Planet/Binary Degeneracy I

- High-magnification events with double-peak structure
- Not only planets but also very wide or very close binaries can also produce such a perturbations.
- Can we distinguish them without detailed modelling?

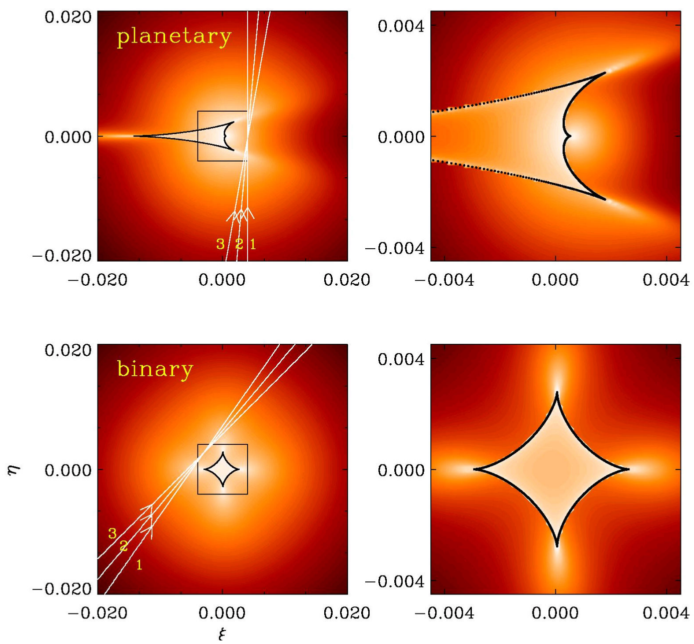

Fig 1. Magnification pattern maps in the central perturbation region of a planetary (upper panels) and binary lensing events, respectively. Right panels are blow-ups of the left panels.

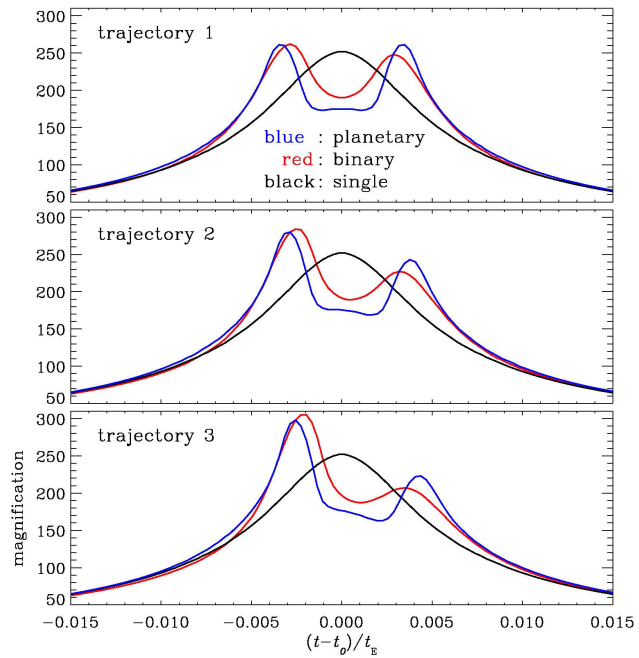

Fig 2. Light curves resulting from the source trajectories in the maps of Fig. 1.

☐ An example of a high-magnification events with double-peak structure

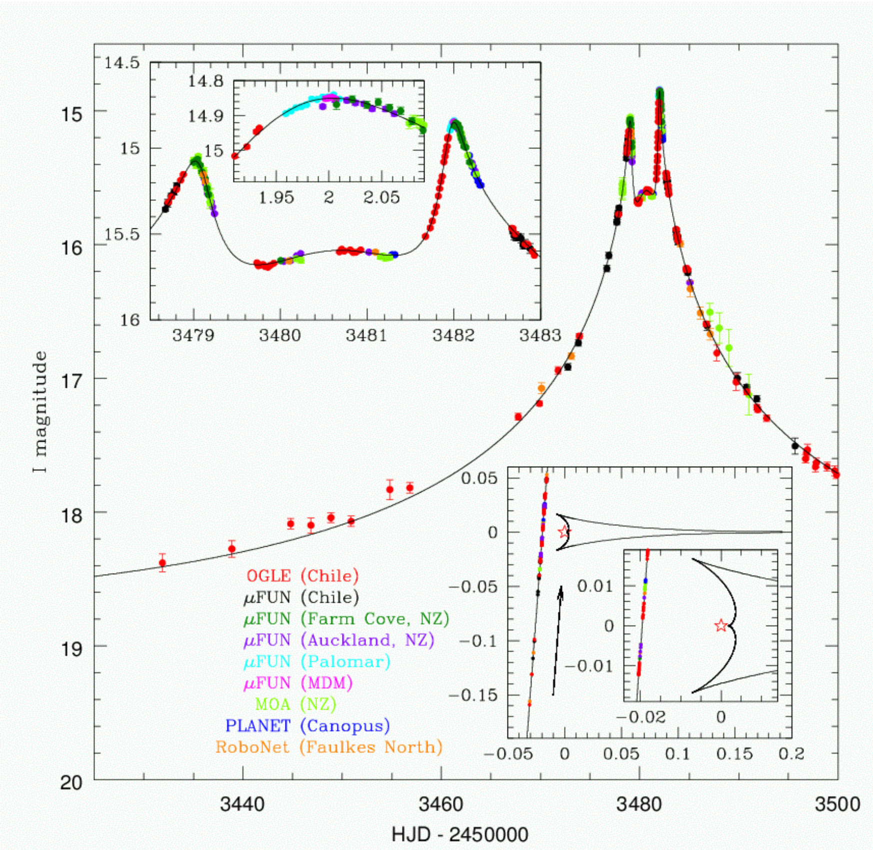

Fig 3. Light curve of the microlensing event OGLE-2005-BLG-071. It shows a double-peak structure near the peak.

- MACHO 99-BLG-47
- OGLE-2005-BLG-071
- OGLE-2007-BLG-349/MOA-2007-BLG-379
- OGLE-2007-BLG-514
- OGLE-2007-BLG-137/MOA-2007-BLG-091

☐ Difference in the morphology

- A simple diagnostic that can be used to immediately distinguish between the perturbations caused by the planetary and binary companions.
- The diagnostic is based on the difference in the shape of the intra-peak region of the light curve.
  - ▷ Binary lensing: The shape is smooth and concave.
  - ▷ Planetary lensing: either boxy or convex
- The convex structure for planetary lensing is due to the small, weak cusp between the two strong cusps.
- Good coverage of the intra-peak region is very important.
- See the light curve of OGLE-2005-BLG-071 again.

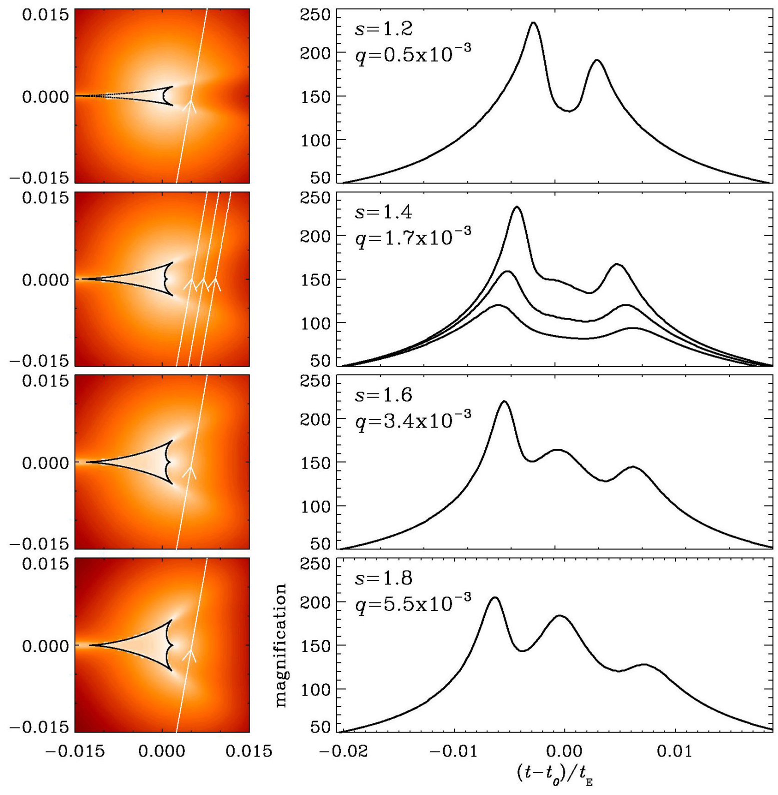

Fig 4. Variation of the planetary light curves with double peaks.

Planetary Feature under Severe Finite-Source Effect

☐ High-magnification events with severe finite-source effect

☐ **Effect of finite-source effect on perturbation pattern**

- As the angular extent of the source size becomes bigger, the effect becomes more important. As the effect increases, the planetary signal is attenuated.
- It is believed that the signal is completely washed out when the source size is substantially greater than the caustic size. → Is this true?
- We find that perturbations with fractional magnification excess ≳ 5% *survive* when the source star is roughly 4 times bigger than the caustic.

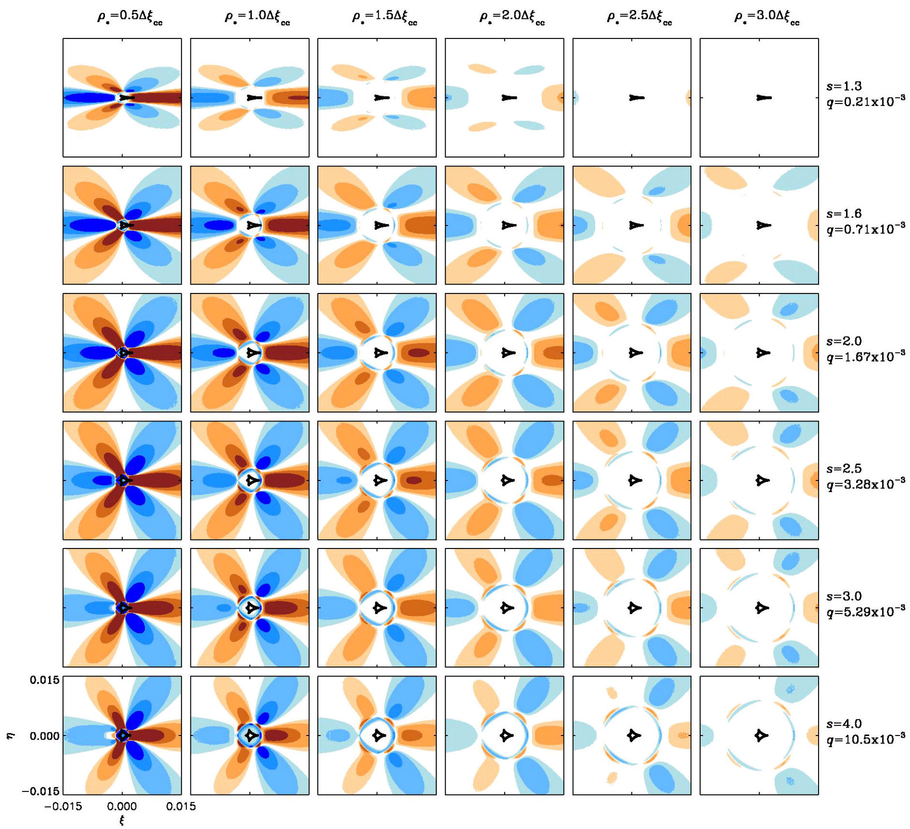

Fig 5. Variation of perturbation pattern depending on finite-source effect.

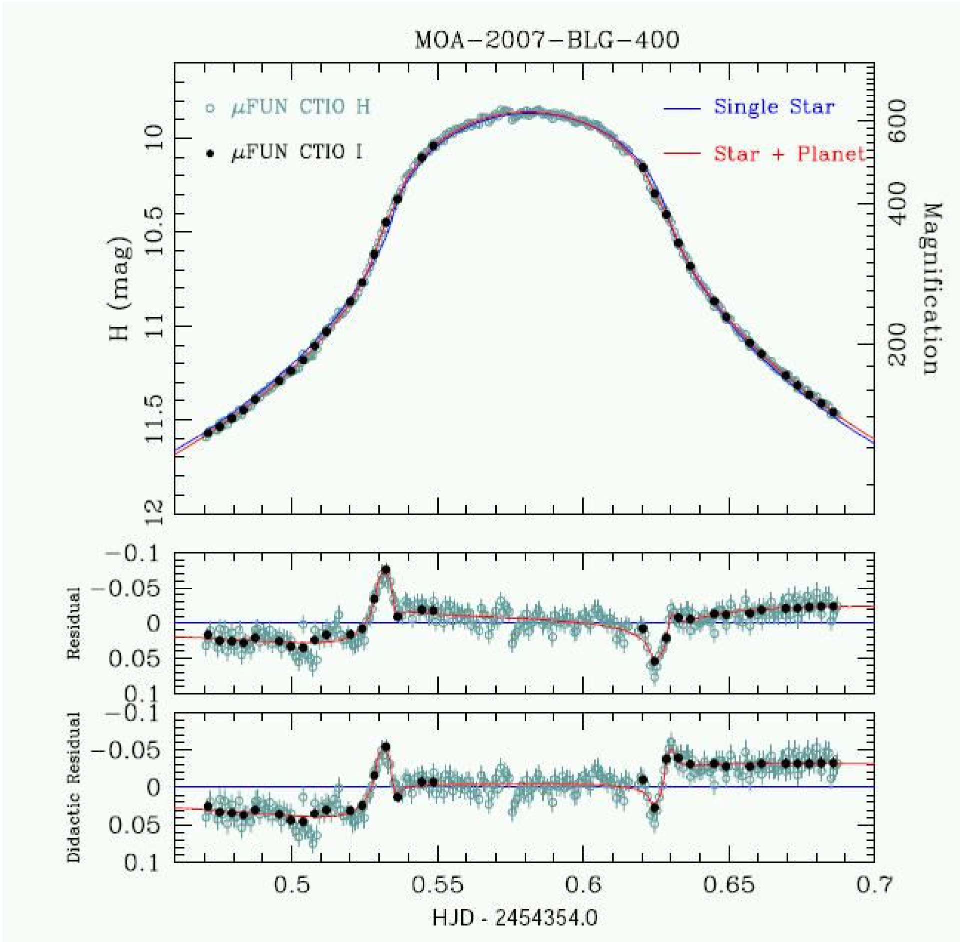

Fig 6. Light curve of the microlensing event MOA-2007-BLG-400

- **Characteristic Features:** characteristic features that commonly appear in the perturbation patterns of planetary lens systems affected by severe finite-source effect

- Localized, arc-shaped perturbation regions around the circle with radius corresponding to the radius of the source star.

- These features form in and around a circle with its center located at the caustic center and a radius corresponding to that of the source star.

- The light curve of an event where the source crosses these features will exhibit a distinctive signal that is characterized by <u>short-duration perturbations of either positive or negative excess and a flat residual region between these short-duration perturbations.</u>

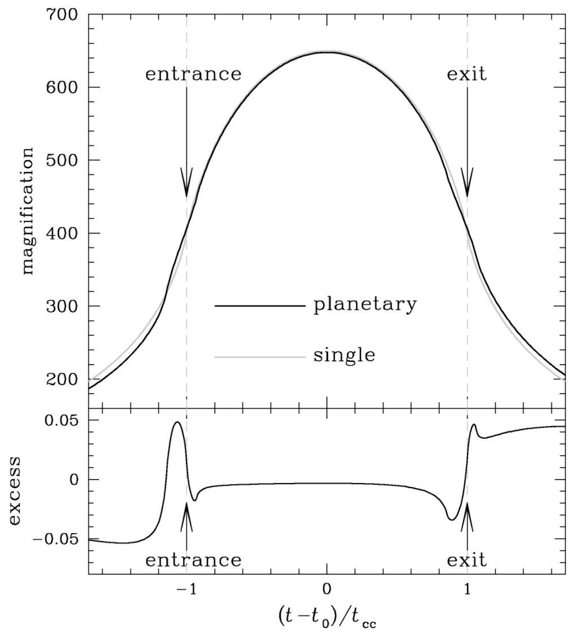

Fig 8. Light curve and residual of an example planetary lensing event under severe finite-source effect.

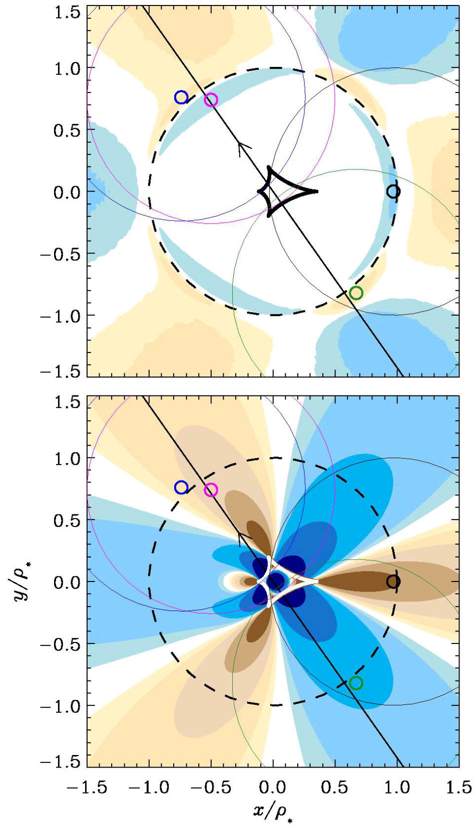

Fig 7. Morphology of central perturbation of a planetary lens system.

Planet/Binary Degeneracy II

- Signals of events under severe finite-finite can also be produced by a binary companion. How can we distinguish the planetary and binary interpretations?

- **Comparison of the perturbation patterns**

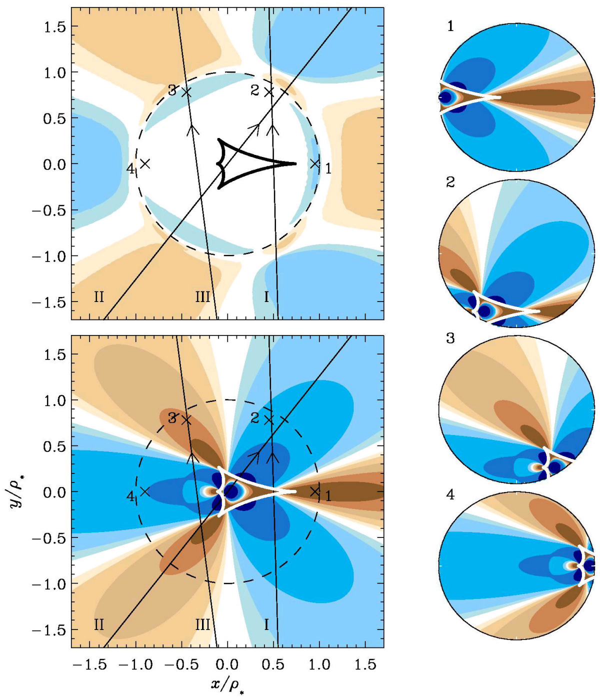

Fig 9. Morphology of central perturbation induced by a planet.

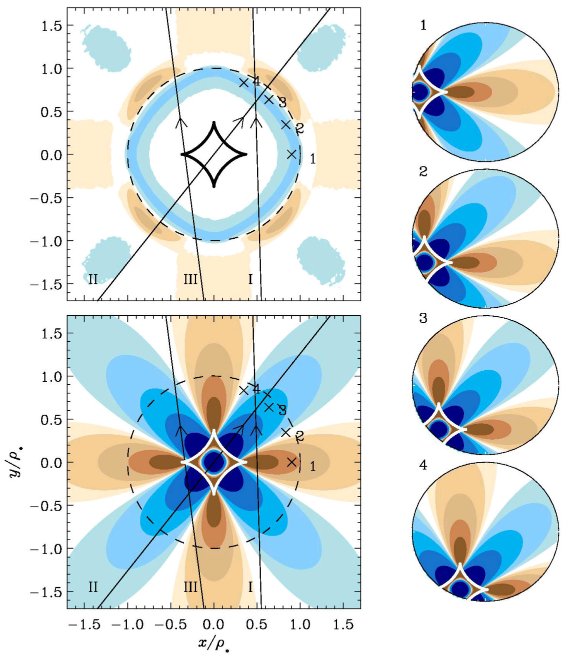

Fig 10. Morphology of central perturbation induced by a wide-separation binary companion.

- The most prominent difference shows up in the **morphology** of the edge feature with *negative* excess.
  - Binary lensing: The edge feature forms a complete circle.
  - Planetary lensing: The edge feature appears as several arc segments.

- The difference is basically caused by the difference in caustic shape.
  - Binary lensing: symmetric
  - Planetary lensing: asymmetric and elongated

- **Diagnostic**

The *absence of a well-developed dip in the residual* from the single-lensing light curve at both or either of the moments of the caustic center's entrance into and exit from the source star surface indicates that the perturbation is produced by a planetary companion.

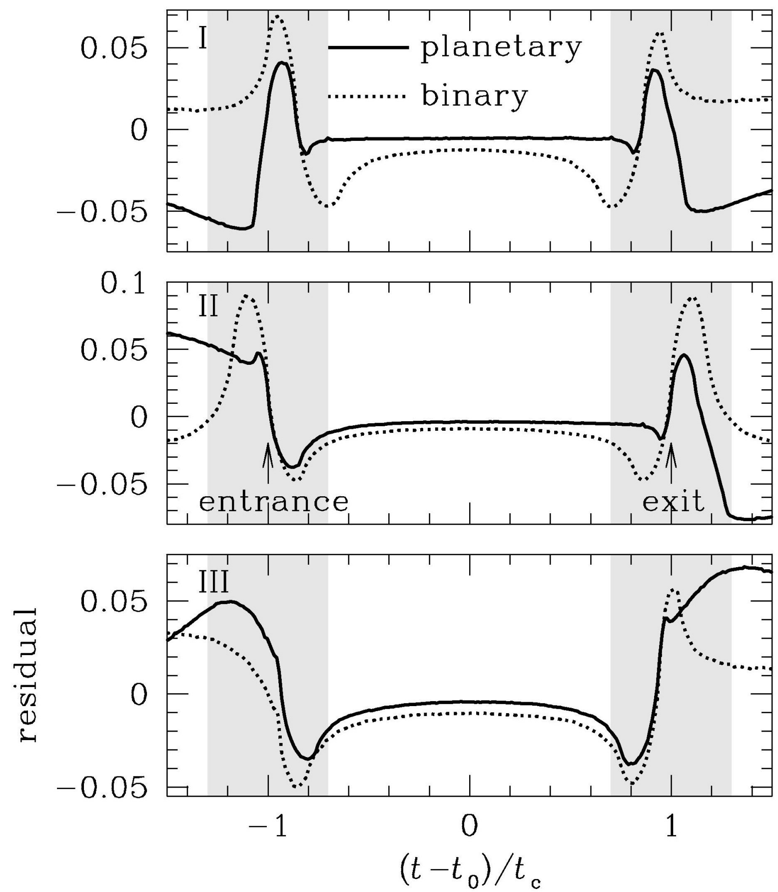

Fig 11. Residuals from single lensing for evenets produced by a planetary and a wide-separation binary systems.

Planet/Binary Degeneracy III

- A diagnostic applicable to caustic-crossing events

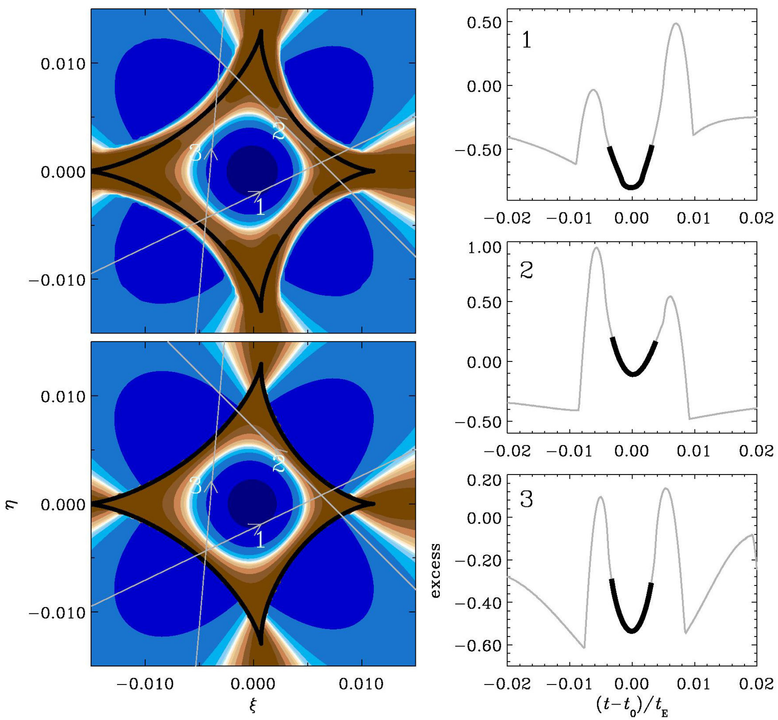

Fig 13. Morphology of central perturbation induced by a planet.

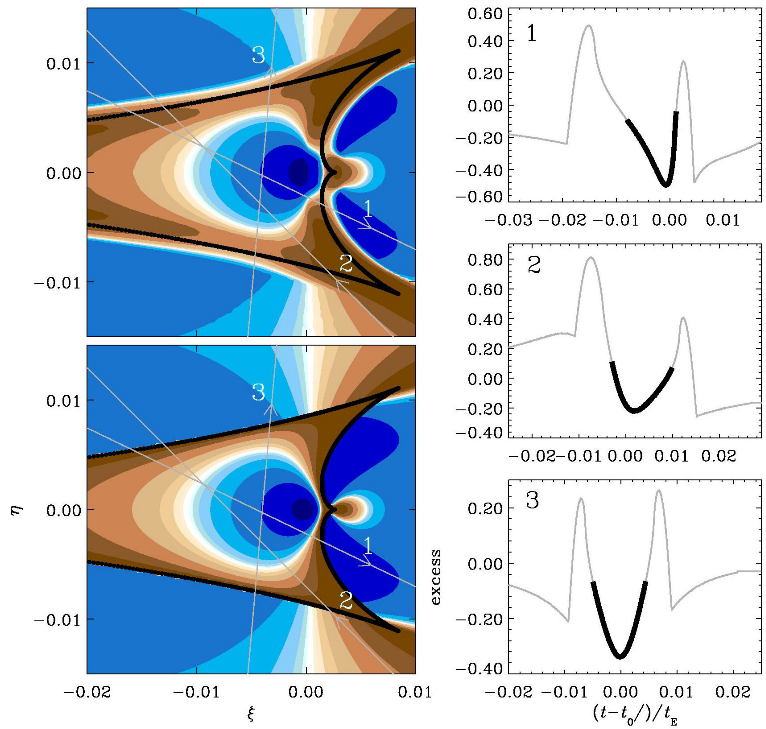

Fig 12. Morphology of central perturbation induced by a wide-separation binary.

- **Morphology** of perturbation inside caustics
  - Binary lensing: concentric circular pattern around the caustic center
  - Planetary lensing: elongated and off-centered

- **Diagnostic**
  - Distinctive features of the individual lens populations in the residual of the trough region between the two peaks of the caustic crossings.
  - Binary lensing: symmetric residual
  - Planetary lensing: asymmetric in general

- **Applicability**
  - The proposed diagnostic is useful for massive planets, which would be most common.

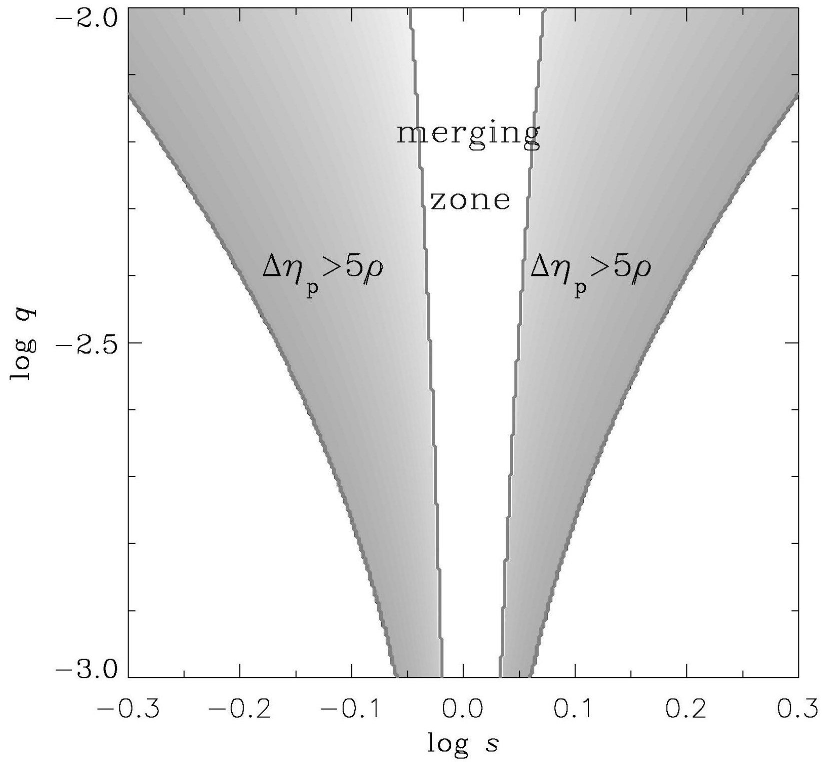

Fig 14. Ranges in the parameter space where the proposed diagnostics can be applicable.

Close/Wide Degeneracy ($s \leftrightarrow s^{-1}$ degeneracy)

- ☐ Perturbations induced by a planet with a projected separation in units of the Einstein radius, *s*, is very similar to the perturbation induced by a planet with a separation 1/*s*.
- ☐ In what cases can this degeneracy resolved?

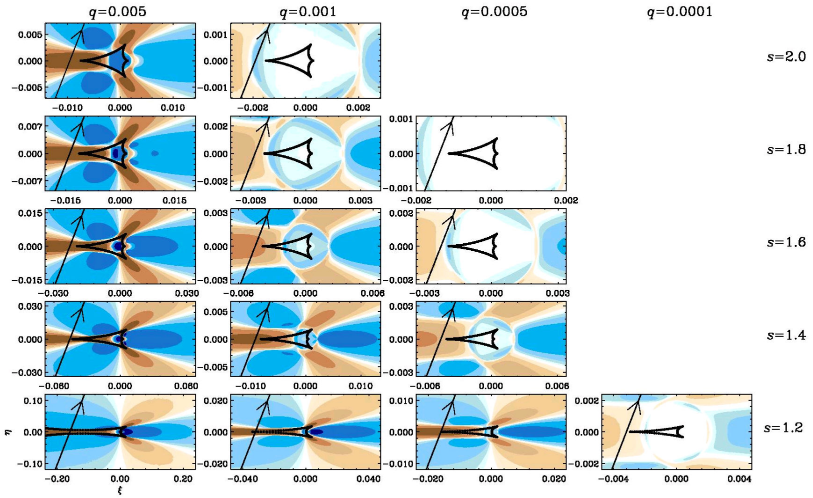

Fig 16. Color-scale maps of magnification excess for planets with separation from the star greater than the Einstein radius (s>1). Brown is positive excess and blue is negative excess. Color-scale becomes darker at the excess levels of 1%, 2%, 4%, 8%, 16%, and 32%.

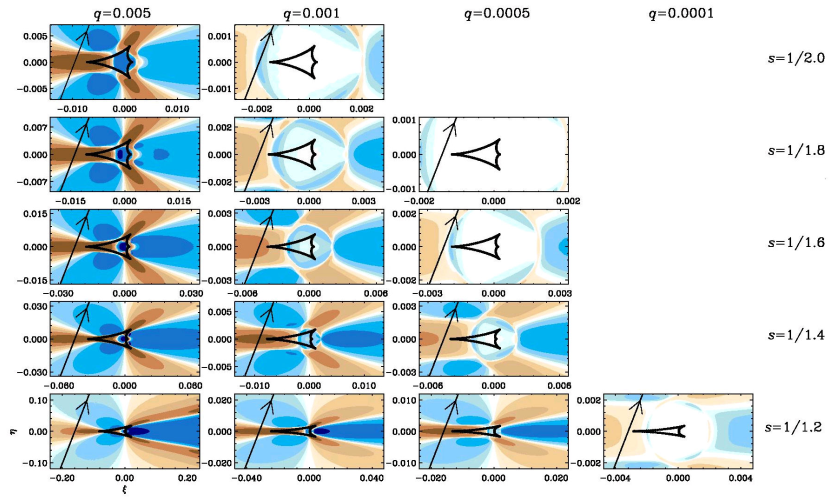

Fig 15. Color-scale maps of magnification excess for planets with separation from the star less than the Einstein radius (s<1).

□ Tendencies

- Although similar, the patterns of perturbations induced by a close and wide a planets are not identical.
- The magnification difference becomes larger as the planet/primary mass ratio increases and primary-planet separation approaches the Einstein radius.
- For a given pair of a close and a wide planets, the region of major difference is confined in the region around the line connecting the central and the planetary caustics.

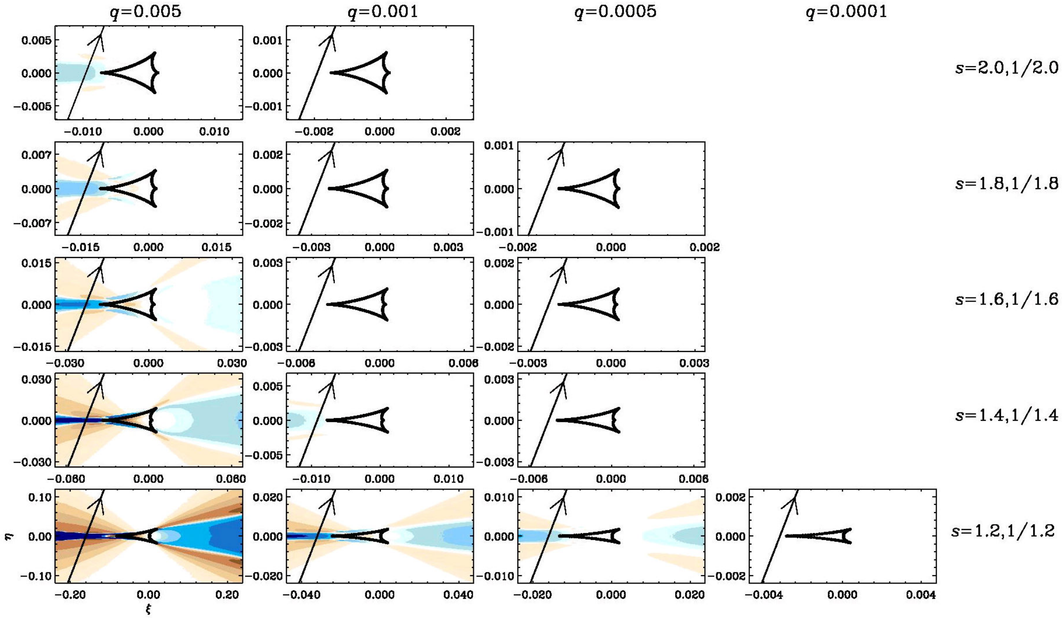

Fig 17. Color-scale maps of the difference in the magnification excess between close and wide planetary systems.

□ Cause of the difference

- The difference between the perturbation patterns of close and wide planets are due to the effect of the planetary caustic.
- Central perturbation is not isolated and instead it is connected to the region of perturbation induced by the planetary caustic.
- As the planet/primary mass ratio increases and the planet-primary separation approaches the Einstein radius, the planetary caustic becomes bigger abd its effect on the central perturbation region increases. → This matches the tendency of the difference between the central perturbations induced by the close and a wide planets.

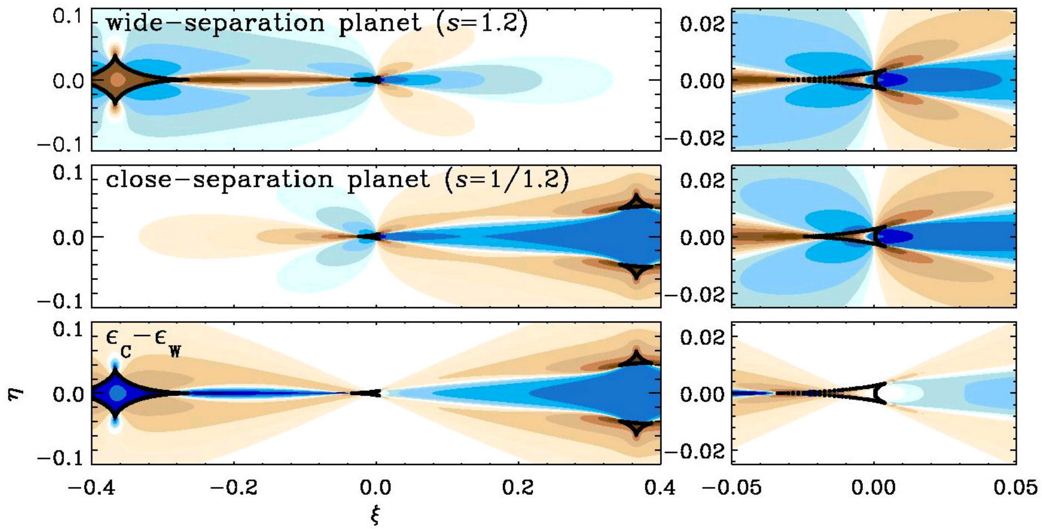

Fig 18. Maps of magnification excess (upper two panels) and excess difference (bottom panel) for an example pair of a close and a wide planet.