Microlensing Planets: Modeling and Unique Solutions

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How Do I Figure Out If It’s Really a Planet?

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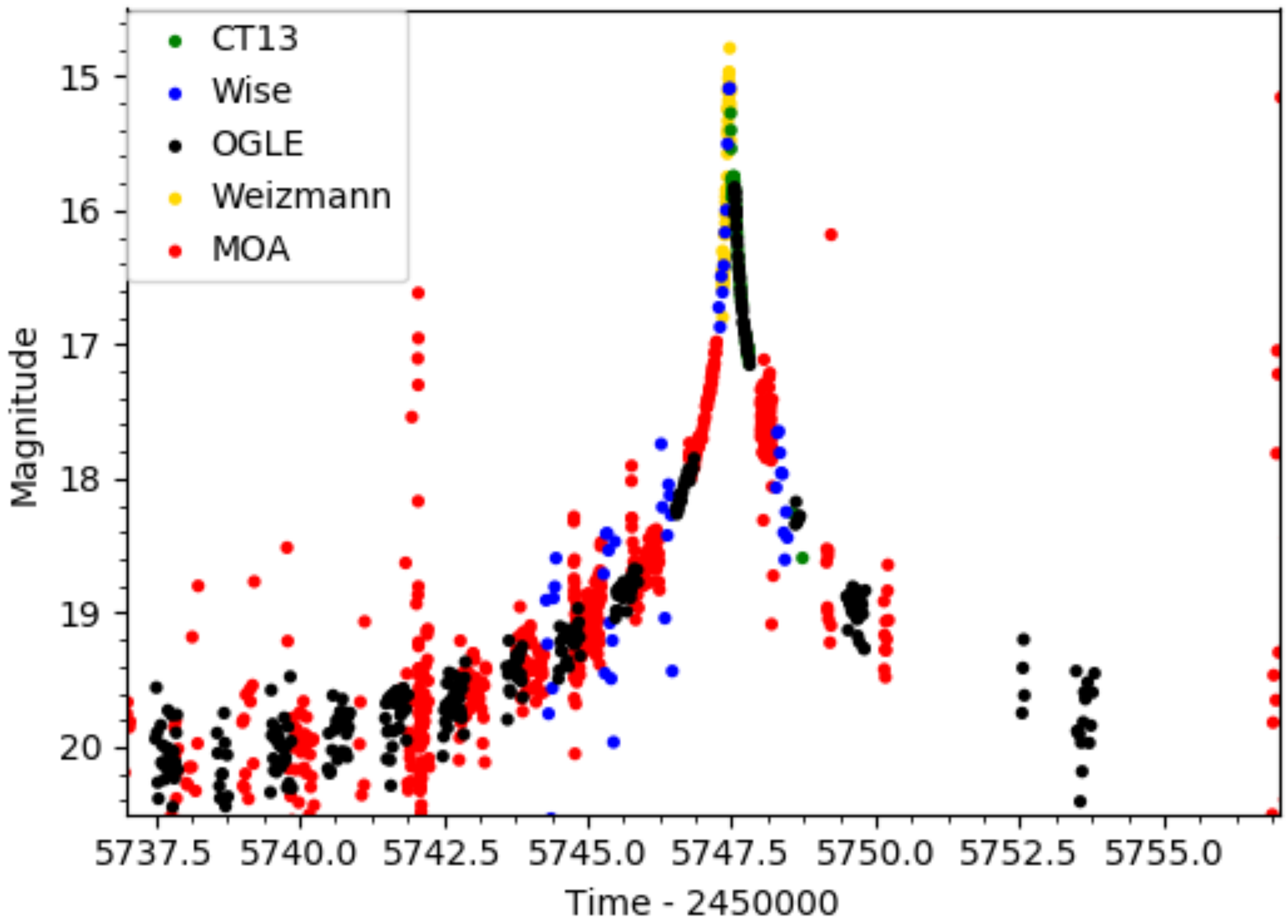
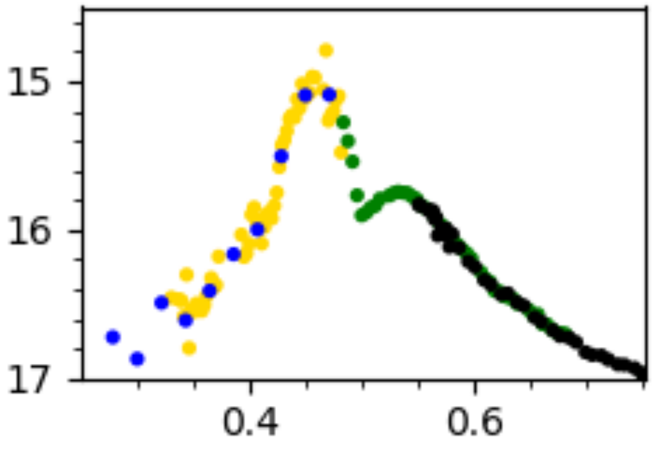
Why is this a Planet Candidate?



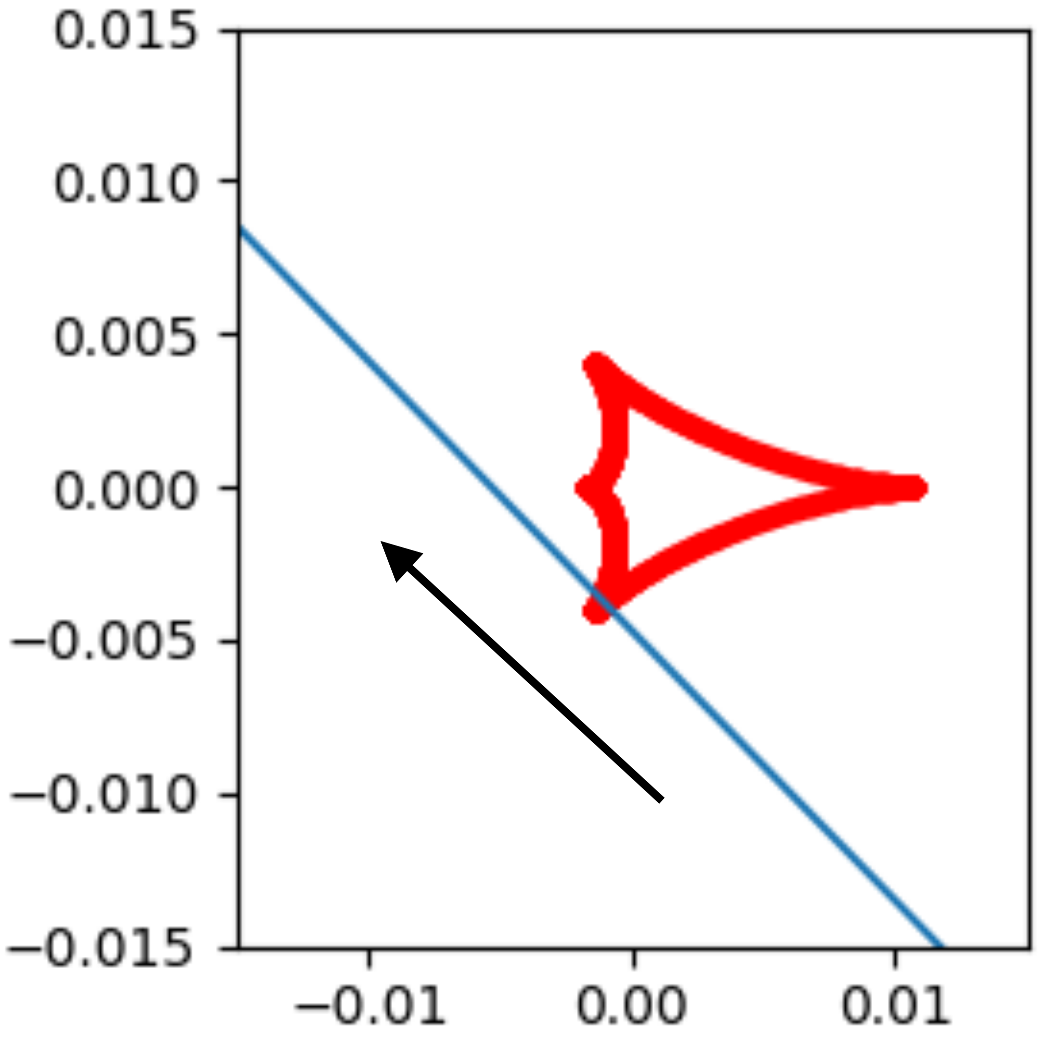


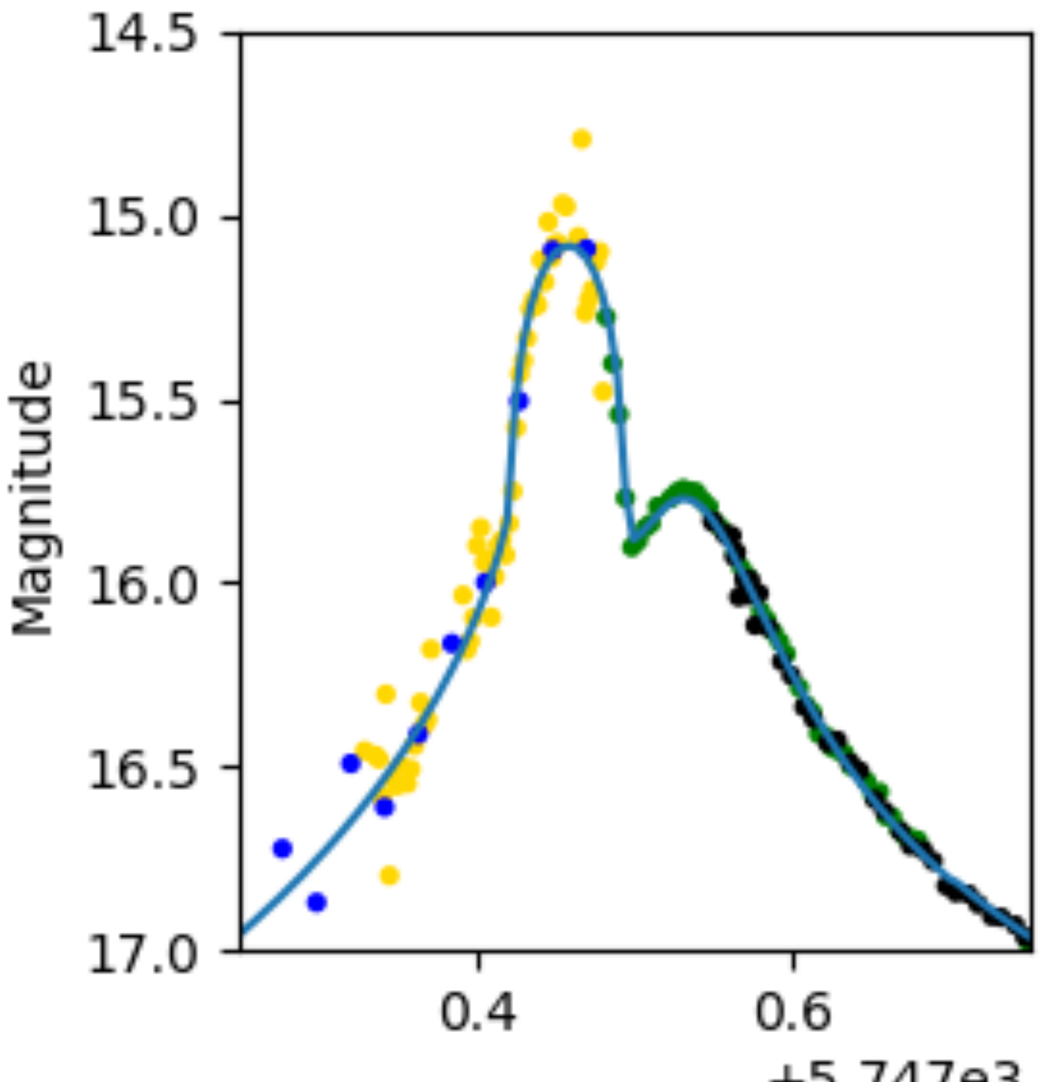
1. Mostly follows a point lens → dominated by a single star.
2. The perturbation occurs at high magnification → caustic is small.
3. The perturbation is small (< 1 mag)

→ Could be a planet!

Part I: Relating Caustics/Magnification Patterns to Light Curves

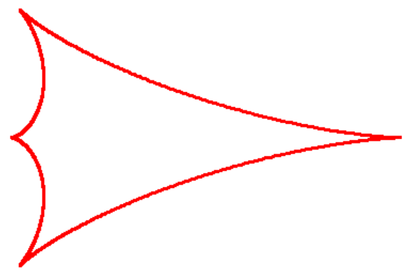
A model with mass ratio (q) = 0.005 = 5 M_{Jup}/M_{Sun}



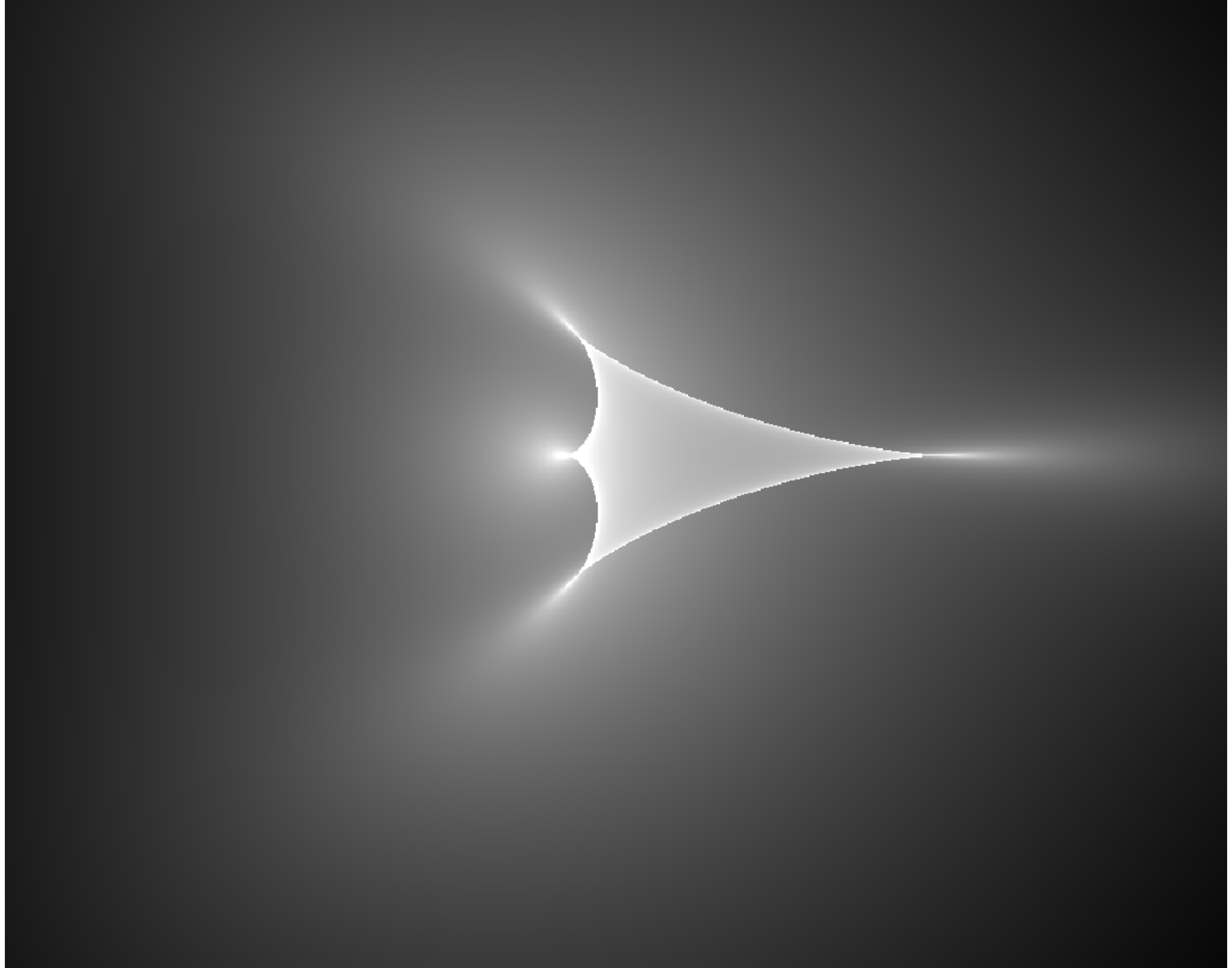


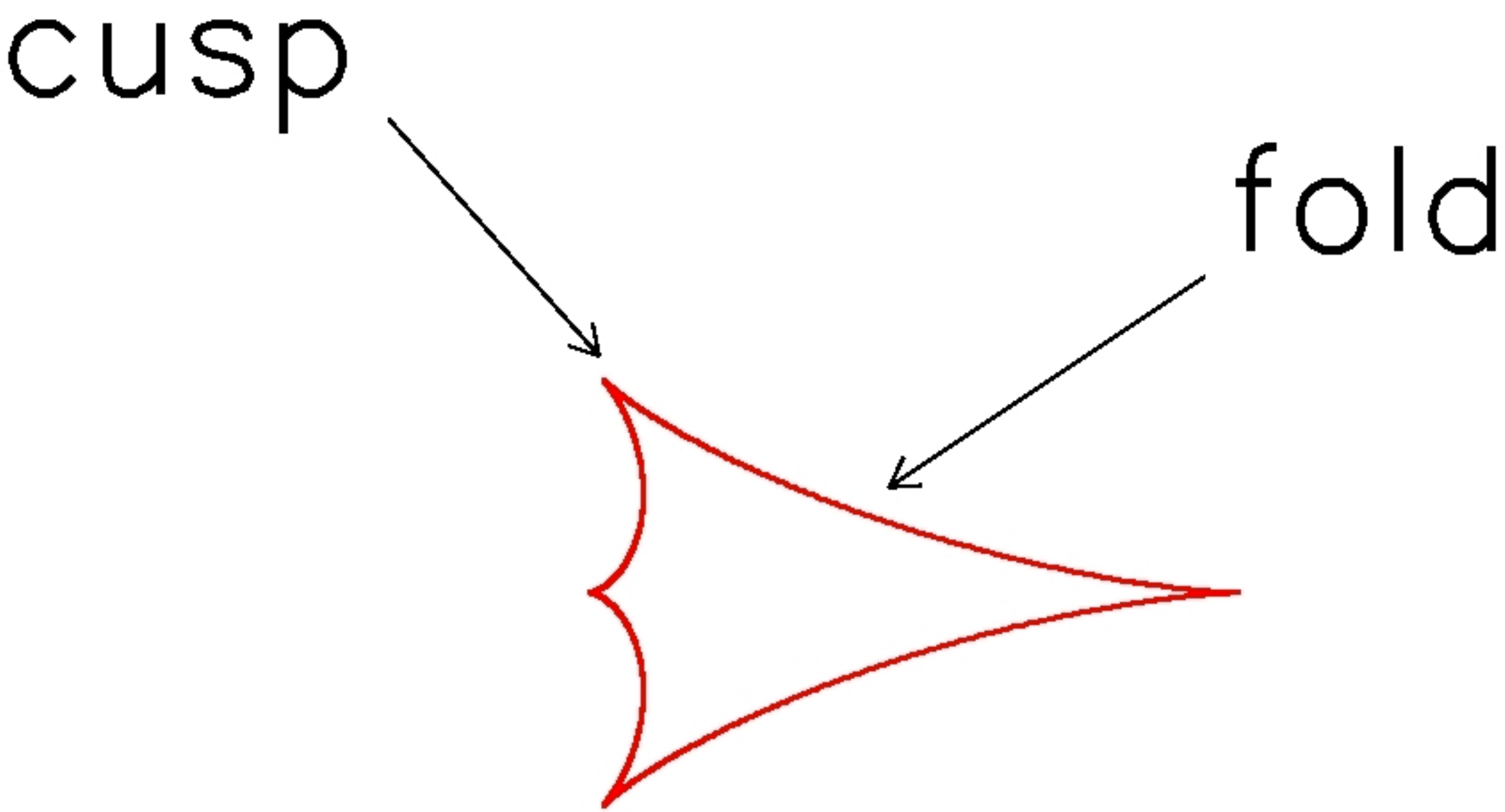
Caustic Reflects the Full Magnification Pattern

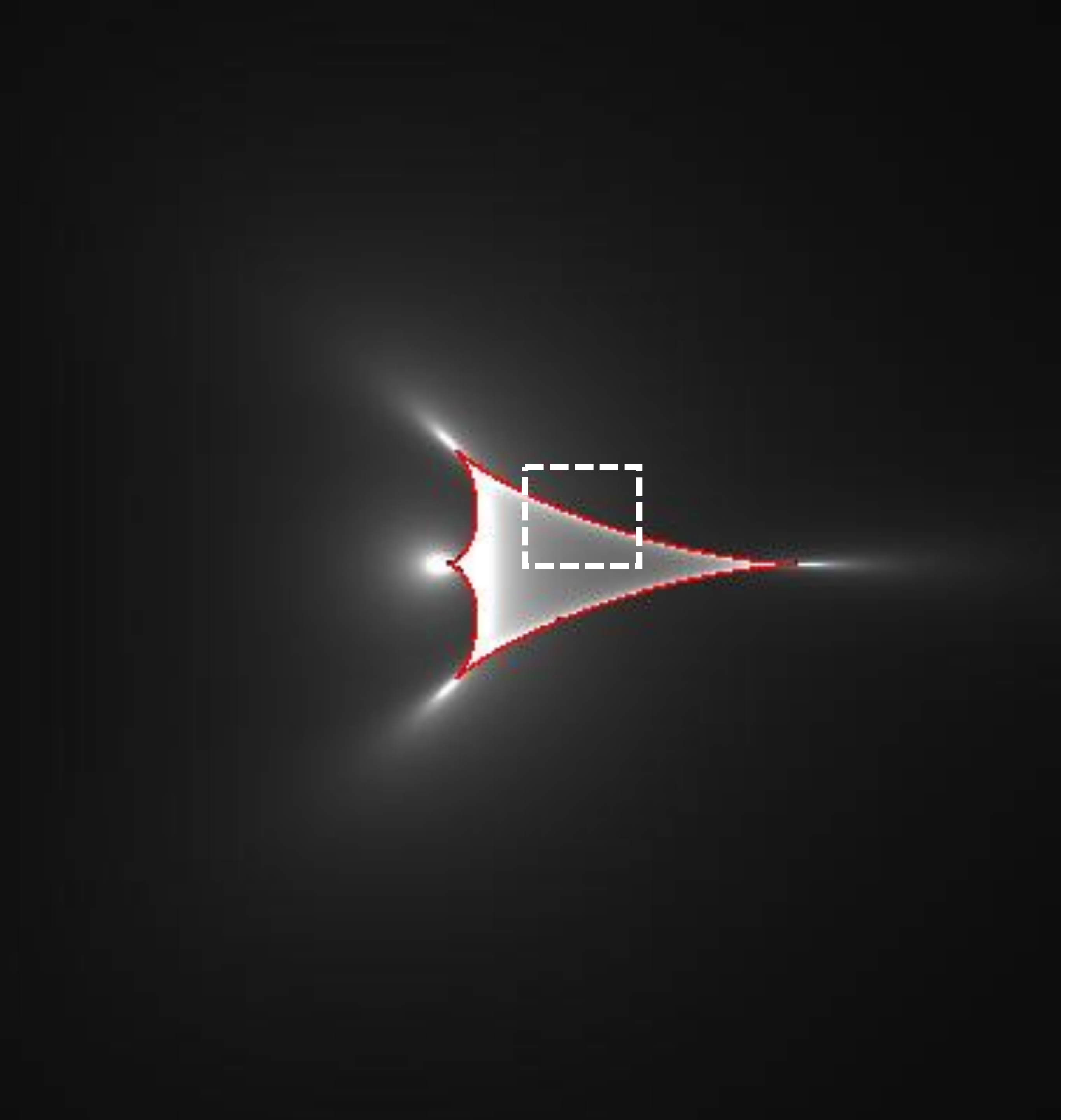
Caustic



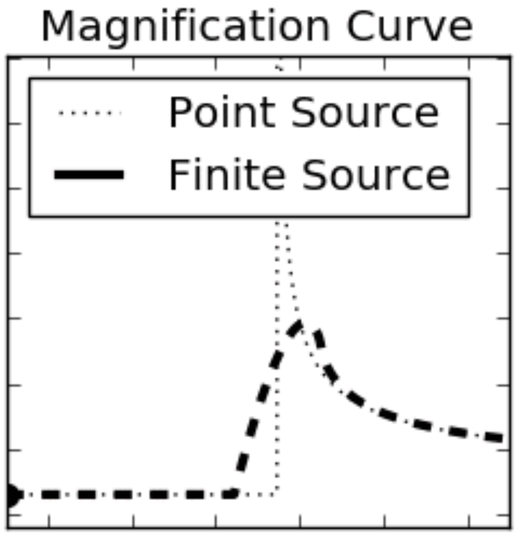
Magnification Pattern

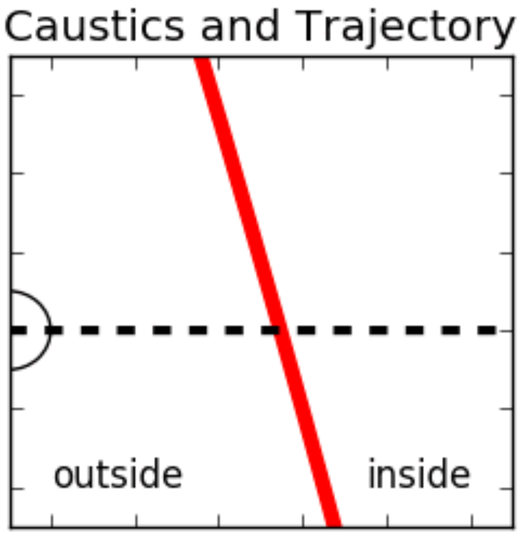


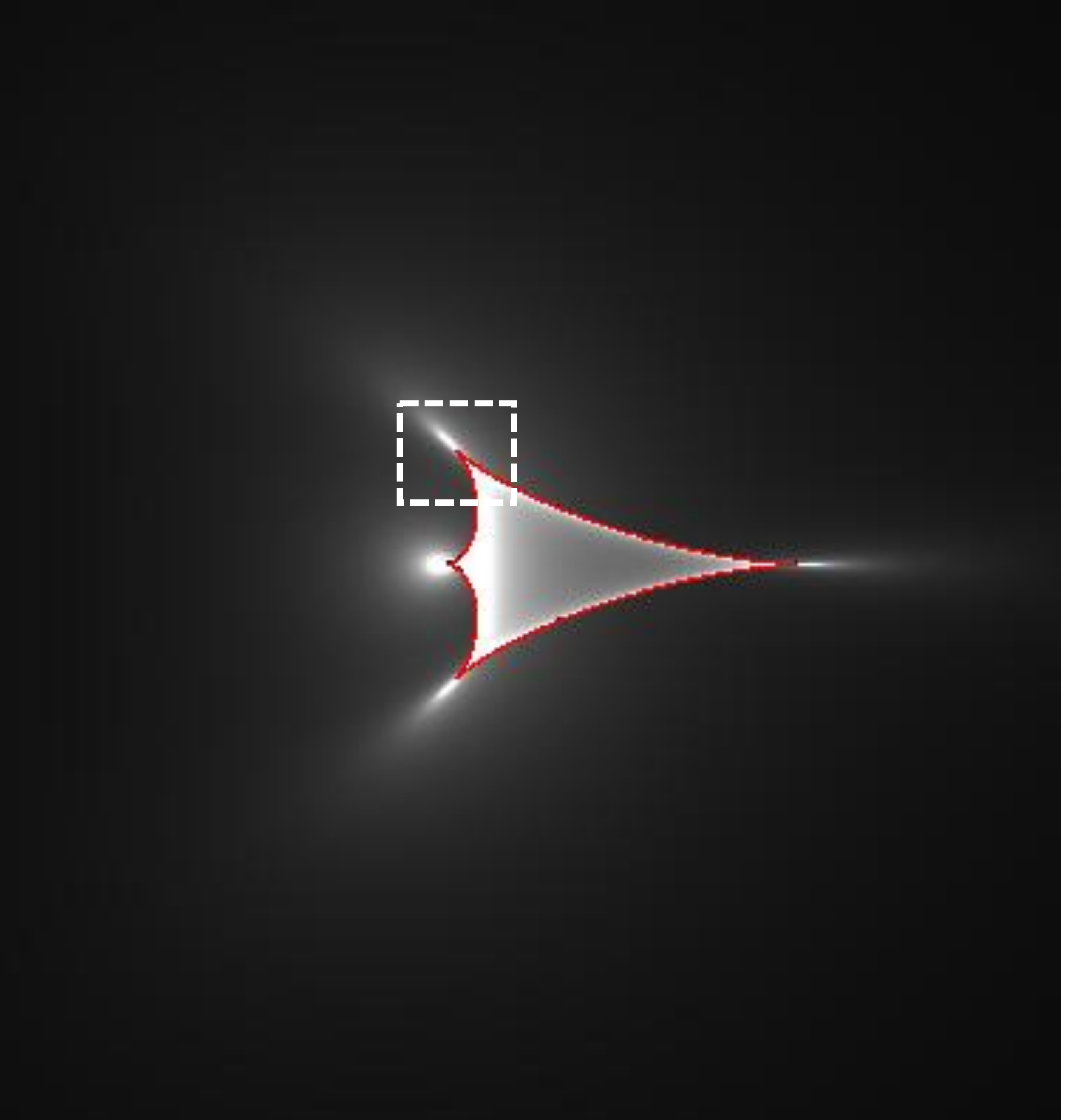

cusp
fold



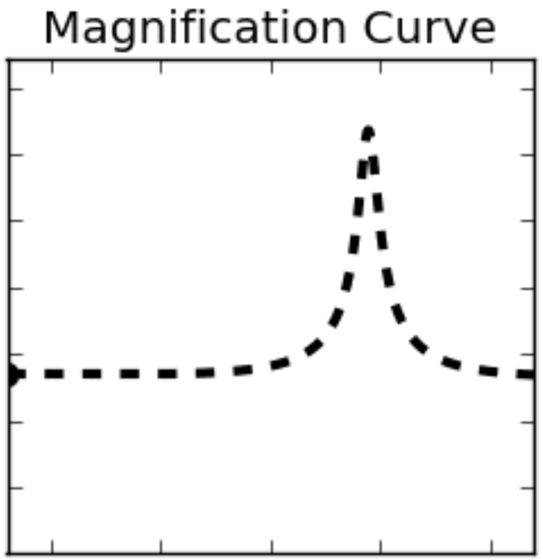
There is a strong magnification change at a **fold**.

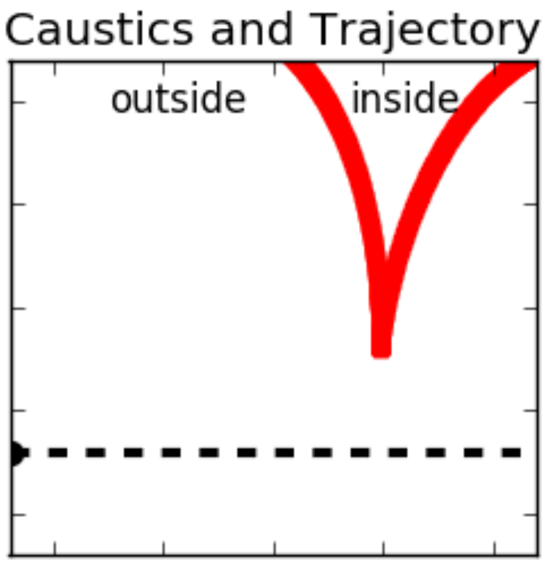




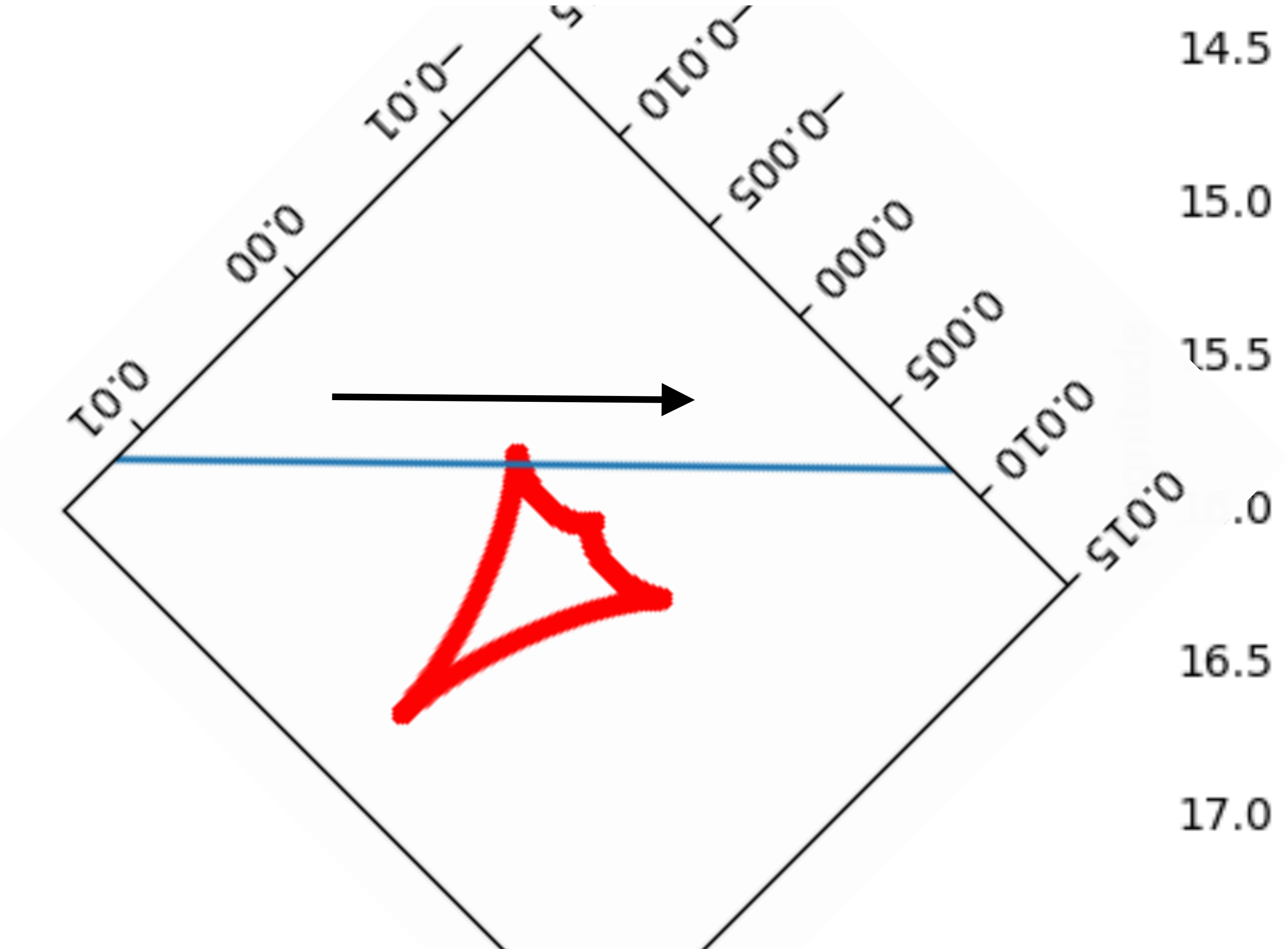


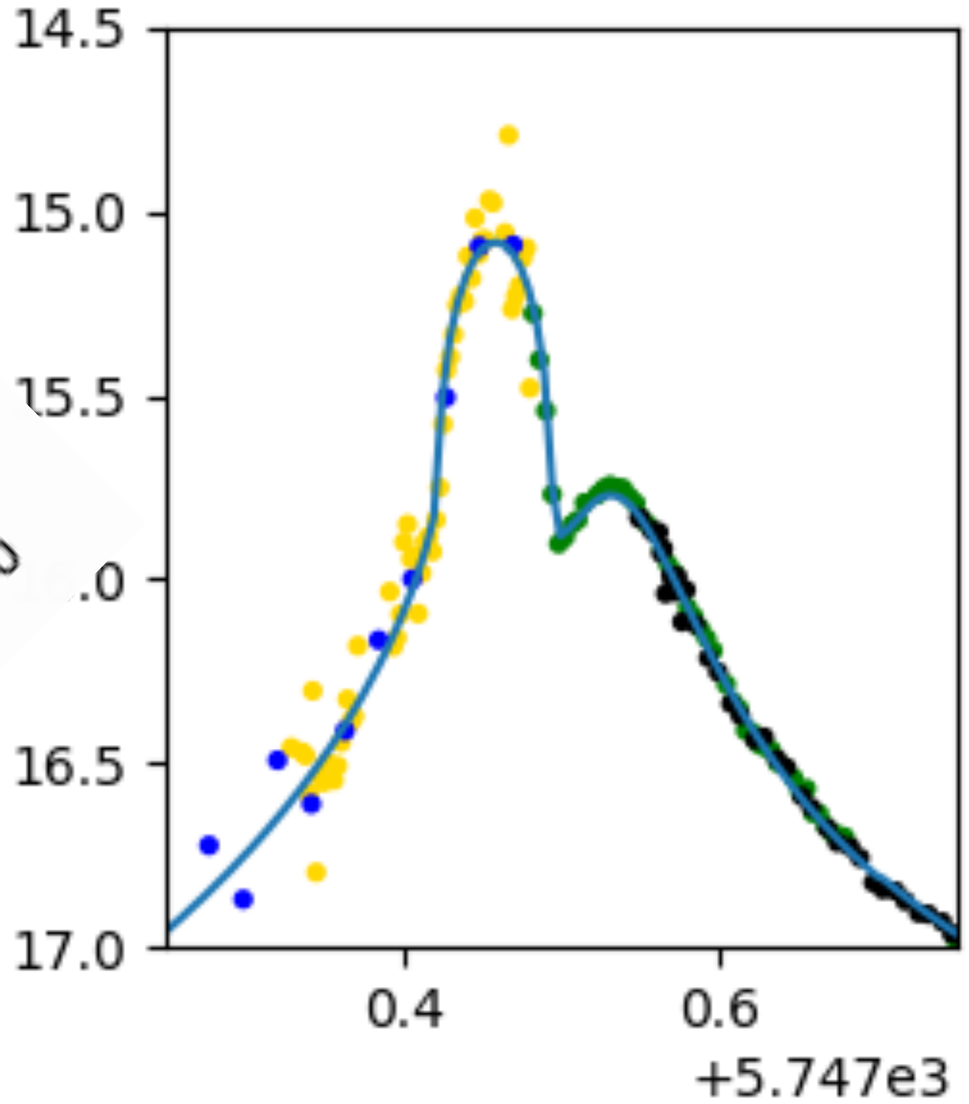
A **cusp** creates a spike in magnification outside the caustic.



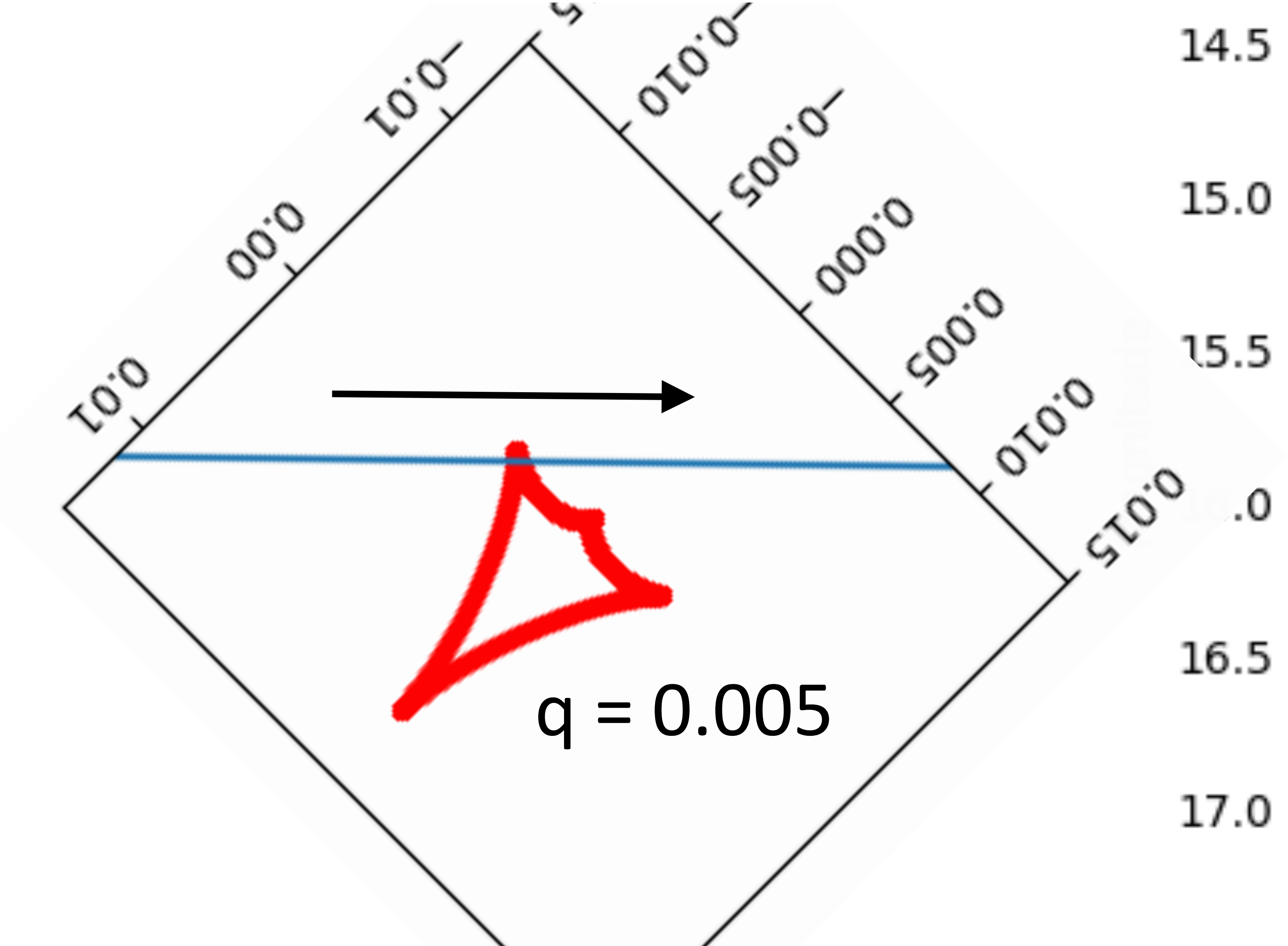


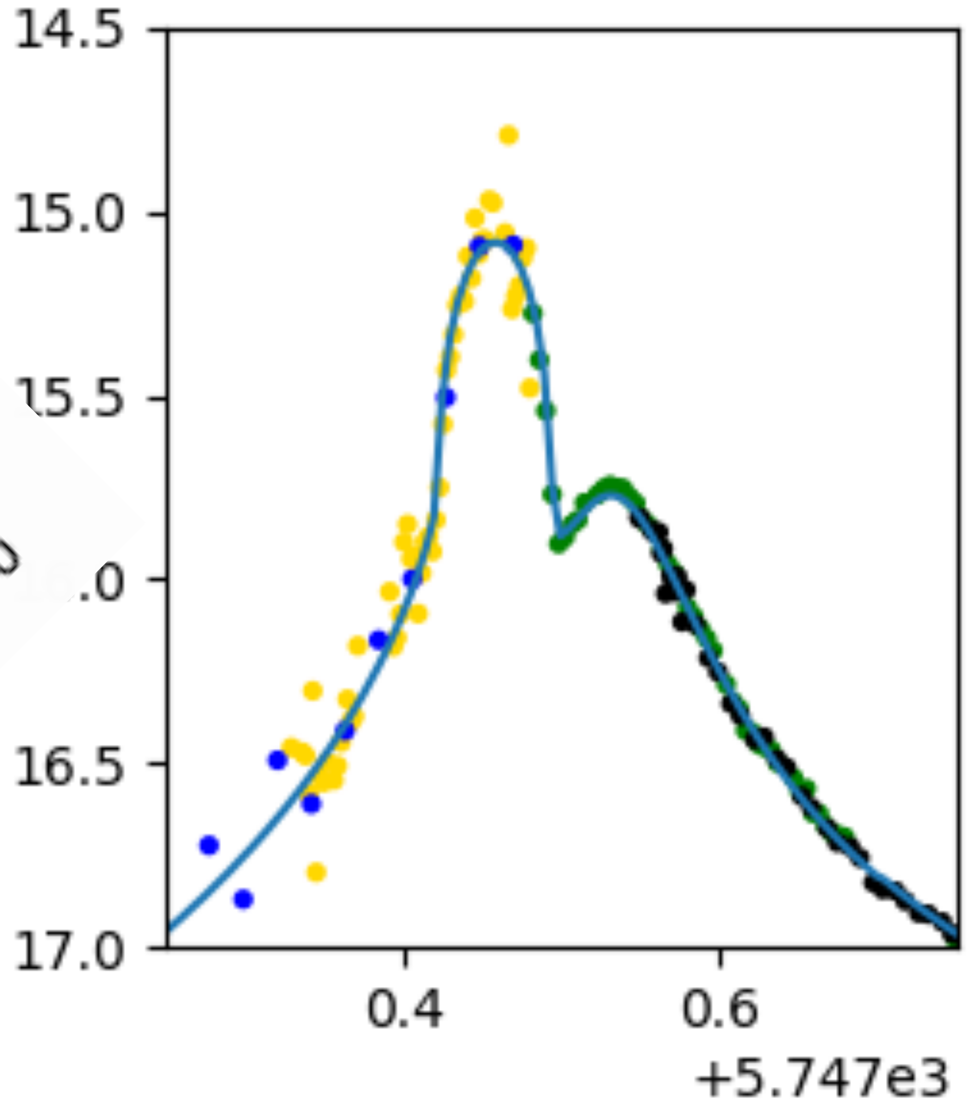
Two cusps → two bumps



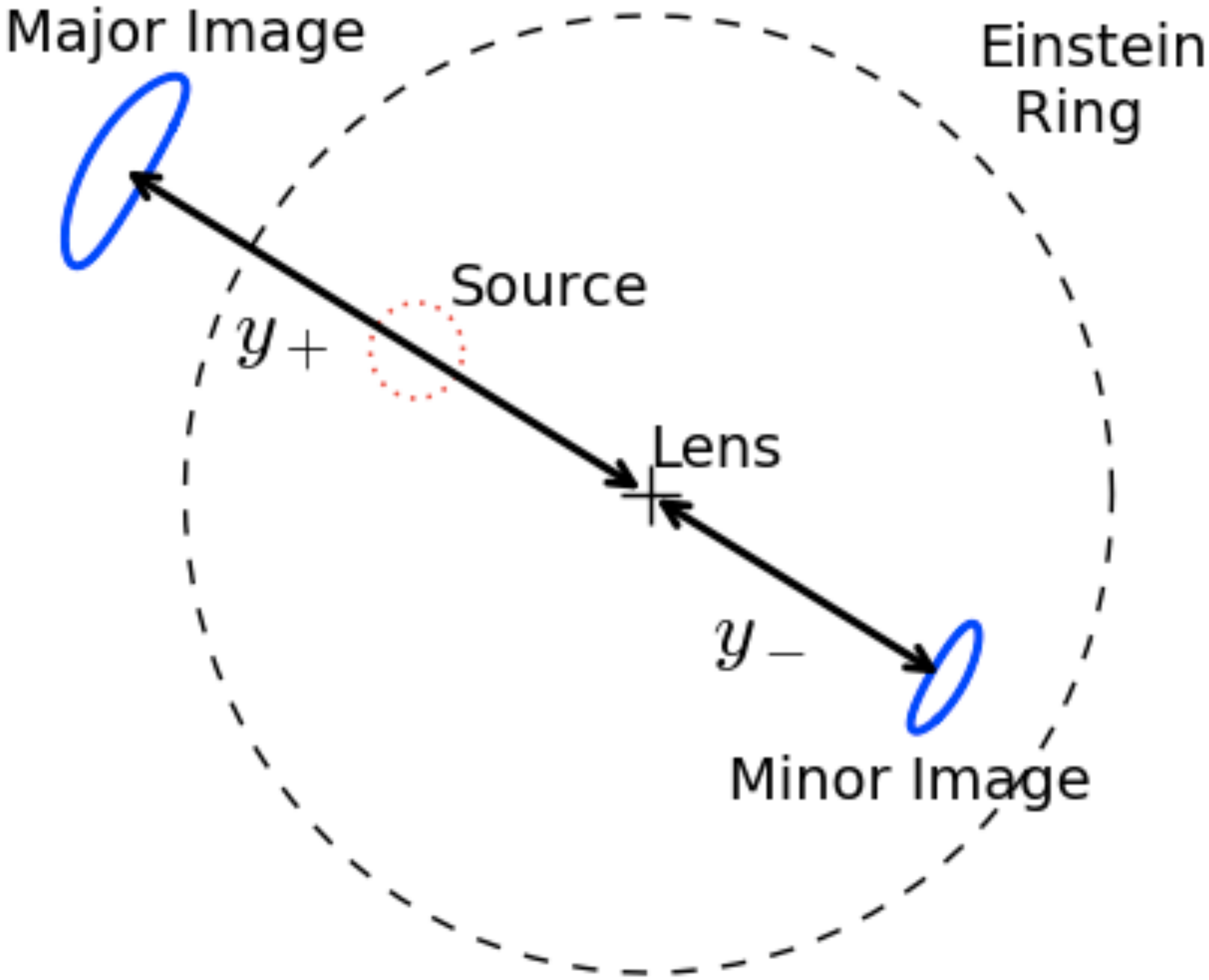


Light curve can be explained by a planet! But…

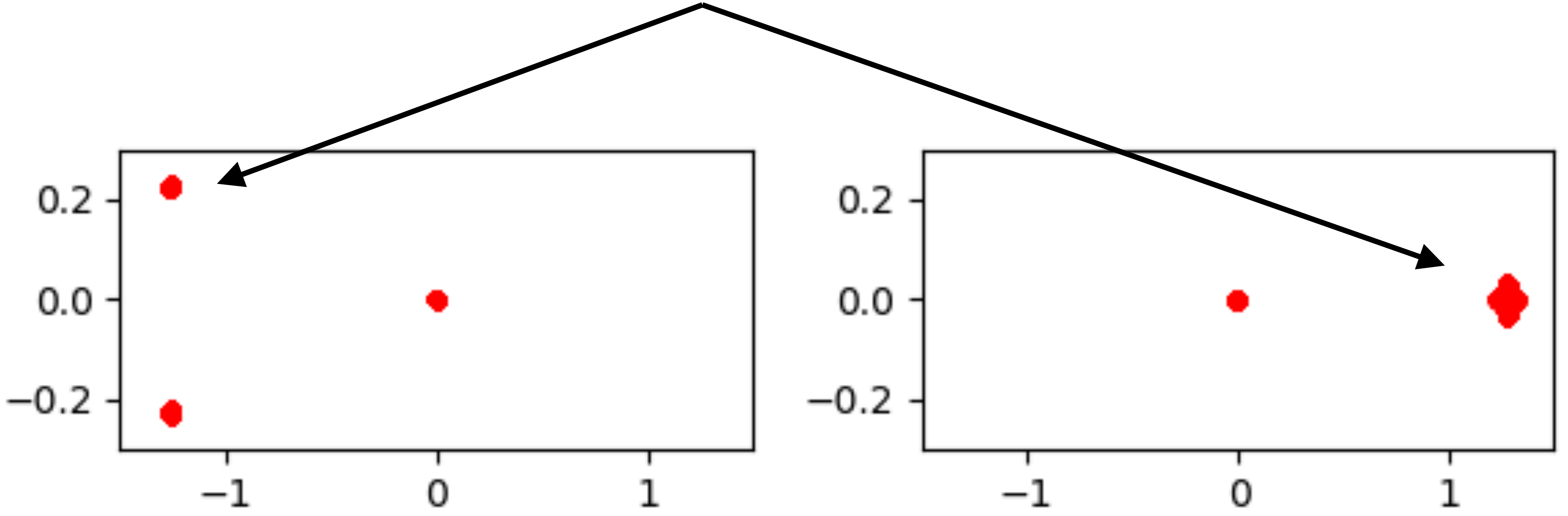




There are TWO images → TWO solutions



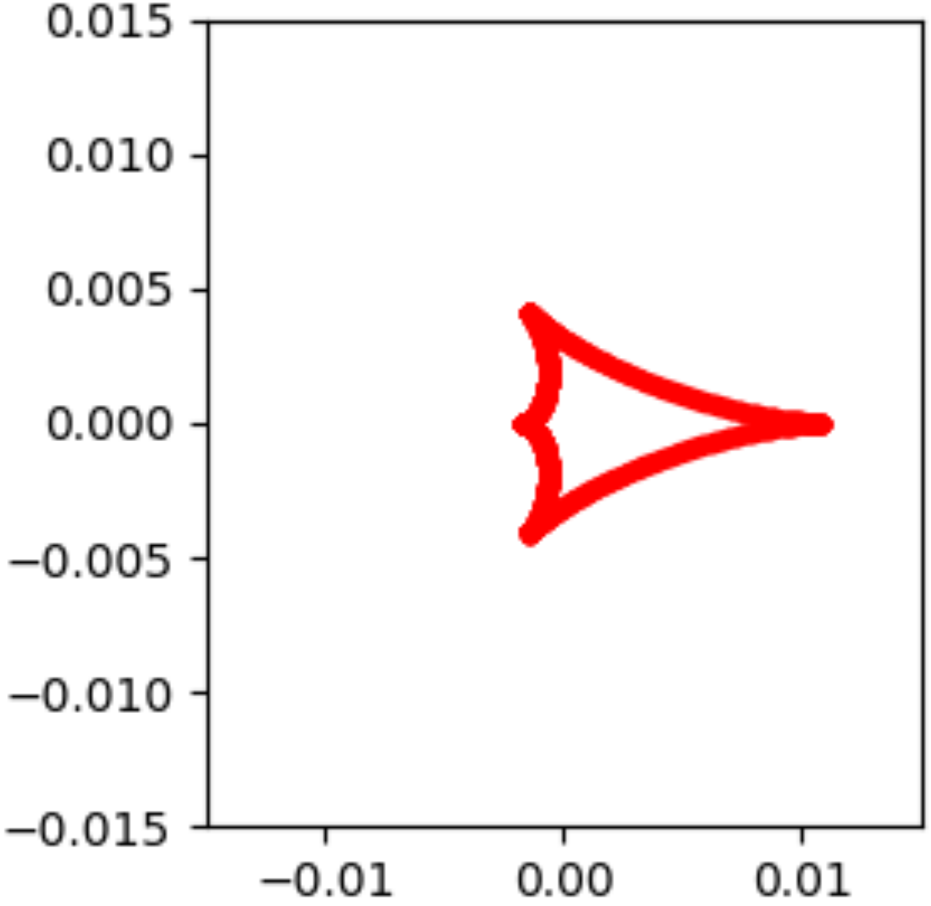
The planetary caustics are different…



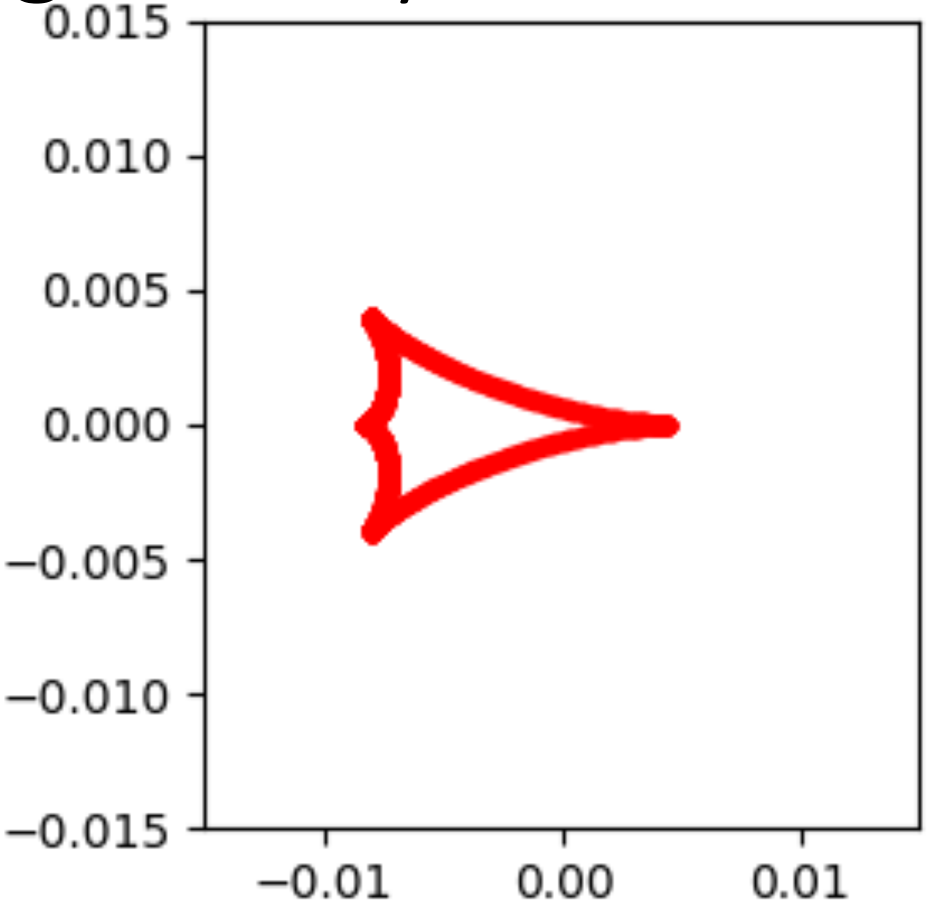
separation = s = 0.55 "close"

s = 1.83 "wide"

The central caustics are the same
“s ⟷ 1/s degeneracy”

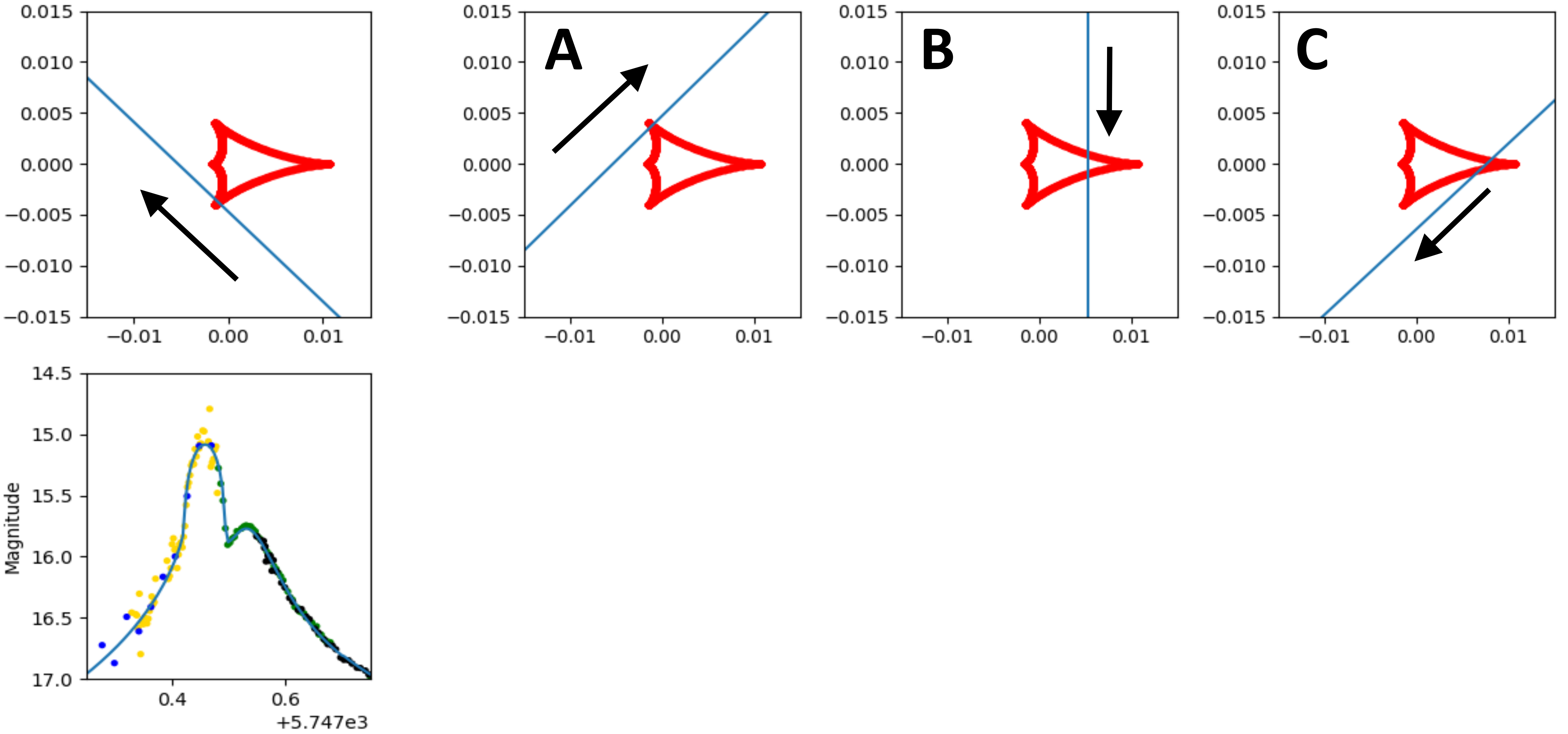


separation = s = 0.55
“close”

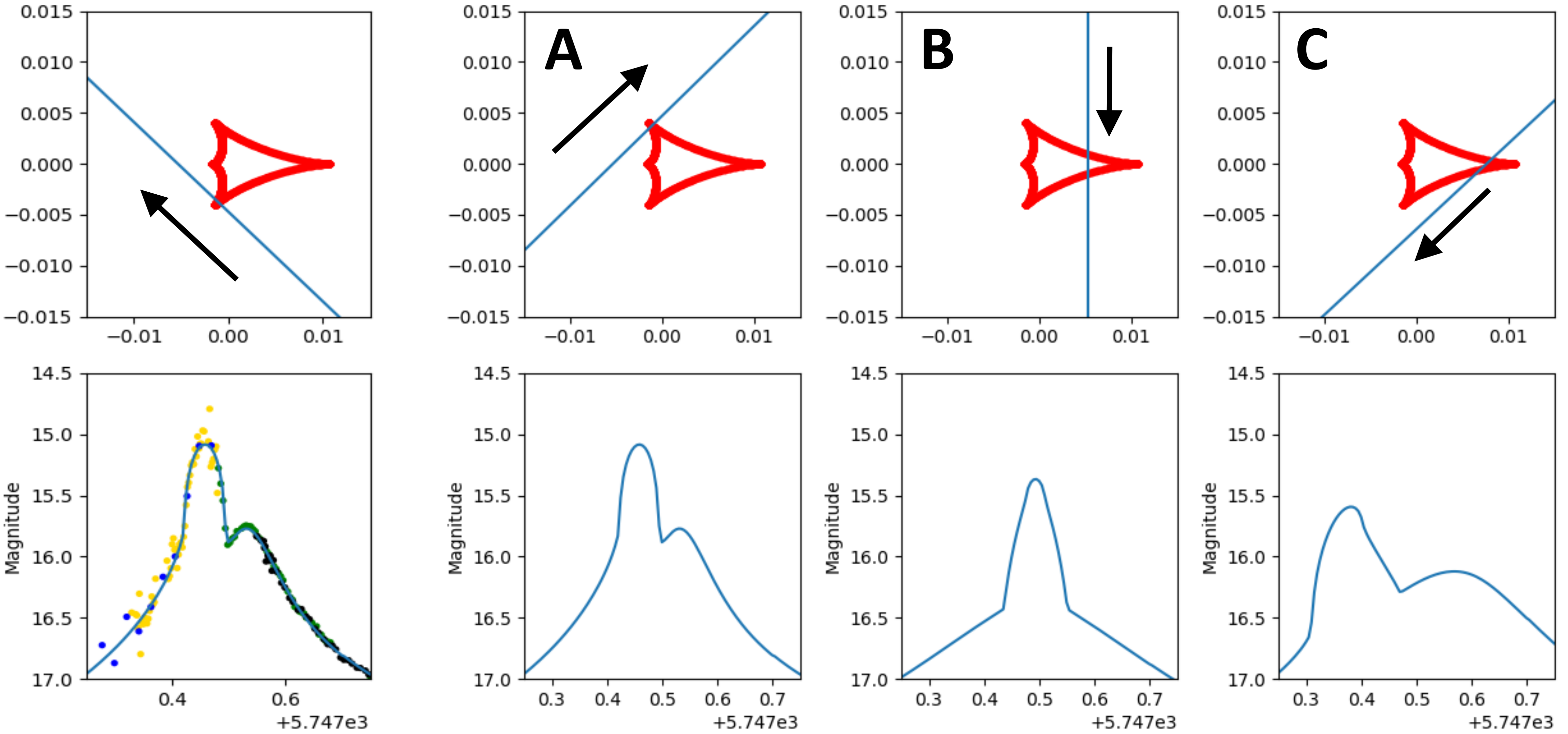


s = 1.83
“wide”

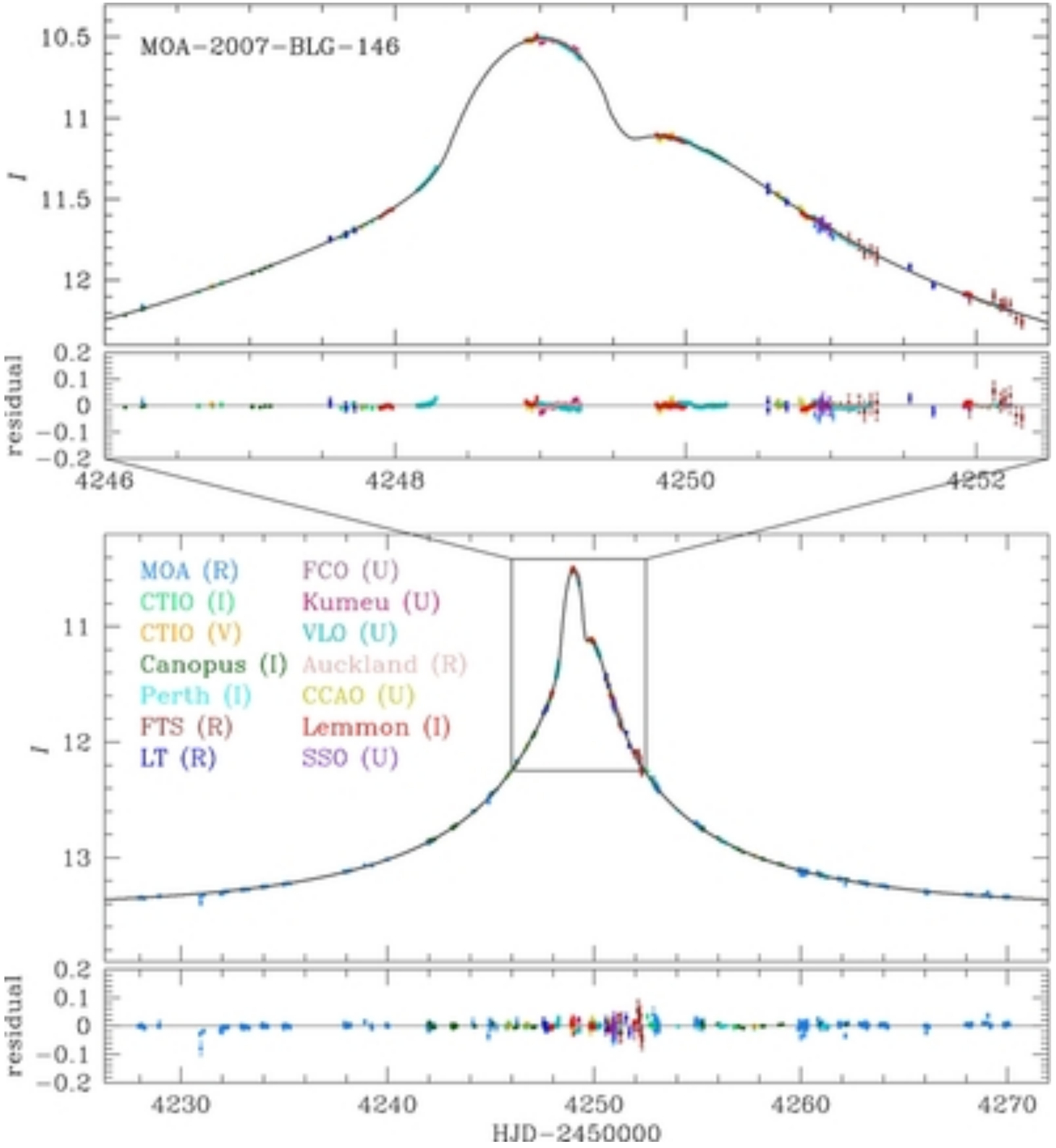
Which Trajectories Produce a Similar Light curve?

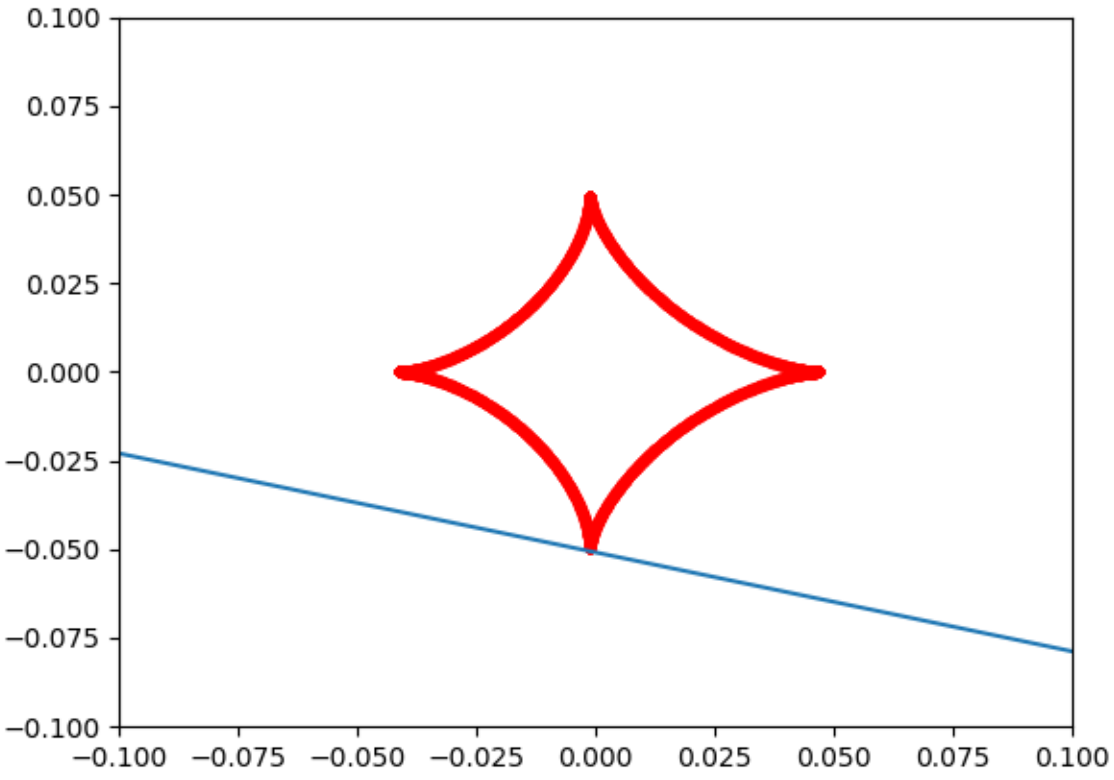


Which Trajectories Produce a Similar Light curve?

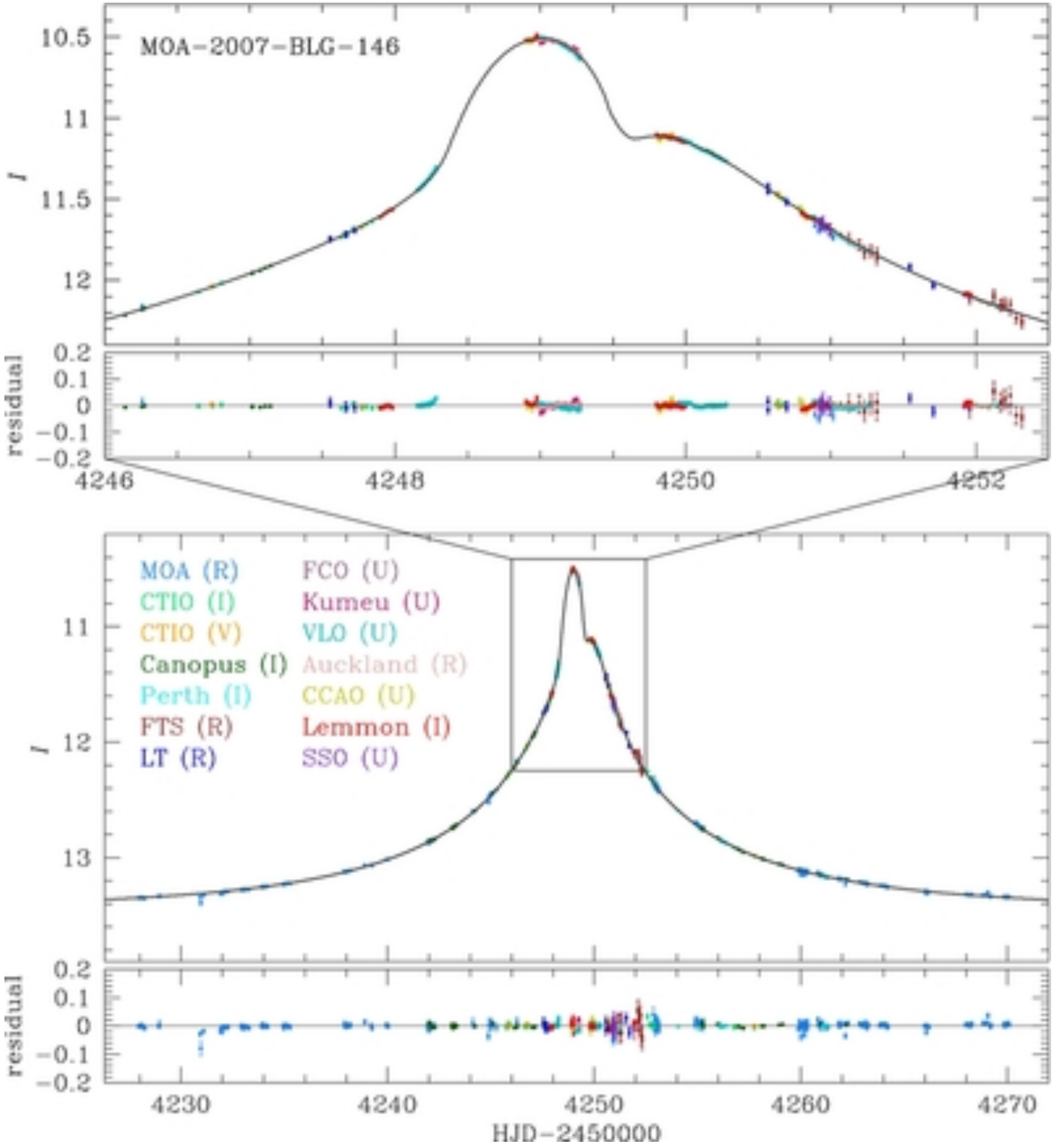


Is this also a planet?



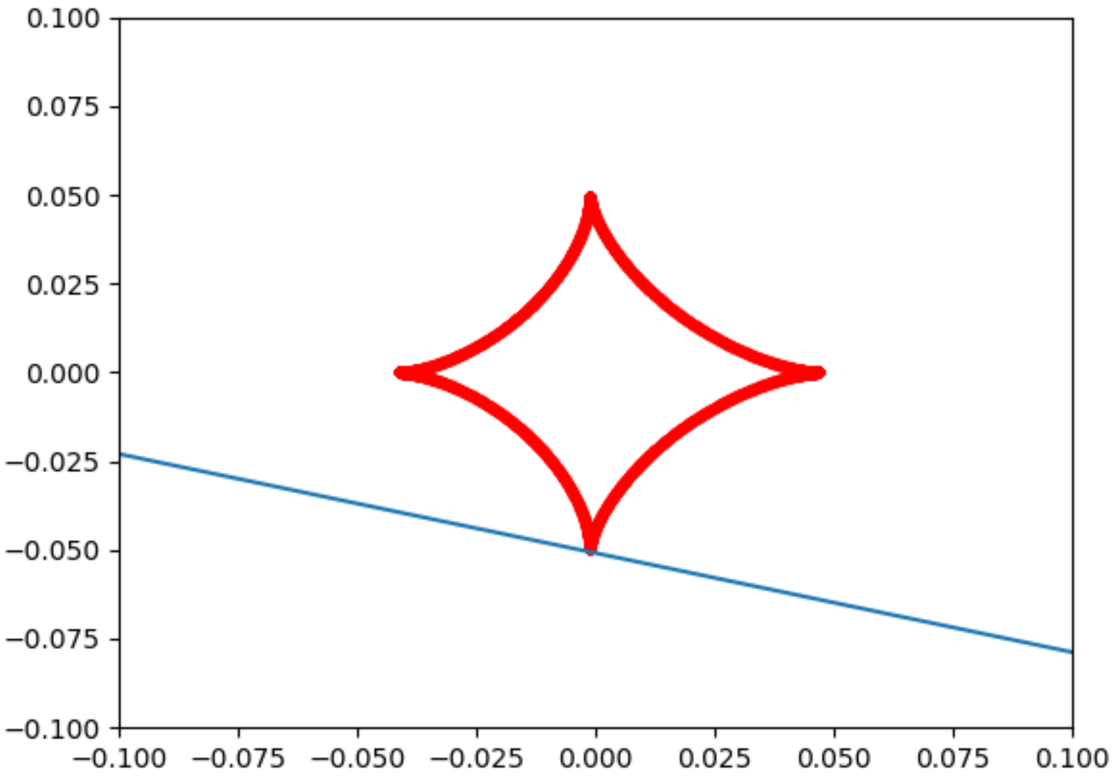


Shin et al. 2012 ApJ 746, 127



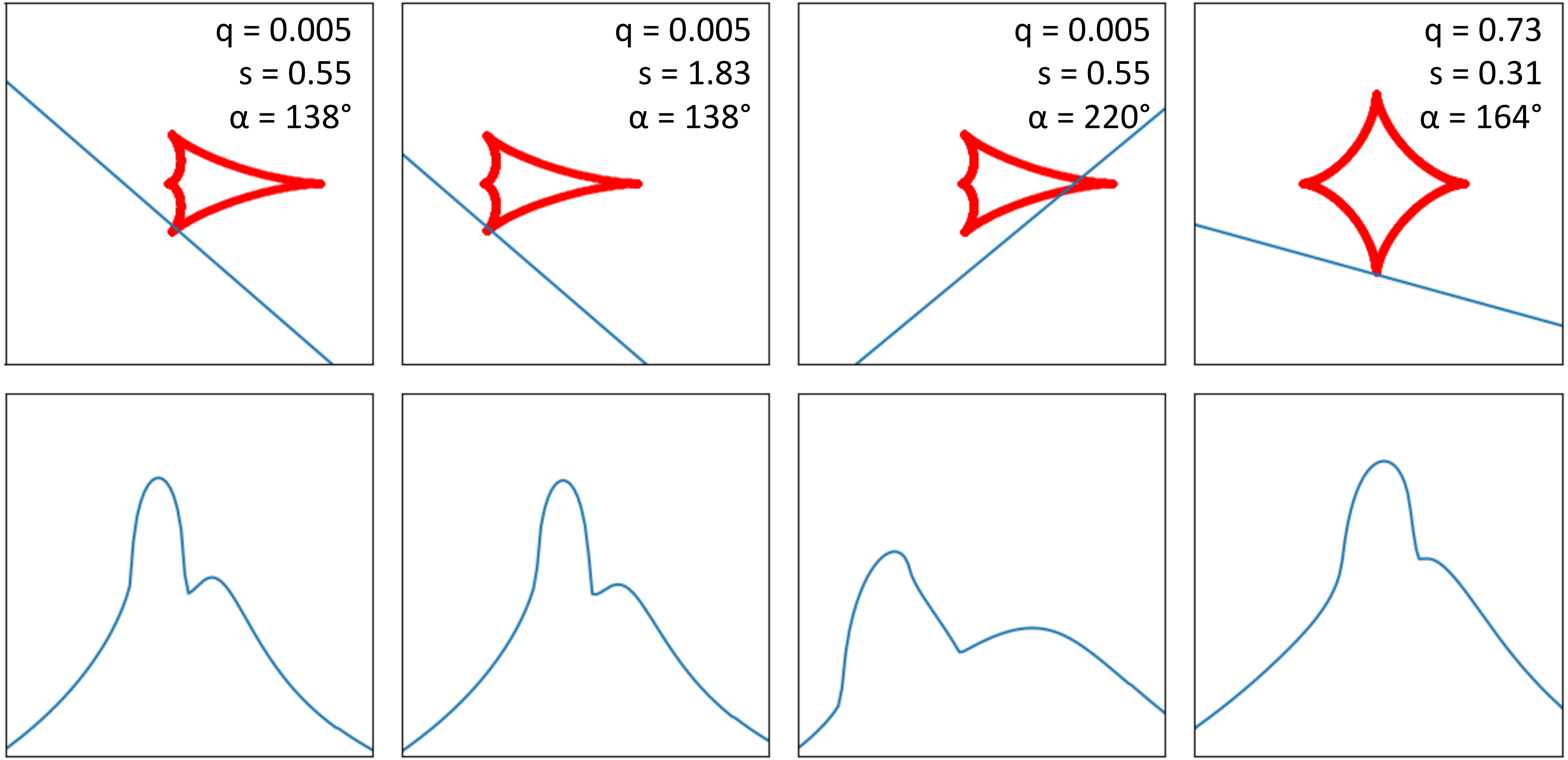
Is this also a planet?

NO. q = 0.729



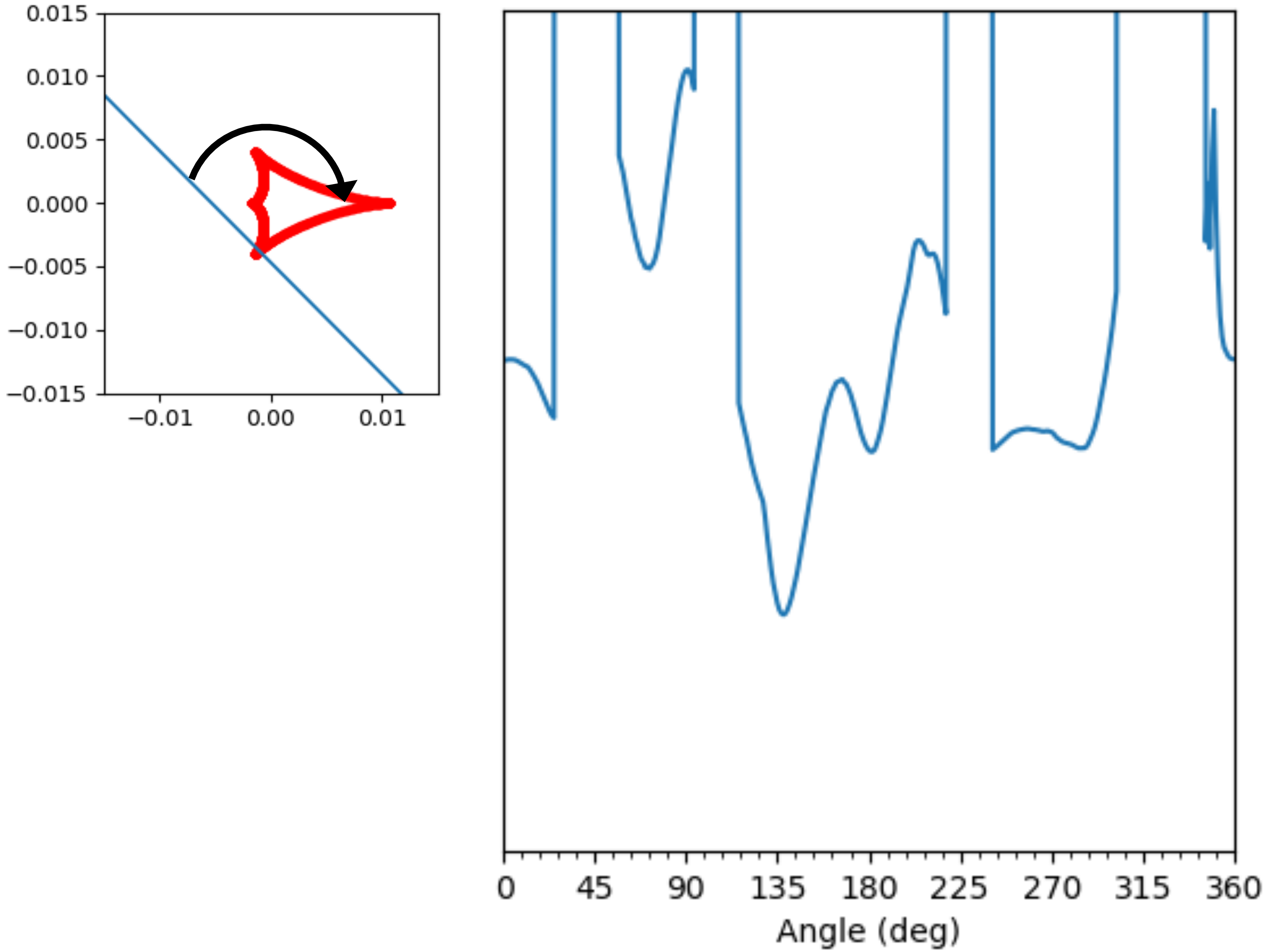
Shin et al. 2012 ApJ 746, 127

Symmetries/Similarities in the Magnification Pattern Make It Non-Trivial to Solve a Light curve

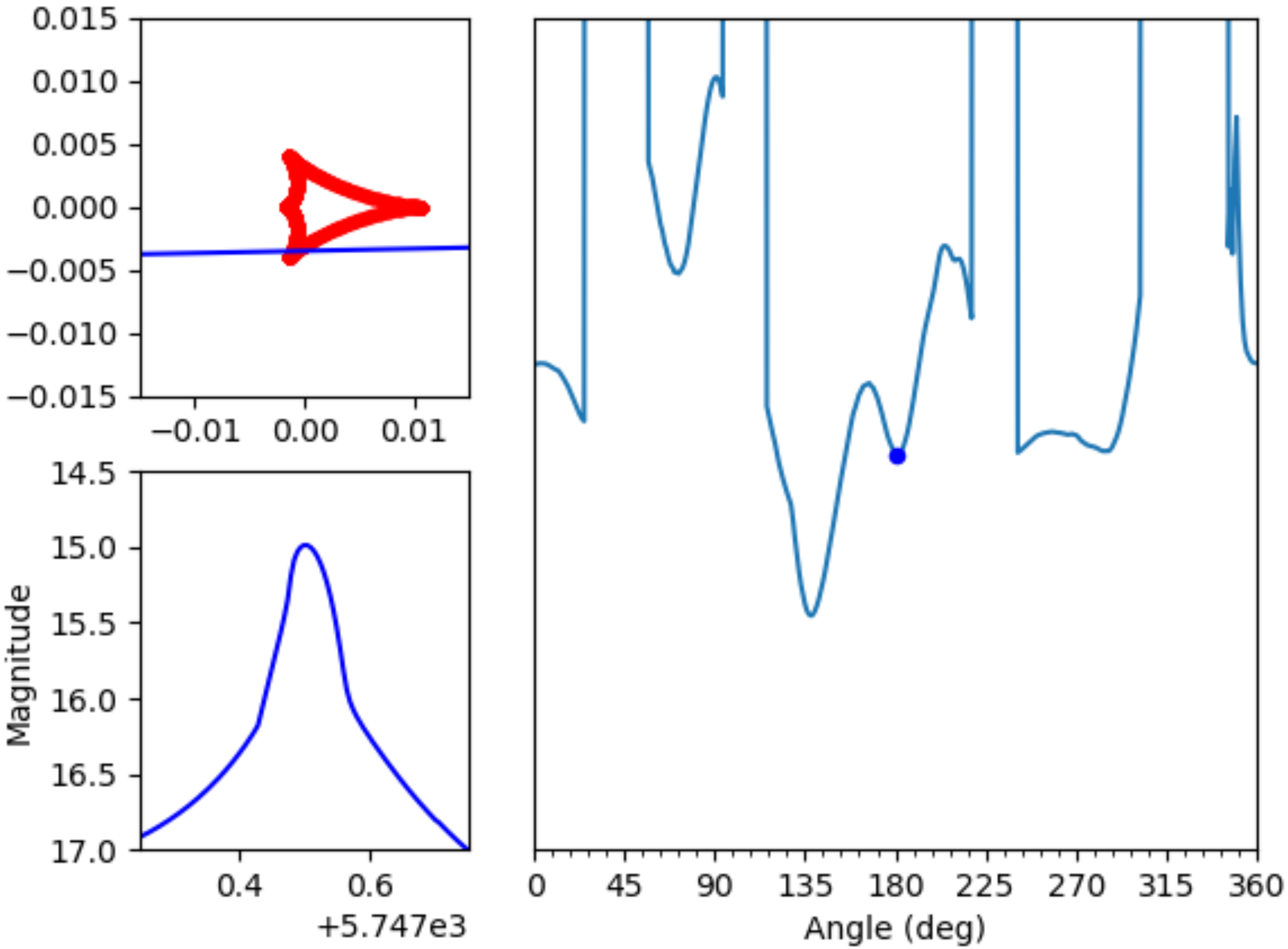


Part II: Techniques for Finding the Right Model

The χ^2 surface is complex.



A simple downhill algorithm won't work.



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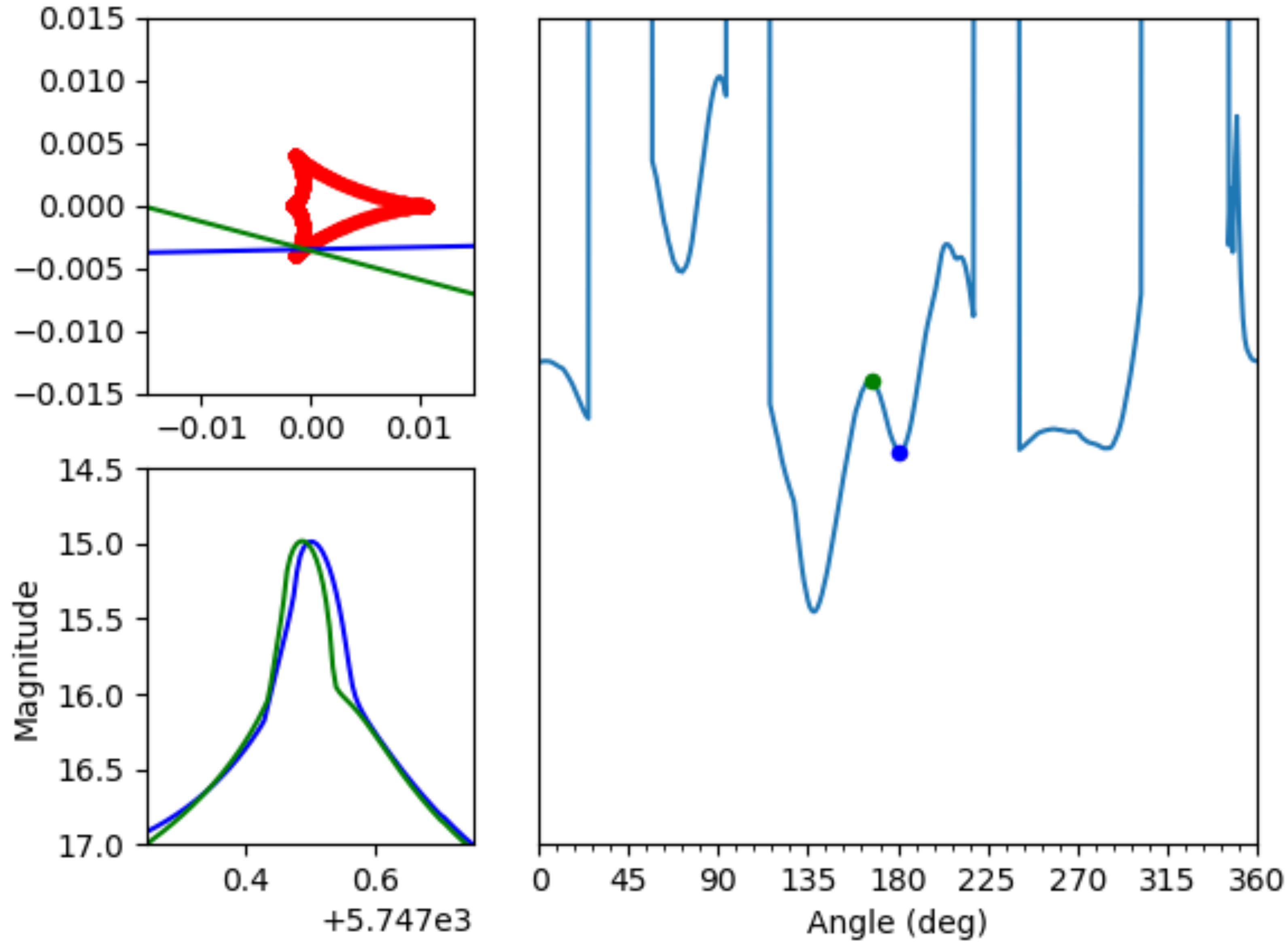

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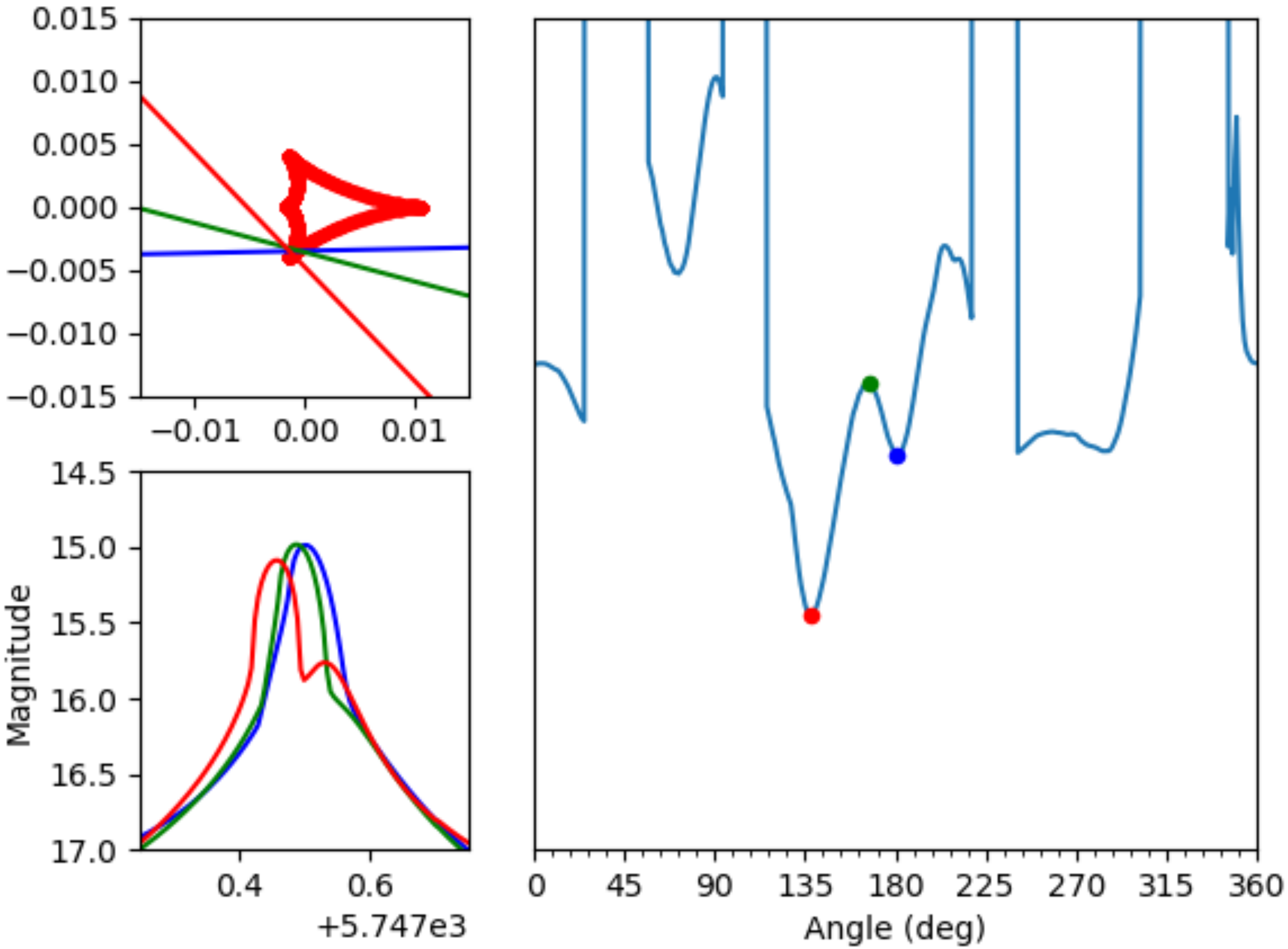
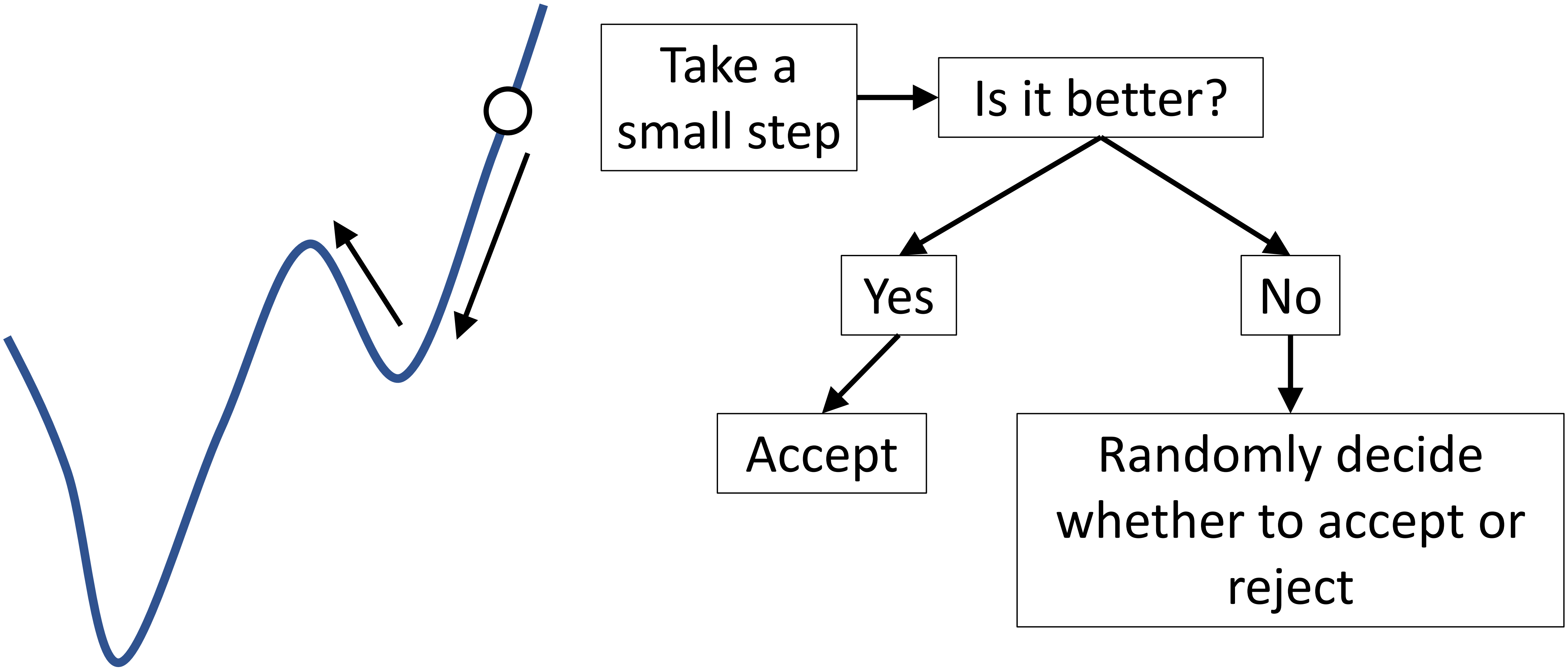


One Approach: Markov Chain Monte Carlo

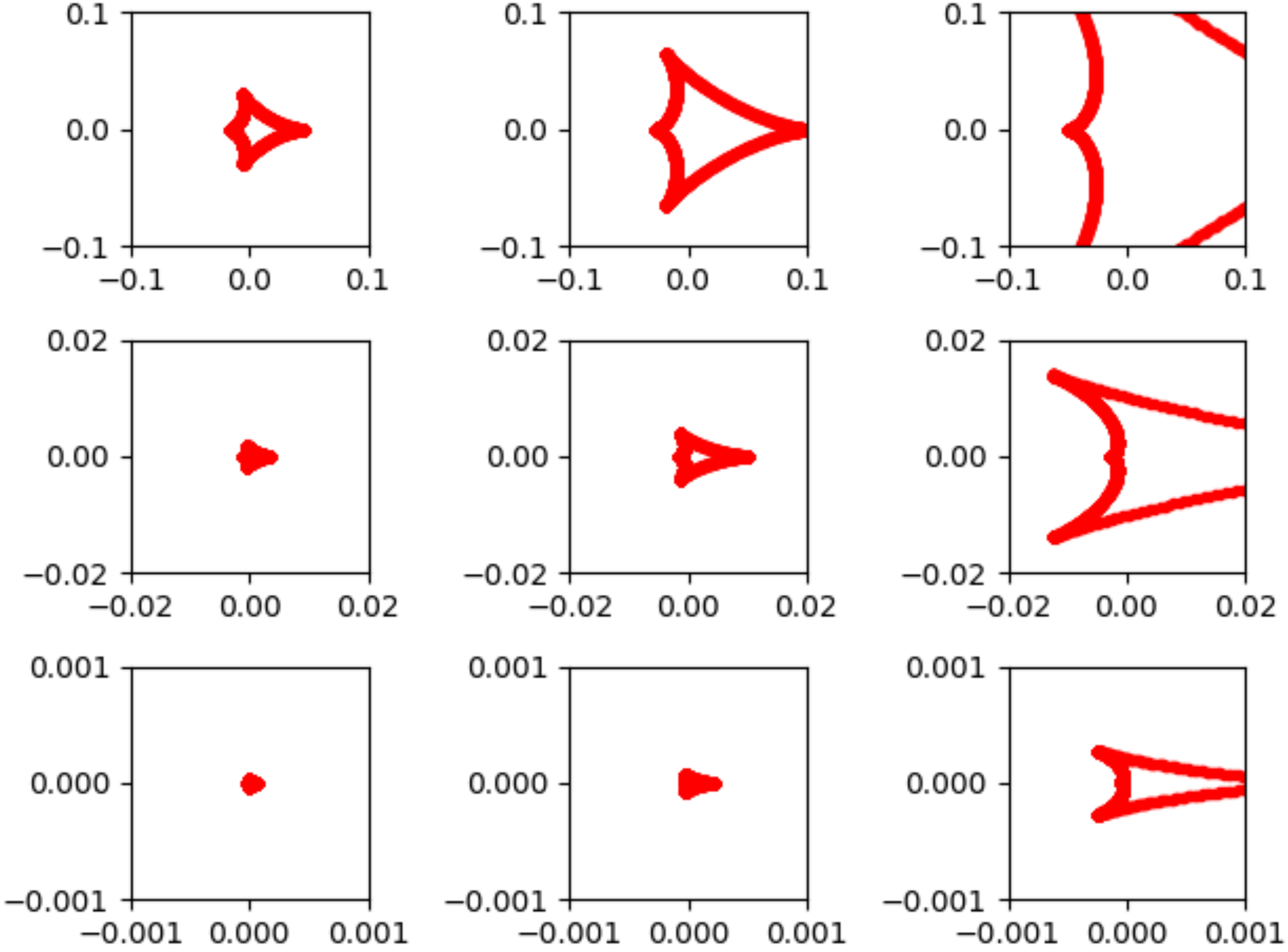


Markov Chain Monte Carlo (Random Walk)

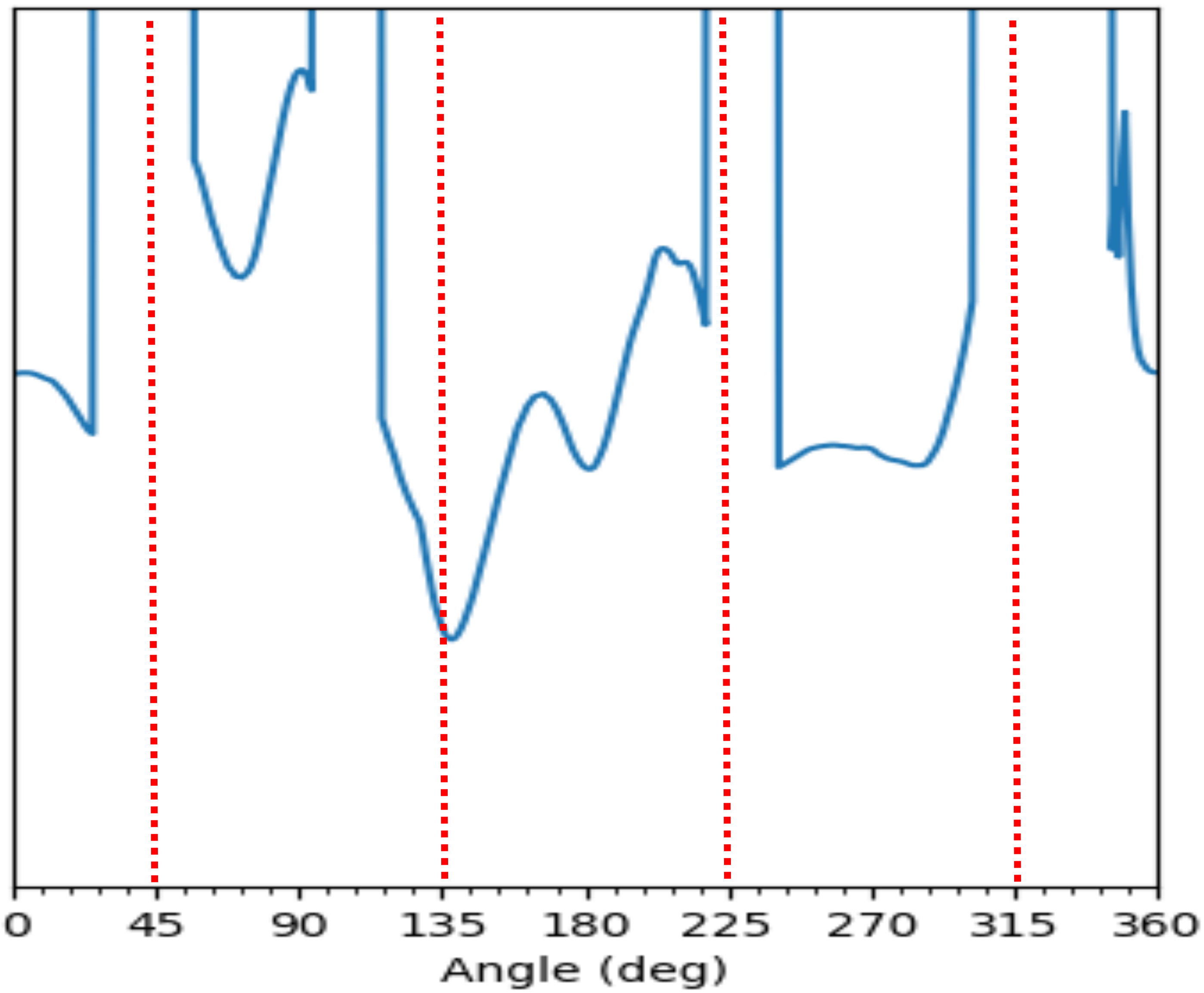
- Advantage: It will eventually explore all of parameter space including multiple minima.

- Disadvantage: It may take the age of the universe to do it.

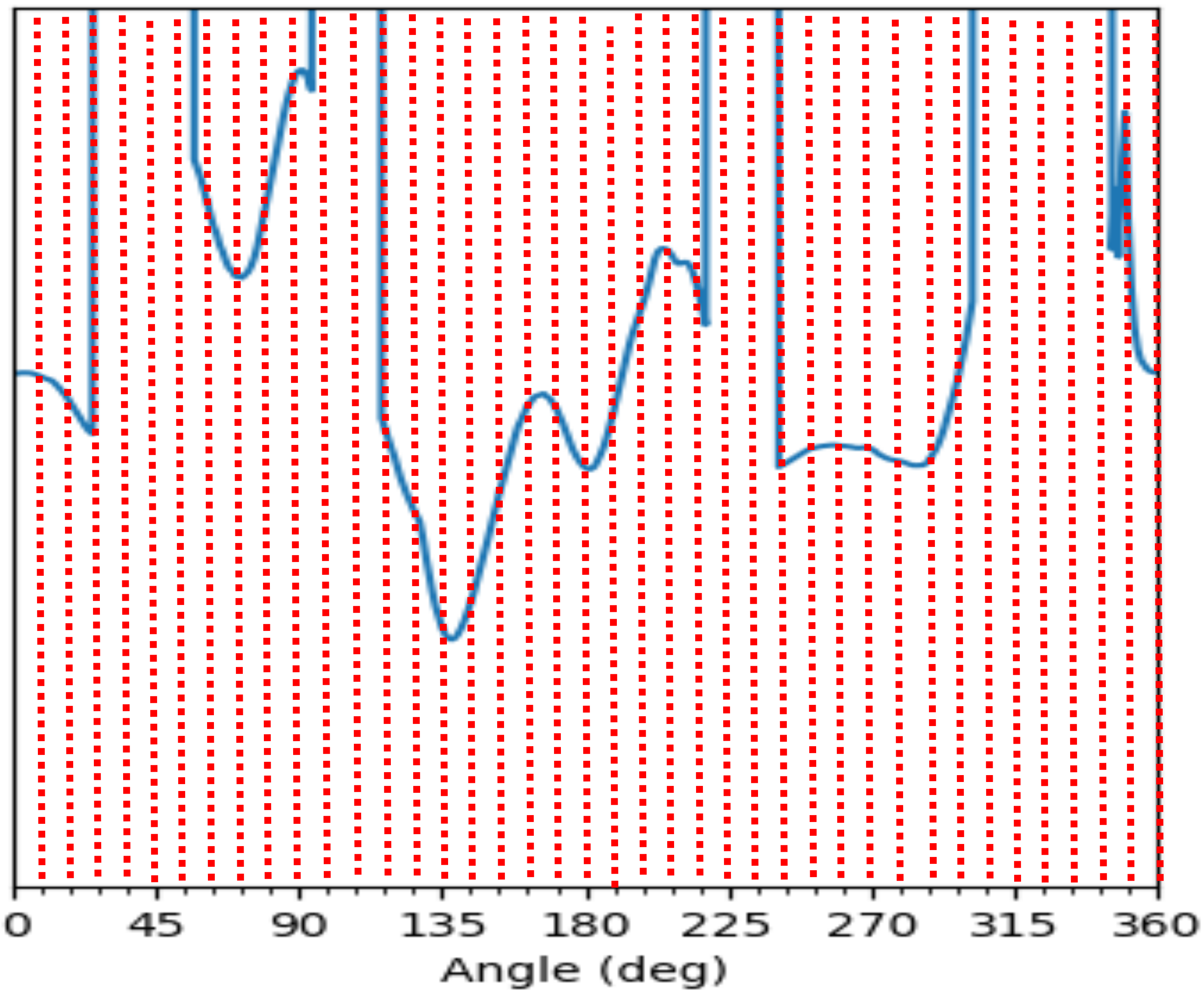
Hybrid Approach: Grid Search in s, q, angle



If the grid is too sparse, solutions are missed.



If the grid is too dense, it takes too long (inefficient).

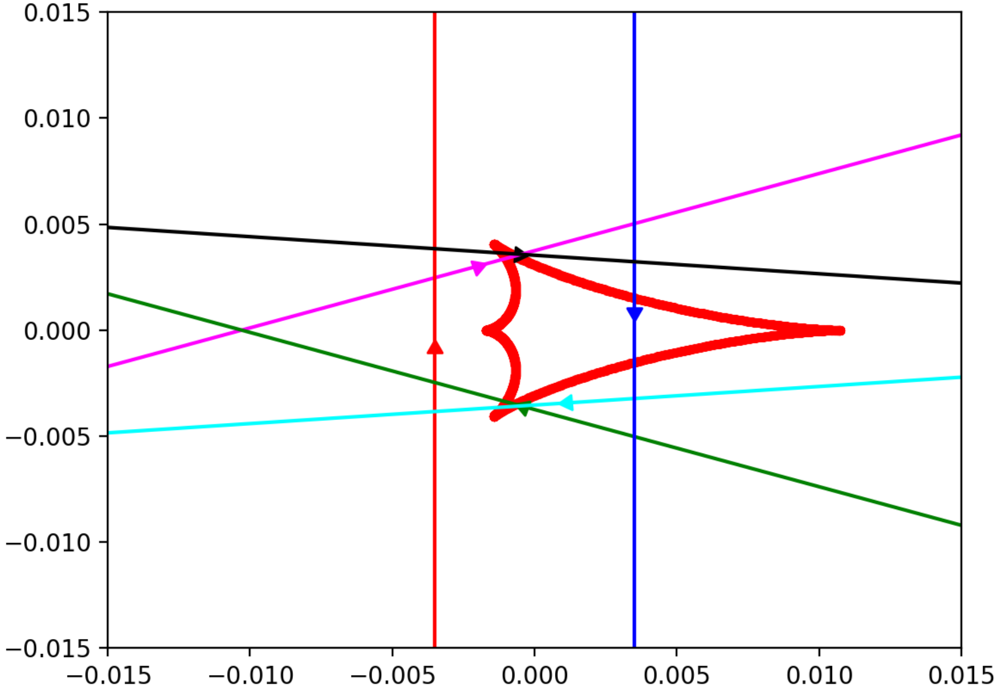


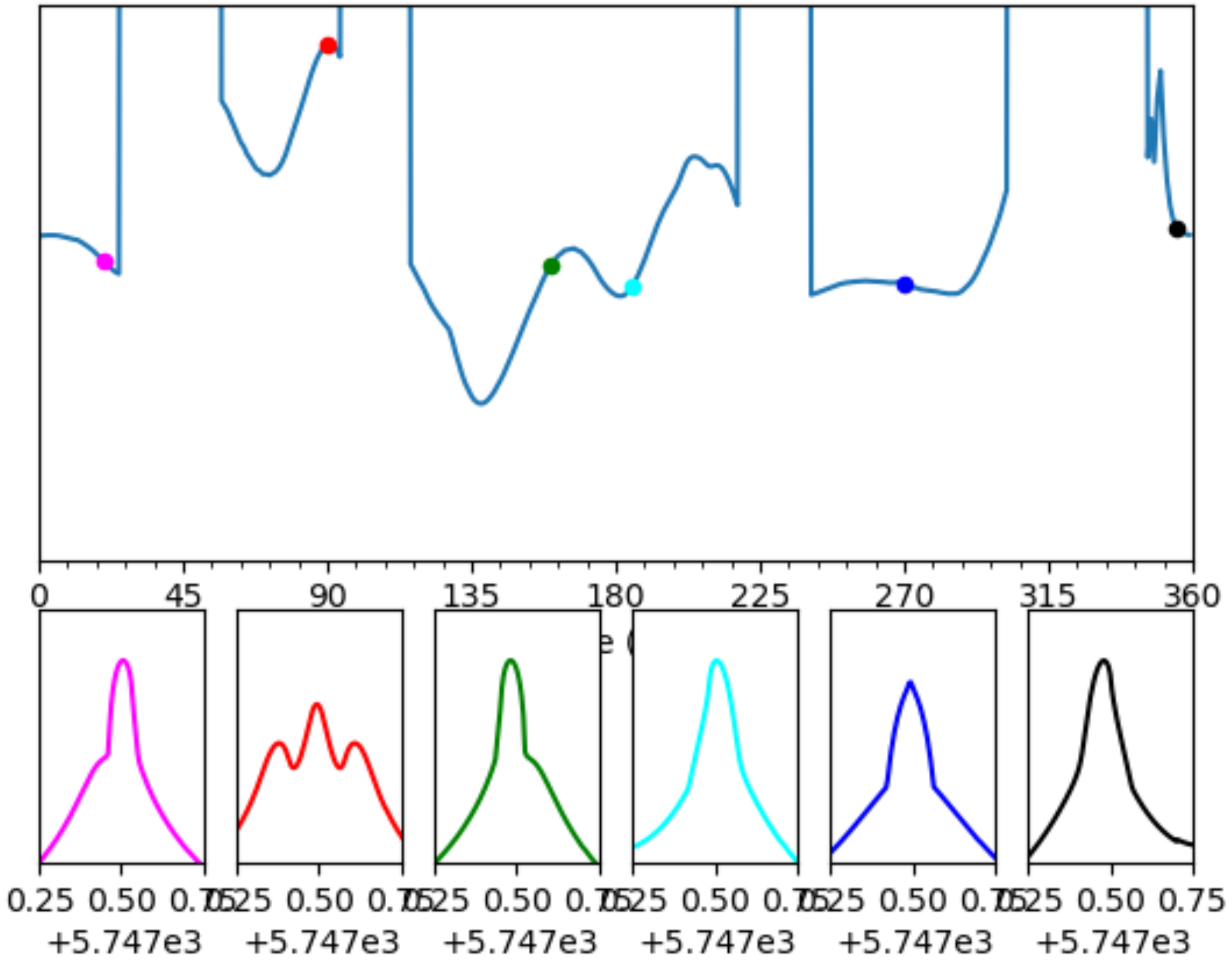
MCMC + Grid Search

- Advantage: It can improve efficiency of MCMC alone (fewer parameters)
- Advantage: Good for a blind, systematic search

- Disadvantage: There is an art to selecting the grid size

Alternative Approach: Light Curve Library



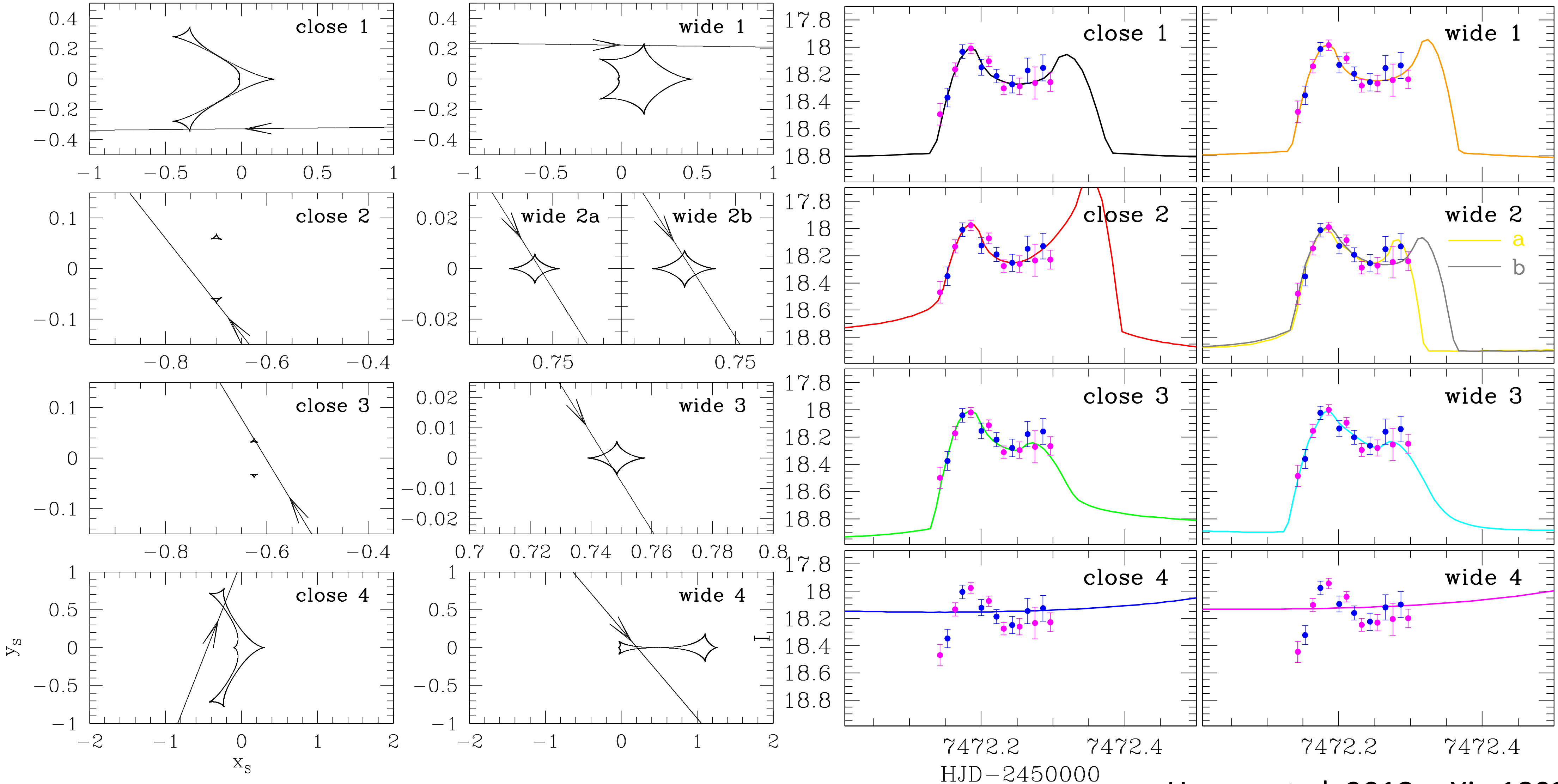


Light Curve Library

- Advantage: Optimal sampling of parameter space
  - Less likely to miss solutions
  - Can be more efficient

- Disadvantage: Significant effort to set up. Requires a deep knowledge of caustic structures.

Partial data = More degeneracies



Hwang et al. 2018 arXiv:1802.10246

Summary

- The magnification pattern + source trajectory determines the light curve
- Symmetries/similarities in the magnification make it hard to find the true solution
- Methods for searching for the correct model:
  - MCMC + grid search
  - Light curve library

Part III: Resources

Resources: Modeling

- MulensModel: Python, generates models, includes examples
  https://github.com/rpoleski/MulensModel/releases/tag/v1.4.0

- pyLIMA: Python, fits models to data, includes examples
  https://github.com/ebachelet/pyLIMA/tree/master/pyLIMA

- VBBL (Valerio Bozza Binary Lensing): C++, generates models
  http://www.fisica.unisa.it/GravitationAstrophysics/VBBinaryLensing.htm

Resources: Public Data

- Exoplanet Archive: Data from Published Planets
  https://exoplanetarchive.ipac.caltech.edu/
- Korea Microlensing Telescope Network: Data for Microlensing Events from 2015 and K2C9 data are fully public.
  http://kmtnet.kasi.re.kr/ulens/
- UKIRT Microlensing Survey: Data for all stars for 2015—2017 campaigns
  https://exoplanetarchive.ipac.caltech.edu/docs/UKIRTMission.html

Microlensing Data Challenge: “Solve” 293 WFIRST-like lightcurves http://microlensing-source.org/data-challenge-guidelines/