Expectations for the population of free floating planets by the current microlensing observations

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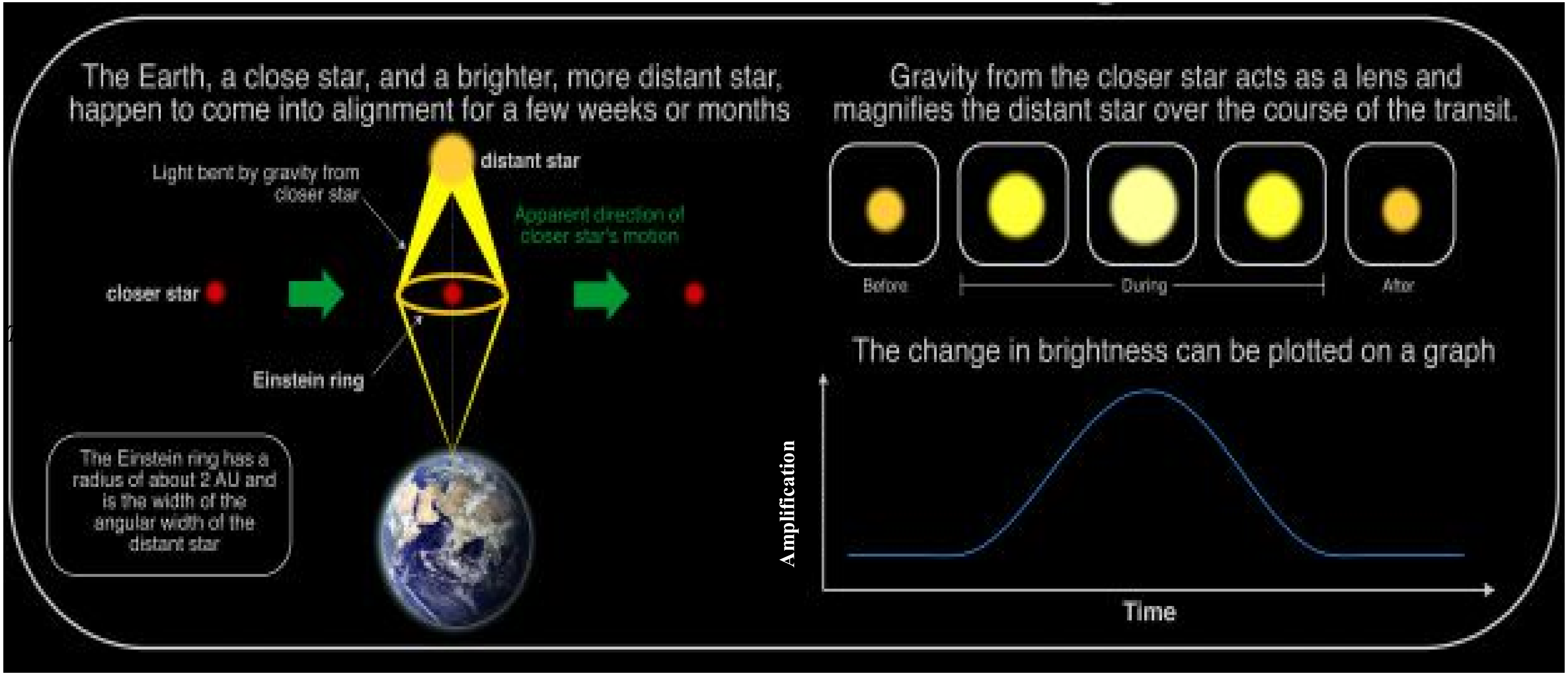
Gravitational microlensing



The Earth, a close star, and a brighter, more distant star, happen to come into alignment for a few weeks or months

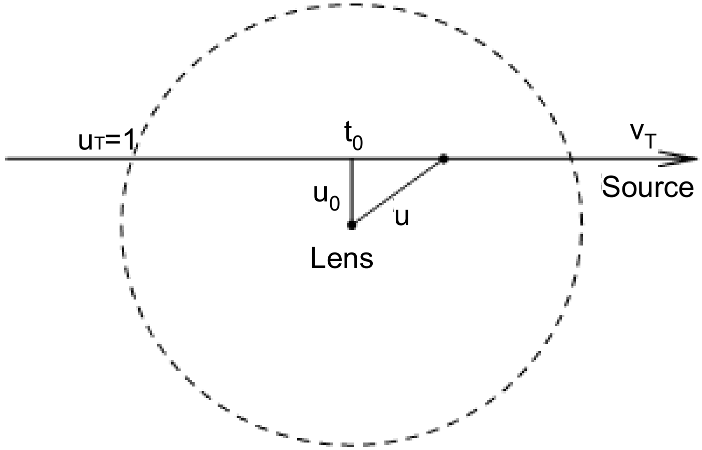
Gravity from the closer star acts as a lens and magnifies the distant star over the course of the transit.

The Einstein ring has a radius of about 2 AU and is the width of the angular width of the distant star

The change in brightness can be plotted on a graph

Gravitational microlensing geometry

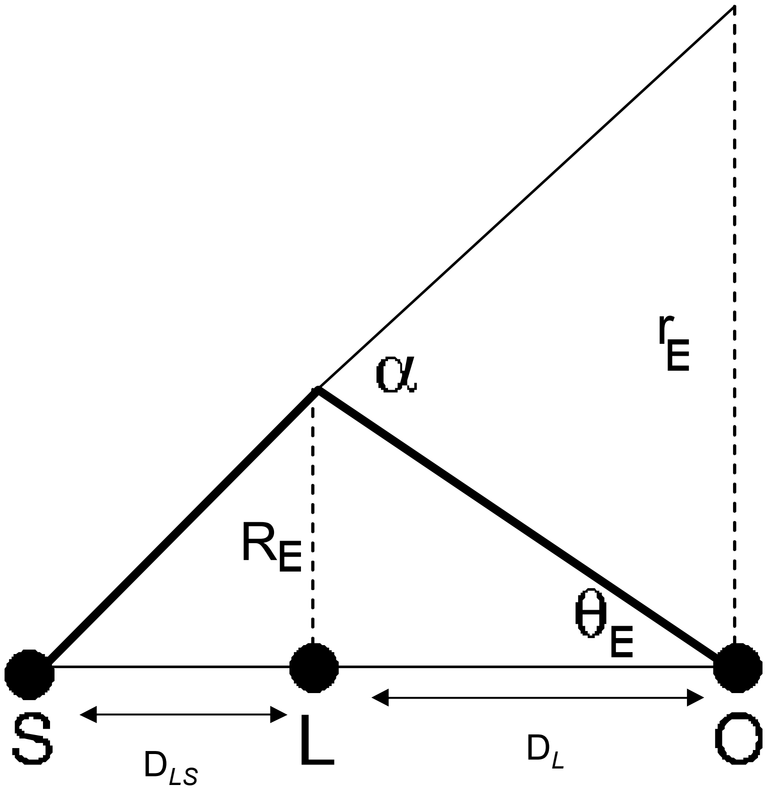
Measurable parameters are: u_0, t_0, T_E



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

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

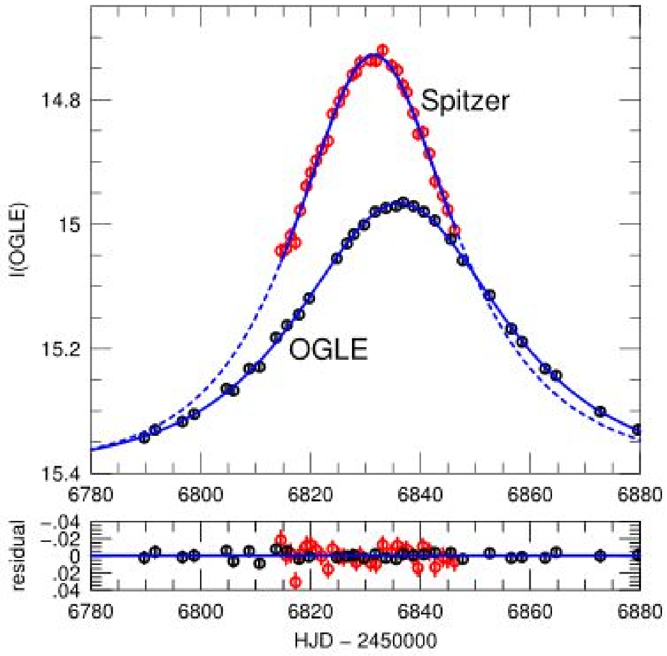
$$u(t) = \sqrt{u_0^2 + (\frac{t-t_0}{T_E})^2}$$



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

$$T_E = \frac{R_E(M, D_L)}{\mathrm{v}_T}$$

Gravitational microlensing



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

Anomalies in the light curves

- Parallax effect $\longrightarrow$ r_E
    1. Orbital parallax
    2. Trigonometric parallax
- Binary lens
- Finite source effects $\longrightarrow$ θ_E

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

$$\frac{D_\perp}{r_E} = \Delta u = \left(\frac{\Delta t_0}{t_E}, \Delta u_0\right) \qquad \Delta t_0 = t_0 - t_{0s} \qquad \Delta u_0 = \left| u_0 \pm u_{0S} \right|$$

The current microlensing observation towards the Galactic bulge

- **K2C9:** The observation lasted about 3 months (7/Aprill to 1/July 2016)

  - K2 is moving in an Earth-trailing Solar orbit, the distance from Earth is about **0.5AU**.
  - Equatorial coordinates (RA =$17^h56^m54^s$,Dec =$28^d22^m5^s$)
  - Cadence is 30 min
  - The threshold amplification $\mathbf{A_{th} = 1.004}$

  (Vanderburg, A. & Johnson, J.A. 2014, PASP, 126, 948)

- **Spitzer:** The first observation lasted from June 18 to July 26 (13 days overlap with K2C9)

  - It is moving in an Earth-trailing Solar orbit, the distance from Earth is about **1.48AU**
  - The threshold amplification $\mathbf{A_{th} = 1.066}$

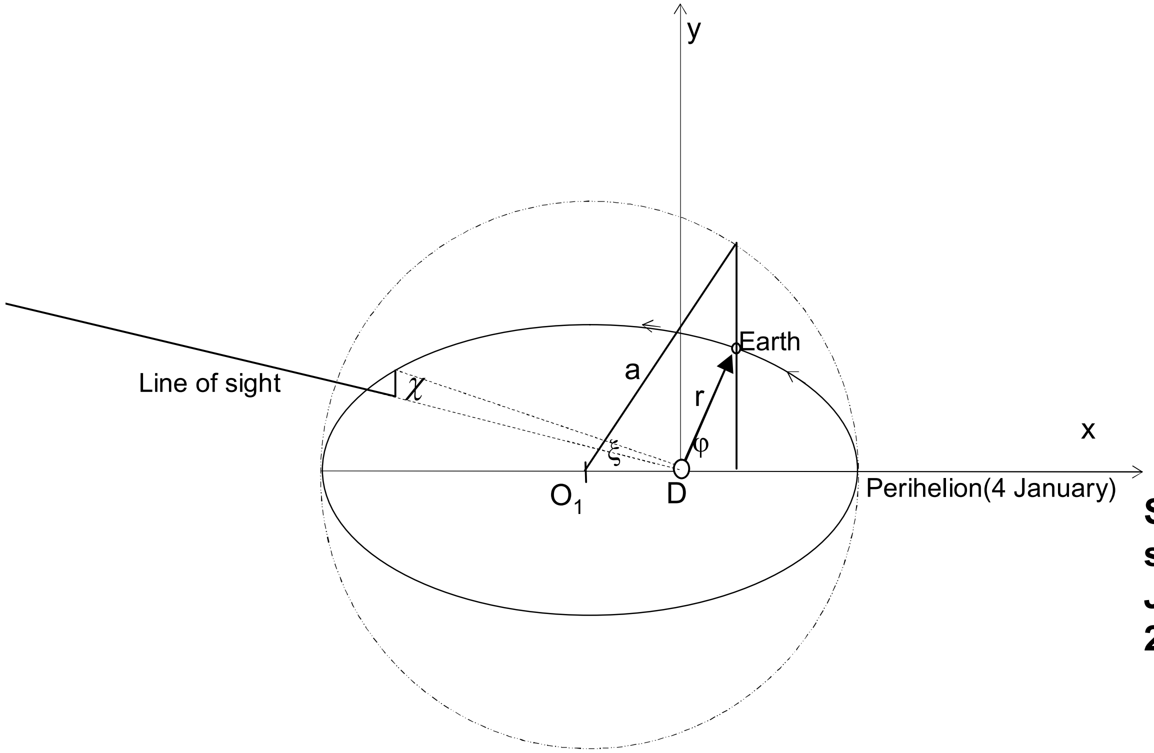
  (Lanotte A.A. et al., 2014, Astron. Astrophys., 572, 73)

- **OGLE** (Optical Gravitational Lensing Experiment)

  - The threshold amplification $\mathbf{A_{th} = 1.028}$

  (http://ogle.astrouw.edu.pl/ogle4/ews/ews.html)

The current microlensing observation towards the Galactic bulge



ξ_0 =105°(April)

ξ_0 =135°(May)

ξ_0 =165°(June)

ξ_0 =195°(July)

ξ_0 =225°(Aug)

ξ_0=255°(Sept)

ξ_0 =285°(Nov)

K2C9 survey since 7/April to 1/July 2016

Spitzer starts on June 18, 2016

K2C11 survey since 24/September to 8/December 2016

The parameters of K2C9's line of sight towards the Galactic bulge are $\varphi \simeq 166.7^\circ$ and $\chi \simeq -4.9^\circ$.

Dominik. M A&A. 329, 361–374 (1998)

Free-floating planets (FFPs)

- **Population of objects with M < 0.01MSun**
  - Direct observations in Sigma Orionis and Taurus (*Zapatero Osorio et al. 2000*)
  - Gravitational microlensing towards Galactic Bulge (*Sumi et al. 2011*)

- **Unbound to a host star or very distant (over 100 AU)**
- **Their origin is uncertain**

  -These objects were originally formed in protoplanetary disks and were subsequently ejected.

  - These objects formed via direct collapse of molecular clouds.

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

Free-floating planets (FFPs)

- **Mass function of FFPs :**

$$\frac{dN}{dM} \sim M^{-\alpha_{PL}} \qquad \alpha_{PL} = 1.3^{+0.3}_{-0.4} \qquad 10^{-5} M_{Sun} < M < 10^{-2} M_{Sun}$$

Sumi, T. et al., 2011, Nature, 473, 349

- **Spatial distribution of FFPs:**

a) triaxial bulge with mass density given by

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

b) double exponential disk with mass density given by

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

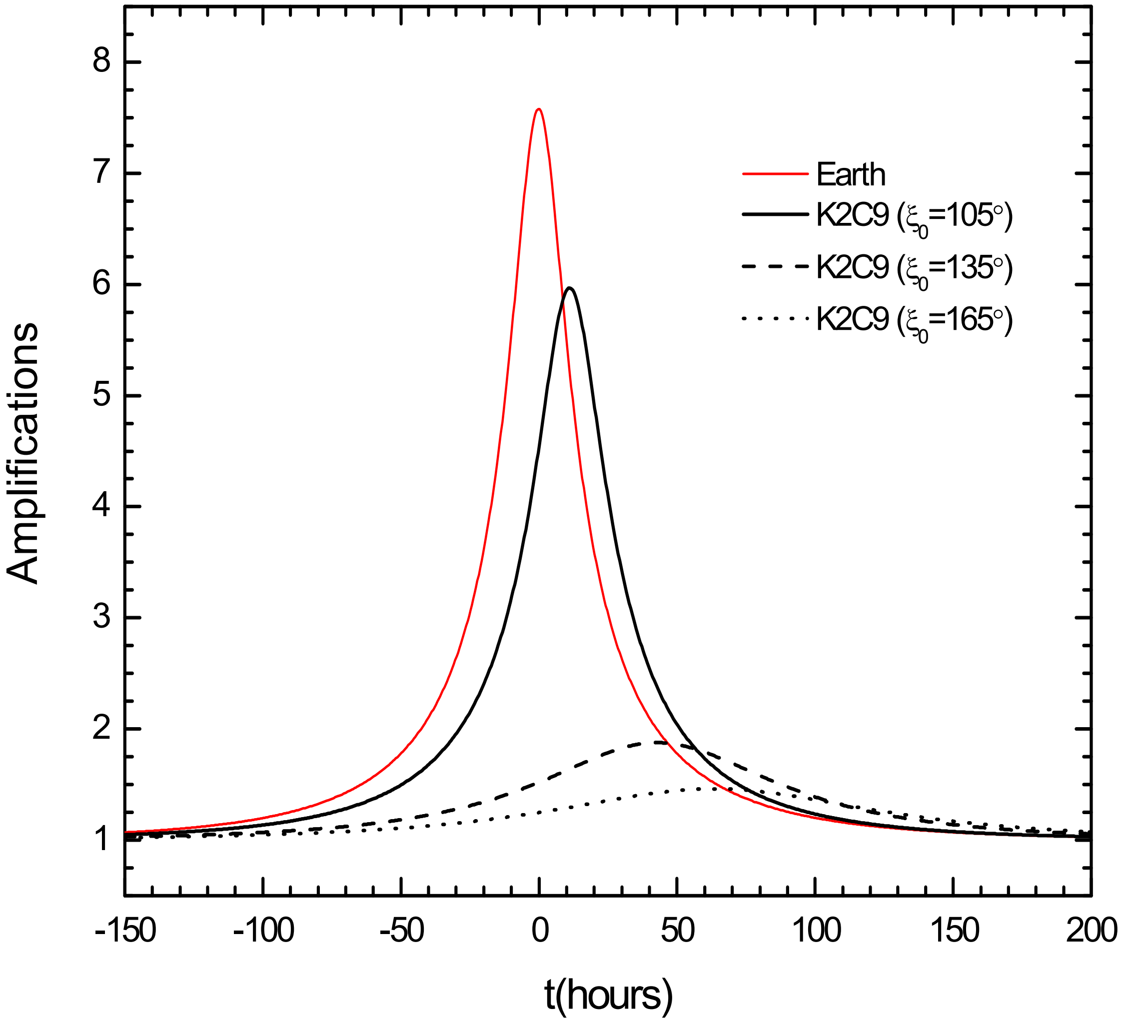
Hafizi, M. et al., 2004, Int. Journ. Mod. Phys. D, 13, 1831

- **Velocity distribution of FFPs:**

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

Han, Ch. & Gould, A. 1995, Astrophys. J., 447, 53

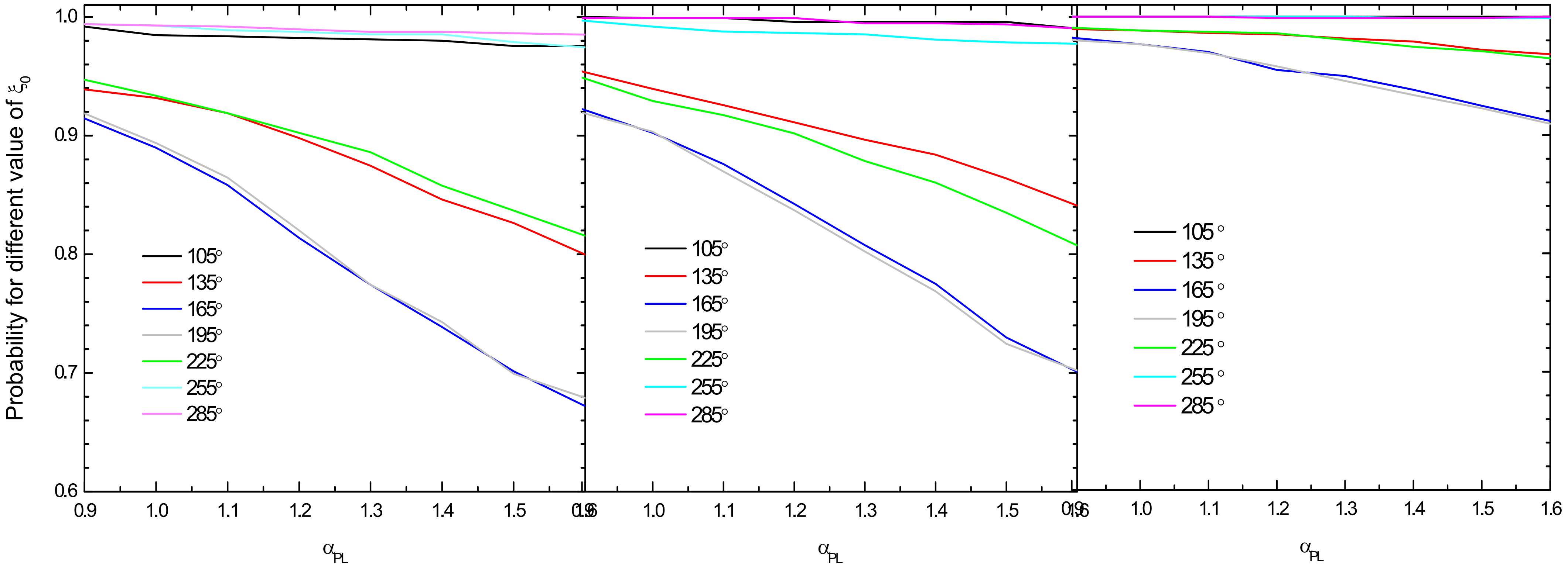
Results Earth-K2



Simulated light curves for an event with $T_E \simeq 76\,h$ as observed by the Earth and by K2 for different values ξ_0: 105° ($\Delta t_0 \simeq 11.5$h; $\Delta u_0 \simeq 0.3$) , 135° ($\Delta t_0 \simeq 43.5$h; $\Delta u_0 \simeq 0.7$) and 165° ($\Delta t_0 \simeq 64.3$h; $\Delta u_0 \simeq 0.99$).

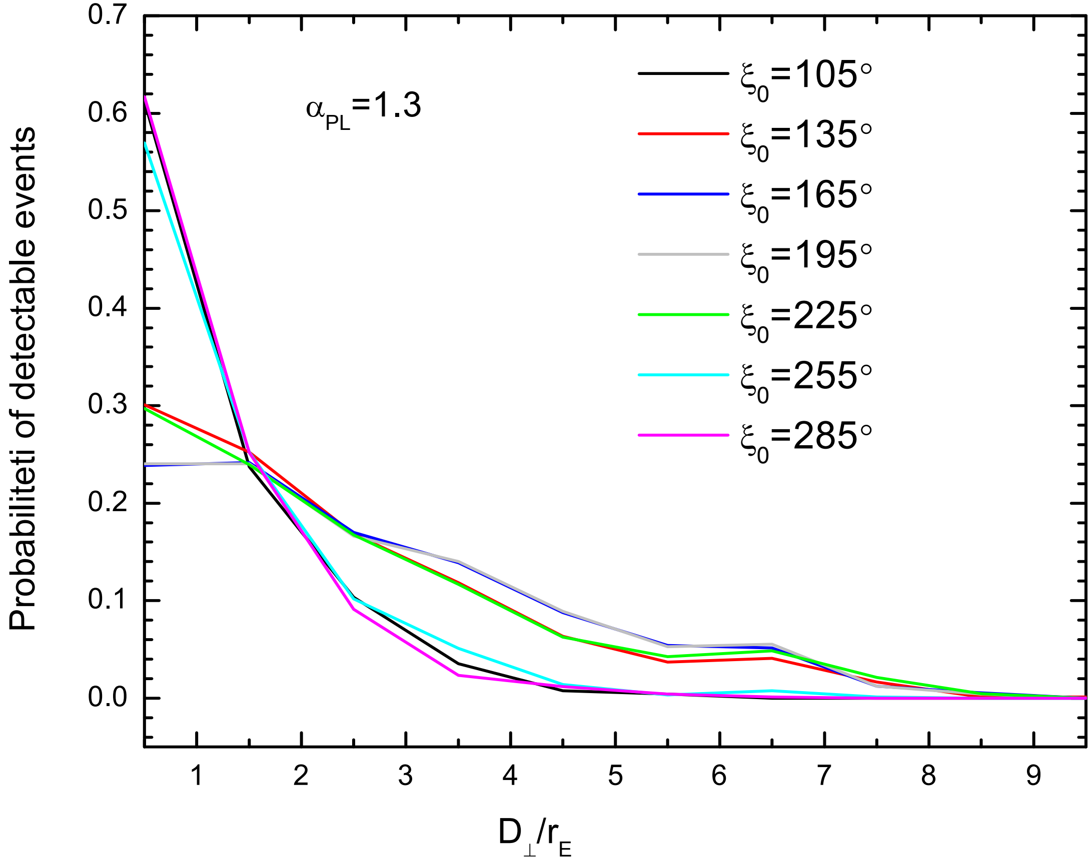
Results Earth-K2

Probability, for different value of ξ_0, that a microlensing event caused by a FFP is detectable by Earth and K2 as a function of α_{PL} for three different distributions of FFPs: thin disk (left panel), thick disk (middle panel) and bulge (right panel).

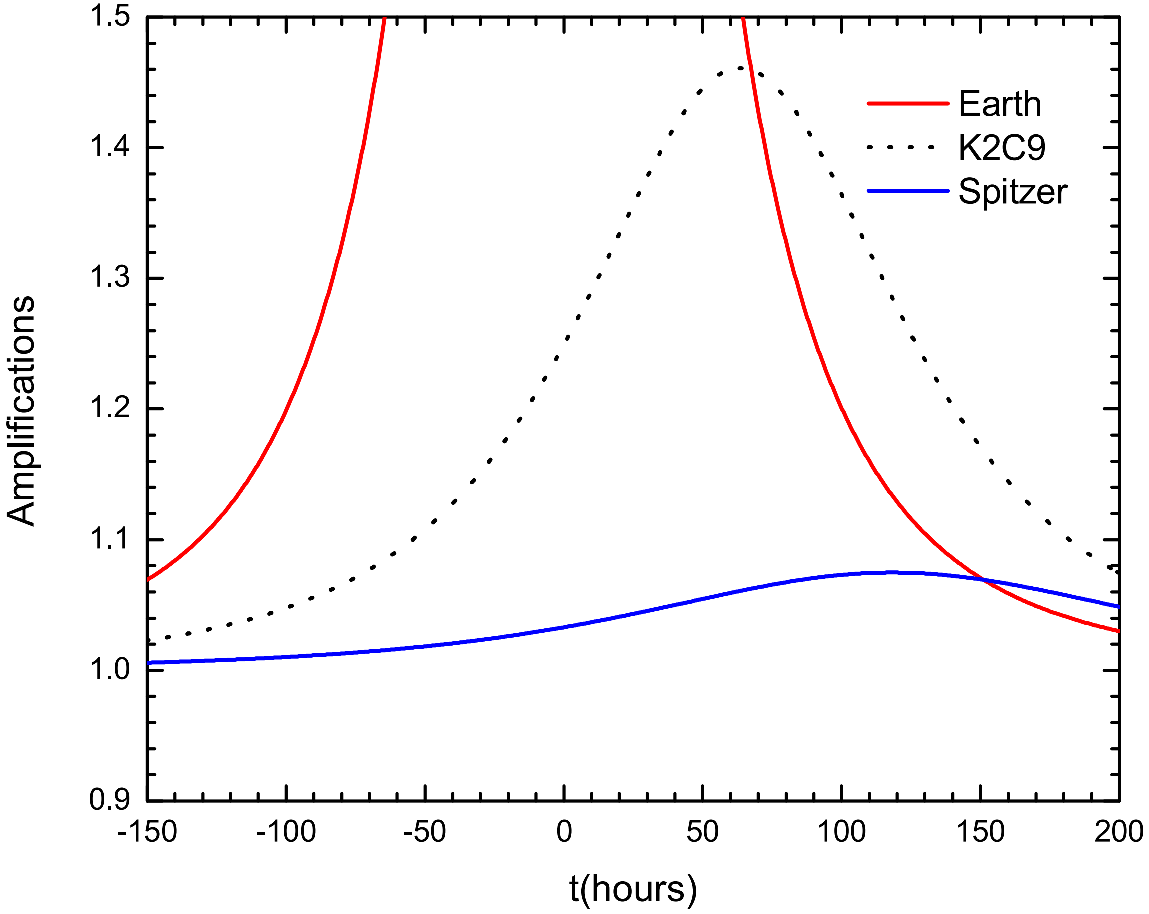


Results Earth-K2

The probability that a microlensing event caused by FFPs in thin disk is detectable by the ground-based telescope and by K2 as a function of **$D_{\perp}/r_E$** for different values **ξ_0** and for **α_{PL}=1.3.** As one can see the detection probability for events with **$D_{\perp} \leq 2r_E$** gets the largest value at the beginning of the K2C9 campaign and decreases towards its end.



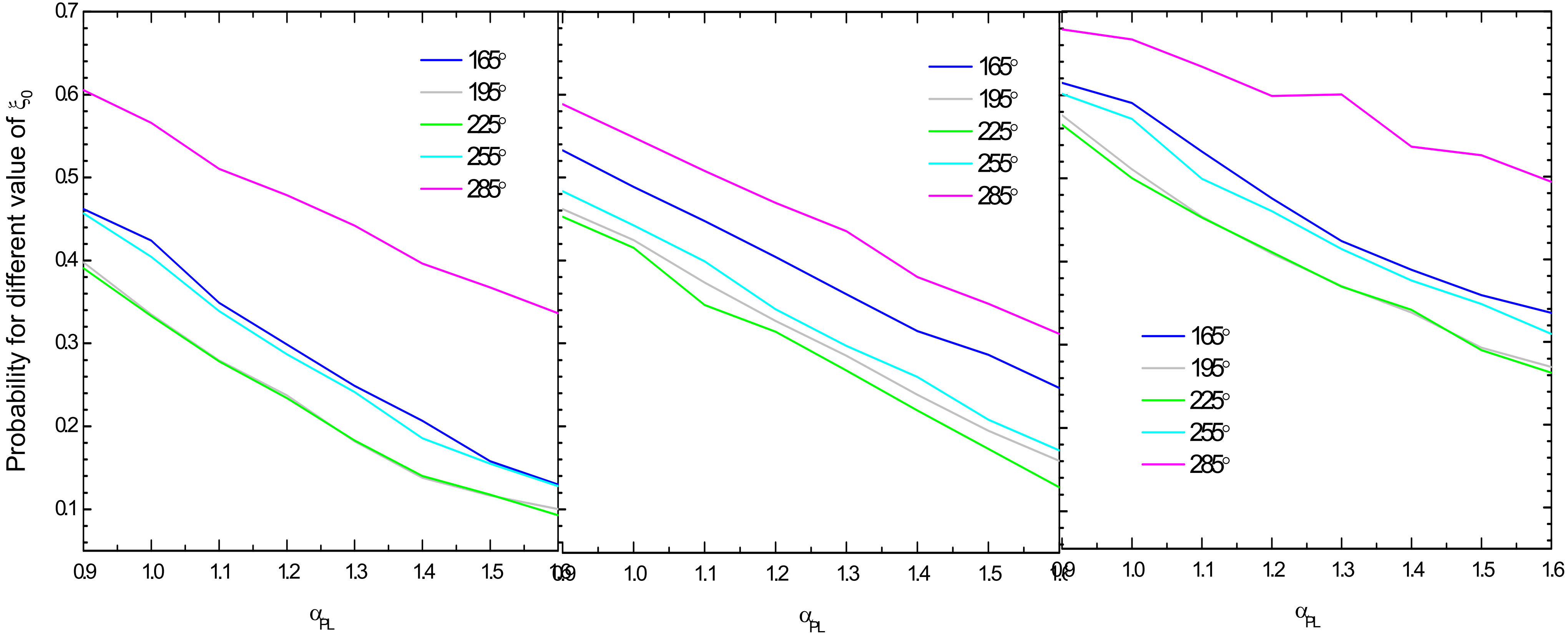
Results Earth-Spitzer



Simulated light curves as observed by three telescopes for the value of **ξ_0=165°** ($\Delta t_0 \simeq 119$h; $\Delta u_0 \simeq 1.99$), $D_\perp$(E-K2)=0.47AU and $D_\perp$(E-S)=0.96AU. The event parameters are the same as with the figure above.

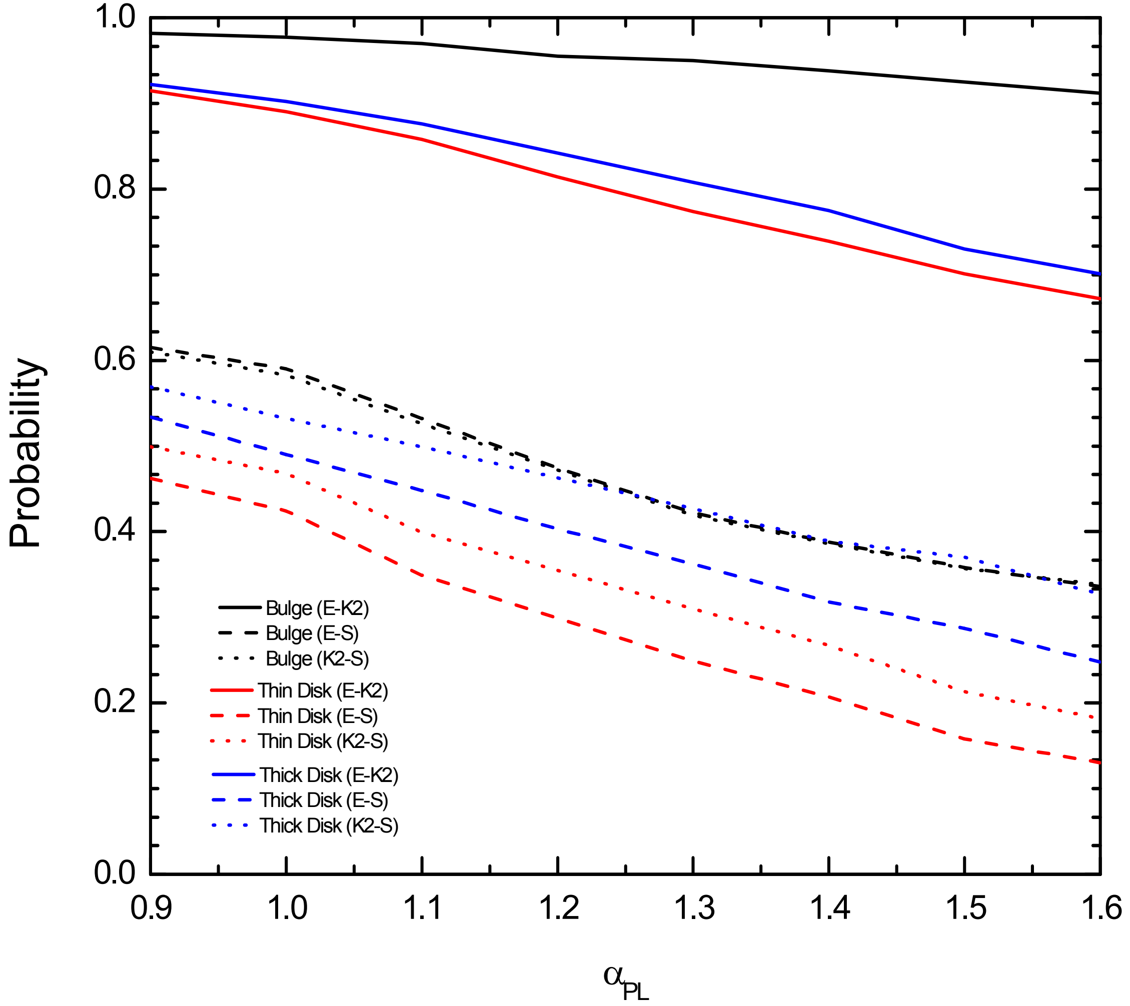
Results Earth-Spitzer

Probability, for different values of ξ_0, that a microlensing event caused by a FFP is detectable by Earth and K2 as a function of α_{PL} for three different distributions of FFPs: thin disk (left panel), thick disk (middle panel) and bulge (right panel).



Results Earth-K2C9-Spitzer

Probability that a microlensing event caused by a FFP is detectable by different pairs of telescopes: **Earth-K2C9**, **Earth-Spitzer** and **K2C9-Spitzer**, as a function of $\boldsymbol{\alpha}_{PL}$, during the 2 weeks of observational overlap. As usual we consider three different FFP distributions: bulge (black curves), thin disk (red lines) and thick disk (blue lines).



Conclusions

- The detection probability of a FFP microlensing event by Earth and K2C9 telescopes is larger at the beginning of the compaign while decreases towards the end of it.

- The detection probability by Earth and Spitzer telescopes results smaller with respect to the Earth-K2C9 case because its threshold and the projected separation from Earth is larger.

- The probability that a FFP microlensing event is detectable contemporarily by three telescopes (Earth, K2C9, Spitzer), results to be the same as for the Earth-Spitzer detection.

Thank you