

Soczewkowanie grawitacyjne 4

- Przypomnienie
- Soczewki podwójne
- Soczewki planetarne
- Równanie na obrazy w modelu kosmologicznym

Wzmocnienie w pobliżu kaustyki

$$\vec{b} \stackrel{def}{=} (x, y) \quad \vec{b}_0 \stackrel{def}{=} (x_0, y_0)$$

$$\|A_{ij}\| = \begin{vmatrix} 0 & 0 \\ 0 & c_y \end{vmatrix}$$

$$x_0 = 0 + \frac{1}{2}c_{xx}x^2 \quad y_0 = 0 + c_y y$$

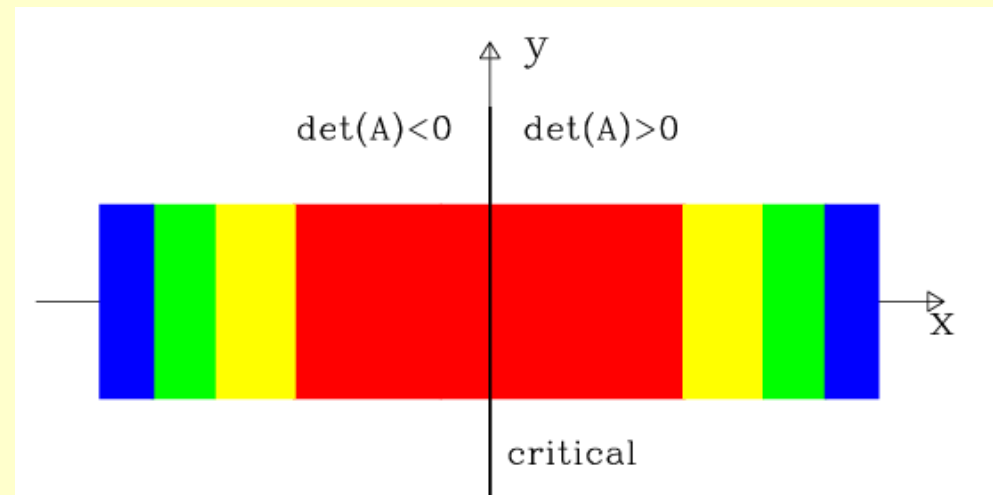
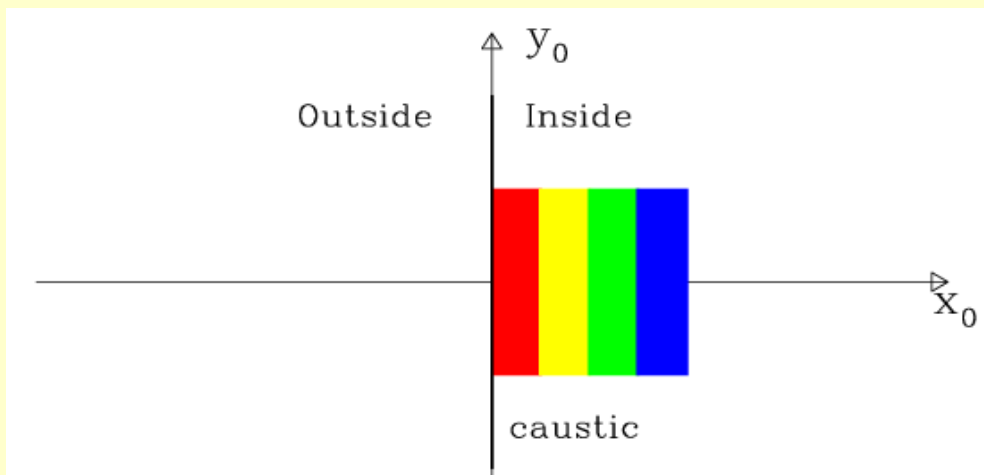
$$x_{1,2} = \pm \sqrt{\frac{2x_0}{c_{xx}}} \quad y = \frac{y_0}{c_y}$$

$$\mathcal{M} = \left| \frac{dx_1 dy}{dx_0 dy_0} \right| + \left| \frac{dx_2 dy}{dx_0 dy_0} \right| = \sqrt{\frac{2}{c_{xx} c_y^2 x_0}} \stackrel{def}{=} \sqrt{\frac{d}{x_0}}$$

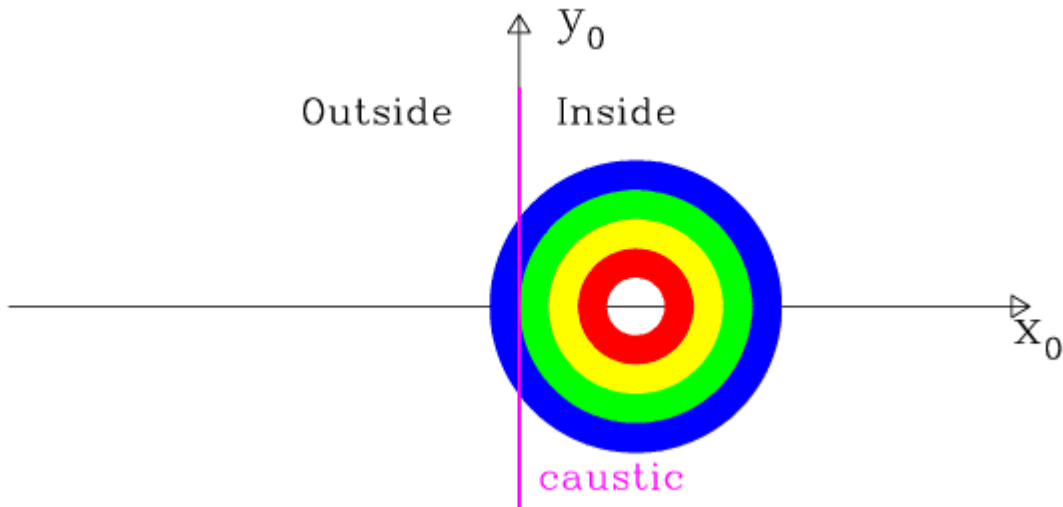
Wybór współrzędnych w otoczeniach punktu na krzywej krytycznej i odpowiadającego mu punktu na kaustyce pozwalają na taką formę zależności.

„Wejście” +2 obrazy

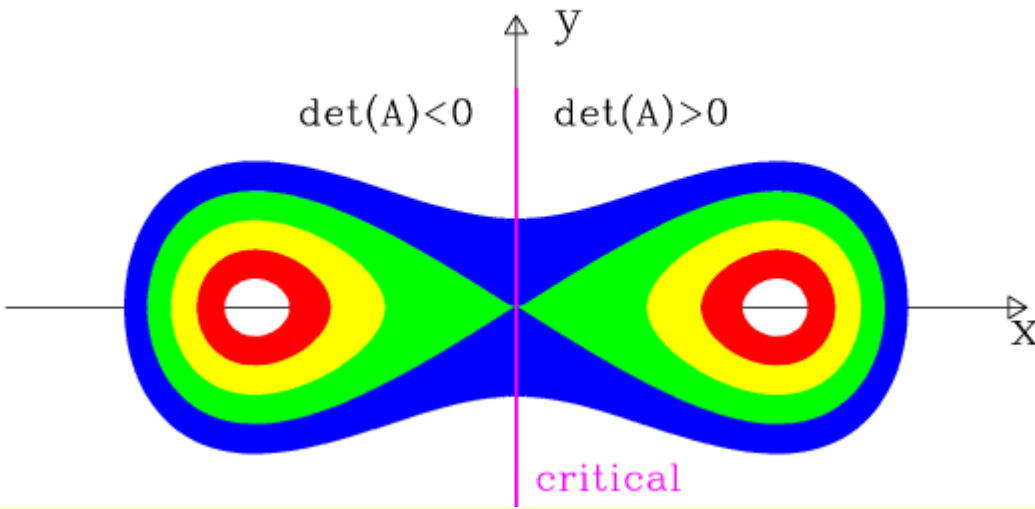
„Wyjście” -2 obrazy



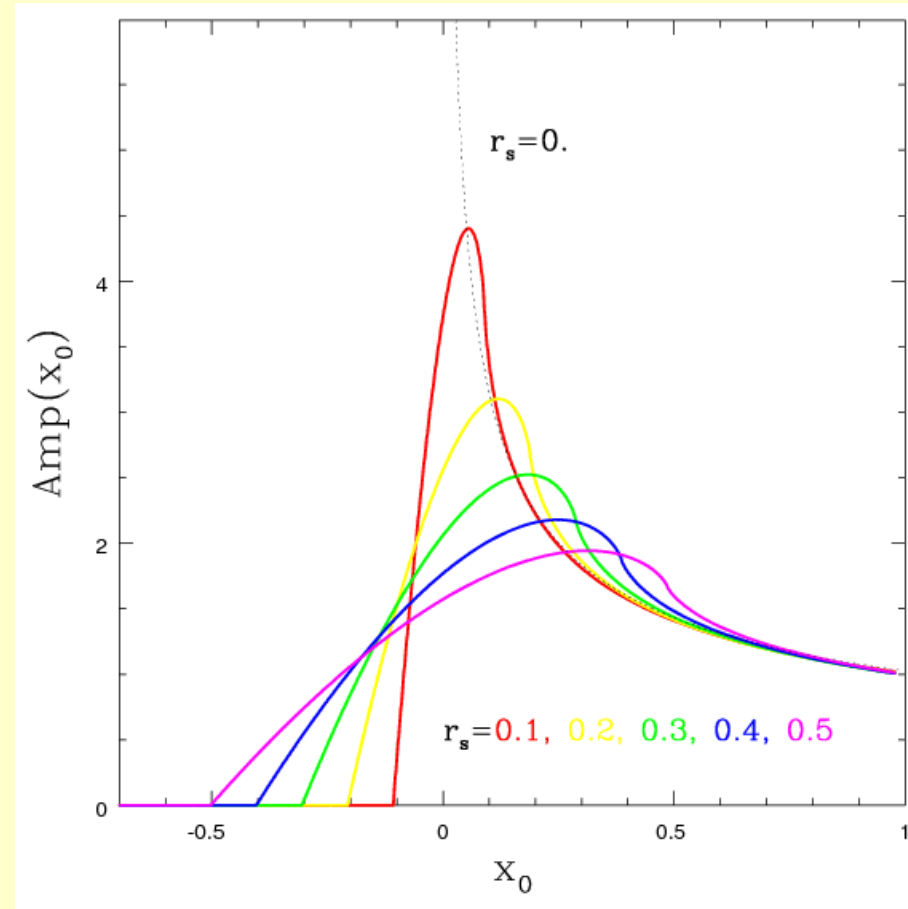
Wzmocnienie w pobliżu kaustyki



Źródło w pobliżu kaustyki...



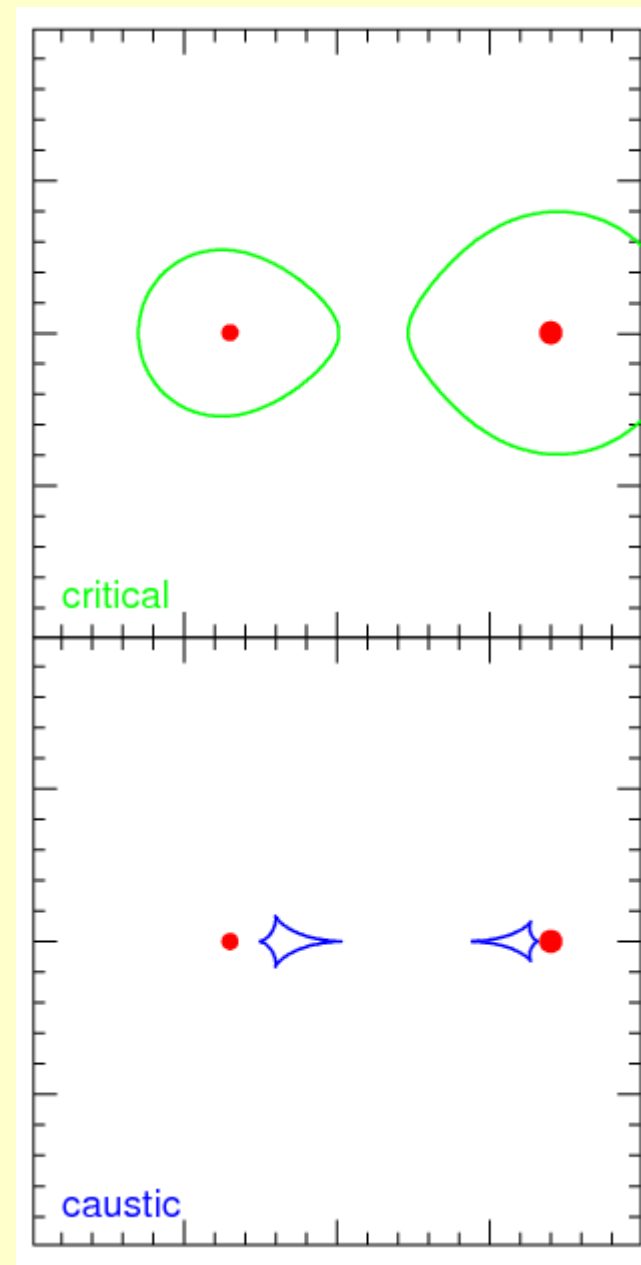
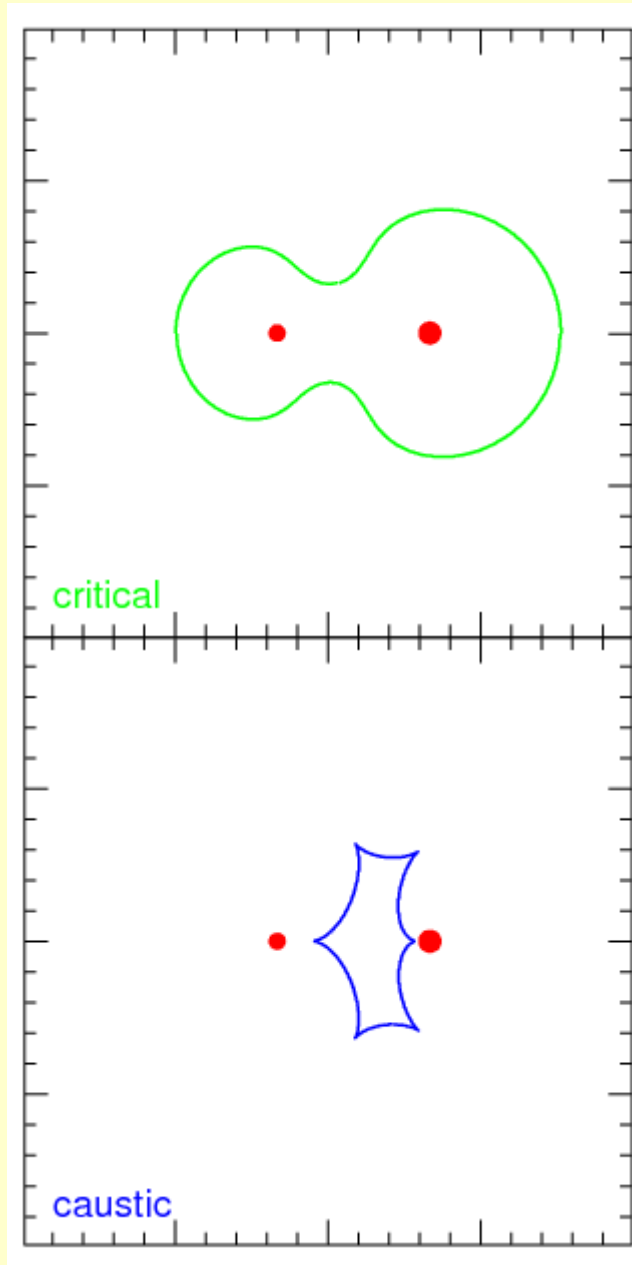
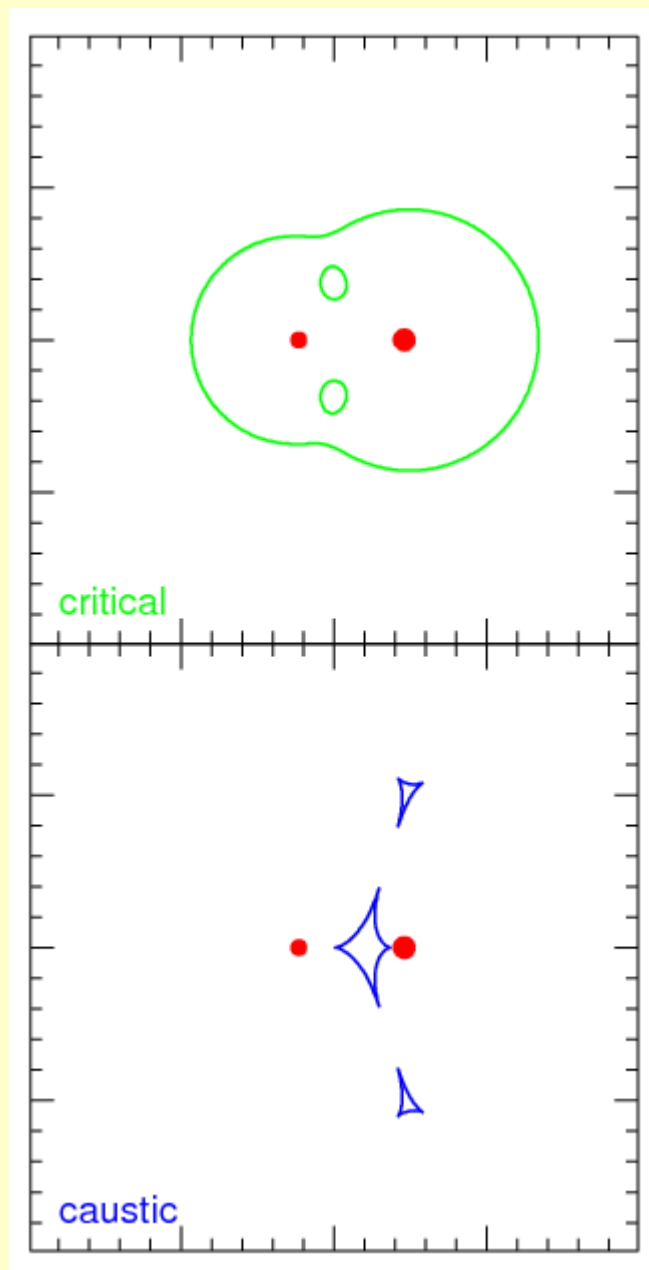
...i jego obrazy w pobliżu linii krytycznej.



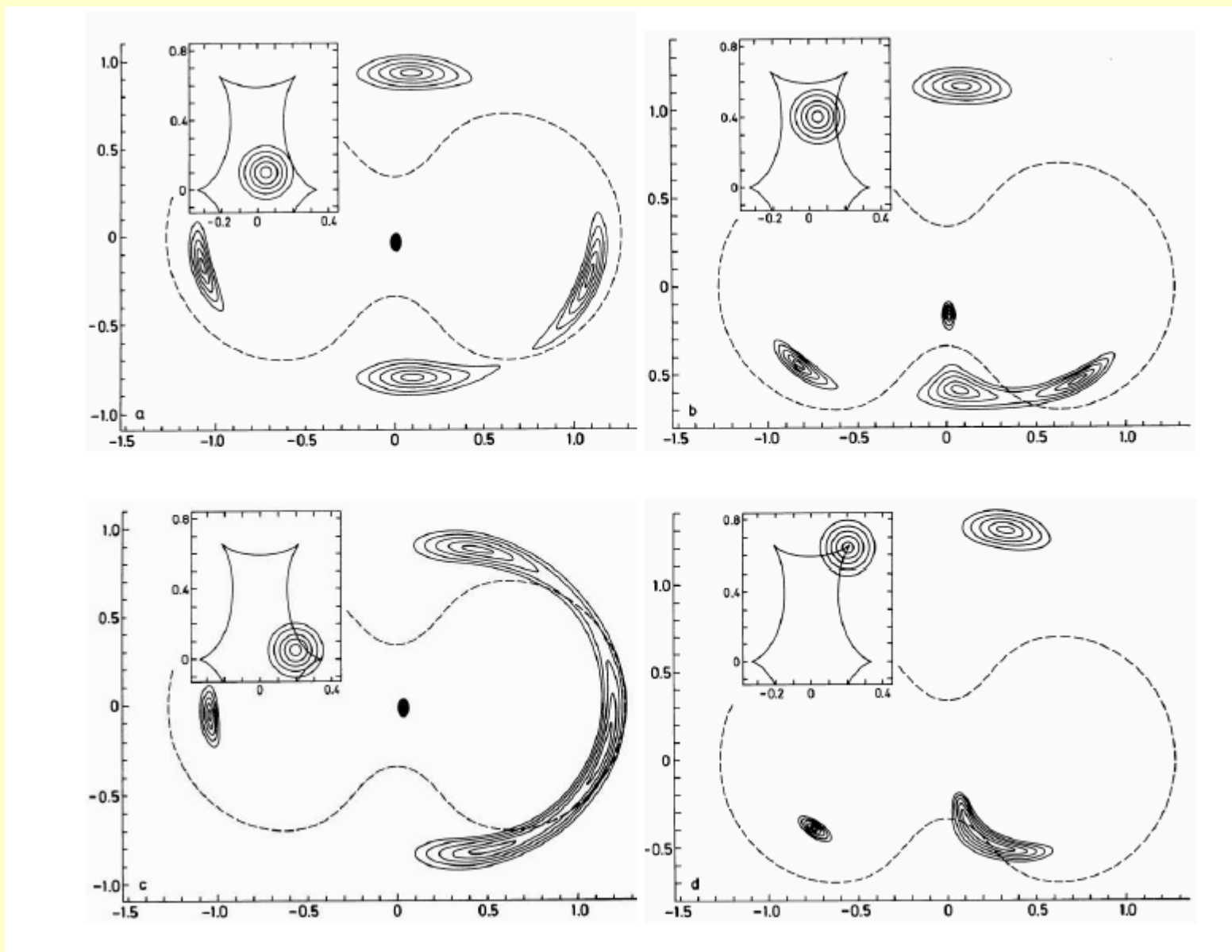
Zależność wzmocnienia od położenia środka kołowej, jednorodnej tarczy względem kaustyki.

\implies względne rozmiary źródła

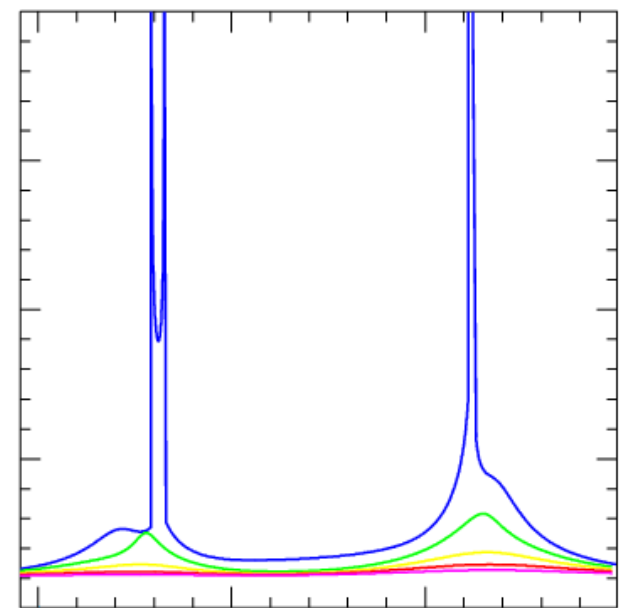
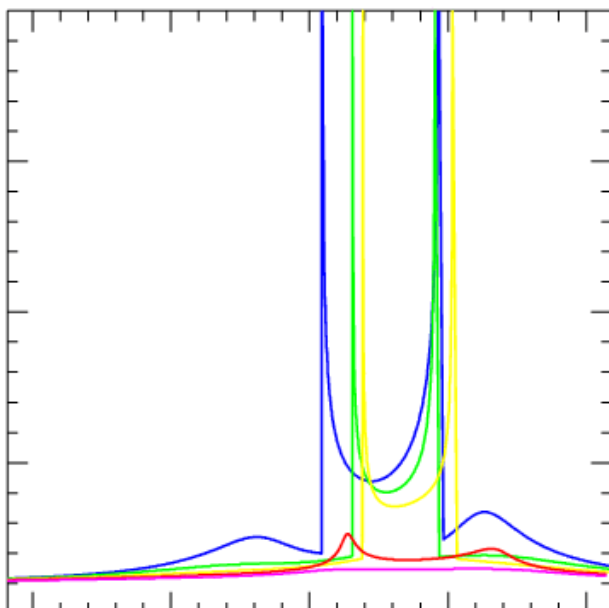
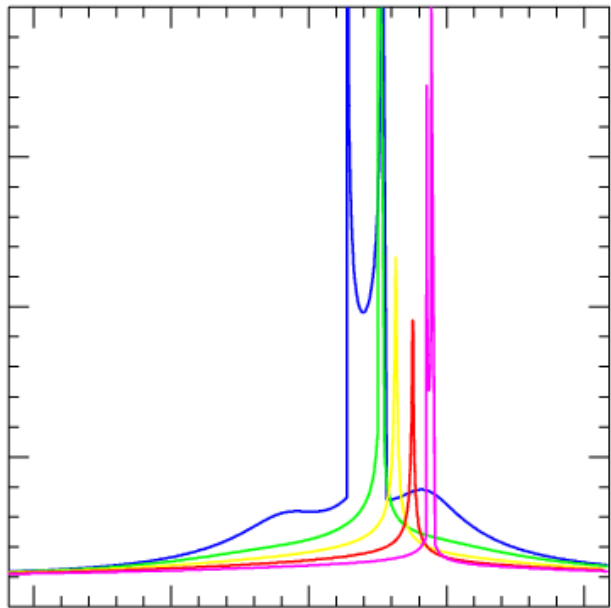
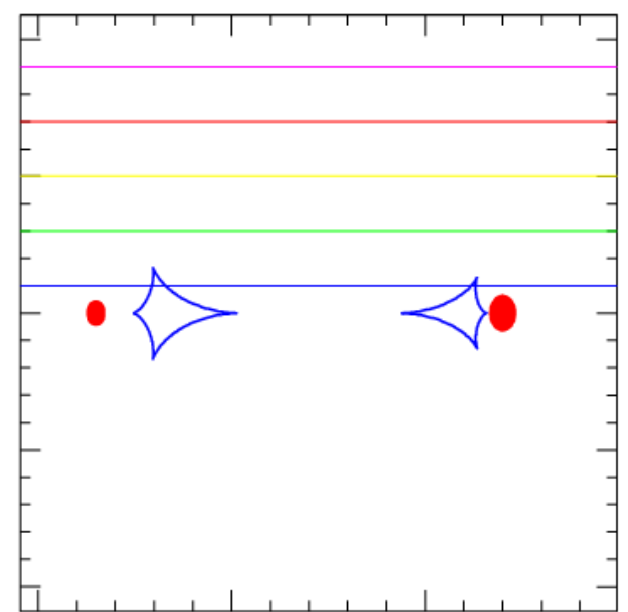
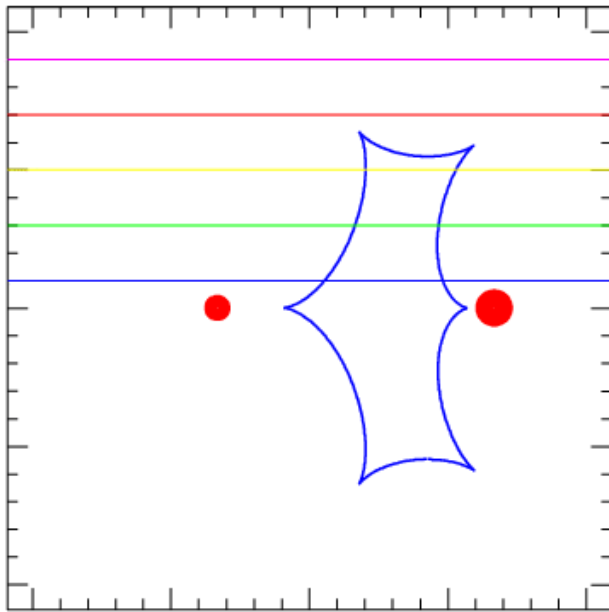
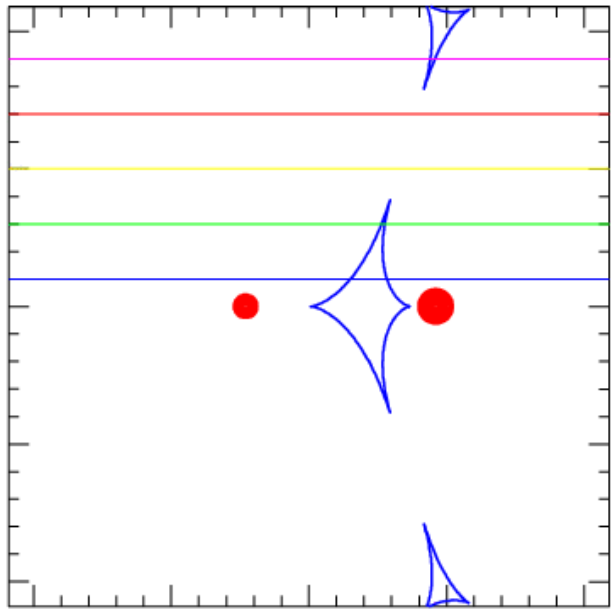
Linie krytyczne i kaustyki: „podwójna”



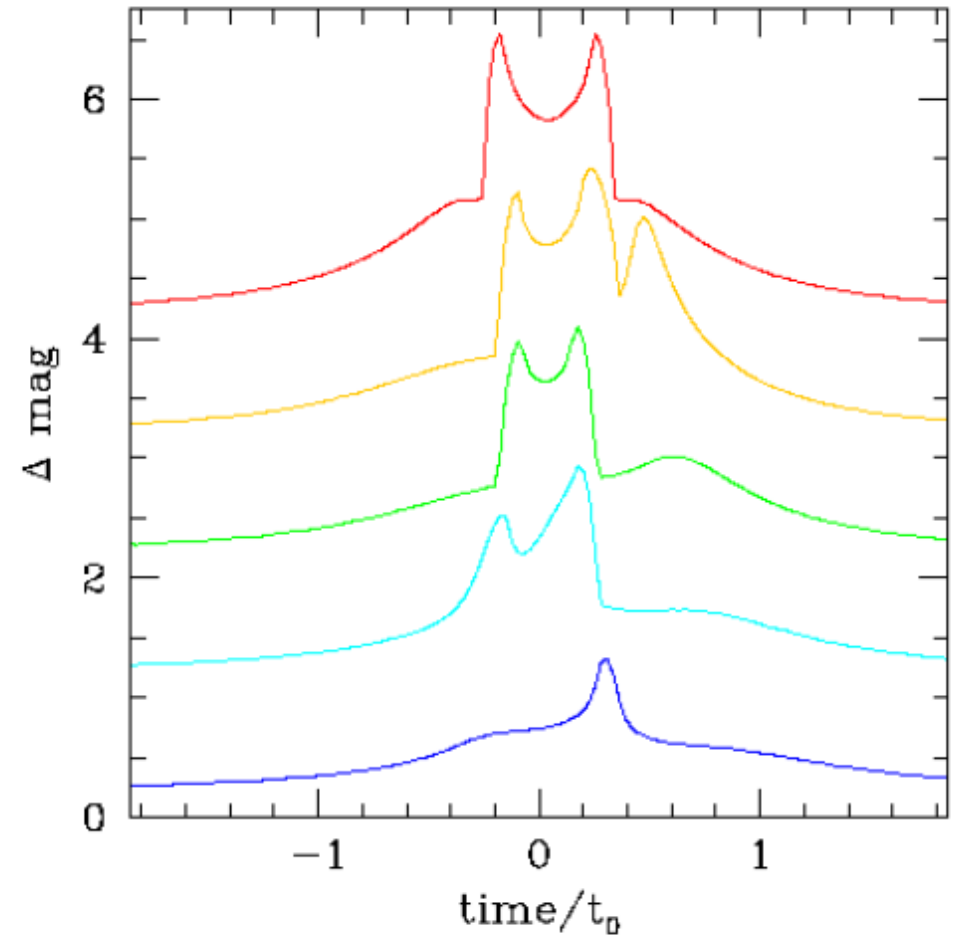
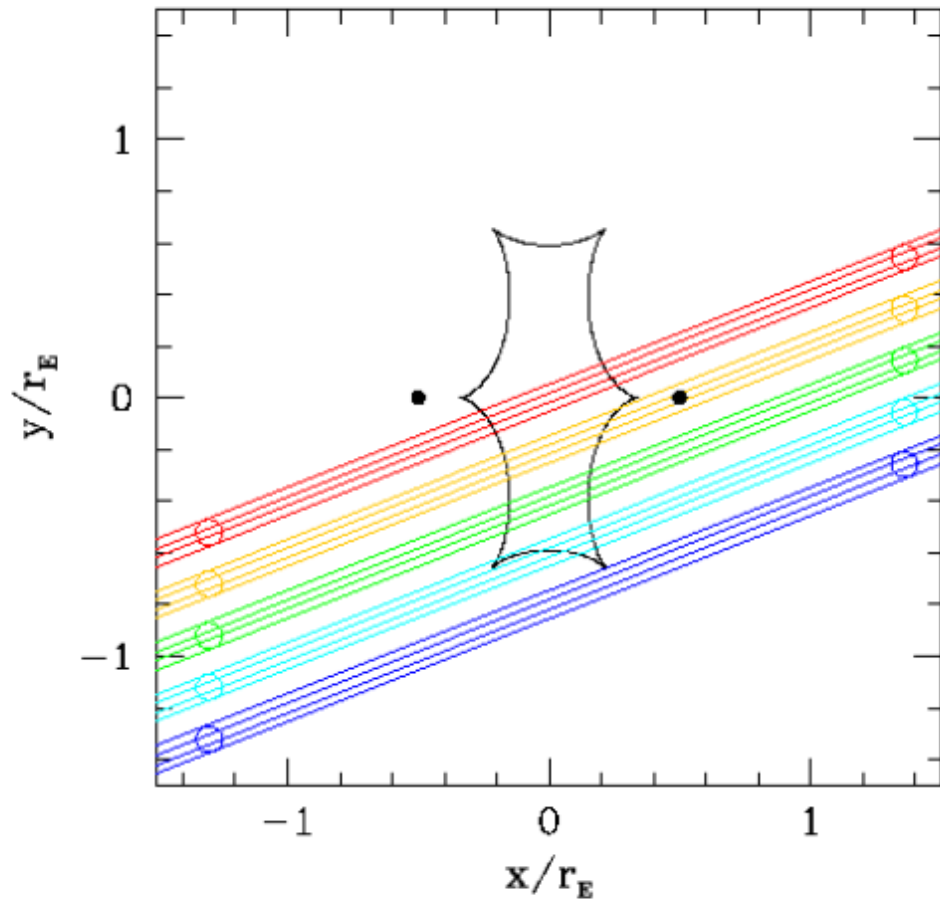
Linie krytyczne i kaustyki: „podwójna”



Krzywe zmian blasku (podwójna)



Krzywe zmian blasku (podwójna)



Wzmocnienie (podwójna)

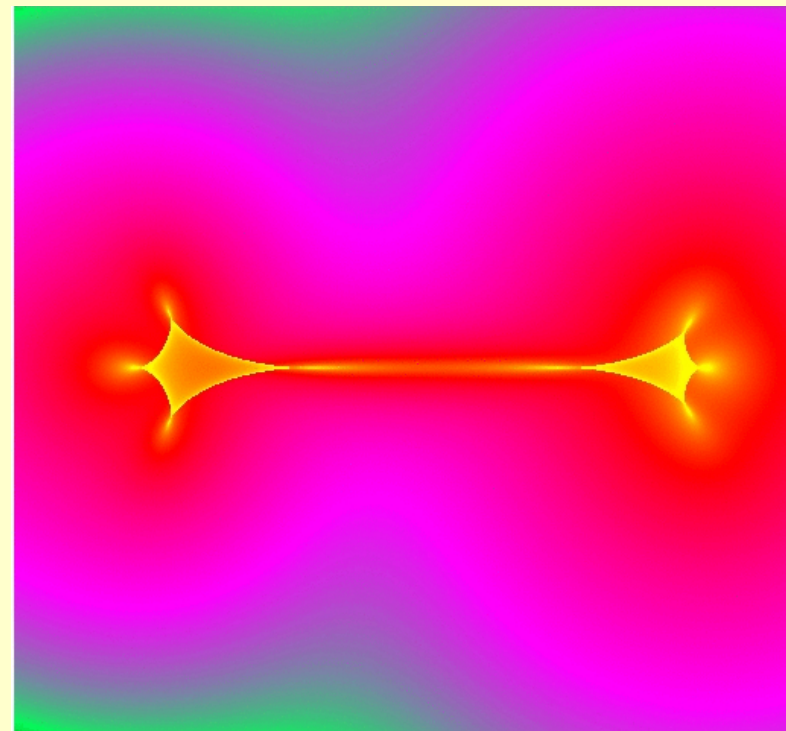
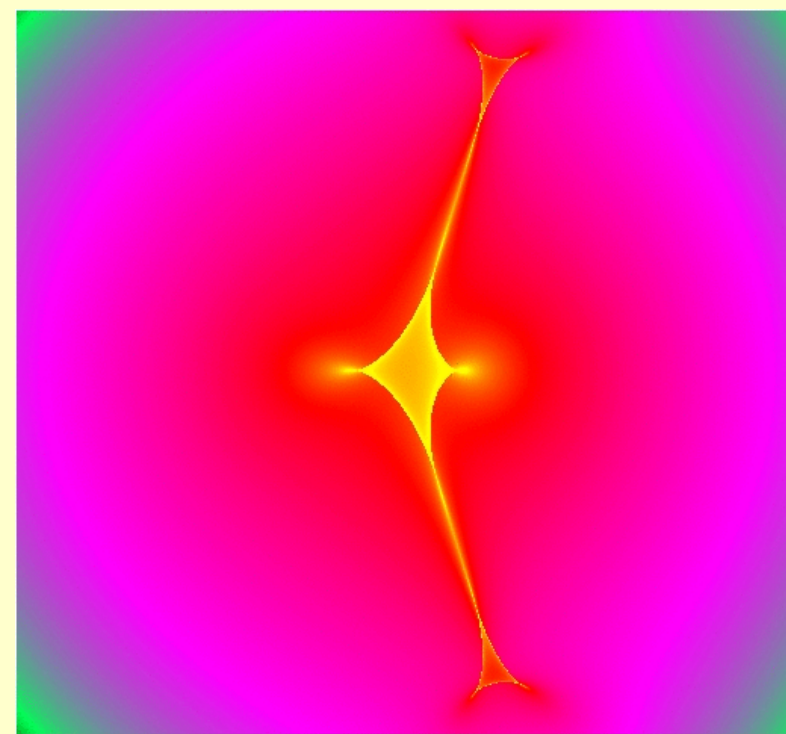
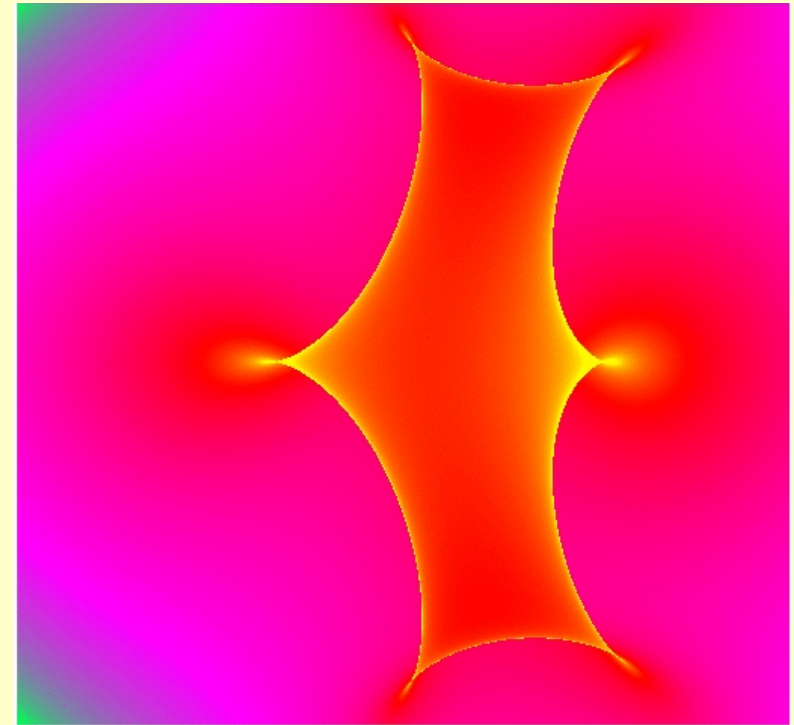
„ciasny” $q=0.5$ $d=0.69$

„pośredni”

$q=0.5$

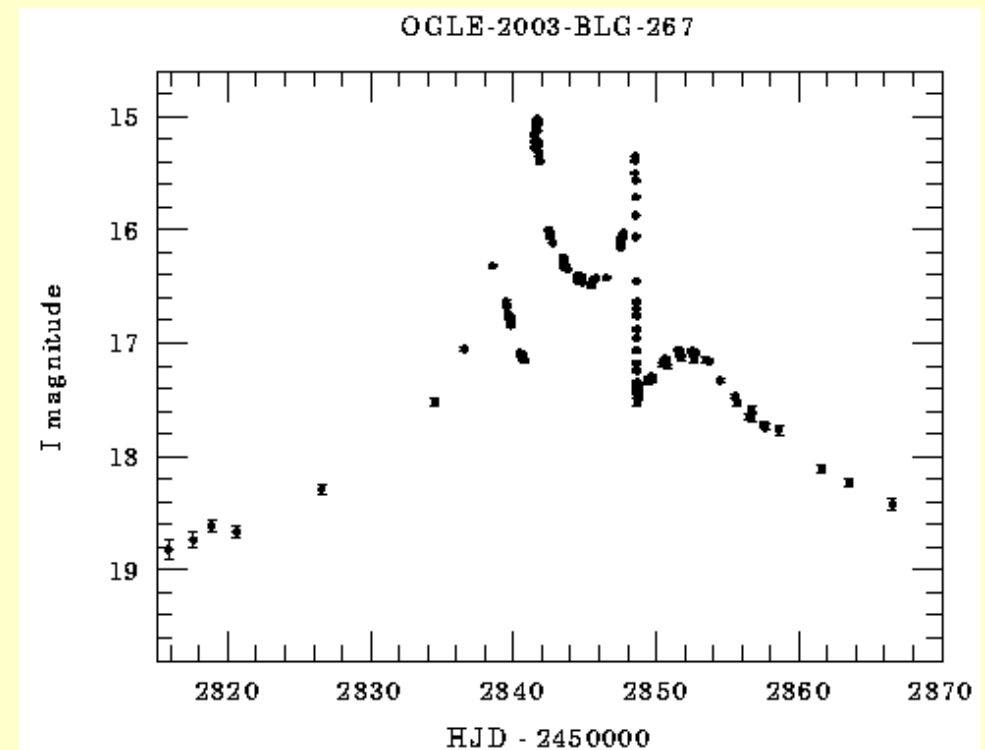
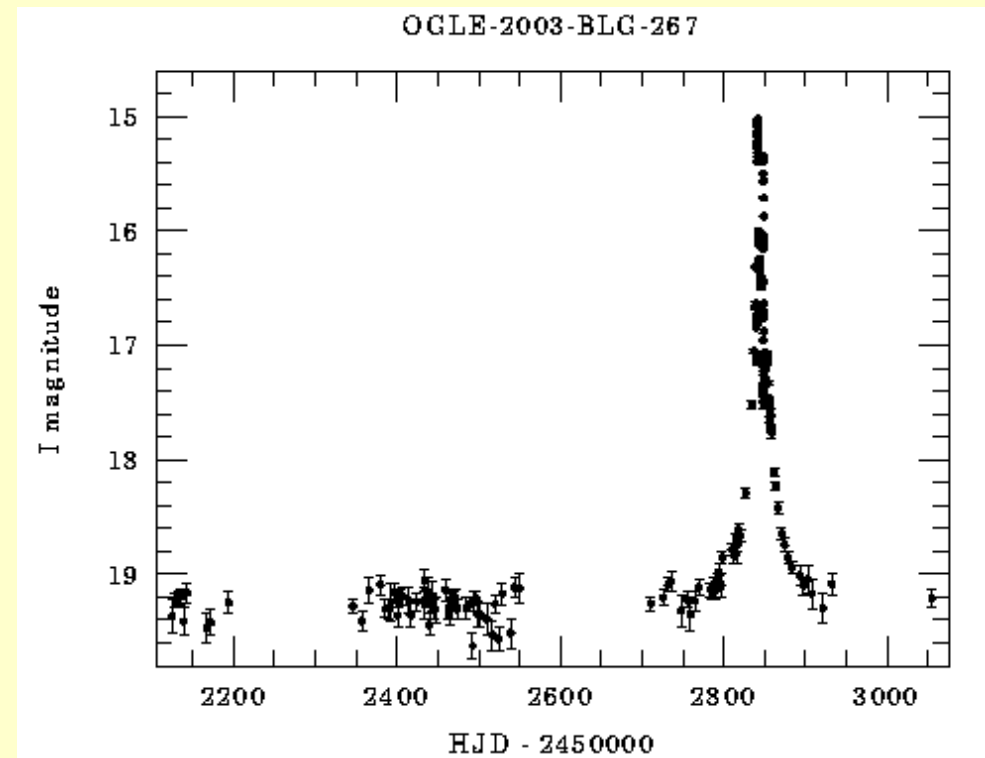
$d=1.0$

„rozległy” $q=0.5$ $d=2.1$

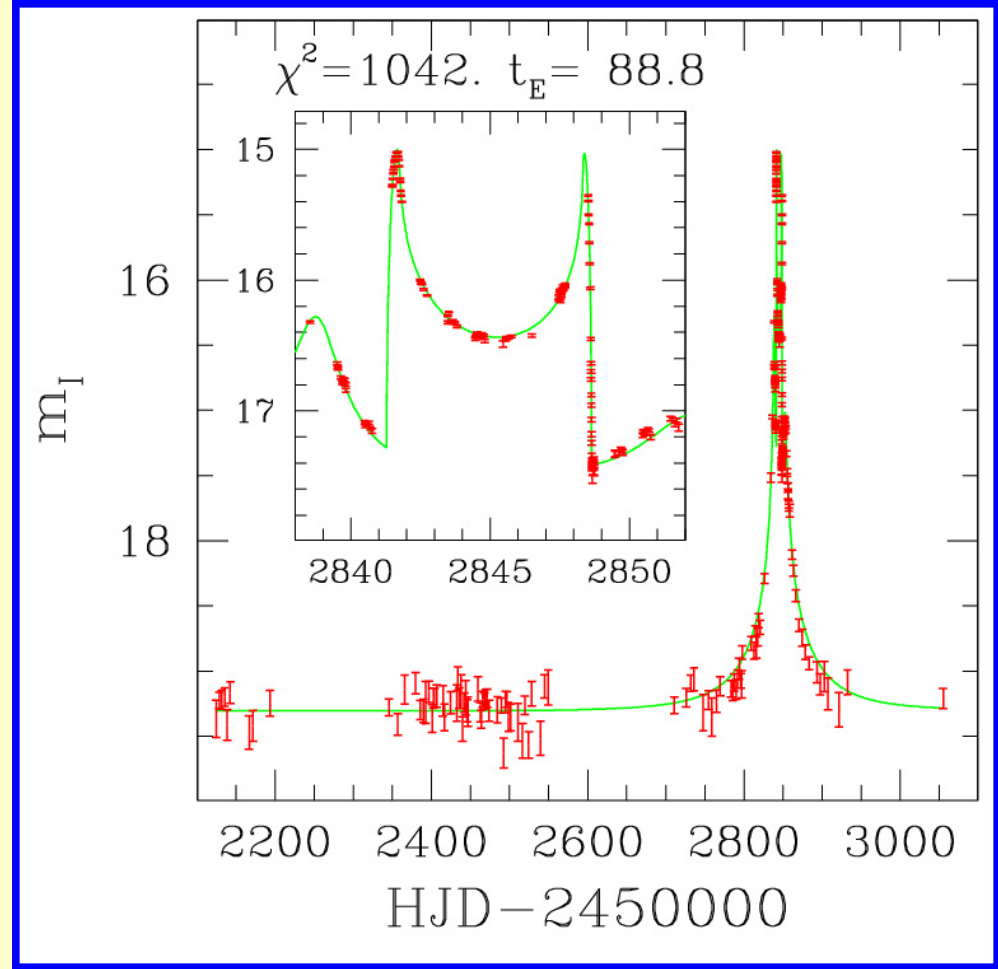
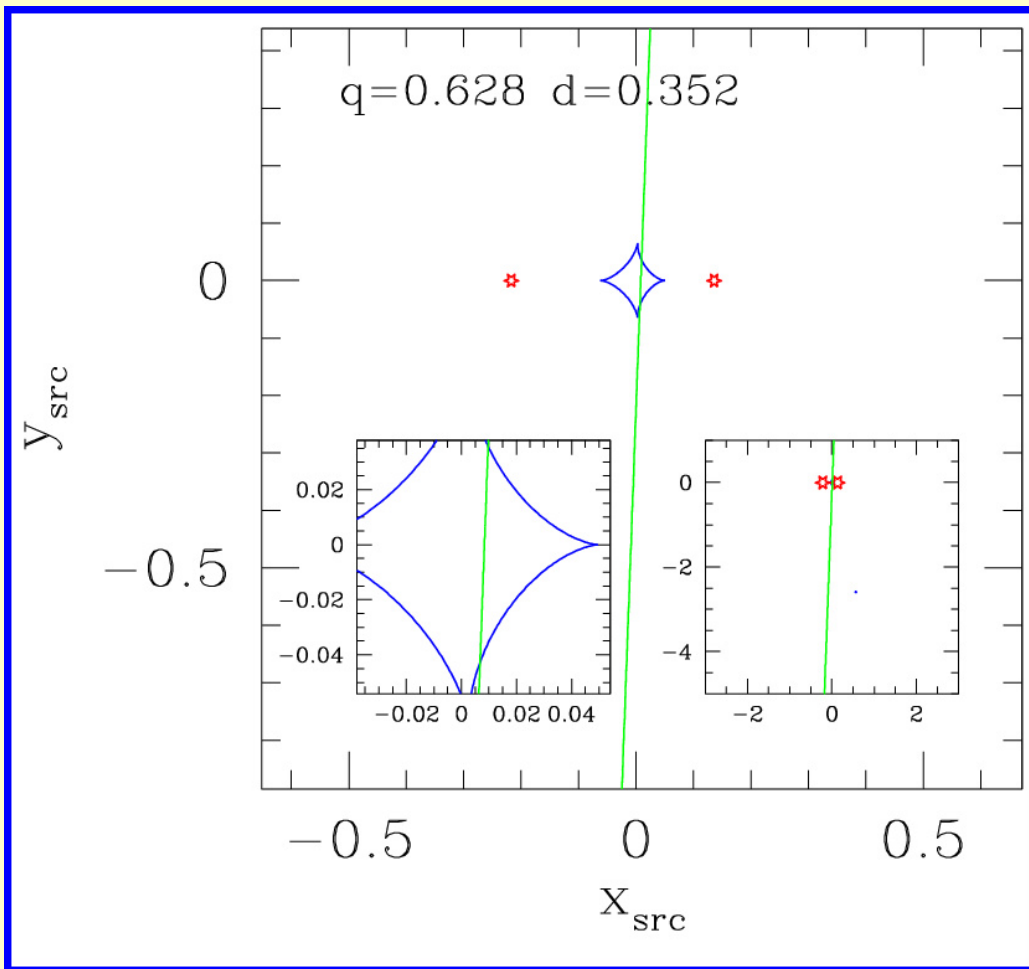


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- T_{max} 2452841.640
(2003-07-21.14 UT)
- $I_0 = 19.22$
- RA (J2000.0) 17:42:28.86
- Dec (J2000.0) -23:27:15.3
- $w_{\text{sp. eklipt}}$ (265.98; -0.076)

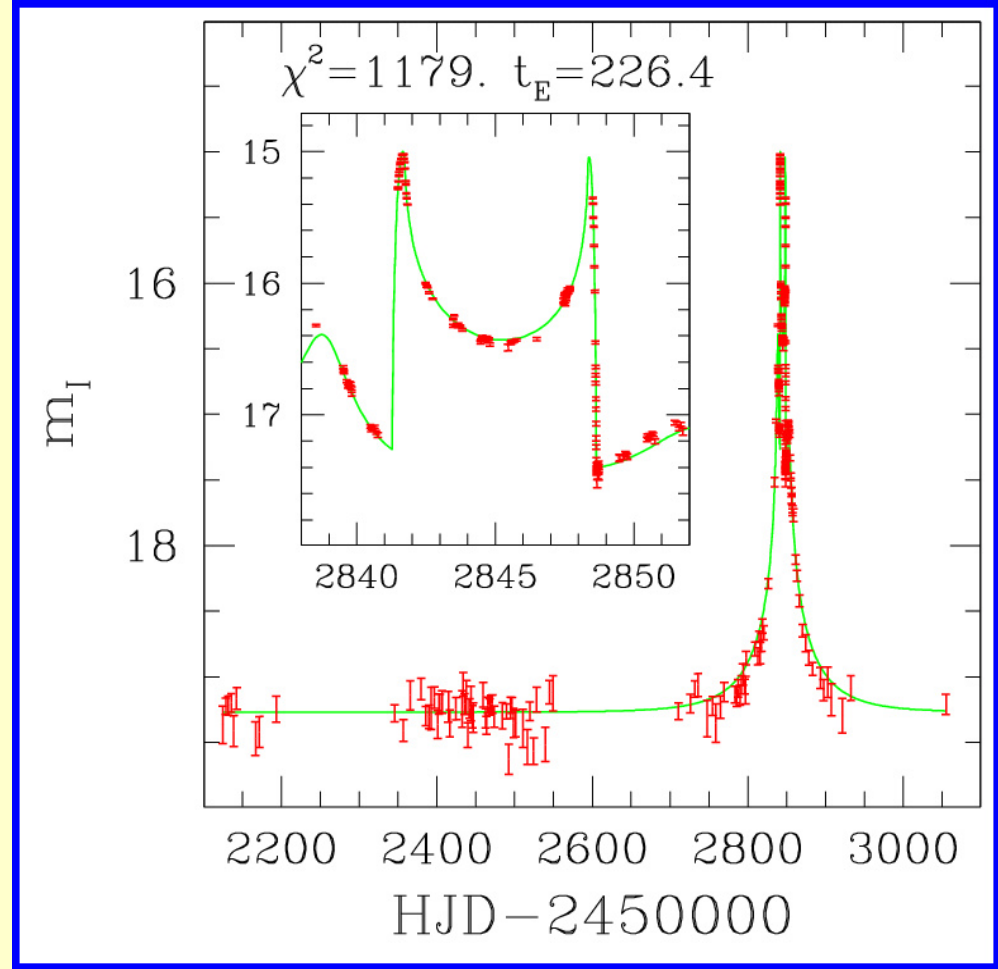
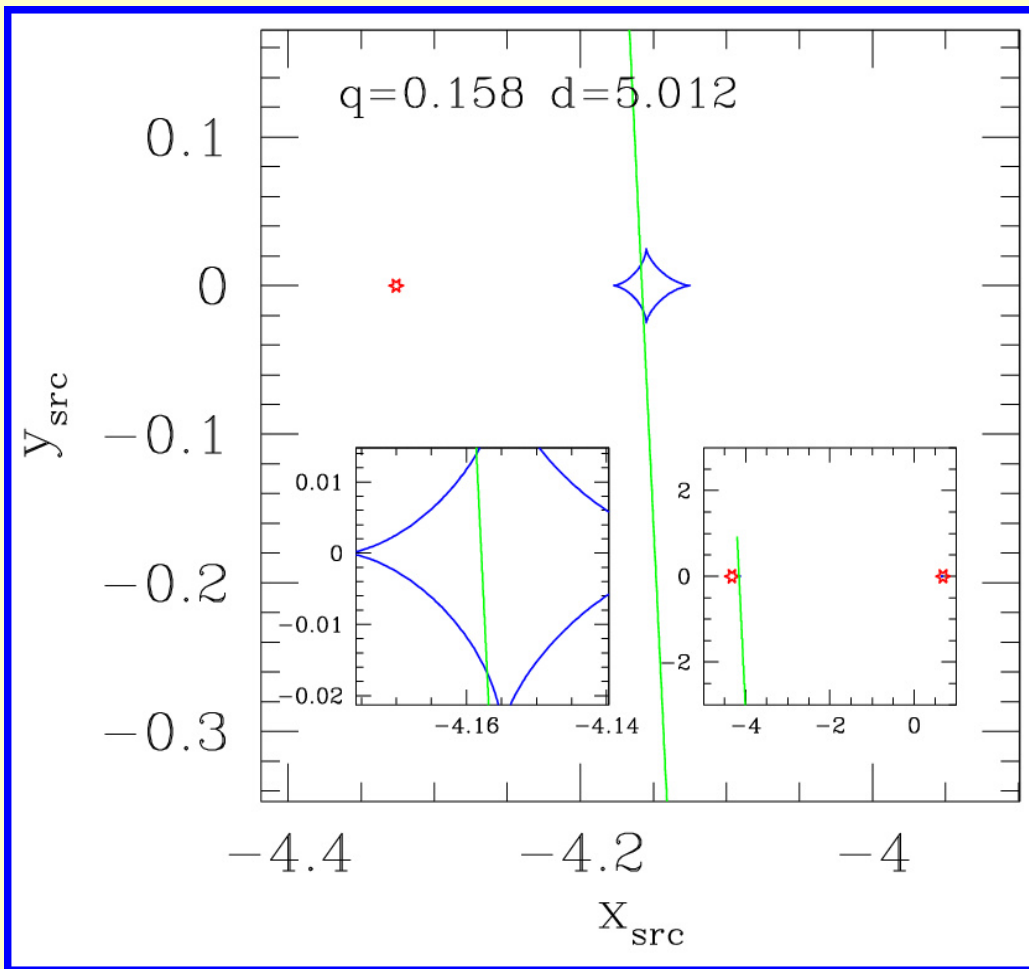


OGLE 2003-BLG-267



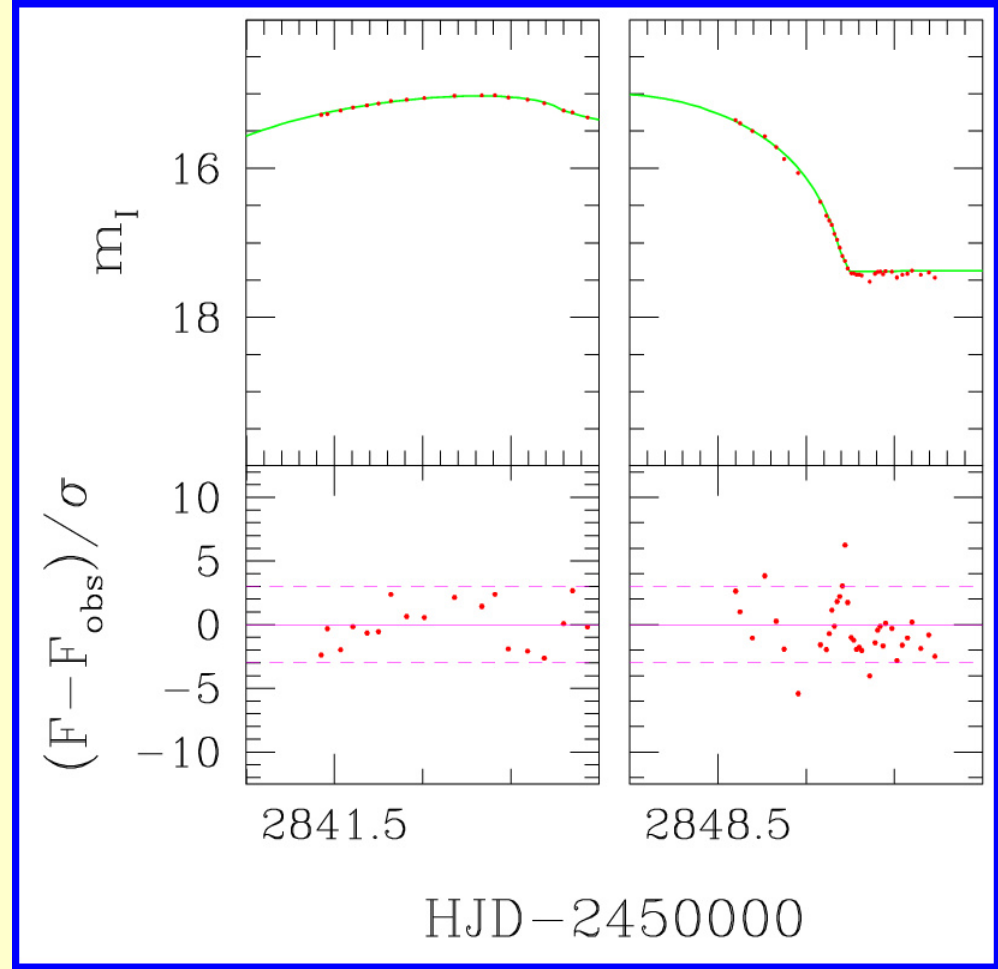
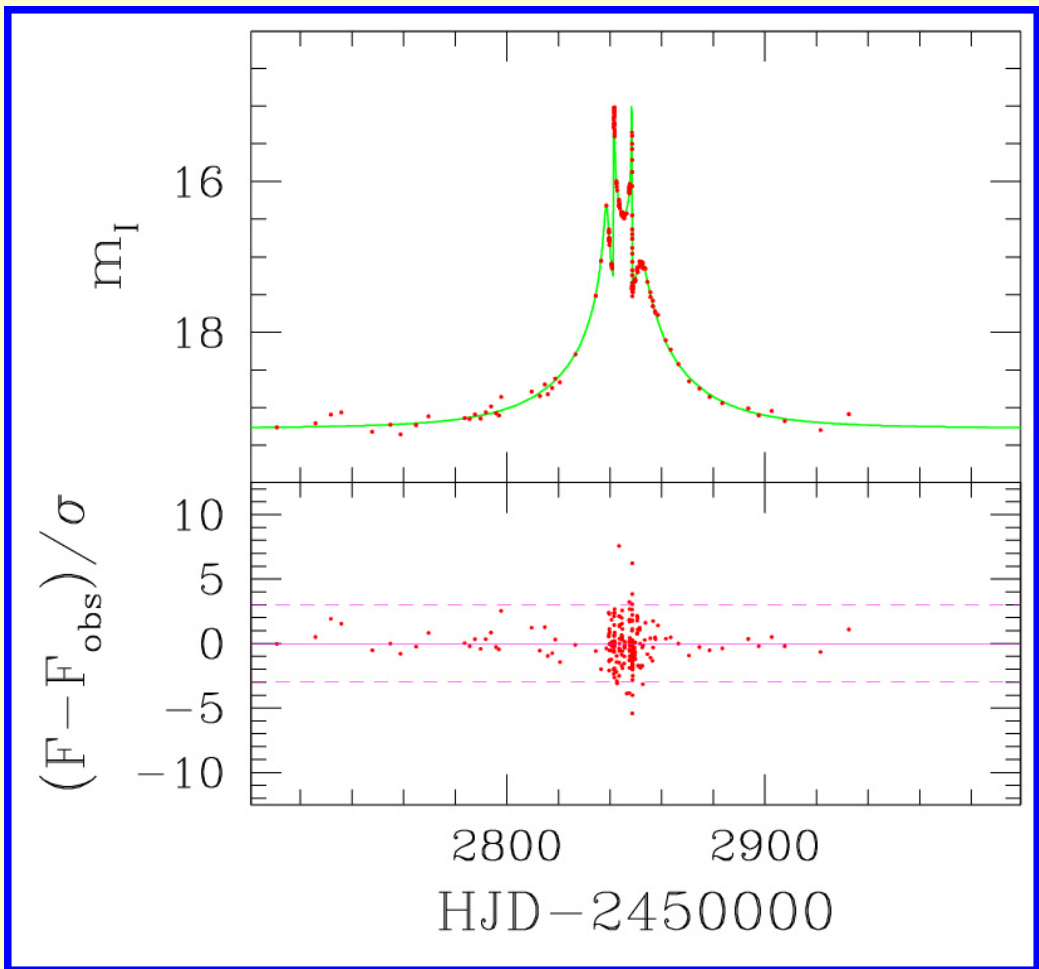
Ciasny układ soczewek (nieruchomy, bez efektu paralaksy)

OGLE 2003-BLG-267



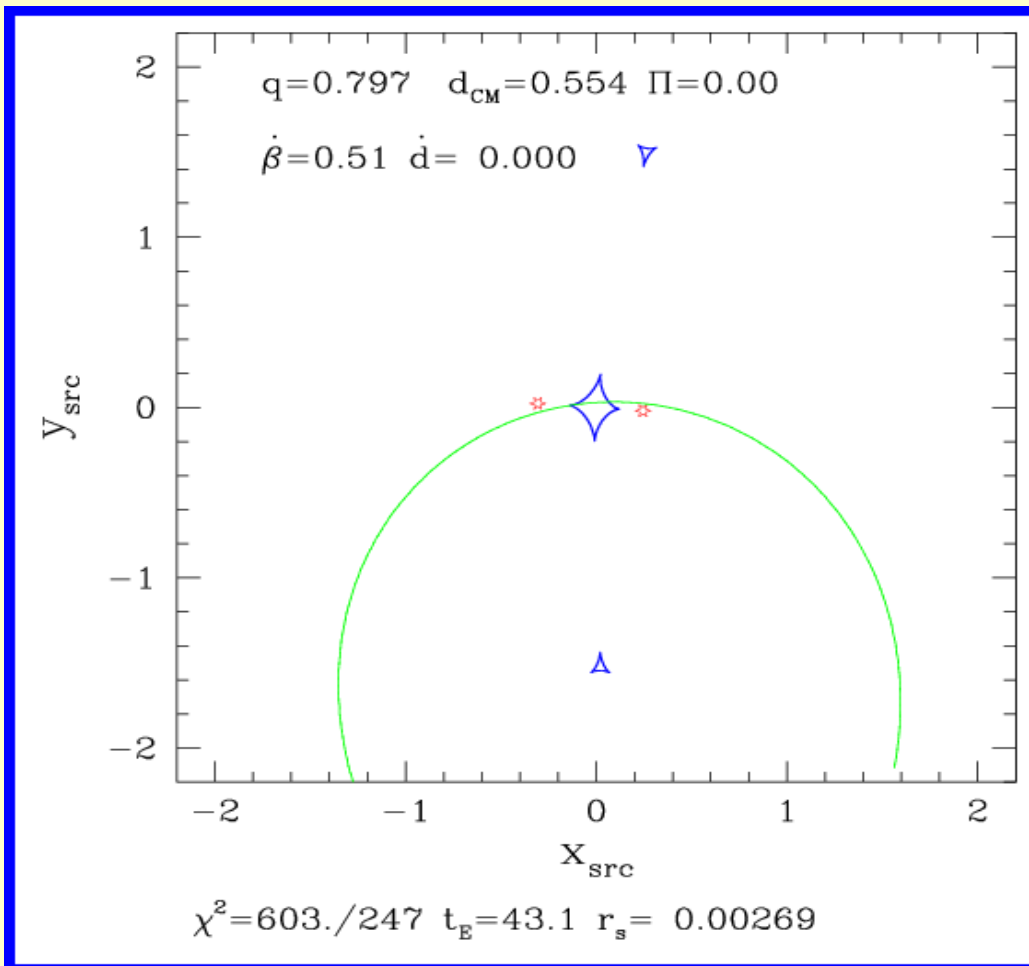
Rozległy układ soczewek (nieruchomy, bez paralaksy)

OGLE 2003-BLG-267

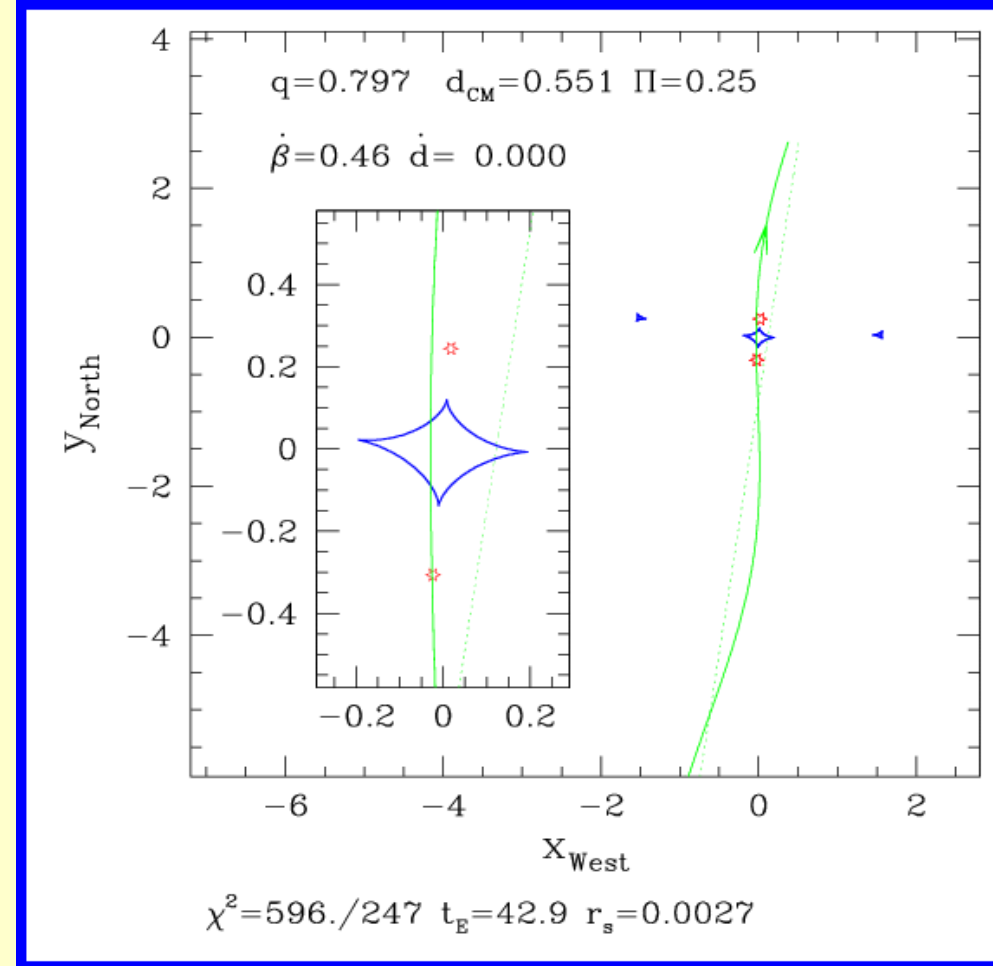


Szczegół: przejścia przez kaustyki

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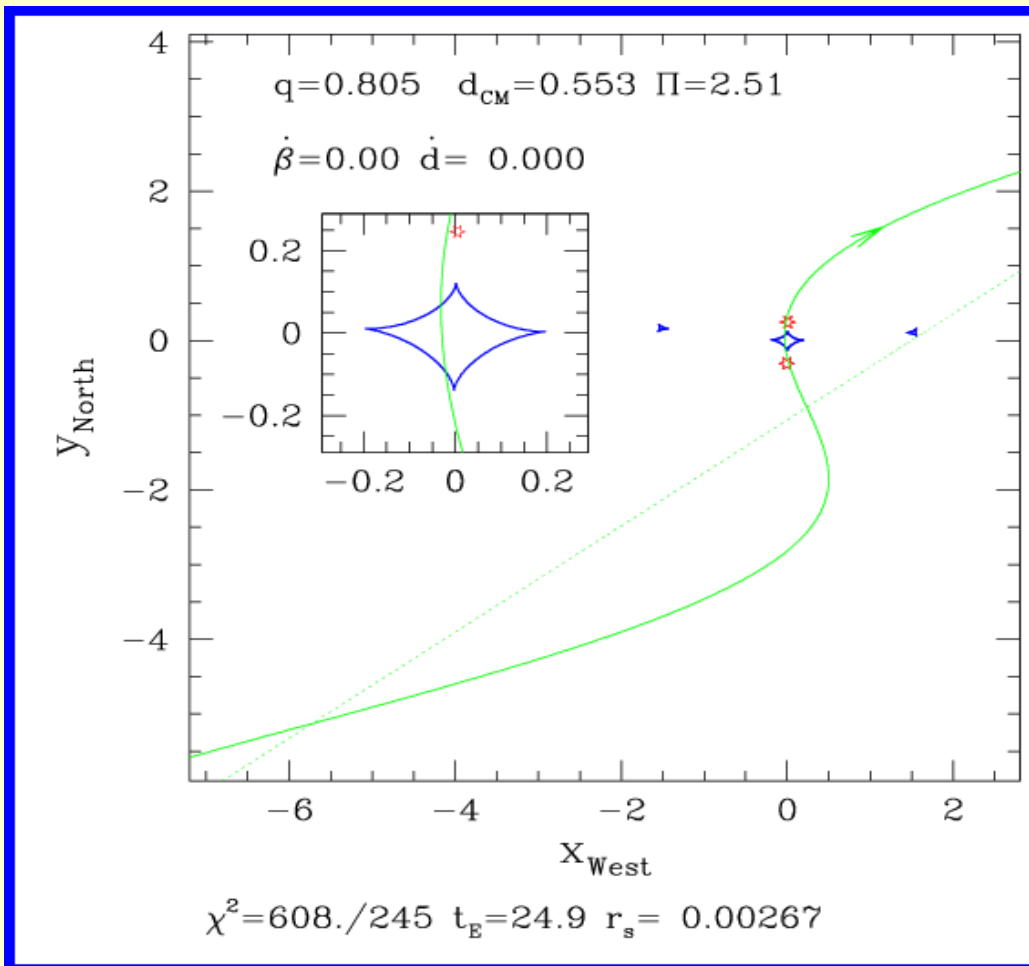


(tylko rotacja)

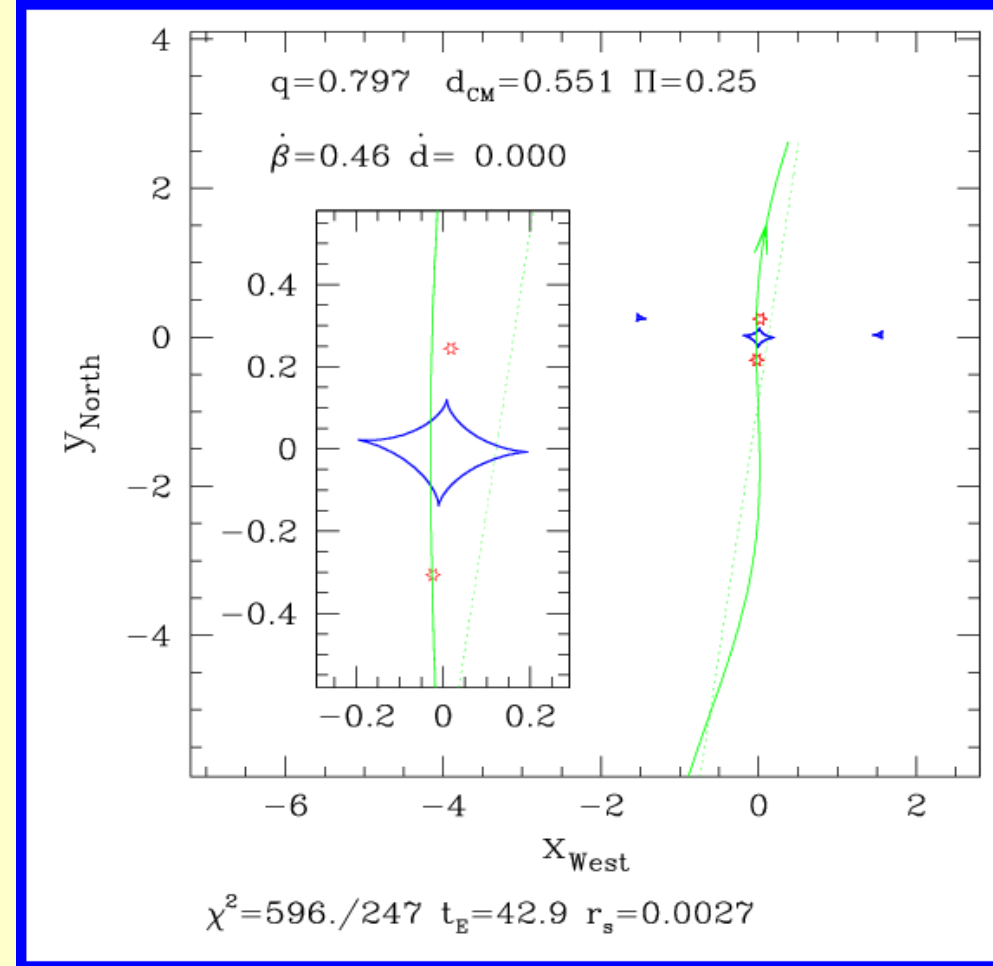


(paralaksa + rotacja)

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(tylko paralaksa)



(paralaksa + rotacja)

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Formalne (statystyczne) błędy dopasowań parametrów modelu są nieistotne w porównaniu z dokładnością pomiaru rozmiarów kątowych źródła

$$q = 0.797 \quad d = 0.551$$

$$t_{CM} = 2844.74 \quad t_E = 42.88$$

$$r_s/r_E = 0.00266$$

$$\Pi = 0.250 \quad \psi = 81.63^\circ$$

$$\dot{d} = 0.000 \quad \dot{\beta} = \omega = -169^\circ/y$$

$$F_s/F_0 = 1$$

$$\alpha_* = (0.67 \pm 0.15) \mu as$$

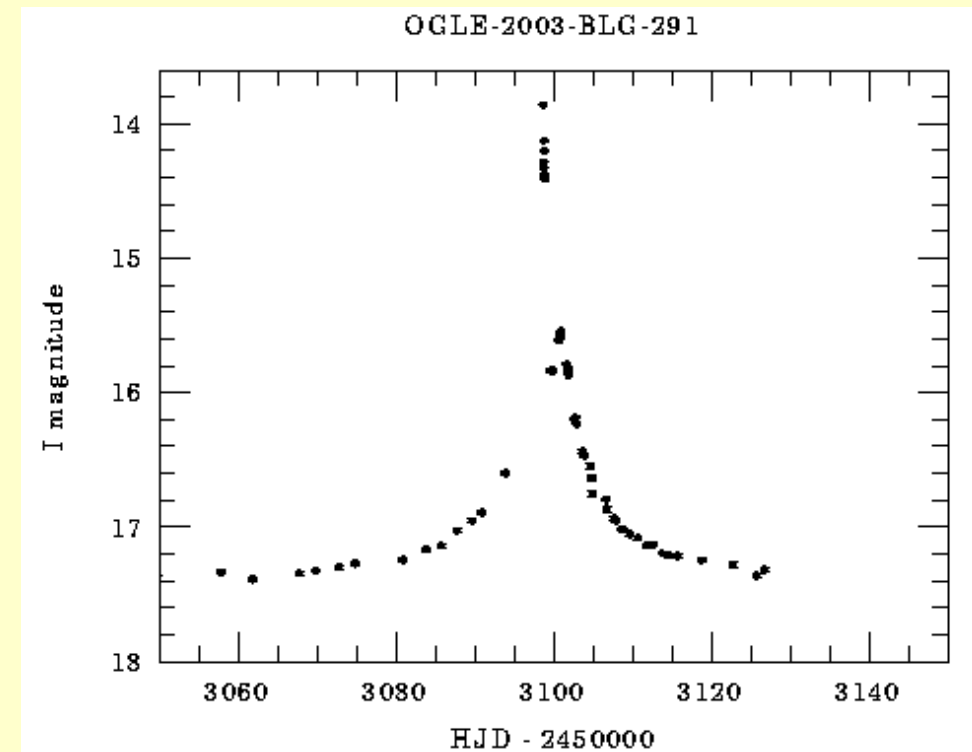
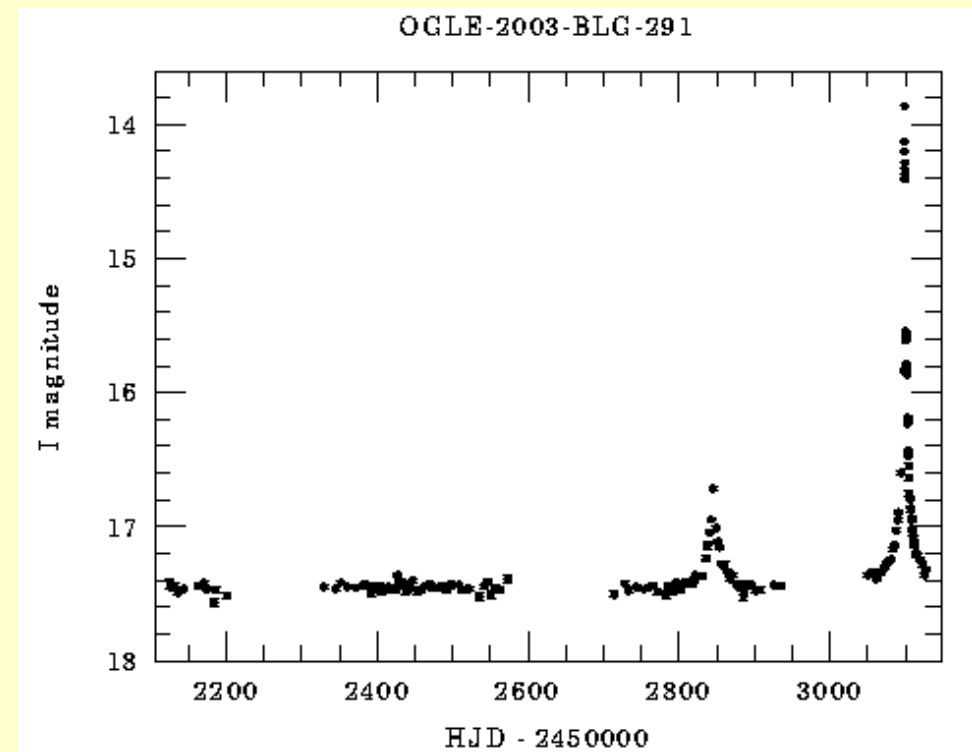
$$m_1 = (0.054 \pm 0.012) M_\odot$$

$$m_2 = (0.067 \pm 0.015) M_\odot$$

$$d_{OL} = (5.3 \pm 0.5) \text{ kpc}$$

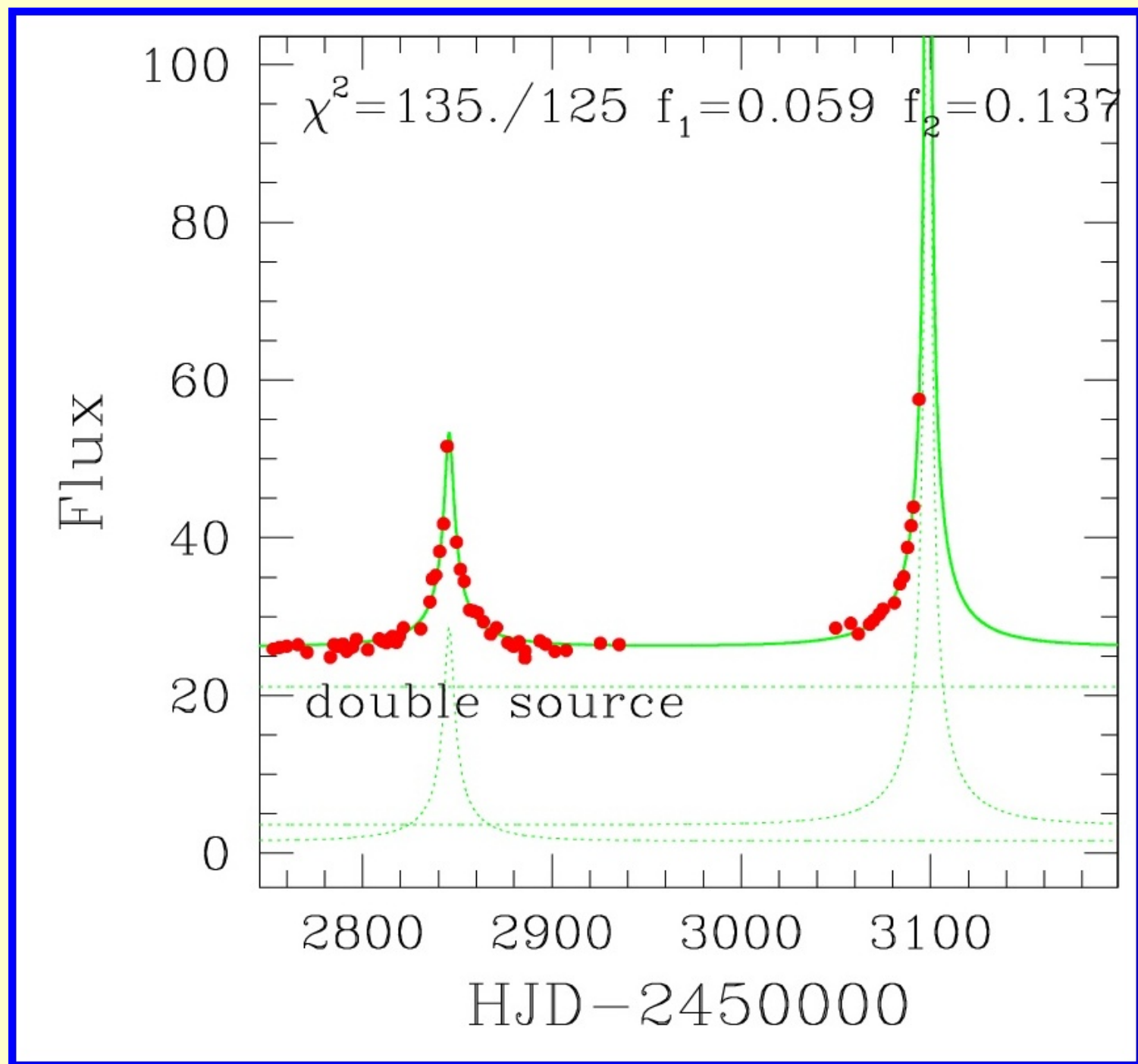
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- $T_{\max} = 2453098.166$
(2004-04-02.67 UT)
- $I_0 = 17.367$
- RA (J2000.0) 17:55:17.67
- Dec (J2000.0) -33:40:49.0
- wsp. eklipt. (269.01; -10.24)

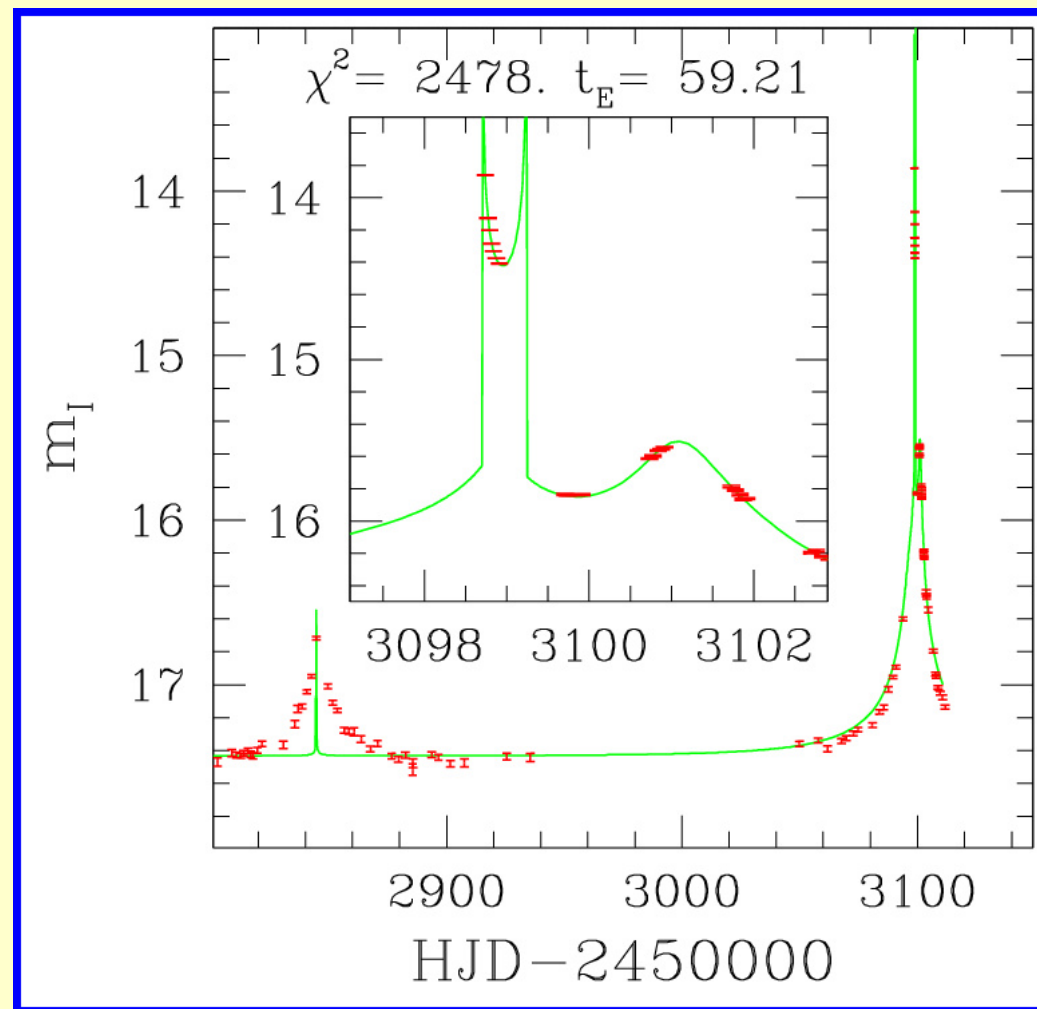
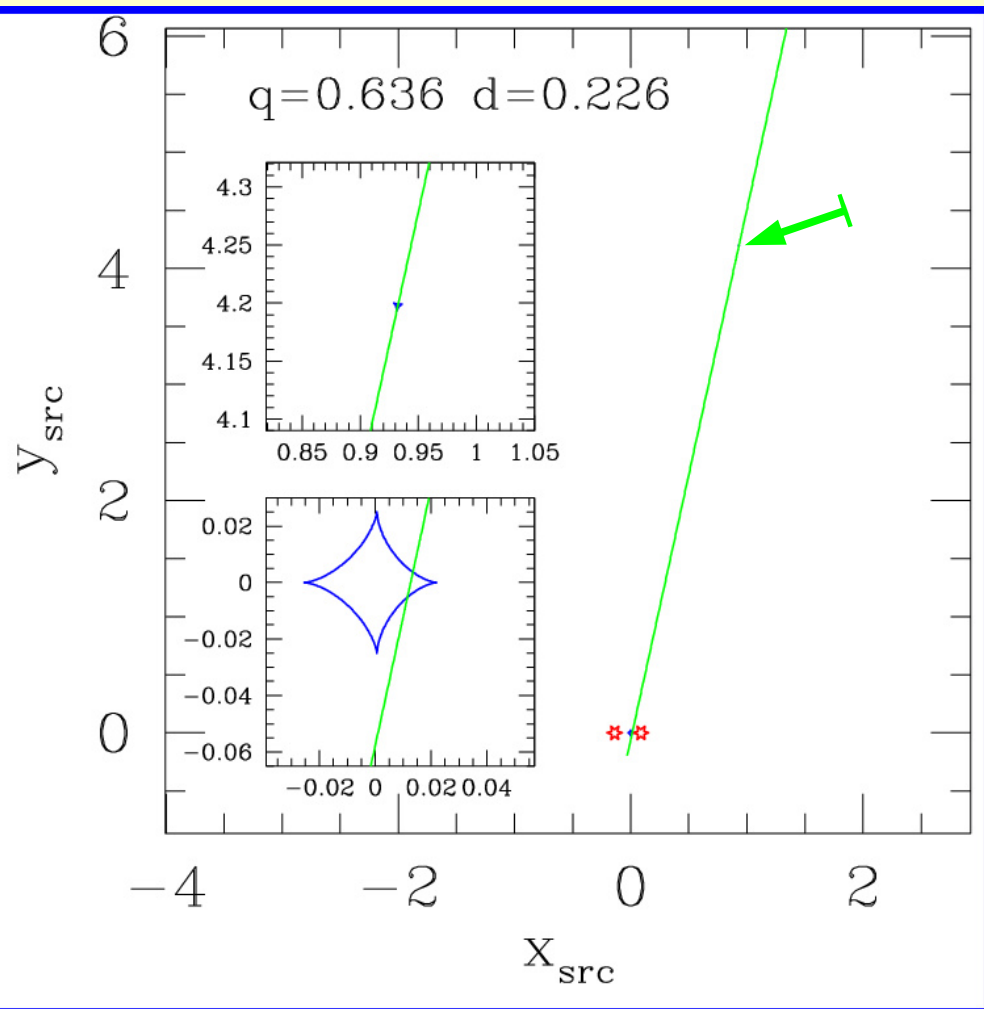


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do 01.04.2004:
model
podwójnego
źródła



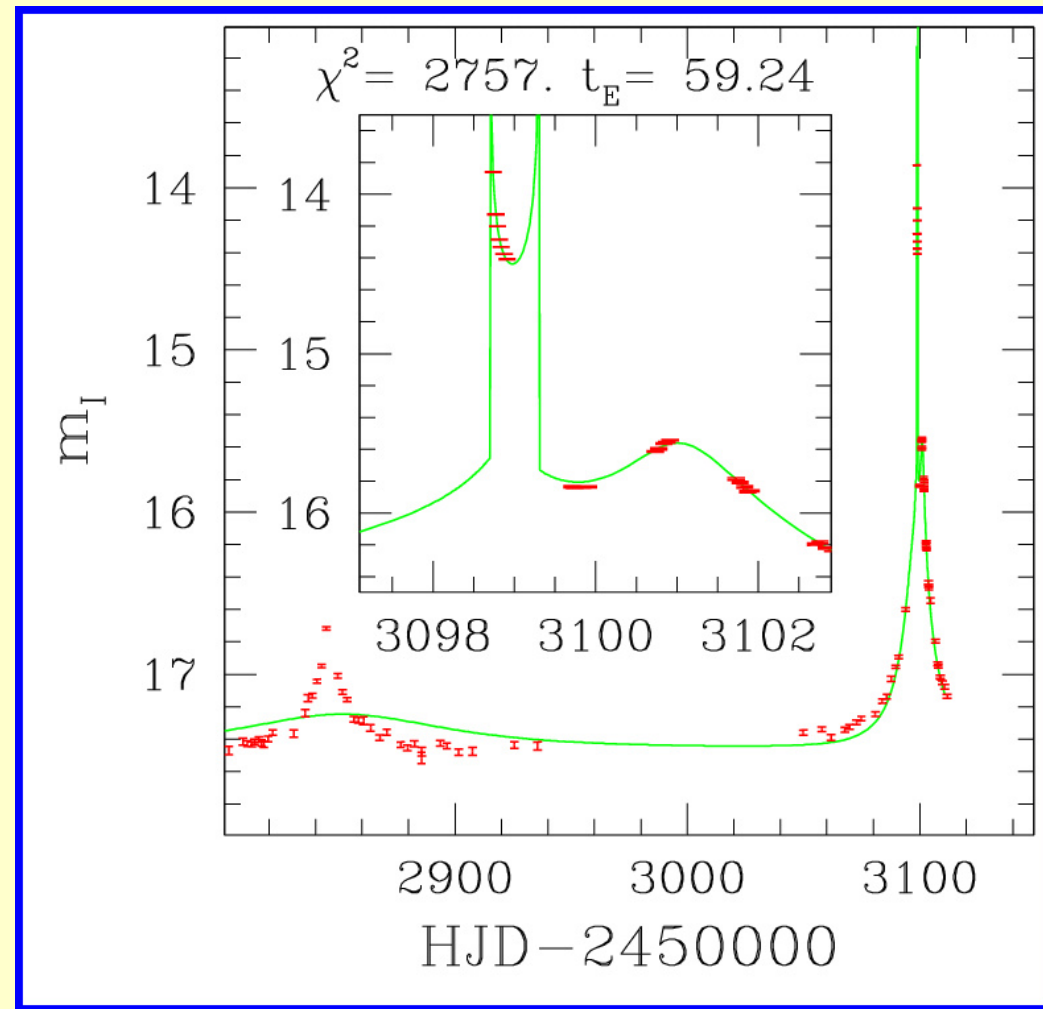
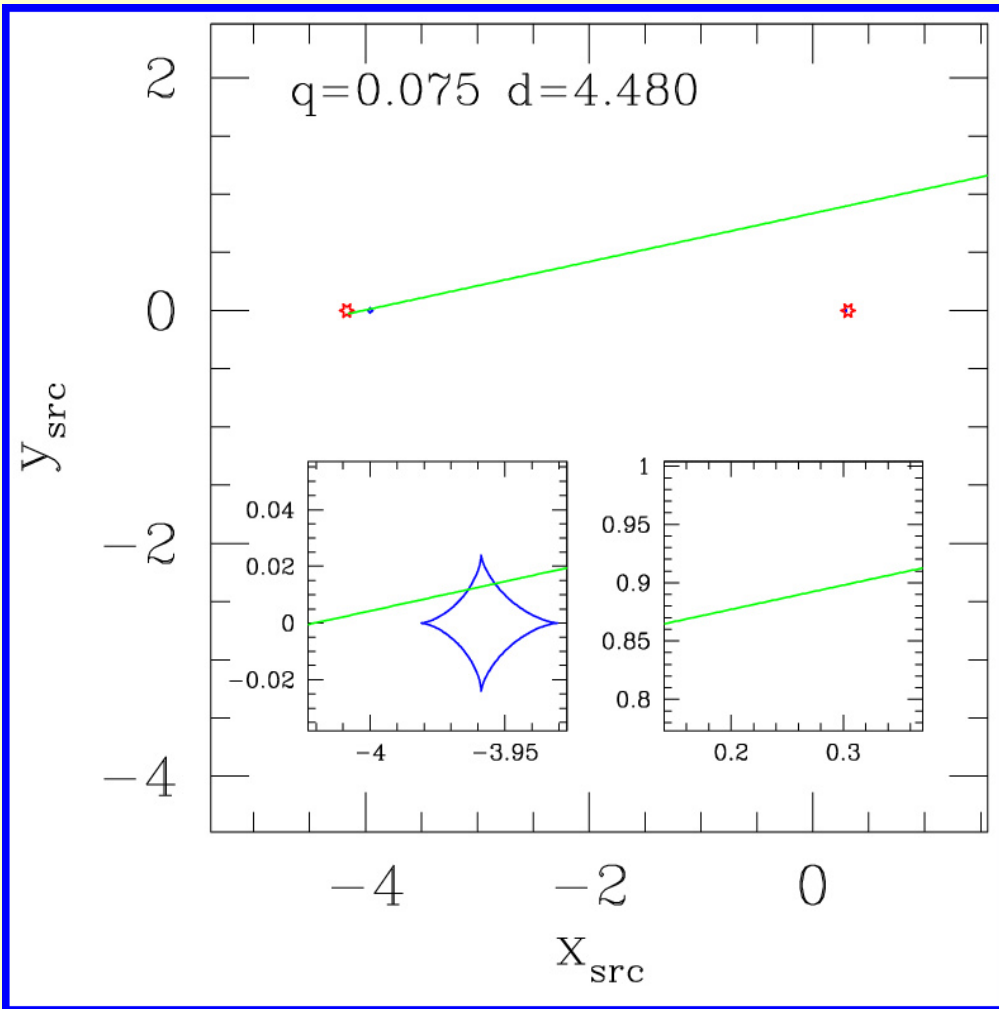
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(+obserwacje z kwietnia 2004)

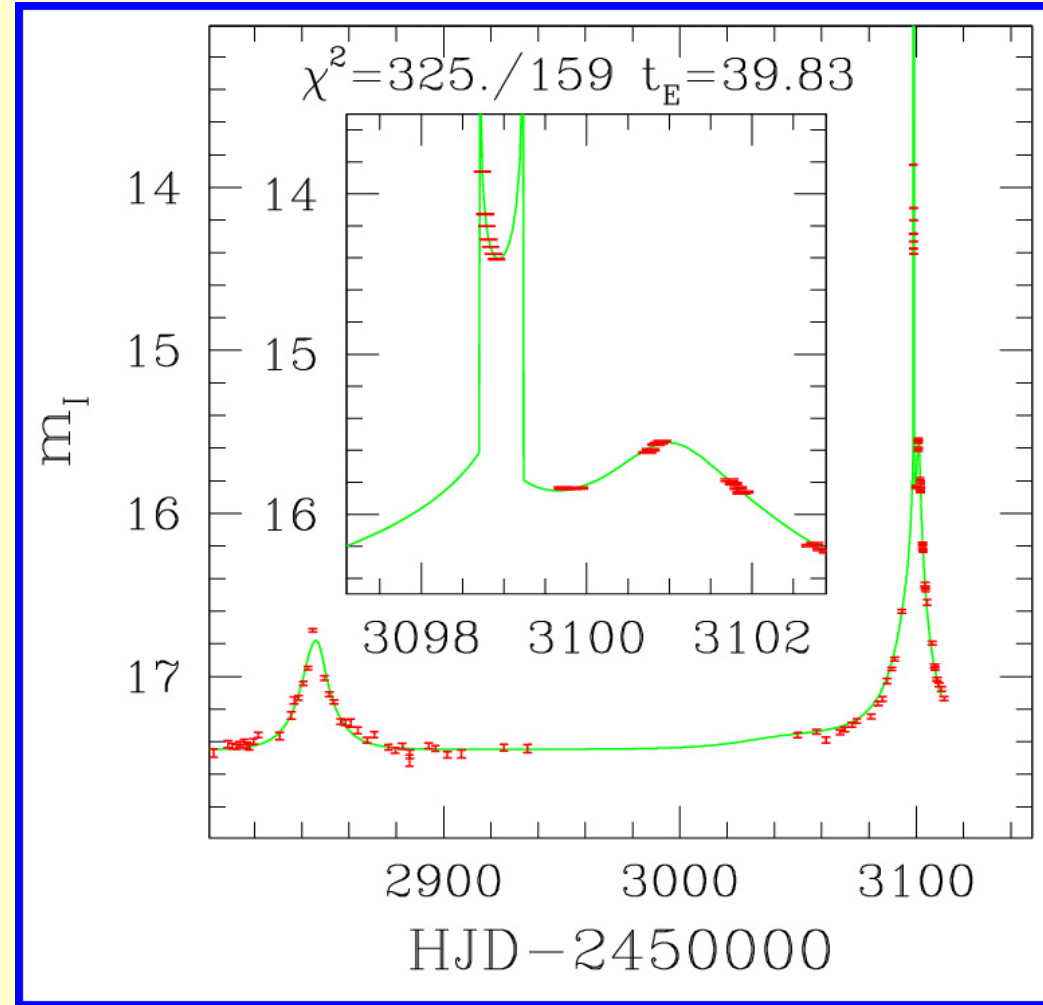
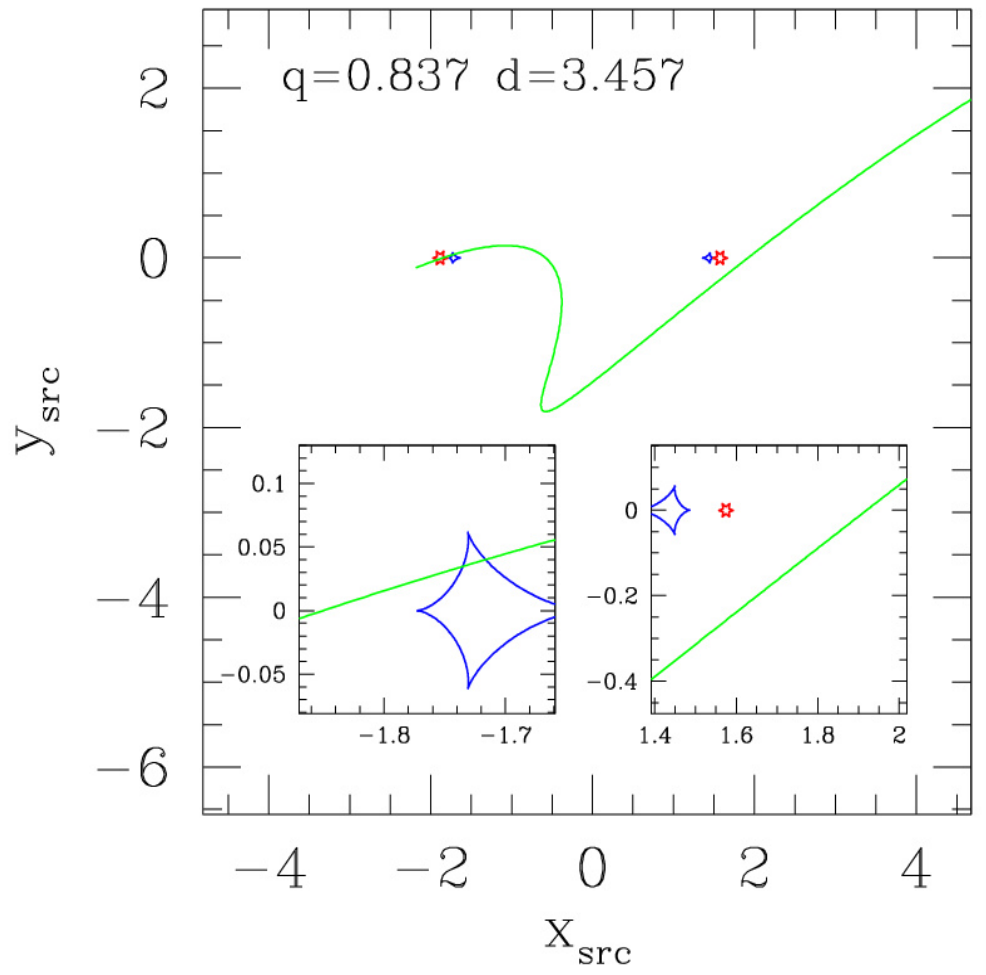
Ciasny układ soczewek (nieruchomy, bez efektu paralaksy)

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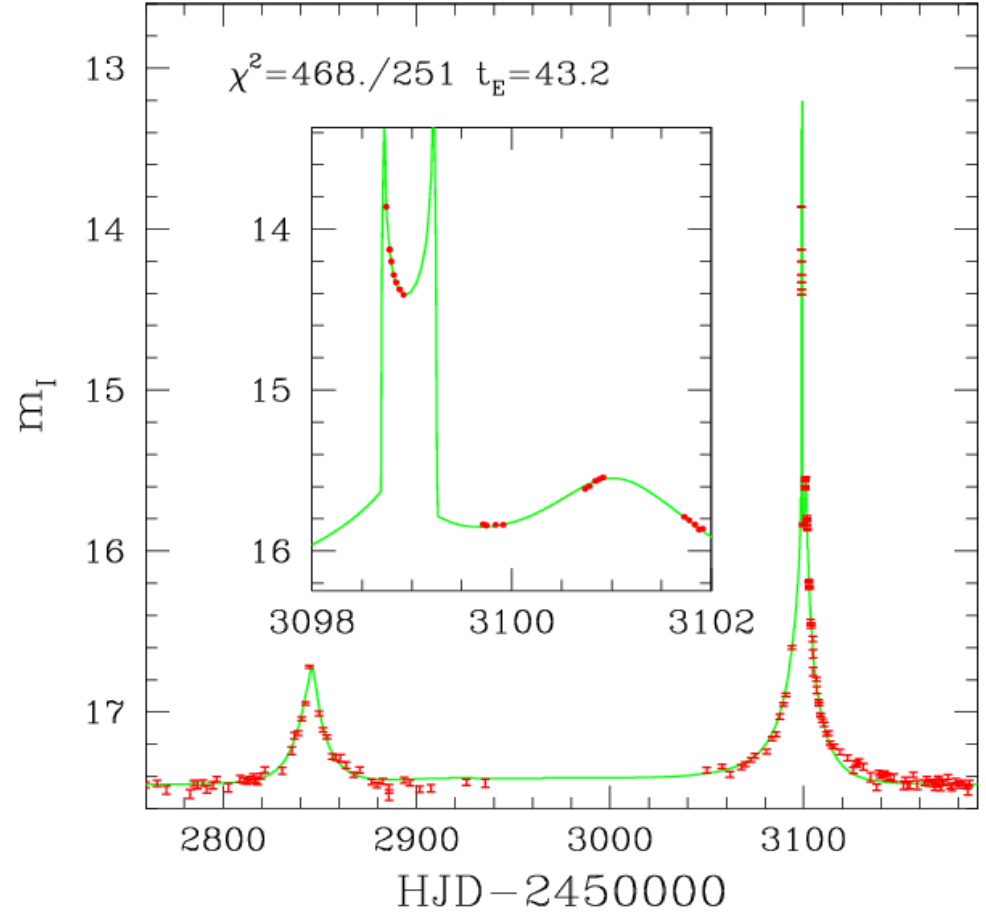
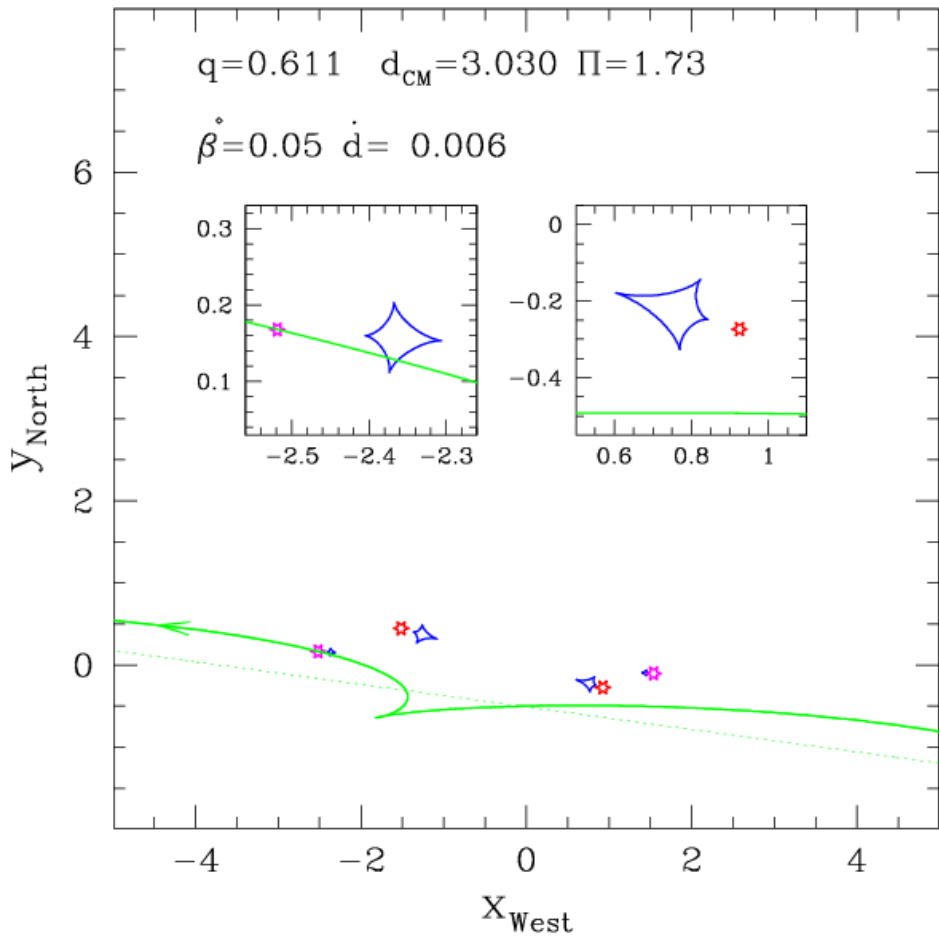
Rozległy układ soczewek (nieruchomy, bez paralaksy)

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Rozległy układ soczewek (nieruchomy, z paralaksą)

OGLE 2003-BLG-291

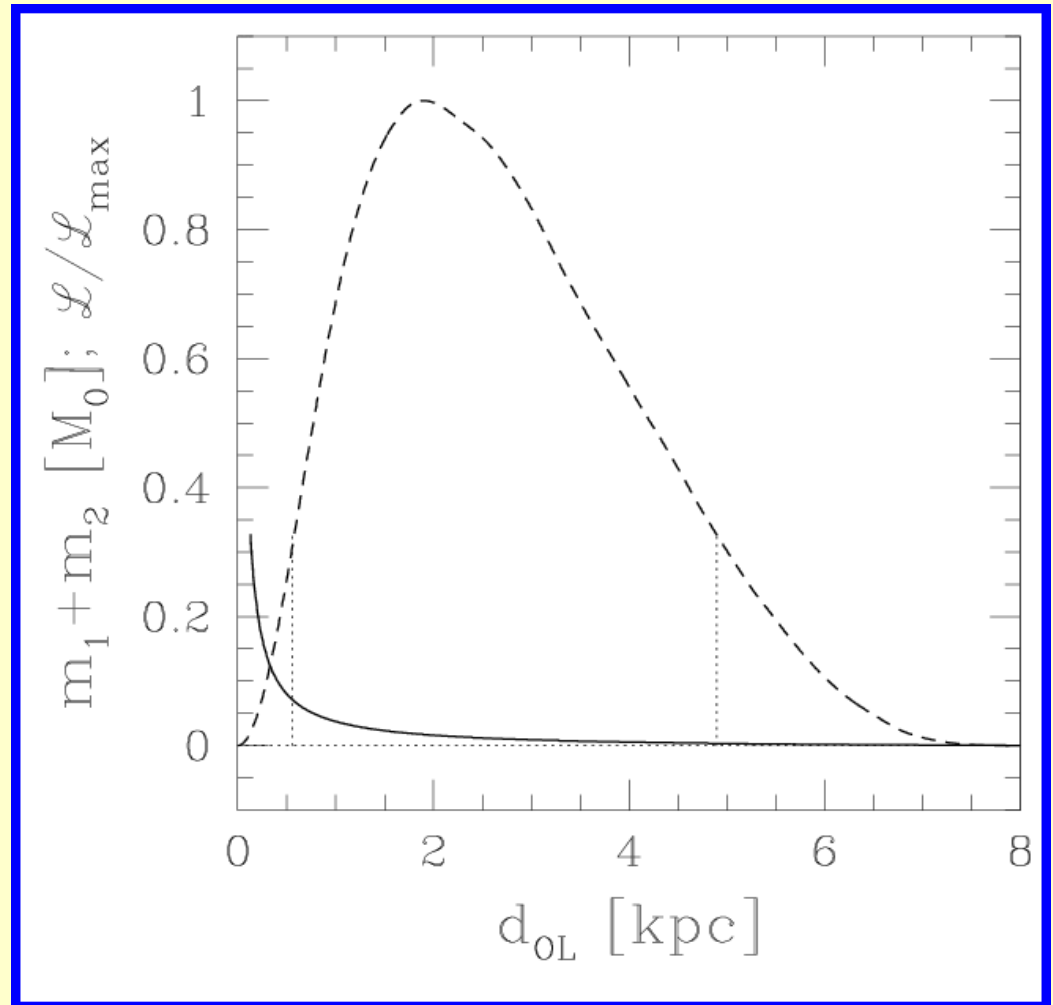


Rozległy układ soczewek (rotacja + paralaksa)

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Prawdopodobne położenie soczewki w oparciu o pomiar czasu Einsteina i jej względnej prędkości (paralaksa).

Linia ciągła pokazuje zależność masy soczewki od jej odległości.



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$$\tilde{r}_E \approx 0.577 \text{AU}$$

$$m_1 = 1 M_{\odot} \frac{15 \text{pc}}{d_{OL}}$$

$$m_2 = 1 M_{\odot} \frac{25 \text{pc}}{d_{OL}}$$

$$I_{\text{soczewka}} > 17.9 \text{mag}$$

Ograniczenie na względne rozmiary źródła \implies

- minimalne masy
- maksymalna odległość

Ograniczenie blasku soczewki \implies

- maksymalne masy
- minimalna odległość

$$q = 0.611 \quad d_{CM} = 3.030$$

$$t_{CM} = 2926.02 \quad t_E = 43.17$$

$$r_s/r_E \leq 0.0005$$

$$\Pi = 1.733 \quad \psi = 172.18^\circ$$

$$F_s/F_0 = 0.39$$

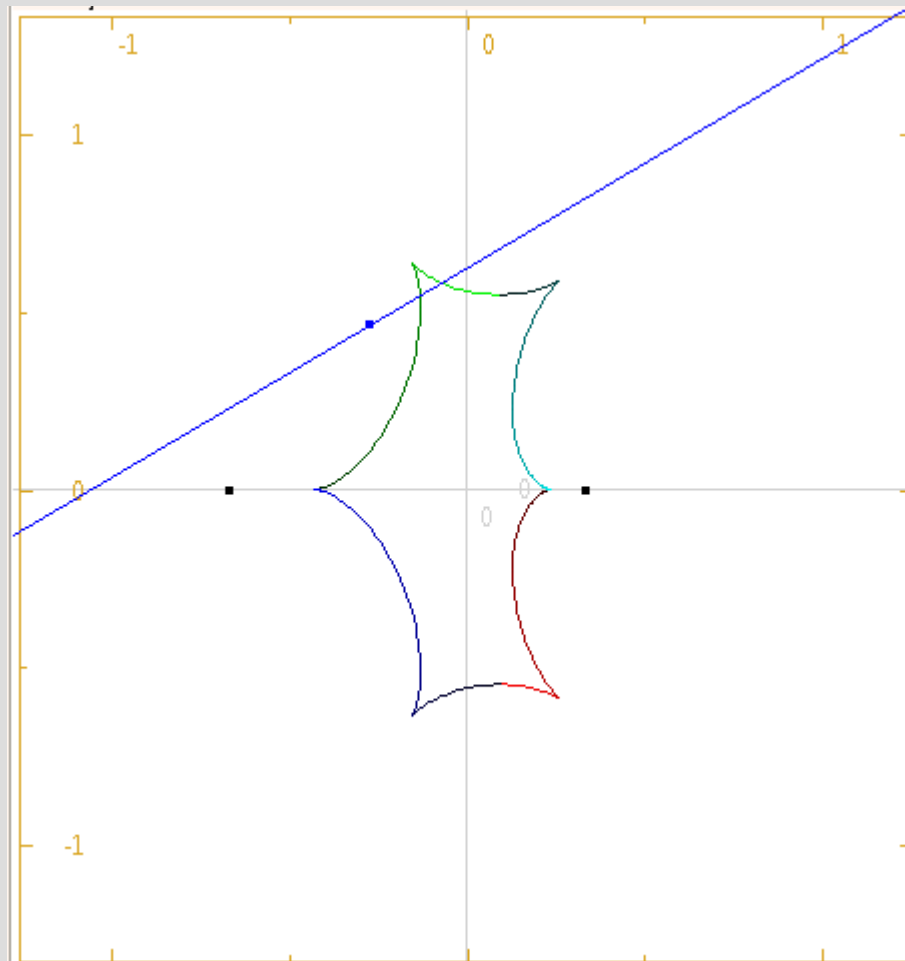
$$\alpha_* = (0.97 \pm 0.10) \mu\text{as}$$

$$0.049 M_{\odot} < m_1 < 0.19 M_{\odot}$$

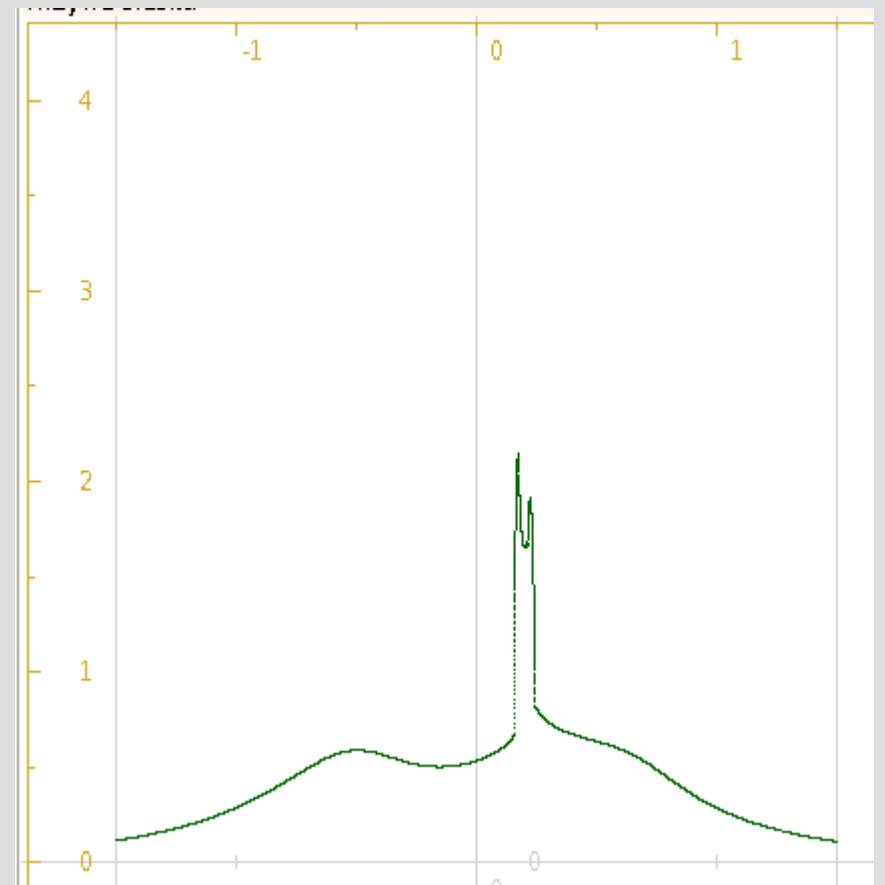
$$0.081 M_{\odot} < m_2 < 0.32 M_{\odot}$$

$$0.14 \text{ kpc} < d_{OL} < 0.55 \text{ kpc}$$

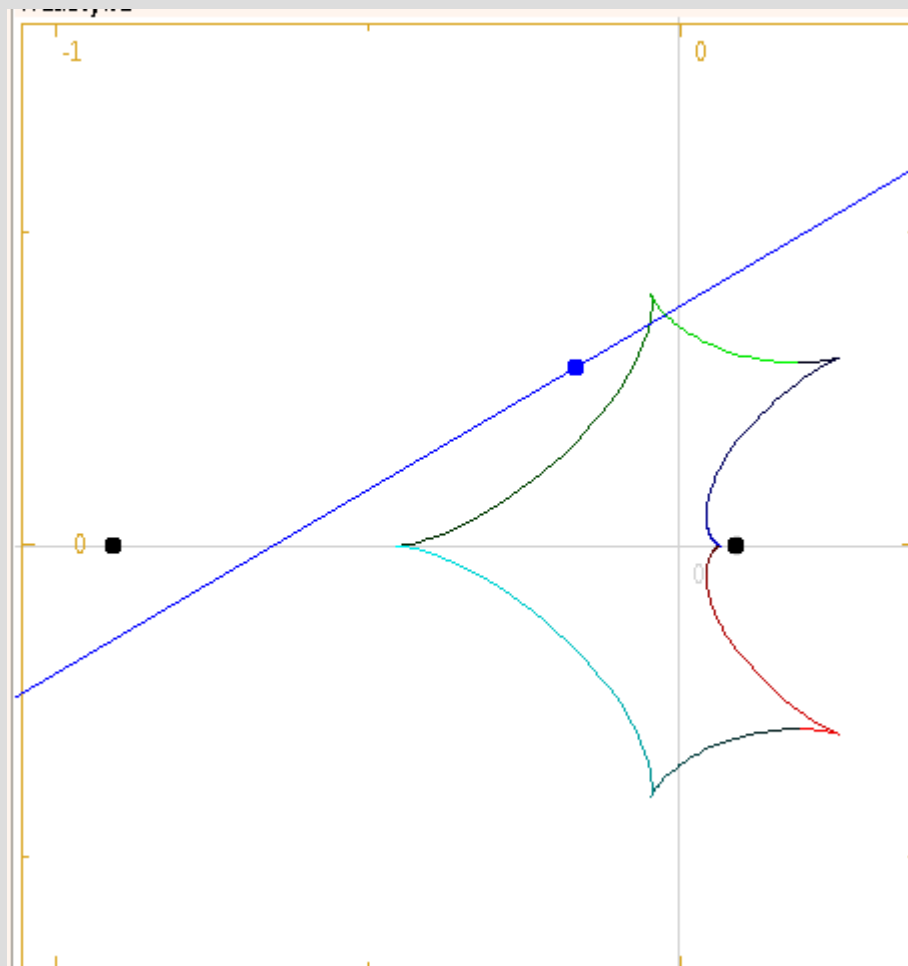
Podwójna soczewka



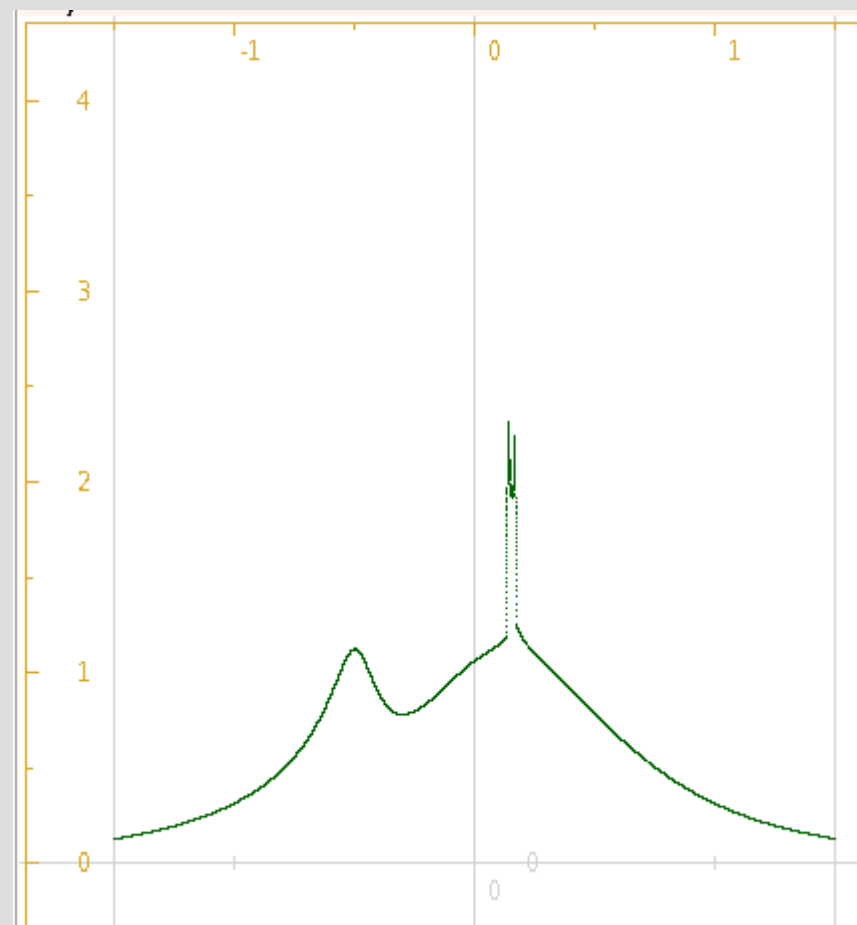
$q = 0.5$



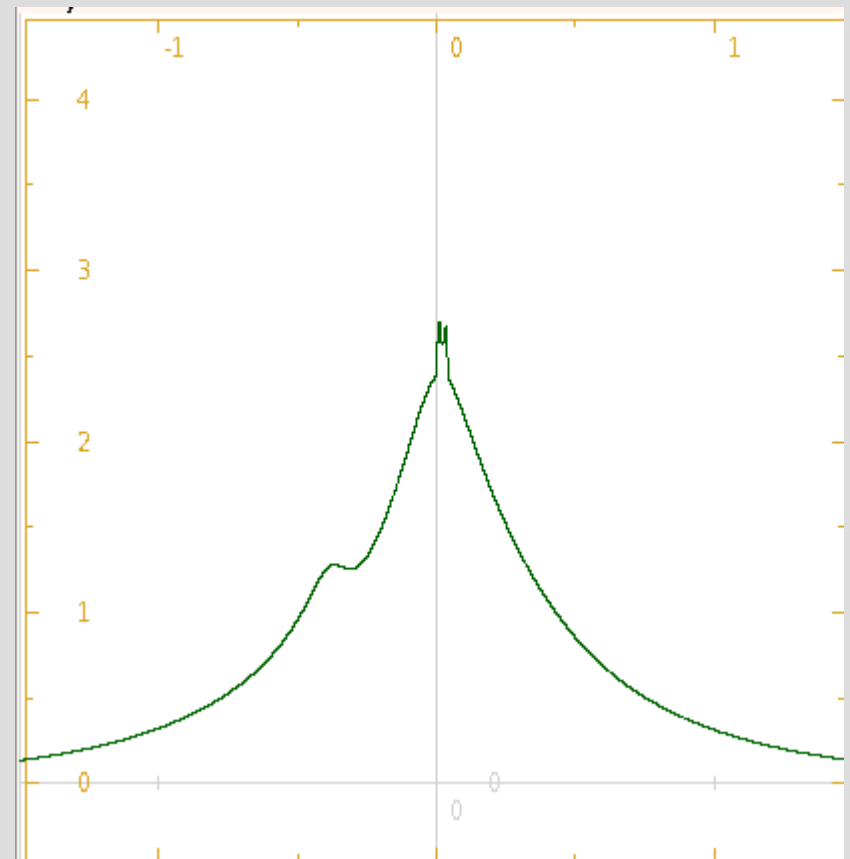
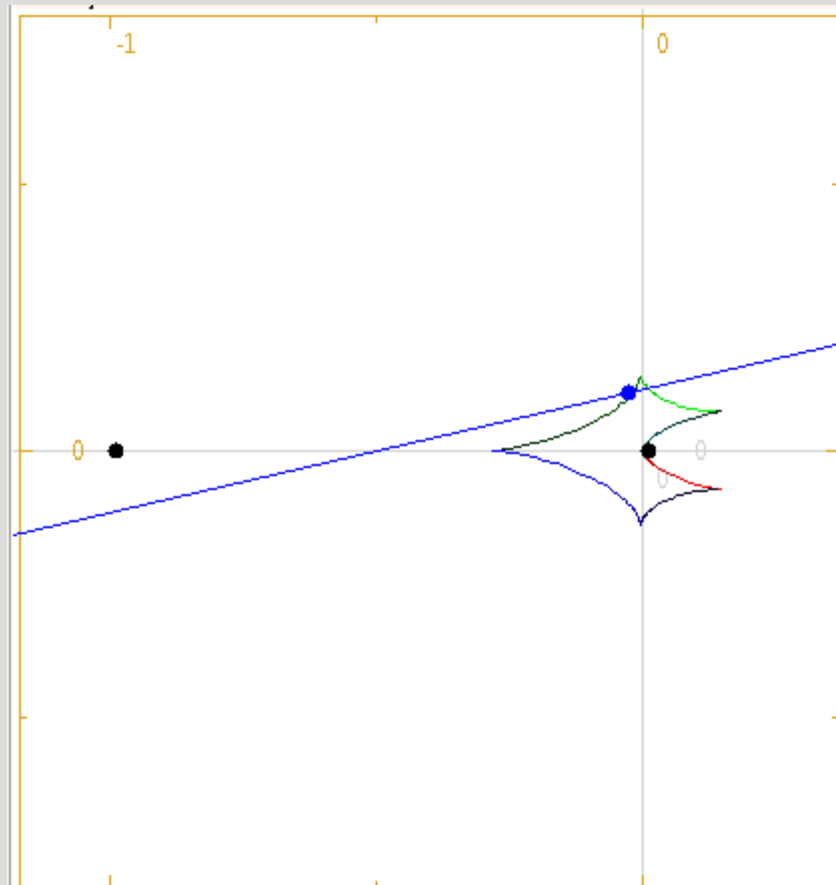
Podwójna soczewka



$q = 0.1$

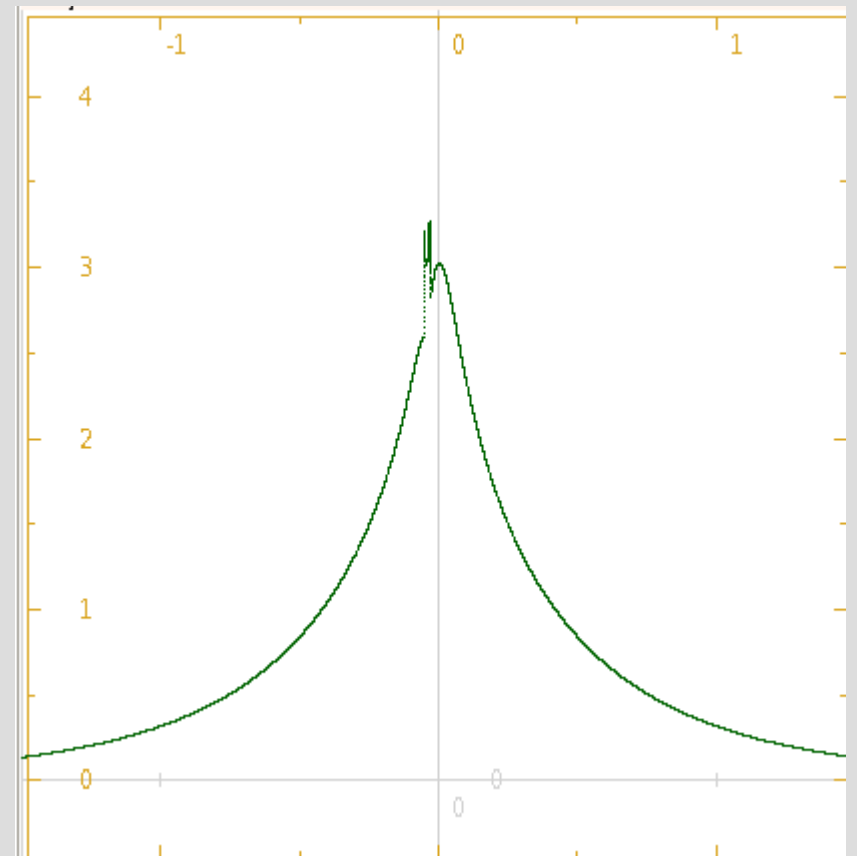
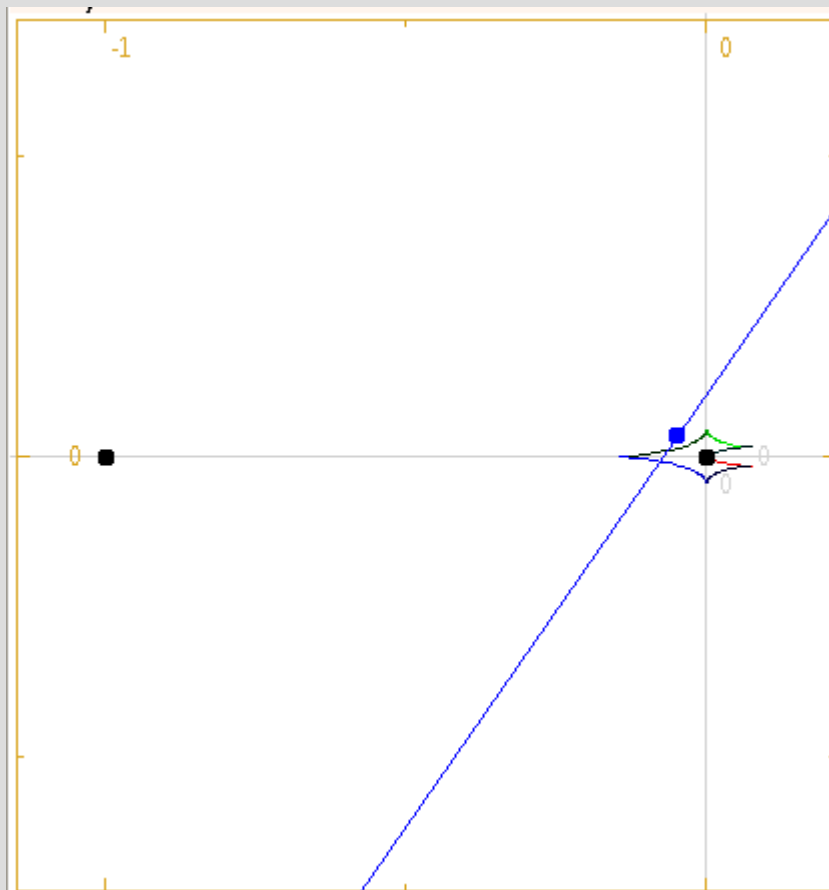


Podwójna soczewka



$$q = 0.01$$

Podwójna soczewka



$$q = 0.001$$

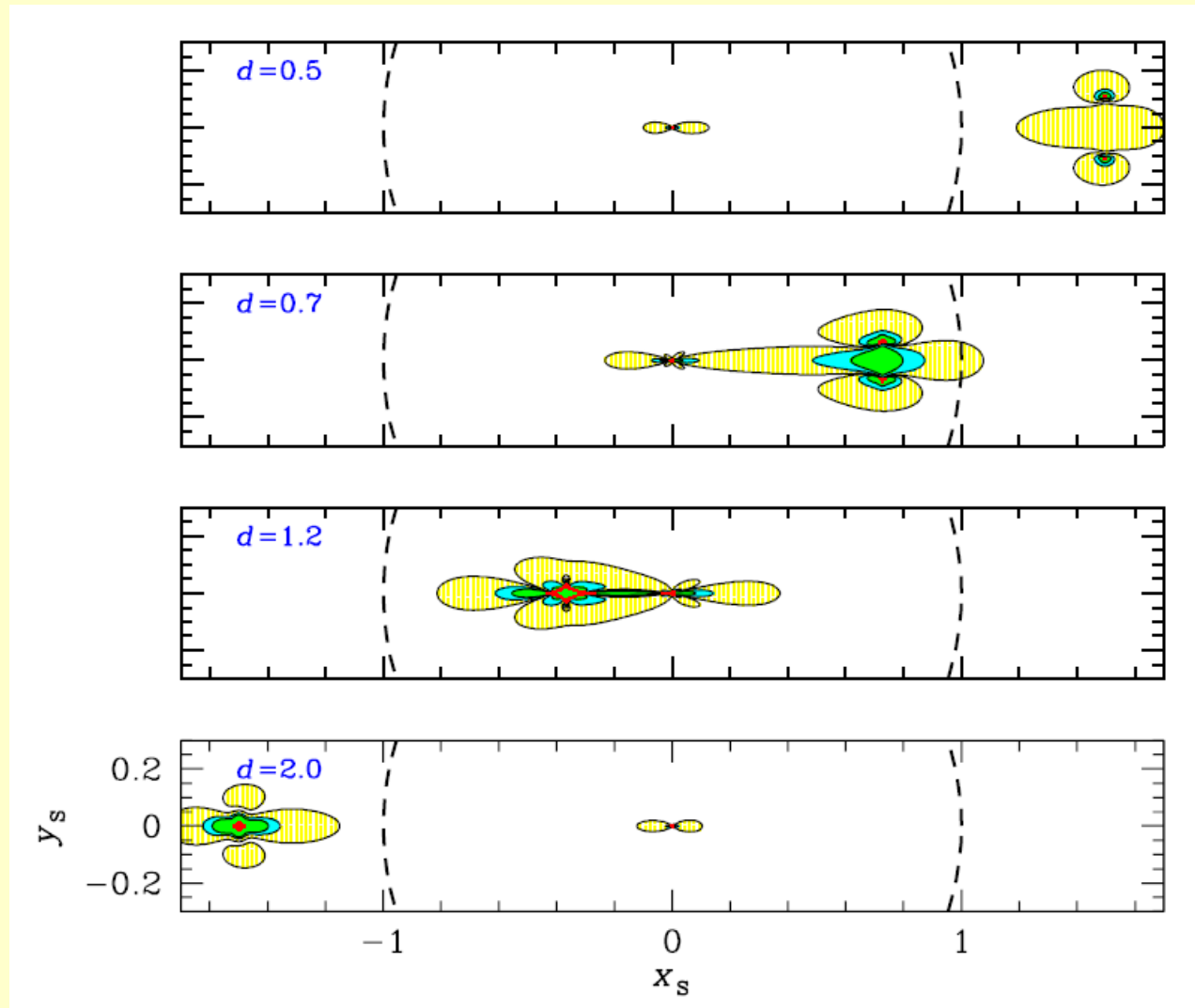
Układy „planetarne”

$q=0.001$

mapy pokazują zmianę
wzmocnienia w stosunku do
pojedynczej soczewki

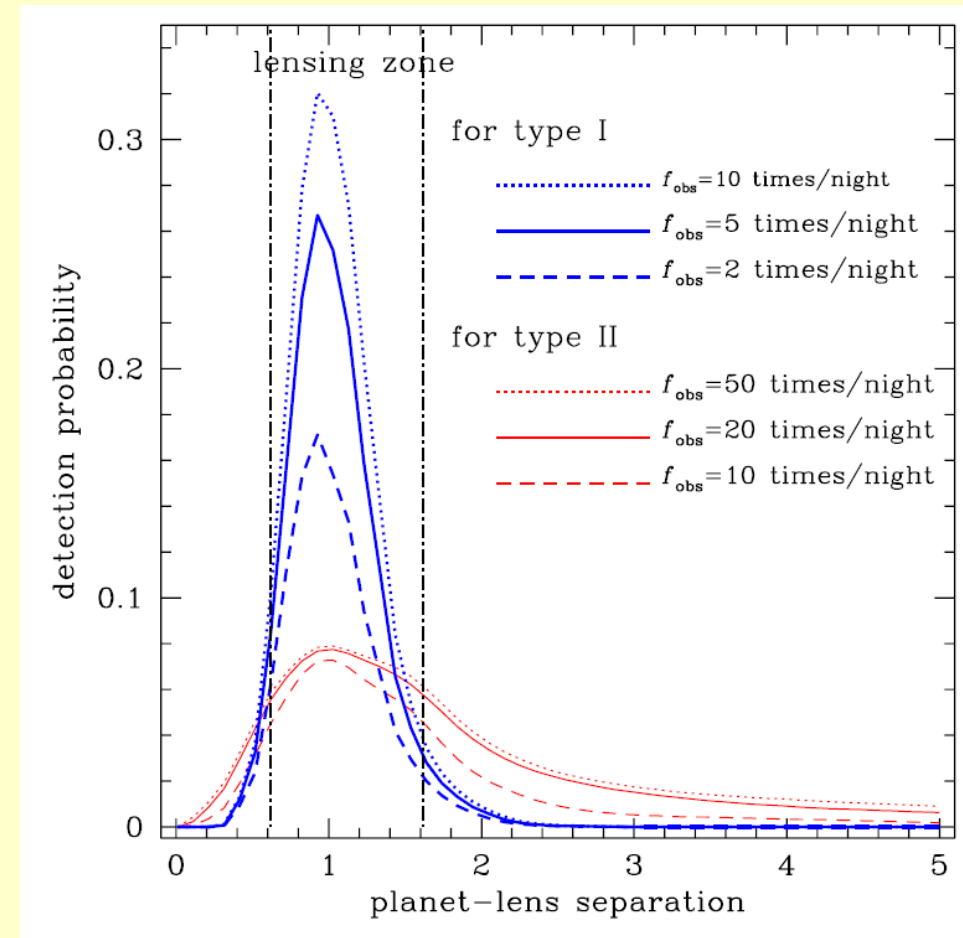
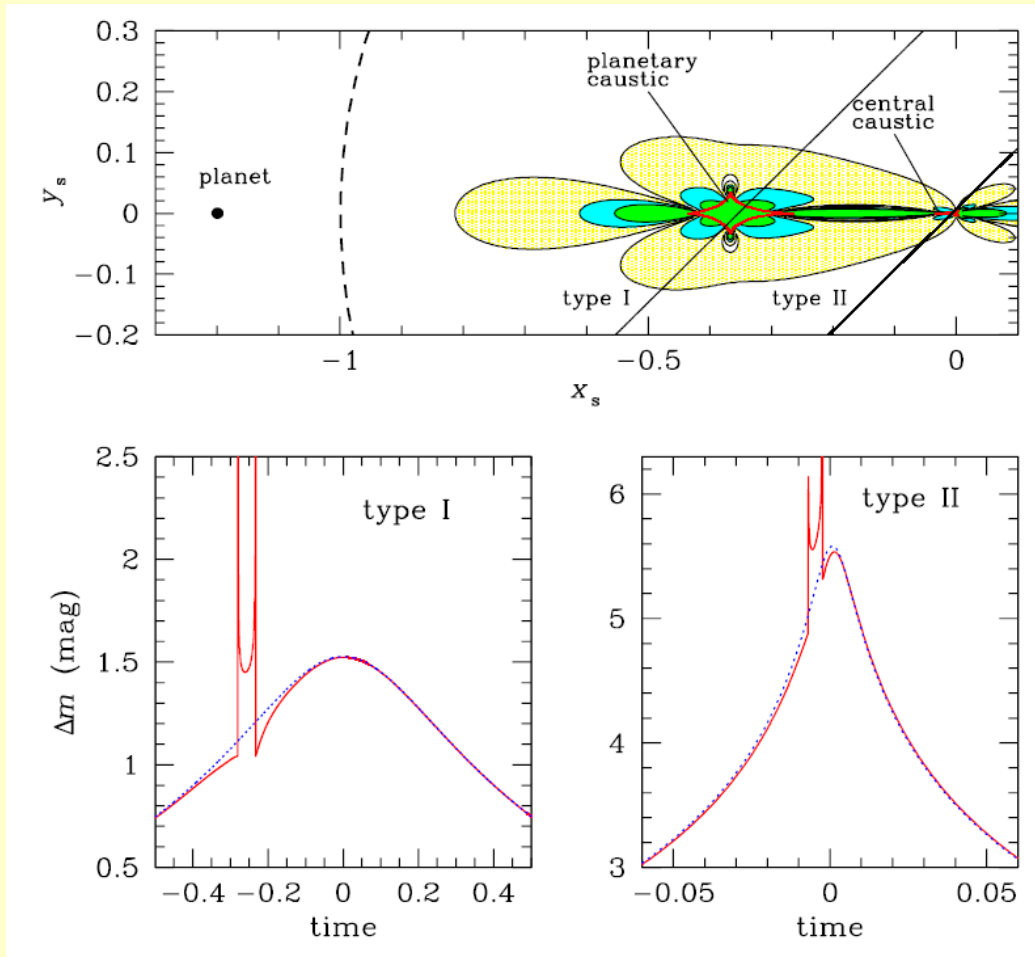
o 1% 5% 10%

czyli położenia źródła, dla
których w krzywej blasku
zaznaczy się „anomalie”.



Han i Kim (2000) CNU-A&SS-08/2000, astro-ph/0008332

„Anomalie“



Han i Kim (2000) CNU-A&SS-08/2000, astro-ph/0008332

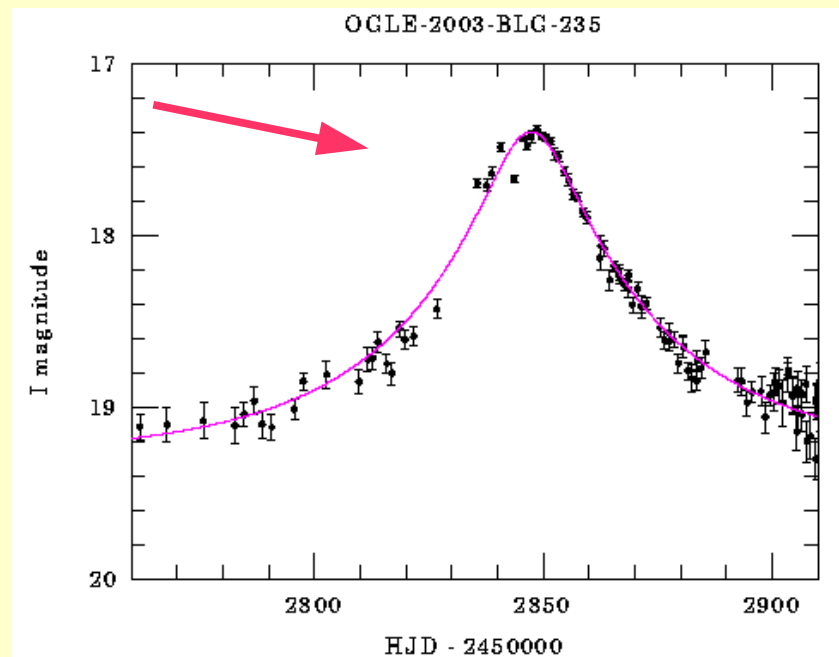
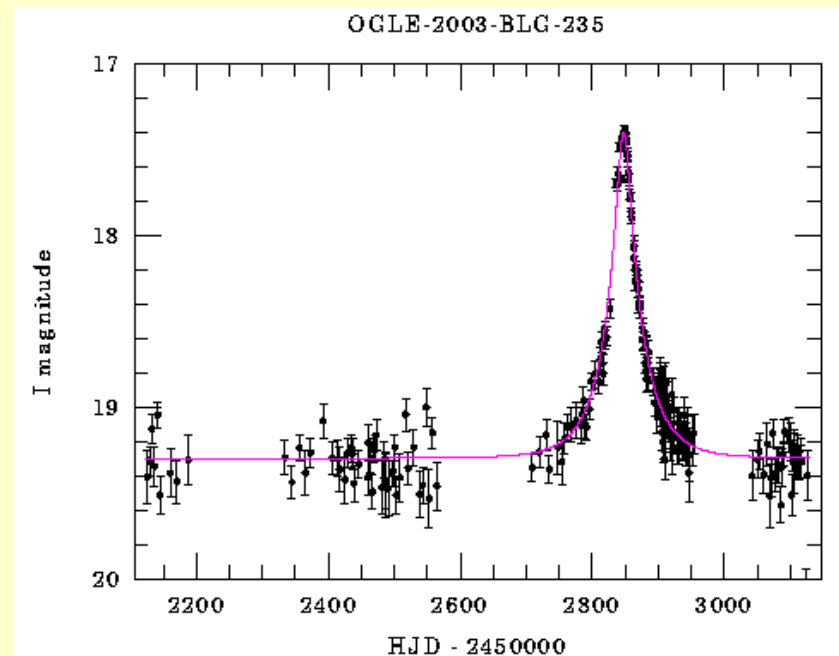
OGLE 2003-BLG-235

(OGLE EWS 22 VI 2003)

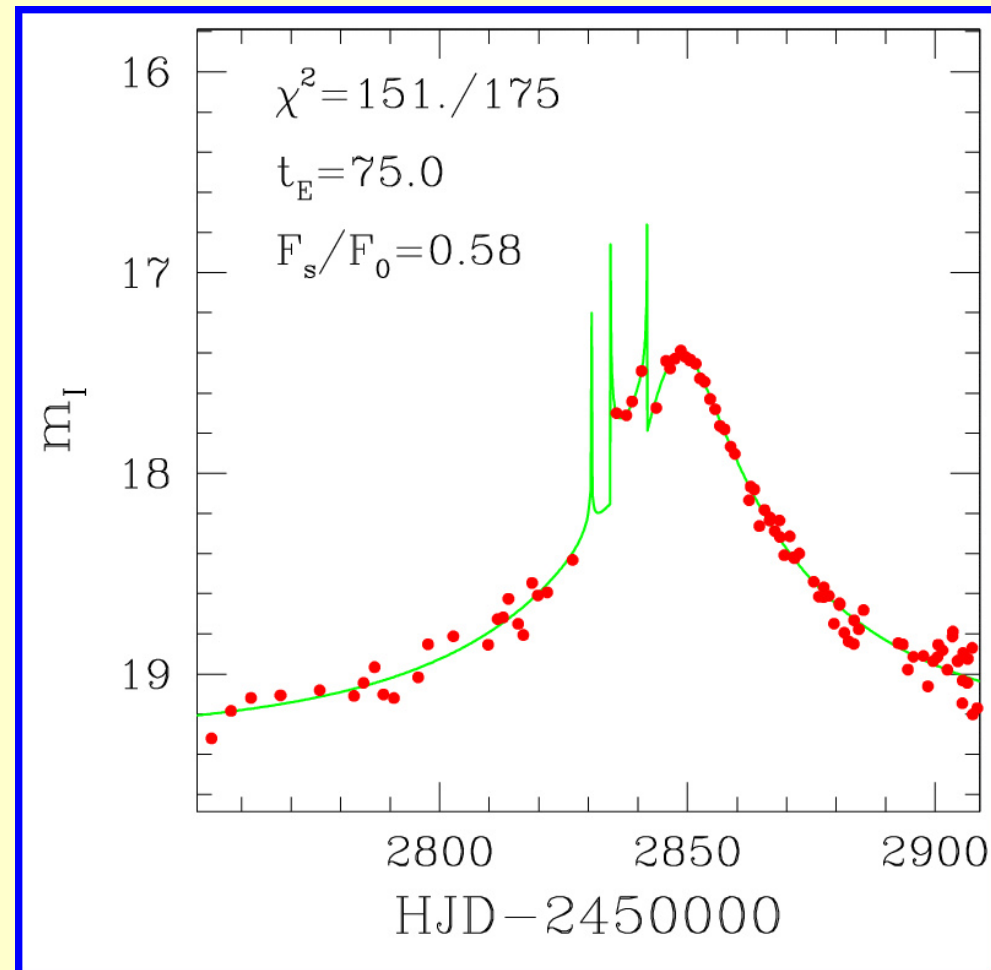
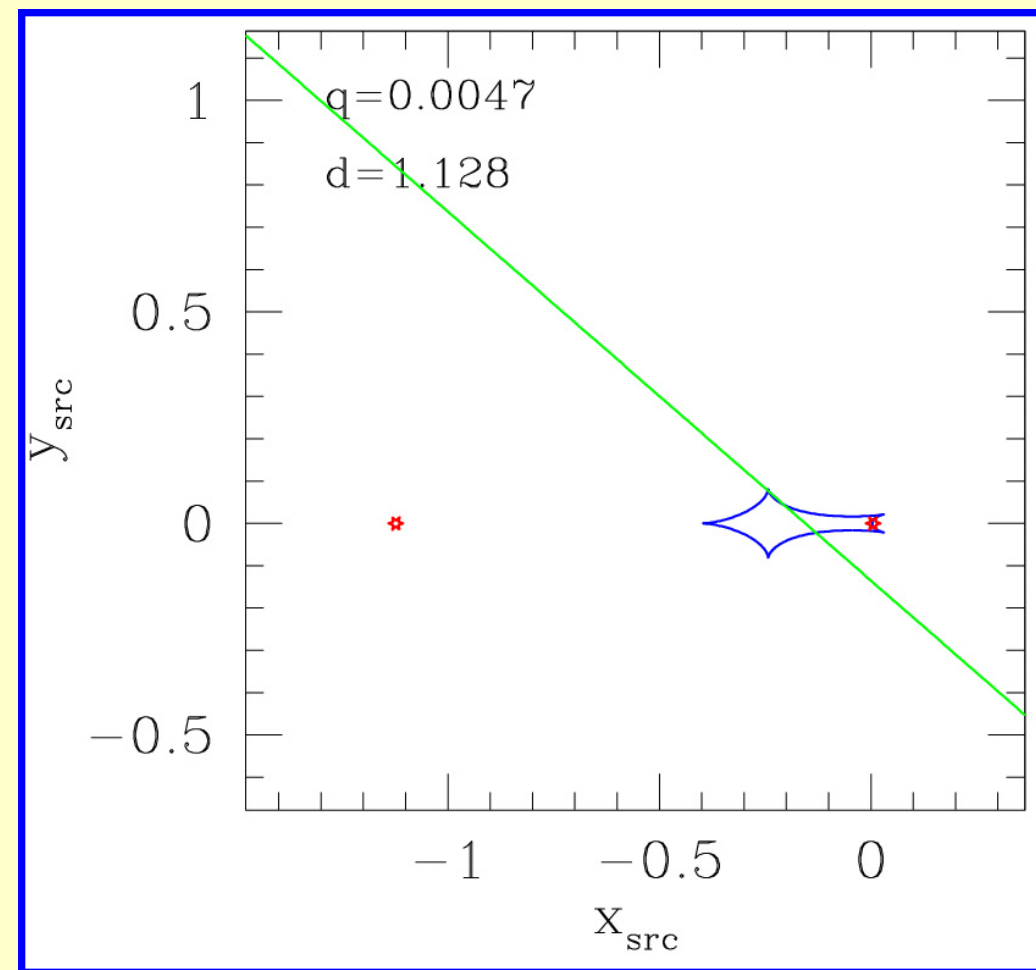
$T_{\text{max}} = 2847.398$ (27 VII 2003)

$t_E = 55\text{d}$

$I_0 = 19.301$

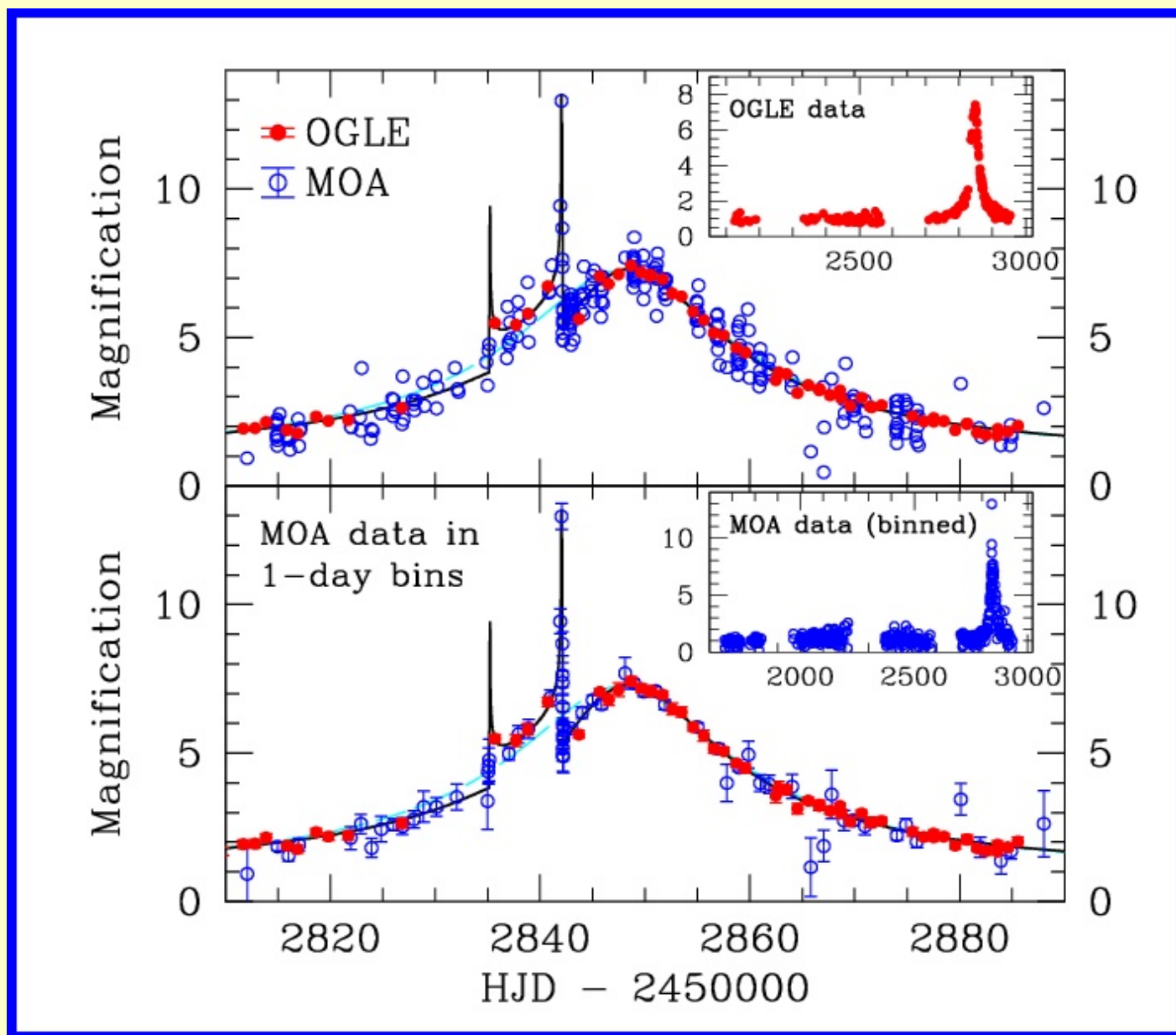


OGLE 2003-BLG-235



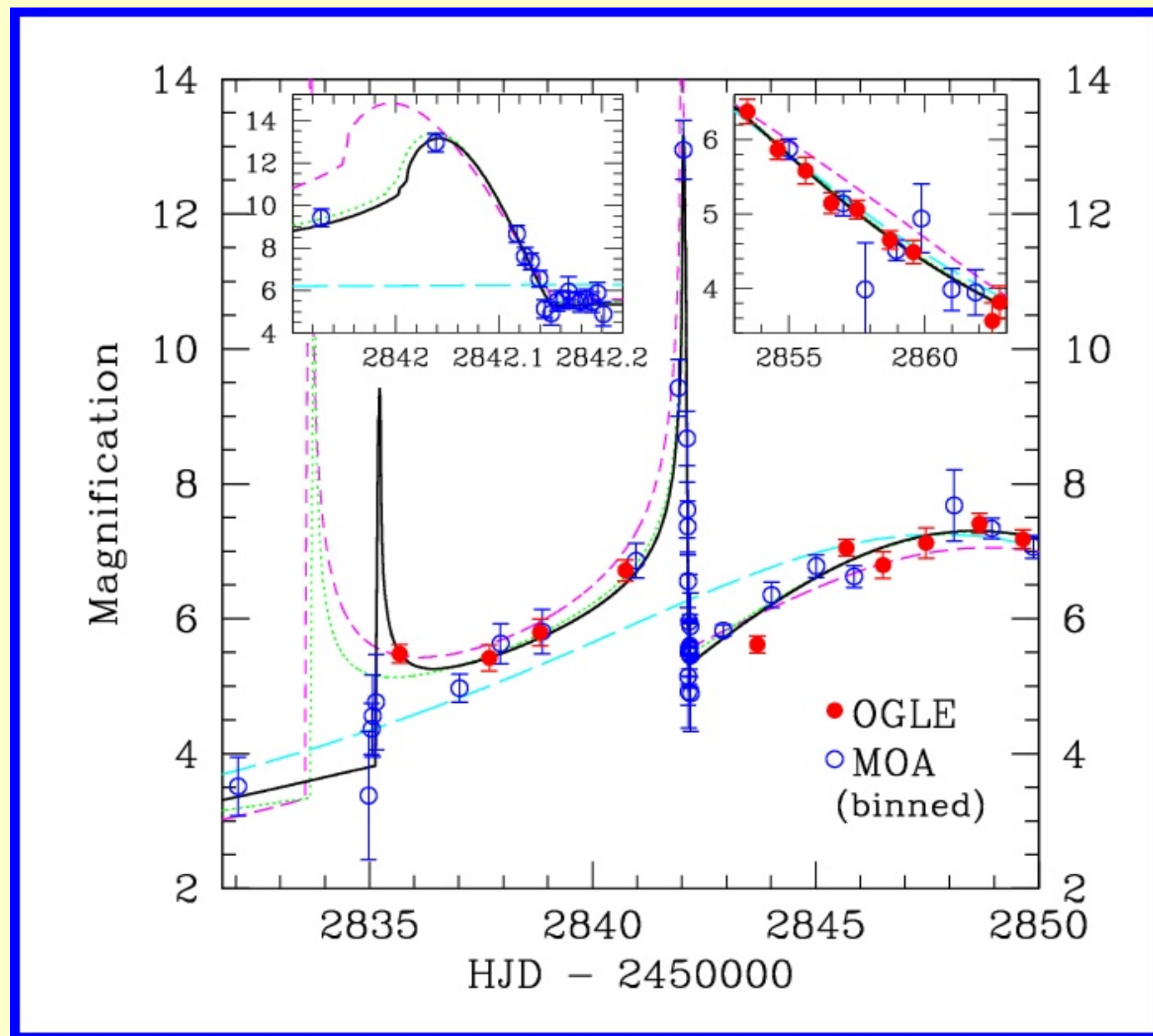
Model oparty tylko na obserwacjach OGLE przy **założeniu**, że około HJD=2452840 miało miejsce przejście przez kaustykę

OGLE 2003-BLG-235 / MOA 2003-BLG-53



Alert MOA: 21.VII.2003

OGLE 2003-BLG-235 / MOA 2003-BLG-53



MOA:

większy rozrzut
więcej obserwacji
przejście kaustyki

OGLE 2003-BLG-235 / MOA 2003-BLG-53

Planeta bo małe q

Małe q :
 kaustyka mała (12% t_E)
 kaustyka słaba

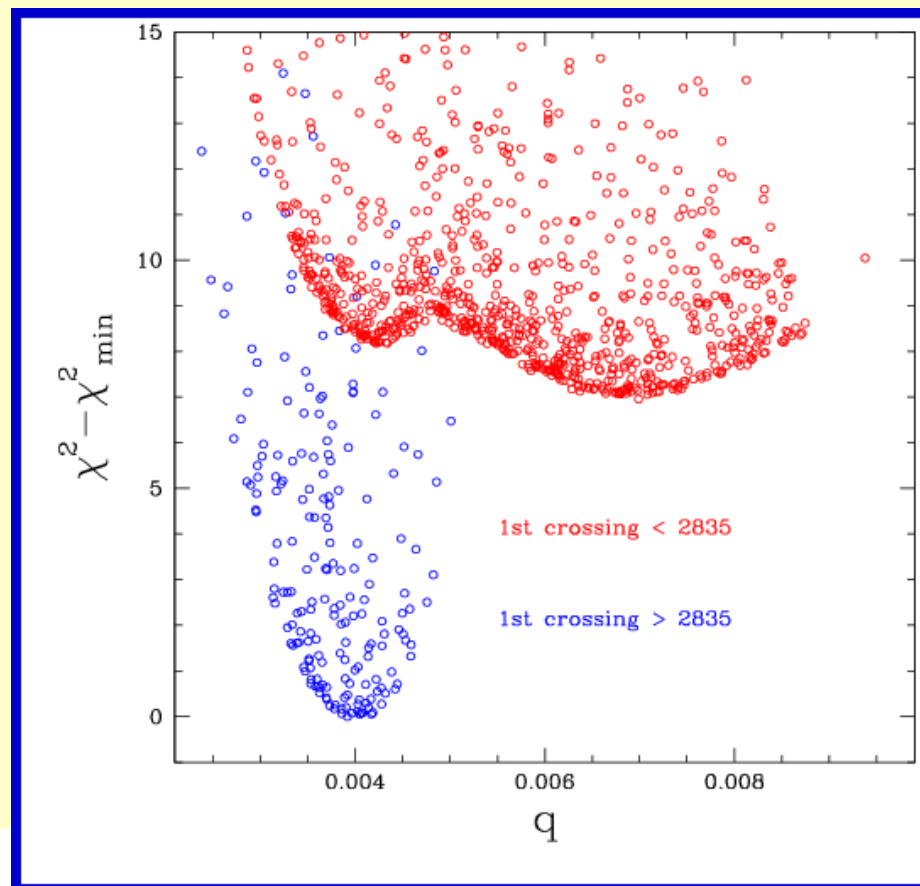


Table 1. Microlens Model Parameters

Model	M_p/M_*	θ_*/θ_E	a_{proj}/R_E	ϕ	u_0	t_0	t_E (days)	χ^2 (1267 dof)	χ^2_{MOA} (1089 dof)	χ^2_{OGLE} (178 dof)
Best Fit	0.0039^{+11}_{-07}	0.00096(11)	1.120(7)	$223^\circ 8(1^\circ 4)$	0.133(3)	2848.06(13)	61.5(1.8)	1390.49	1151.00	239.50
Early Caustic	0.0070	0.00104	1.121	$218^\circ 9$	0.140	2847.90	58.5	1397.87	1149.37	248.49
Best Non-planet	0.0300	0.00088	1.090	$187^\circ 9$	0.144	2846.20	57.5	1601.44	1229.47	371.98
Single Lens	—	—	—	—	0.222	2847.77	45.2	2041.45	1624.17	417.28

Note. — The units for t_0 are HJD - 2450000.

OGLE 2003-BLG-235 / MOA 2003-BLG-53

MS star:

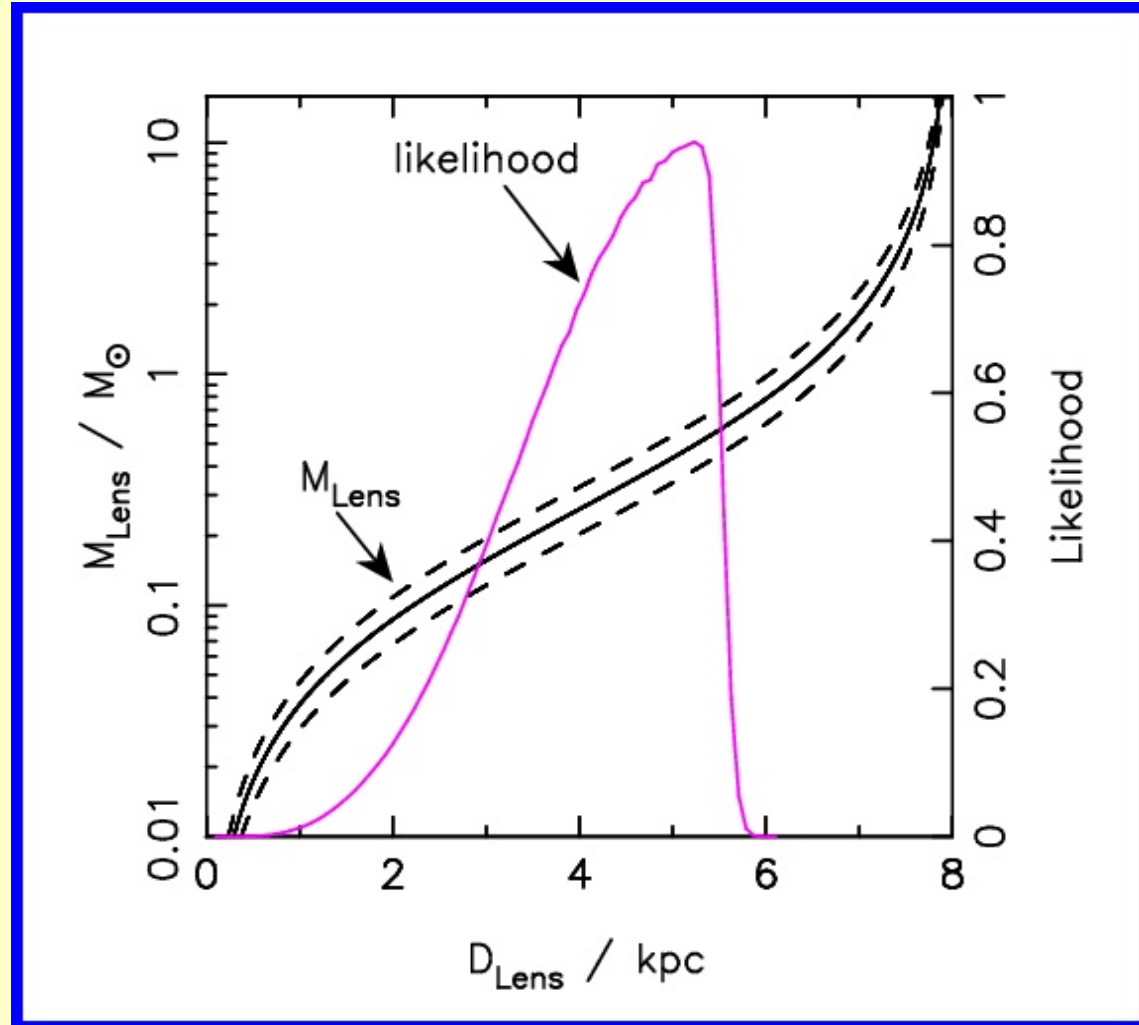
90%: $3.3\text{kpc} < d < 5.4\text{kpc}$

\Rightarrow karzeł M2-M7

$(0.12 - 0.39) M_{\text{sun}}$

+ $(0.3 - 1.6) M_{\text{jup}}$

w odległości 1.3 – 3.1 AU

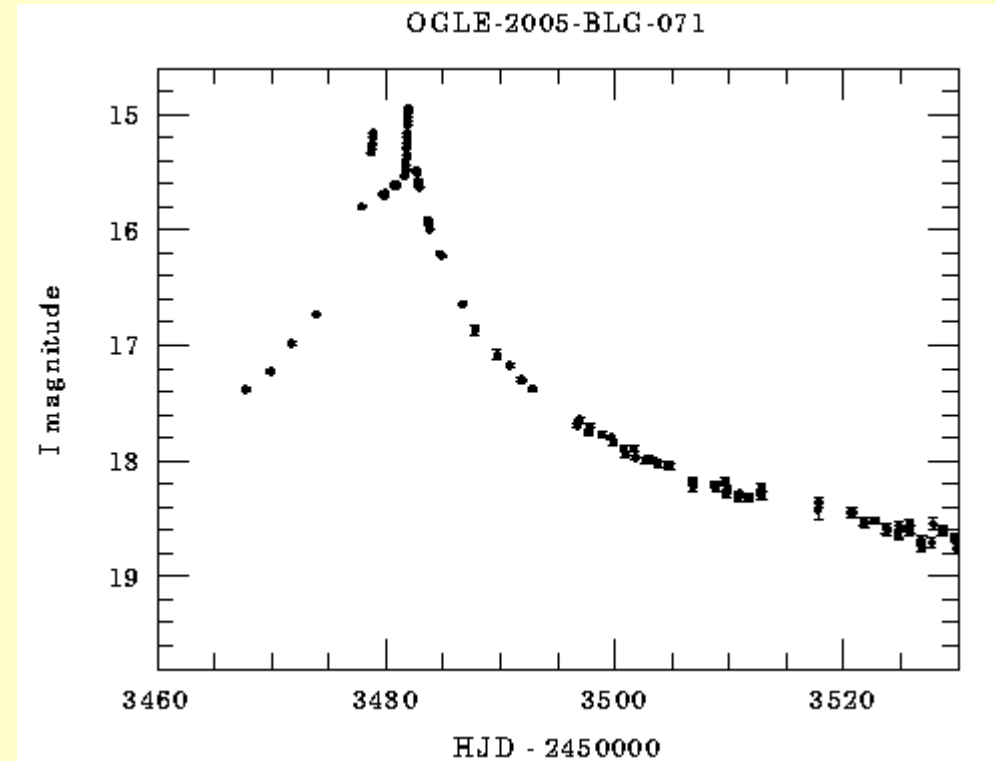
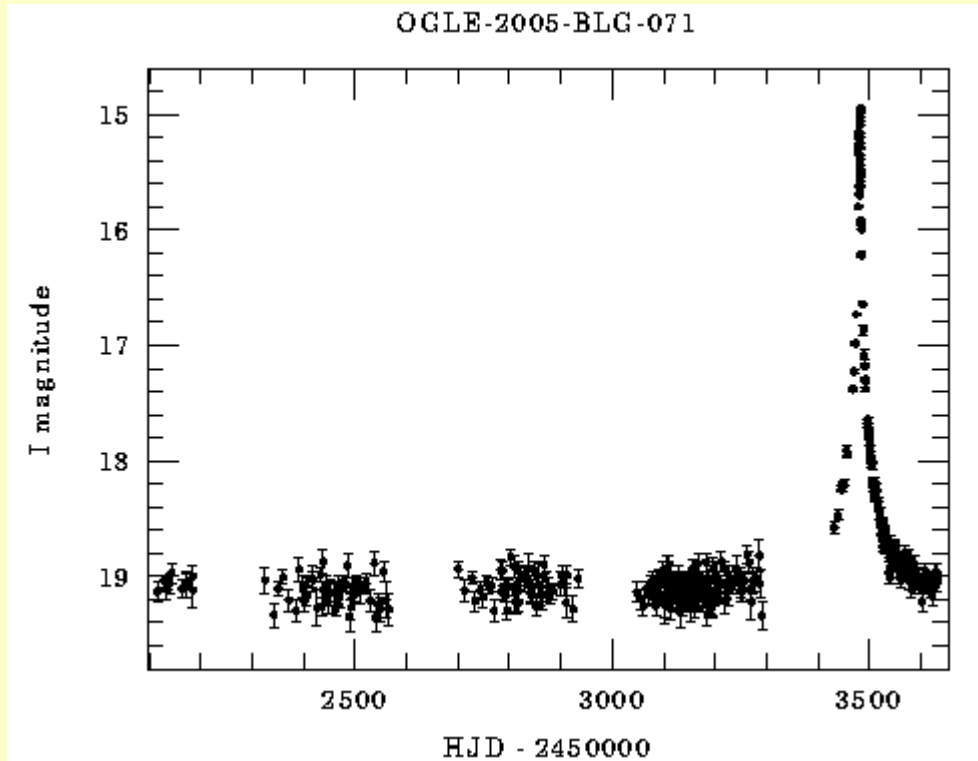


OGLE 2003-BLG-235/MOA 2003-BLG-53: A planetary microlensing event.

I.A. Bond¹, A. Udalski², M. Jaroszyński^{2,4}, N.J. Rattenbury³, B. Paczyński⁴, I. Soszyński², L. Wyrzykowski², M.K. Szymański², M. Kubiak², O. Szewczyk^{2,4}, K. Żebruń², G. Pietrzyński^{2,5}, F. Abe⁶, D.P. Bennett⁷, S. Eguchi⁶, Y. Furuta⁶, J.B. Hearnshaw⁸, K. Kamiya⁶, P.M. Kilmartin⁸, Y. Kurata⁶, K. Masuda⁶, Y. Matsubara⁶, Y. Muraki⁶, S. Noda⁹, K. Okajima⁶, T. Sako⁶, T. Sekiguchi⁶, D.J. Sullivan¹⁰, T. Sumi⁴, P.J. Tristram³, T. Yanagisawa¹¹, and P.C.M. Yock³

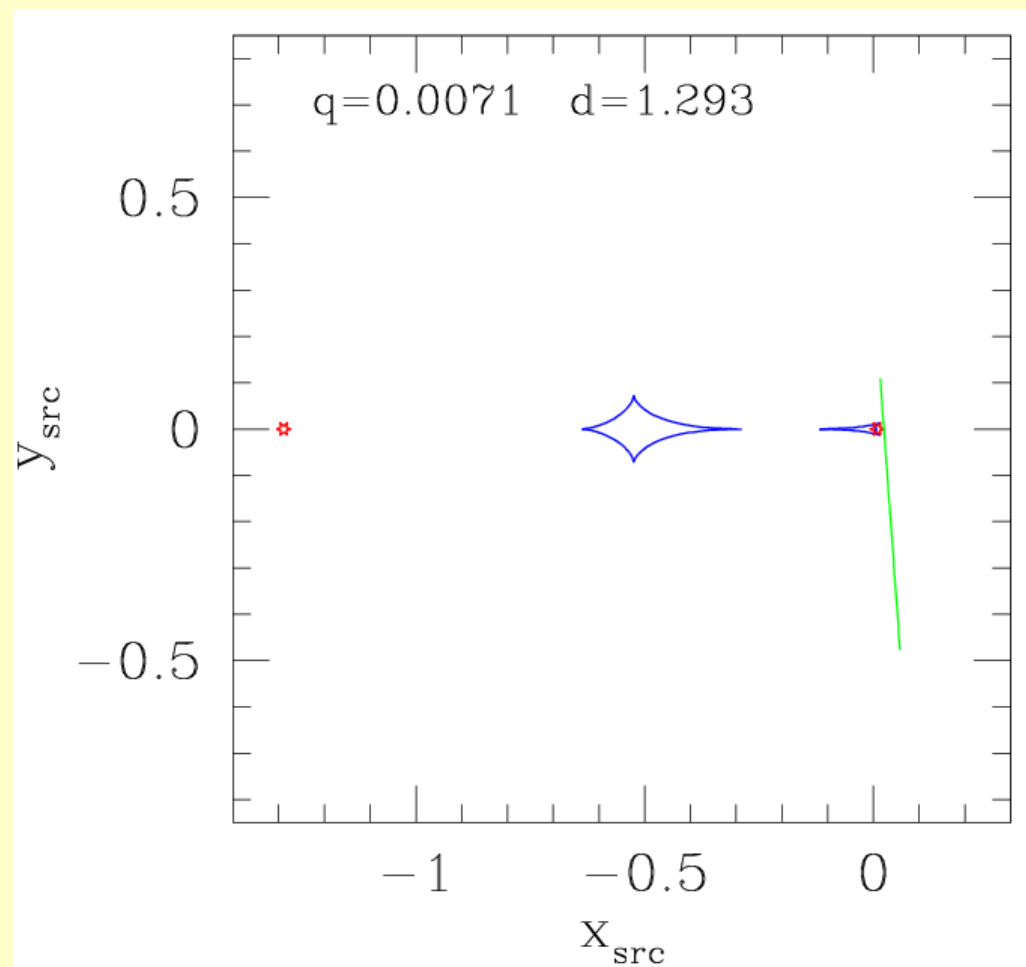
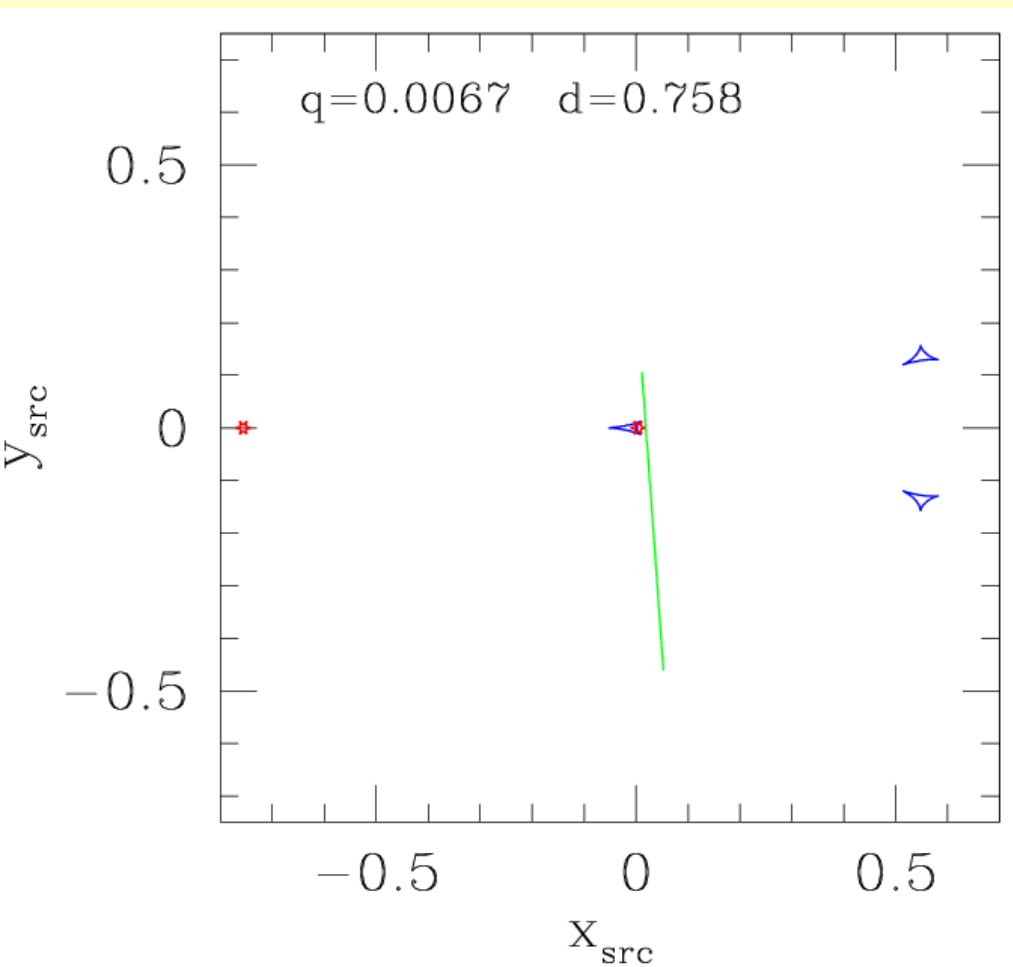
(The MOA and OGLE Collaborations)

OGLE 2005-BLG-071



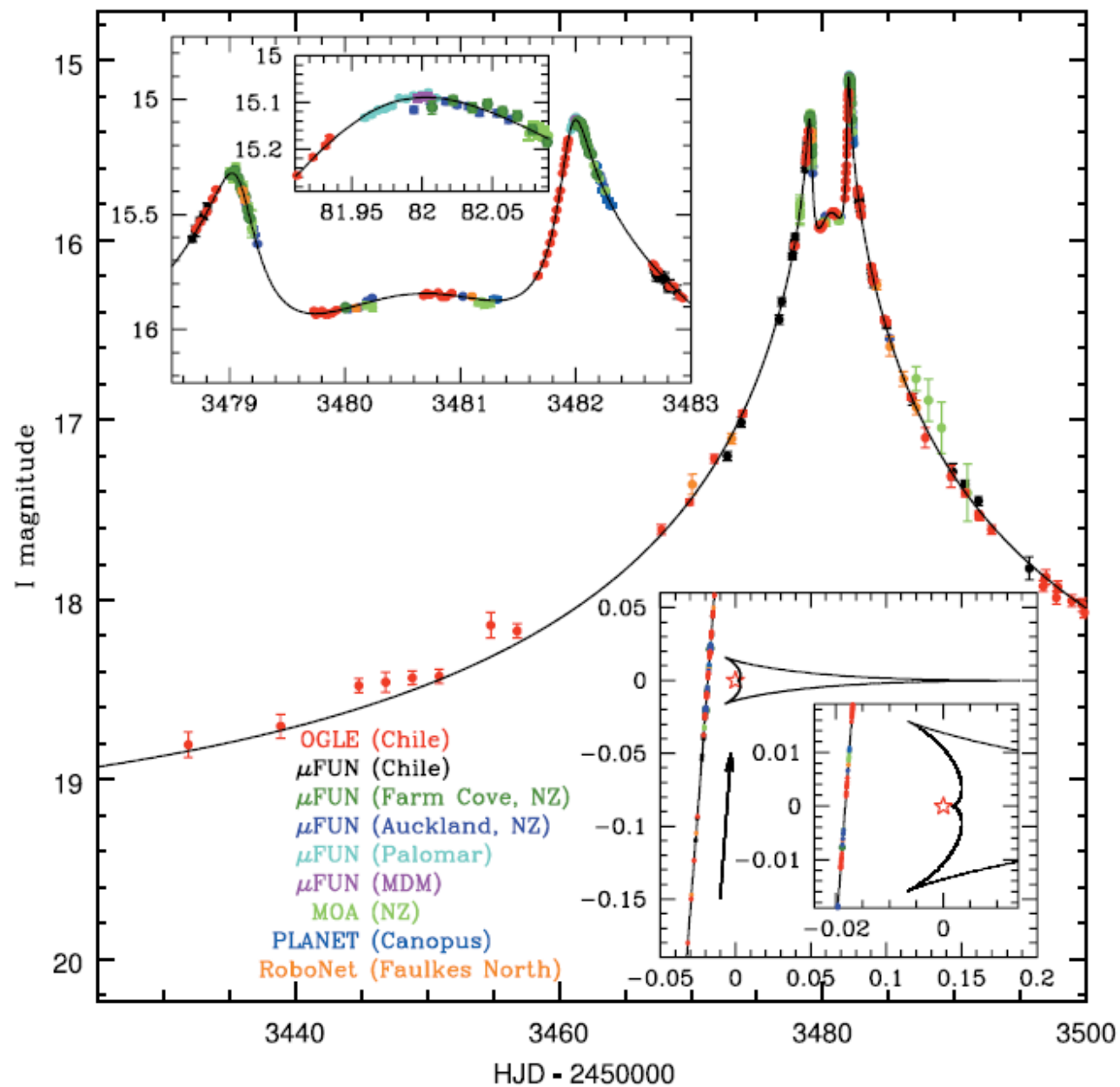
[www.astrouw.edu.pl/~ogle/ogle3/ews]

OGLE 2005-BLG-071



Znana dla podwójnych soczewek degeneracja rozwiązań
Różne rozmiary orbity, ale stosunek mas bardzo podobny.

OGLE 2005-BLG-071

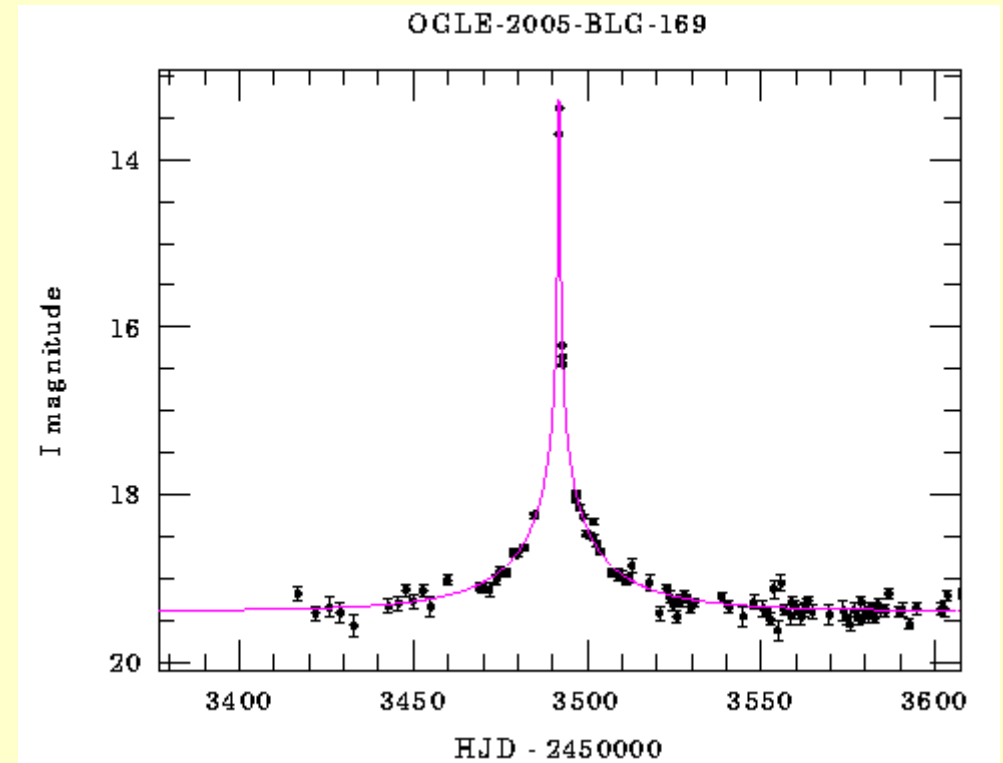
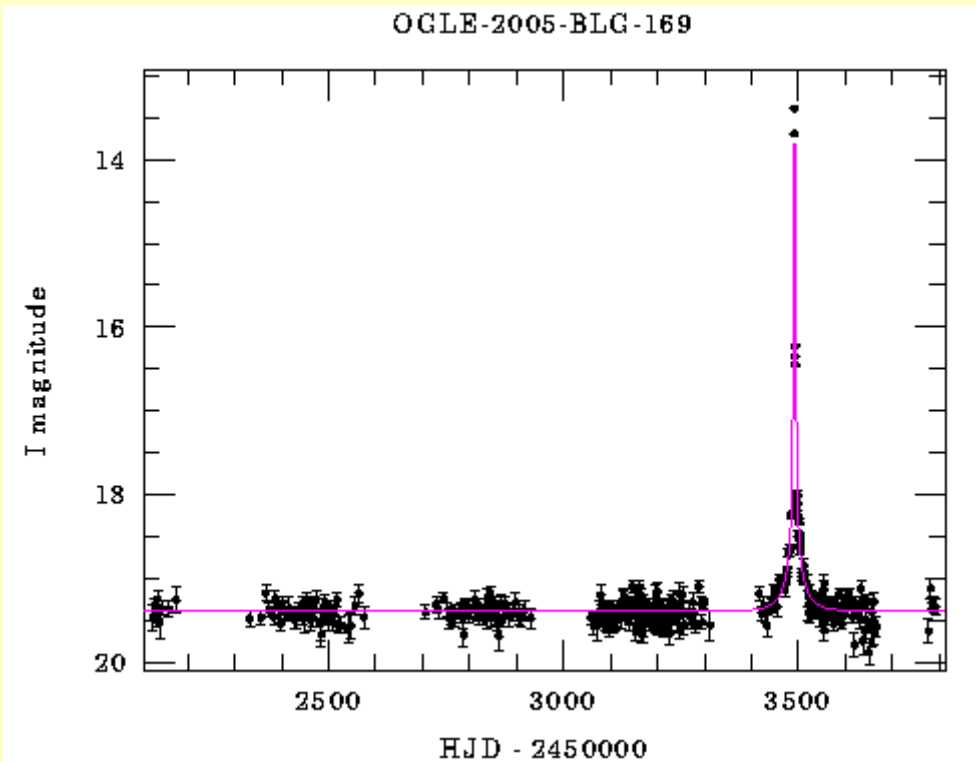


Udalski i in. (2005) ApJ, 628, L109

OGLE-2005-BLG-071 MODEL PARAMETERS

Model	t_0 (HJD - 2,453,400)	u_0	t_E (days)	q	b	α (deg)	I_s (mag)	I_b (mag)	χ^2 (1092 dof)
Wide	80.6791 ± 0.0020	0.0236 ± 0.0013	70.9 ± 3.3	0.0071 ± 0.0003	1.294 ± 0.002	274.23 ± 0.04	19.53	21.29	1105.6
Close	80.6919 ± 0.0023	0.0225 ± 0.0012	73.9 ± 3.5	0.0067 ± 0.0003	0.758 ± 0.001	274.48 ± 0.05	19.59	21.05	1127.6

OGLE 2005-BLG-169

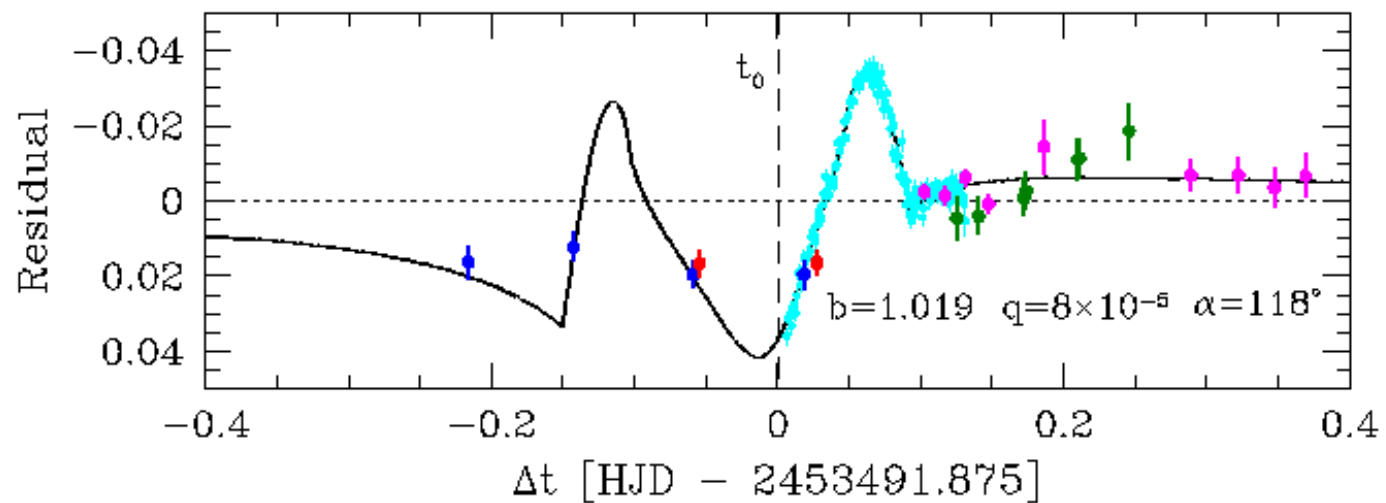
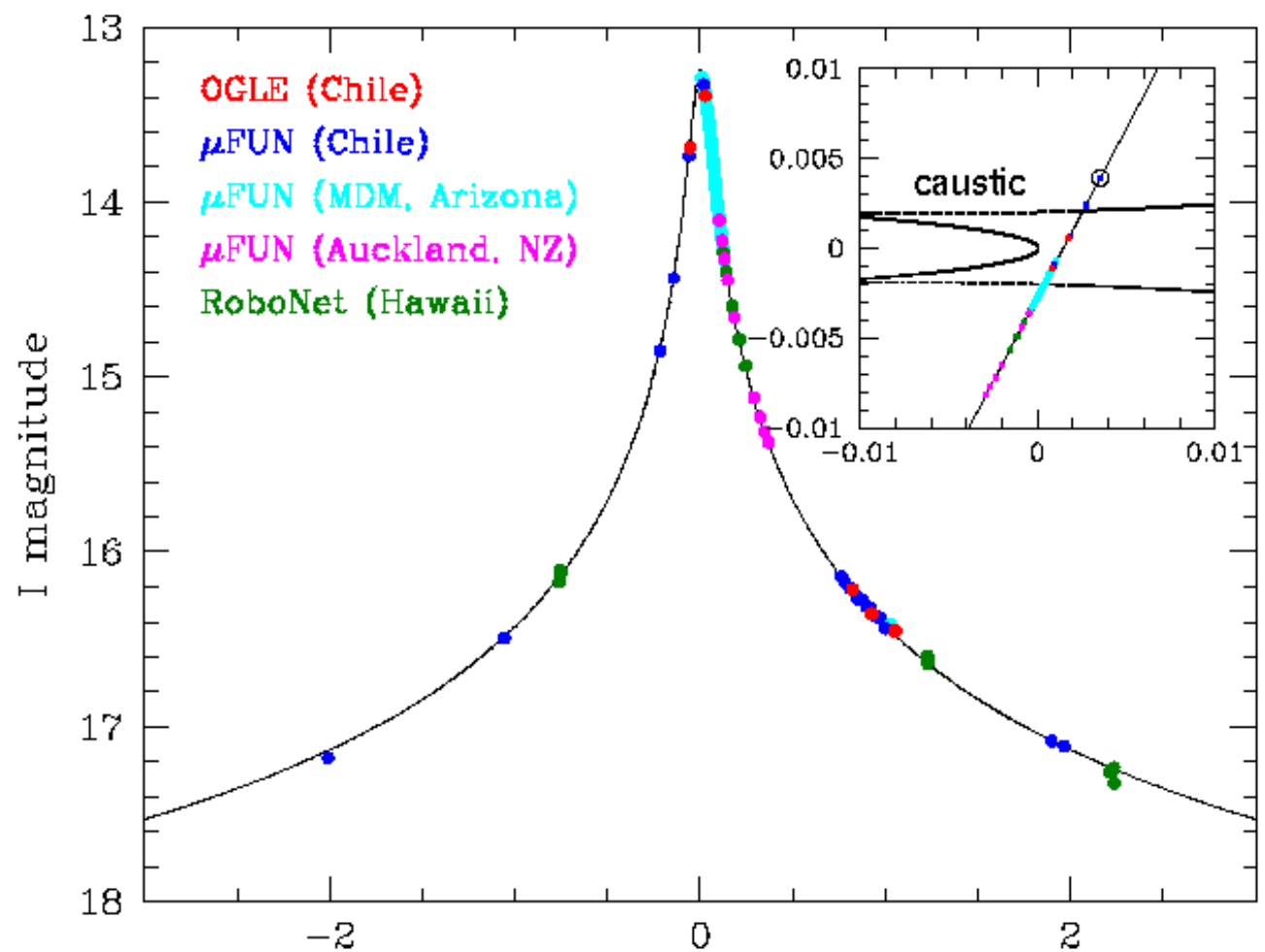


[www.astrouw.edu.pl/~ogle/ogle3/ews]

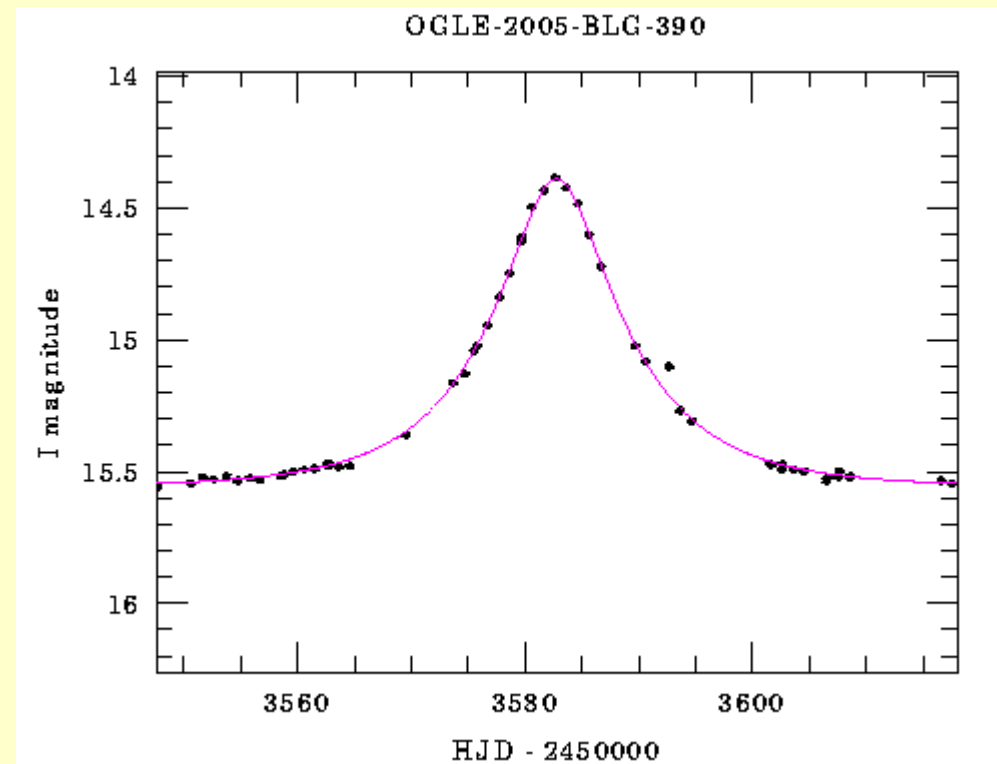
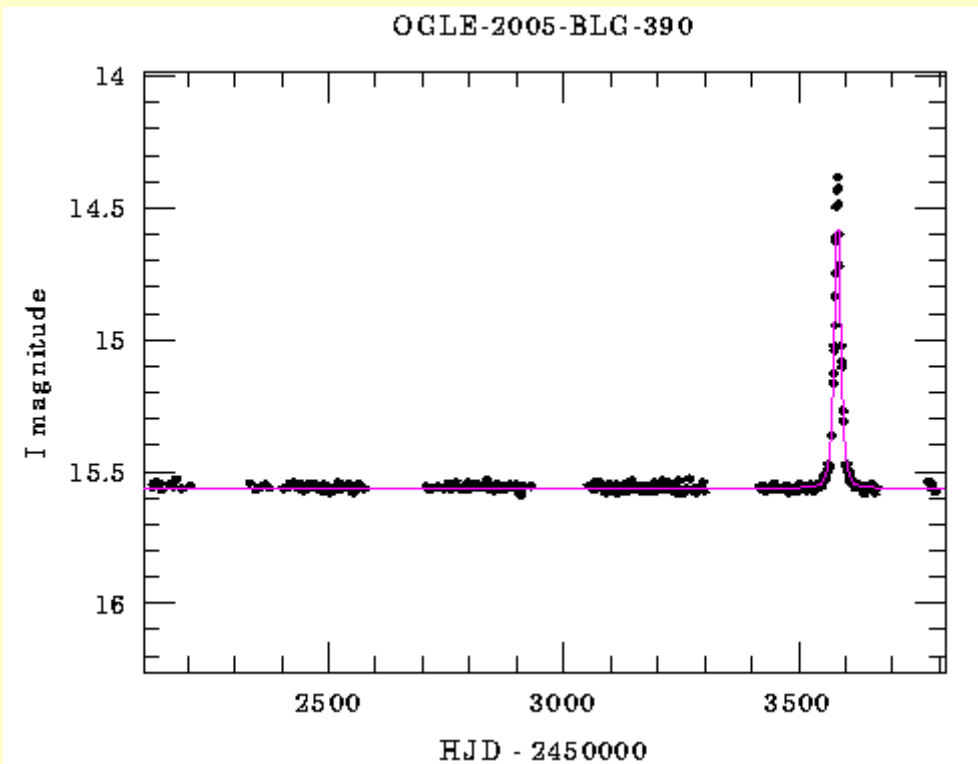
OGLE 2005- BLG-169

0.5 M_{Sun}
+13 M_{Earth}
2.7 AU

Gould, Udalski i in.
(2006) ApJ, 644, L37

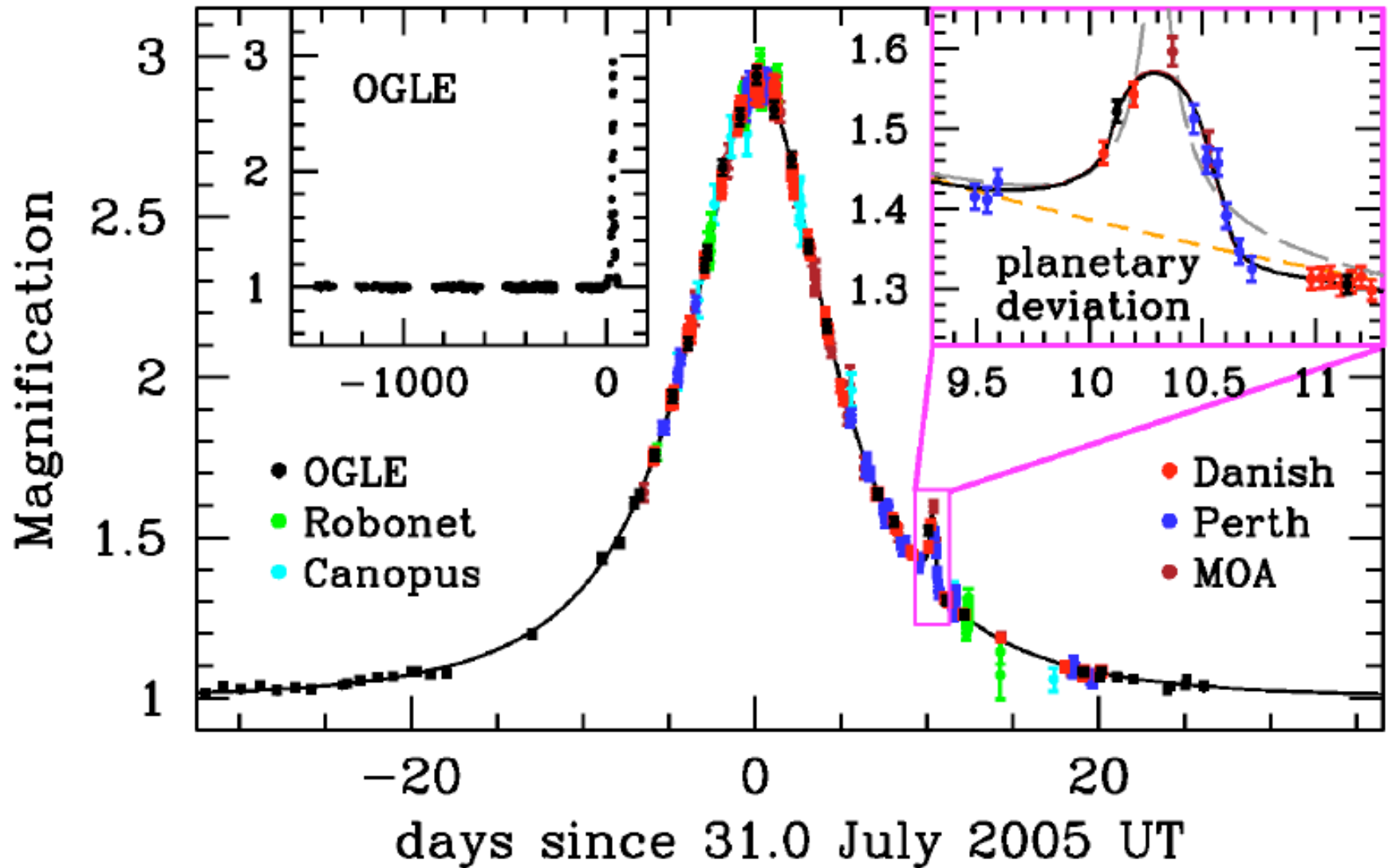


OGLE 2005-BLG-390



[www.astro.uw.edu.pl/~ogle/ogle3/ews]

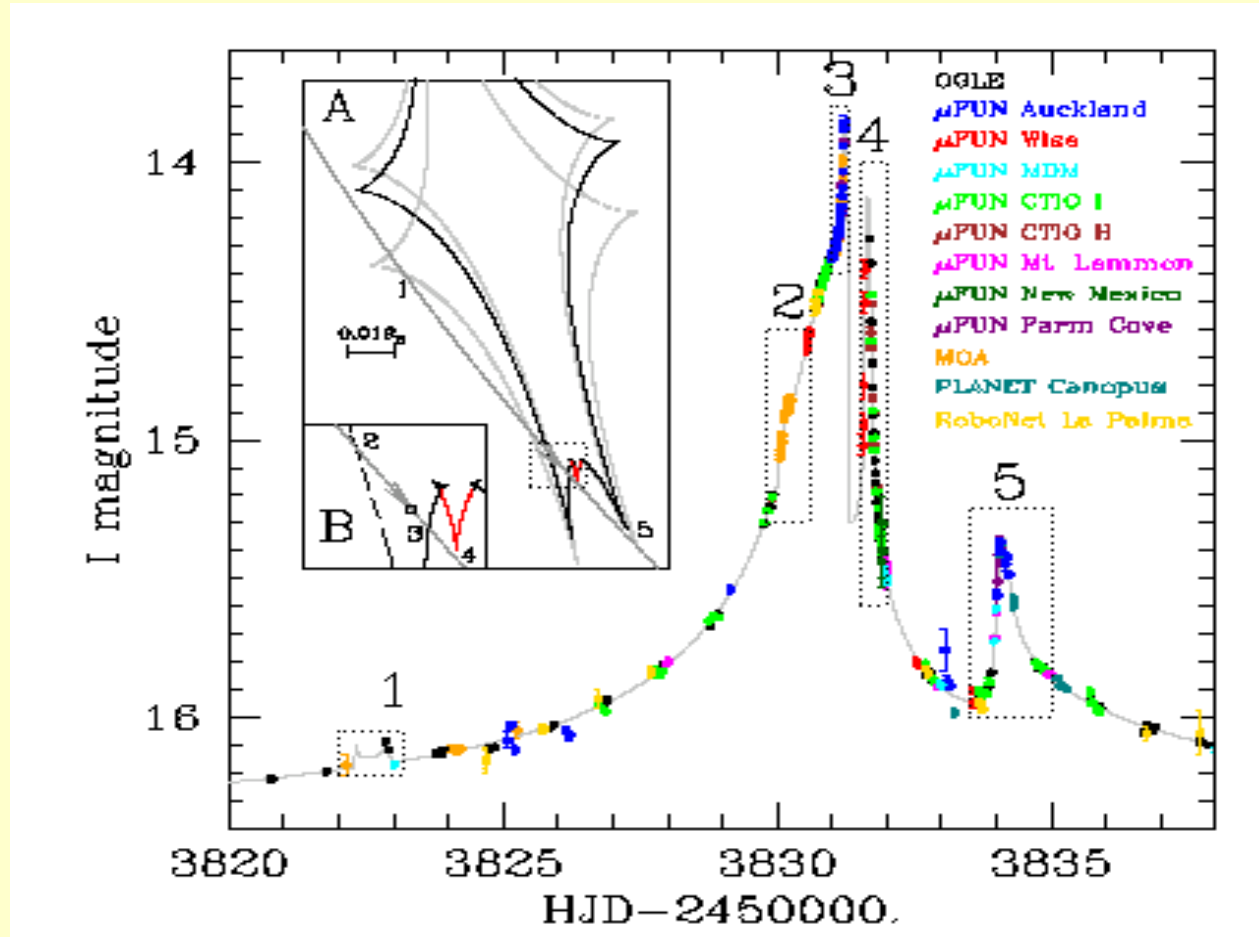
OGLE 2005-BLG-390



oceny: $0.22M_{\text{Sun}} + 5.5 M_{\text{Earth}}$, 2.9 AU, w odległości ok. 5.5 kpc

PLANET+OGLE+MOA (2006) Nature 439, 437

OGLE 2006-BLG-109



2 planety: ~ 0.71 i ~ 0.27 mas Jowisa w odległościach ~ 2.3 and ~ 4.6 AU od gwiazdy 2 razy lżejszej od Słońca, w odległości ~ 5000 l. św.
Stosunki mas i odległości przypominają układ Słońce-Jowisz-Saturn.

Planety wykryte przez mikrosoczewkowanie

Interactive Extra-solar Planets Catalog

Version: 2.02 Maintained by © 2009 [Jean Schneider](#) (CNRS-LUTH, Paris Observatory)
 Technical support : **Renaud Savalle**

For the use of this catalog [README](#) first.

Candidates detected by microlensing update : 10 August 2009

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[Data Catalog](#)

[Histograms](#)

[Correlation Diagrams](#)

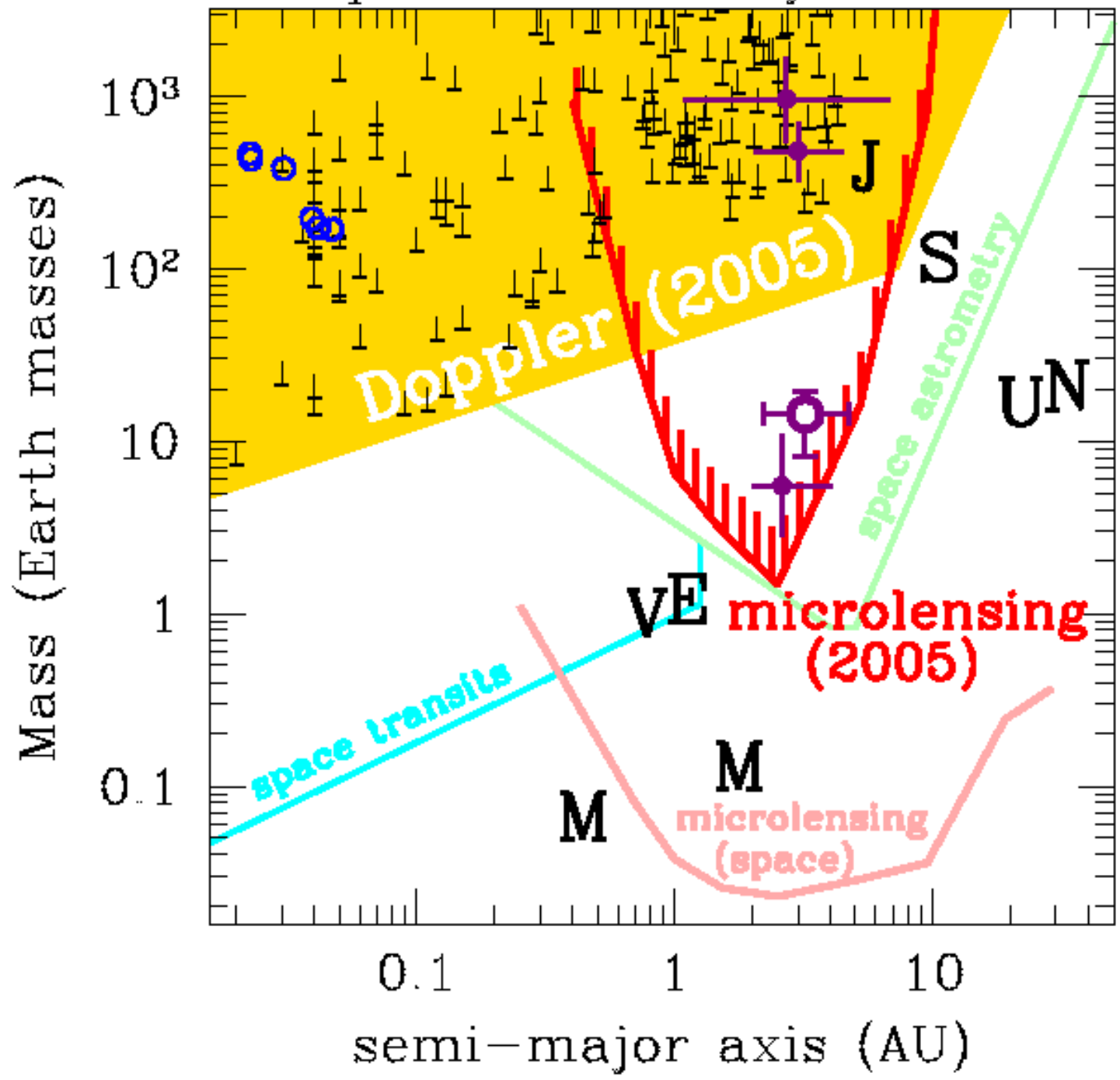
[Planet Table](#)

(sorted by **increasing period of the closest planet**)

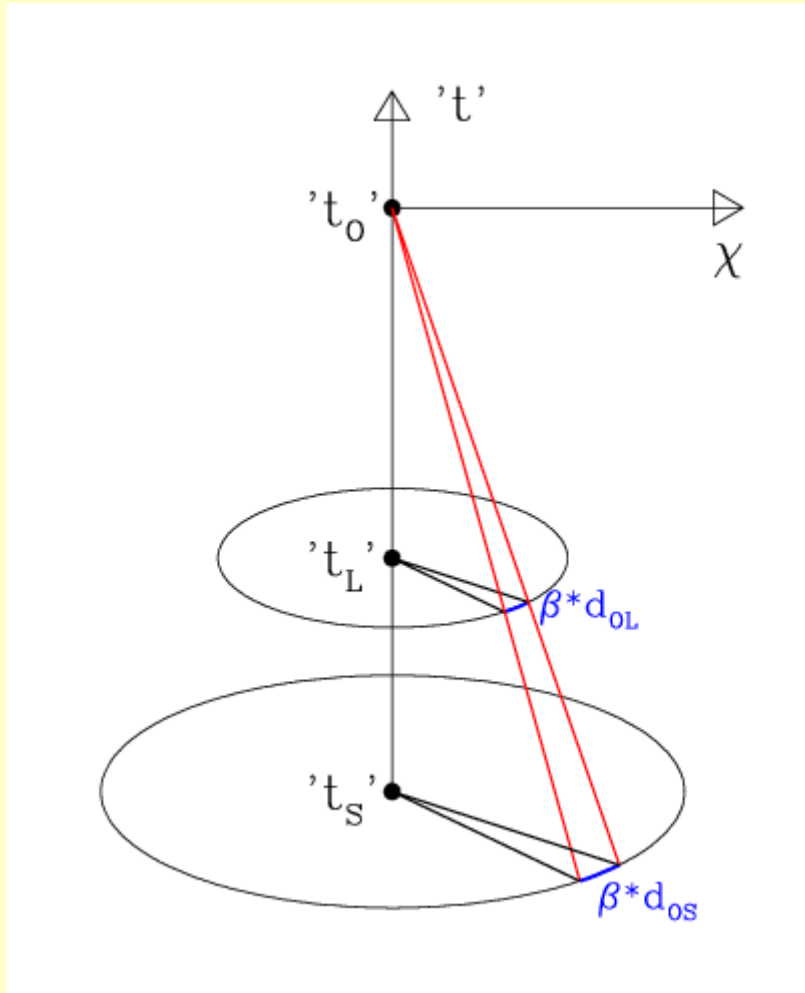
Statistics : 8 planetary systems / 9 planets / 1 multiple planet systems

Planet Data (- ALL FORMATS)									
PLANET	M. (M_{jup}) - stats	Radius (R_{jup}) - stats	PERIOD (days) - stats	SEM-MAJ AXIS (AU) - stats	ECC.	INCL. (deg) - stats	STATUS i	DISCOV. (year)	UPDATE
OGLE235-MOA53 b	2.6	-	-	5.1	-	-	R	2004	10/06/06
MOA-2007-BLG-192-L b	0.01	-	-	0.62	-	-	R	2008	02/06/08
MOA-2007-BLG-400-L b	0.9	-	-	0.85	-	-	S	2008	19/09/08
MOA-2008-BLG-310-L b	0.23	-	-	1.25	-	-	S	2009	10/08/09
OGLE-06-109L b	0.71	-	1825	2.3	-	-	R	2008	14/02/08
c	0.27	-	5100	4.6	0.11	59	R	2008	05/05/08
OGLE-05-169L b	0.04	-	3300	2.8	-	-	S	2005	12/04/06
OGLE-05-390L b	0.017	-	3500	2.1	-	-	R	2005	12/04/06
OGLE-05-071L b	3.5	-	~ 3600	3.6	-	-	R	2005	10/04/08

Exoplanet Discovery Potential



W modelu kosmologicznym



(przypomnienie...)

$$ds^2 = c^2 dt^2 - a^2(t) (d\chi^2 + S^2(\chi) (d\theta^2 + \sin^2 \theta d\phi^2))$$

$$S(\chi) \stackrel{def}{=} \begin{cases} \sin(\chi) & k = +1 \\ \chi & k = 0 \\ \sinh(\chi) & k = -1 \end{cases}$$

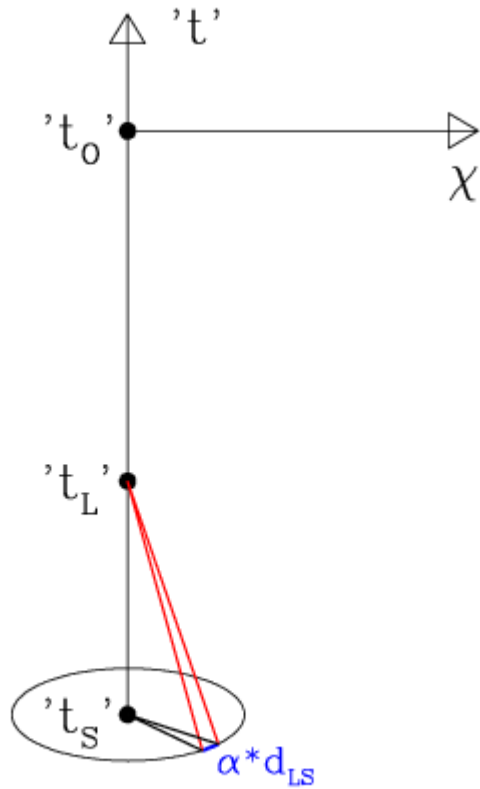
$$ds = 0 \Rightarrow \chi_{OL} \stackrel{def}{=} \int_{t_L}^{t_0} \frac{cdt}{a(t)} \quad \chi_{OS} \stackrel{def}{=} \int_{t_S}^{t_0} \frac{cdt}{a(t)}$$

$$\beta \cdot d_{OL} = \beta \cdot a(t_L) S(\chi_{OL}) \equiv \beta \cdot \frac{a(t_0)}{1+z_L} S(\chi_{OL})$$

$$\beta \cdot d_{OS} = \beta \cdot a(t_S) S(\chi_{OS}) \equiv \beta \cdot \frac{a(t_0)}{1+z_S} S(\chi_{OS})$$

$$\Rightarrow d_{OL} = \frac{a_0}{1+z_L} S(\chi_{OL}) \quad d_{OS} = \frac{a_0}{1+z_S} S(\chi_{OS})$$

W modelu kosmologicznym



$$\chi_{LS} \stackrel{def}{=} \int_{t_S}^{t_L} \frac{cdt}{a(t)} \quad [= \chi_{OS} - \chi_{OL}]$$

$$\alpha \cdot d_{LS} = \alpha \cdot a(t_S) S(\chi_{LS}) \equiv \alpha \cdot \frac{a(t_0)}{1 + z_S} S(\chi_{LS})$$

$$\Rightarrow d_{LS} = \frac{a_0}{1 + z_S} S(\chi_{LS}) \quad [\neq d_{OS} - d_{OL}]$$

$$\Rightarrow D \stackrel{def}{=} \frac{d_{OL} d_{LS}}{d_{OS}} = \frac{a_0}{1 + z_L} \frac{S(\chi_{OL}) S(\chi_{LS})}{S(\chi_{OS})}$$