MASS 2023 Course:

Gravitational Lenses

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Lecture 06

1. Microlensing (Paczyński) light curves
2. Gravitational microlensing by point-like and binary lenses:
   - Applications for detection of extrasolar planets in our Galaxy
3. Pixel lensing:
   - Detection of microlensing events in Andromeda galaxy
4. Exercises

Reminder to previous lecture

- **Total magnification** of a point-like lens is:

$$\mu = |\mu_1| + |\mu_2| = \frac{y^2 + 2}{y\sqrt{y^2 + 4}} > 1,$$

where μ_1 and μ_2 are magnifications of both images and y is position of the source, normalized to θ_E

Paczyński light curves

- Relative motion of the lens across the observer-source line-of-sight with some **transverse velocity $v_\perp$** ⇒ μ varies with time ⇒ microlensing **light curve**
- Characteristic **time scale** is given by the **Einstein radius crossing time t_E**:

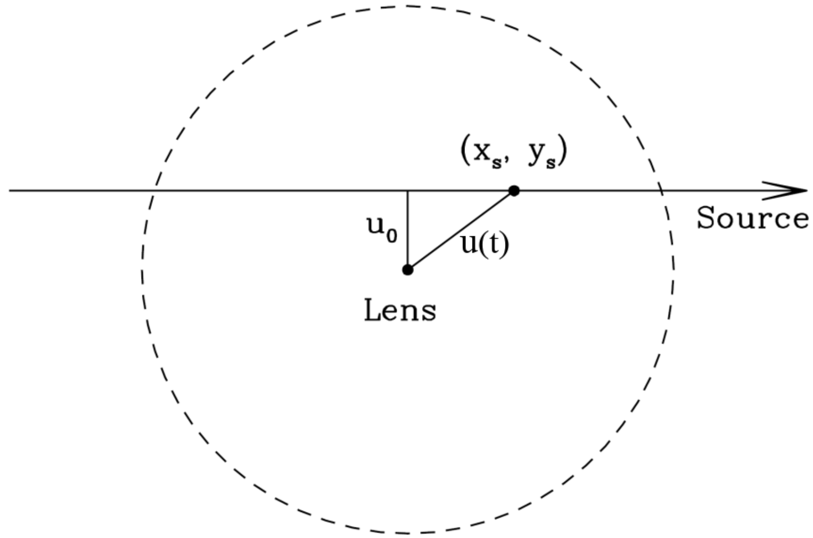
$$t_E = \frac{\xi_E}{v_\perp}, \quad \xi_E = \theta_E D_d$$

- Typical time scales t_E for microlensing events toward the Galactic bulge are on the order of a month
- Magnification as a function of time:

$$\mu(t) = \frac{u^2(t)+2}{u(t)\sqrt{u^2(t)+4}},$$

$$u(t) = \sqrt{u_0^2 + \left(\frac{t-t_0}{t_E}\right)^2}$$

- The observed light curve $F(t) = \mu(t)\, F_s$, where F_s is the unlensed source flux



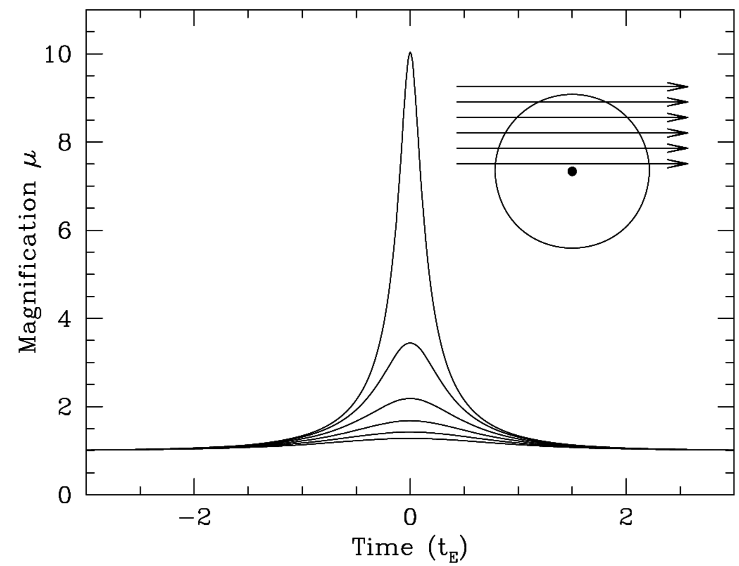
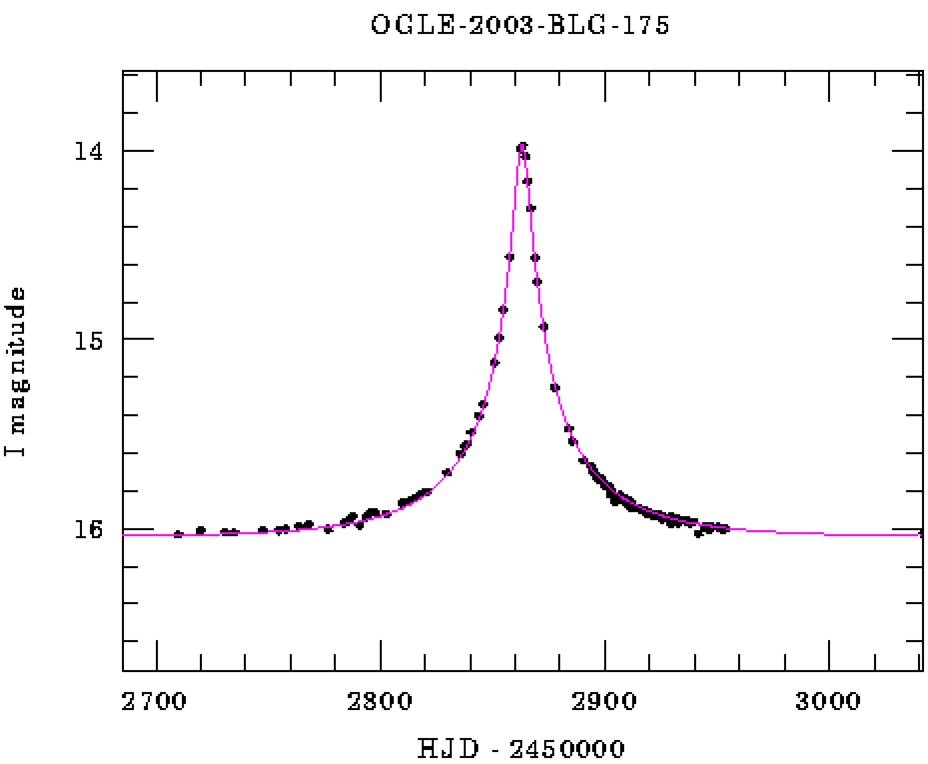


Fig. 2. Point-lens, point-source light curves for minimum impact parameters $y_0 = 0.1$ (*top*), 0.3,...,1.1 (*bottom*) and the corresponding trajectories across the Einstein ring (Figure courtesy Penny Sackett)

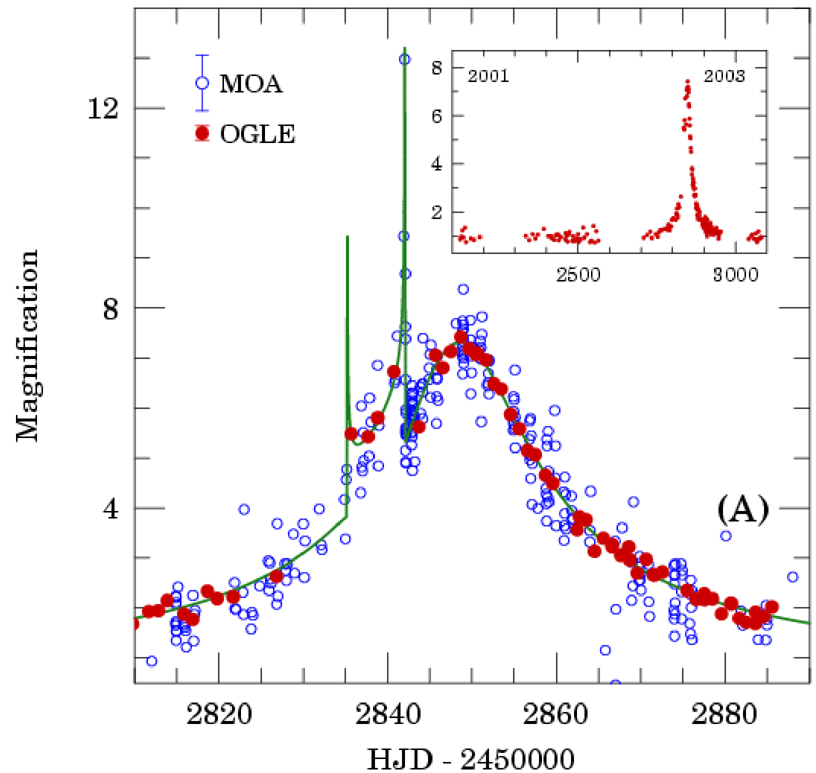
Bohdan Paczyński 1986, ApJ, 304, 1

Binary lenses

- The deflection angle: $\vec{\alpha}(\vec{x}) = \frac{4G}{c^2}\left(\frac{M_A(\vec{x}-\vec{x}_A)}{(\vec{x}-\vec{x}_A)^2} + \frac{M_B(\vec{x}-\vec{x}_B)}{(\vec{x}-\vec{x}_B)^2}\right)$



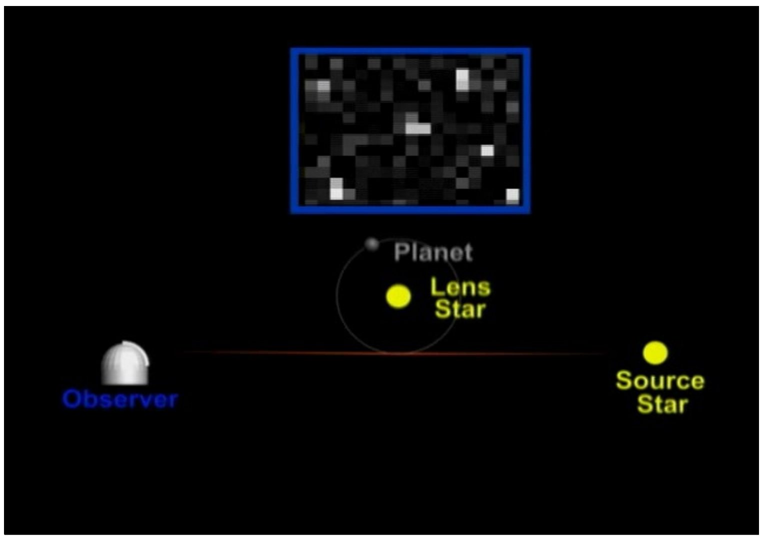
Single lens light curve

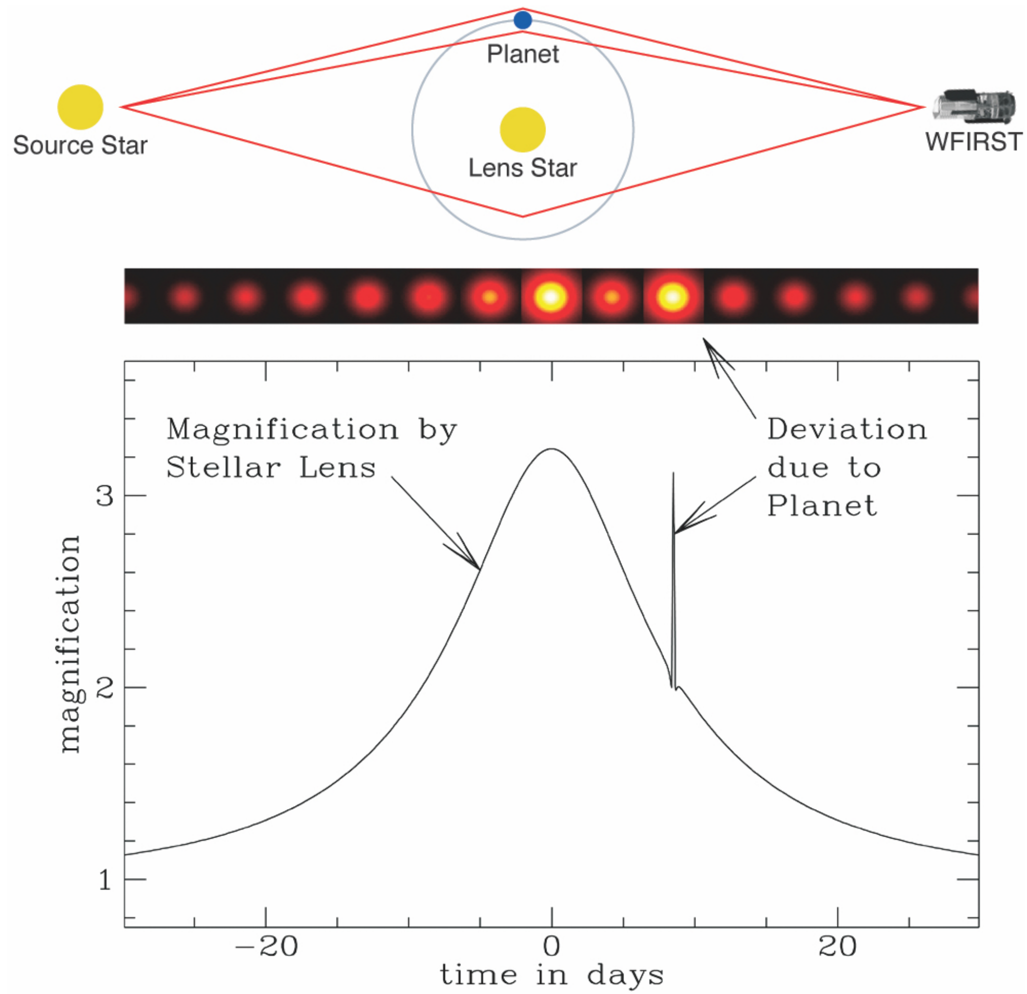


Double lens light curve

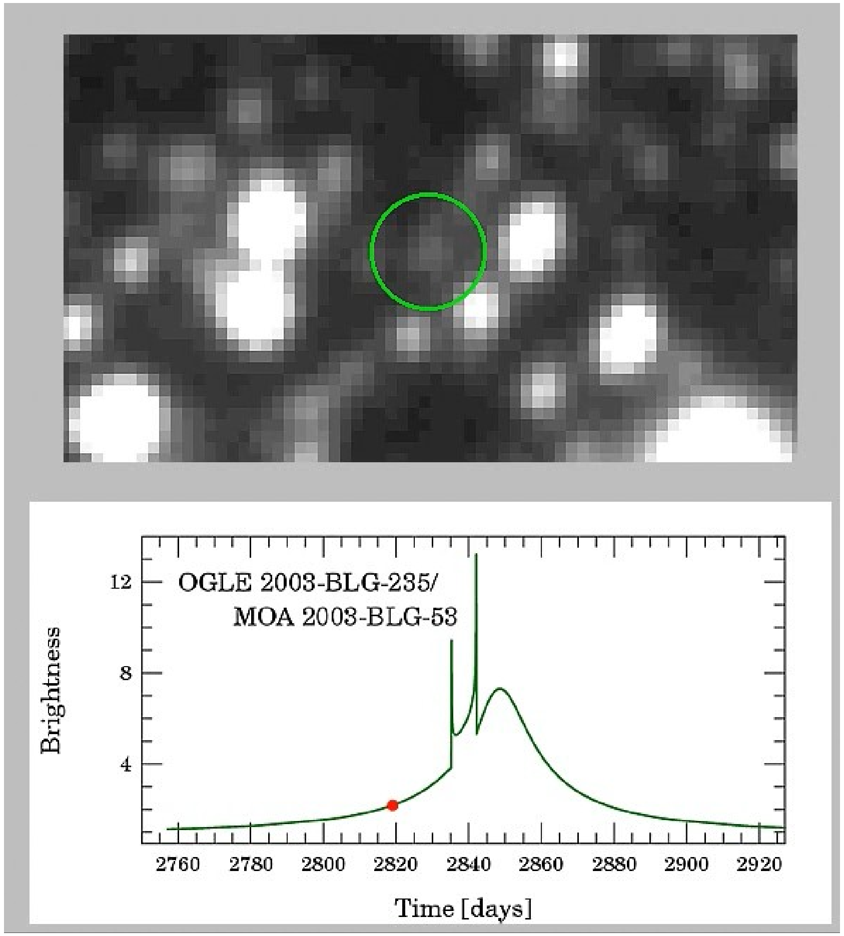
Mao & Paczyński 1991, ApJL, 374, 37

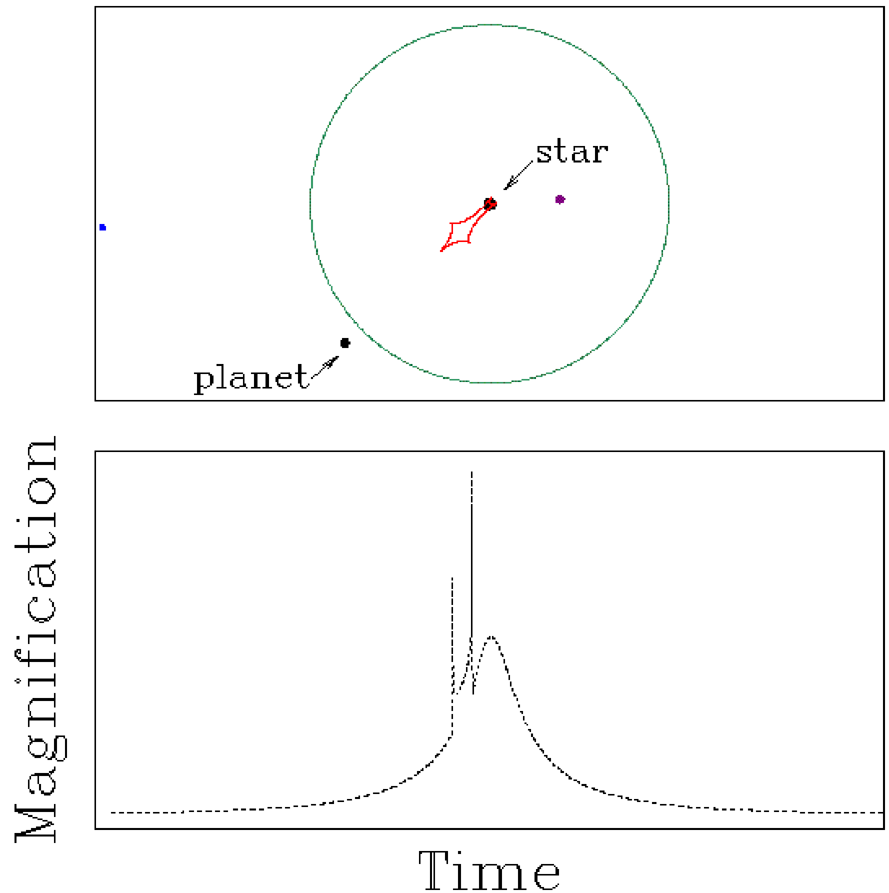
Detection of extrasolar planets by microlensing I





Detection of extrasolar planets by microlensing II



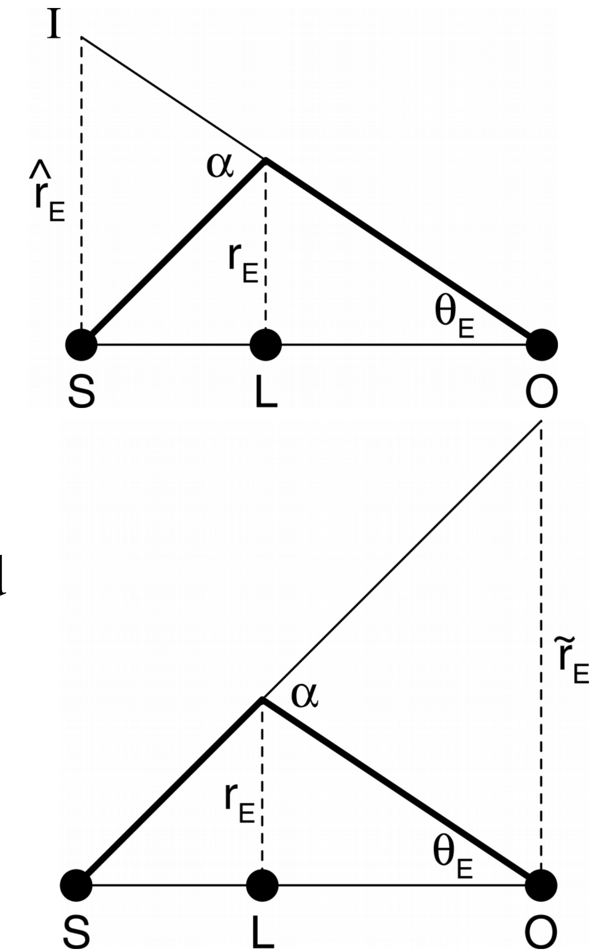


Determnation of microlens masses

- Orbital motion of the Earth around Sun produces a distortion in the observed microlensing light curve
- The amplitude of this distortion is proportional to the **microlens parallax**: $\pi_E = \mathrm{AU} / \tilde{r}_E$, where AU is the size of the Earth's orbit and $\tilde{r}_E$ is the Einstein radius projected onto the observer's plane
- π_E and θ_E could be measured ⇒ microlens mass could be determined from (Gould, 2000, ApJ, 542, 785):

$$M = \frac{\theta_E}{\kappa \pi_E}, \quad \kappa = \frac{4G}{c^2 \mathrm{AU}} \approx 8.144 \, \frac{\mathrm{mas}}{M_\odot}$$

- For binary microlensing events the mass ratio $q = M_1 / M_2$ could be also measured ⇒ **detection of extrasolar planets**



Einstein radius projected onto the source plane (top), as well as onto the observer plane (bottom)

Galactic microlensing experiments

THE OPTICAL GRAVITATIONAL LENSING EXPERIMENT

OGLE

MOA

Microlensing Observations in Astrophysics

MACHO

LLNL

MSSSO

CfPA

EROS Experiment Microlensing Survey

EROS stands for ***'Expérience pour la Recherche d'Objets Sombres'***
and has known 2 observational phases :
EROS-1 *(1990-1995)* and ***EROS-2*** *(1996-2003)*

PLANET Homepage

Probing Lensing Anomalies NETwork

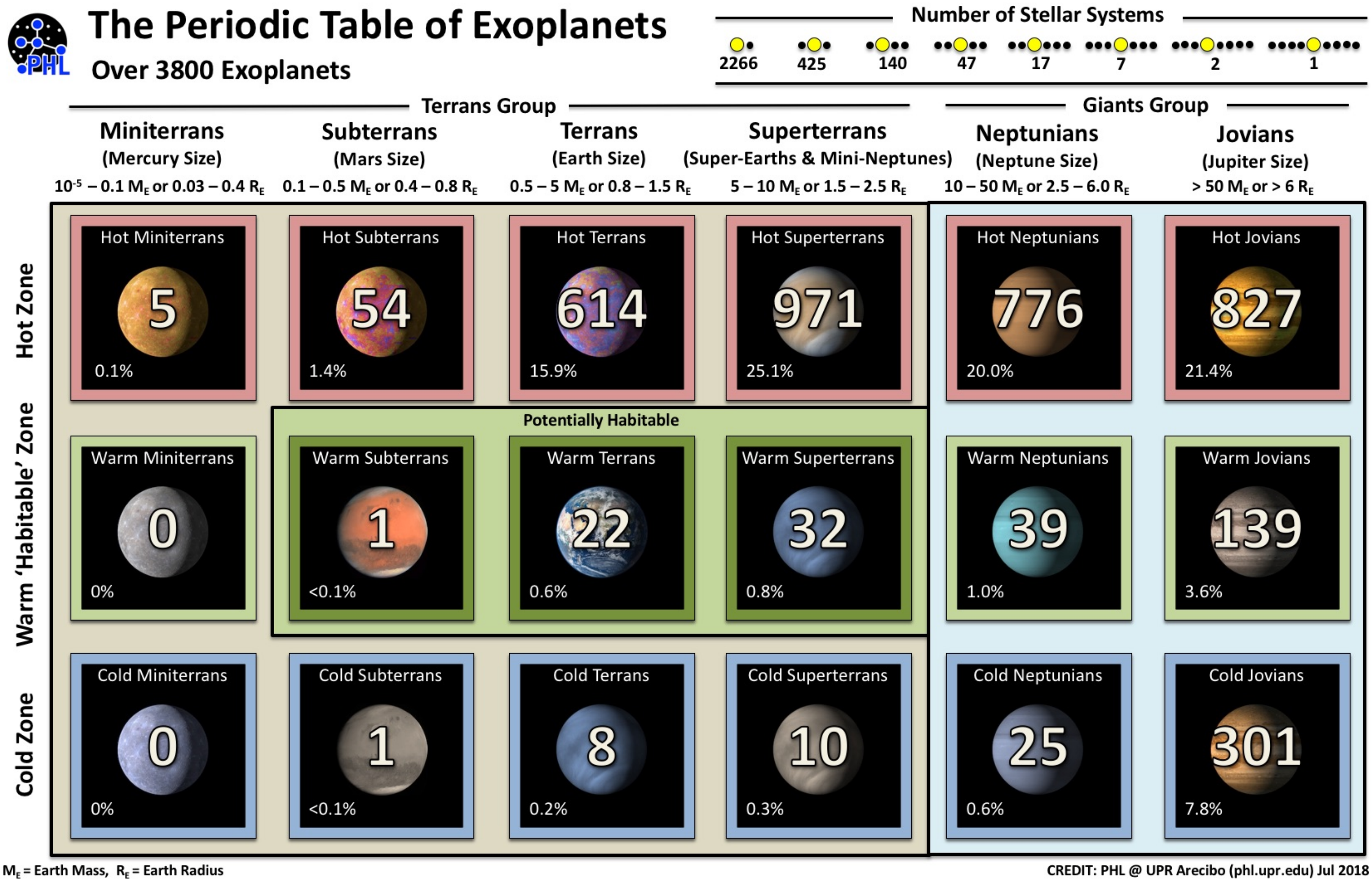
THE OHIO STATE UNIVERSITY

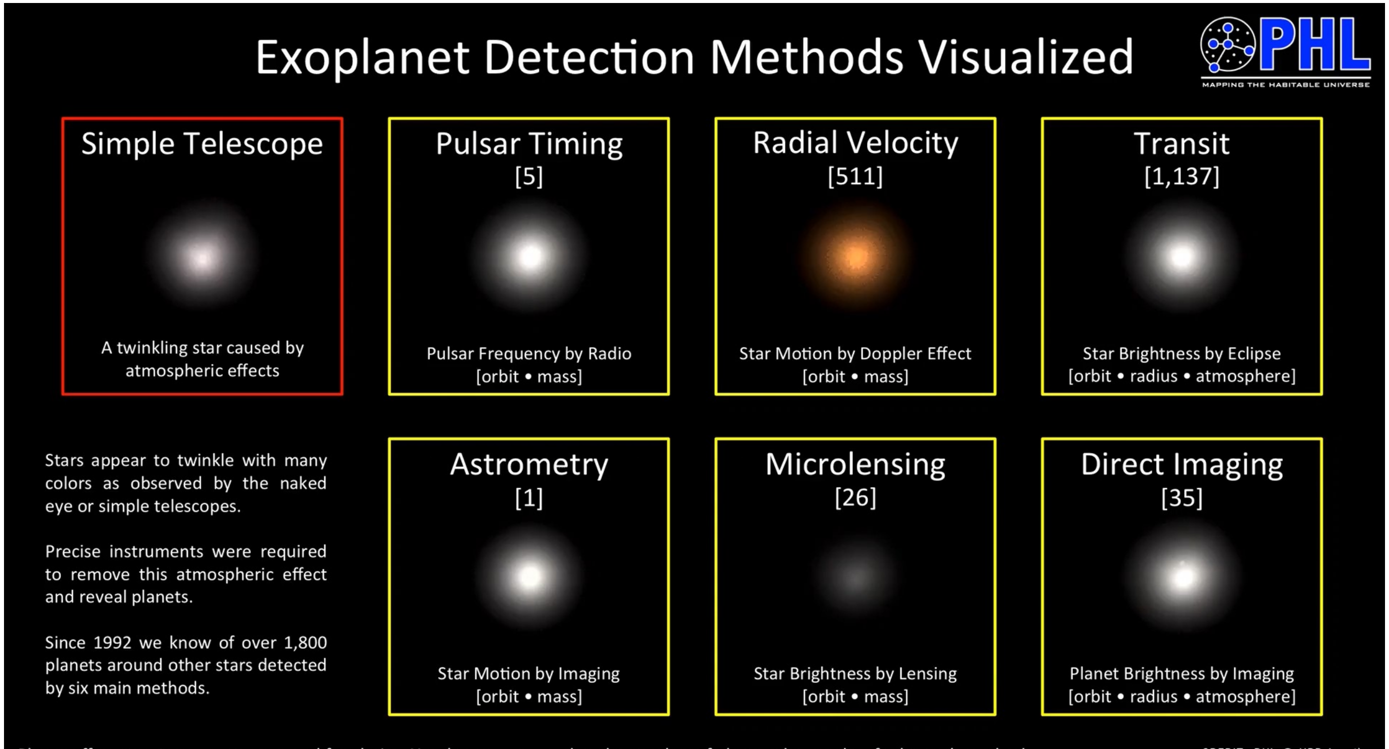
DEPARTMENT OF **ASTRONOMY**

MicroFUN

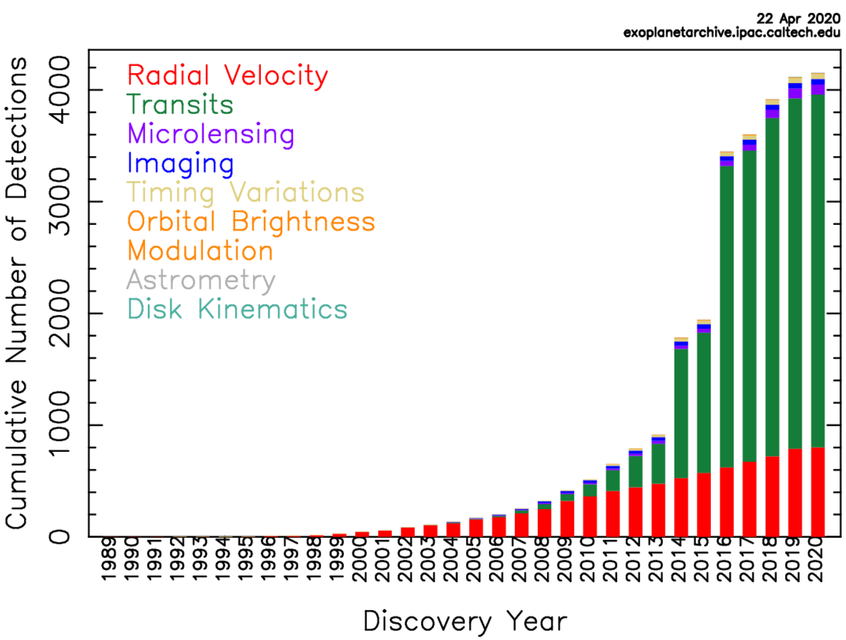
MICROLENSING FOLLOW-UP NETWORK

Confirmed exoplanets: number and types

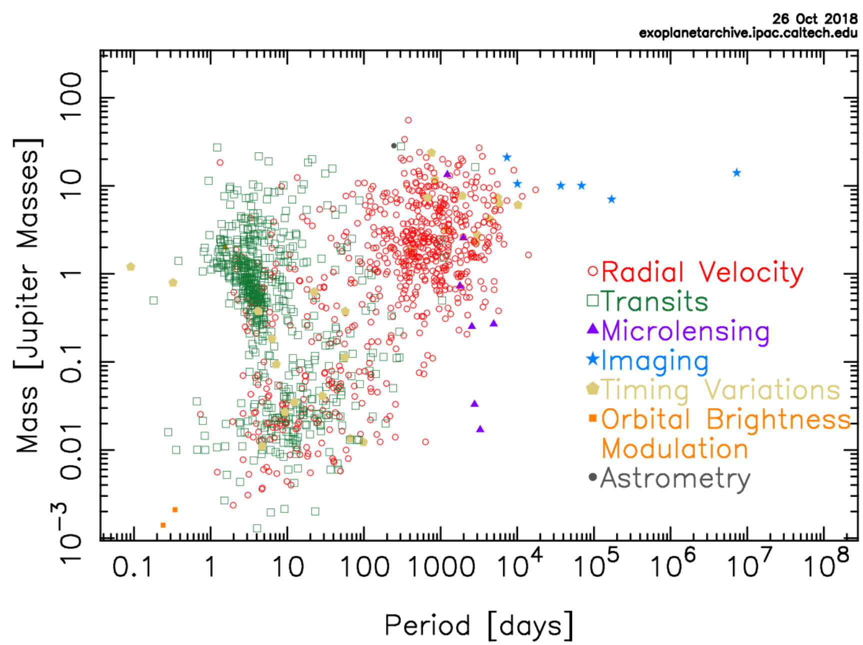




Cumulative Detections Per Year

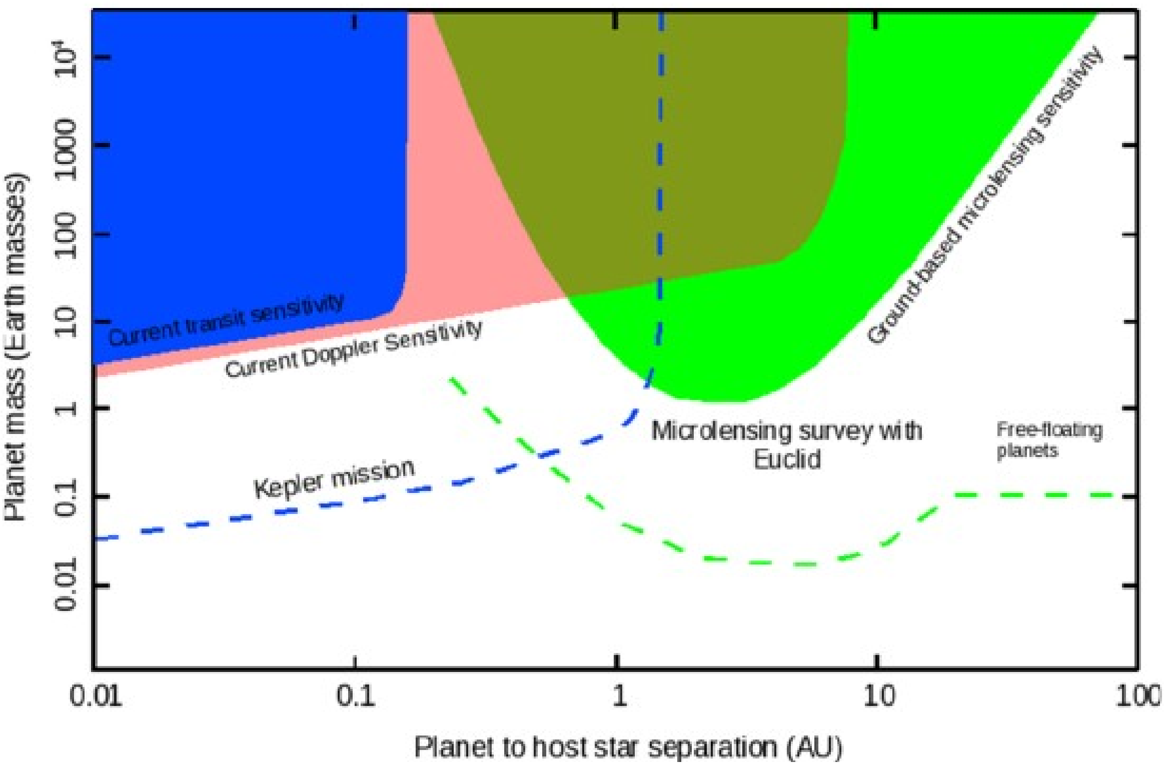


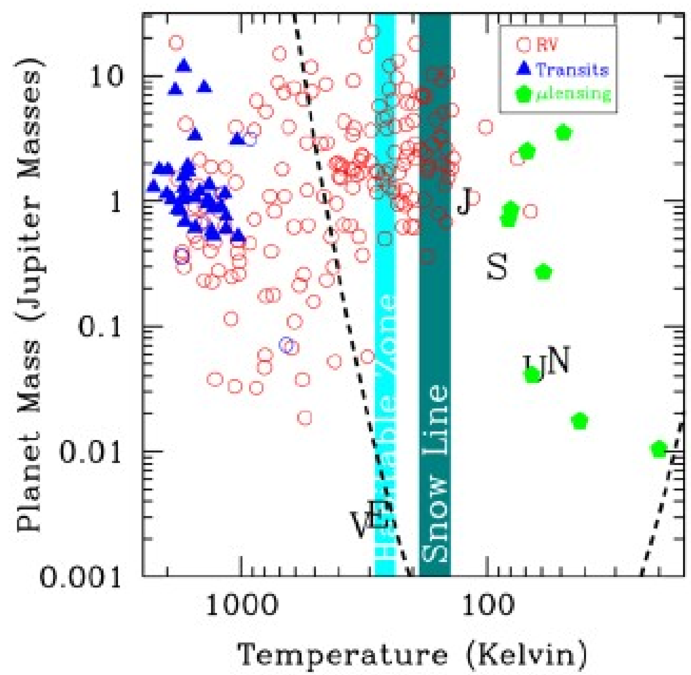
Mass — Period Distribution



Main potential of microlensing

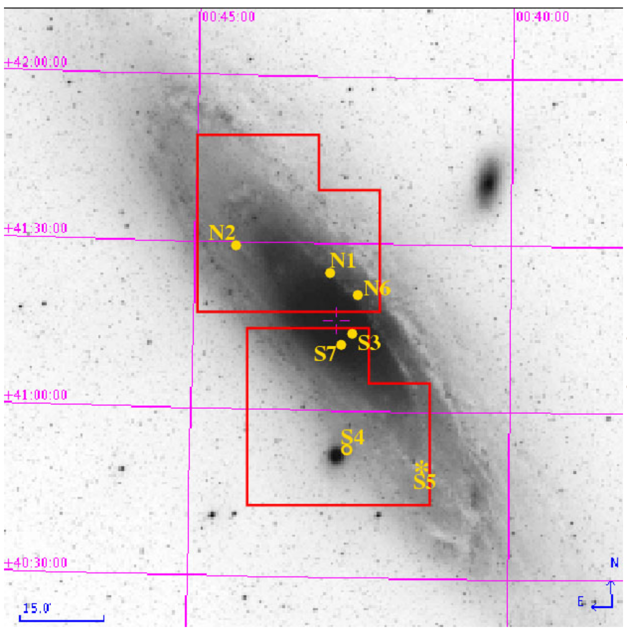
- Full status and characterization of exoplanets in regions located 0.5-10 AU from host stars (the regions at and behind the snow line)
- Status of exoplanets around wide range of types of host stars
- Discovery of low mass planets from the ground
- Current (EUCLID) and future space missions (WFIRST)

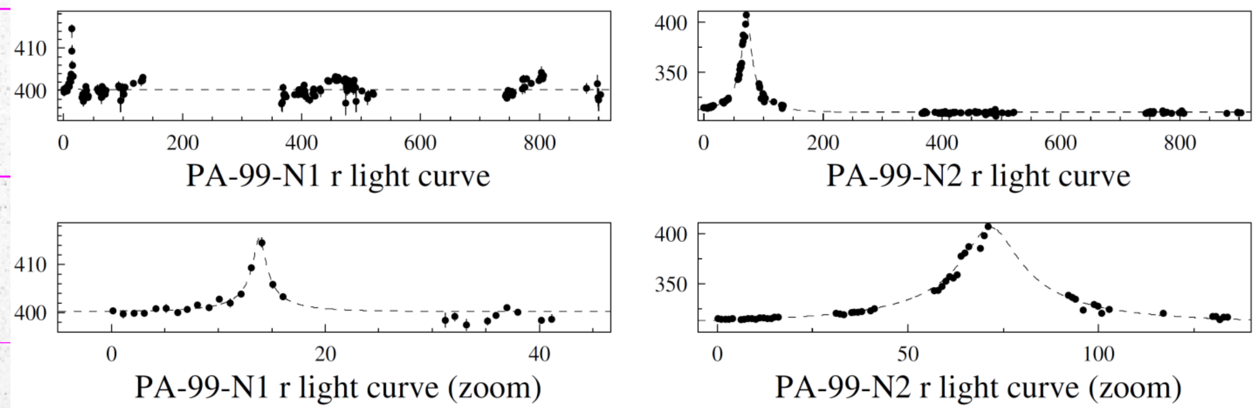




Andromeda galaxy pixel lensing

- **Pixel lensing**: the source stars are not resolved by telescopes
- Only bright sources (i.e. giant stars with large radii), sufficiently magnified, can give rise to detectable microlensing events
- Finite size effects: smaller planetary deviations in pixel lensing light curves with respect to microlensing towards the Galactic bulge





- **POINT-AGAPE**: Pixel-lensing Observations with the Isaac Newton Telescope - Andromeda Galaxy Amplified Pixels Experiment

Pixel Lensing towards Andromeda

Exam question

1. Microlensing light curves and applications for detection of extrasolar planets

Literature

Textbook:

- *Gravitational Lensing*: Strong, Weak and Micro, Book Series: Saas-Fee Advanced Courses
  1. P. Schneider - *Introduction to Gravitational Lensing and Cosmology*
  2. C. S. Kochanek - *Strong Gravitational Lensing*
  3. P. Schneider - *Weak Gravitational Lensing*
  4. J. Wambsganss - *Gravitational Microlensing*

Exercise 1

Plot two microlensing light curves corresponding to the following dimensionless impact parameters: $u_0 = 0.1$ and 0.3. Assume that the time is centered on the peak time t_0 and normalized to the Einstein radius crossing time t_E.

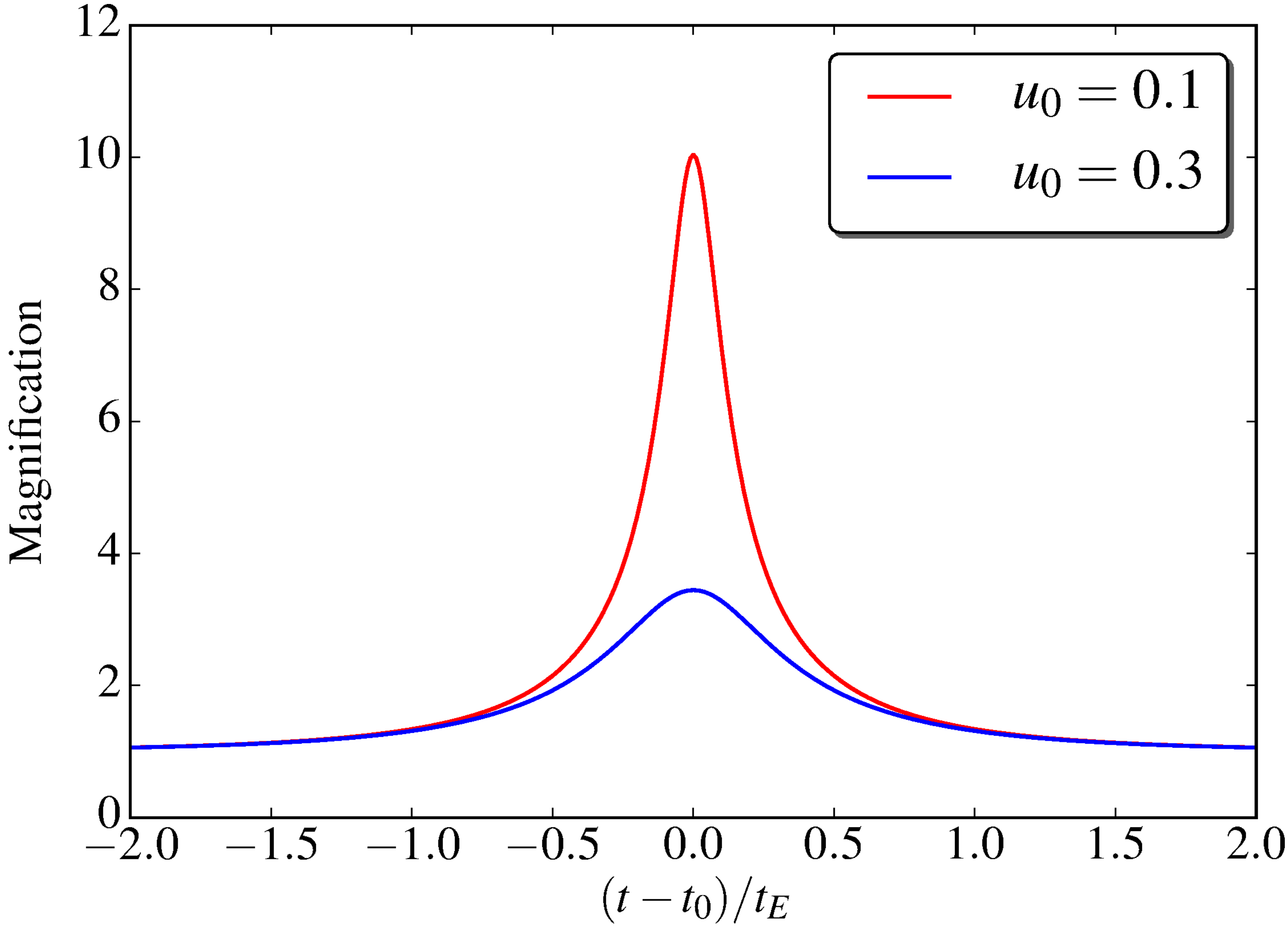
Exercise 2

Compare the observed light curve of the microlensing event OGLE-2003-BLG-175 from the photometry data file "phot.dat" (which 3 columns are: JD, *I*-band magnitude and magnitude error) with the corresponding theoretical light curve. Use the best fit values of parameters from the file "params.dat" to calculate the theoretical amplification and magnitude light curves, knowing that *I*-band magnitude is given by:

$$I = I_{bl} - 2.5 \log (f_{bl} A + 1 - f_{bl}),$$

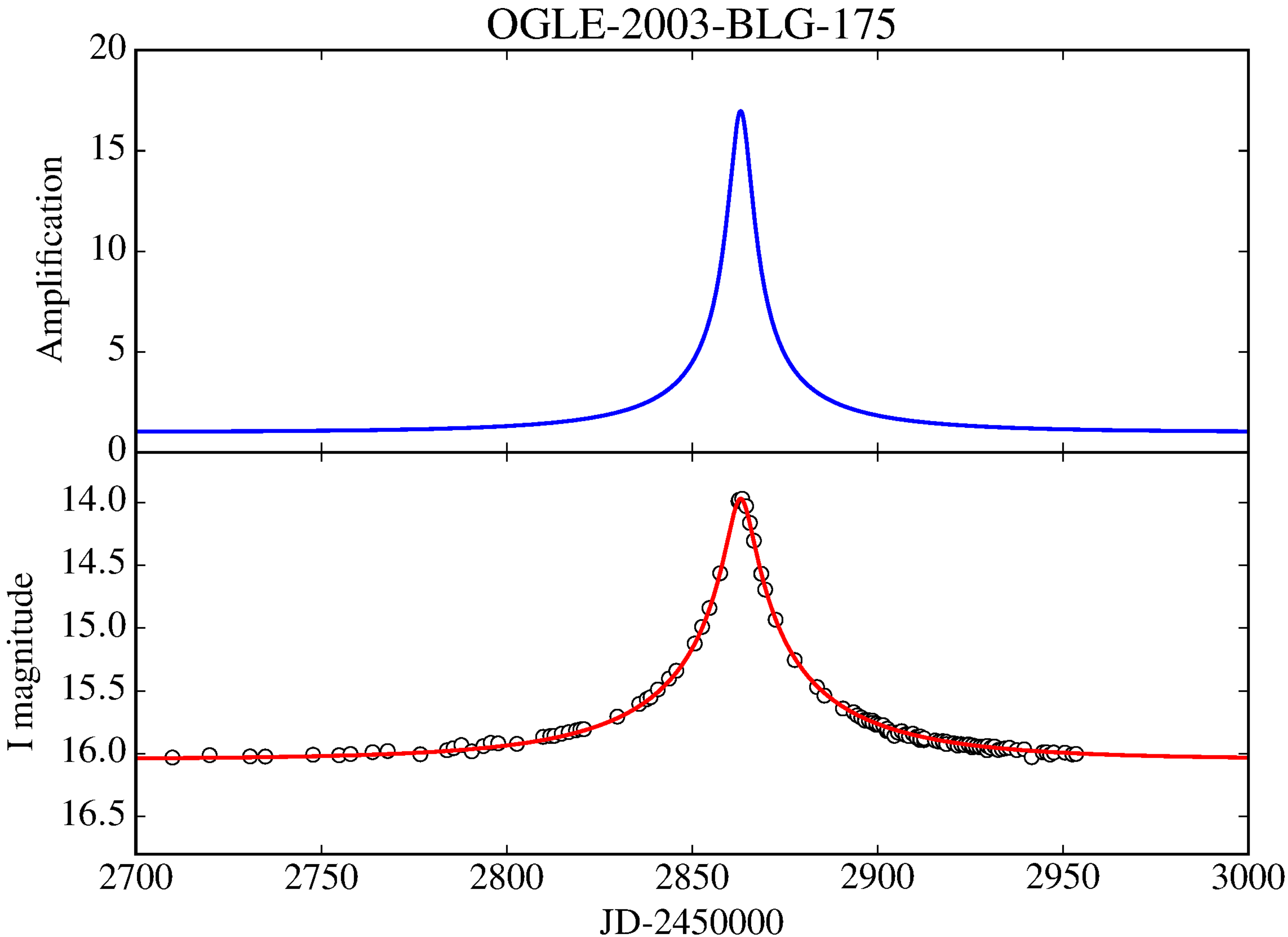
where I_{bl} is total base *I*-band magnitude, f_{bl} is blending ratio and A is microlensing amplification.

Solution 1



Solution is obtained by Python script "mlamp.py"

Solution 2



Solution is obtained by Python script "OGLE-2003-BLG-175.py"