Light Curve Phenomenology and By-Eye Characterization

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Goals

- Why is a familiarity with the phenomenology of microlensing light curves important?
- Allows one to identify whether an observed deviation is:
  - Due to microlensing as opposed to other astrophysical or instrumental causes.
  - Due to a potentially interesting cause, i.e. planets.
- Knowing what is likely causing an anomaly helps to:
  - Determine whether resources should be expended to collect more data.
  - Whether the event should be a priority for analysis
  - Provide initial conditions for fitting.

"Library" of Lightcurves

- People that have staring at microlensing lightcurves for over a two decades have built up a "library"of lightcurves in their heads.
- Each lightcurve in this library is linked to the underlying set of parameters (planet mass ratio, planet/star separation, etc.)
- Since we haven't figured out how to download this library into other people's brains…
- Must identify another way of extracting and condensing this information.

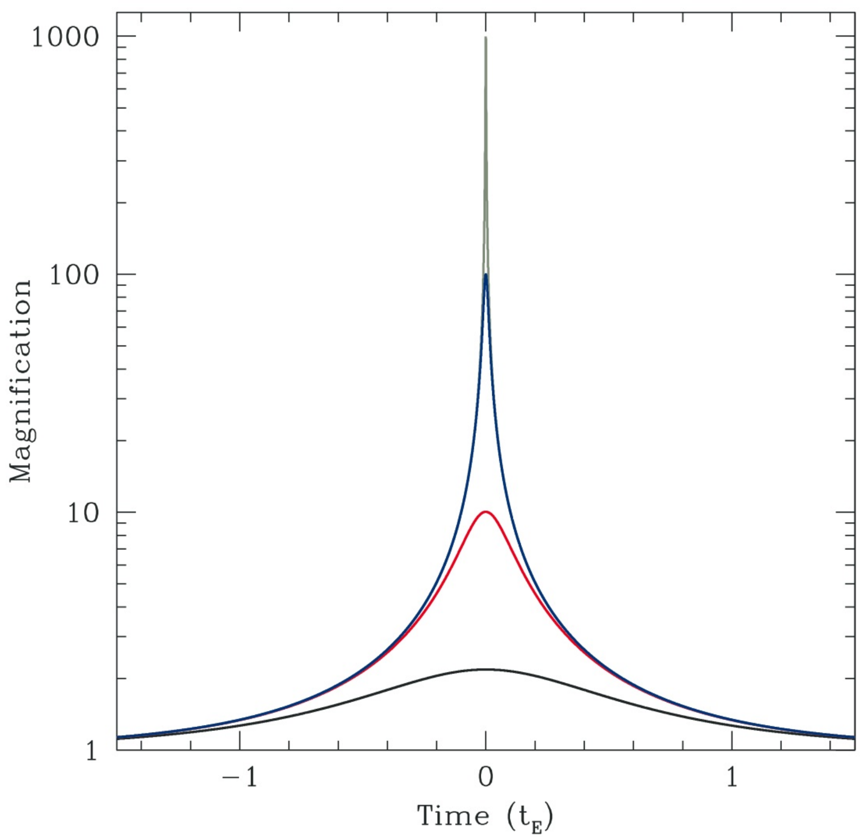
Lightcurve Phenomenology

Looking for deviations from the simple single lens curve.

General considerations:

1. These deviations come in three basic types.
2. Likely sources of anomalies are finite and understood.
3. Although the phenomenology is rich, all microlensing lightcurves obey general rules.
4. Binary lenses can be almost completely understood by their ***caustics.***

Generic Single Lens Lightcurve



- Smooth
- Symmetric
- Timescale ~ 20-200 days
- Magnification ~ 1.5-1000
- For high magnification events, flux is proportional to time^{-1}

Rule #1

- Generic single lens lightcurves are smooth and symmetric, with no sharp changes in the flux as a function of time.

Causes of Anomalies

There are a finite number of likely causes of deviations from the single lens form:

1. Roughly equal mass binary (~10%).
2. Parallax. (long timescale events)
3. Finite source. (high-magnification events)
4. Planetary companion.
5. Xallarap. (looks like parallax)
6. Binary Source. (rare)

Rule #2

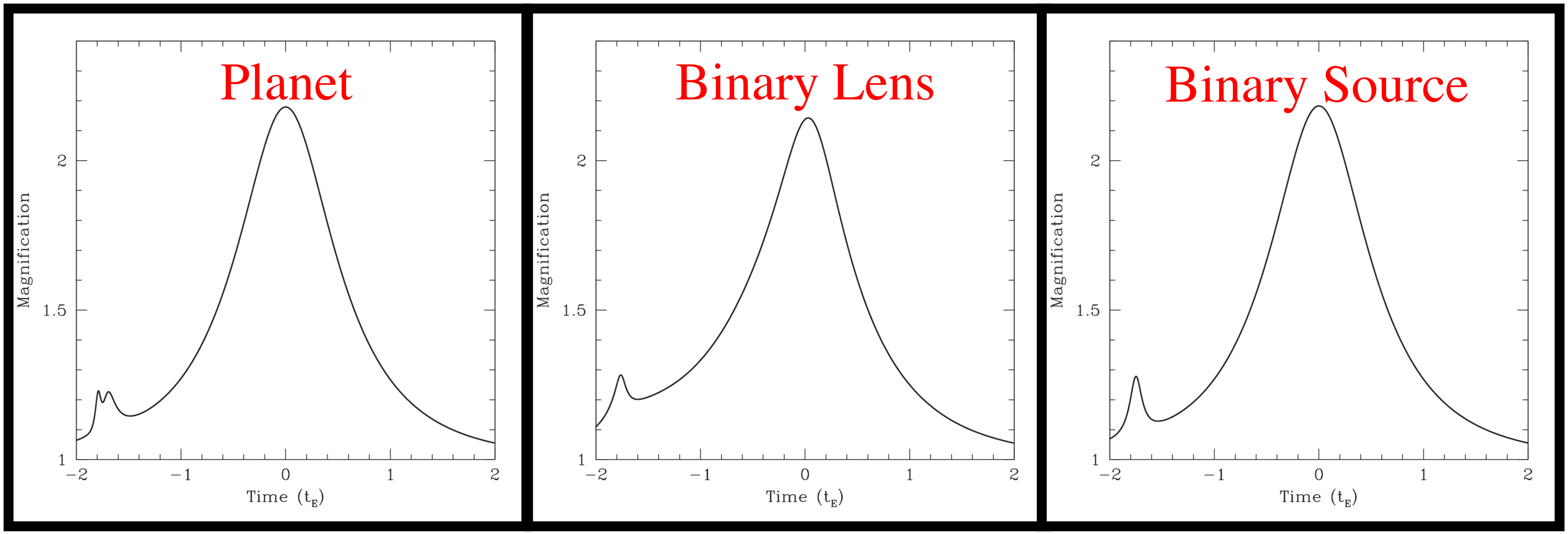
- There are a finite number of likely causes of lightcurve anomalies, and the vast majority are due to equal-mass binary lenses for typical lightcurves.

Lightcurve Anomalies

Come in three basic flavors:

- Short duration deviations in the wings of the lightcurve.
- Short duration deviations at the peak of the lightcurve.
- Long duration deviations (a significant fraction of the lightcurve timescale).

Short Duration Deviations in the Wings



Short duration deviations in the wings are caused almost exclusively by:

- Planets
- Close binary lenses
- Extreme flux ratio binary sources

Negative deviations are exclusively planets.

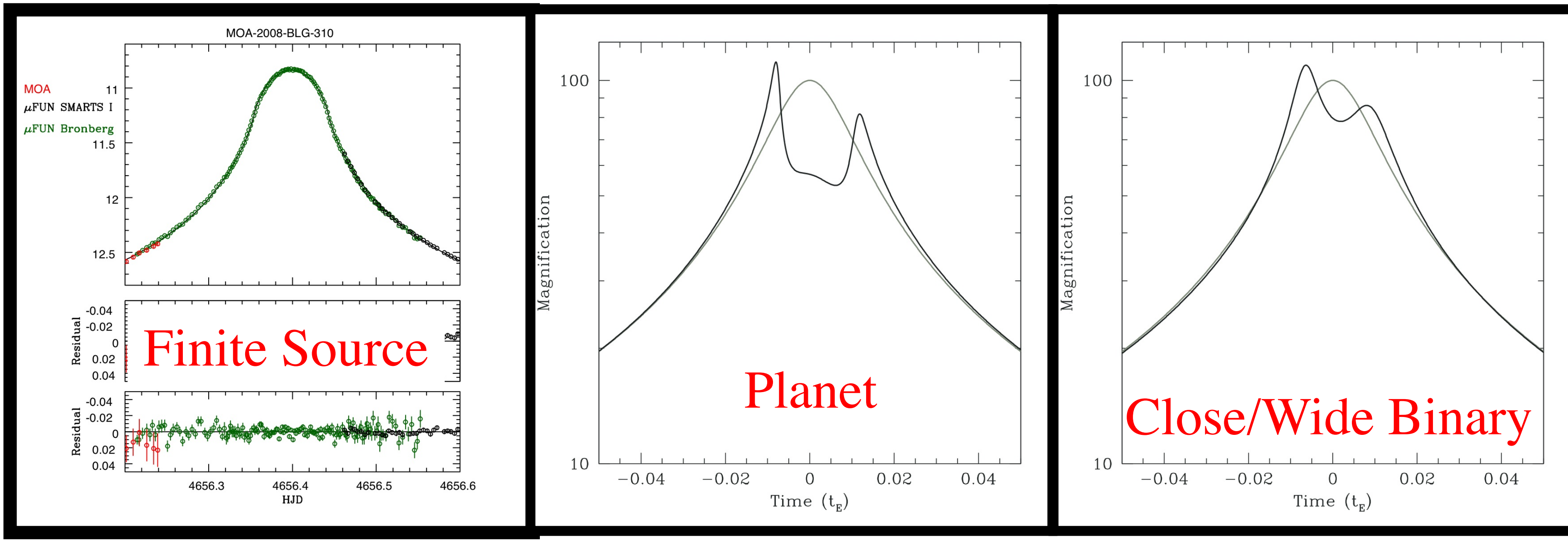
Rare!

Rule #3

- Short duration deviations in the wings are likely due to planets, so should be monitored!

(Note: deviations due to planets can be dips as well as bumps!)

Short Duration Deviations at the Peak



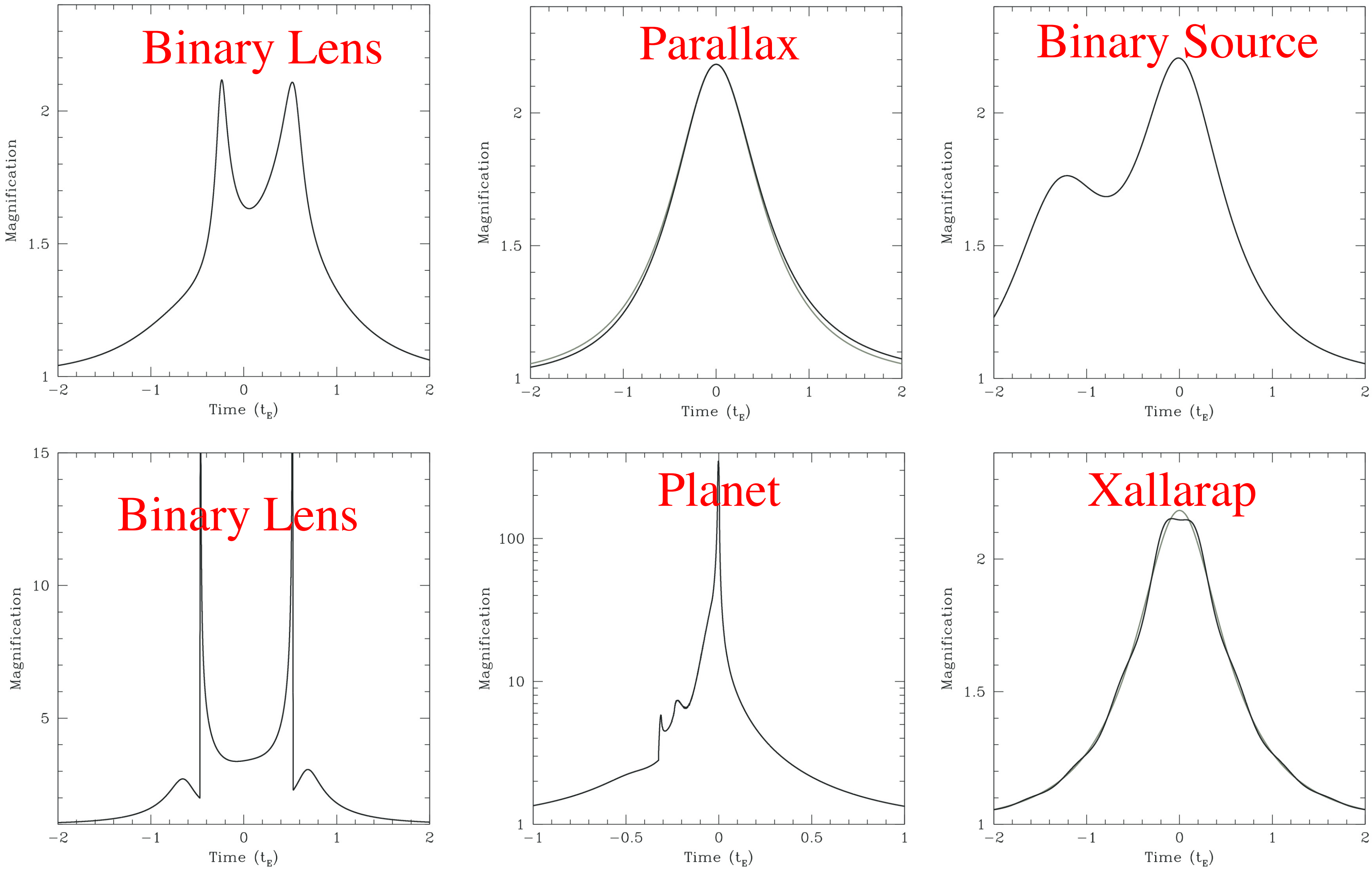
Short duration deviations in the peaks are caused almost exclusively by:

- Planets
- Finite source effects (symmetric)
- Very close or very wide binaries.

Rule #4

- Short duration deviations at the peak of high-magnification events are due to a small caustic, either the central caustic from planet or a wide/close binary.

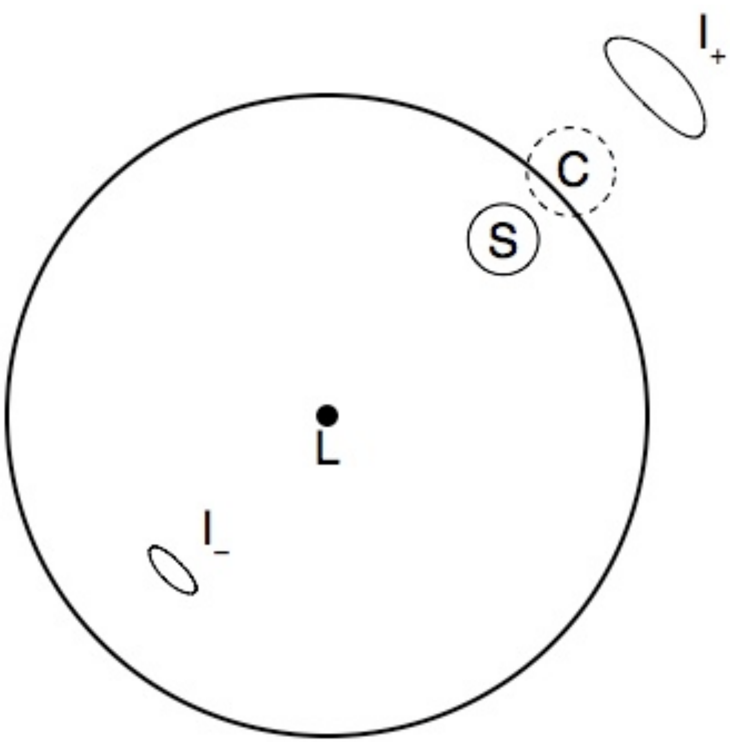
Long Duration Deviations



Rule #5

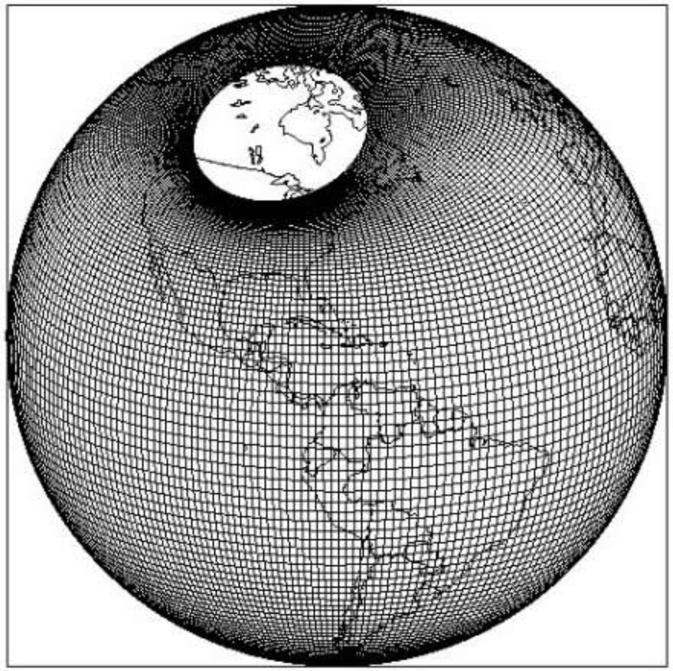
- Long duration deviations are generally not planets, but can be… so be careful!

How lensing works.



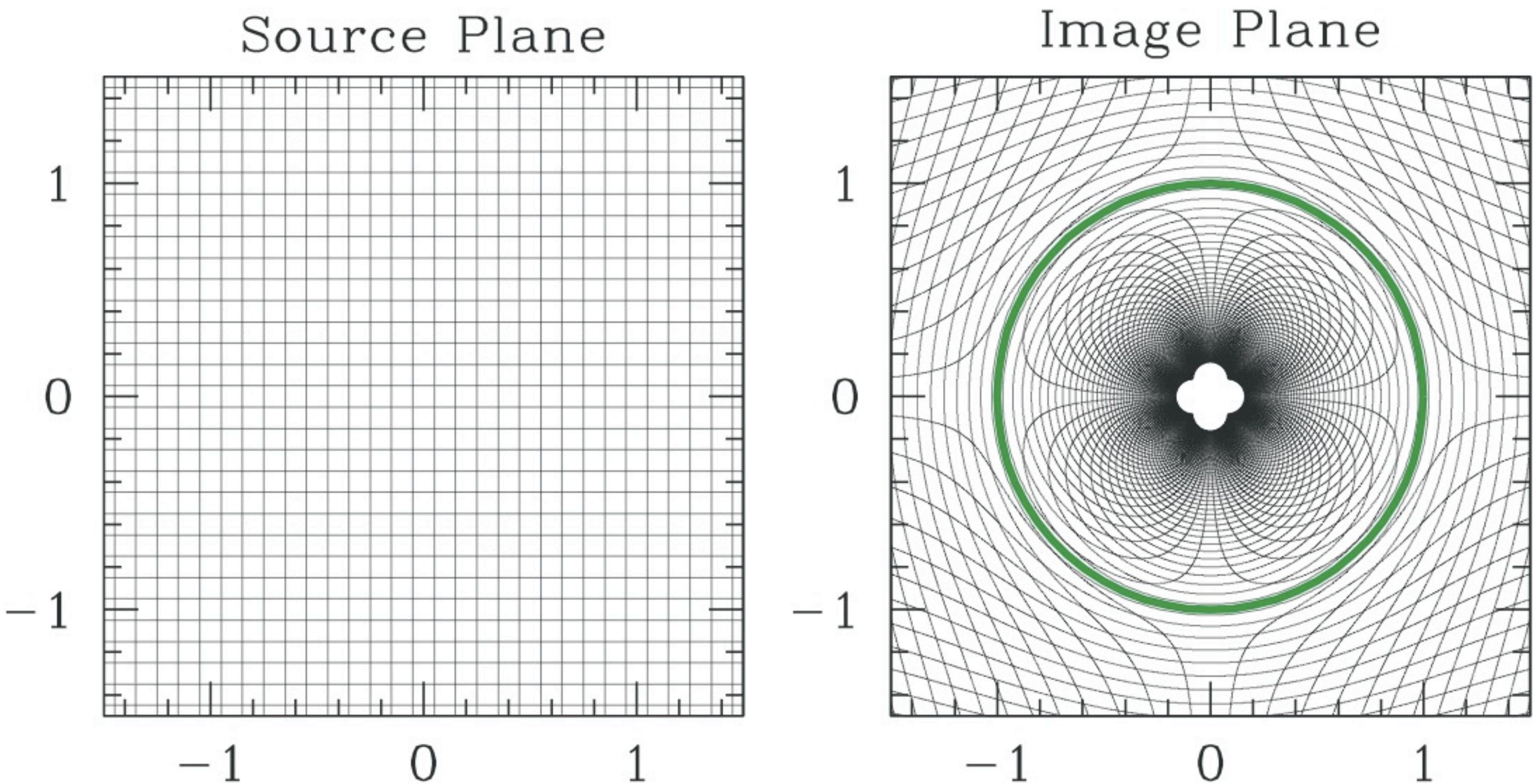
- Lensing is a mapping between source plane and image plane.
- Magnification is just the area of the images relative to the area of the source.
- Large magnification means a small patch of the source source maps to a large patch in the image plane.
- The mapping can be *singular*.

Maps



The Mercator map projection is an example of a mapping with a singularity or catastrophe (at the poles).

Catastrophes and Caustics

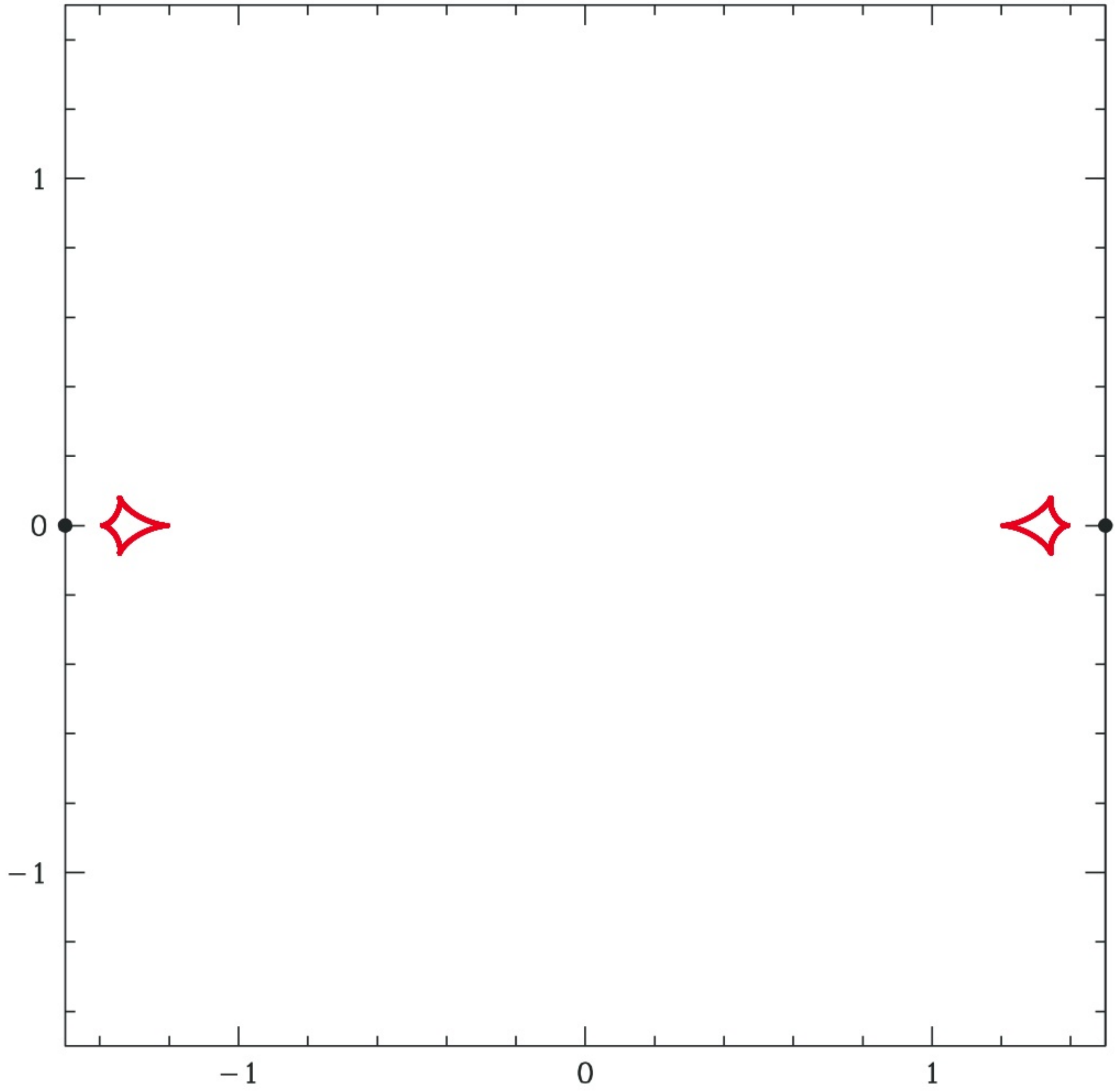


Caustics

- The set of source positions where the mapping is singular (or catastrophic).
- Infinite magnification for a point source.
- Large but finite magnification for a finite source.
- For a single lens, the caustic is a point (the position of the lens).
- For binary lenses, it is more complicated.

Rule #6

- The phenomenology of lightcurves can be largely understood by examining the caustics.



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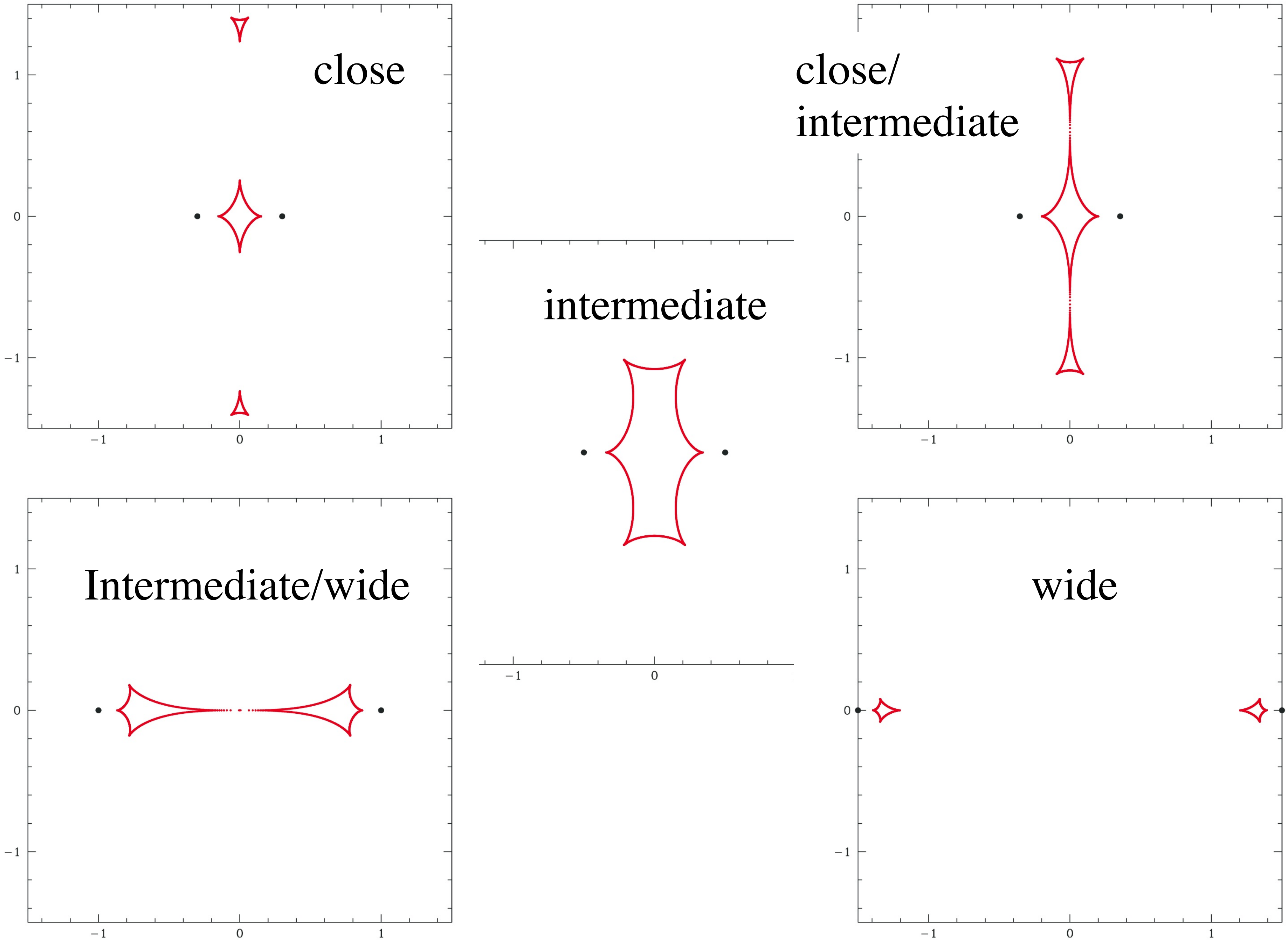
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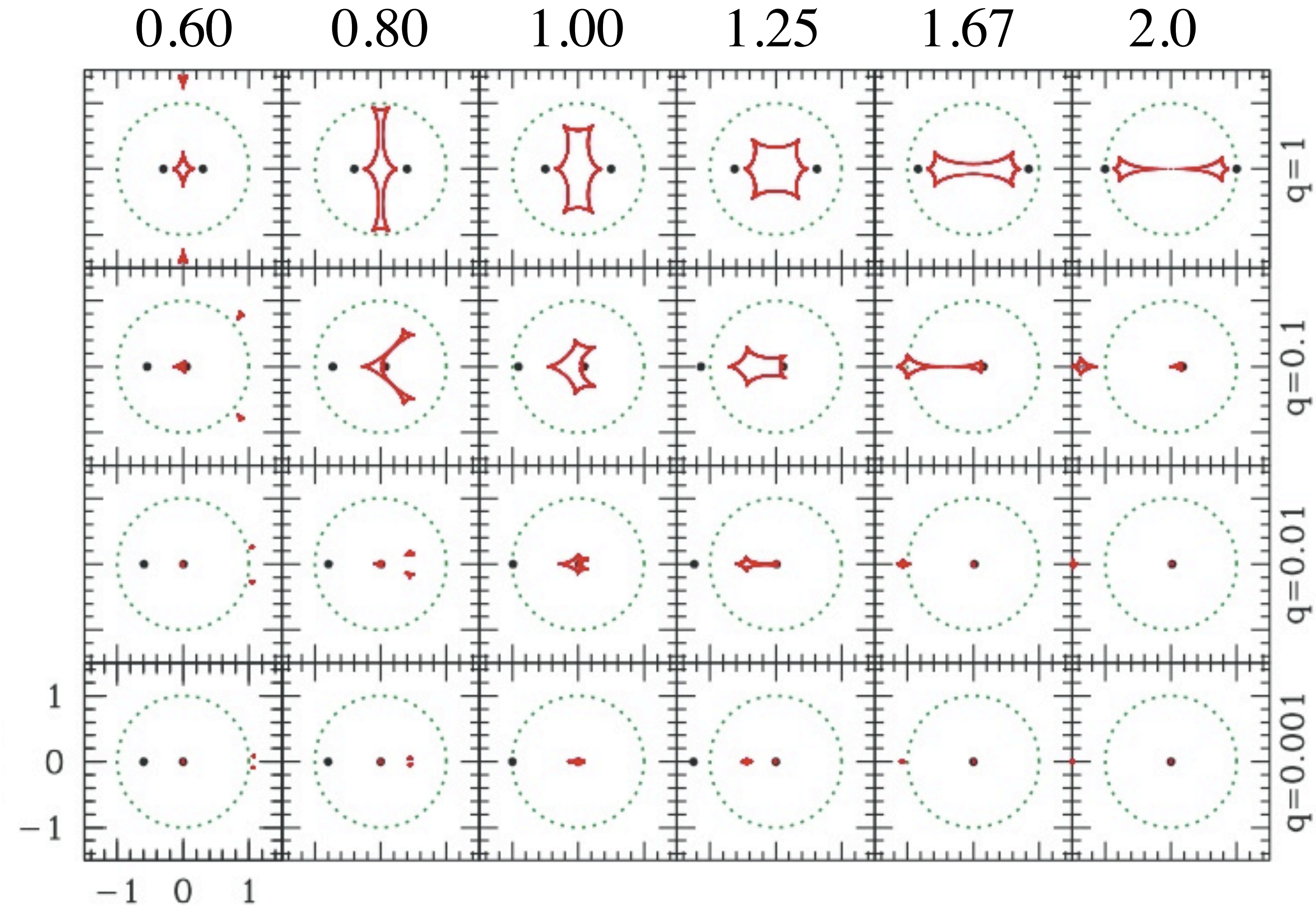
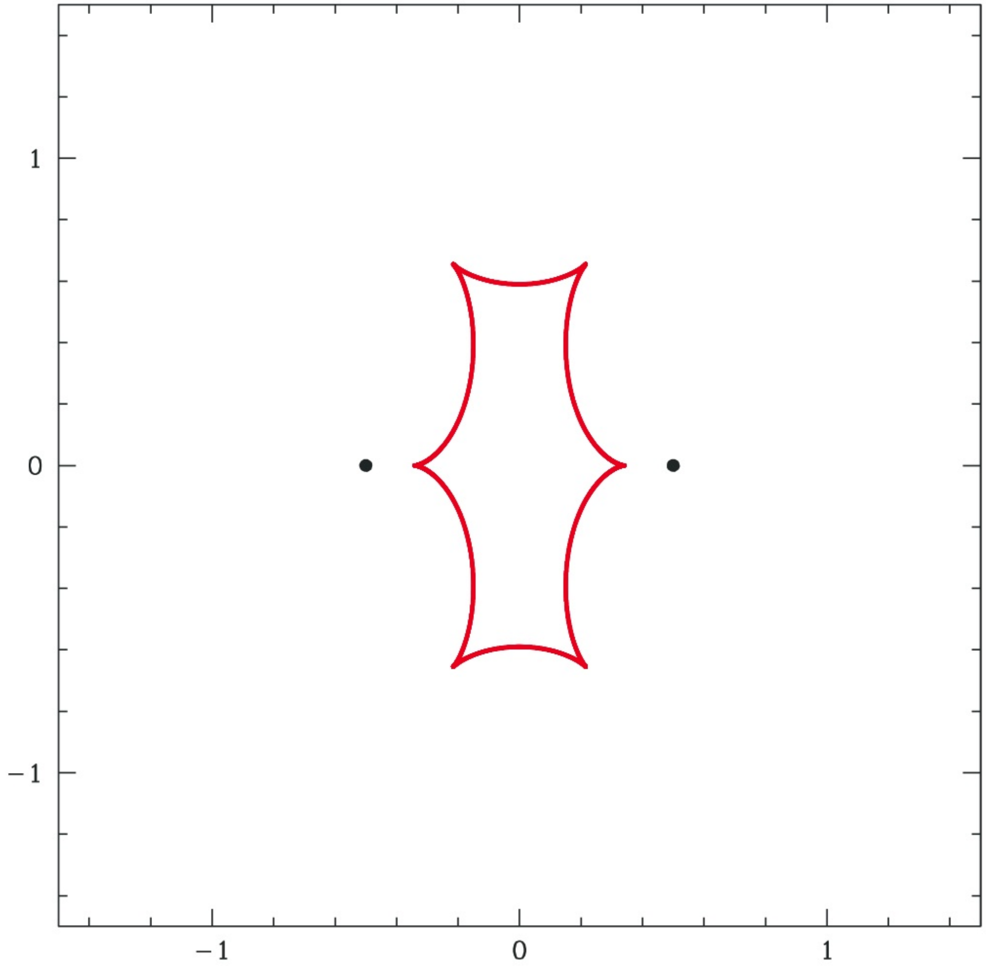


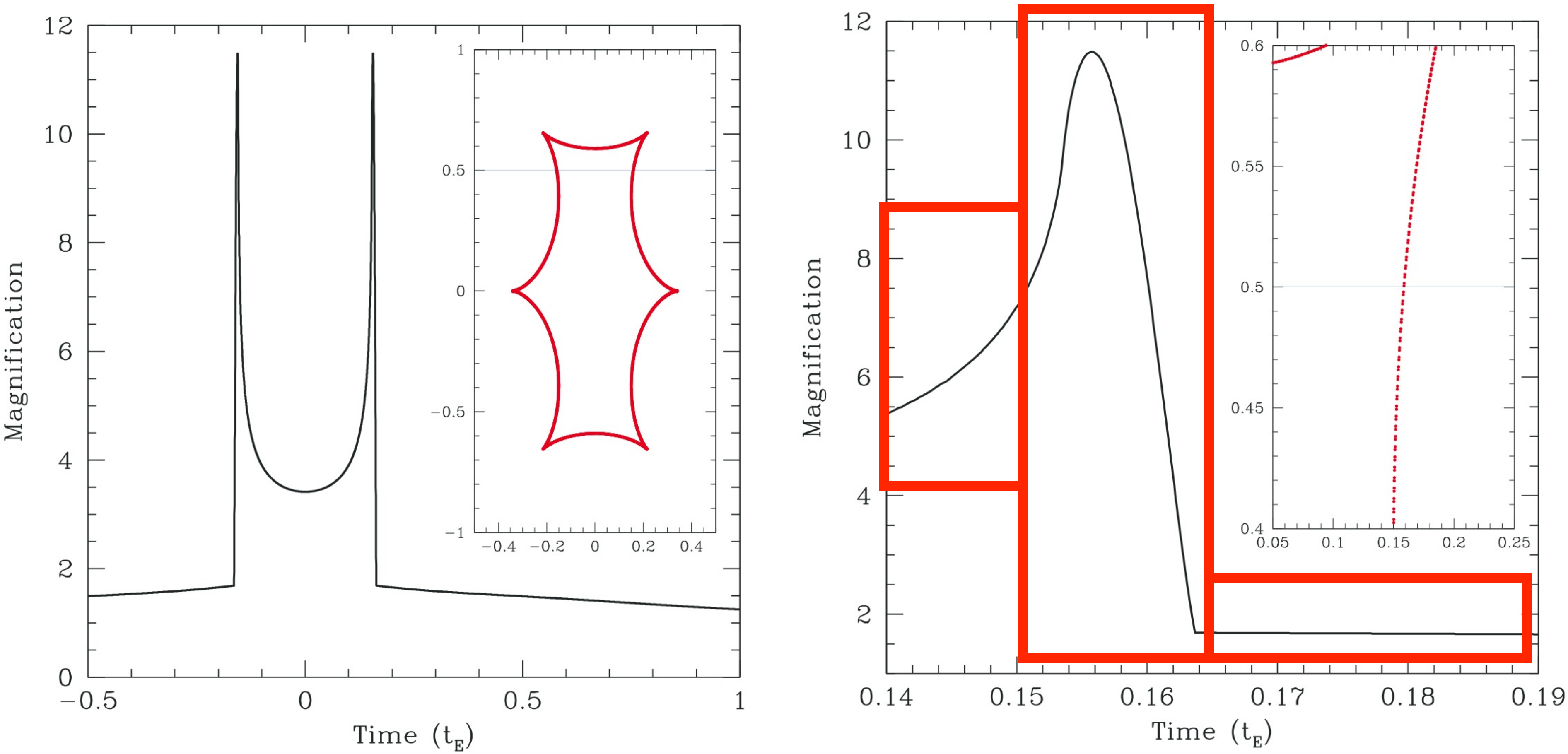
Binary lens caustics are specified by only two parameters:

- ***q*** - Mass ratio
- ***s*** - Projected separation in units of θ_E



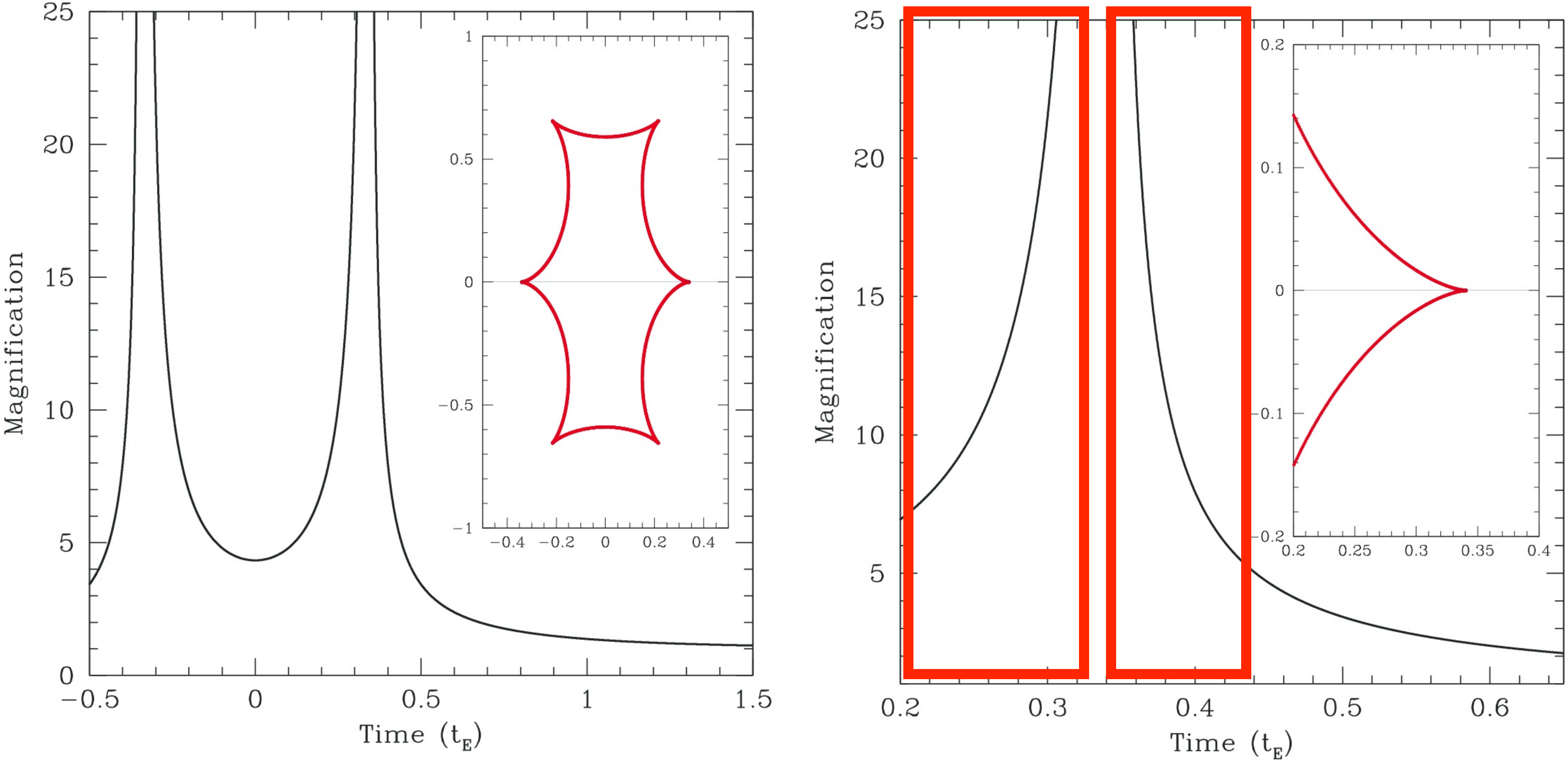
Caustics are closed concave curves that meet at points.

- Concave curves are ***fold caustics***.
- Points are called ***cusp caustics*** (or just cusps).



Fold caustics have a universal form.

- Magnification is proportional to 1/sqrt(distance)
- Fold crossings always come in pairs. (well, almost)

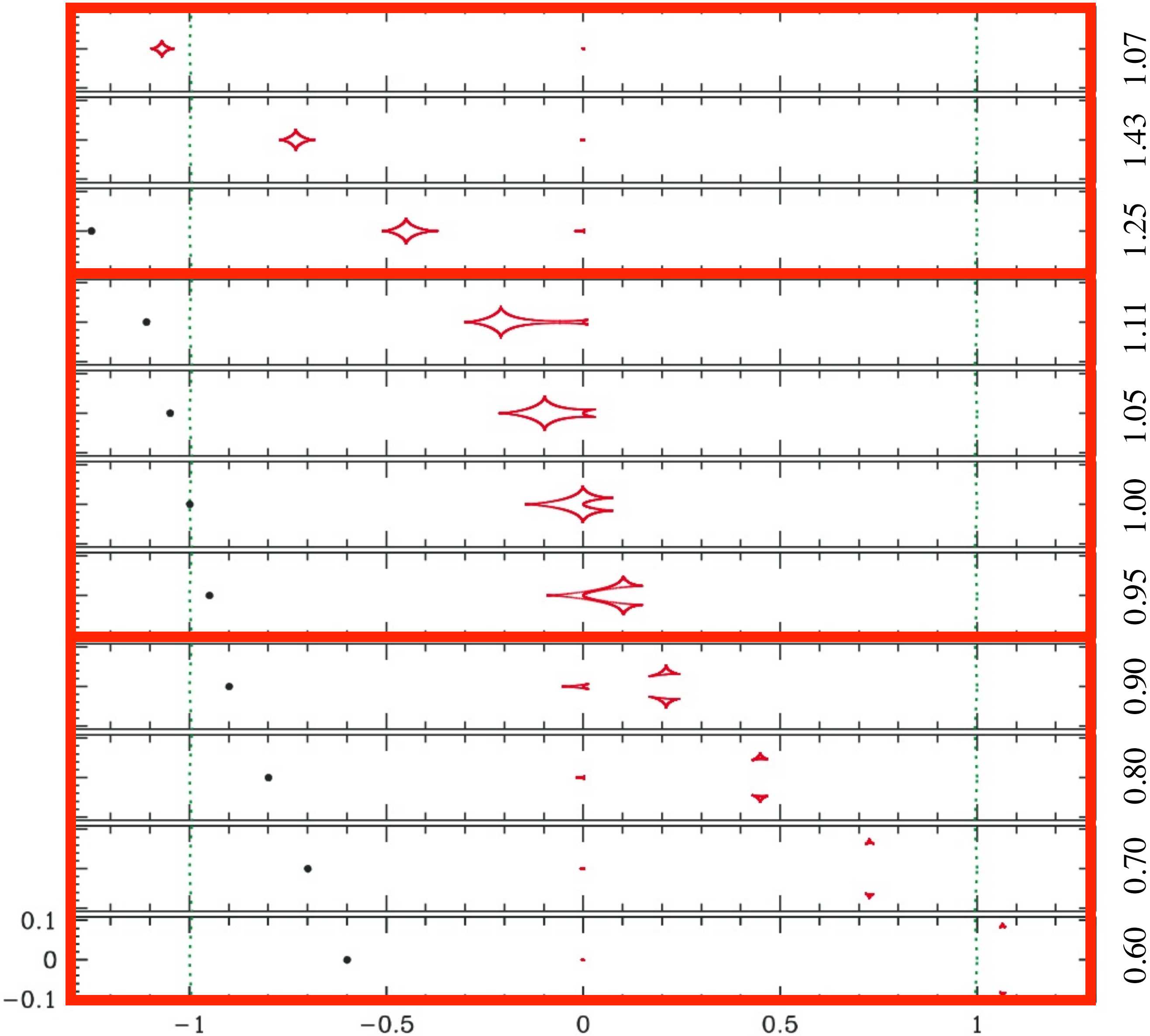


Cusp caustics have a universal form.

- Magnification is proportional to 1/distance
- Cusps have a lobe of high-magnification exterior to the cusp.

Rules #7-#9

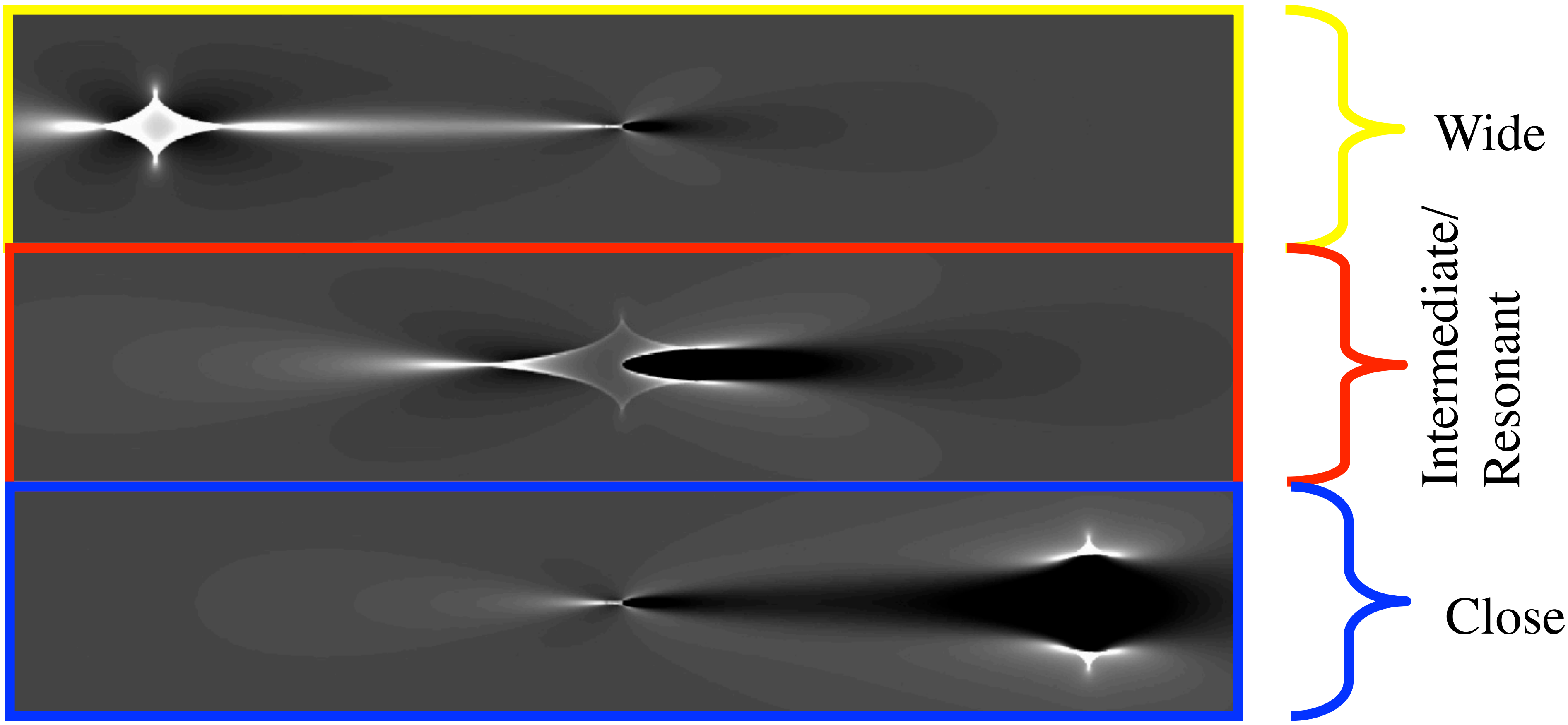
- Caustics are made of folds and cusps, which have universal forms.
- Fold crossings come in pairs.
- Cups have lobes of high-magnification that extend *exterior* to the cusp.



Wide:
- Two caustics
- Central/Planetary

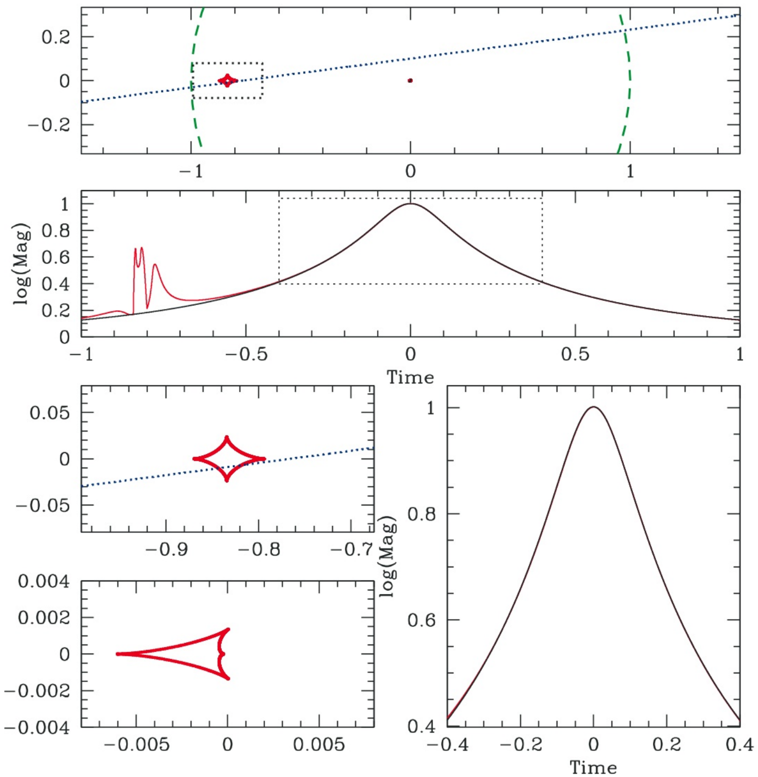
Intermediate or resonant:
- Narrow range around s~1
- Large caustics

Close:
- Three caustics
- Central
- Two planetary



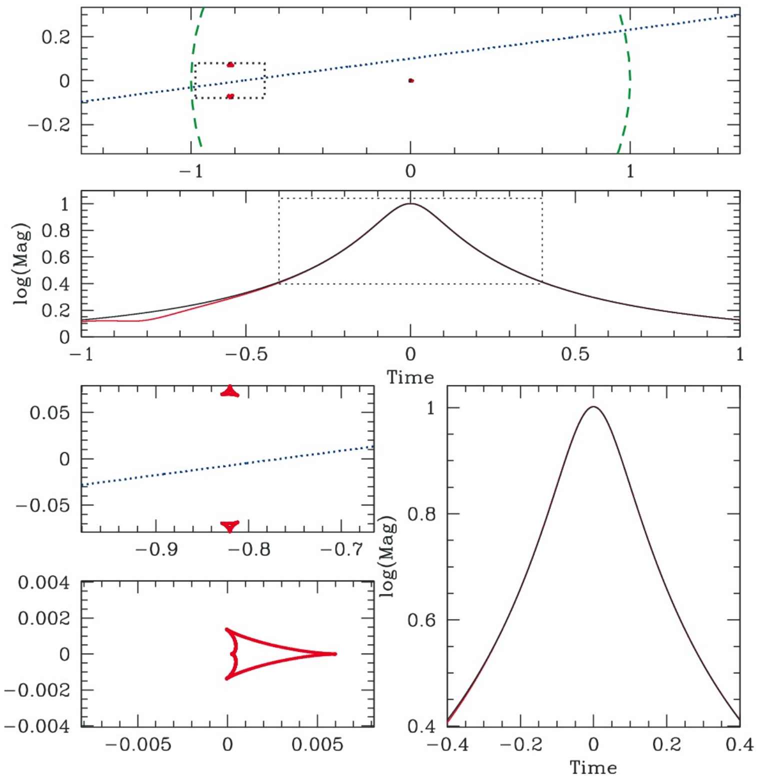
Wide
Intermediate/
Resonant
Close

Planetary Caustic Perturbations (s >1)



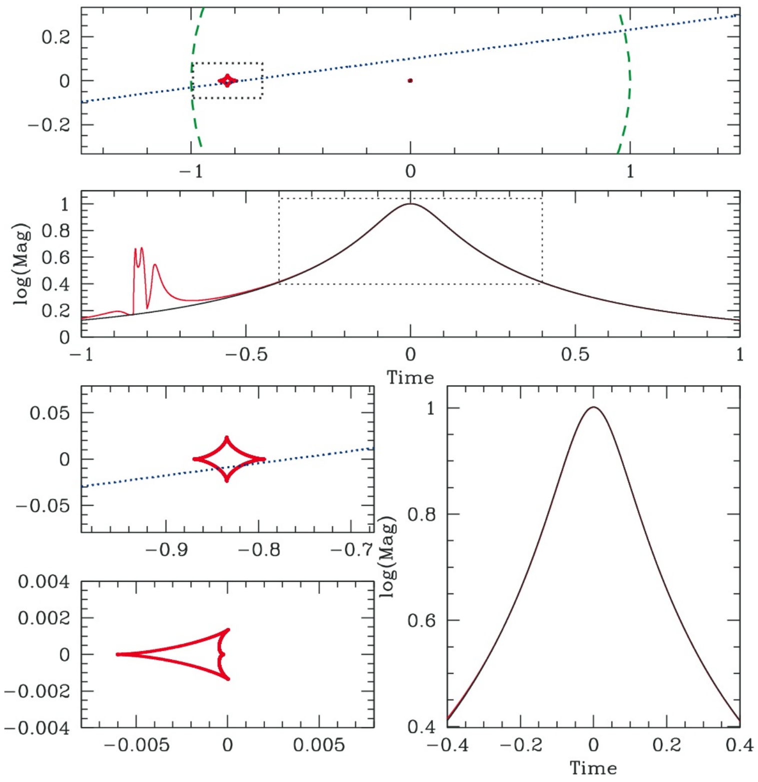
- Can happen anywhere, but usually on wings
- Unpredictable.
- For *s* >1, perturbations are mostly posutive, and the size of caustic is proportional to $q^{1/2}s^{-2}$

Planetary Caustic Perturbations (s < 1)



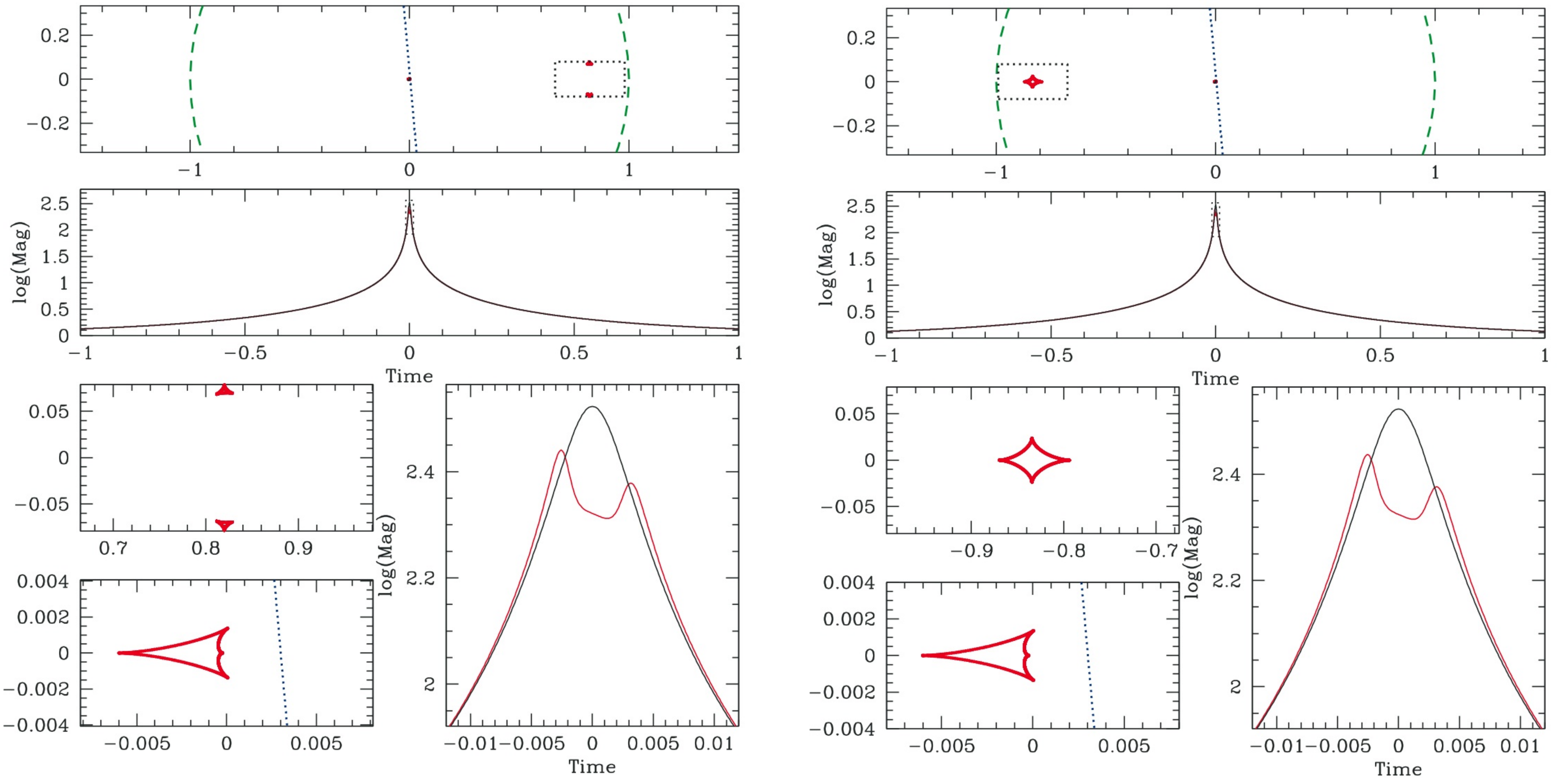
- For $s<1$, perturbations are mainly negative.
- "Trough" of demagnification between the triangular caustic.
- Size of caustic is proportional to $q^{1/2}s^3$
- For $s \rightarrow 1$ the trough becomes deeper.

Central Caustic Perturbations

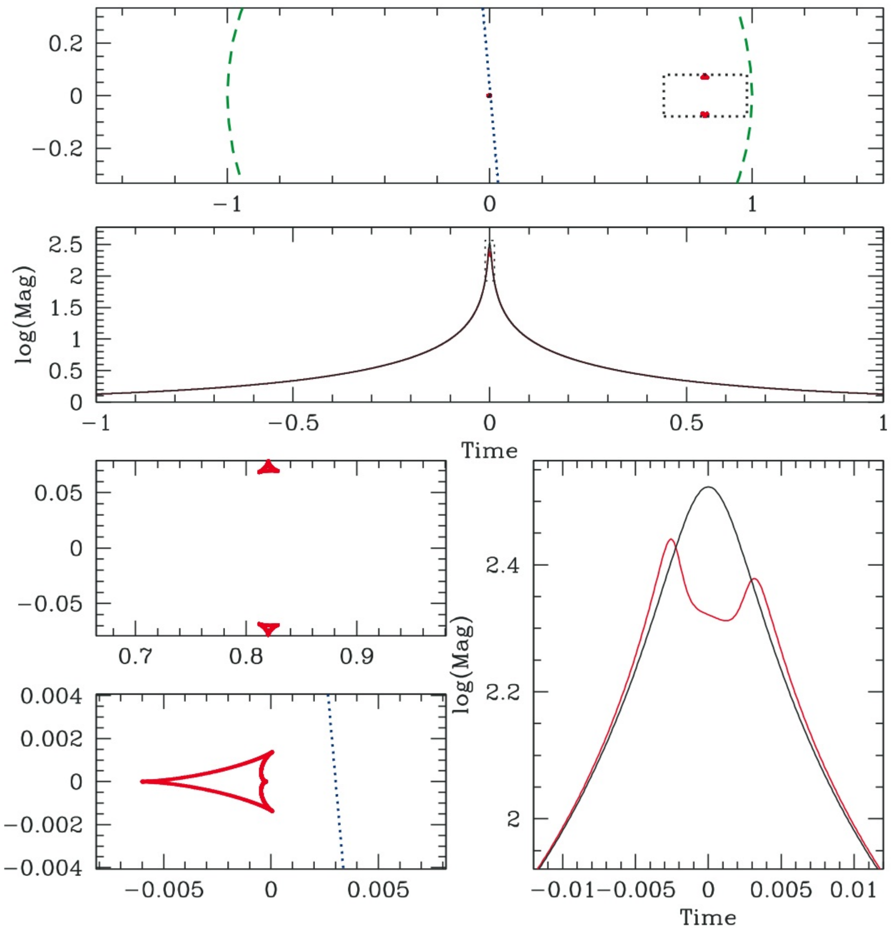


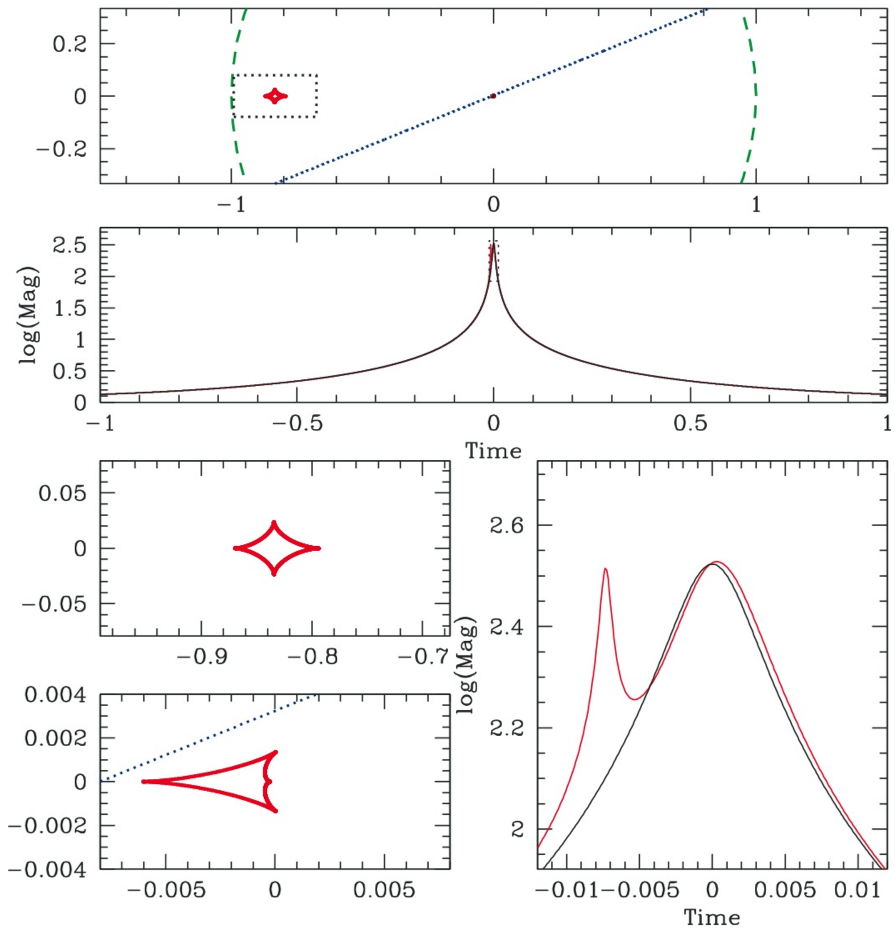
- Central caustic is always located at the position of the primary.
- Localized and predictable.
- Size of caustic is proportional to q.
- Central caustics nearly identical for $s \leftrightarrow s^{-1}$
- Caustic is asymmetric, by an amount that depends on d.
- The caustic becomes more symmetric as $s \to 0$ or $s \to \infty$.

$s \leftrightarrow s^{-1}$ close/wide degeneracy

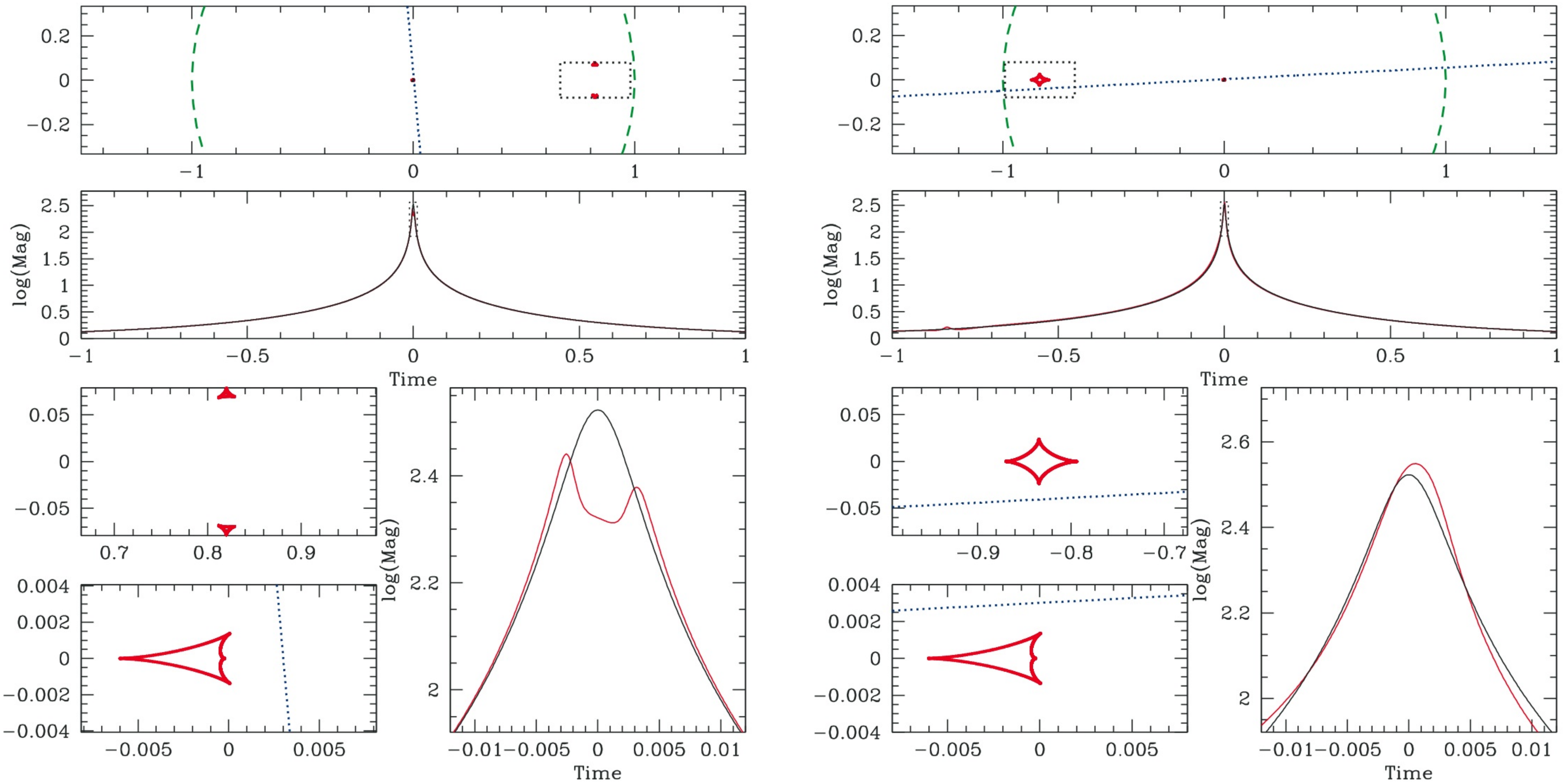


Double Horned or Bump

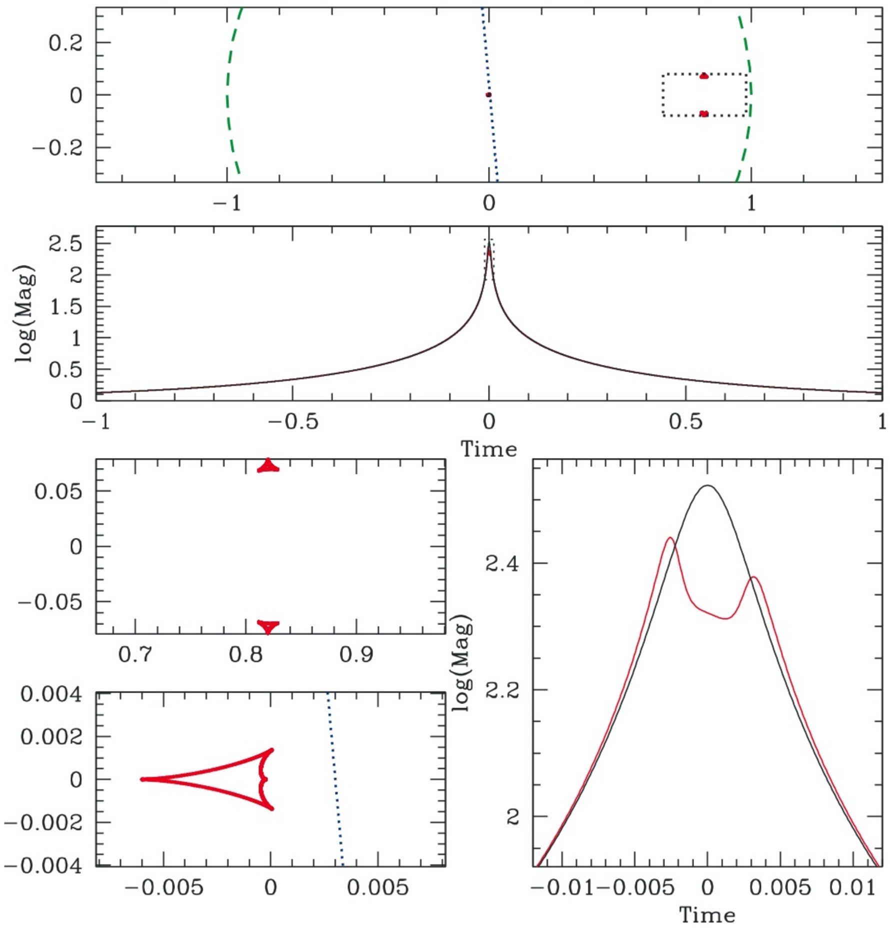


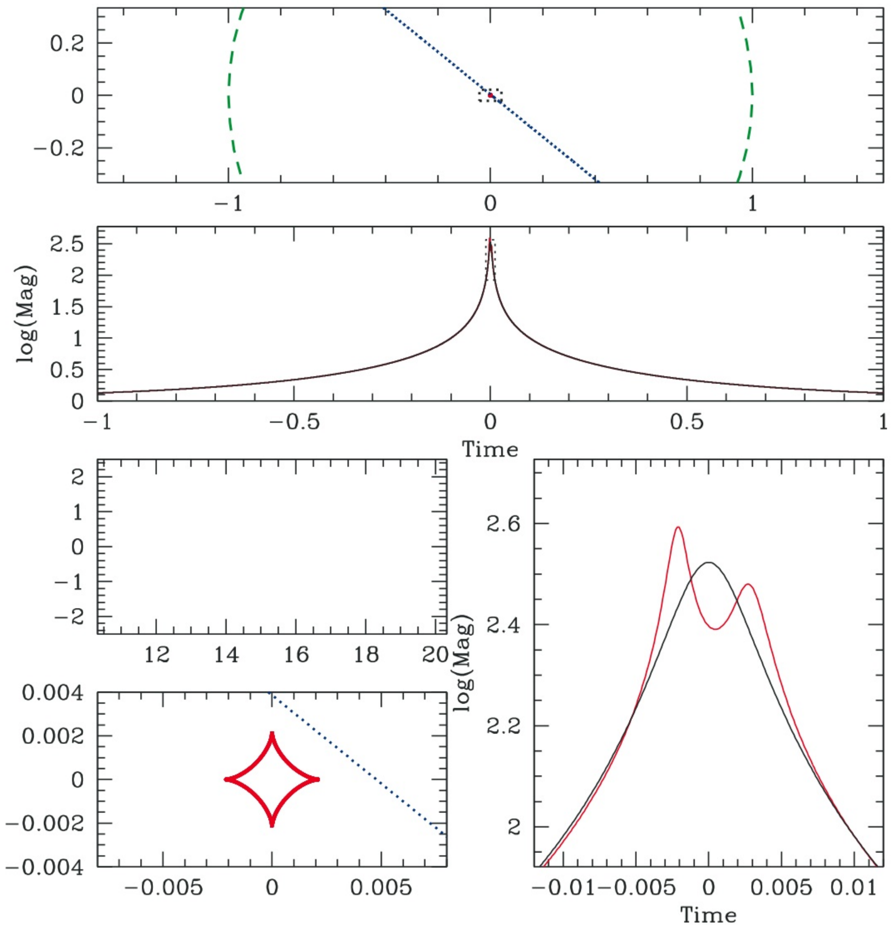


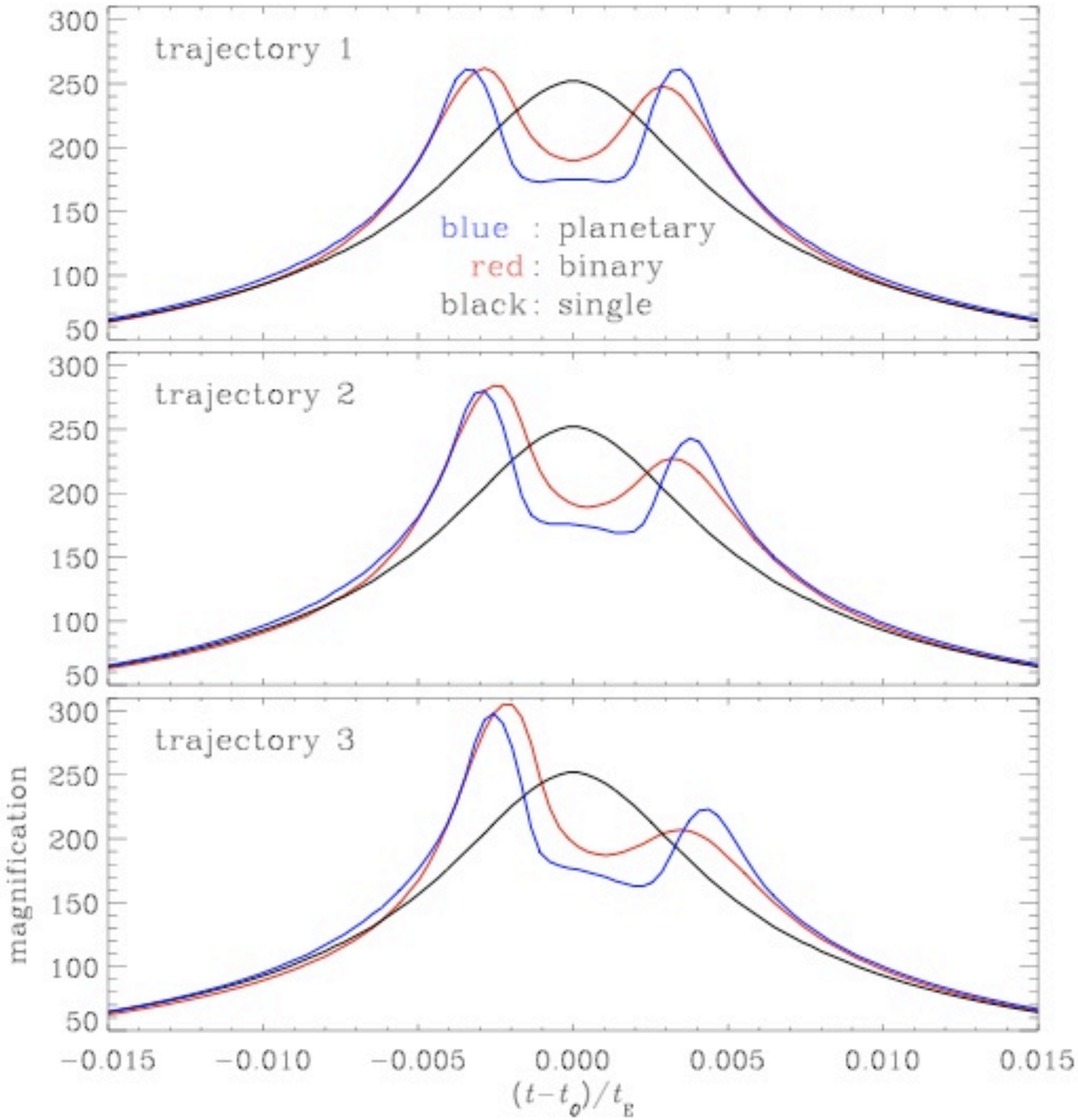
Perturbations Small Along Axis



Extreme Binaries versus Planets





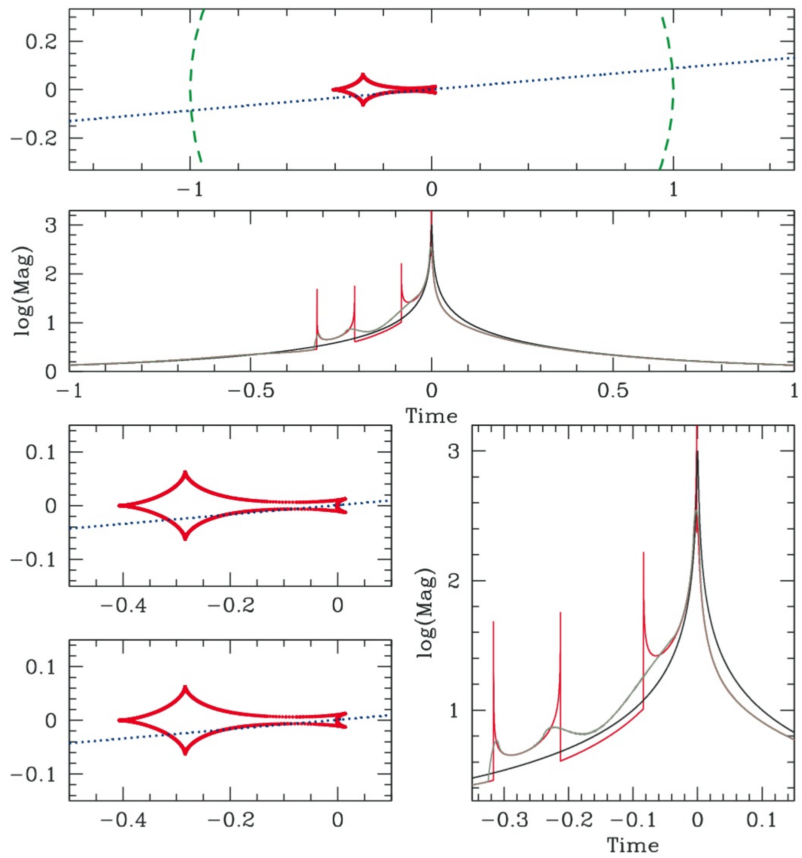


Han & Gaudi 2008

Rule #10

- Planetary and wide/close binary perturbations at the peak can be distinguished from the precise morphology of the deviation.

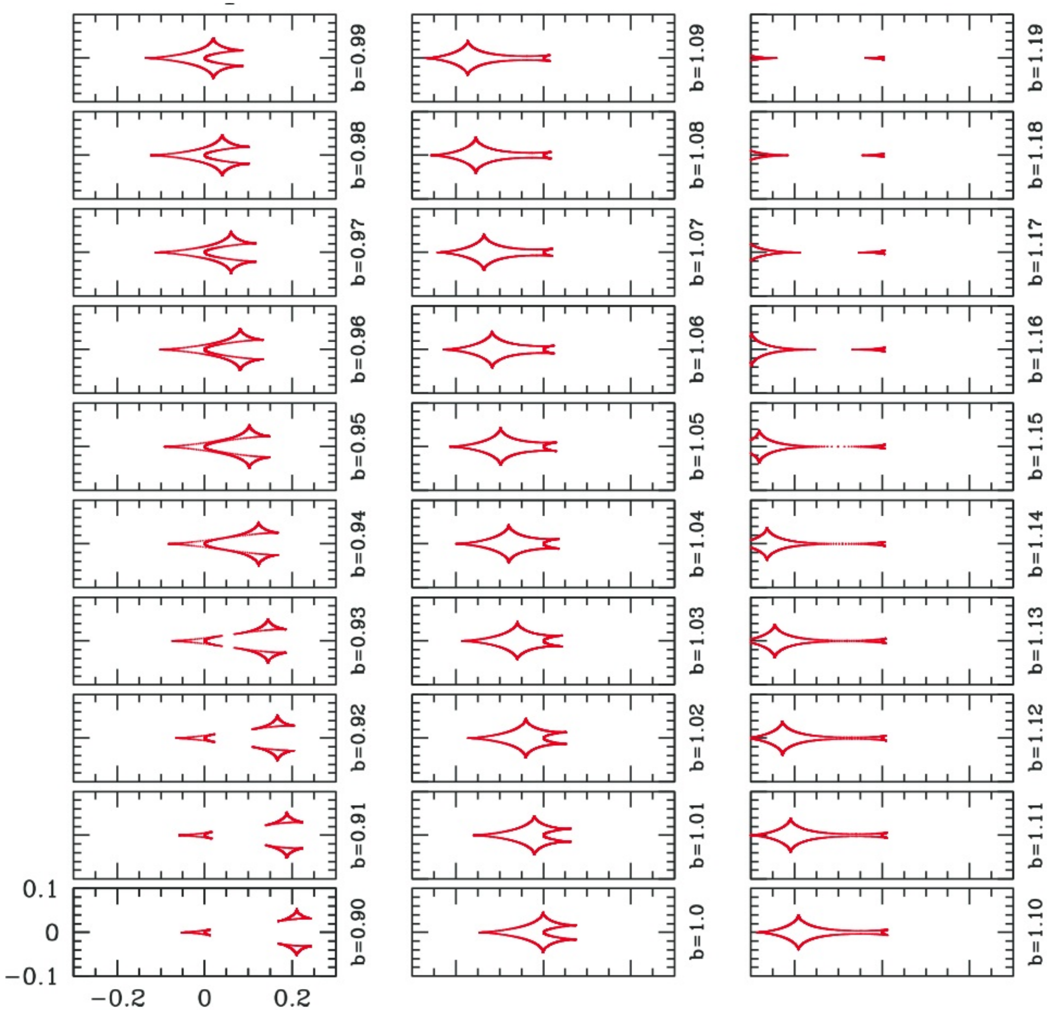
Resonant Caustics



- Big! Scale as $q^{1/3}$
- At fixed q, larger than planetary or central caustics
- Shape very sensitive to $s \rightarrow$ enhanced sensitivity to orbital motion
- Weak!
  - Caustic crossings
  - Intracaustic magnification
- Caustics stronger near primary lens.
- Troughs of demagnification near primary lens.
- Troughs are a sure sign of planetary compainions!

Resonant Caustics

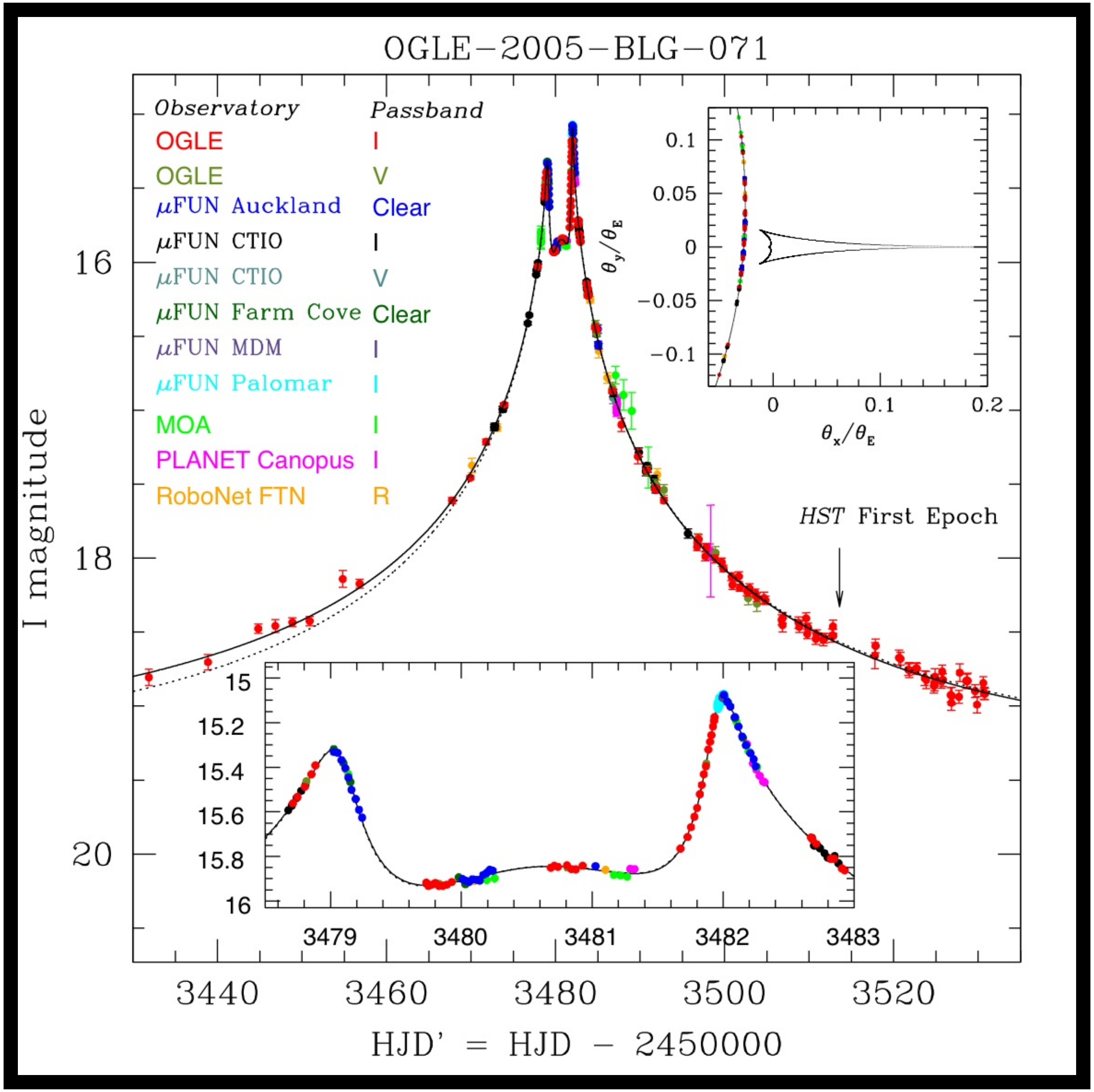
$$q = 0.001,\ s = 0.90 - 1.19,\ \Delta s = 0.29$$



Rule #11

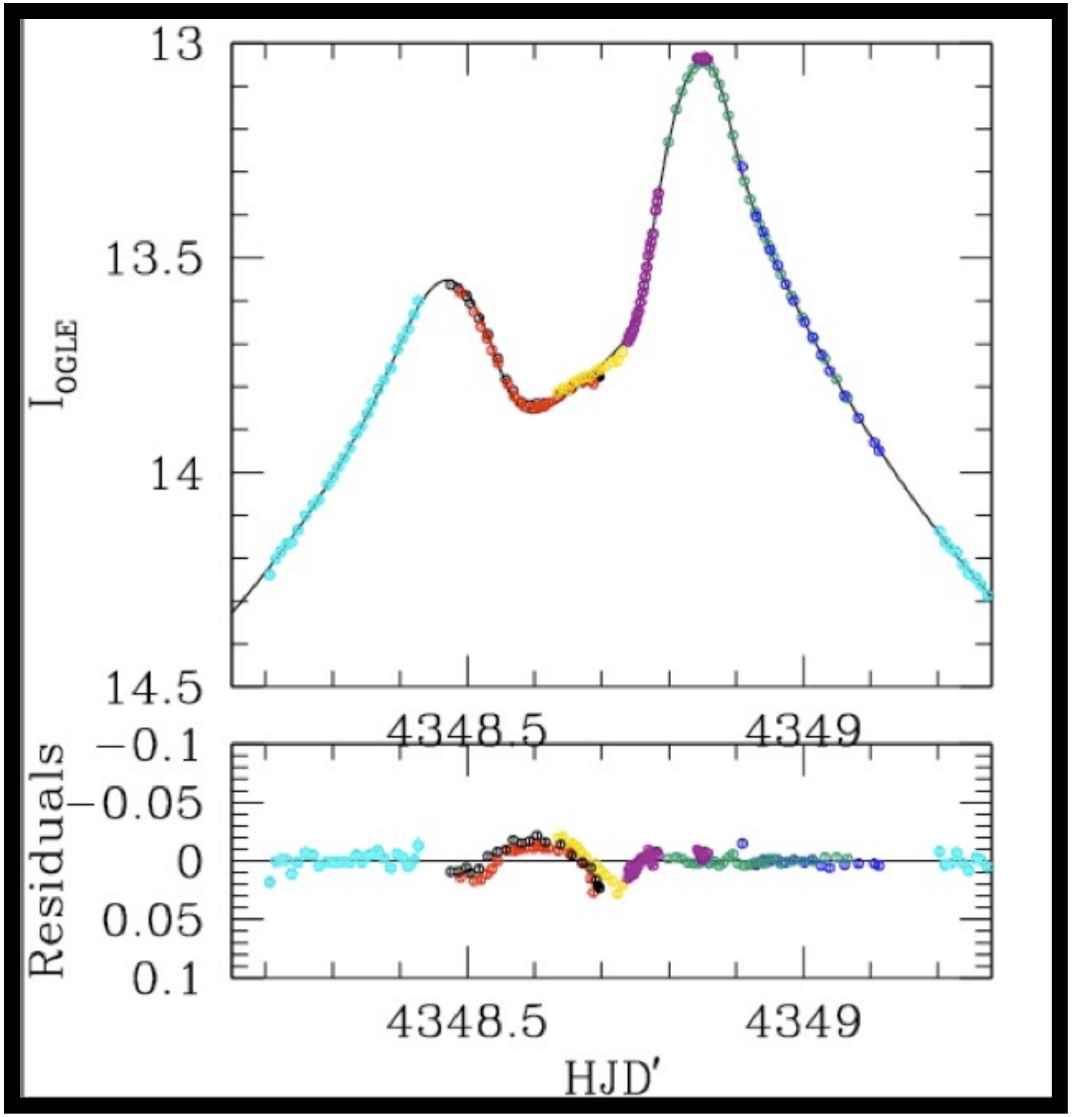
- Perturbations from resonant caustics are weak, long-lasting, and can show characteristic demagnification troughs.

Examples



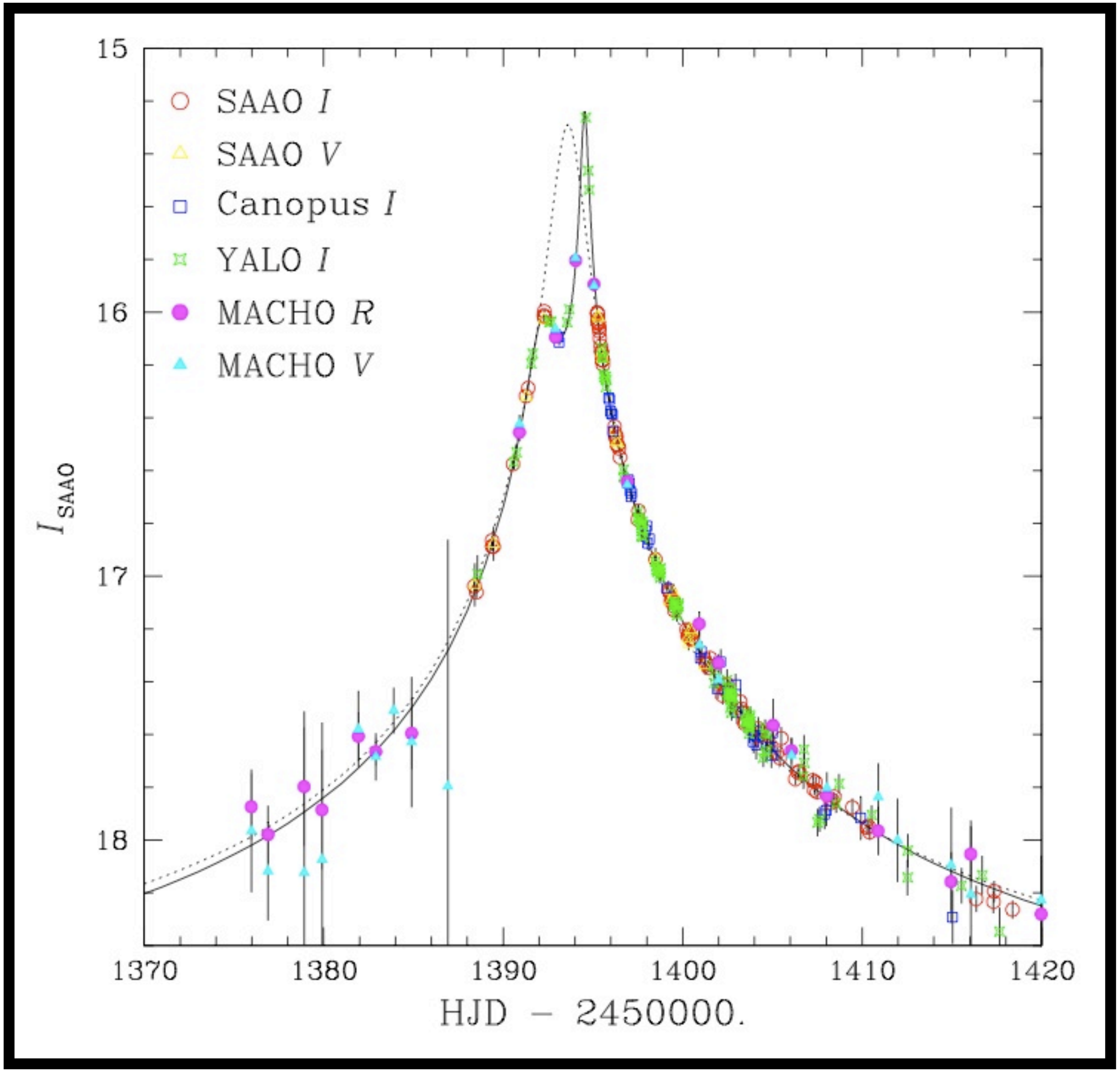
Udalski et al. 2005, Dong et al. 2009

OGLE-2005-BLB-071



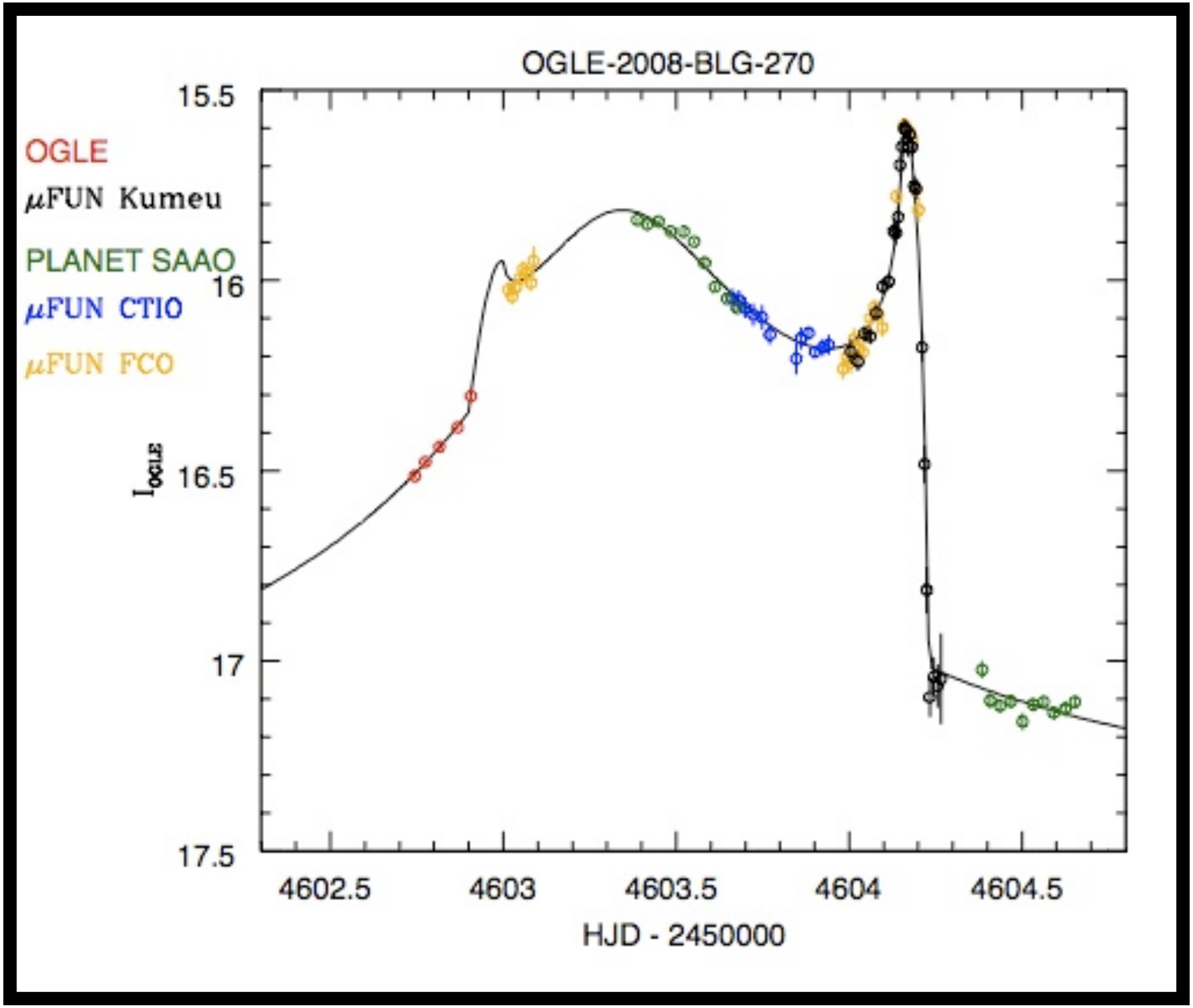
Bennett et al. 2016

OGLE-2007-BLG-349



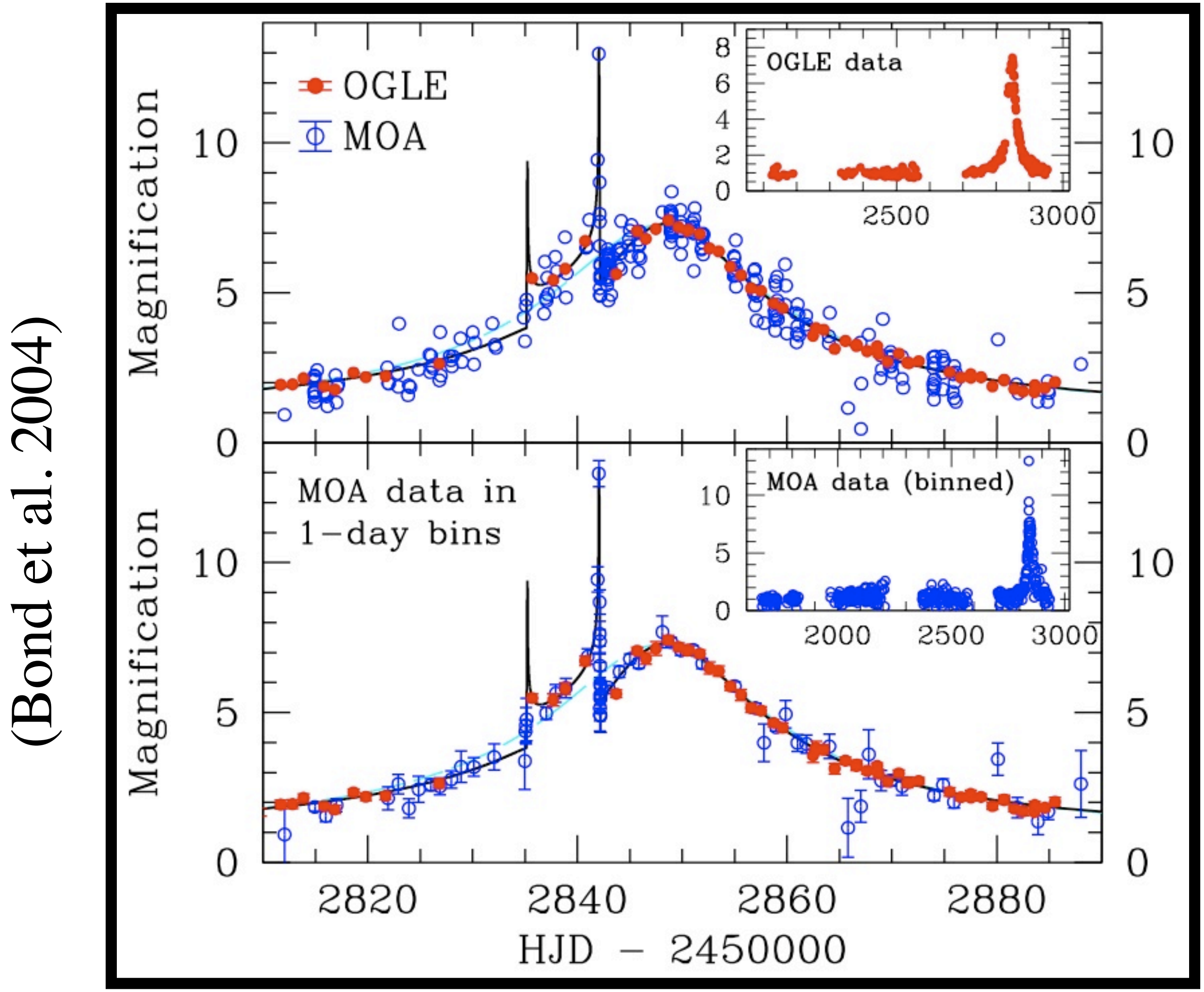
Albrow et al. 2002

MACHO 99-BLG-47



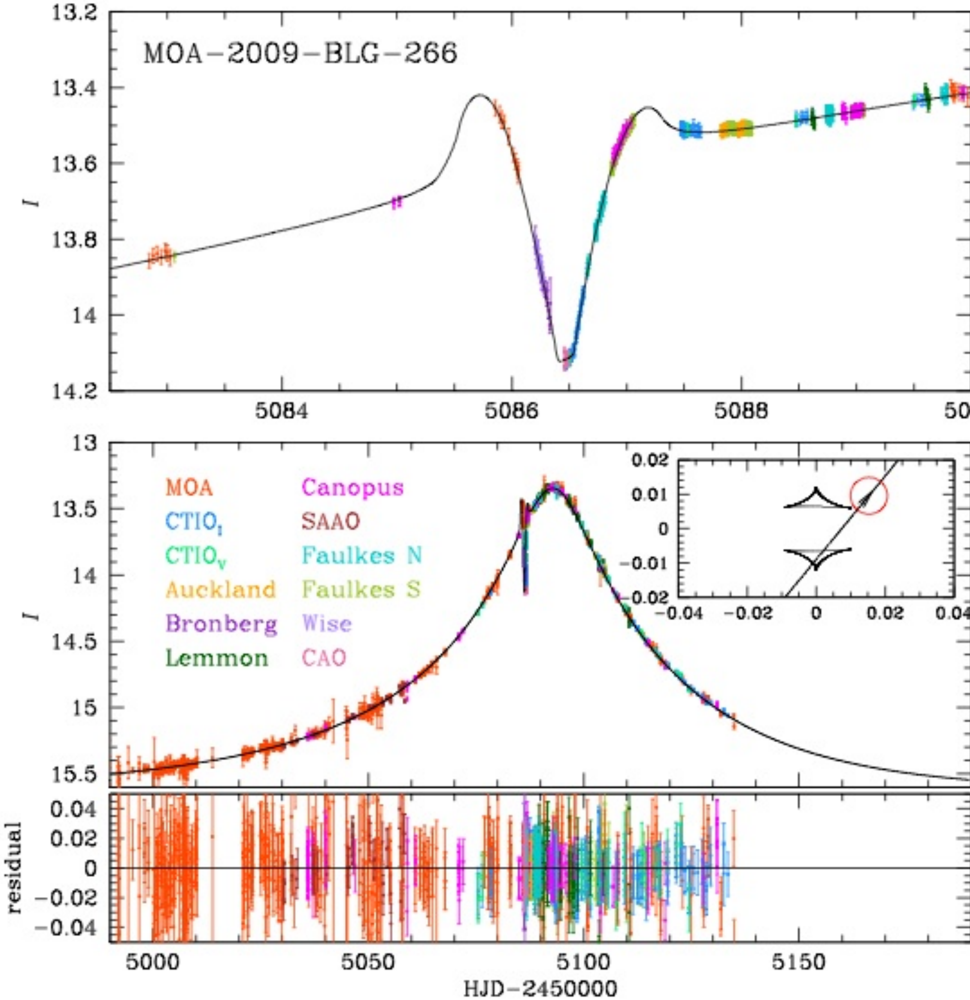
Unpublished

OGLE-2008-BLG-270

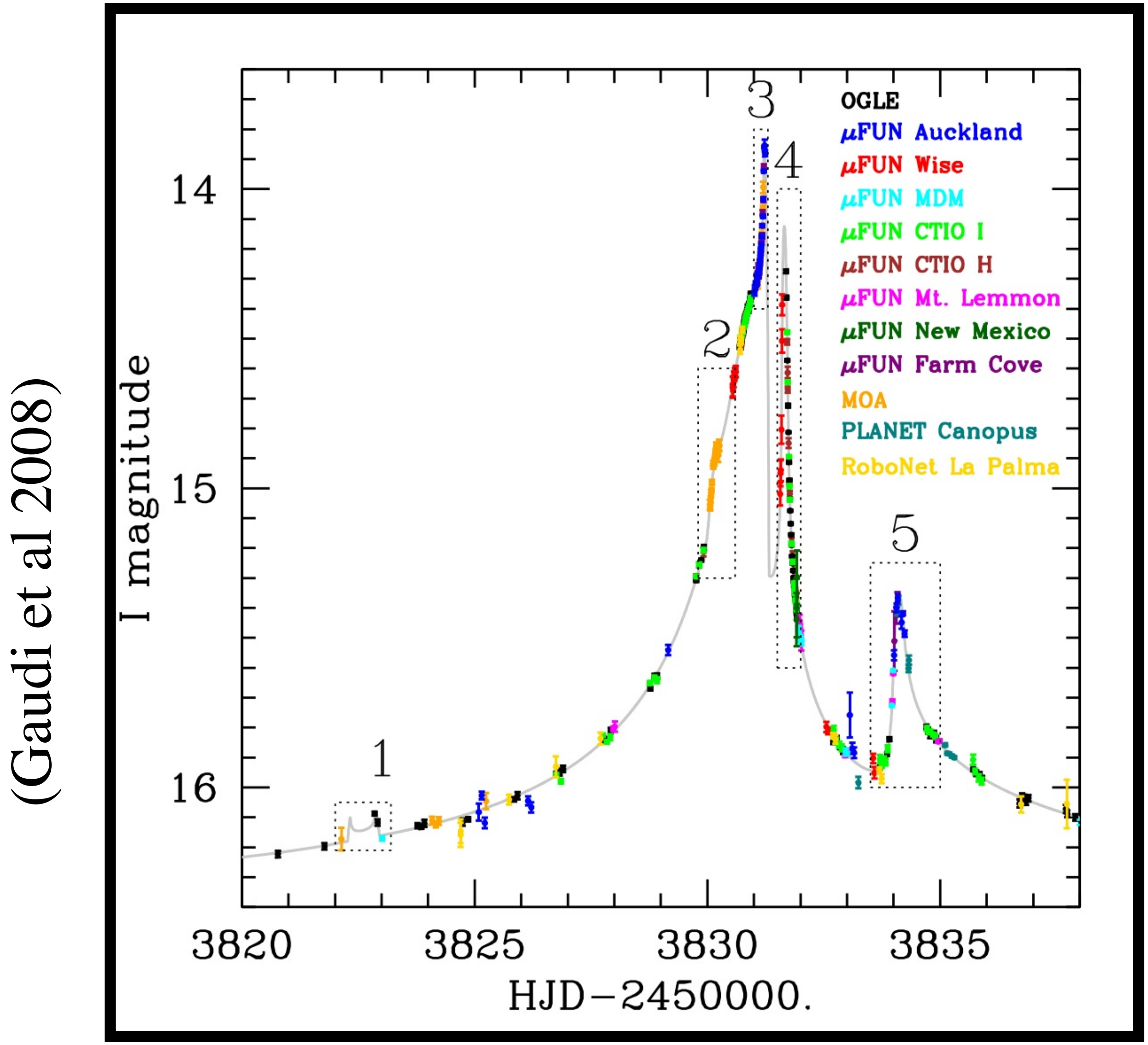


OGLE-2003-BLG-235/ MOA 2003-BLG-53

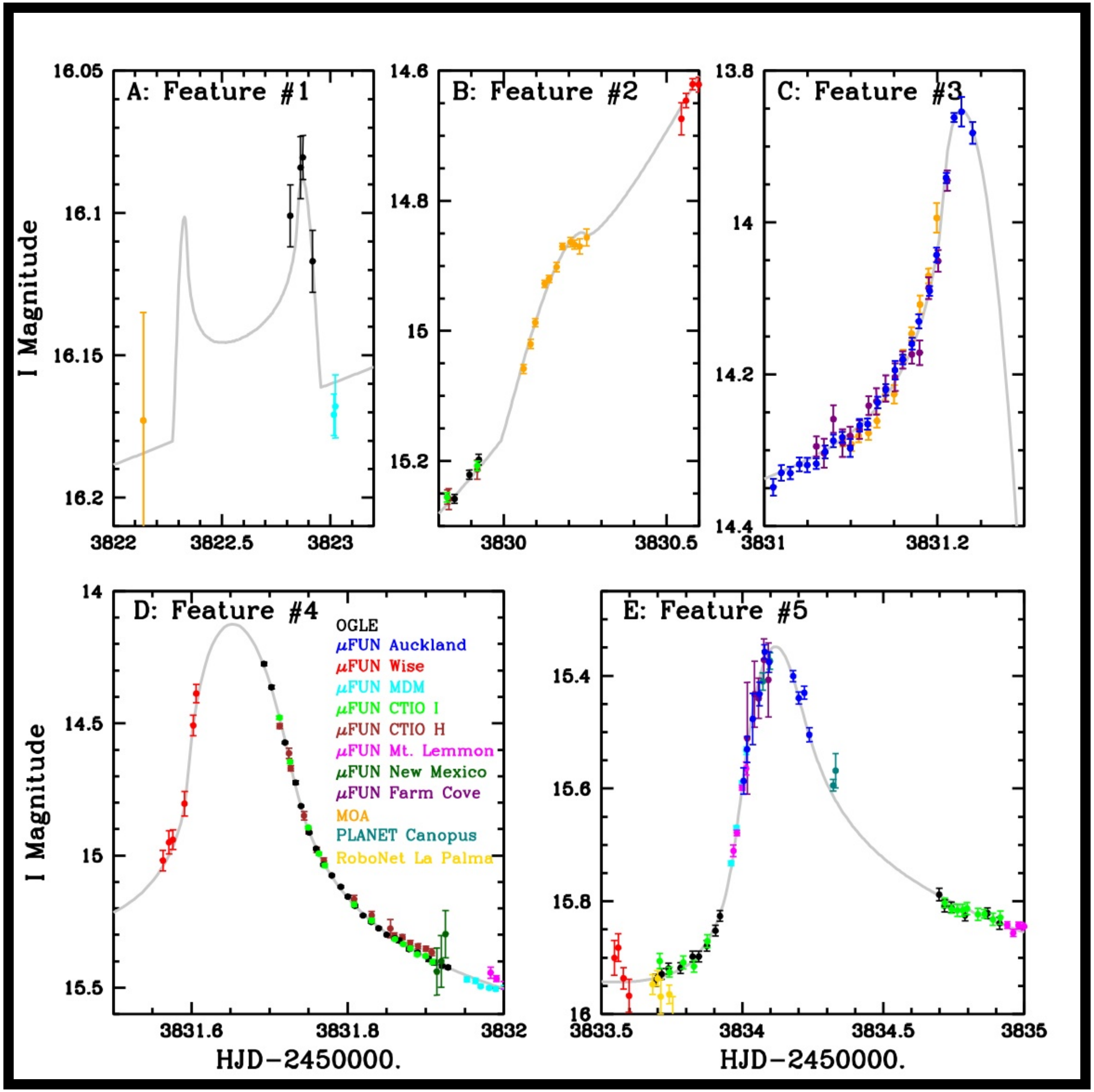
(Muraki et al. 2011)



MOA-2009-BLG-266



OGLE-2006-BLG-109



A: Feature #1
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D: Feature #4
E: Feature #5
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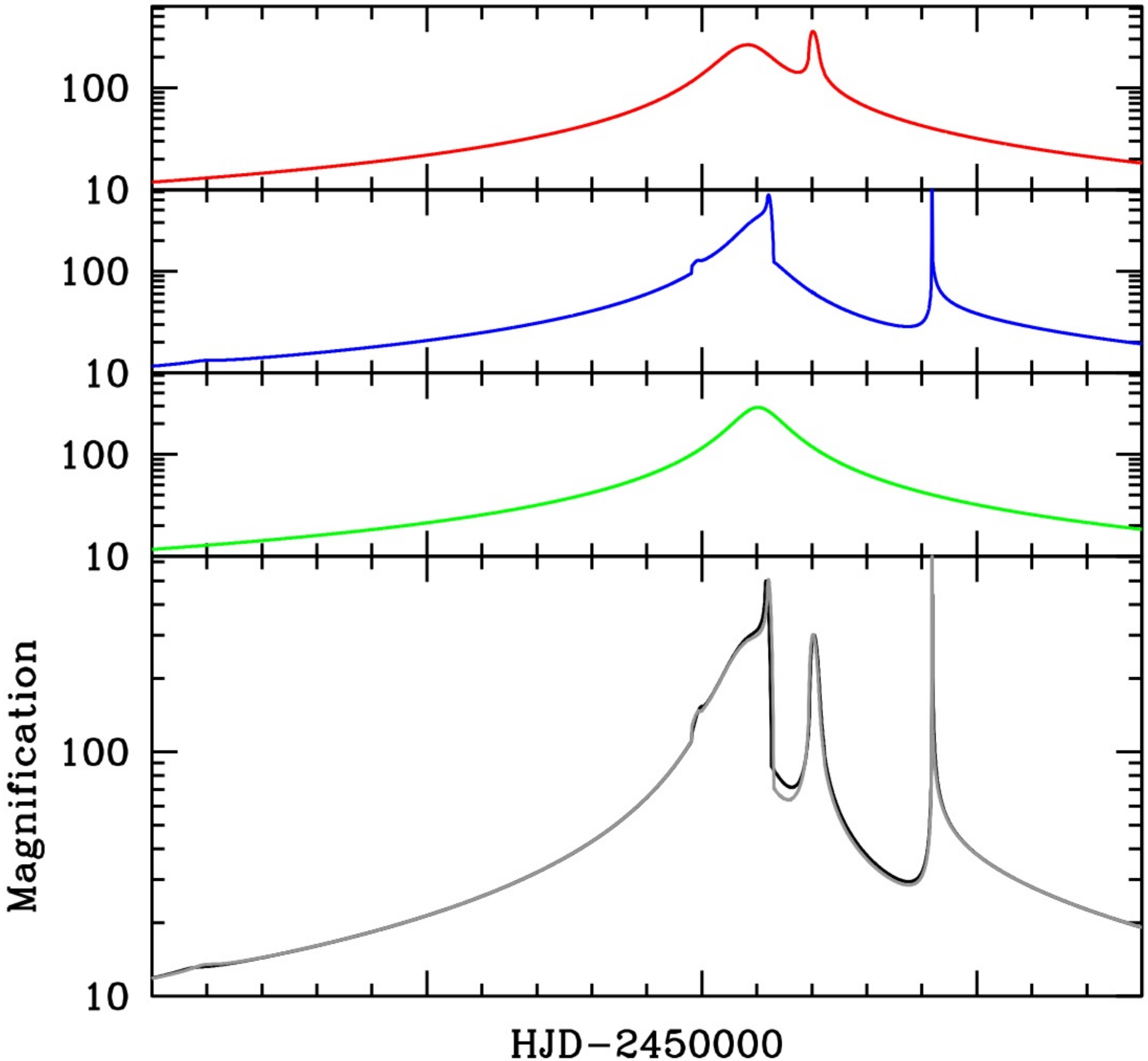
μFUN Mt. Lemmon
μFUN New Mexico
μFUN Farm Cove
MOA
PLANET Canopus
RoboNet La Palma



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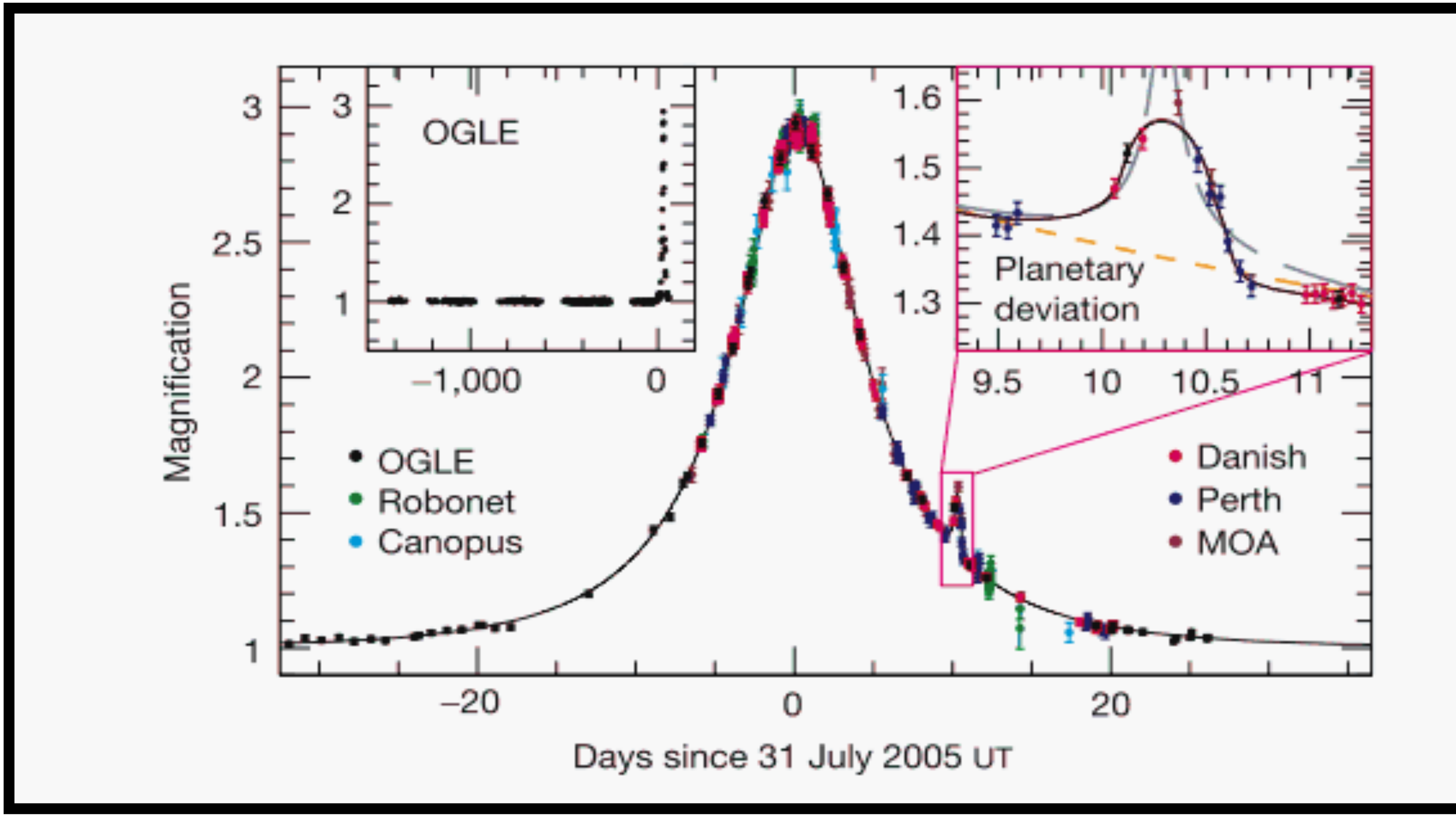

(Beaulieu et al 2006)

OGLE-2005-BLG-390