Free floating planets in Milky Way

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Free floating planets (FFPs)

- **The objects with $M < 0.01\ M_{Sun}$ that is not orbiting around any host star are called:**

  - Free floating planet (FFP)

  - Rogue planet

  - Orphan planet

  FFPs are detected in young star forming region by infrared imaging surveys:

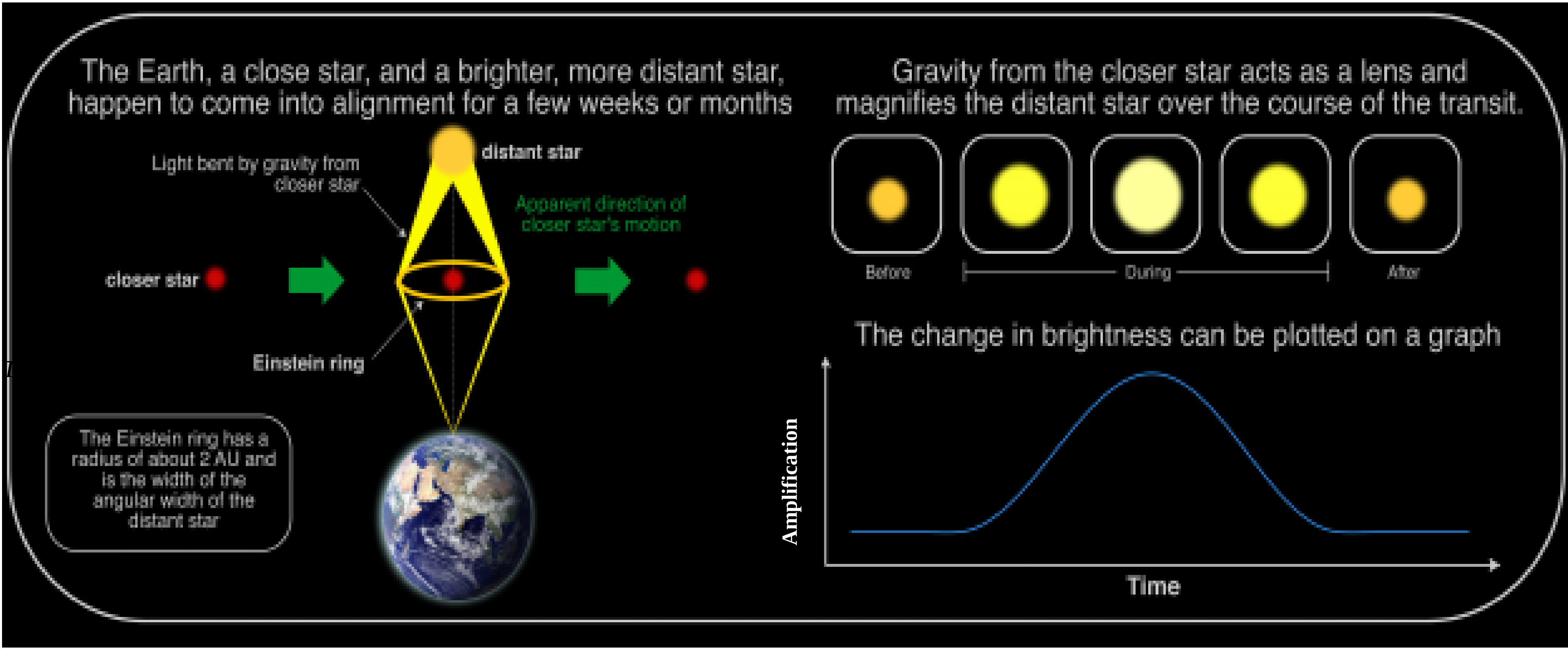
  WISE 0855−0714 ($M \sim 3 \div 10 M_{J}$, $D \sim 2.2pc$) ***Luhman et al. 2014***

- **Their origin is uncertain**

- Formed in protoplanetary disks and subsequently ejected. ***Veras et al., 2012***
- Formed by direct collapse of molecular clouds. **Silk, J. 1997**

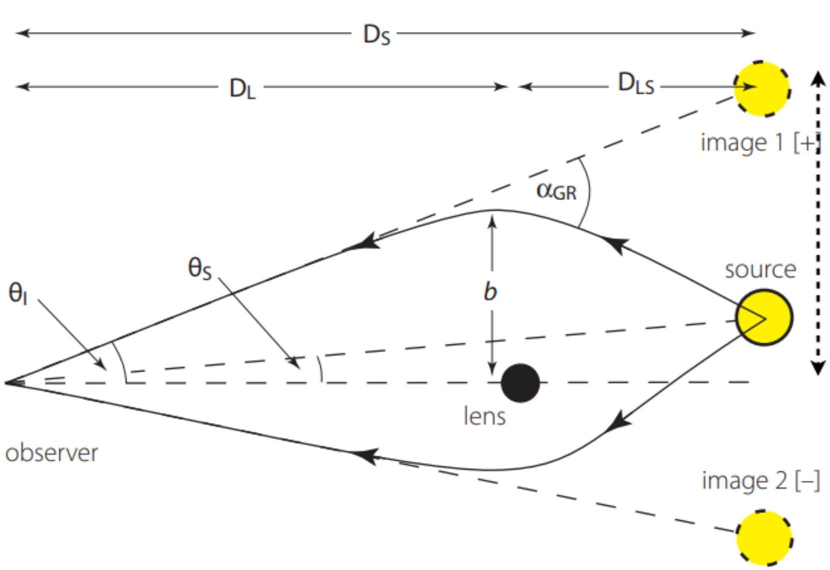
- **The gravitational microlensing, is the only way, to detect these objects at distances larger than a few tens of parsecs.**

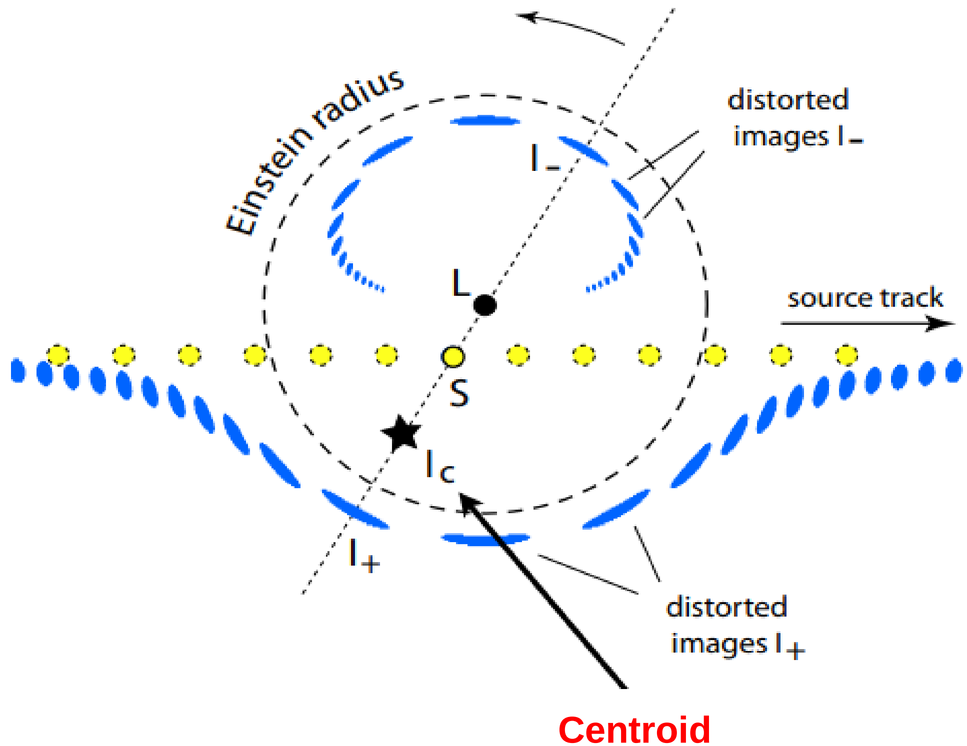
Gravitational microlensing



- Just see a distant star magnified.
- Eistein predicted 1936, but concluded imposible to observe. ***Einstein, A. 1936***
- in 1986, Paczynski suggested it is possible if watch millions of stars. ***Paczynski, B. 1986***

Gravitational microlensing: Geometry





$$\alpha = \frac{4GM}{R_E c^2}$$

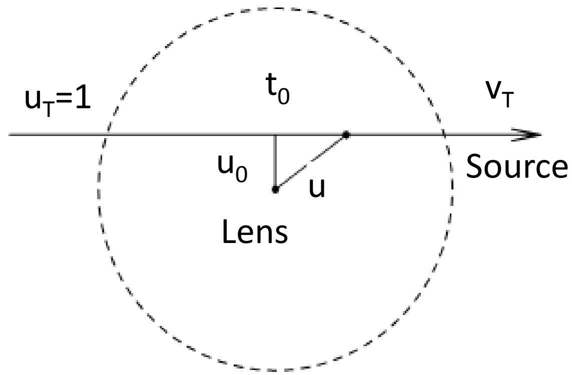
$$R_E(M, D_L) = D_L \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S}} \qquad T_E = \frac{R_E(M, D_L)}{v_T}$$

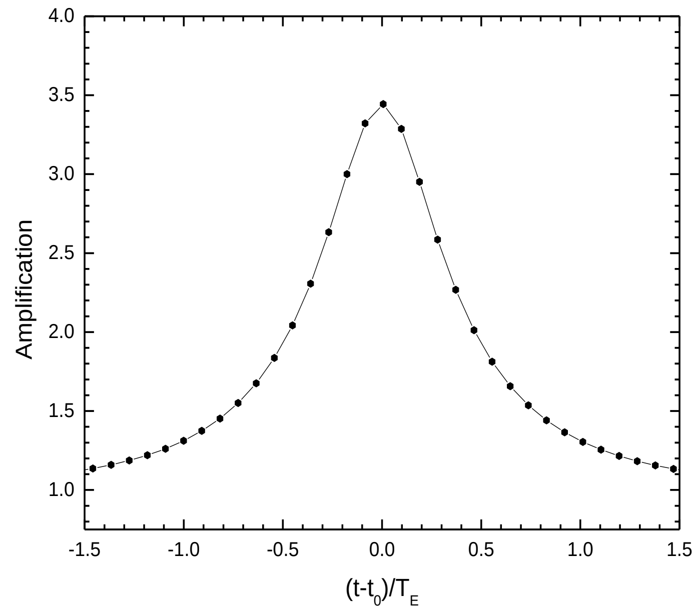
$$\theta_E = \frac{R_E}{D_L} = \sqrt{\frac{4GM}{c^2} \frac{D_{SL}}{D_L D_S}} \approx 2851\mu as \sqrt{\frac{M(M_\odot)}{D_L(kpc)}(1 - \frac{D_L}{D_S})}$$

Θ_E ~ 1mas $\rightarrow$ M=M_{Sun}

Θ_E ~ 1µas $\rightarrow$ M=$10^{-4}M_{Sun}$

Gravitational microlensing: photometric observations





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

$$u = 1$$

$$A_{th} \simeq 1.34$$

$$u(A) = \sqrt{2}[(\frac{A^2}{A^2 - 1})^{1/2} - 1]^{1/2}$$

$$u_0 = \sqrt{2}[(\frac{A_{\max}^2}{A_{\max}^2 - 1})^{1/2} - 1]^{1/2}$$

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

Measurable parameters are: $\mathbf{u_0, t_0, T_E}$

A microlensing event is detectable if in its curve there are at least **8** consecutive points with $\mathbf{A > A_{th}}$.

Gravitational microlensing: the second order effects

1. **Finite source effect**

2. **Parallax effect**
    a) **Orbital parallax**
    b) **Trigonometric parallax**

3. **Binary lens**

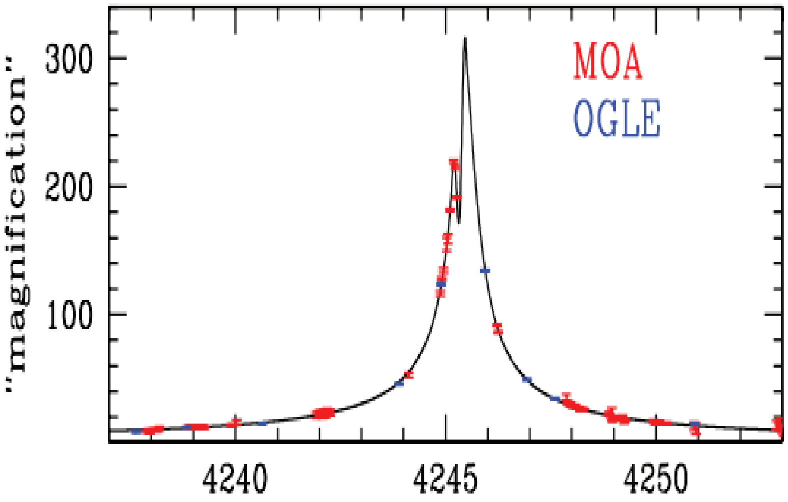
3. Binary lens (Bound Exoplanets)

3823 confirmed exoplanets

- ~ 74 %, Transit method
- ~ 20 %, Radial Velocity method
- ~ 2 %, Gravitational Microlensing

website
https://exoplanetarchive.ipac.caltech.edu/index.html

The first exoplanet: **OGLE-2003-BLG-235Lb**
(Bond et al. 2004)



MOA-2007-BLG-192L b

$M_{PL} \sim 3.3 M_{Earth}$

Semi-Major Axis ~ 0.62 AU

(Bennett et al. 2008)

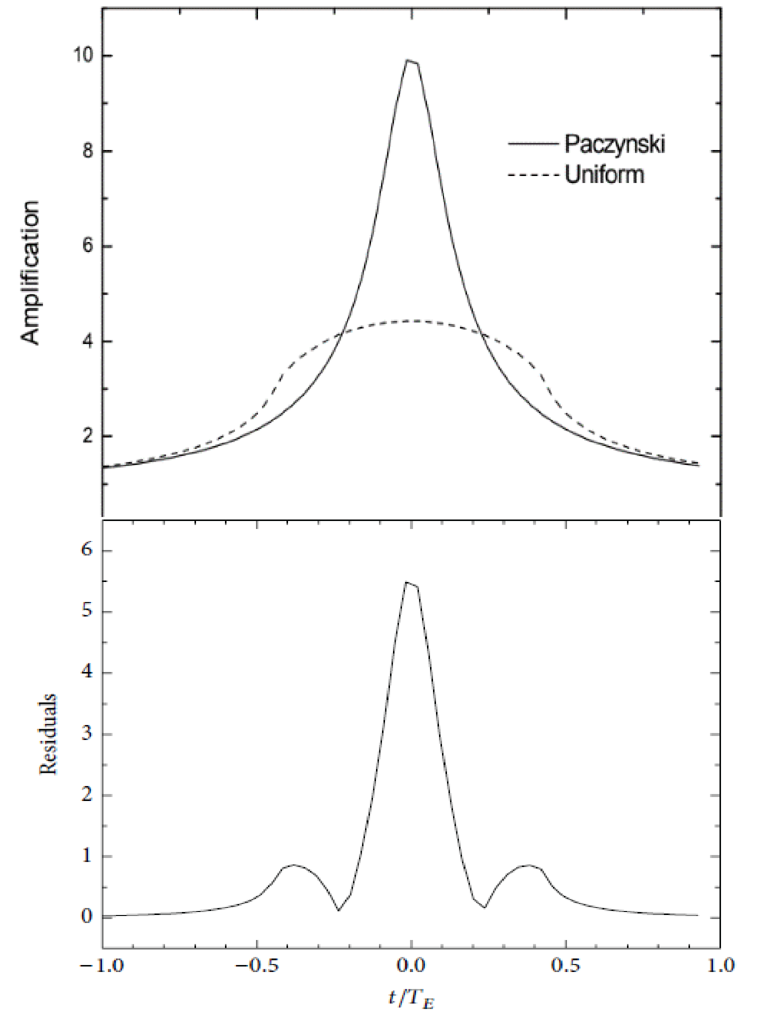
1. Finite source effect

- This effect is detected in events where **u_0** is comparable to **ρ_***.
- The amplification for **uniform source brightness**, is calculated using polar coordinates centered at the source center

$$A_{fs} = \frac{1}{\pi\rho_*^2}\int_0^{2\pi} d\theta \int_0^{\rho_*} rA(u')dr \qquad \rho_* = \frac{R_* D_L}{R_E D_S} = \frac{\theta_*}{\theta_E}$$

- By the fiting can defined **ρ_***.
- The **angular size** of the source estimates through the color and magnitude diagram (**CMD**) and then the **Θ_E** can be measured.
- Finite source effects can be detected on a light curve when it contains at least **8** points with **Res > photometric error** around the event peak.

$$\left|AF - A_{fs}F\right| > \Delta F \Rightarrow \left|A - A_{fs}\right| > \frac{\Delta F}{F} \Rightarrow \mathrm{Res} > photometric\_error$$



u_0=0.1, ρ_*=0.46 T_E=9.2 hours

Hamolli et al., 2015

2/a. Orbital parallax effect

- The parameter of line of sight **ϕ, χ**
- The observer coordinates projected in lens plane:

$$\begin{cases} x_1(t) = \rho\{-\sin\chi\cos\Phi(\cos\xi(t)-e) - \sin\chi\sin\Phi\sqrt{1-e^2}\sin\xi(t)\} \\ x_2(t) = \rho\{-\sin\Phi(\cos\xi(t)-e) + \cos\Phi\sqrt{1-e^2}\sin\xi(t)\} \end{cases}$$

$$\rho = \frac{a_\oplus(1-x)}{R_E} = \frac{a_\oplus}{r_E}$$

$$u(t)^2 = p(t)^2 + d(t)^2$$

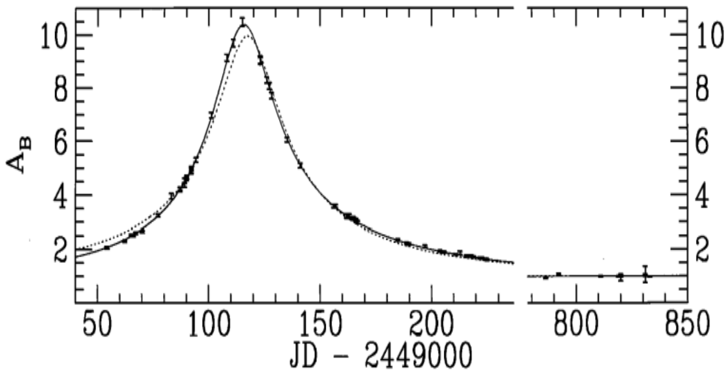
$$p(t) = p_0(t) + \cos\psi[x_1(t) - x_1(t_0)] + \sin\psi[x_2(t) - x_2(t_0)]$$

$$d(t) = d_0 - \sin\psi[x_1(t) - x_1(t_0)] + \cos\psi[x_2(t) - x_2(t_0)]$$

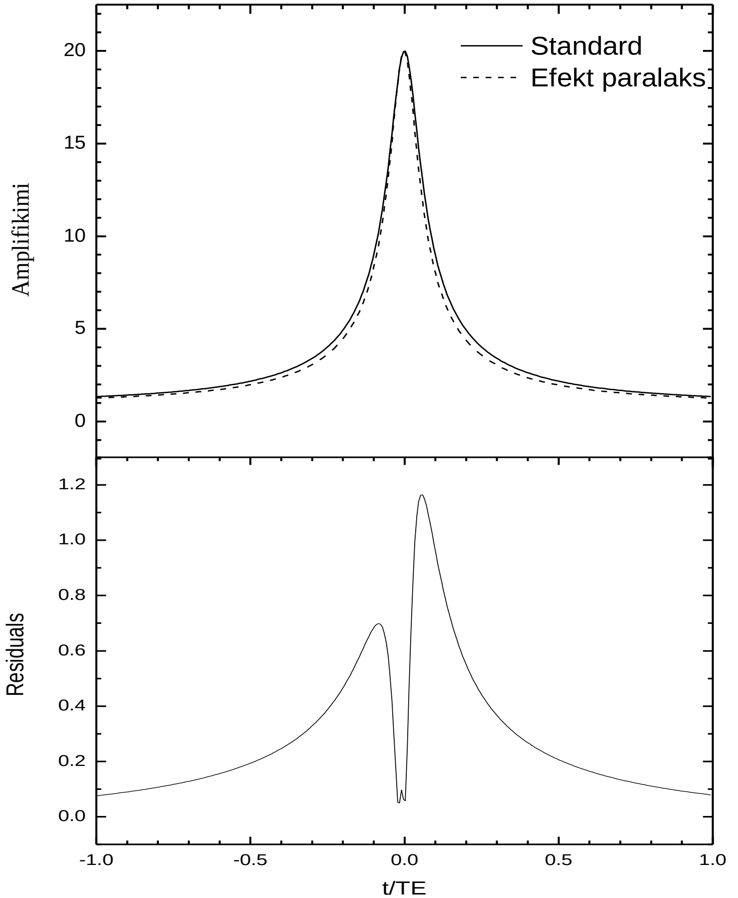
$$A_p(t) = \frac{u(t)^2+2}{u(t)\sqrt{u(t)^2+4}} \qquad p_0(t) = \frac{(t-t_0)}{T_E} \qquad d_0 = u_0$$

$$|AF - A_pF| > \Delta F \Rightarrow |A - A_p| > \frac{\Delta F}{F} \Rightarrow \mathrm{Res} > photometric\_error$$

- By the fiting can defined **ρ** and then **r_E**



Alcock et al., 1995

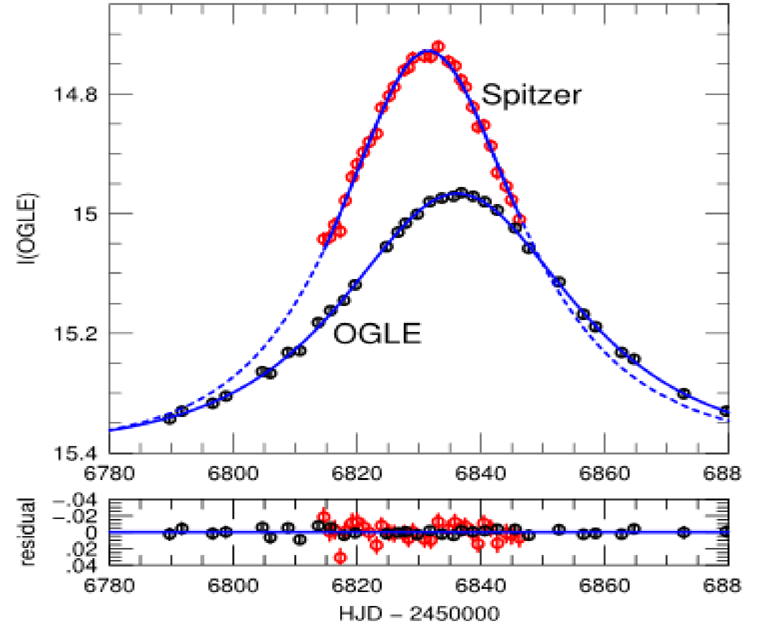


2/b. Trigonometric parallax effect

- The **simultaneous observation** of the same event by two telescopes
- For each curve can be defined the max time and impact parameter and then find

$$\Delta t_0 = |t_{01} - t_{02}| \qquad \Delta u_0 = |u_{01} \pm u_{02}|$$

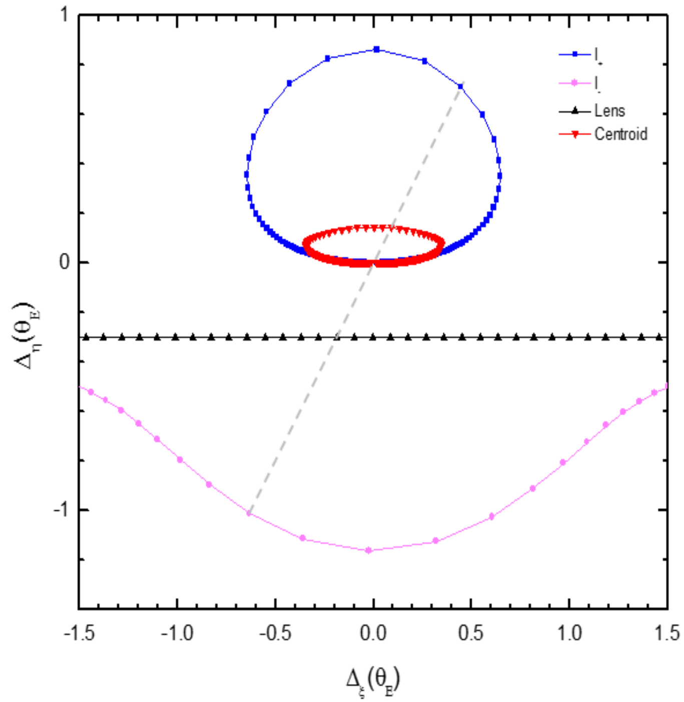
$$\frac{D_\perp}{r_E} = \Delta u = (\frac{\Delta t_0}{t_E}, \Delta u_0)$$



Yee et al., 2015, ApJ, 802, 76

- The $\mathbf{\Delta u_0}$ has a two-fold degeneracy : the "±" depends on whether the two telescopes lie on the same "–" or opposite sides "+" of the direction of motion of the lens.
- So, $\mathbf{r_E}$ value cannot be uniquely determined.
- $\mathbf{D_\perp}$, is the projected separation between the two telescopes in the observer plane.

Gravitational microlensing: Astrometric observations



- The light centroid traces the elliptic trajectory.

- The centroid of the image pair is defined as the average position of + and − images weighted by the associated magnifications

$$\bar{u} = \frac{u_+ A_+ + u_- A_-}{A_+ + A_-} = \frac{u(u^2+3)}{u^2+2}$$

- The measurable quantity during an event is the **centroid shift** of the image pair relative to the source,

$$\Delta = \bar{u} - u = \frac{u}{u^2+2}$$

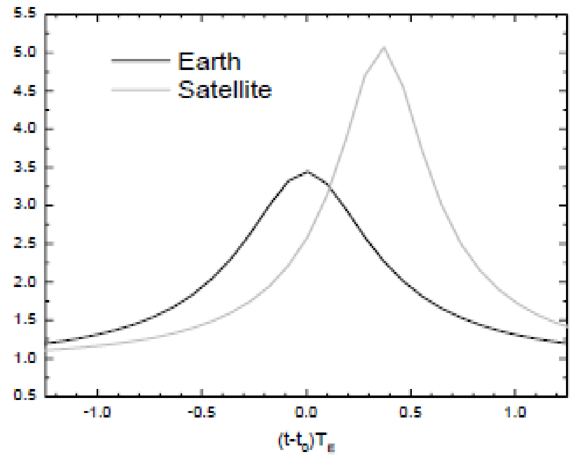
- Unlike A, which is a dimensionless quantity that depends only on the dimensionless separation u, the **Δ** is a function of both **u** and **Θ_E**.

$$\Delta = \frac{u}{u^2+2}\theta_E \qquad b = \frac{1}{2}\frac{u_0}{u_0^2+2}\theta_E \qquad a = \frac{1}{2}\frac{\theta_E}{\sqrt{u_0^2+2}}$$

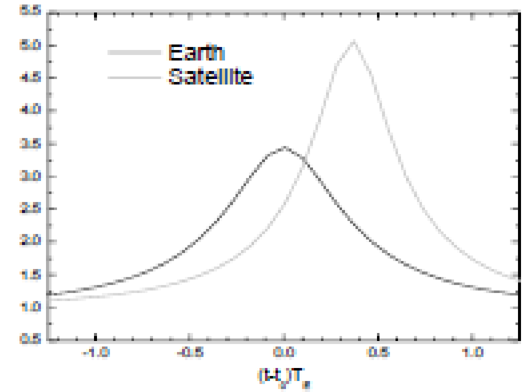
- From the measurement of the **a** and **b** can be defined **Θ_E.**

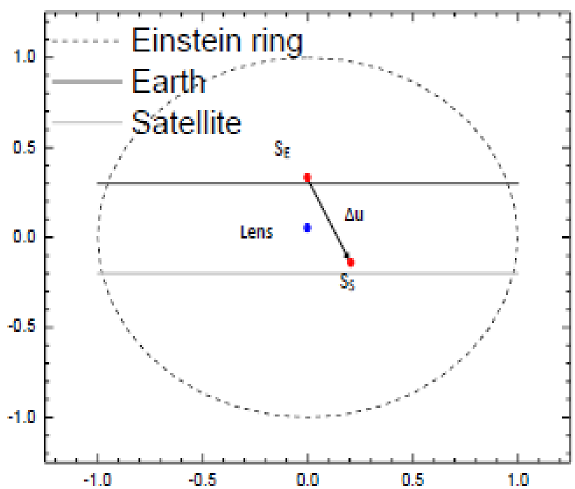
$$M = \frac{c^2}{4G} r_E \theta_E$$

- If by a microlensing event **Θ_E** and **r_E** are measured, then the **mass can be defined uniquely**:

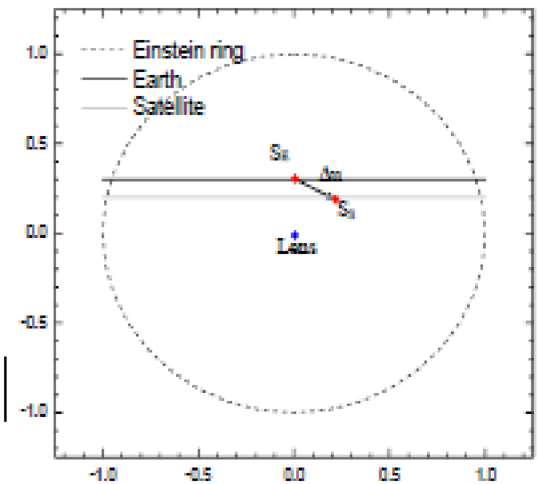


Photometric observation

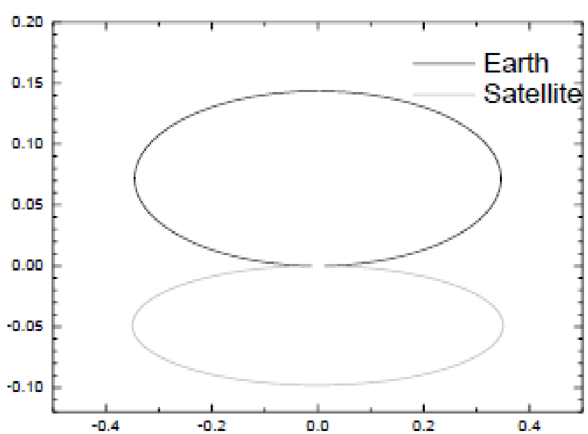




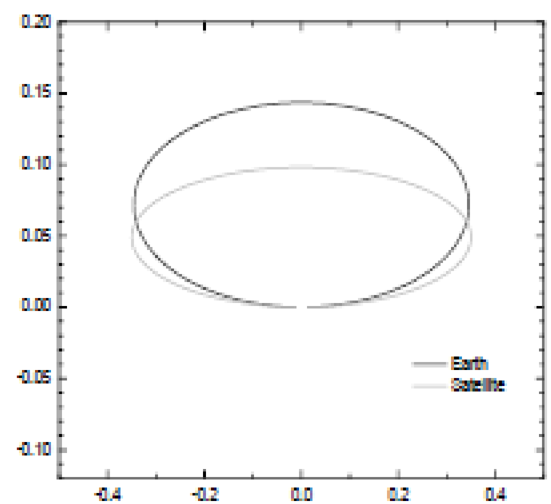
$$\Delta u_0 = \left| u_{0T} + u_{0S} \right|$$



$$\Delta u_0 = \left| u_{0T} - u_{0S} \right|$$



Astrometric observation



The current microlensing observations

Present

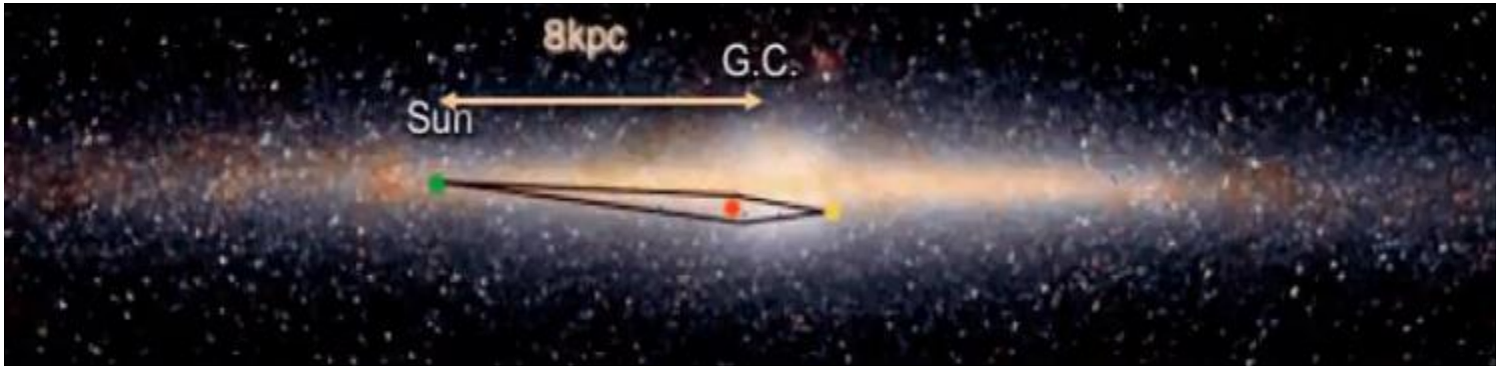
- **MOA**, since 1995. Discovered 21 exoplanets.
- **OGLE**, since 1992, Discovered ~ 50 exoplanets towards the bulge.
- **Kepler 2,** is moving in an Earth-trailing Solar orbit, the distance from Earth is about **0.5AU.**
- **Spitzer,** is about **1.48 AU** behind the Earth on the orbit , is used for trigonometric paralla with OGLE and MOA.
- **Gaia**, L2 point, Astrometric observations of all the sky since December 2013, **precision down to 4 μas,**

Future

- **WFIRST**, in 2020, ~3 sq. deg (10 fields), ~432 days (6 seasons of 72 days each), **cadence ~15 minute, A_{th}=1.001 (u_{max} = 6.54), photometric error 0.1%.**
- **Euclid**, in 2021, 0.54 deg FoV, 6 years duration, **A_{th}=1.001 (u_{max} = 6.54), cadence ~20 minute, photometric error is 0.1%.**

Survey towards the Galactic Bulge

- **Why?** → microlensing probability : **~ 10^{-6}** **(**caused by stars)
  → **dense field** with stars



- **Optical depth**: the probability that at any time a random star is magnified more than **A_{th}**

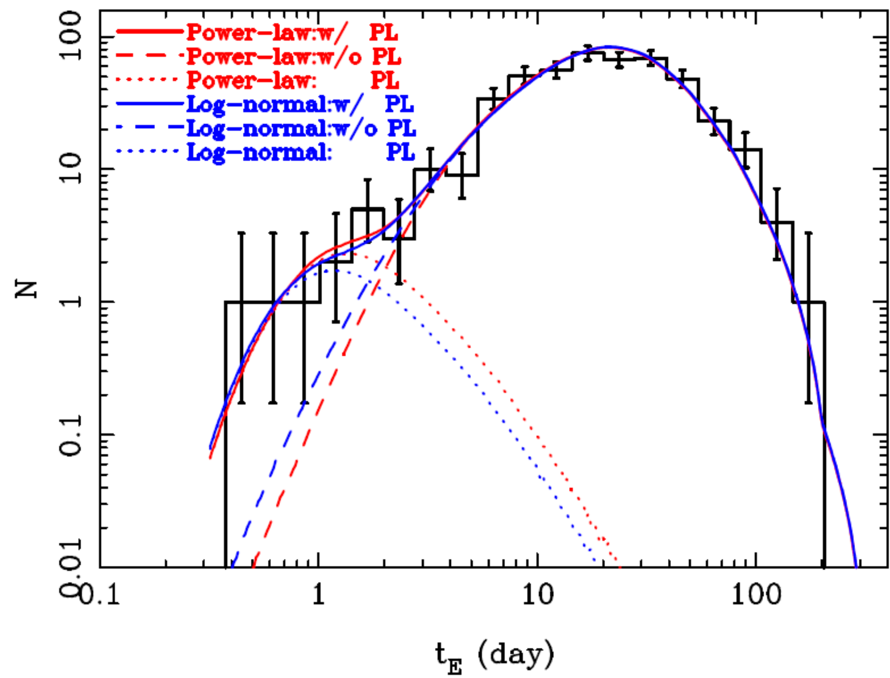
$$\tau = \int_0^{D_S} n(D_L)(\pi R_E^2)dD_L$$

- **Microlensing rate**: the number of events per unit time and per monitored star.

- **Einstein time:** **~ 30 days → M_{Sun}**
  ~ a few days → M_J
  ~ hours → M_{Earth}

Free-floating planets by observations

- From **474** microlensing events of **MOA-II** data set (2006-2007), **10** were found with $T_E < 2$ days. A best fit procedure defines a mass range of FFPs $10^{-5} \leq M/M_S \leq 10^{-2}$, distributed following a power-law mass function $M^{-\alpha_{PL}}$, with $\alpha_{PL} = 1.3^{+0.3}_{-0.4}$ and $N = 5.5^{+18.1}_{-4.3}$ number of planetary mass objects per star.
- Recently there are some reviewed values for the mass distribution, by the analysis of **2617** events of OGLE-IV, 2010-2015, ***Mroz, et al. 2017.***



Sumi et al., 2011

- **Spatial distribution of FFPs:**

a) triaxial bulge with mass density

$$\rho(M,x,y,z) = \rho_0(M)e^{-s^2/2} \qquad s^4 = \left(\frac{x^2}{a^2}+\frac{y^2}{b^2}\right)^2 + \frac{z^4}{c^4}$$

b) double exponential disk with mass density

$$\rho(M,R,z) = \rho_0(M)e^{-|z|/H}e^{-(R-R_0)/h}$$

Hafizi et al., 2004

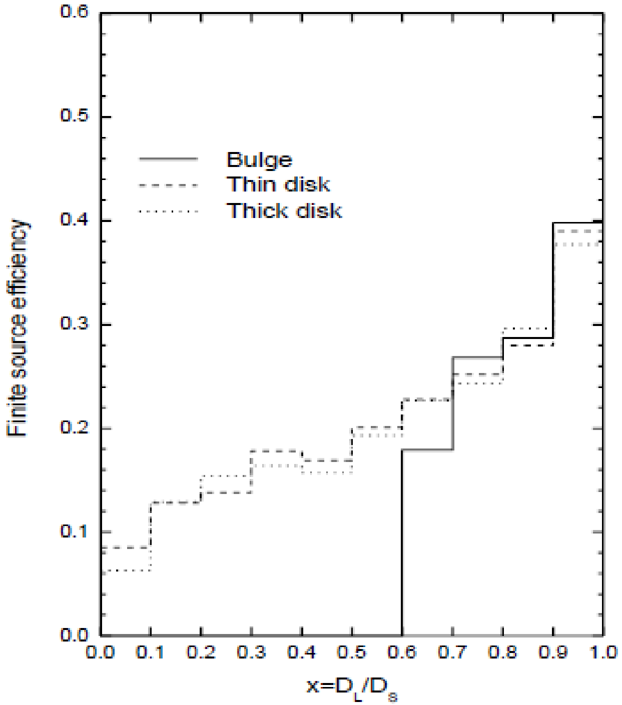
- **Velocity distribution of FFPs:**

$$f(v_i) \propto \exp\left[-\frac{(v_i - \overline{v_i})^2}{2\sigma_i^2}\right]$$

Han & Gould, 1995

Results (Euclid or Wfirst)

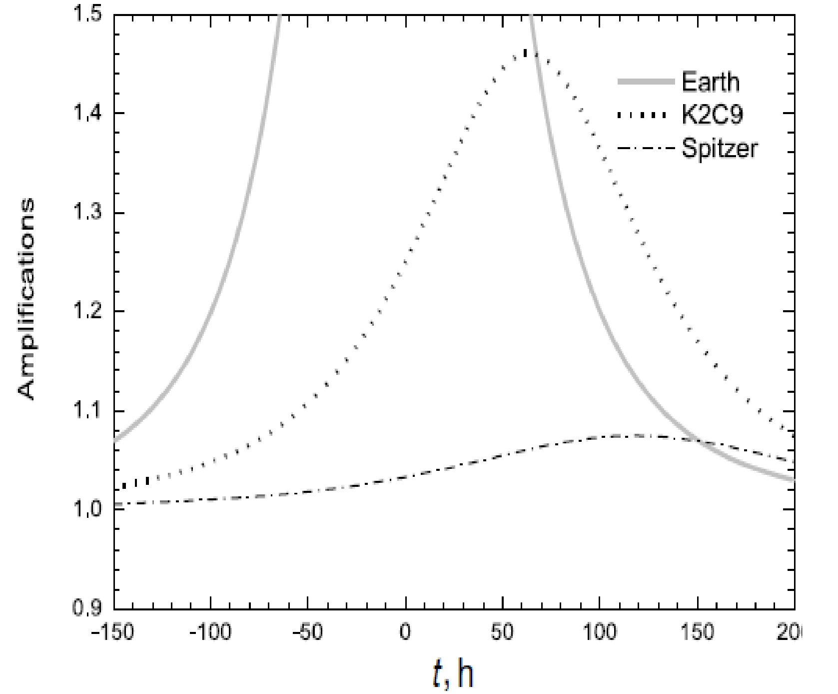
- Since their cadence is planed 20 min, is expected to detect the microlensing events with duration larger than 2.67 hours.
- The **optical depth** of microlensing events caused by FFPs is of order 10^{-8} and the **event rate** is a few hundred events for month.
- The optical depth and microlensing rate depend on the power law index of the FFP mass function.
- Using Monte Carlo numerical simulations, we calculate the **efficiency of orbital parallax** effect, which results ~ 30% and the best period for it is in June.



- In approximately 30% of the microlensing events caused by FFPs it will be possible to detect **the finite source effects** in the light curves.

- The **finite source efficiency increases** with the value of ***x***, so it is more likely to detect finite source effects for FFPs in the Galactic bulge.

Results: The trigonometric parallax effect (OGLE-K2-Spitzer)



T_E=76 h, M=4 × 10^{-3} M_{Sun}, D_L =3.1 kps ,u_0 =0.13

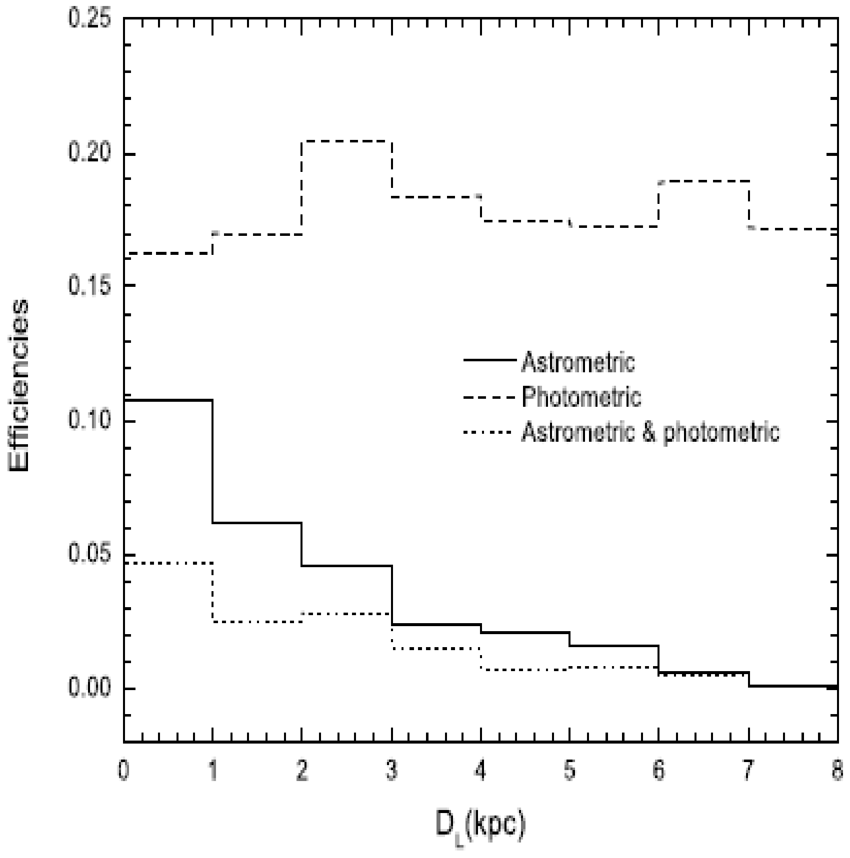
- Since, from **April 22 to June 2 (2016),** was planed microlensing survey towards the bulge, by **K2, Spitzer** and **OGLE**, we calculate the efficiency of the trigonometric parallax effect.
- For OGLE the threshold amplification is taken the minimum value of the peak amplification of events detected during the 2015 campaign, $\mathbf{A_{th-E} = 1.028}$.
- For the K2C9 mission the threshold amplification is $\mathbf{A_{th-K2} = 1.004}$.
- Concerning the Spitzer observations, the threshold amplification is $\mathbf{A_{th-S} = 1.066}$.
- We assume that the observational cadence is **30 min**.

- Probability that a microlensing event is detected by two telescopes depends by the **spatial distributions of FFPs**. The bigger is for FFPs in the **bulge**.
- Probability that a microlensing event is detectable by **OGLE and K2C9** telescopes is larger at the **beginning** of the campaign, while it decreases towards the end of it.
- The probability for **OGLE- K2** telescopes is bigger then **OGLE-Spitzer**, due to the larger values of both the $\mathbf{A_{th-S}}$ and the $\mathbf{D_\perp}$ between Spitzer and Earth.

Results: Astrometric microlensing (Gaia, OGLE)

- Using Monte Carlo simulation, the astrometric efficiency of the events photometrically detectable depends on the index value of FFP mass function.
- Also, the astrometric signal efficiency decreases when the value of D_L is increased.

- The efficiency of the astrometric effect varies from about 10%, for close FFPs, to zero for FFPs in the Galactic bulge.
- On the contrary, the photometric detection efficiency is roughly independent from D_L and turns out to be between 15% and 20%.
- The efficiency for events astrometrically and photometrically detectable is only a few percent.
- By OGLE observations during 2016 are detected 34 events with $T_E < 2$ days. For $\alpha_{PL} = 1.3$ and cadence 2 hours, we find that $2 \div 3$ of them could have astrometric signal observed by Gaia telescope.



Results: Second order effects (thin disk)

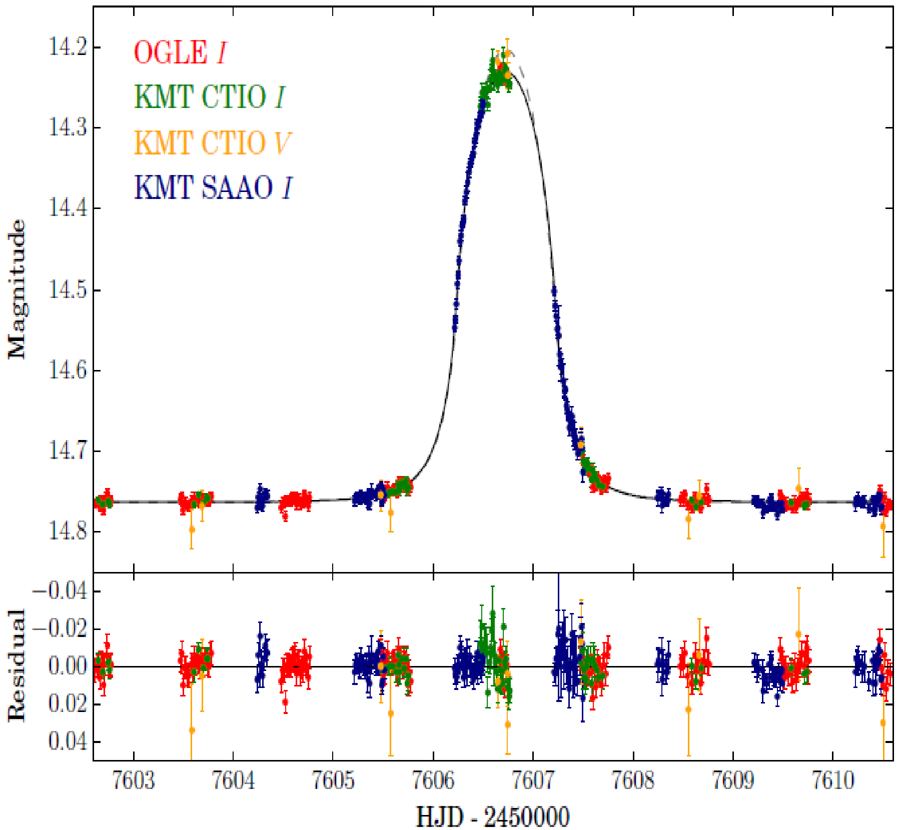
Table 1: Efficiency of some second order effects in microlensing events caused by FFPs towards the Galactic bulge as a function of the α_{PL} value in the range 0.9 - 1.6 and for observing cadence of 20 min and 30 min.

	Cadence 20 min		Cadence 30 min		
α_{PL}	Finite source efficiency	Orbital parallax efficiency	Satellite paralax efficiency ($E-K2C9$)	Satellite parallax efficiency ($E-S$)	Astrometric efficiency
0.9	0.220	0.330	0.915	0.462	0.166
1.0	0.250	0.328	0.890	0.424	0.099
1.1	0.269	0.321	0.858	0.349	0.076
1.2	0.294	0.314	0.814	0.299	0.070
1.3	0.318	0.312	0.774	0.249	0.064
1.4	0.336	0.304	0.739	0.207	0.053
1.5	0.359	0.302	0.701	0.158	0.041
1.6	0.371	0.229	0.672	0.130	0.036

- When α_{PL} gets larger values, only the efficiency of detecting **finite source effect** is increased.

FFP candidate by OGLE

- Recently is presented the discovery of a Neptune-mass free-floating planet candidate in the ultrashort (**$t_E = 0.320 \pm 0.003$ days)** microlensing event OGLE-2016-BLG-1540.
- The event exhibited strong finite-source effects, which allowed us to measure its angular Einstein radius of **$\theta_E = 9.2 \pm 0.5$ μas.**
- However, remains a degeneracy between the lens mass and distance.



(Mroz et al. 2018, ApJ, 155, 121)

Main publications

- **Lindita Hamolli,** Mimoza Hafizi, Achille A. Nuçita: “A theoretical calculation of microlensing signatures caused by free-floating planets towards the Galactic bulge”, botuar në ***International Journal of Modern Physics D,*** Vol. 22, No. 10 (2013) 1350072

- **Lindita Hamolli**, Mimoza Hafizi, Francesco De. Poalis, Achille A. Nuçita: “Parallax effects on microlensing events caused by free-floating planets” botuar në ***Bulgarian Astronomical Journal***, Vol. 19, p.34, (2013)

- **Lindita Hamolli**, Mimoza Hafizi, Francesco De Poalis, Achille A. Nuçita**: “**Estimating finite source effects in microlensing events due to free-floating planets with the Euclid survey**”,** botuar në ***Advances in Astronomy,*** Volume 2015, Article ID 402303, 8 pages

- **Lindita Hamolli**, Mimoza Hafizi, Francesco De Poalis, Achille A. Nuçita**: “**Investigating the free-floating planet mass by Euclid observations**”,** botuar në ***Astrophysics and Space Science,*** *2016, 361(8), 1-5*

- **Lindita Hamolli**, Francesco De Poalis, Mimoza Hafizi, Achille A. Nuçita**:** “Predictions on the detection of the free-floating planet population with K2 and Spitzer microlensing campaigns”, botuar në ***Astrophysical Bulletin,*** 2017, Vol. 72, No. 1, pp. 80–89, DOI 10.1134/S1990341317030099

- **Lindita Hamolli**, Mimoza Hafizi, Francesco De Poalis, Achille A. Nuçita**: “**The astrometric signal of microlensing events caused by free floating planets**”,** botuar në ***Astrophysics and Space Science***, *2018, 365:153*

Thank you