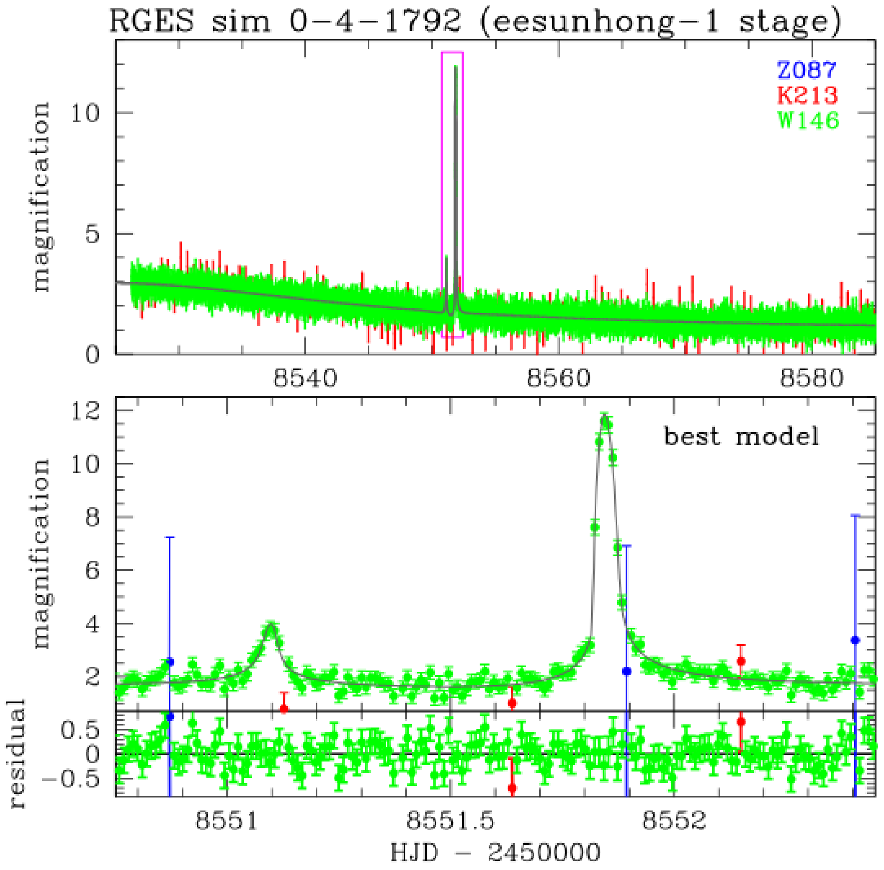
Adding ICGS to RTModel

- Preliminary tests show that the ICGS can increase the RTModel modeling success rate from 43% to 91%
- Some of the remaining failures are likely to corrected when ICGS is included in RTModel
- Jon Hulberg is currently working to update the code with Valerio Bozza's help

- There are still some categories of that fail RTModel+ICGS:
  - Events with strong planetary signals, but weak stellar lensing signals can have their initial single lens (or points-source, point lens PSPL) perturbed, which can interfere with finding the correct solution.
  - Events with strong π_{E}
  - Events with very strong caustic crossings

eesunhong solutions with planetary signal included or removed from PSPL model (for event 0_4_1792)





planetary signal included for PSPL

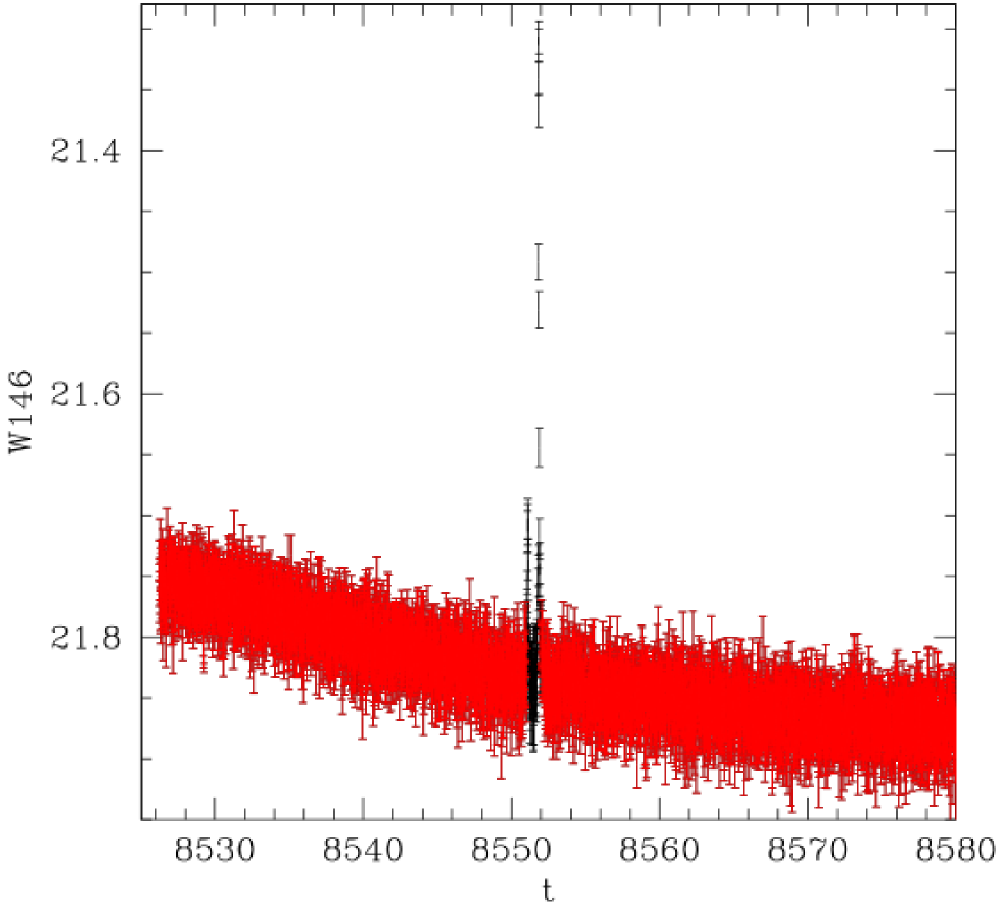
$q_{\mathrm{bad}}, s_{\mathrm{bad}} = 1.6923 \times 10^{-6}\ 2.29127$

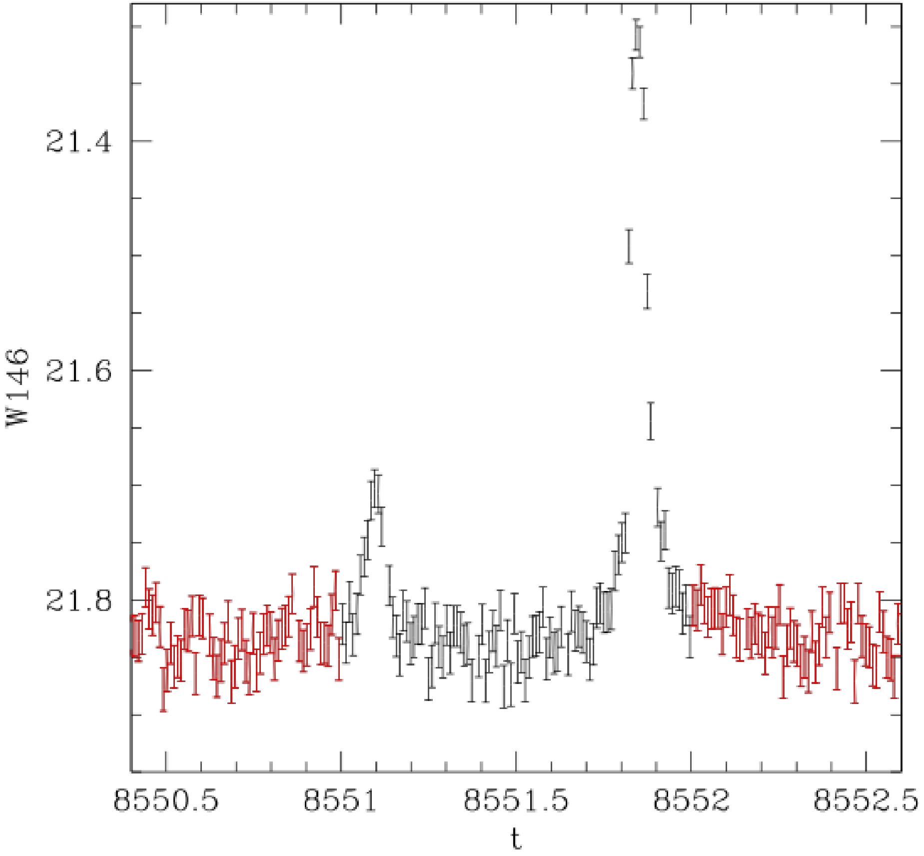
planetary signal **excluded** from PSPL

$q_{\mathrm{mod}}, s_{\mathrm{mod}} = 7.8801 \times 10^{-5}\ 1.37802$

$q_{\mathrm{true}}, s_{\mathrm{true}} = 7.5395 \times 10^{-5}\ 1.3801$

Excluded part of light curve in black (for event 0_4_1792)



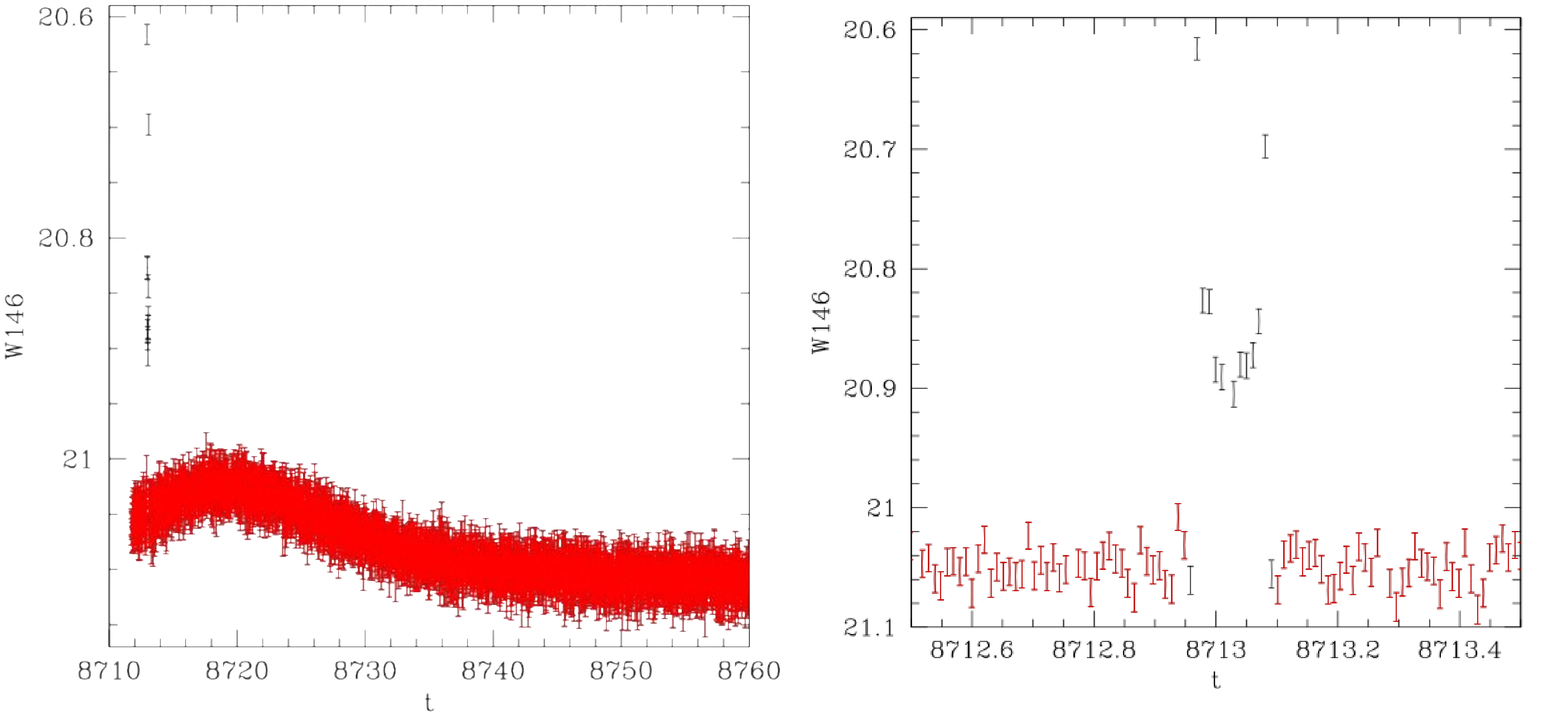


Parameters from PSPL model without planetary signal (in red) is used to run ICGS.

Planetary signal improves χ^2 by $\Delta\chi^2 = 4903.98$ over PSPL (on full data set)

The excluded data interval is $8551 < t < 8552$.

Excluded part of light curve in black (for Event 0_599_3599)



Parameters from PSPL model without planetary signal (in red) is used to run ICGS.

Planetary signal improves χ^2 by $\Delta\chi^2 = 4705.94$ over PSPL (on full data set)

excluded $8712.95 < t < 8713.1$

Remove Planetary Signals for Most ICGS PSPL models

- There aren't known modeling errors caused by removal of planetary signals from ICGS PSPL models
- But, with eesunhong, the selection of the planetary signal data to remove has been made by hand
- Kansuke Nunota is working on selecting data to be removed using a version of his microlensing event anomaly finder code

- It makes sense to base the data removal decision on an automated criteria
  - Data removal may be problematic for events with long duration, low-amplitude planetary signals
  - It also might be problematic for events that make selection of data to be removed difficult

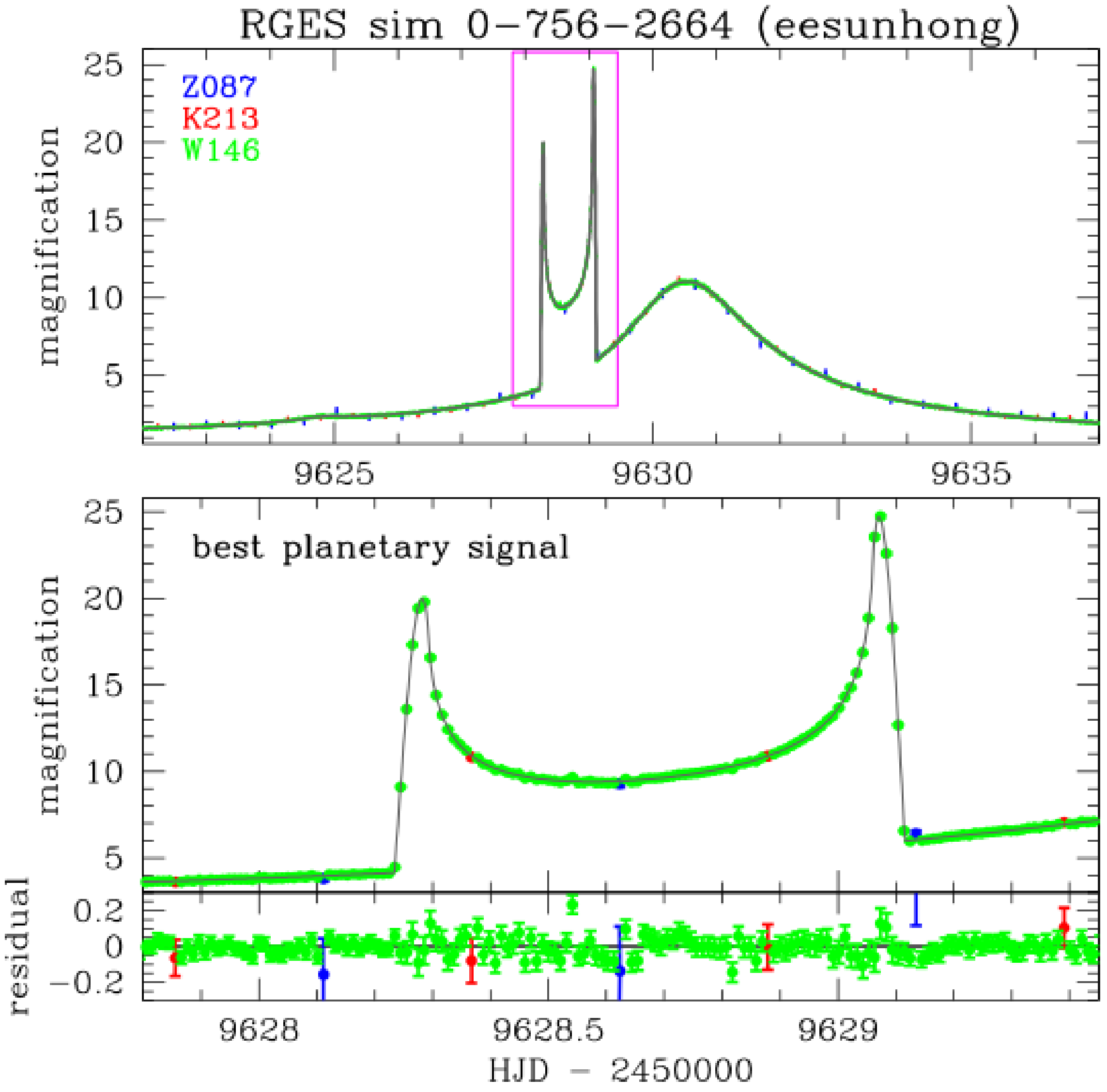
Events with strong caustic signals are modeled efficiently with a change of time variables (event 0_756_2664)

The time of lens-source closest approach, $t_{0,}$ and the angular Einstein radius, t_E,are replaced by 2 caustic crossing times for both the ICGS and the final modeling. This even has

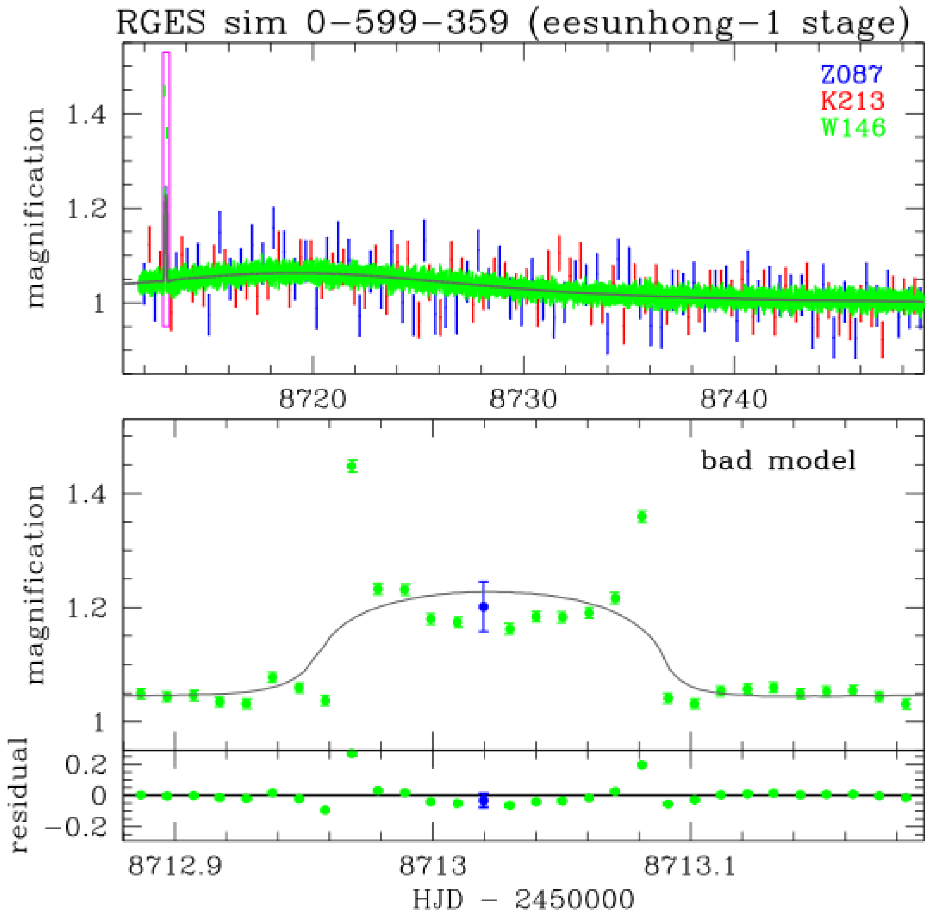
$t_{cc1} = 9628.28557$

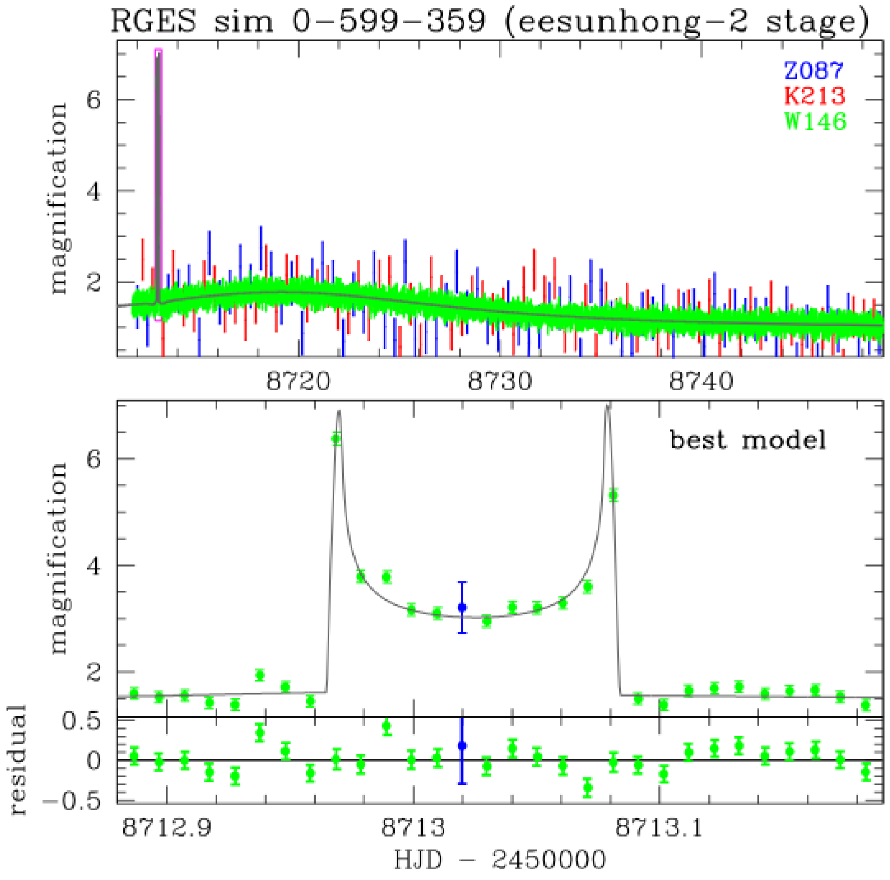
$t_{cc2} = 9629.07330$

based on the brightest measurement at each peak.



For this event, the standard ICGS analysis misses the correct model (0_599_3599)





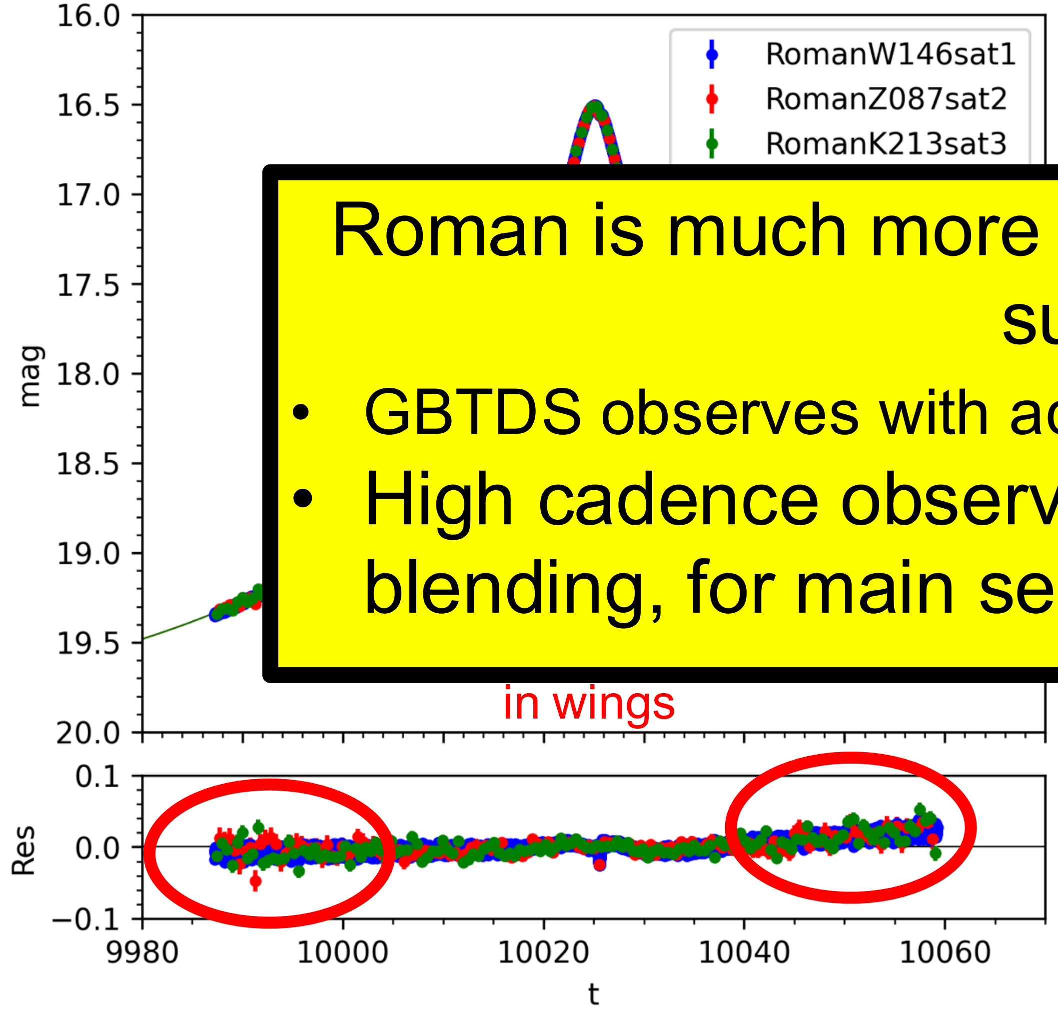
ICGS with t_{cc1}, t_{cc2}, modeling

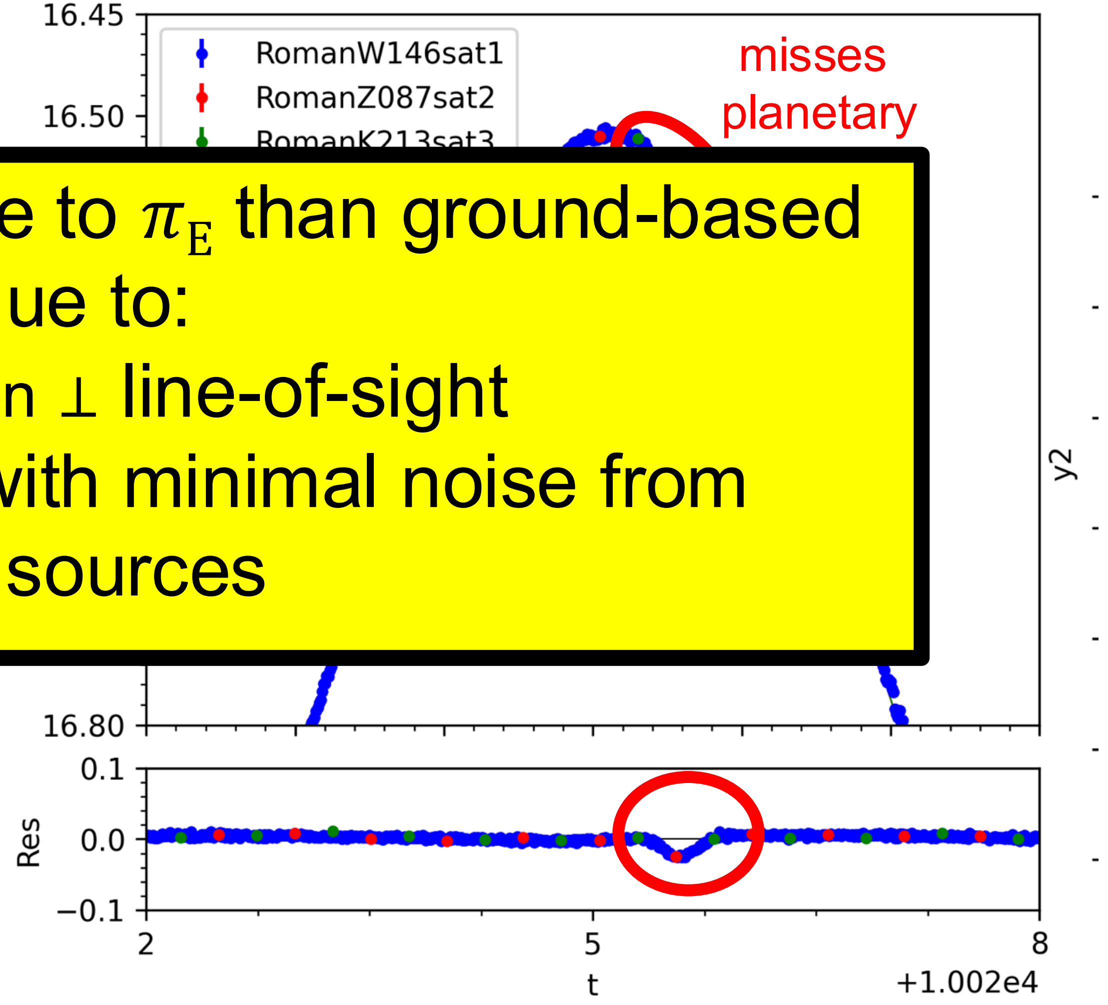
$q_{\text{bad}}, s_{\text{bad}} = 9.3353 \times 10^{-6}\ 2.55421$

$q_{\text{mod}}, s_{\text{mod}} = 7.6114 \times 10^{-5}\ 1.4587$

$q_{\text{true}}, s_{\text{true}} = 7.6108 \times 10^{-5}\ 1.4619$

A Strong π_E signal can interfere with the planetary signal if is not modeled first





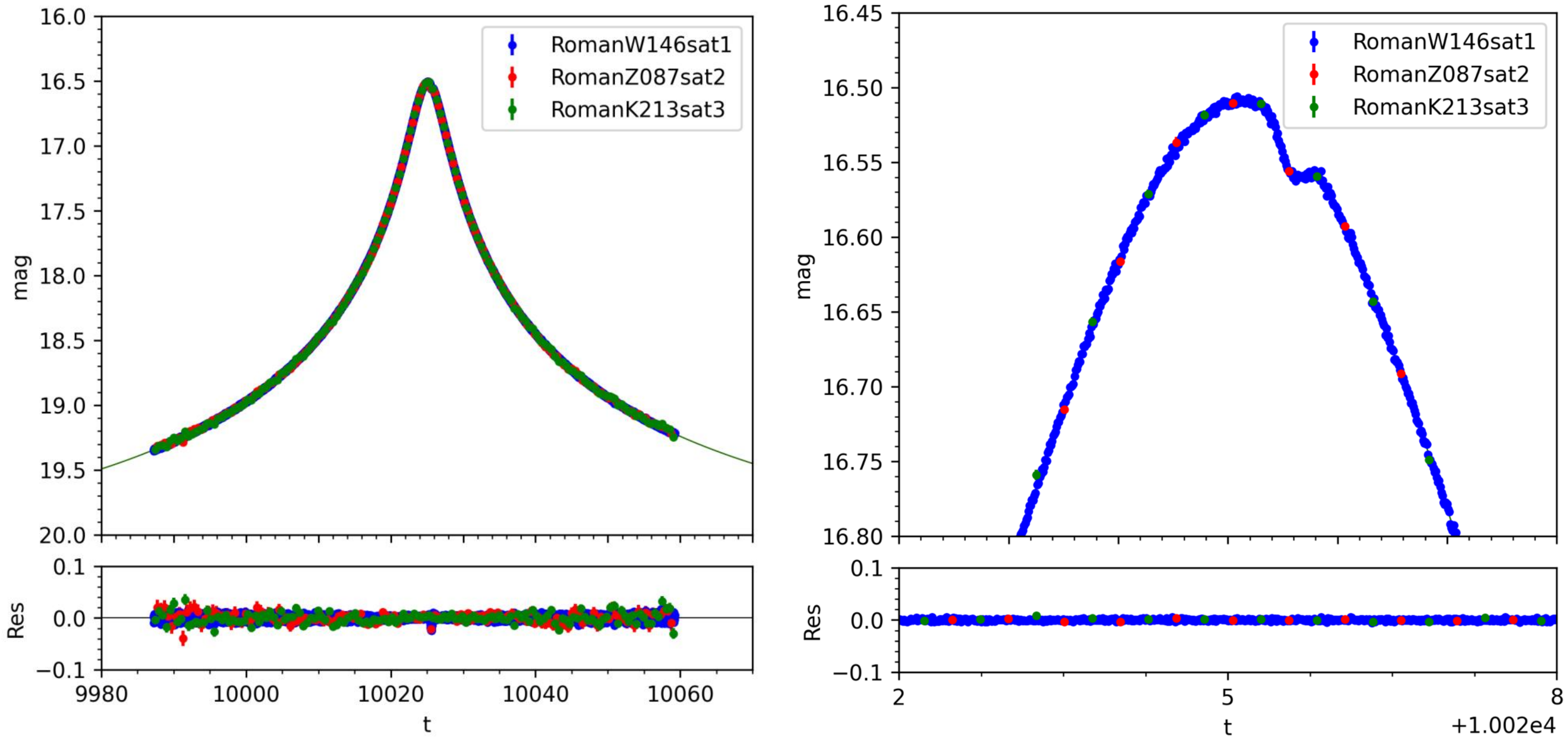
Roman is much more sensitive to π_E than ground-based surveys due to:

- GBTDS observes with acceleration ⊥ line-of-sight
- High cadence observations with minimal noise from blending, for main sequence sources

event 0_ 603_3135: Best fit planetary model misses planetary signal

Finds $q = 2.00 \times 10^{-4}$, s = 2.69, but input values are $q = 6.9 \times 10^{-6}$, s = 0.922

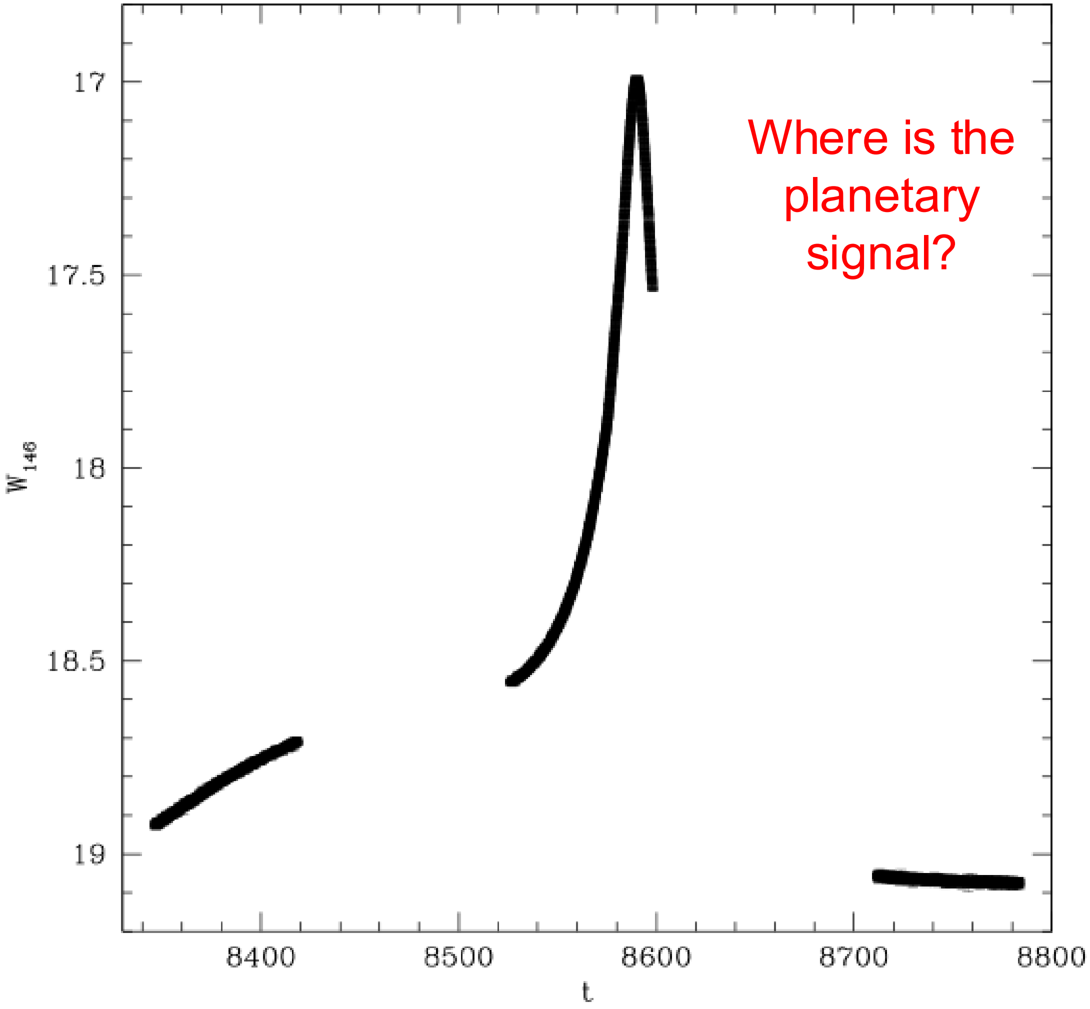
When π_{E} is Fit First



event 0_ 603_3135: Best fit single lens, $\boldsymbol{\pi}_{\mathrm{E}}$, model also misses planetary signal, improves χ^2 by $\Delta\chi^2$ = 45,500

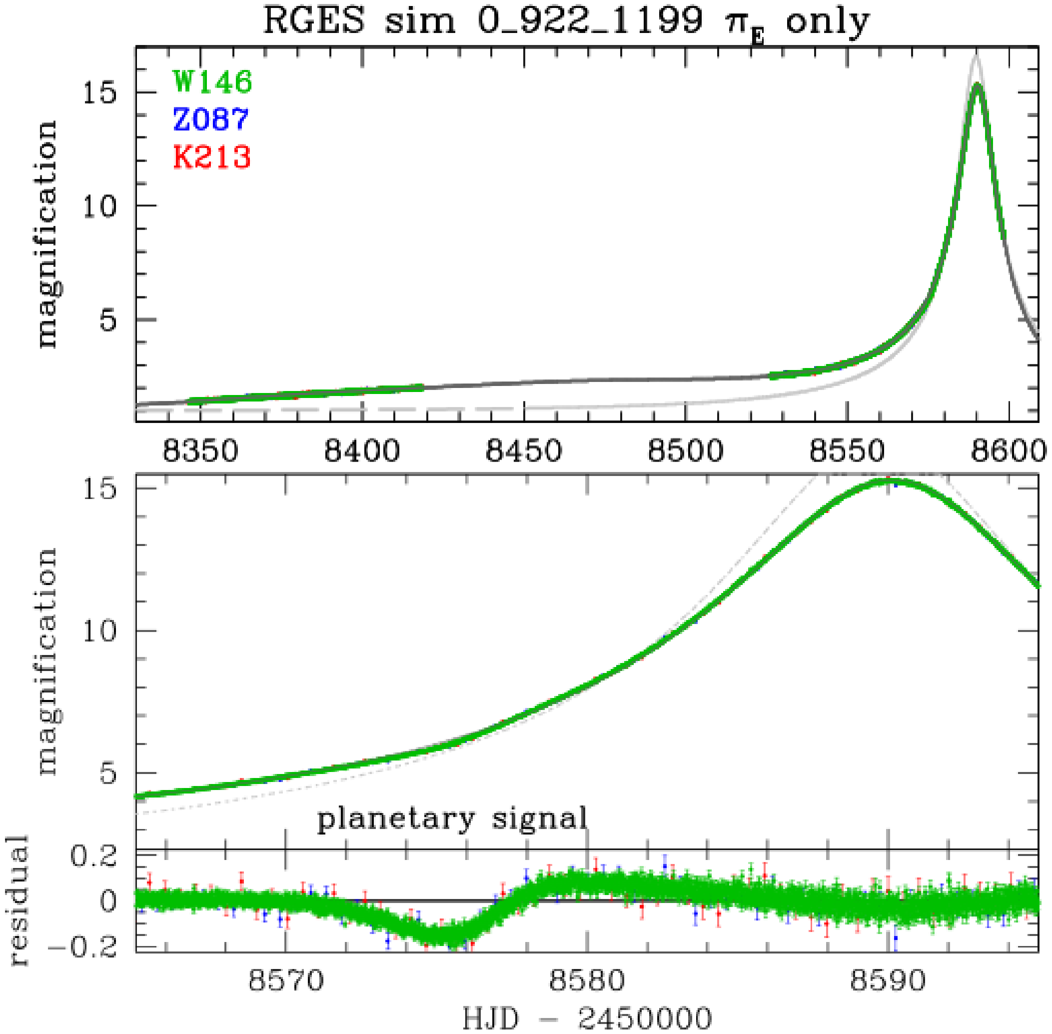
eesunhong with ICGS finds correct model starting from $\boldsymbol{\pi}_{\mathrm{E}}$ model. Planetary signal improves χ^2 by $\Delta\chi^2$ = 3,480

An extreme case: the π_E signal is 800× stronger



event 0_922_1199: obvious parallax ($\boldsymbol{\pi}_E$) signal

$\Delta\chi^2 = 2.1 \times 10^7$ with parallax

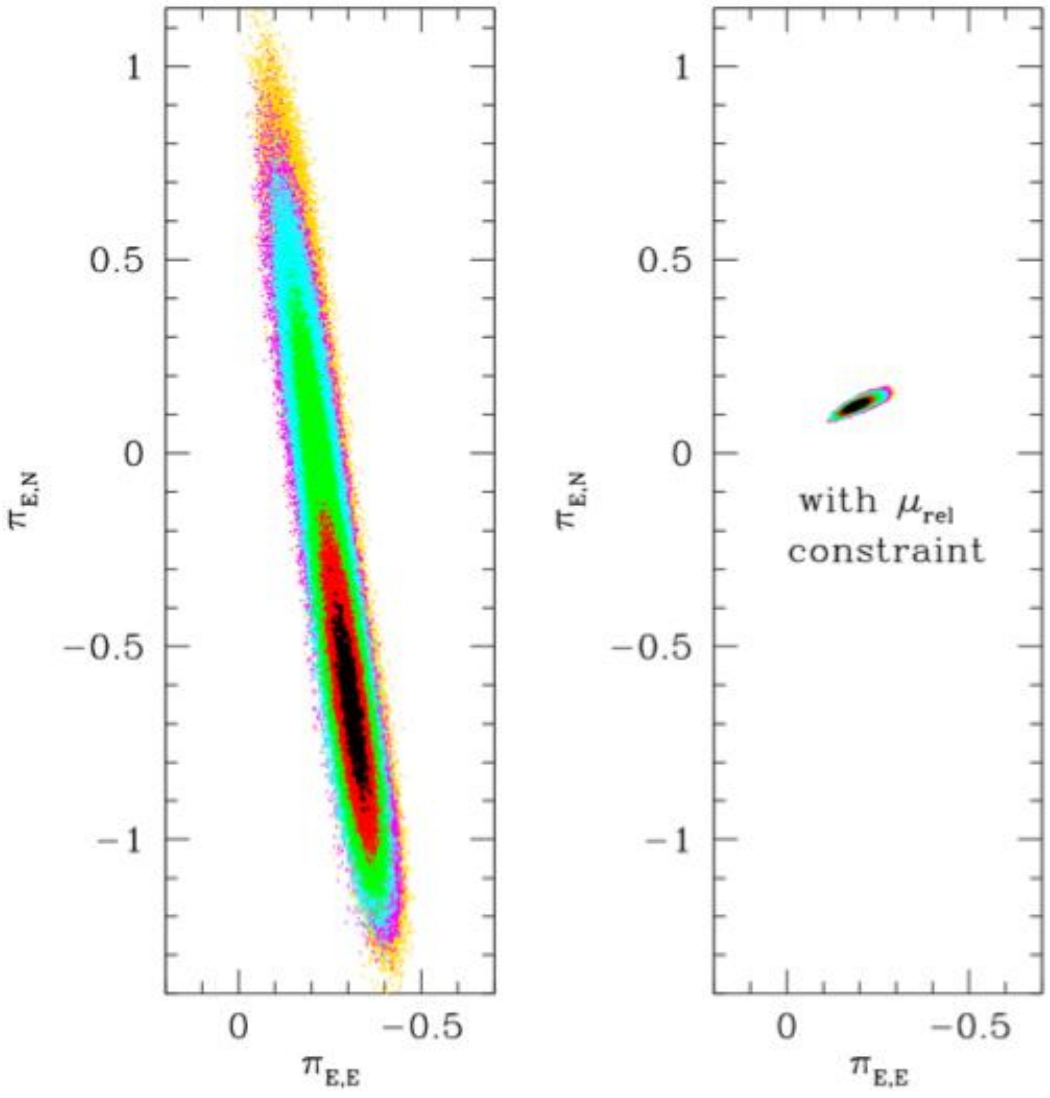


comparison of best single and binary lens models

$\Delta\chi^2 = 2.6\times10^4$ with planet and $\boldsymbol{\pi}_E$ vs. $\boldsymbol{\pi}_E$ only

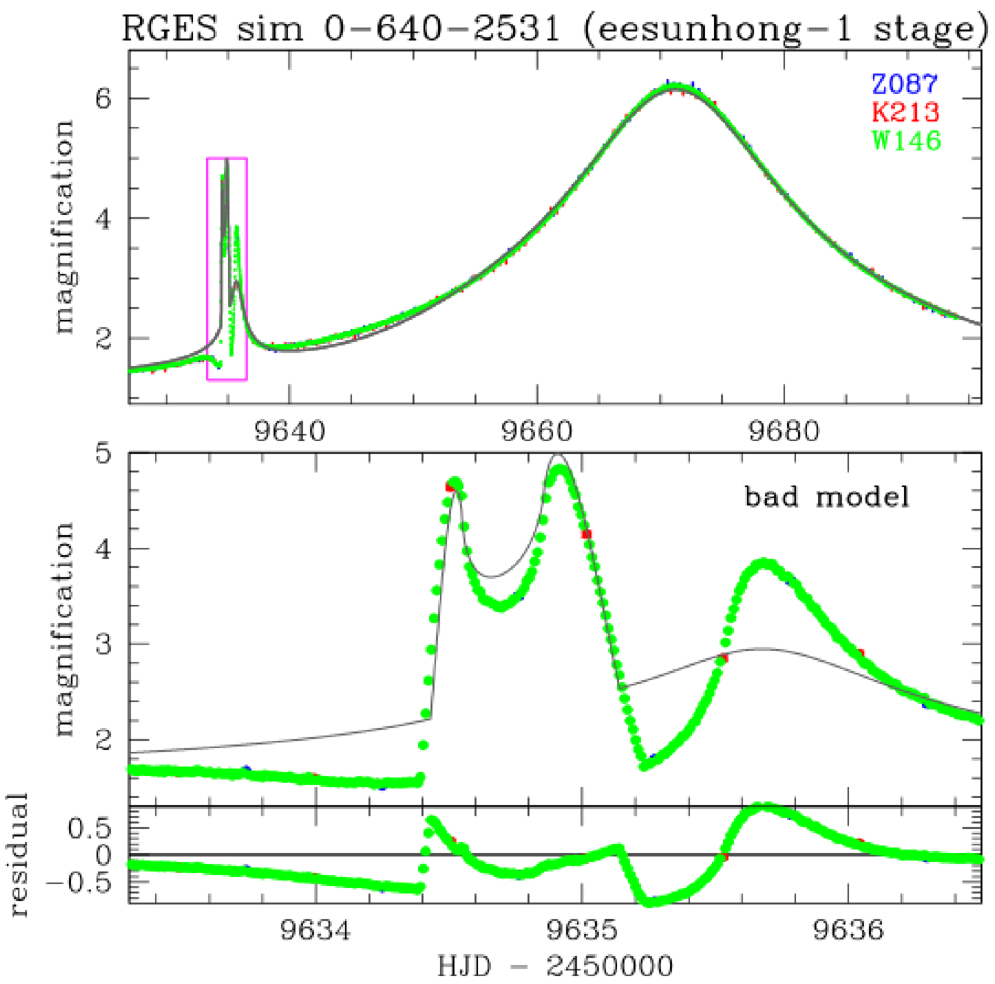
Ultra-Strong π_E Events Are Not the Worst Case π_E Problems

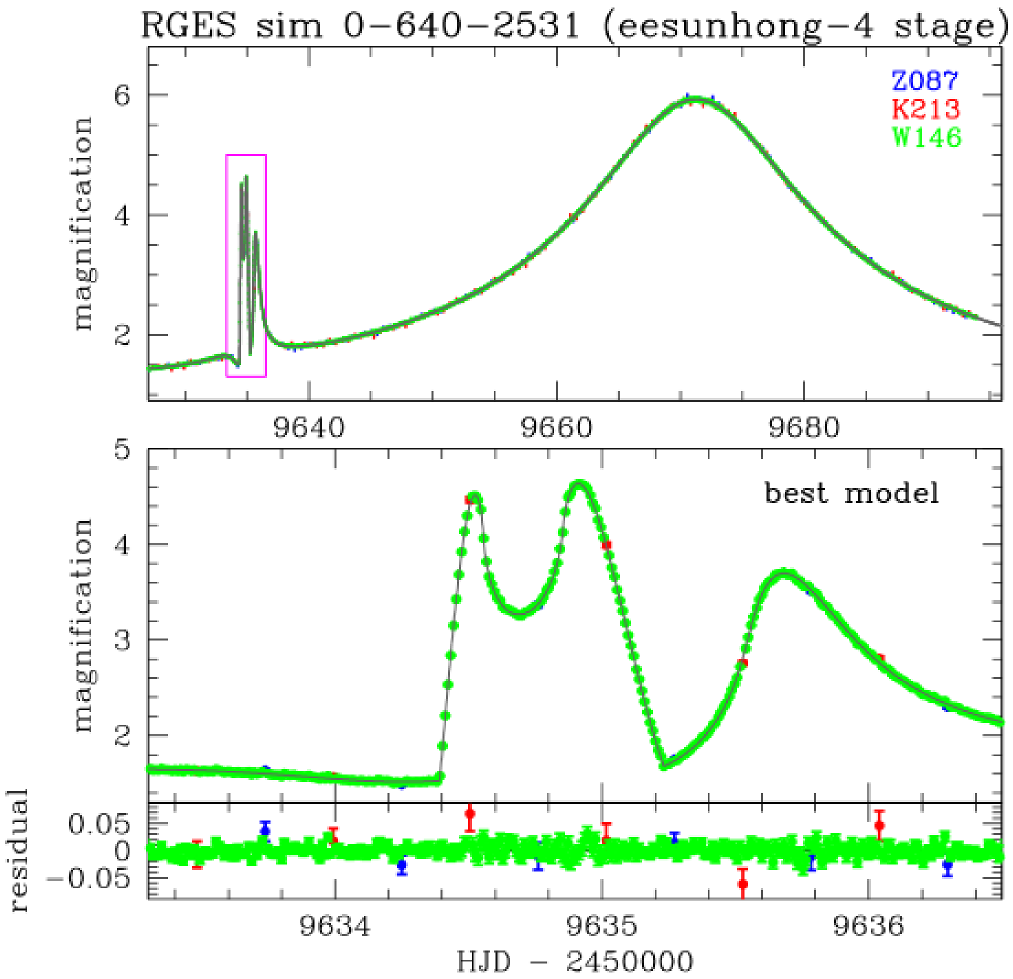
- microlensing parallax, π_E, is represented by a 2-dimensional vector
- When the telescope acceleration during the event is nearly constant, π_E in the direction perpendicular to the acceleration is measured much more precisely
  - This is approximately the East-West direction for Earth and Roman obits
- For the event shown on the right, OGLE-2005-BLG-071, the best fit π_E model has $\pi_{E,N} = -0.7$, but the correct model, with a constraint on the observer lens-source relative proper motion gives $\pi_{E,N} = 0.123 \pm 0.010$
- Despite the strong π_E signal, the best fit π_E model gives $\boldsymbol{\pi_E}$ value further from the correct solution that $\boldsymbol{\pi_E} = 0$.
- This means that this moderately strong π_E can cause a large variation in the angle between the lens axis and the apparent source trajectory direction.



Modeling events with moderately strong π_E signal

(0_640_2531)





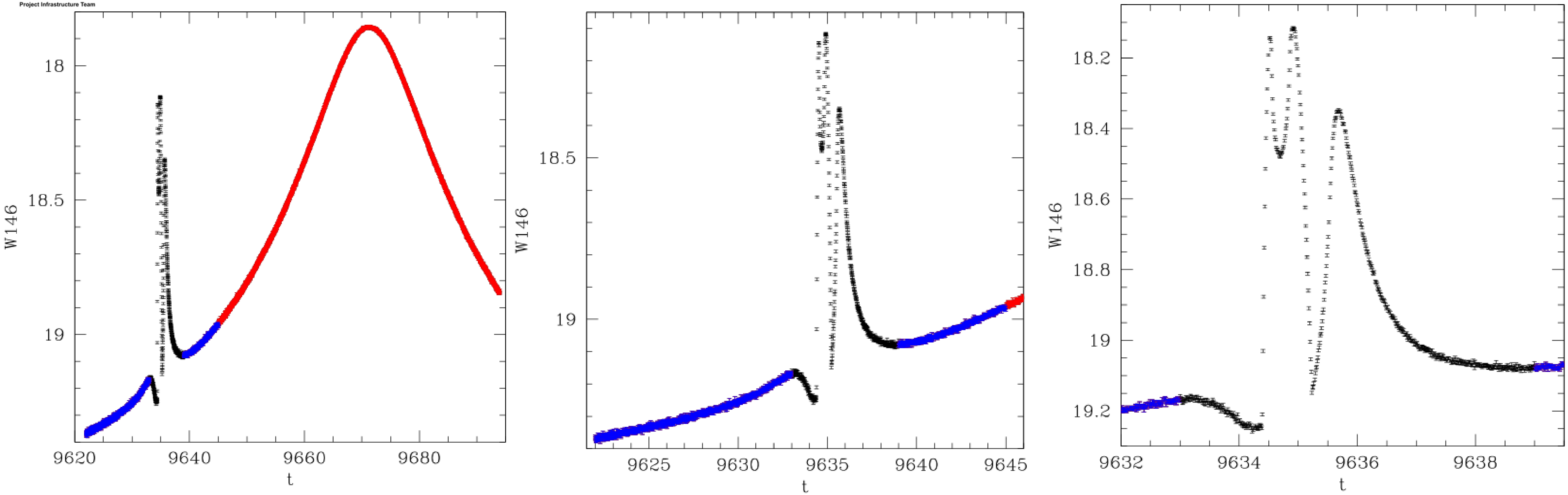
Standard model (eesunhong or RTModel)

$q_{\mathrm{bad}}, s_{\mathrm{bad}} = 1.3521 \times 10^{-3}\ 0.70915$

$q_{\mathrm{mod}}, s_{\mathrm{mod}} = 1.4066 \times 10^{-4}\ 1.44377$

$q_{\mathrm{true}}, s_{\mathrm{true}} = 1.5968 \times 10^{-4}\ 1.4721$

Light curve editing for simulated event 0_640_2531



Break light curve into different segments (other seasons always included)

A. Blue = vicinity of planetary signal

B. Black = planetary signal

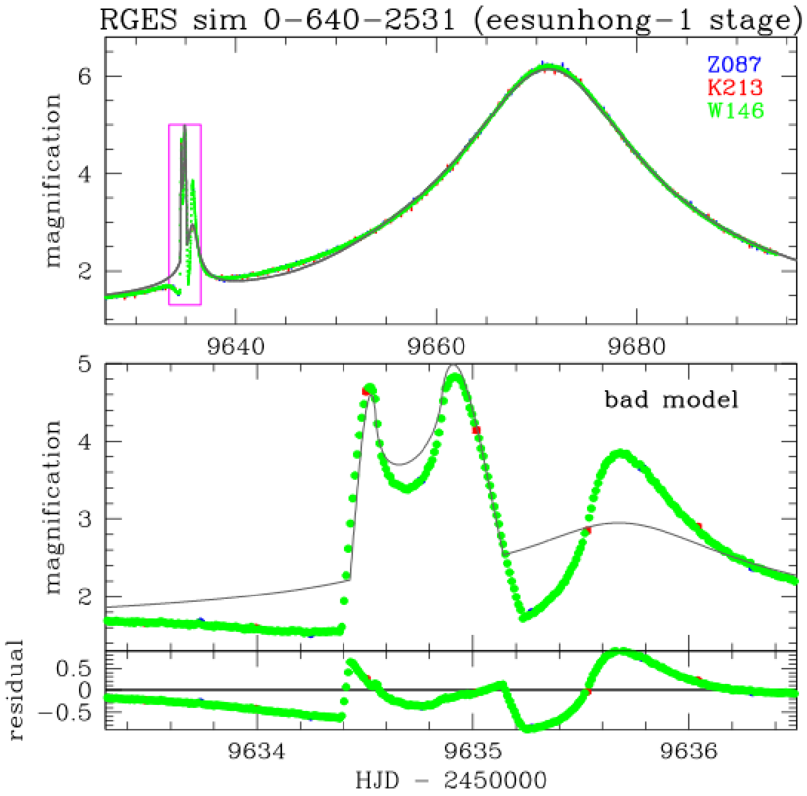
C. Red = strong stellar microlensing segment

4 Modeling Stages

1. Model C. Red data to get t_E estimate from PSPL model
2. Run ICGS on D. Blue data using t_E value from step 1.
3. Run full fit with $\pi_E = 0$ on D. Blue data
4. Run full model with all data and $\pi_E \neq 0$, but use $t_{fix} = t_{0par} = 9635$ as π_E reference time.

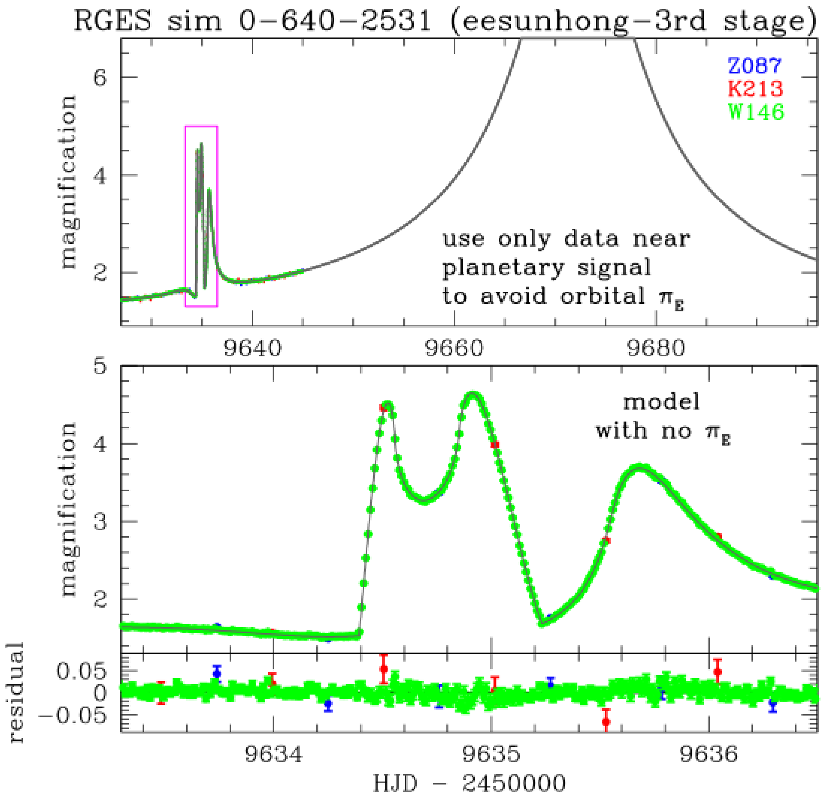
Roman Data Quality Breaks Existing Modeling Codes

multi-stage modeling

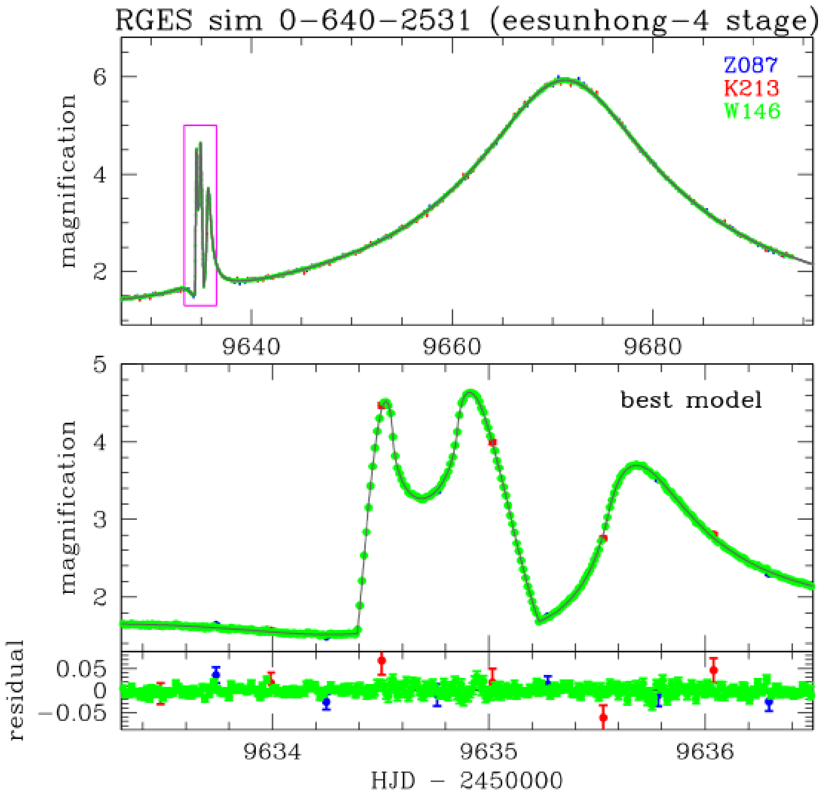


original (bad) eesunhong model
(RTModel is no better)

$q_{\mathrm{bad}}, s_{\mathrm{bad}} = 1.3521 \times 10^{-3}\ 0.70915$



eesunhong model with truncated
data to suppress orbital π_E
allows correct caustic crossing angle

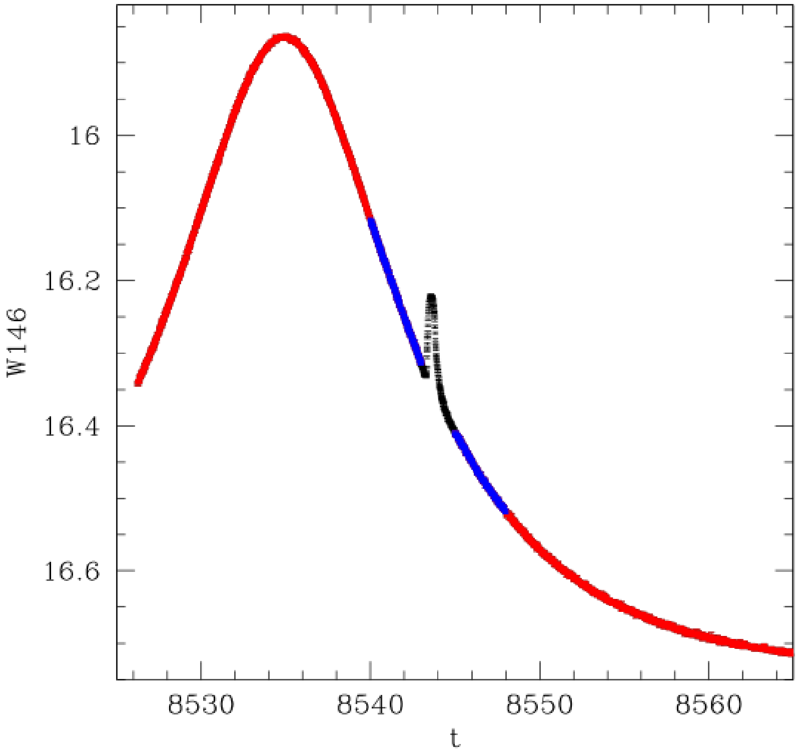


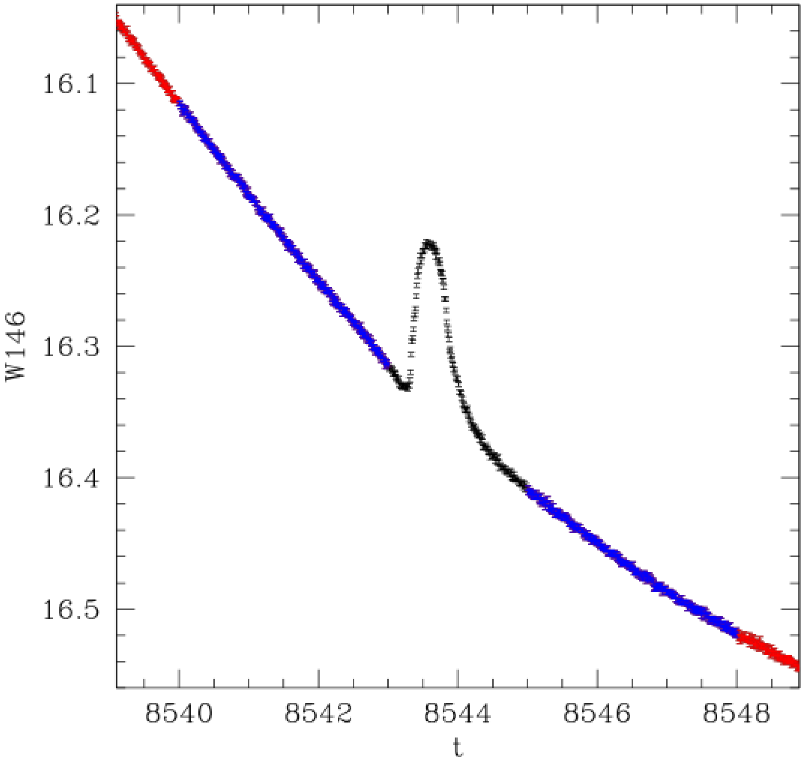
final eesunhong model including π_E
gives correct peak magnification

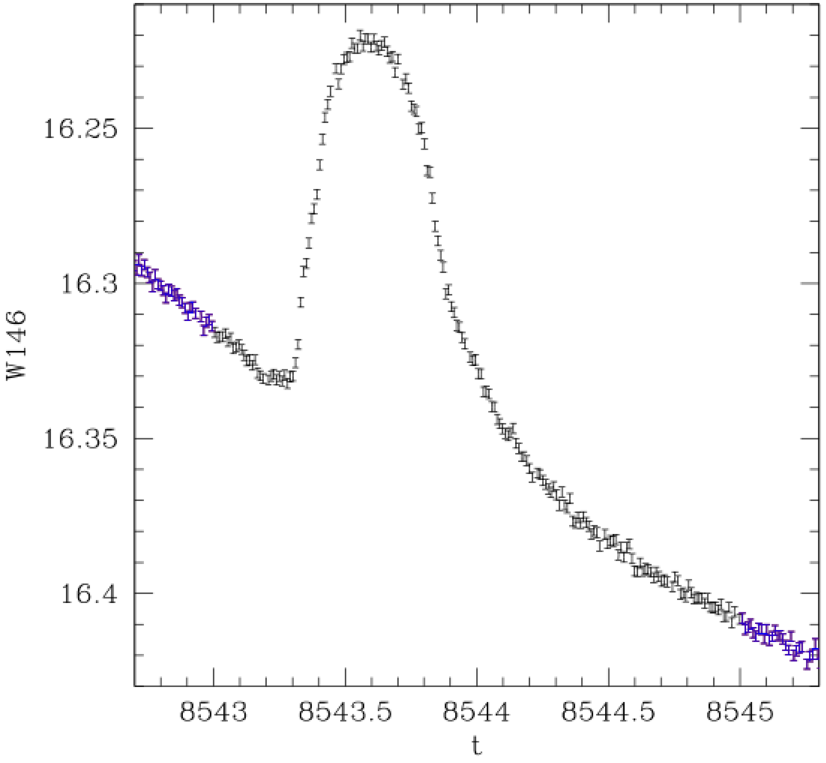
$q_{\mathrm{mod}}, s_{\mathrm{mod}} = 1.4066 \times 10^{-4}\ 1.44377$

$q_{\mathrm{true}}, s_{\mathrm{true}} = 1.5968 \times 10^{-4}\ 1.4721$

Another event with moderately strong π_E signal (1_755_256)

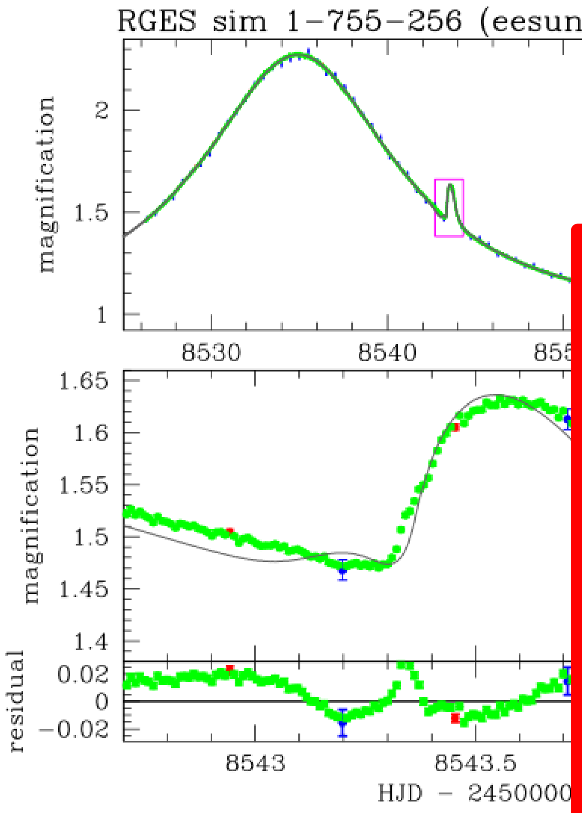


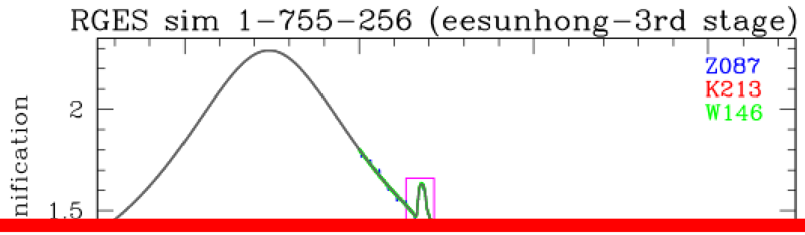


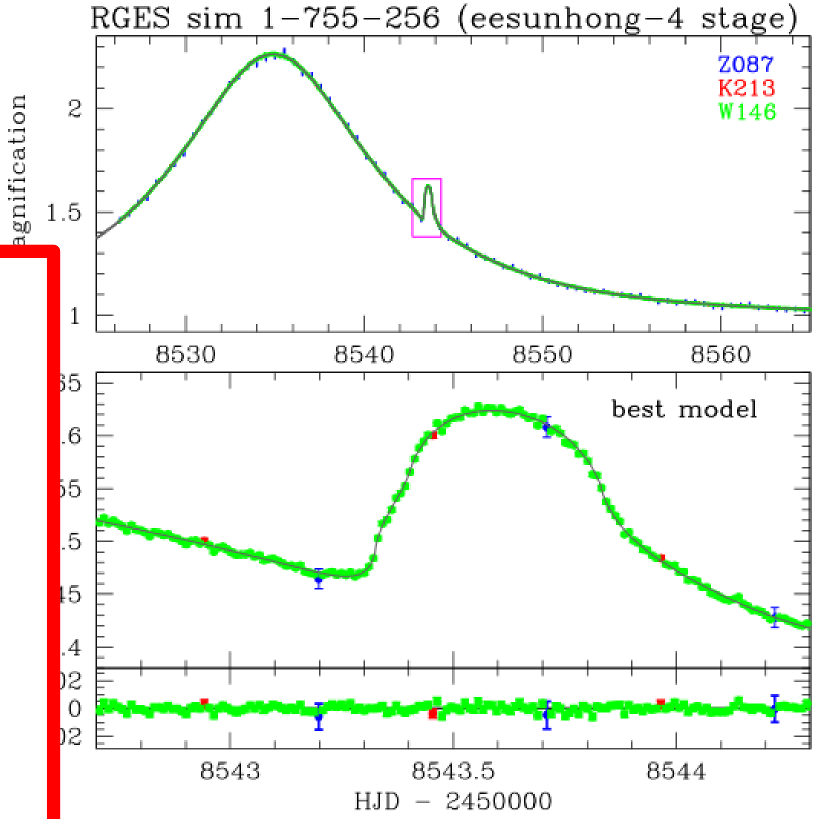


Parameters from PSPL model without planetary signal or peak is used to run ICGS. Planetary signal is found from with the peak (in red) excluded

Event 1_755_256 models







Events with moderately strong π_E are not a large fraction of all RGES planetary events.

But they are a large fraction of events with precisely determined parameters – and they probably dominate events with stellar remnant host star mass measurements.

original (bad) eesunhong model (RTModel no better)

eesunhong model with truncated data to suppress orbital π_E allows correct caustic crossing angle

final eesunhong model including π_E gives correct peak magnification

$q_{\mathrm{bad}}, s_{\mathrm{bad}} = 1.3630 \times 10^{-4}\ 1.49574$

$q_{\mathrm{mod}}, s_{\mathrm{mod}} = 5.0054 \times 10^{-5}\ 1.51889$

$q_{\mathrm{true}}, s_{\mathrm{true}} = 4.9348 \times 10^{-5}\ 1.51377$