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

- MACHO 99-BLG-47
- OGLE-2005-BLG-071
- OGLE-2007-BLG-514

Fig 3. Light curve of the microlensing event OGLE-2005-BLG-071. It shows a double-peak structure near the peak.
**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.
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 $\geq 5\%$ 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 short-duration perturbations of either positive or negative excess and a flat residual region between these short-duration perturbations.

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

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

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**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.
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?

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**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?

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Fig 15. Color-scale maps of magnification excess for planets with separation from the star less than the Einstein radius ($s\lt1$).

Fig 16. Color-scale maps of magnification excess for planets with separation from the star greater than the Einstein radius ($s\gt1$). 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%.
**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 and its effect on the central perturbation region increases. Therefore, this matches the tendency of the difference between the central perturbations induced by the close and a wide planet.

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.