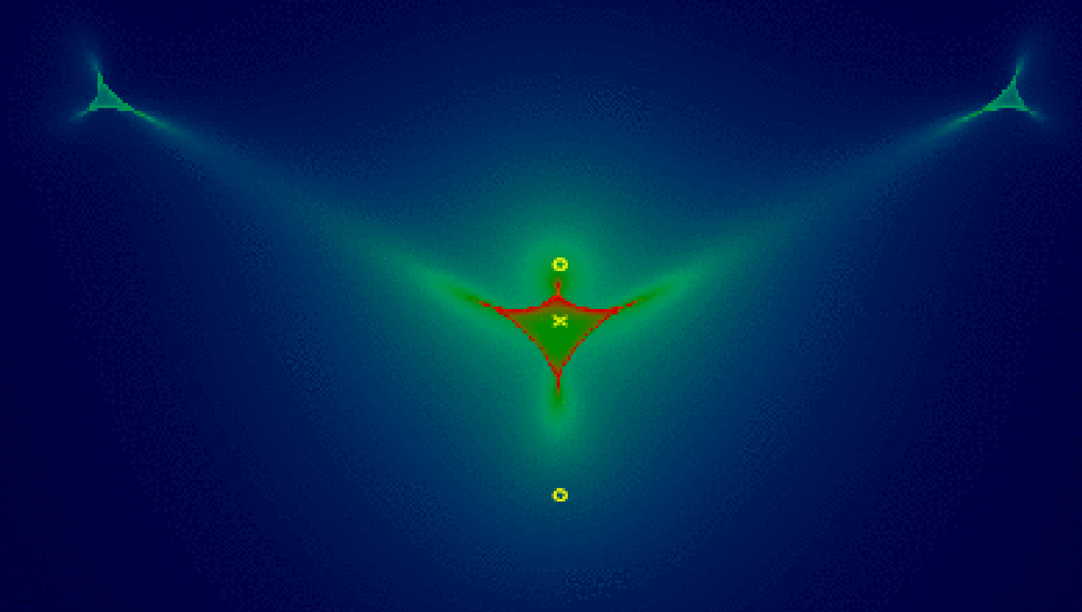
Searching for extrasolar planets using microlensing



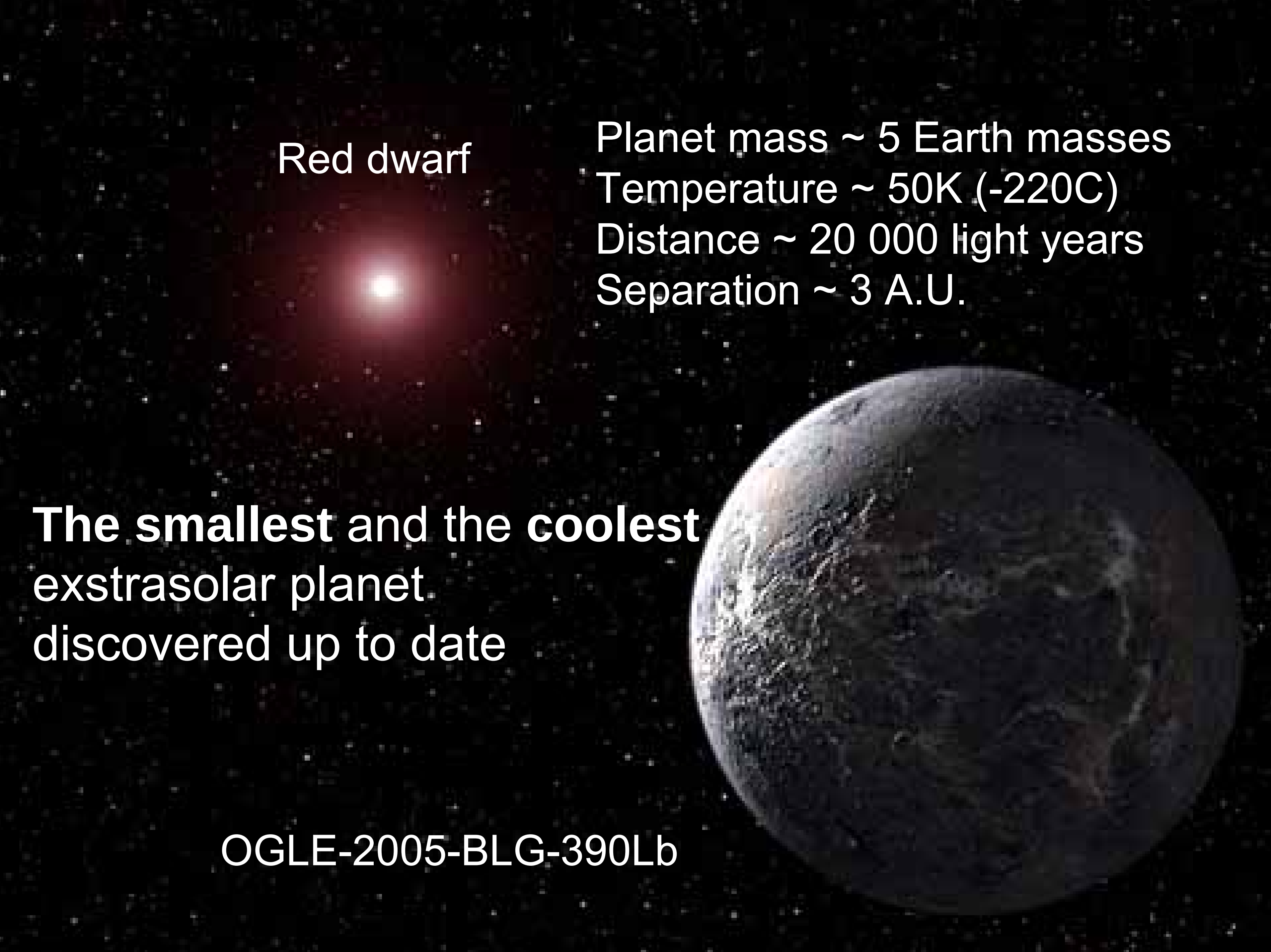
Dijana Dominis Prester

7.8.2007, Belgrade

Extrasolar planets

- Planets outside of the Solar System (exoplanets)
- Various methods: mostly massive hot gaseous planets
- Understanding **formation of planetary systems** in the Universe
- Search for extraterrestrial life: **terrestrial planets** (solid, low mass)

=> **microlensing**



Red dwarf

Planet mass ~ 5 Earth masses
Temperature ~ 50K (-220C)
Distance ~ 20 000 light years
Separation ~ 3 A.U.

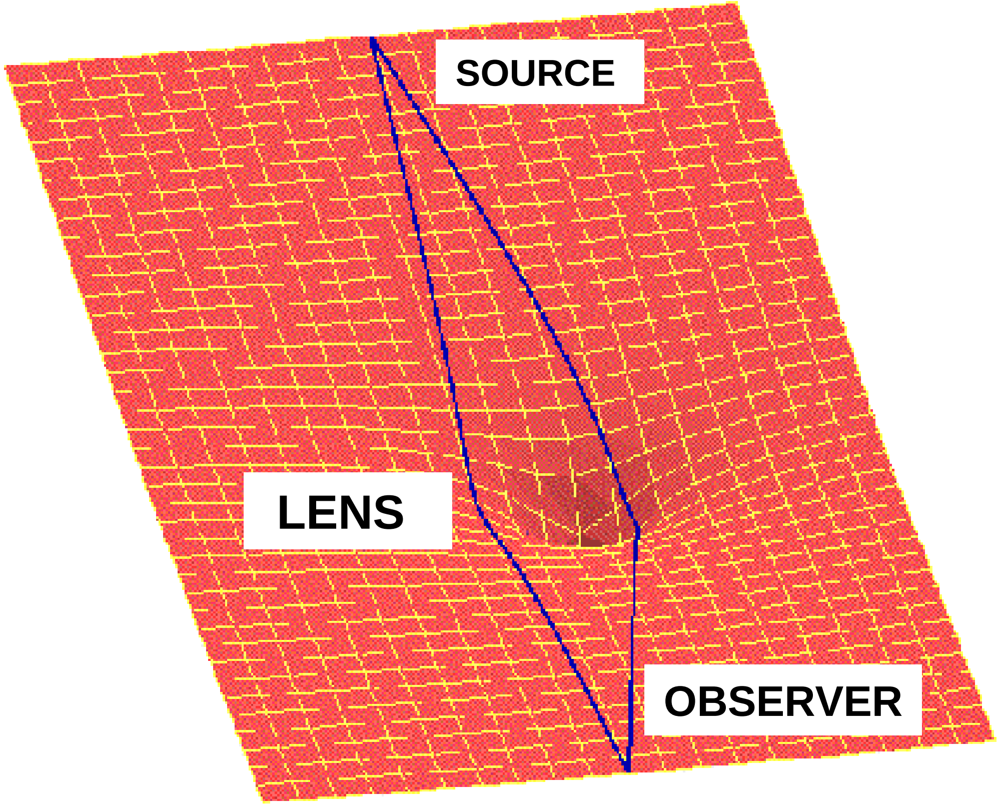
The smallest and the **coolest** exstrasolar planet discovered up to date

OGLE-2005-BLG-390Lb

Outline

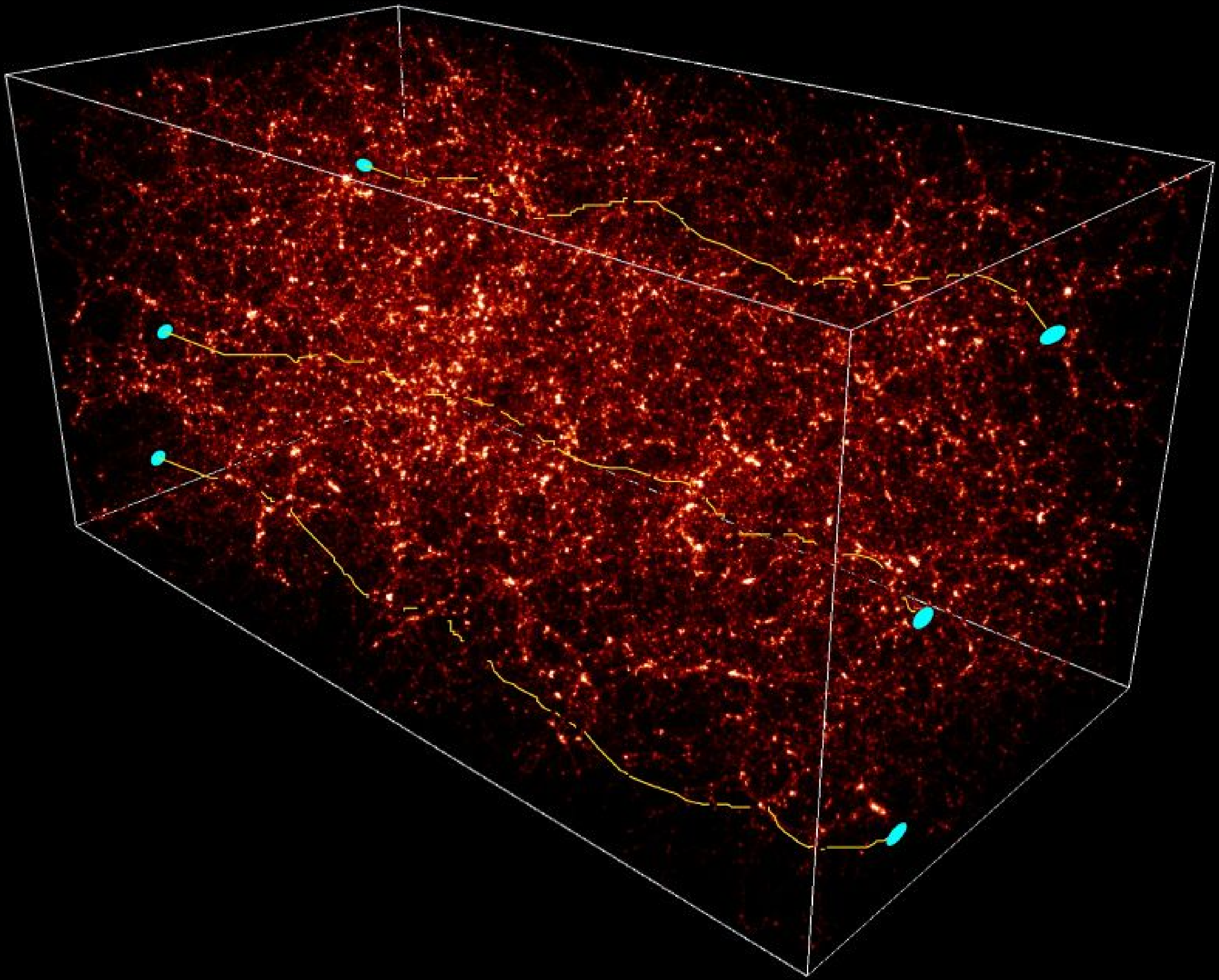
1. Gravitational lensing and microlensing
2. Single and binary lenses and sources
3. Discovery of OGLE-2005-BLG-390Lb
4. Other methods for finding extrasolar planets
5. Modeling techniques (synthetic data, optimization, genetic algorithm)

Gravitational lensing



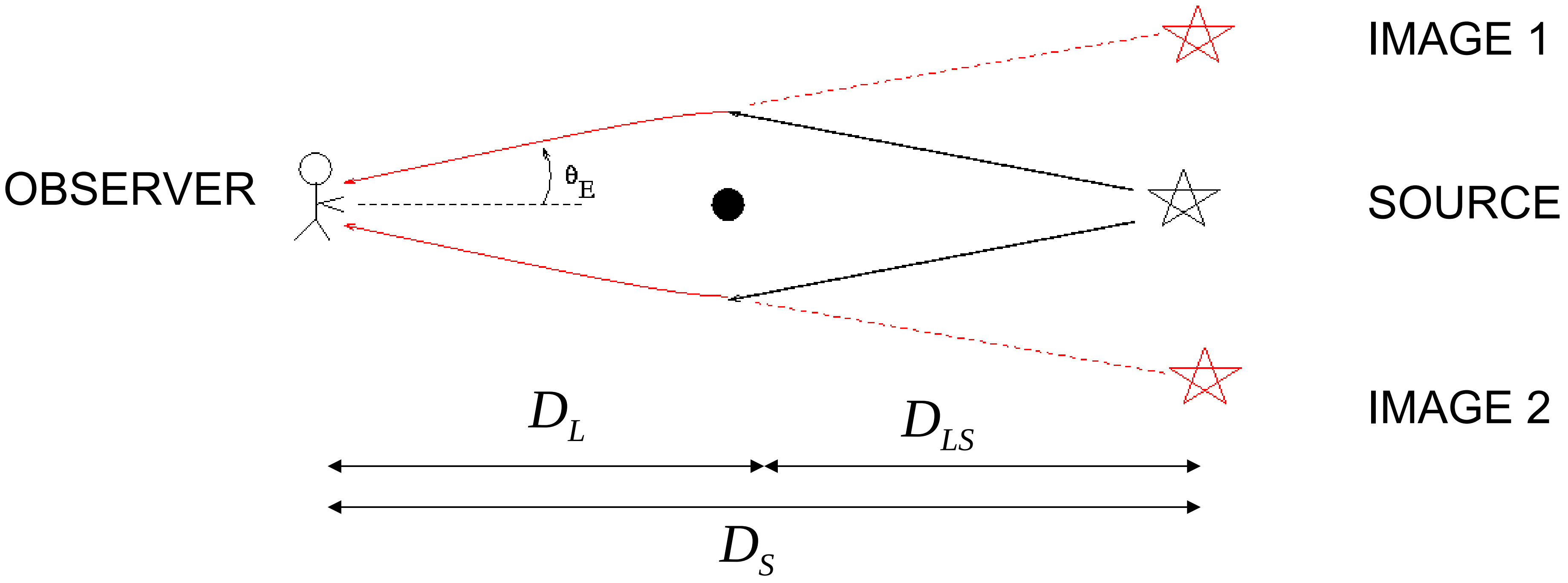
- Gravitational field
- Mass – deflects the light ray
- Larger mass => larger deflection angle

DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES



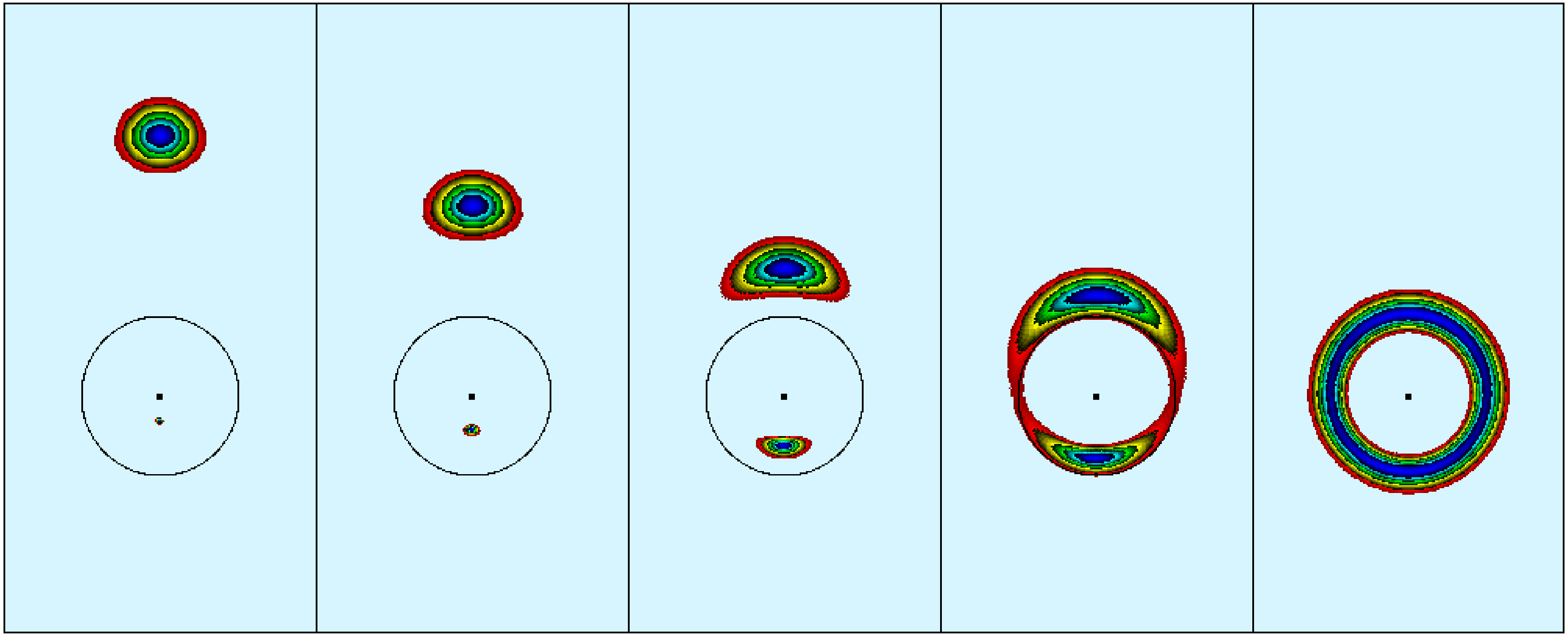
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Single Point Mass Lens

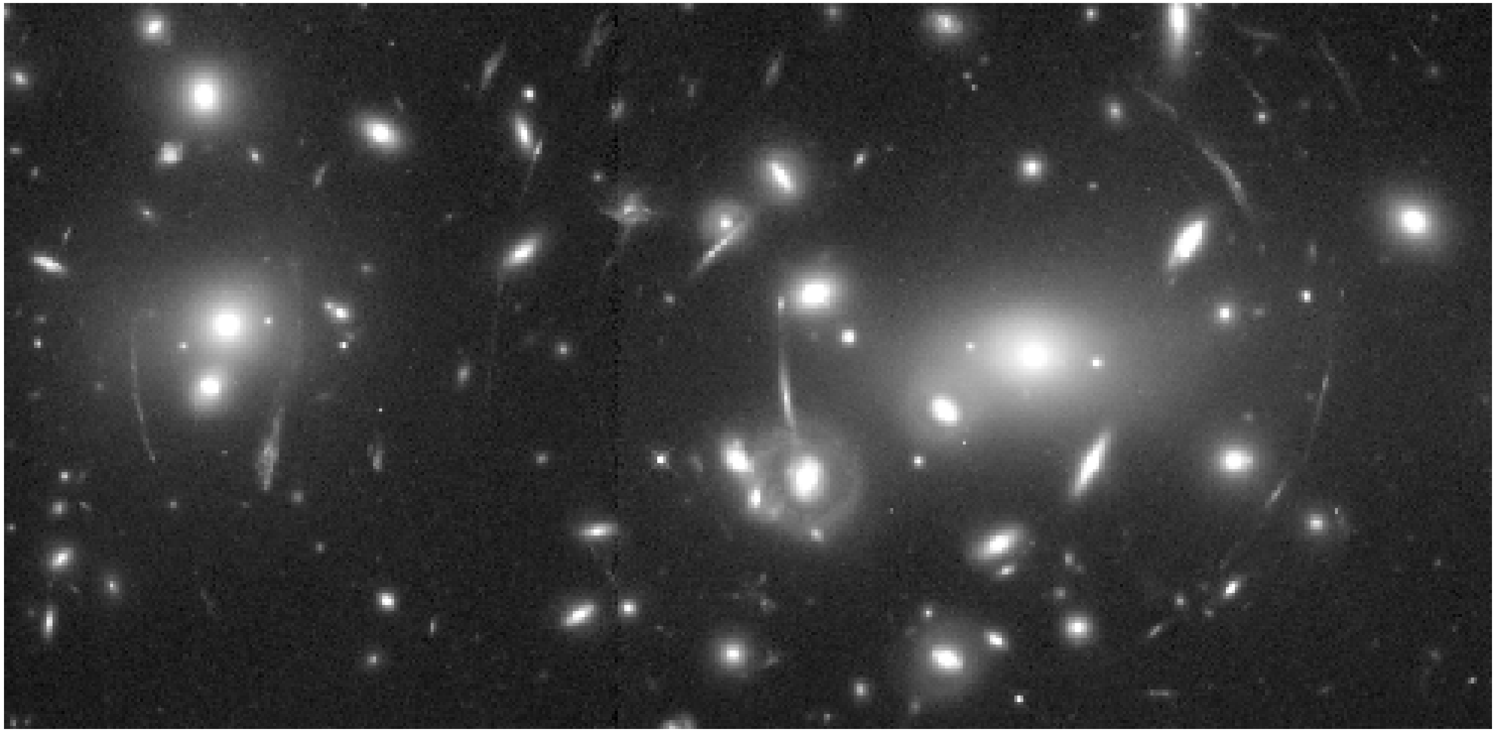


Einstein radius: $$R_0 = \sqrt{\frac{4GM_{tot}D_{LS}}{c^2 D_L D_S}}$$

Einstein ring



Cluster of galaxies Abell 2218 as a gravitational lens



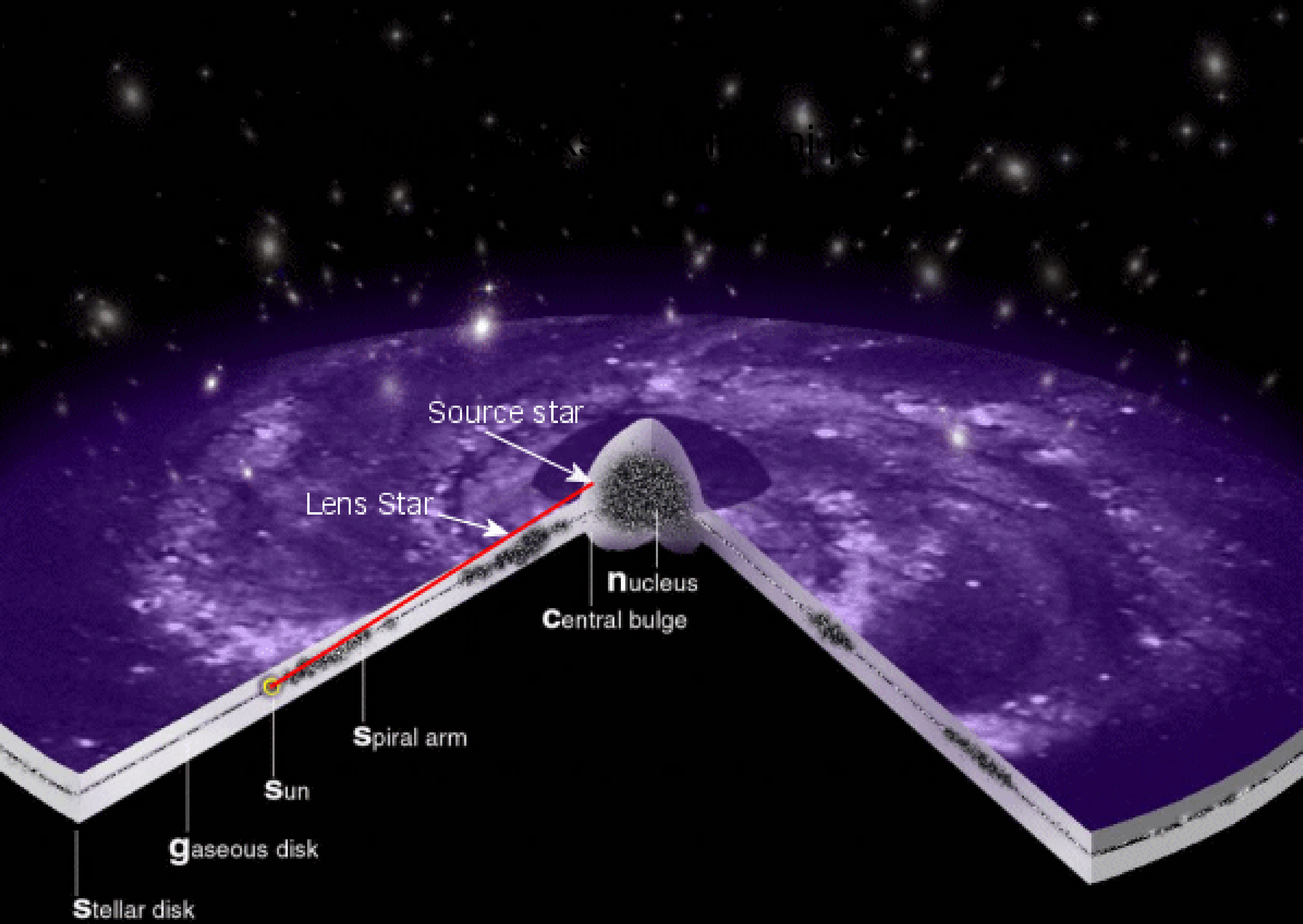


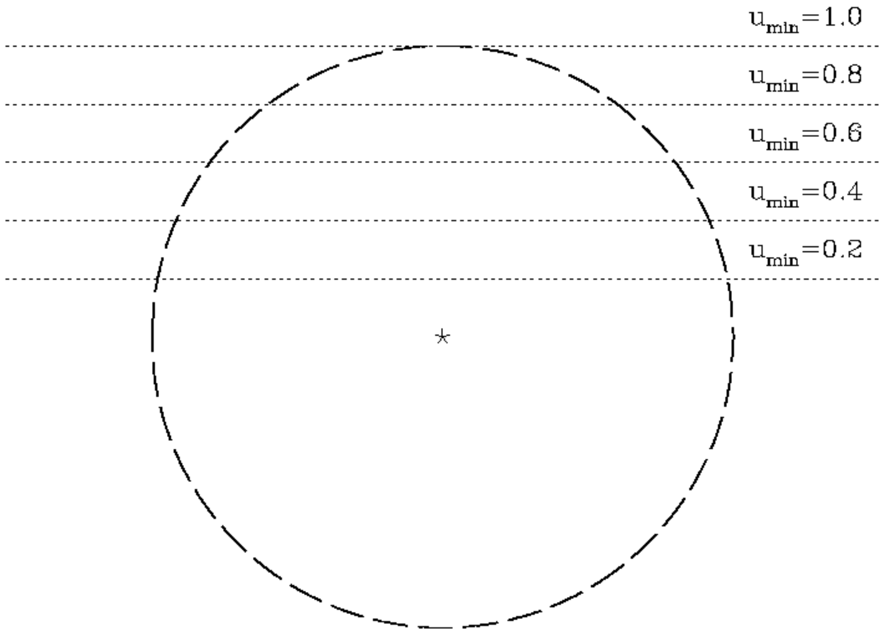
Image Credit - ESA

Microlensing

- the source and the images cannot be resolved

(resolution of the image is larger than the Einstein ring)

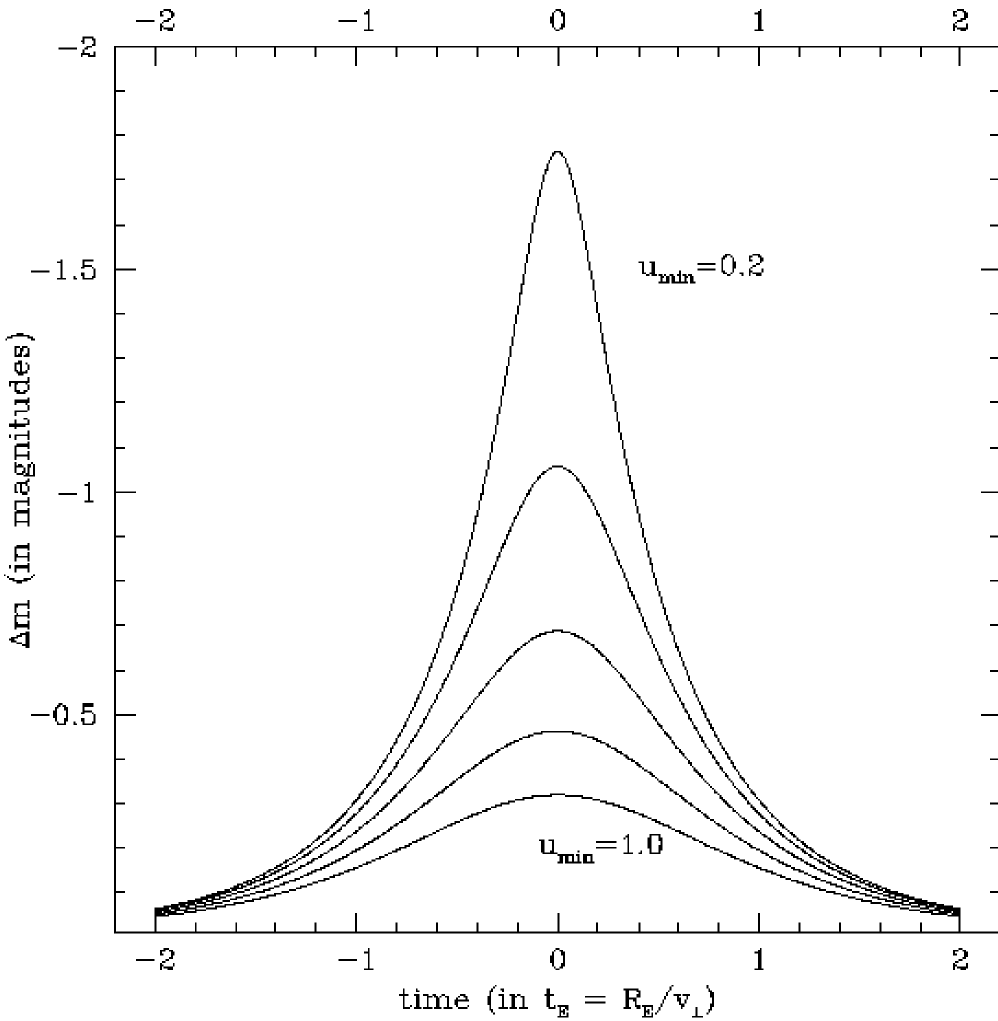
- image fluxes are added to the source flux
- **Magnification** (amplification)



Magnification:

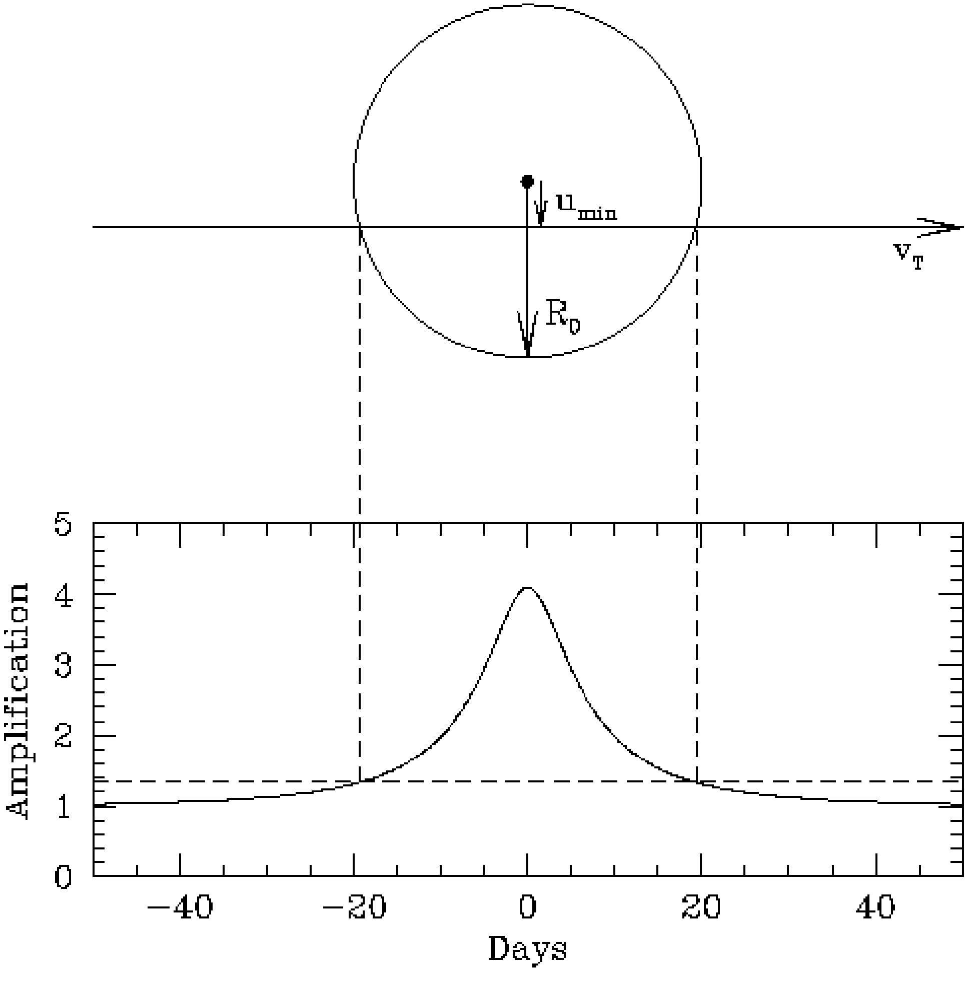
$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

$$u = \sqrt{{u_{\min}}^2 + \left(\frac{t - t_{\max}}{t_E}\right)^2}$$



(Impact factor: $u_{\min}$)

Microlensing effect:
***Source* – 1 star, *L*ens – 1 star**

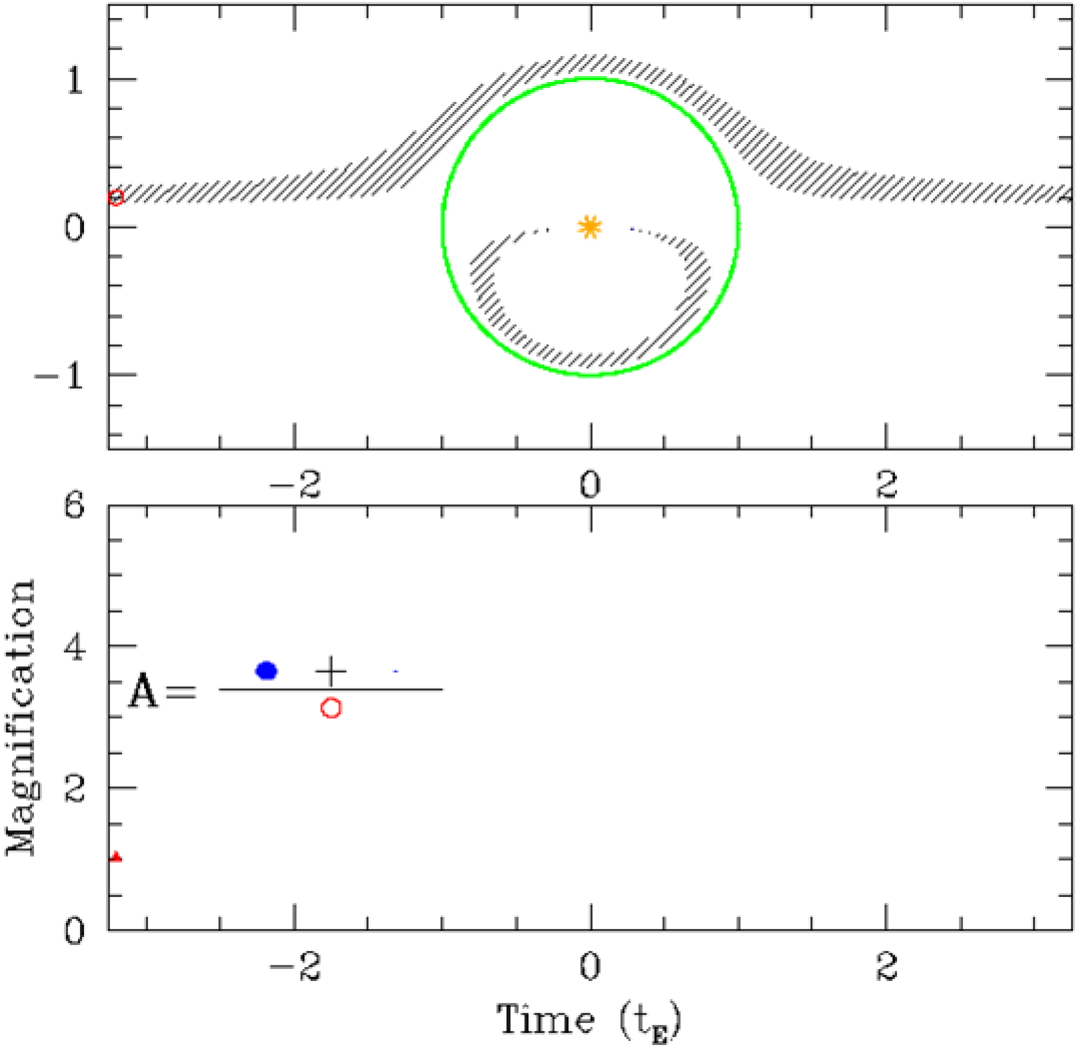


Einstein
crossing time:

$$t_E = \frac{R_0}{v_T}$$

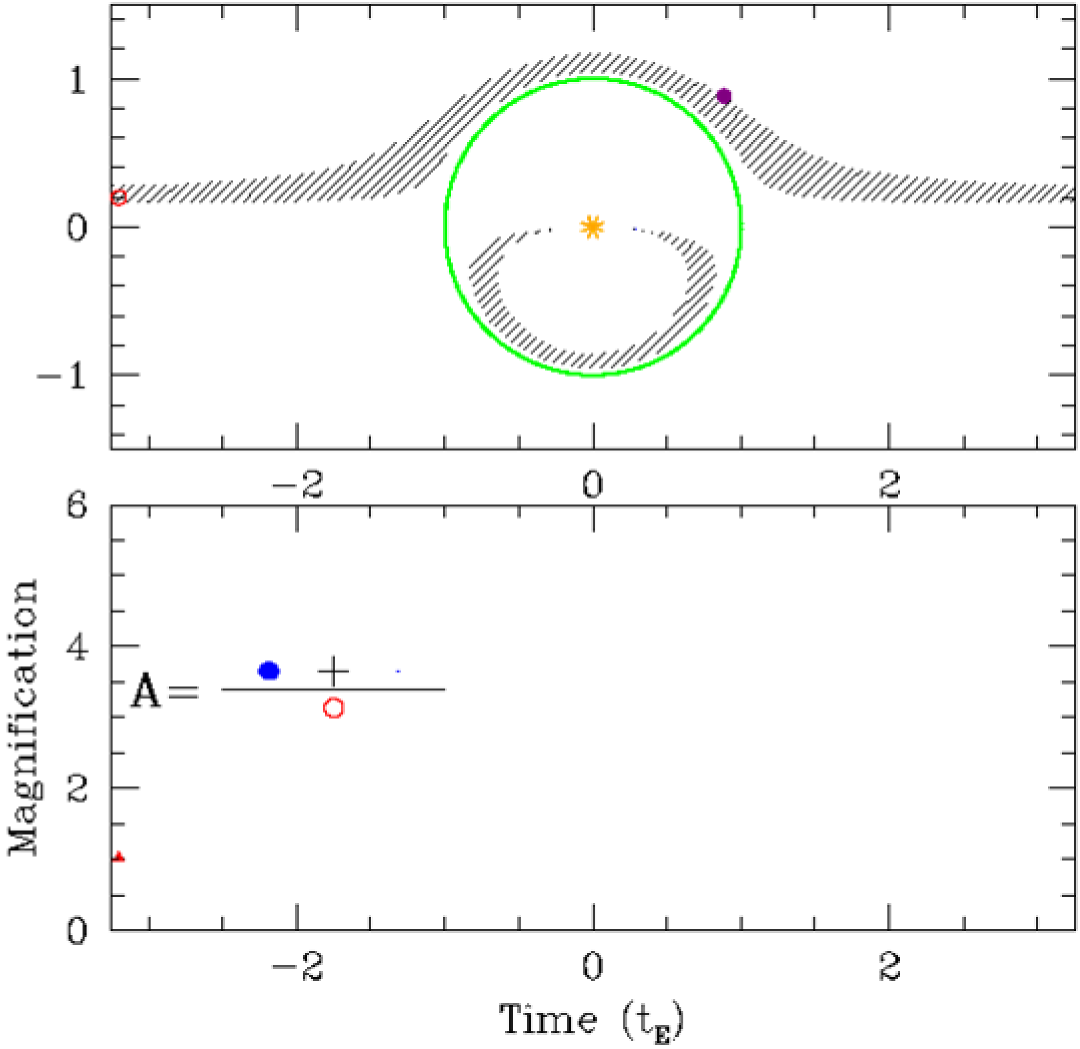
Light curve:
change of brightness
with time

Microlensing effect:
Source – 1 star, *Lens* – 1 star

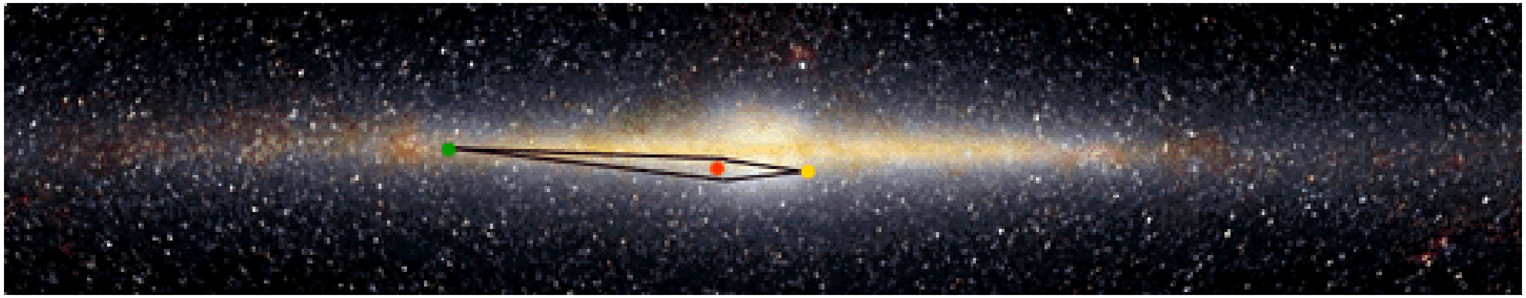


Animation: © Scott Gaudi

Source – 1 star
Lens – star + planet



Microlensing towards the Galactic Bulge



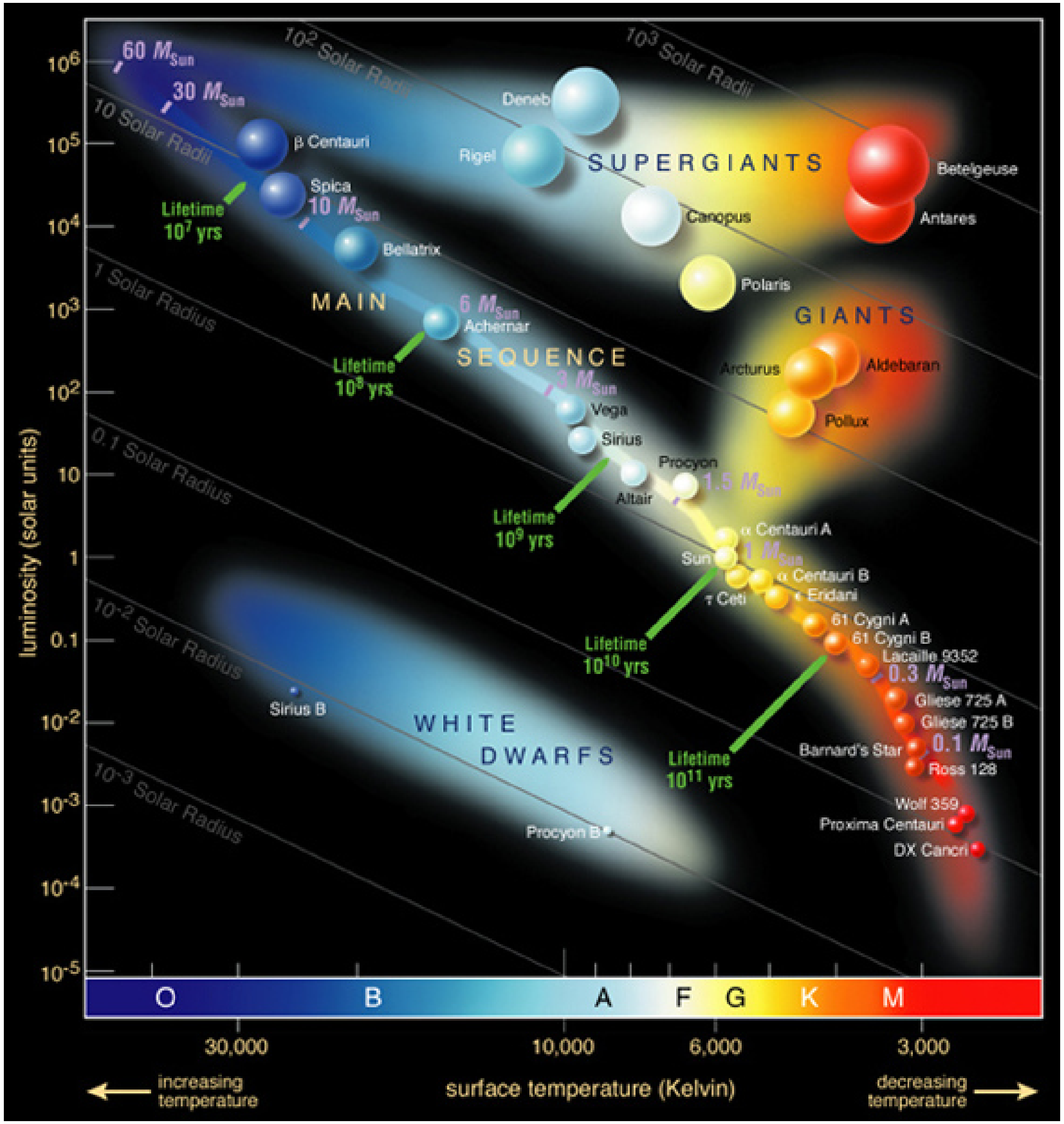
- Paczynski: monitoring stars in LMC (detection of brown dwarfs or Jupiter like objects)

- Monitoring the Galactic Bulge – known population

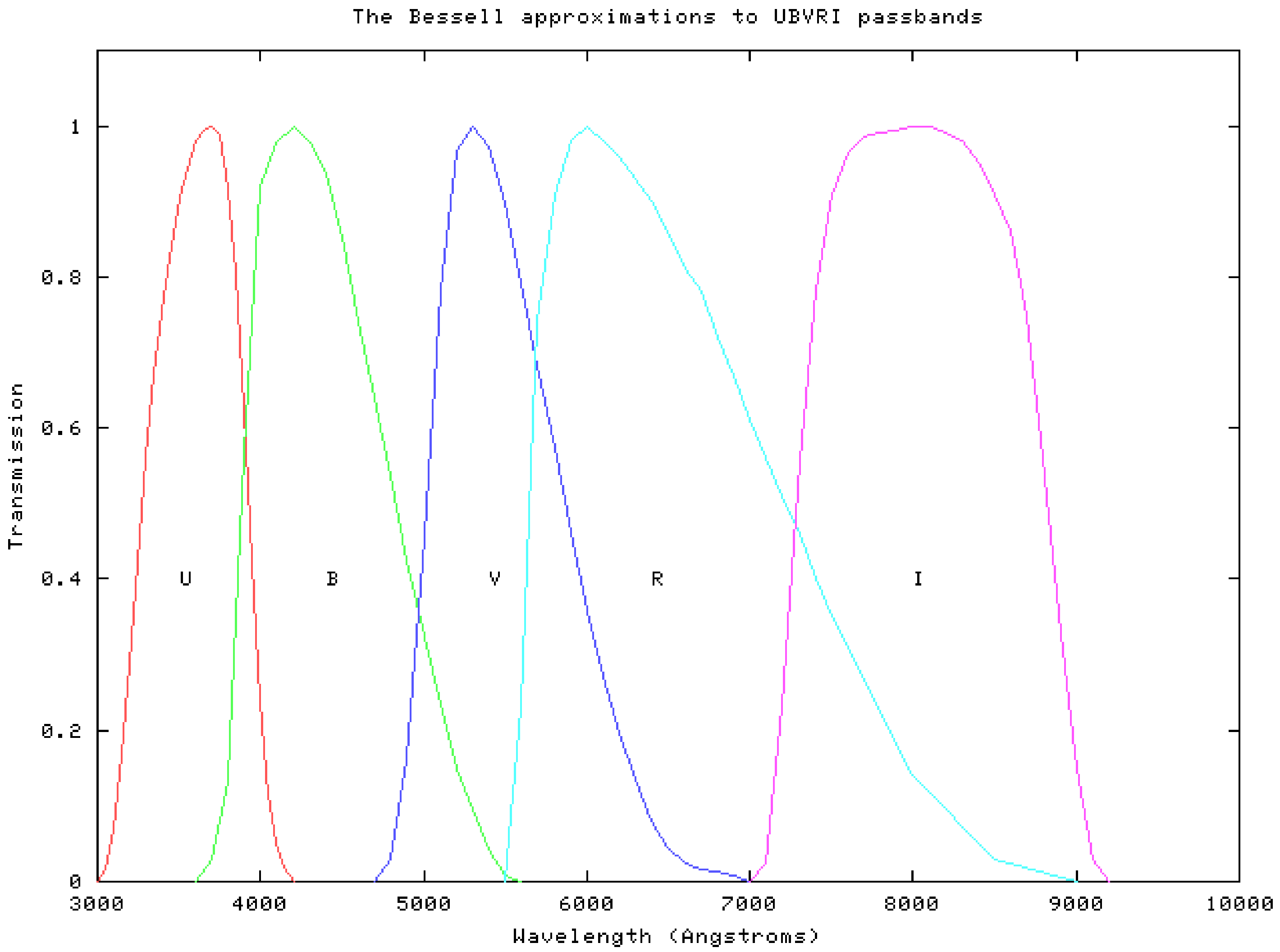
$$D_L \approx 5.0 - 6.0 kpc, D_S \approx 6.0 - 8.5 kpc$$

$$R_E \approx A.U. \sim mas$$

HR diagram (spectral types)



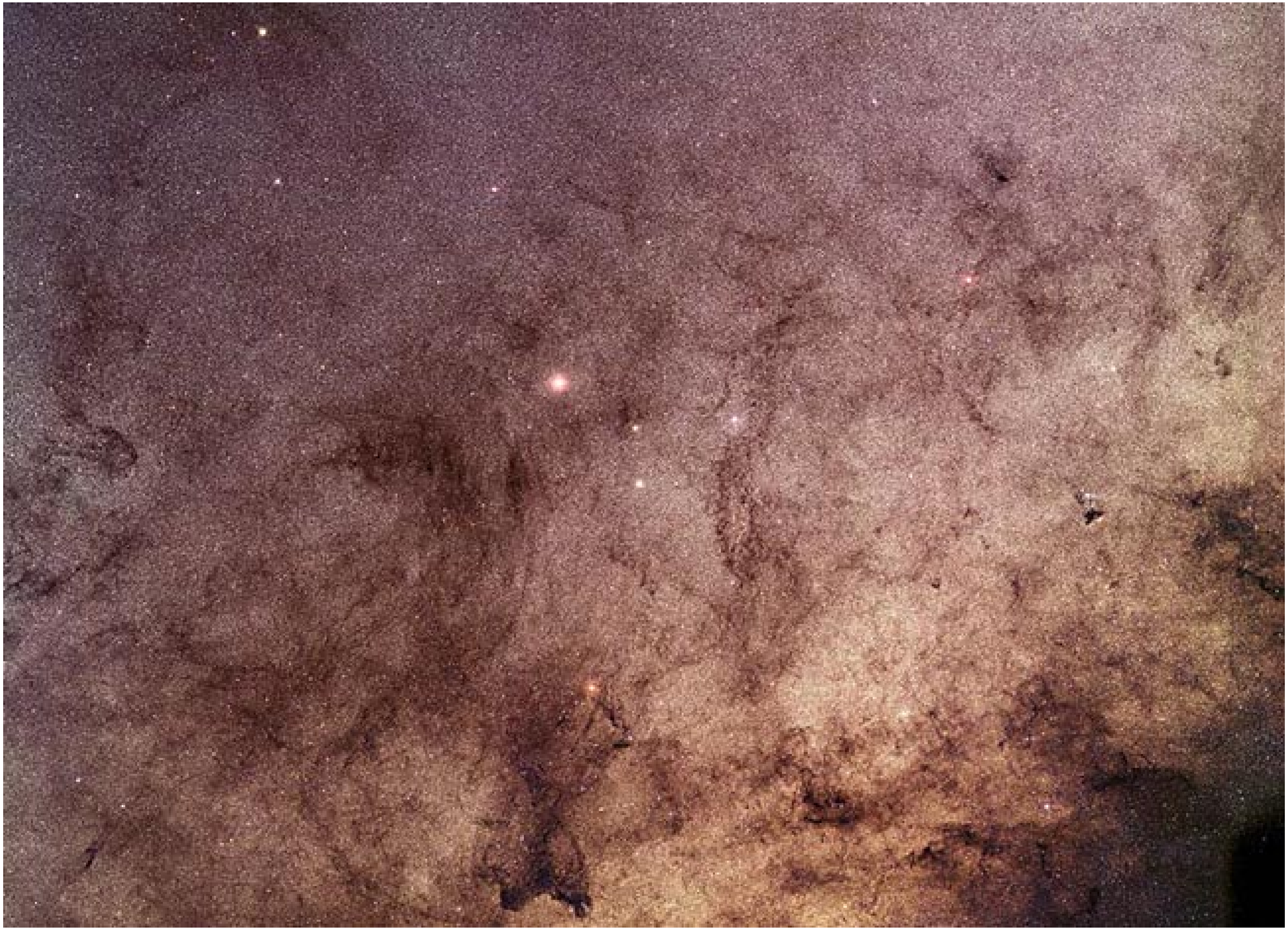
Photometric system UBVRI



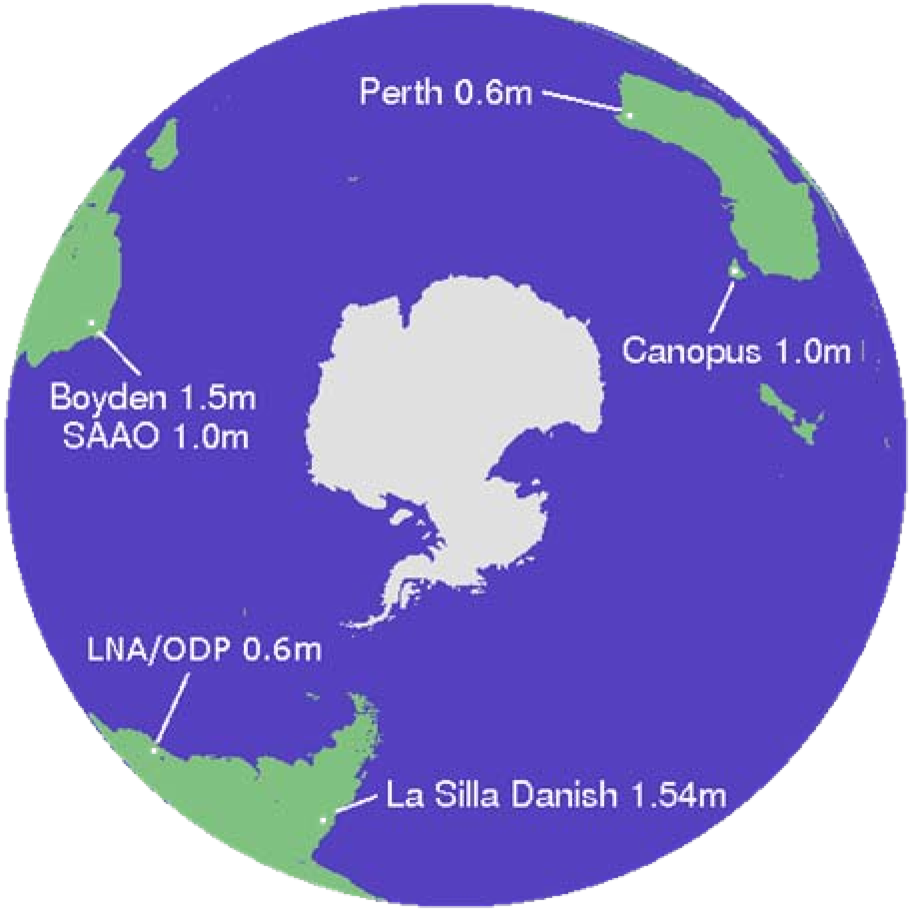
Galactic center

- Interstellar extinction (absorption by dust)
- Lowest in red/infrared part of the spectrum
- I photometric band

Baade’s window



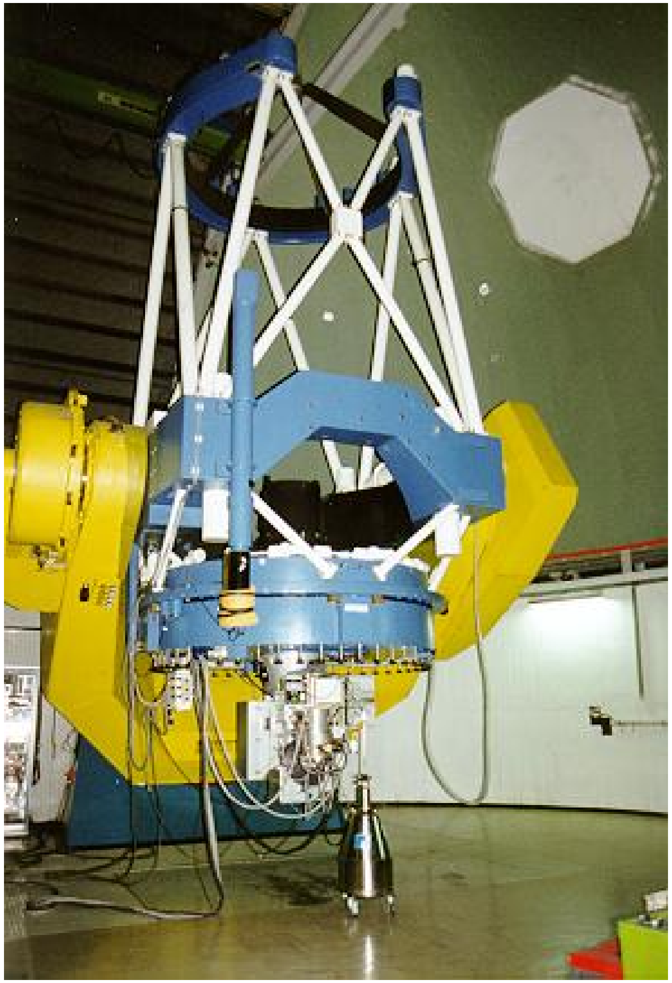
Microlensing surveys



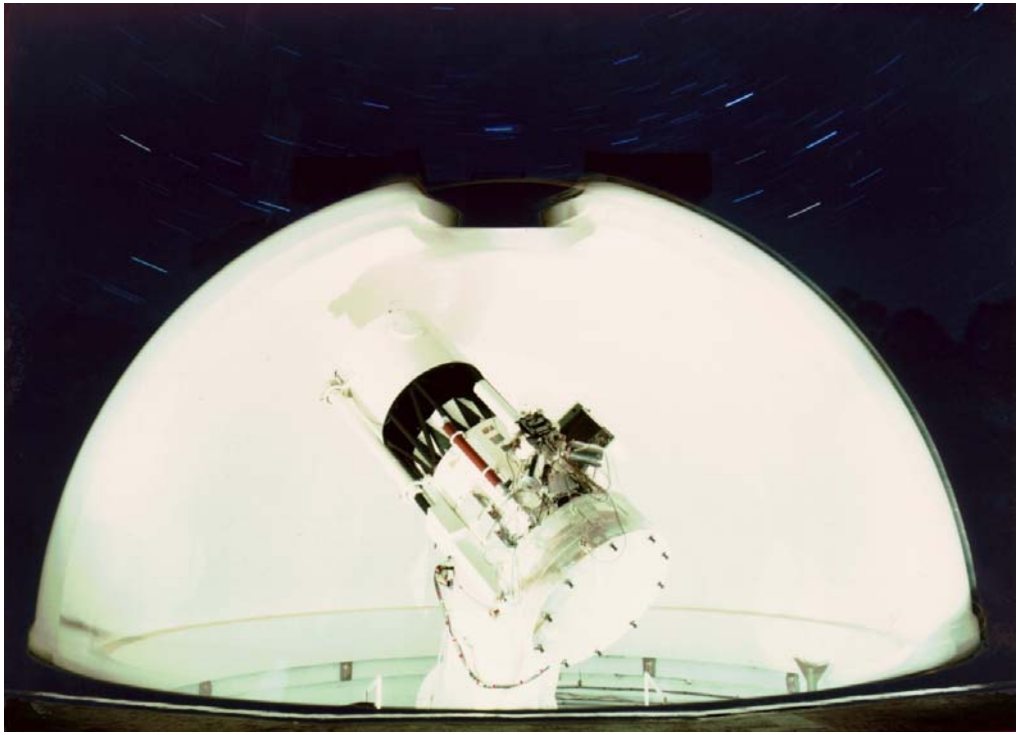
OGLE and **MOA:**
Wide-field monitoring, alerts

PLANET
(*Probing Lensing Anomalies NETwork*)
- 24-hour follow-up photometric observations
- very dense data sampling
- *I*&(*V*,*R*) photometric bands

Telescopes



Chile: 1.5 m



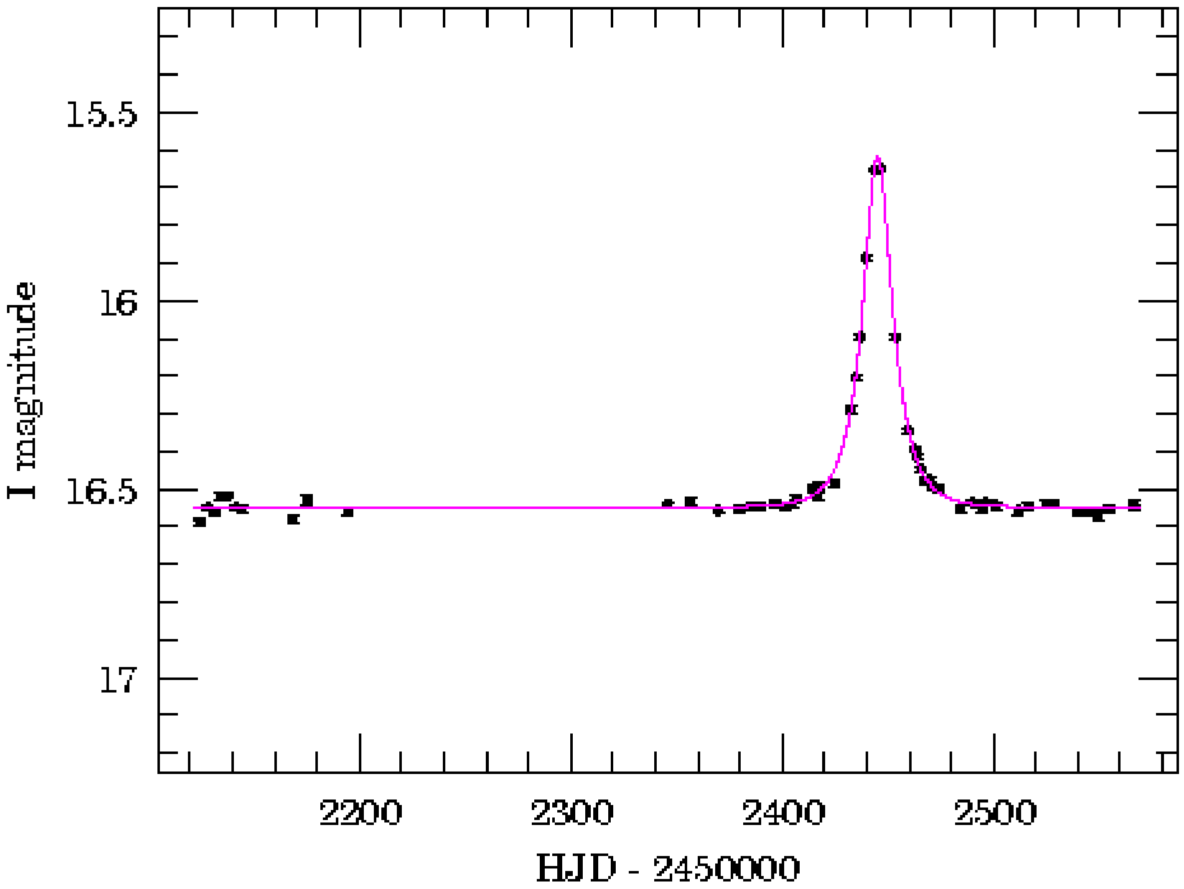
Tasmania (Australia): 1.0 m

La Silla Observatory(Chile)

2400m

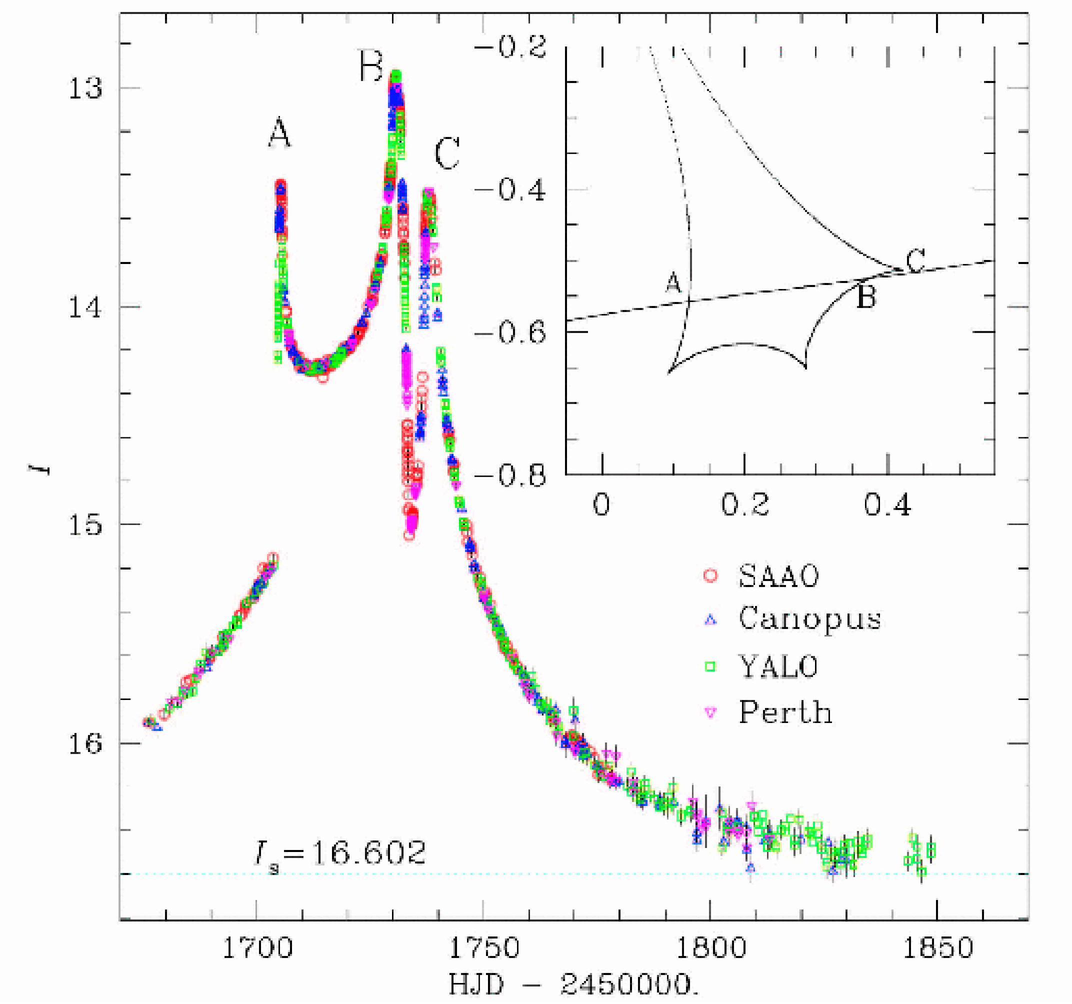
Atacama desert (less problems due to the Earth‘s atmosphere)

Single lens – single source light curve



OGLE-2002-BLG-192

Binary lens – single source light curve

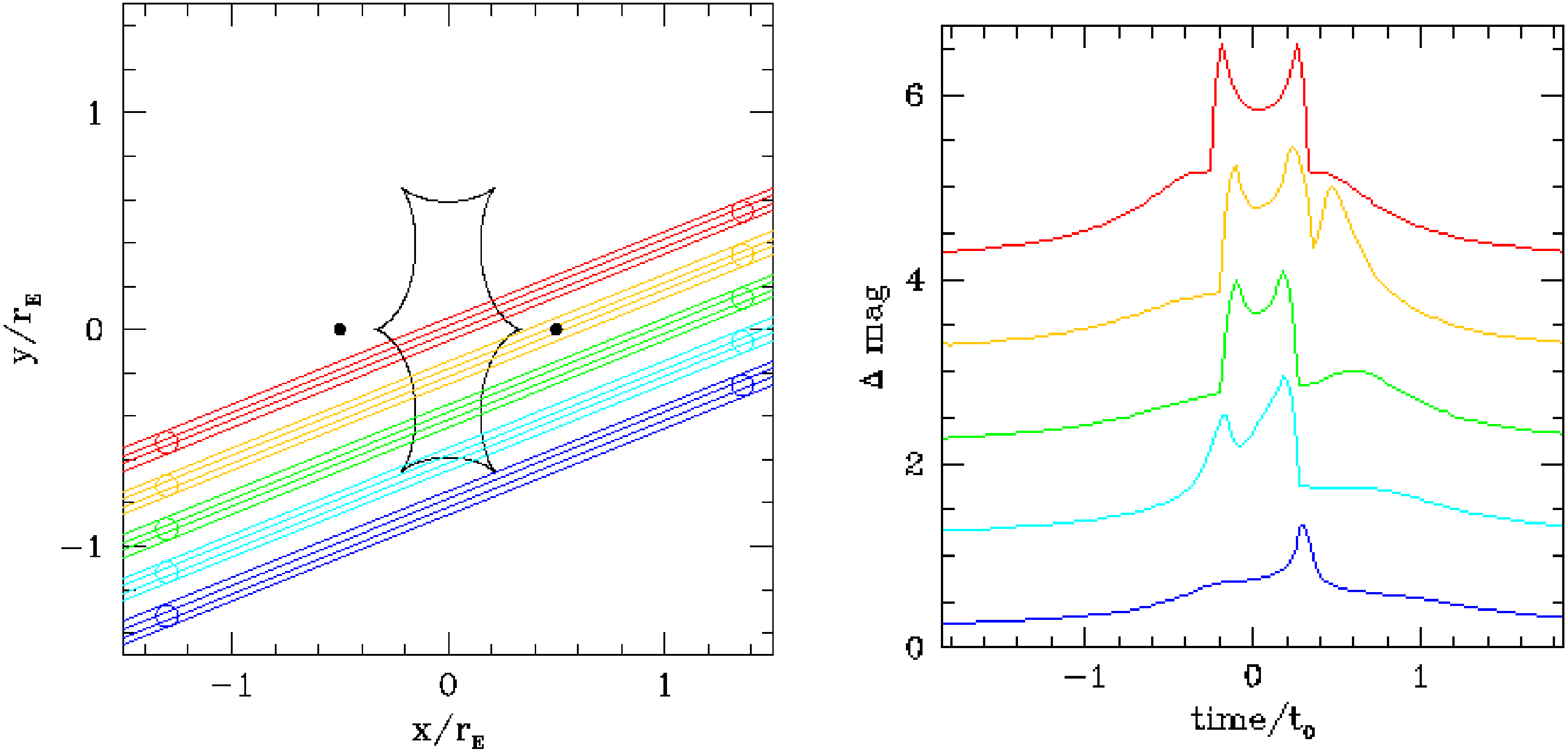


CAUSTIC:

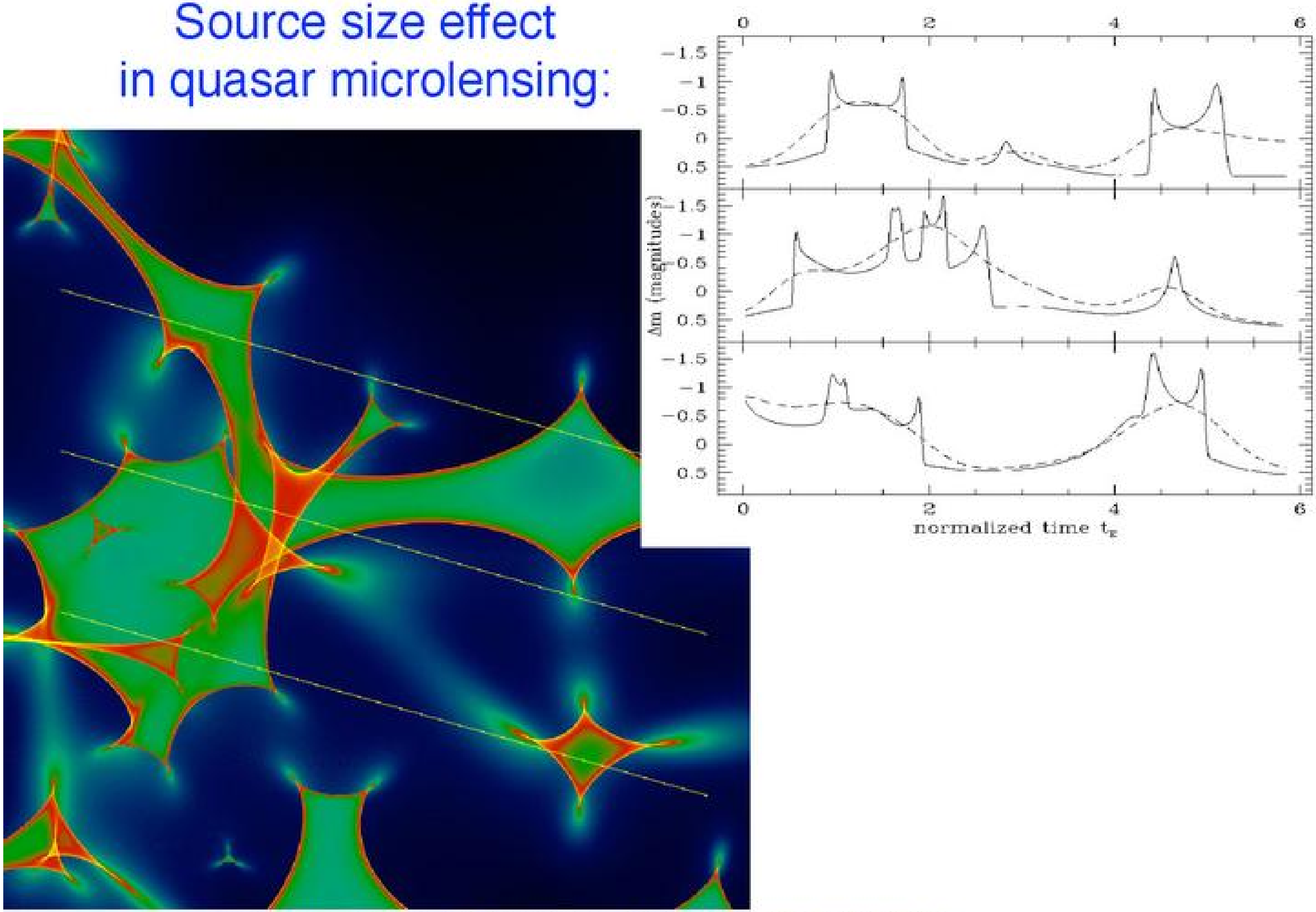
very large magnification

EROS-BLG-2000-5

Binary lens

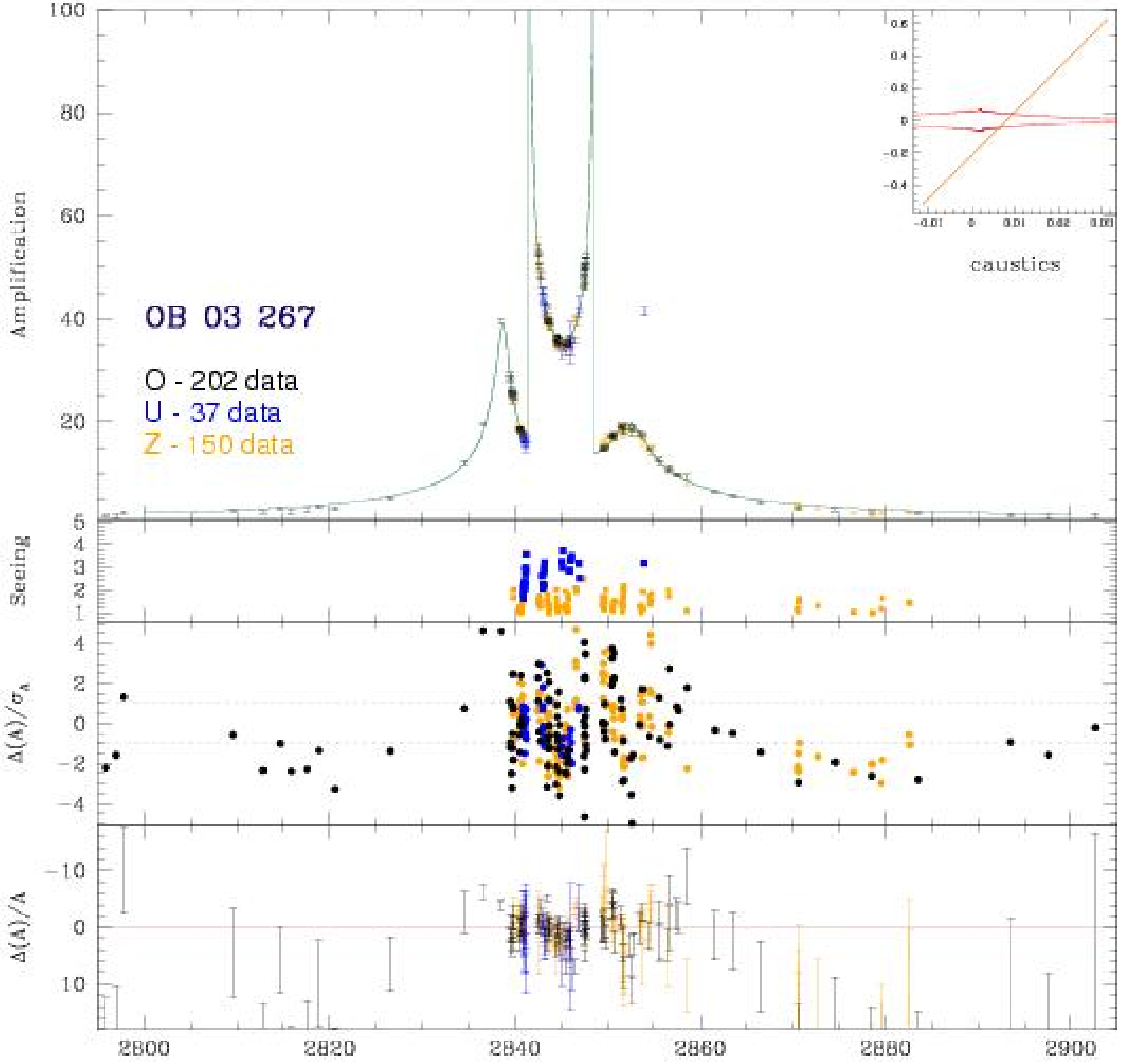


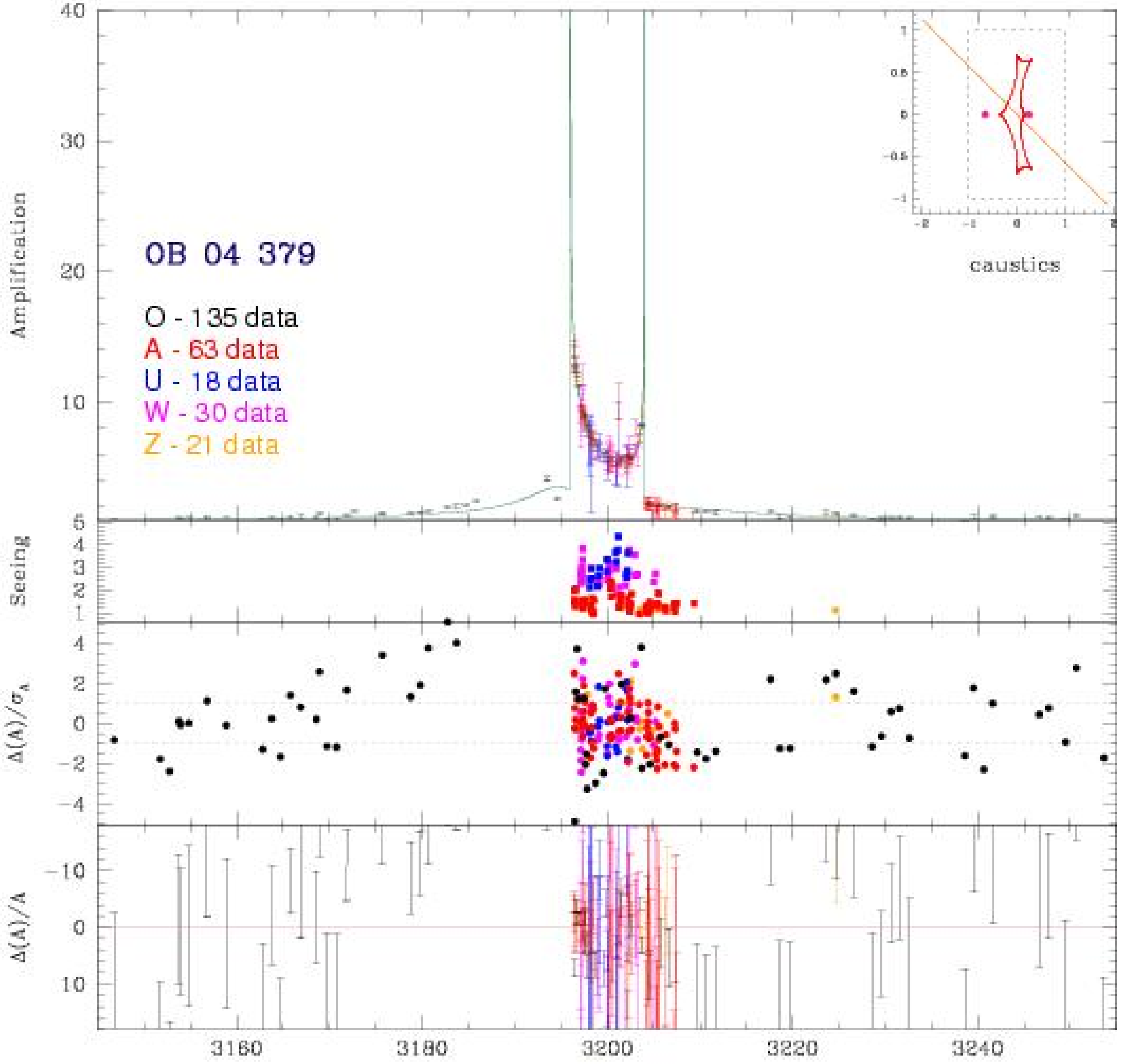
Source size effect in quasar microlensing:

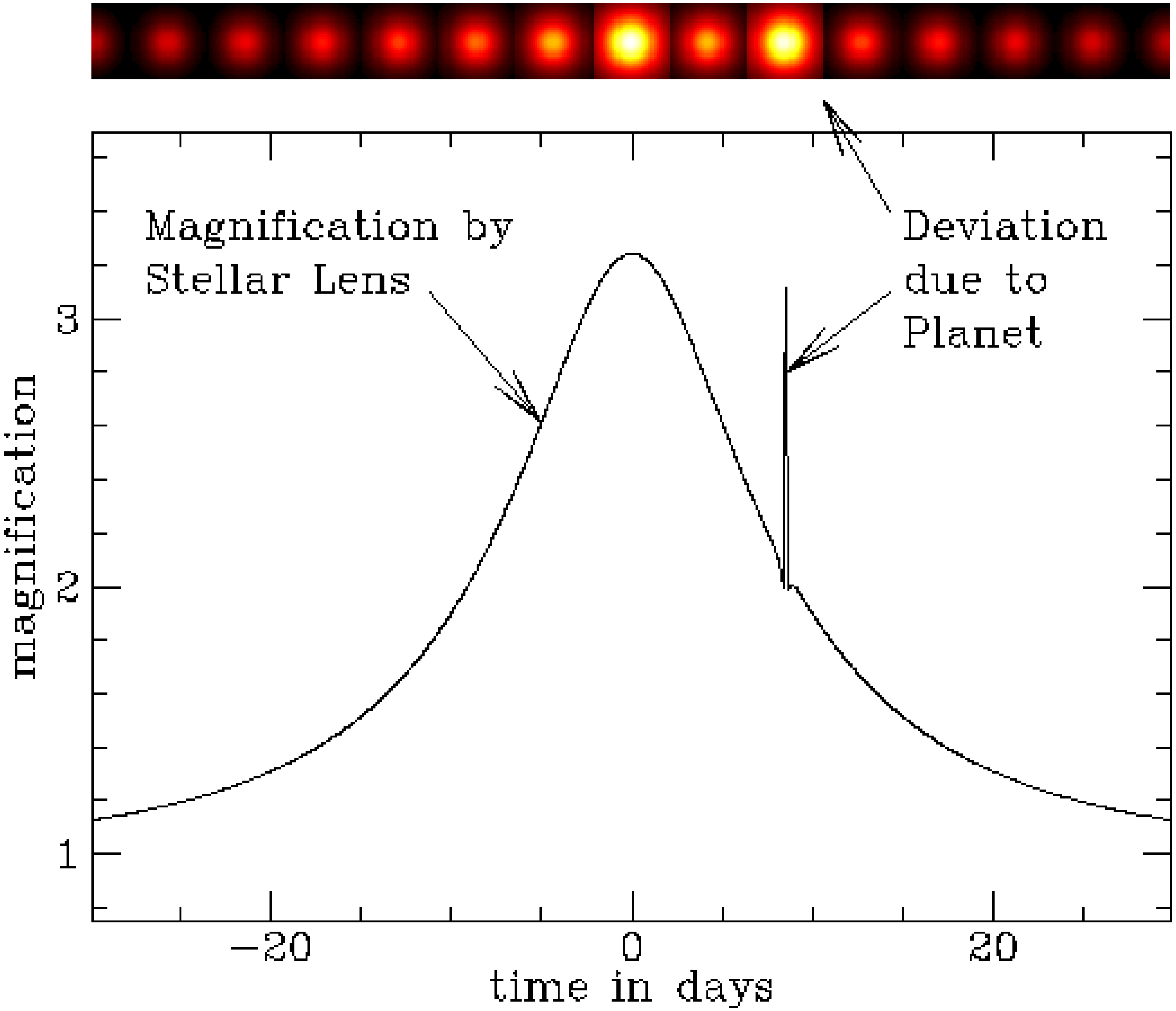


Joachim Wambsganss: "Microlensing and Compact Objects in Galaxies"

at: "Applications of Gravitational Lensing", KITP, Santa Barbara, October 4, 2006


OB 03 267
O - 202 data
U - 37 data
Z - 150 data
Amplification
100
80
60
40
20
caustics
0.6
0.4
0.2
0
-0.2
-0.4
-0.01
0
0.01
0.02
0.03
Seeing
5
4
3
2
1
Δ(A)/σ_A
4
2
0
-2
-4
Δ(A)/A
-10
0
10
2800
2820
2840
2860
2880
2900

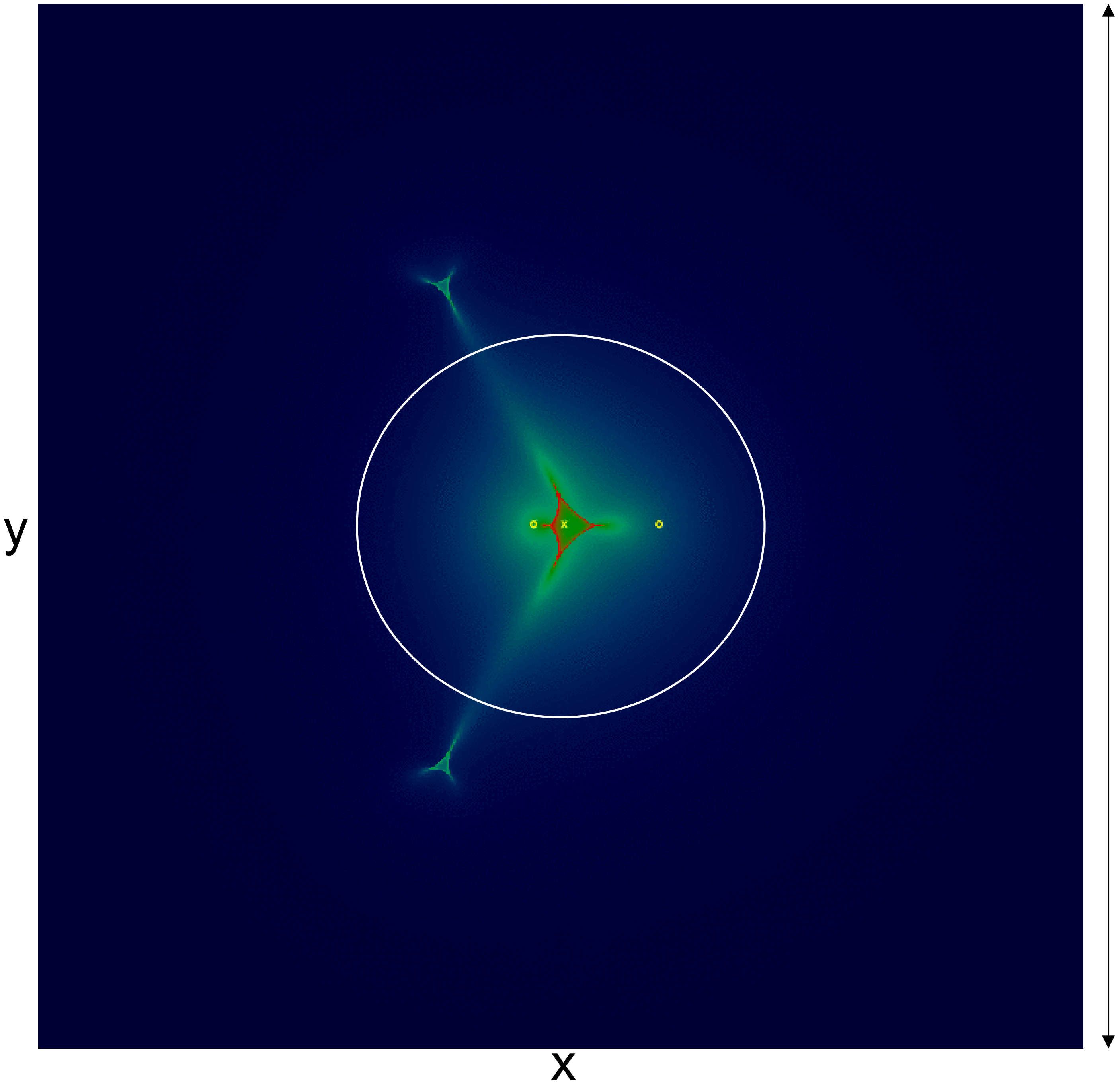

OB 04 379
O - 135 data
A - 63 data
U - 18 data
W - 30 data
Z - 21 data
Amplification
caustics
Seeing
Δ(A)/σ_A
Δ(A)/A
40
30
20
10
5
4
3
2
1
0
-2
-4
-10
3160
3180
3200
3220
3240


Magnification by
Stellar Lens
Deviation
due to
Planet
magnification
1
2
3
−20
0
20
time in days

Modeling orbiting binary lenses

- Non-linear problem
- Optimized ray shooting program MICROLENS (Wambsganss 1990)

=> **Magnification patterns**



$M_{tot} = 1 M_{Sun}$

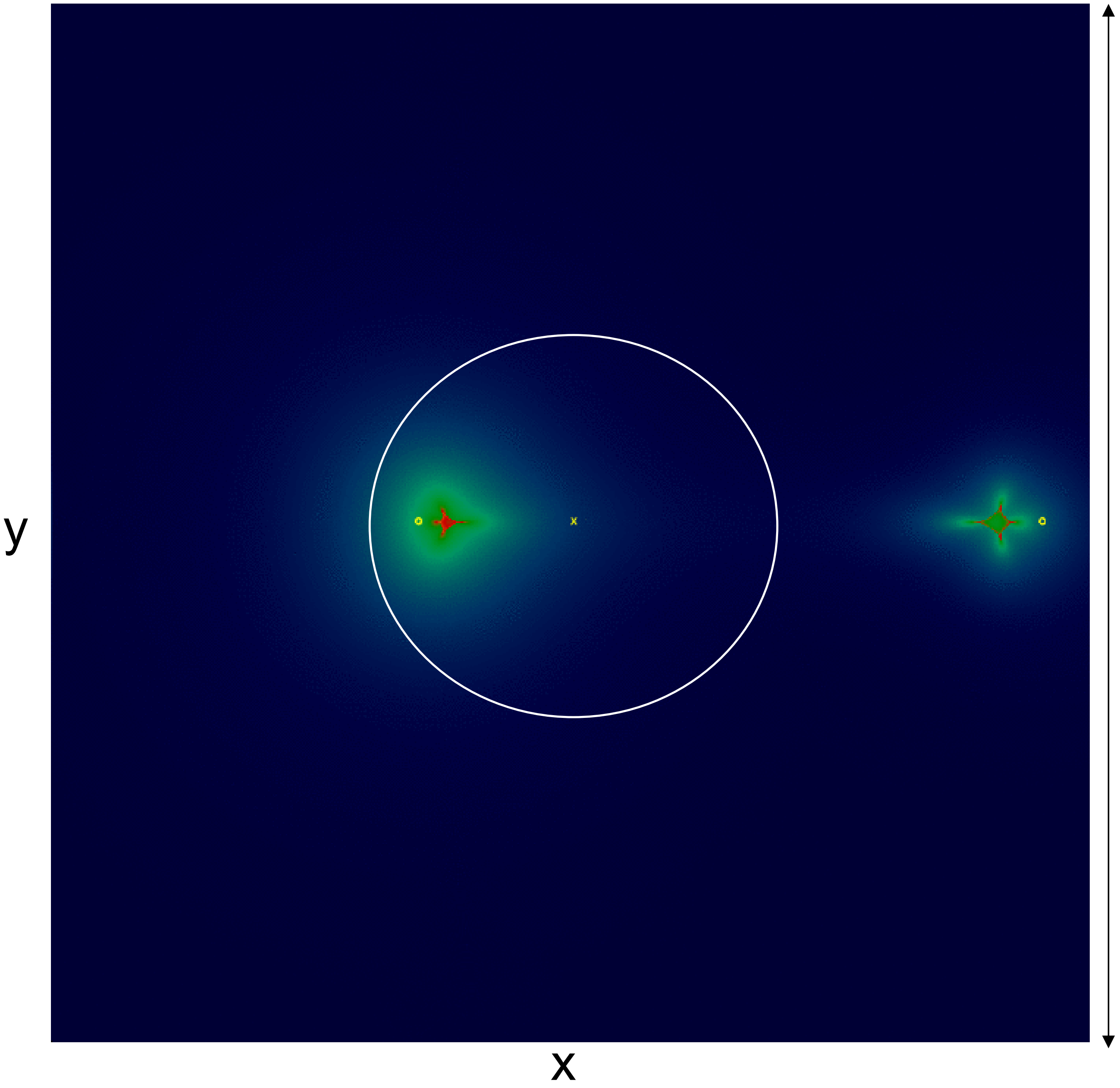
$q = 0.3$

$d = 0.6 R_E$

$5 R_E \equiv$

$1000\, pix$

$1 pix \approx 5 R_{Sun}$



$M_{tot} = 1 M_{Sun}$

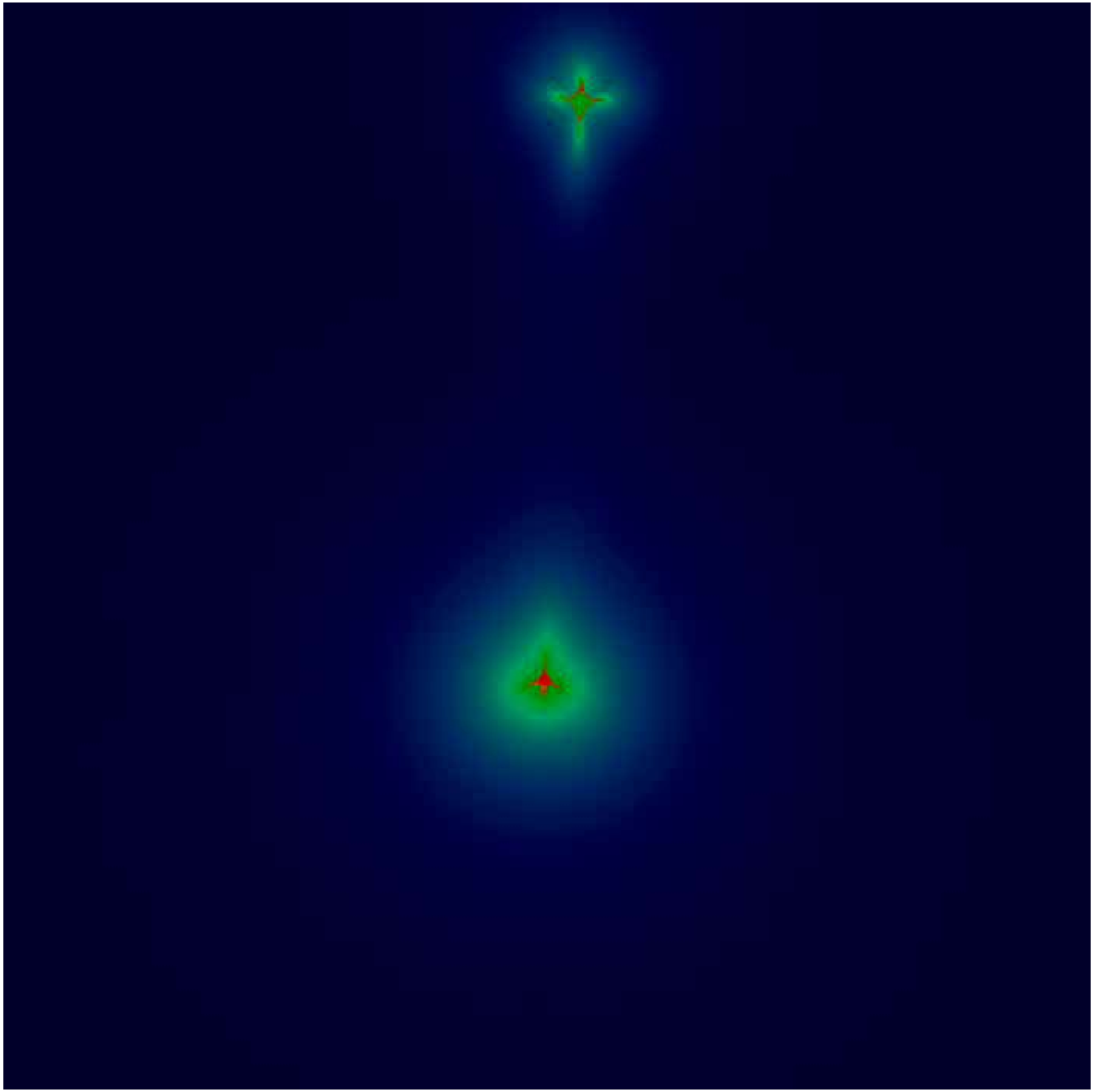
$q = 0.3$

$d = 3.0 R_E$

$5R_E \equiv$

$1000\, pix$

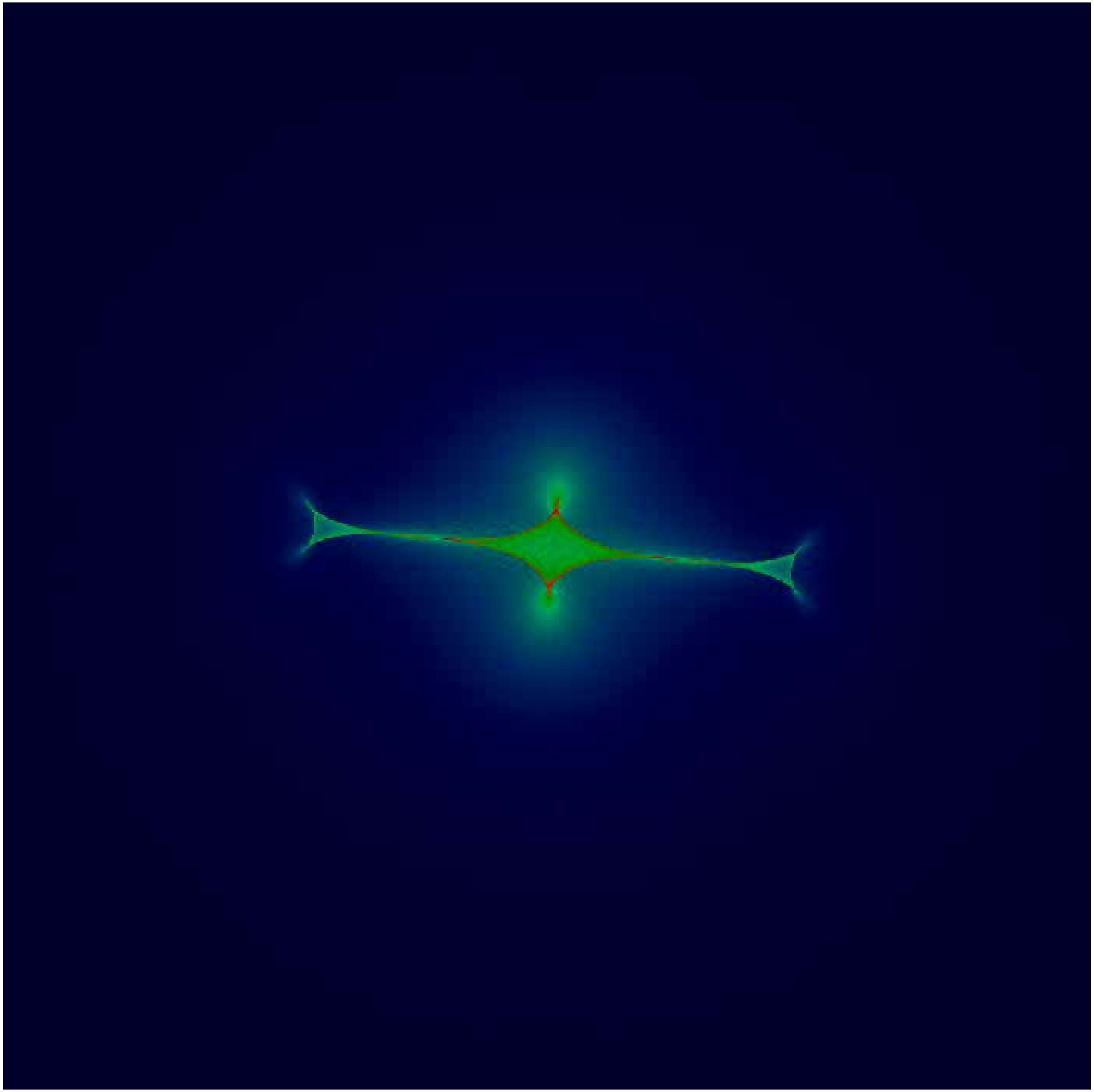
$1 pix \approx 5 R_{Sun}$



$q = 0.3$

$i = 90^o$

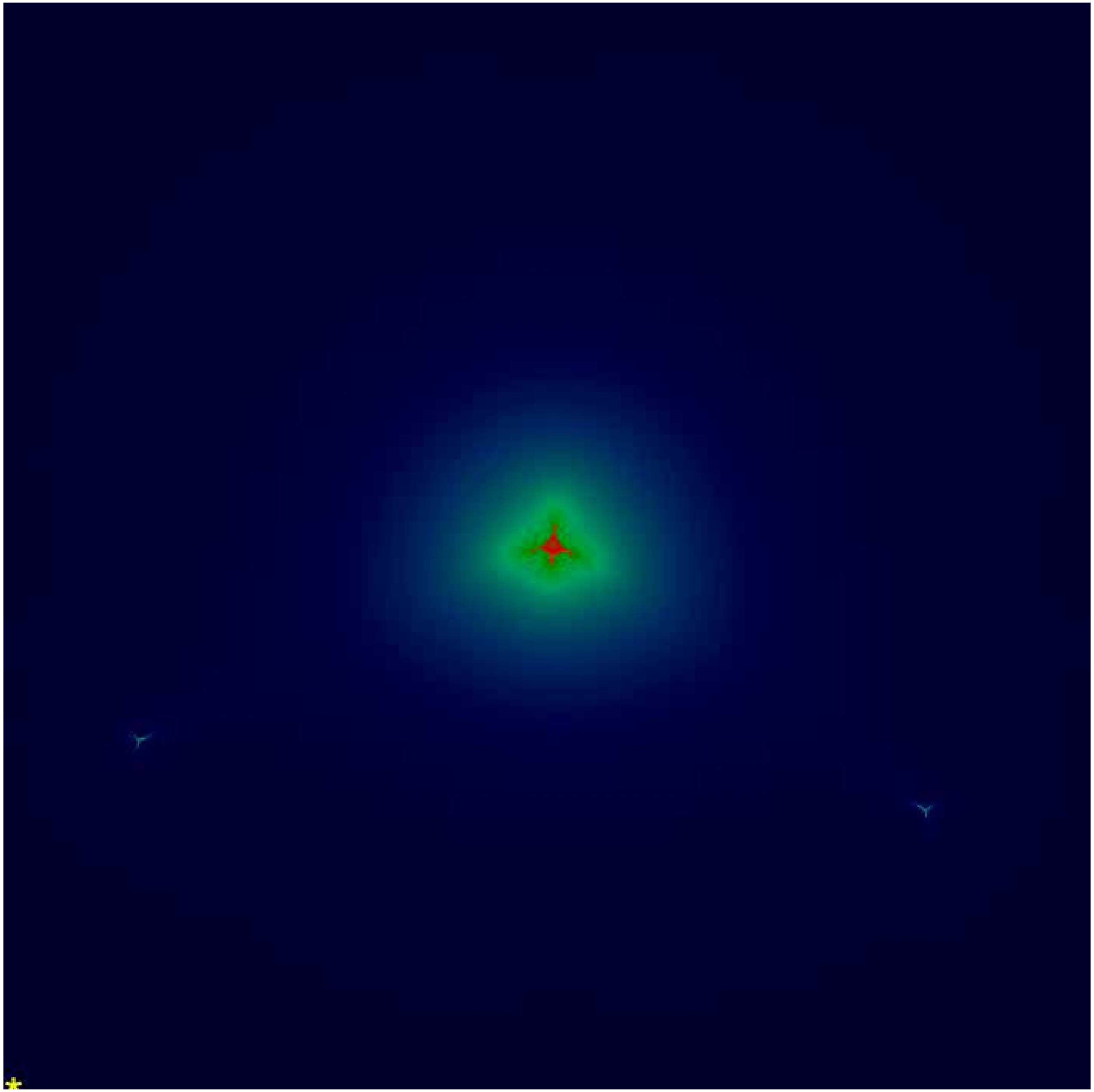
$d = 3R_E$



$q = 1.0$

$i = 45^{\circ}$

$d = 1 R_E$



$q = 0.3$

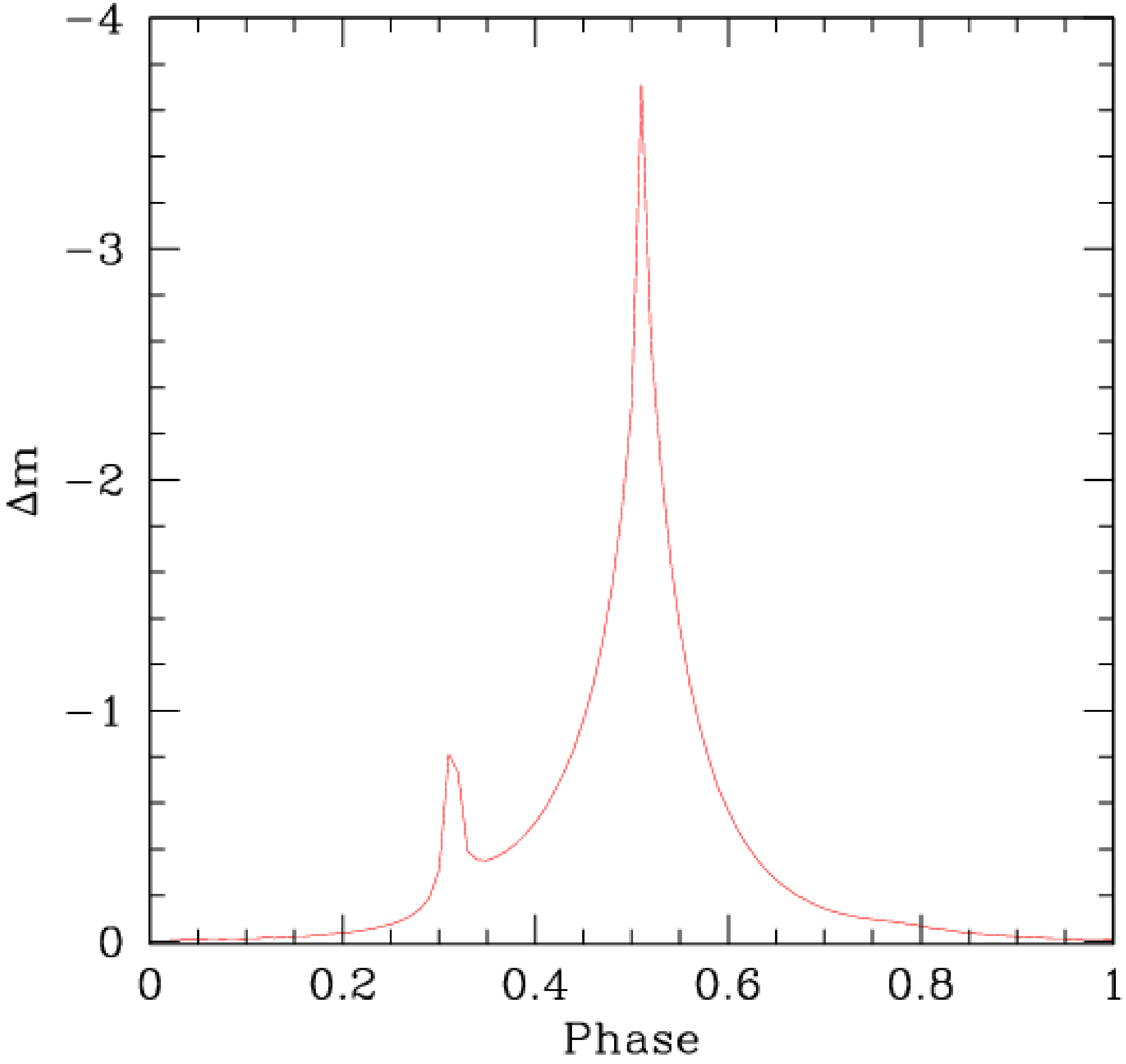
$i = 45^{o}$

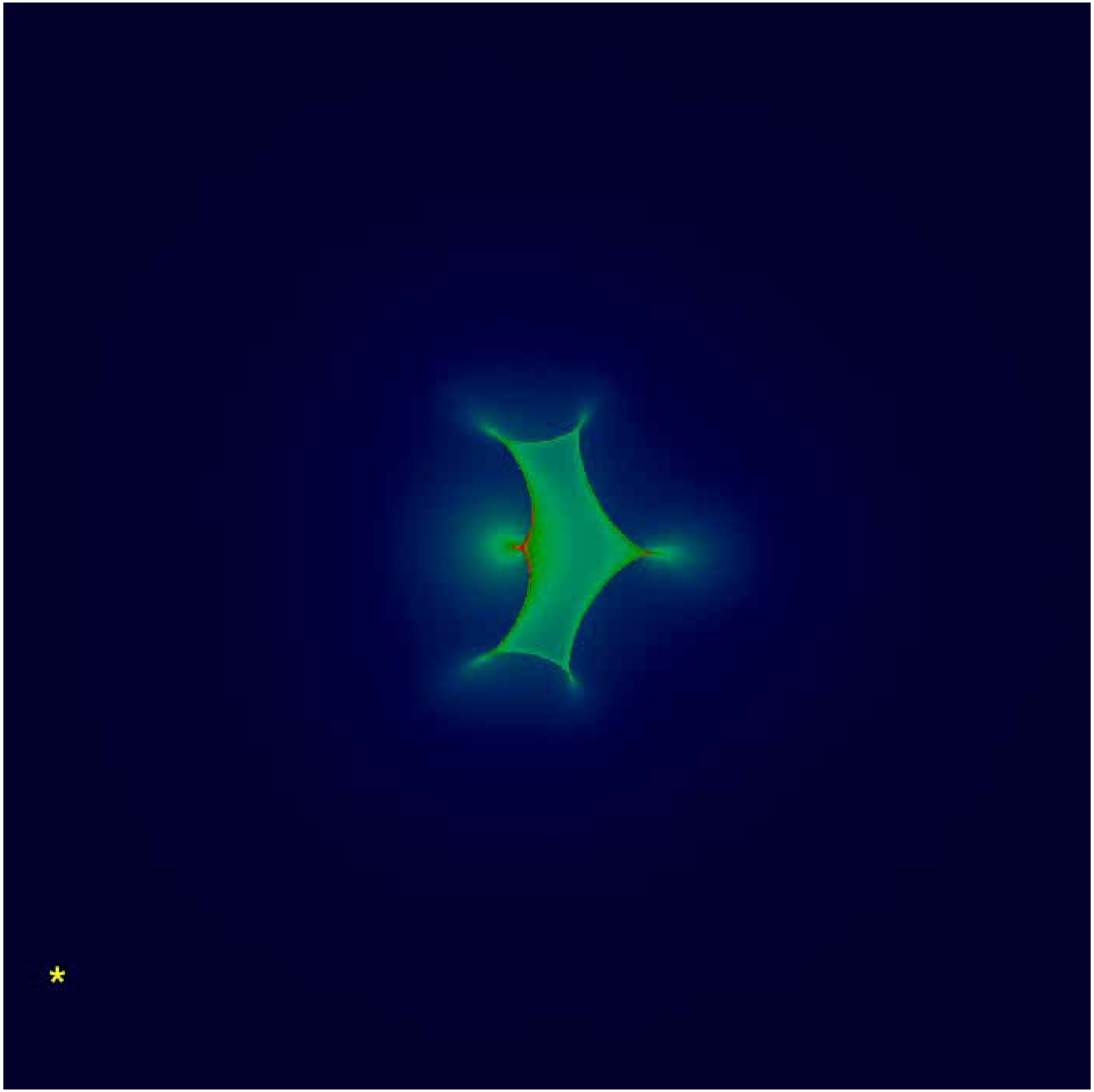
$d = 0.6 R_E$

$P \approx 100 d$

$R_* \approx 10 R_{Sun}$

$q=0.3$, $i=45°$, $d=0.6R_E$





$q = 0.3$

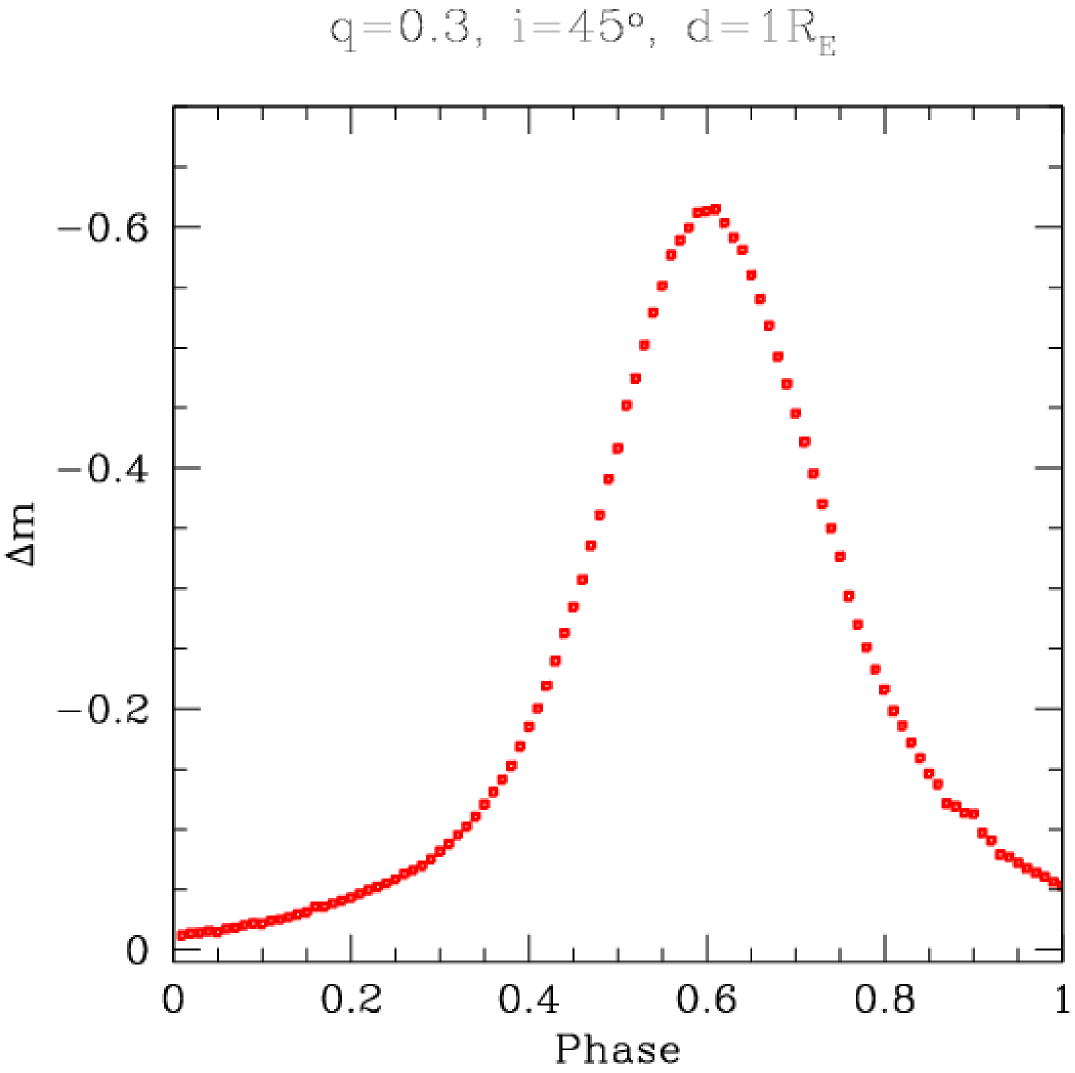
$i = 45^o$

$d = 1R_E$

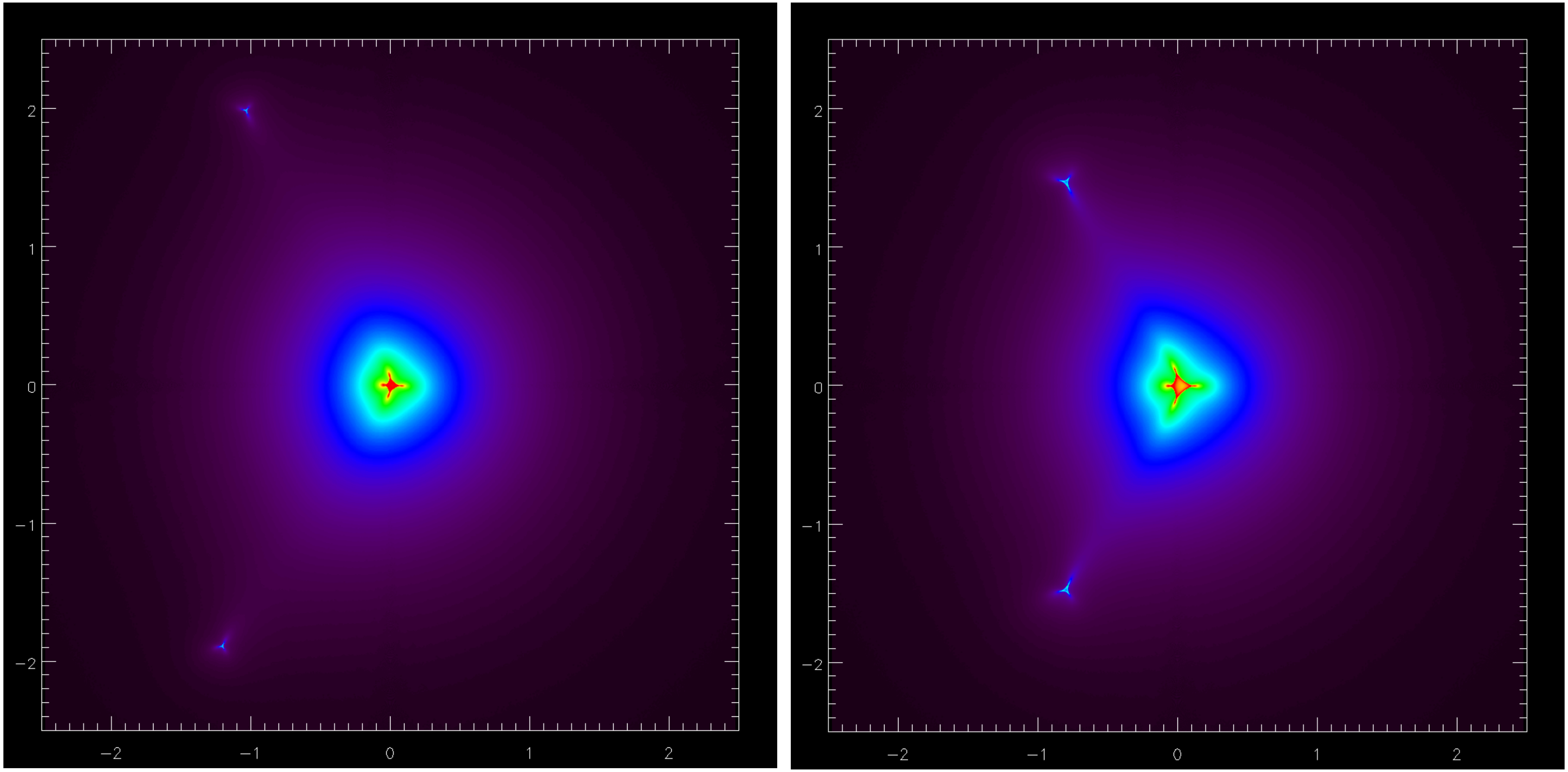
$P \approx 1 year$

$R_* \approx 10 R_{Sun}$

„Ideal“ synthetic light curve



P~1year

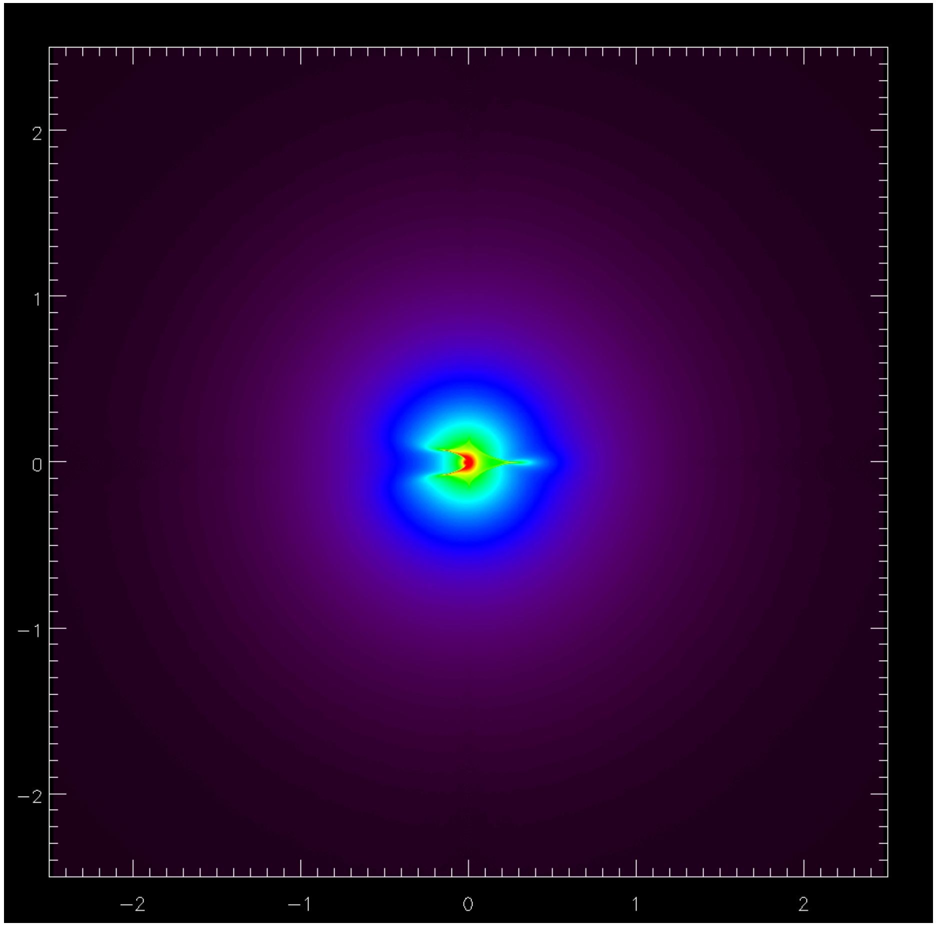


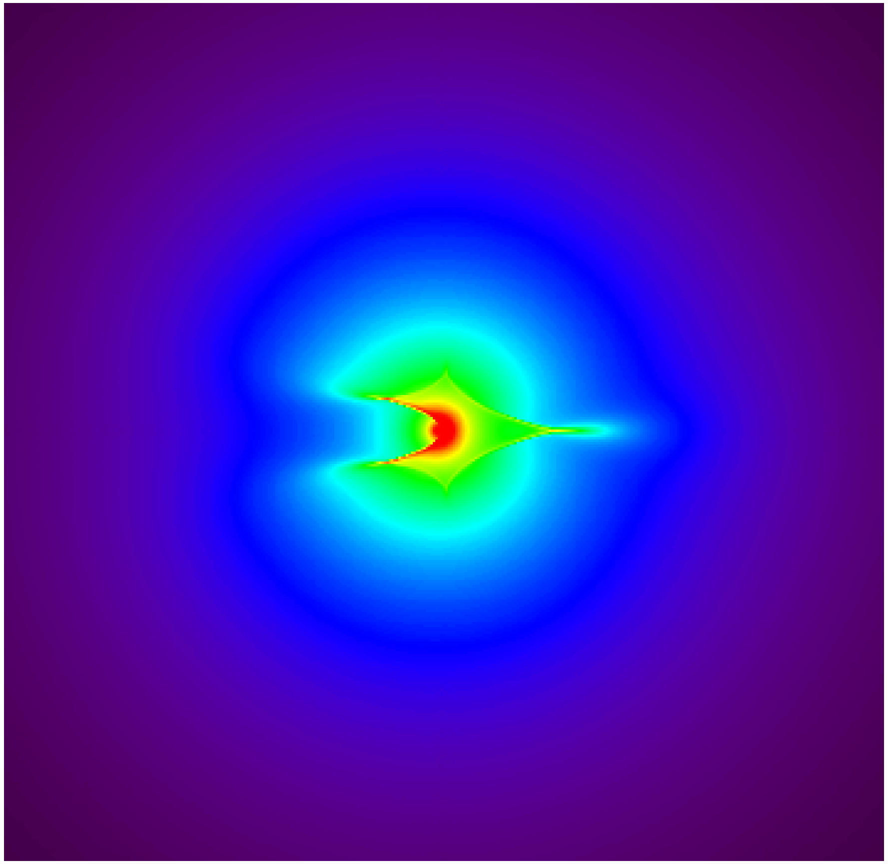
$d = 0.4R_E$

$d = 0.5R_E$

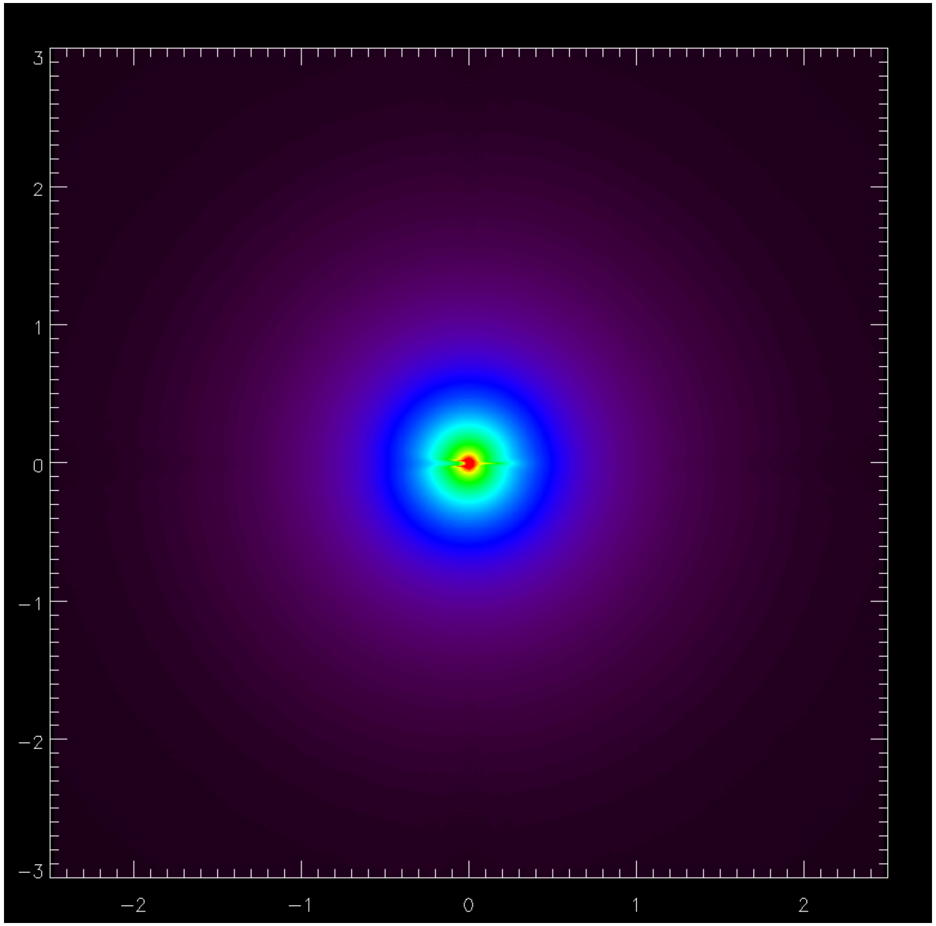
q=0.3

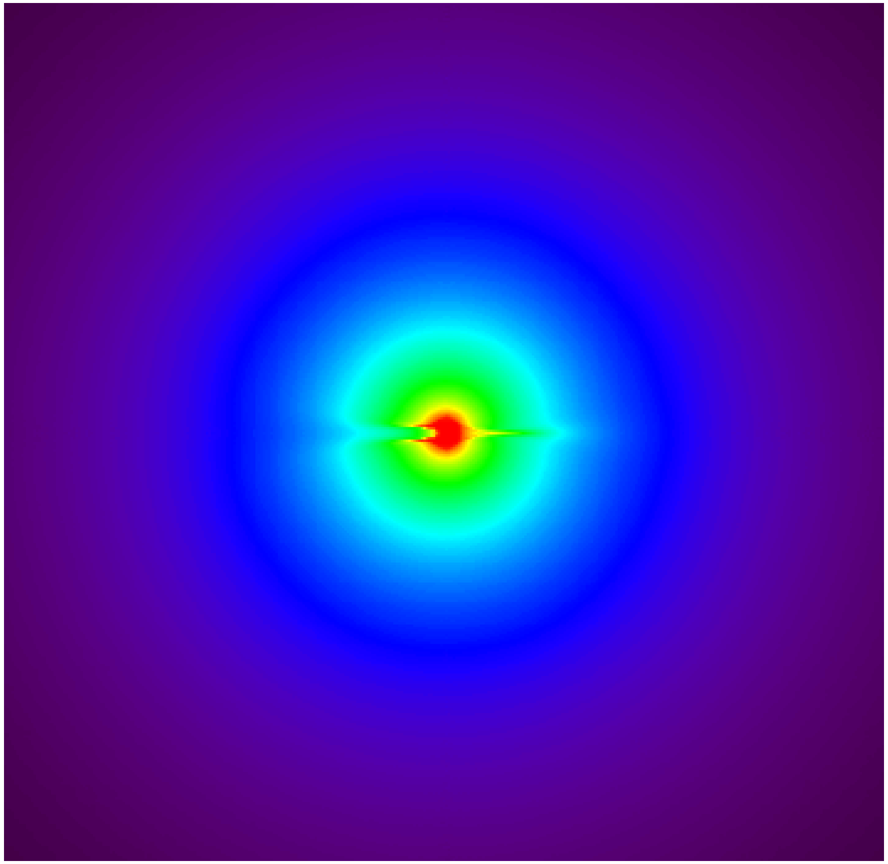
Mass ratio *q=0.01*



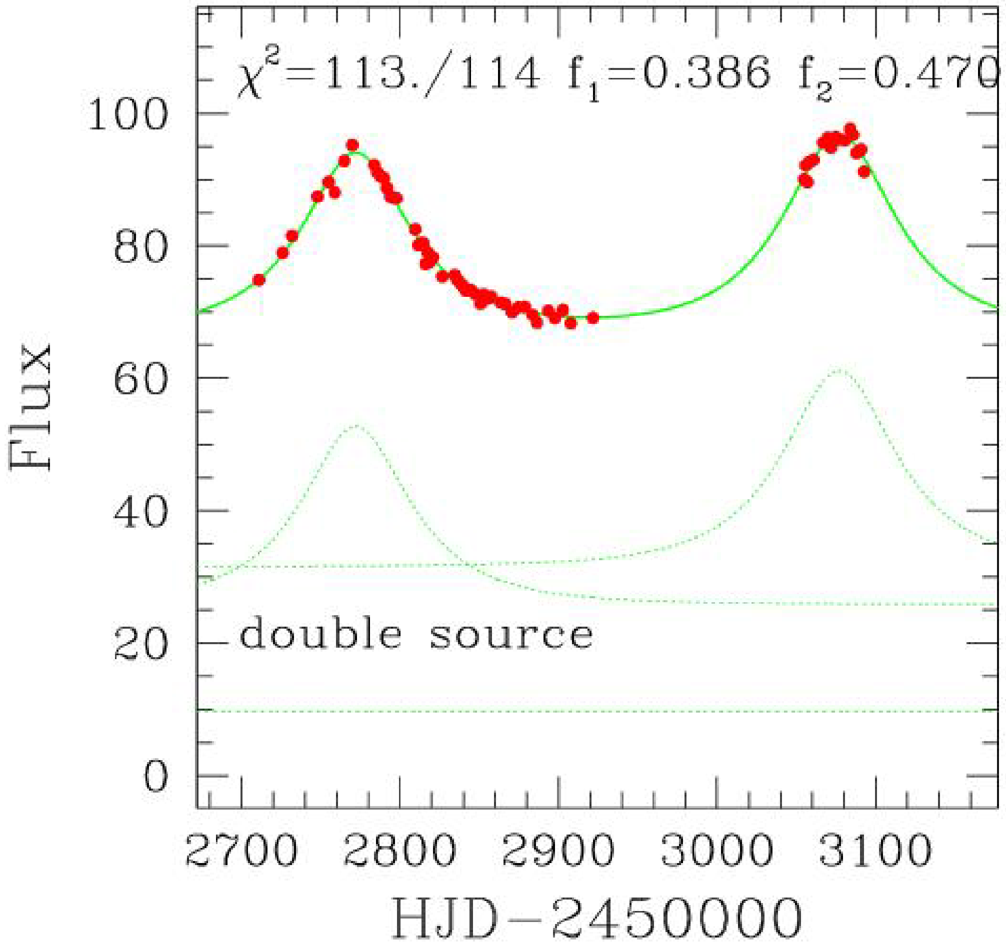


Mass ratio *q=0.001*



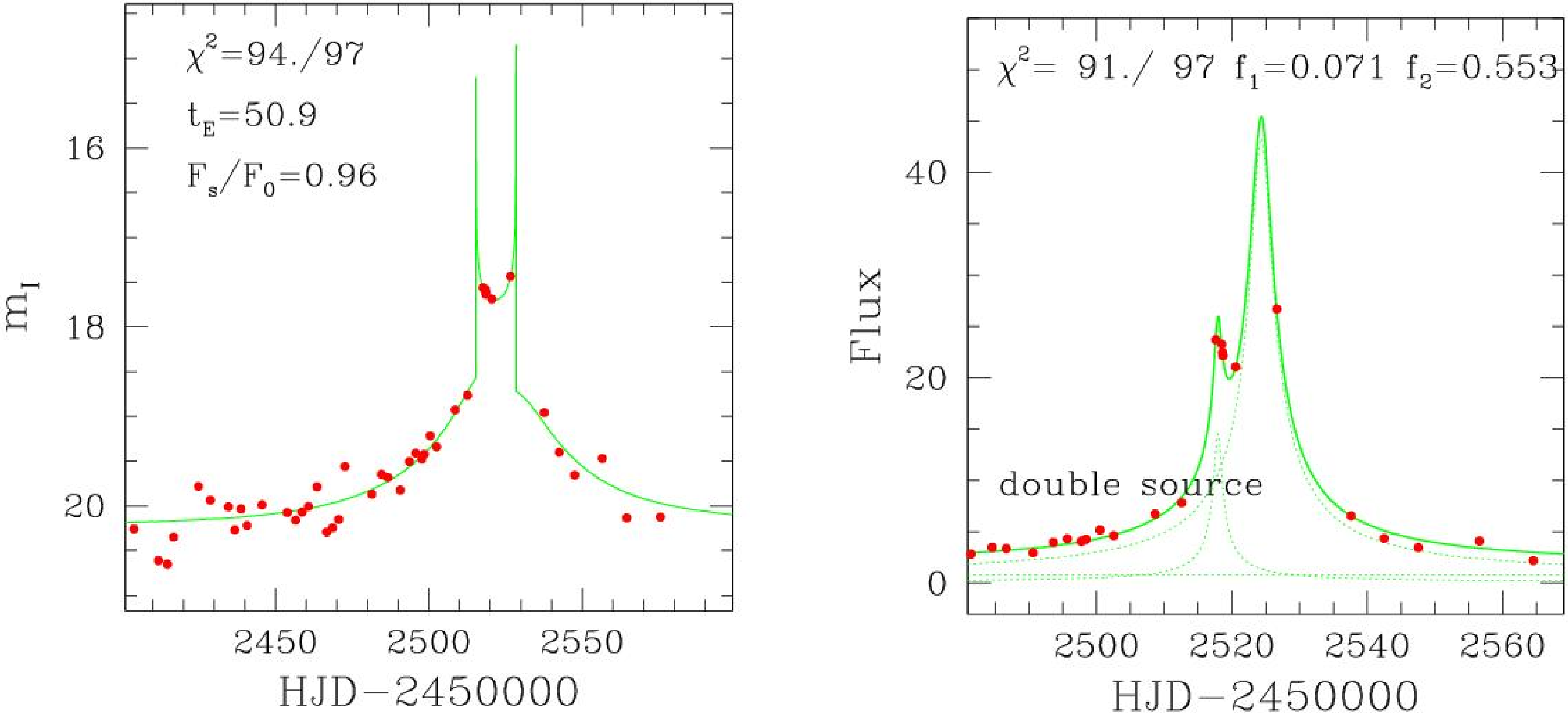


Binary source – single lens light curve



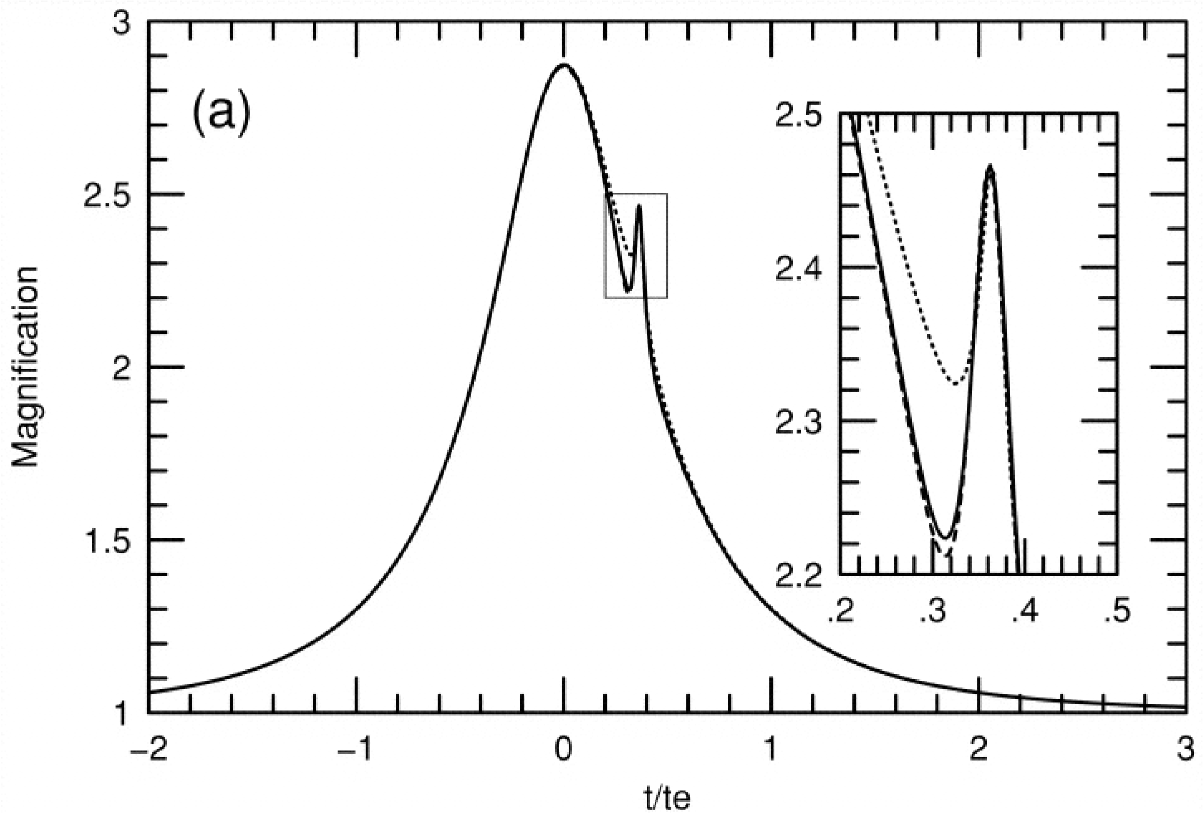
OGLE-2003-BLG-067

Stellar binary lens – binary source degeneracy



(OGLE-2002-BLG-321, Jaroszynsky et al. 2004)

Planetary binary lens – single source vs. binary source – single lens degeneracy



Gaudi (1998)

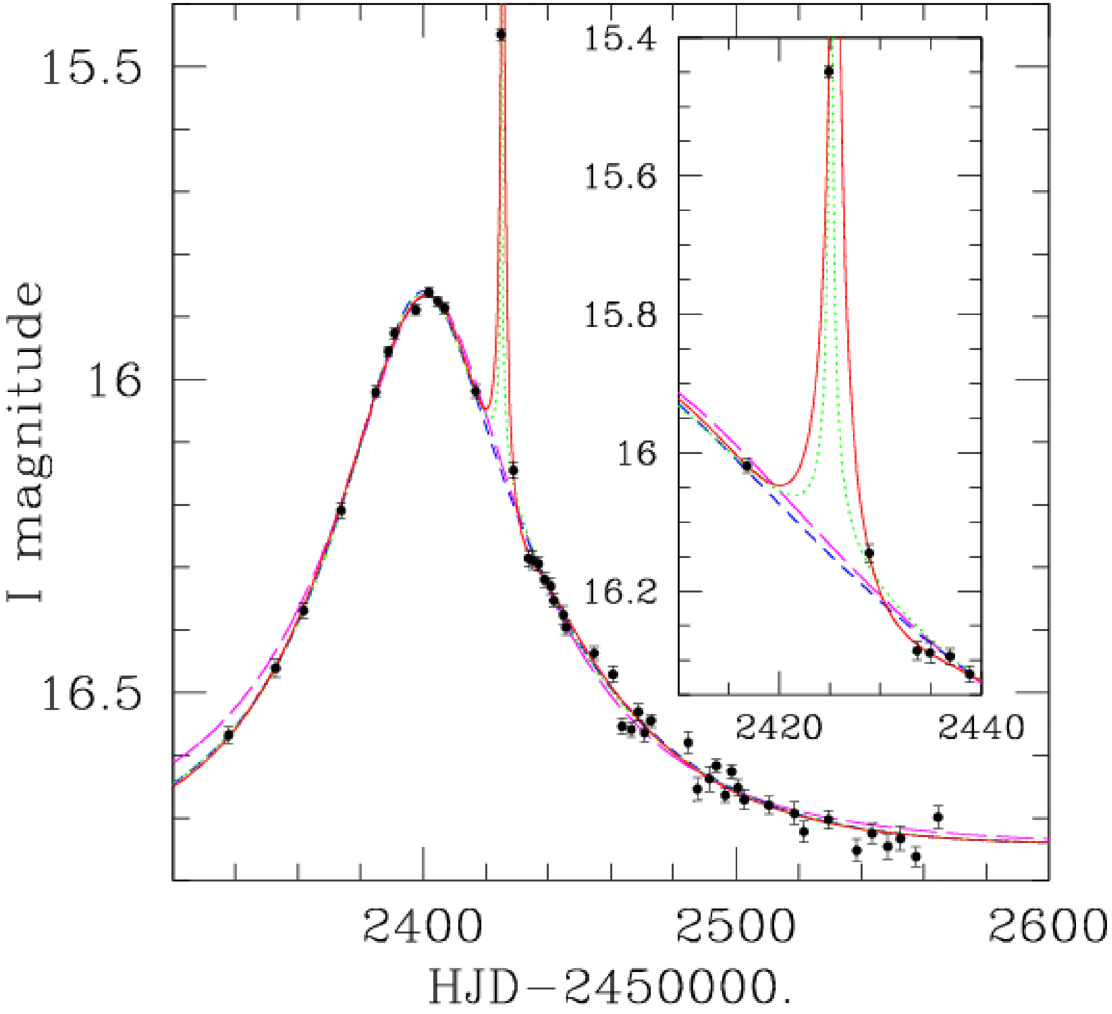
Solid line:
Binary lens

$$q = 10^{-3}$$

$$d = 1.3 R_E$$

Short-dashed line:
Binary source

$$\frac{F_A}{F_B} = 5 \times 10^{-3}$$



OGLE-2002-BLG-055 (Gaudi&Han 2004)

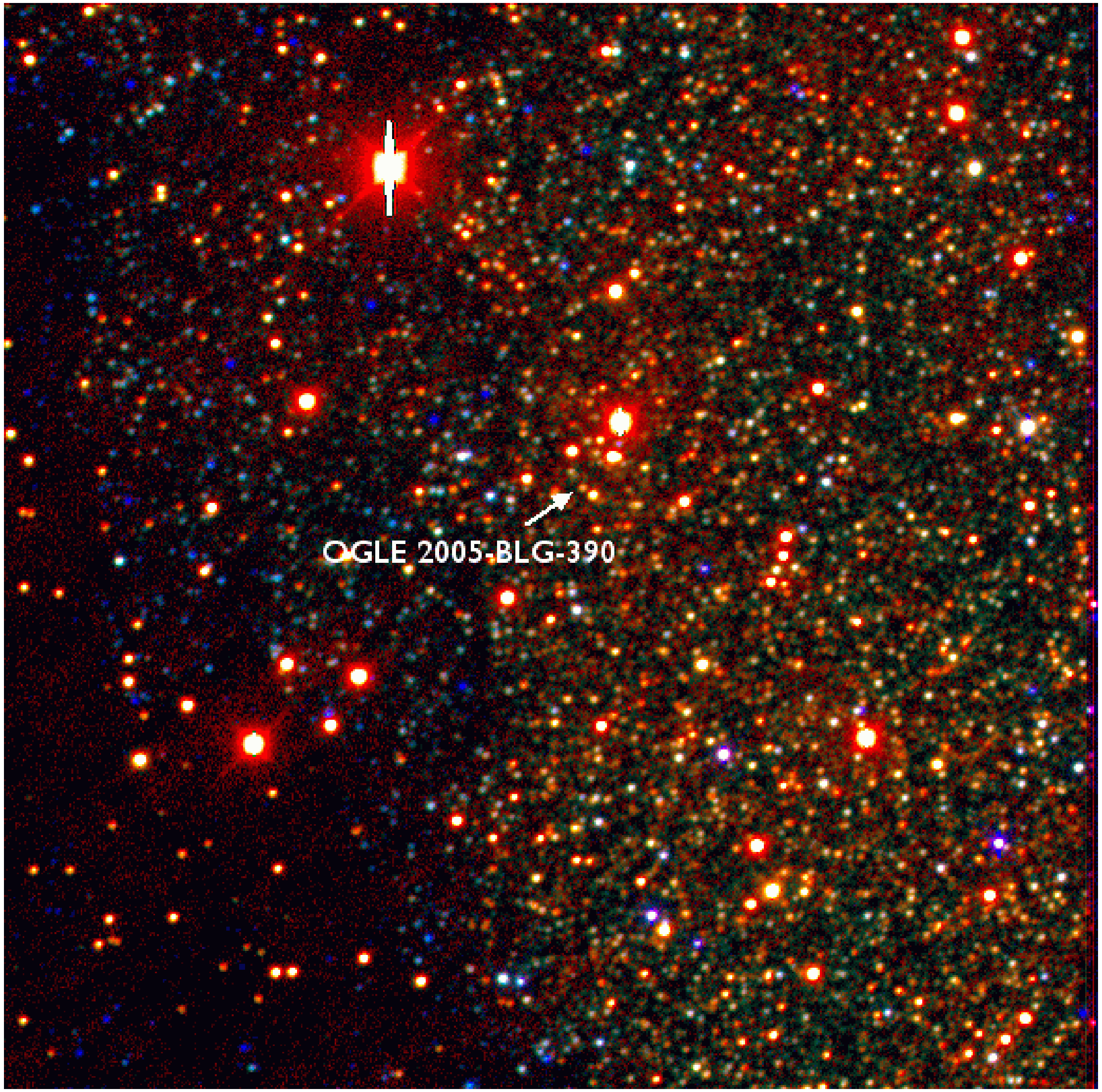
OGLE-2005-BLG-390

$$\alpha = 17h54\text{min}19.2s$$
$$\delta = -30°22'38''$$

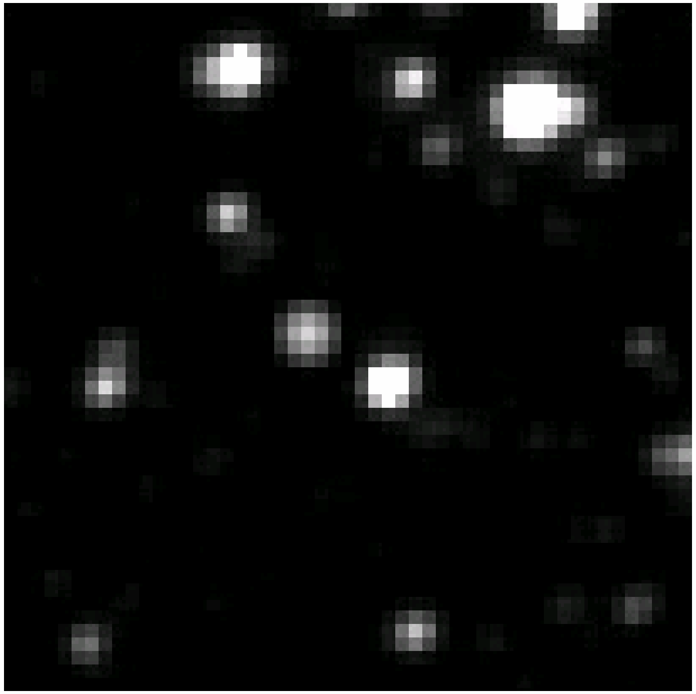
I photom. band

G4III type source star

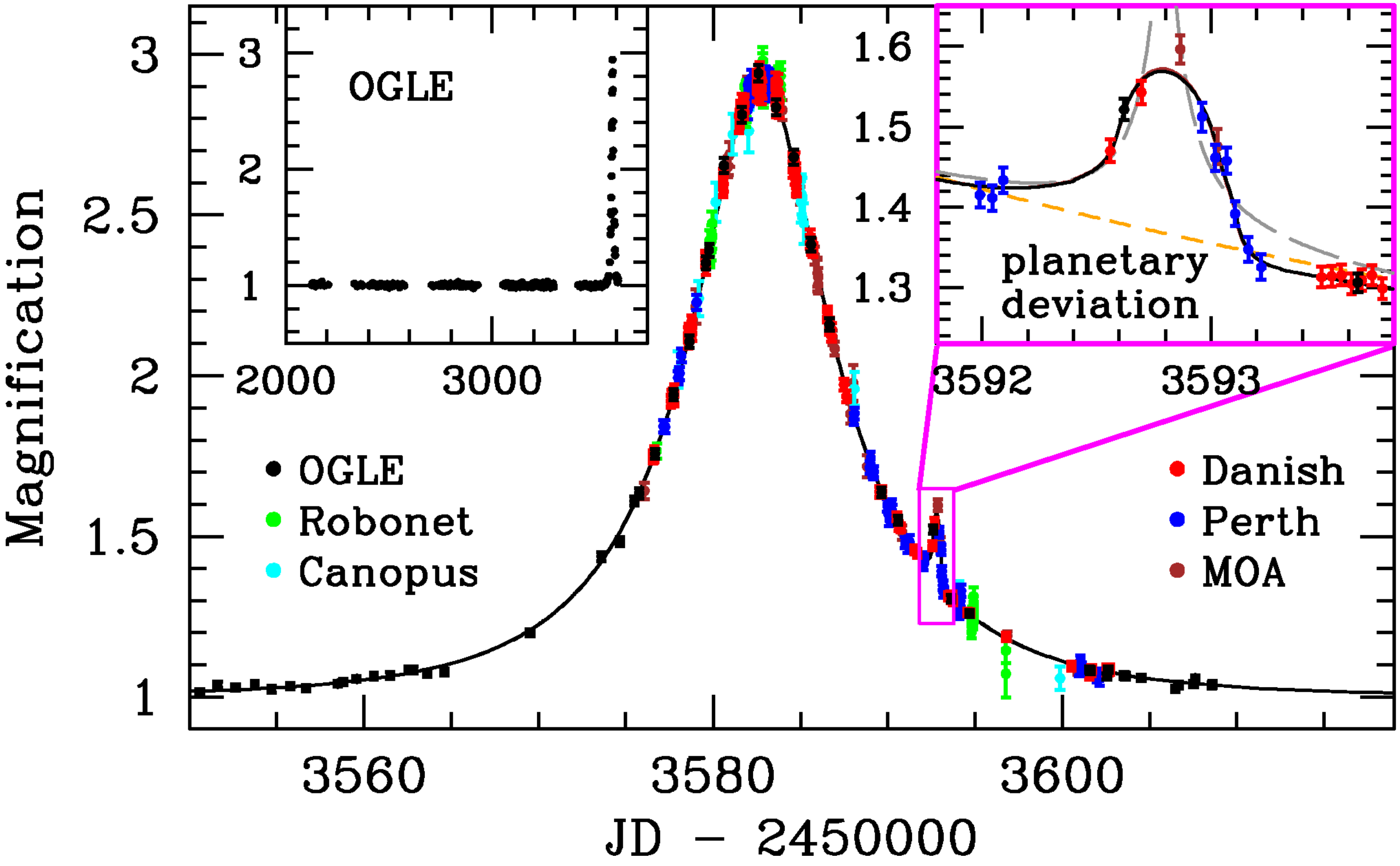
$$R_{G*} \sim 10 R_{Sun}$$
$$T_{G*} \sim 5200K$$



0.5‘x0.5‘



Planet discovery (~ 5 Earth masses)



(Beaulieu et al.: PLANET/RoboNet, OGLE, MOA) 2006, Nature

OGLE-2005-BLG-390 Model comparison:

- **Binary source**

$$t_E = (11.37 \pm = 0.13) d$$

$$u_B = (0.34 \pm 0.01) R_E$$

$$u_A = (0.0059 \pm 0008) R_E$$

$$F_B / F_A = (515 \pm 7)$$

$$\chi^2 / d.o.f. = 608 / 632$$

- **Binary lens**

$$t_E = (11.03 \pm 0.11) d$$

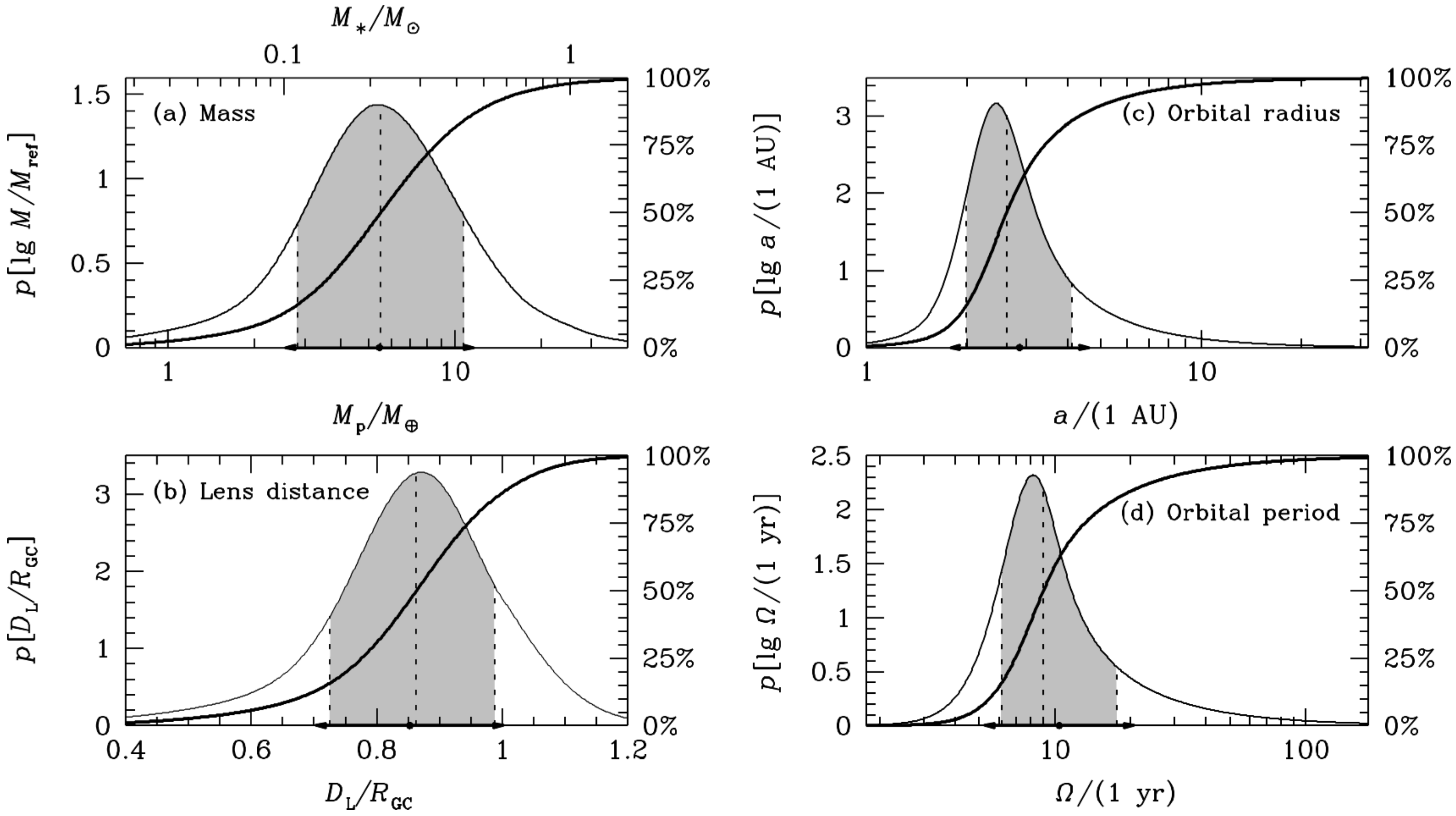
$$u_0 = (0.359 \pm 0.005) R_E$$

$$q = (7.6 \pm 0.7) 10^{-5}$$

$$d = (1.610 \pm 0.008) R_E$$

$$\chi^2 / d.o.f. = 562 / 631$$

Determining system parameters using probability distributions



Solution

(OGLE-2005-BLG-390)

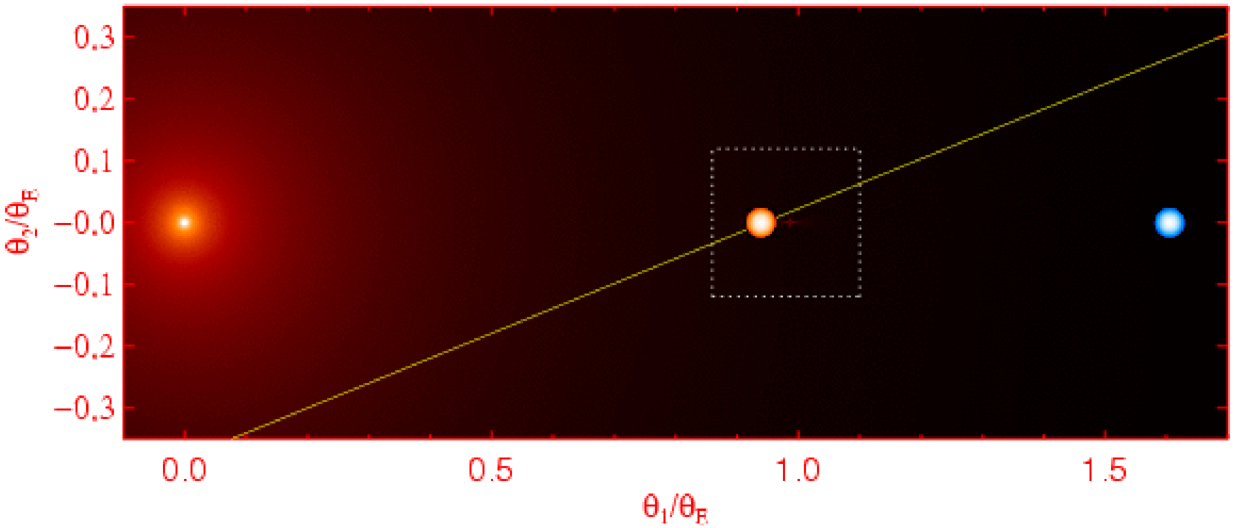
- Planet mass: $M_P = 5.5^{+5.5}_{-2.7} M_{Earth}$
- Host star mass: $M_{M*} = 0.22^{+0.21}_{-0.11} M_{Sun}$
- Separation:

$$d_P = 2.7^{+1.5}_{-0.6} A.U.$$

- Distance to the lens:

$$D_{P+M*} = 6.6^{+1.0}_{-1.0} kpc \sim 20{,}000 ly$$

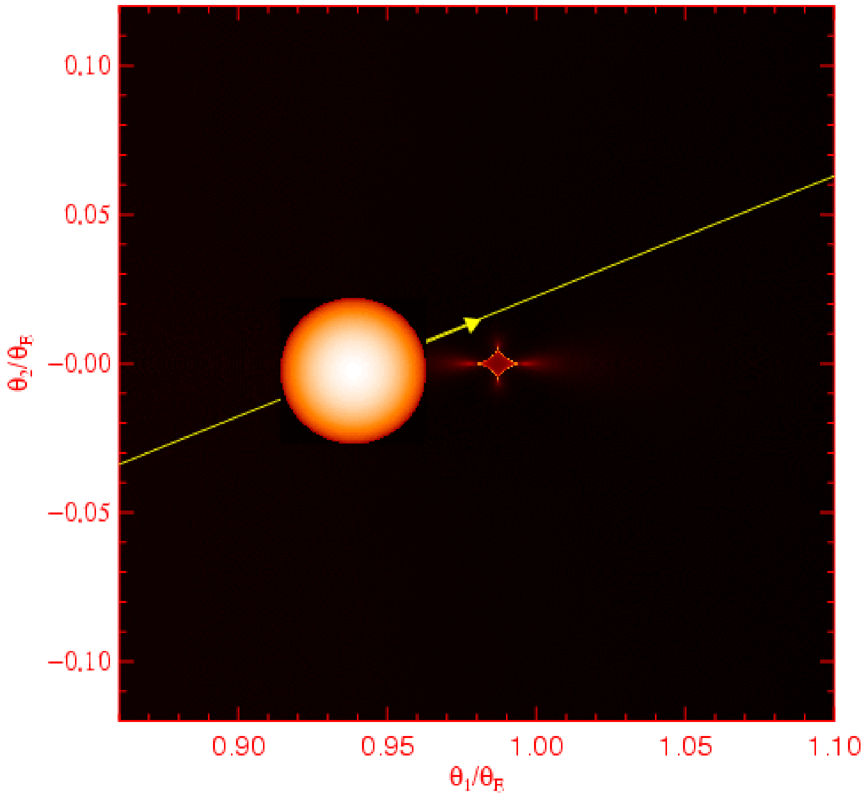
(Beaulieu et al.: PLANET/RoboNet, OGLE, MOA) 2006, Nature, 439, 437)

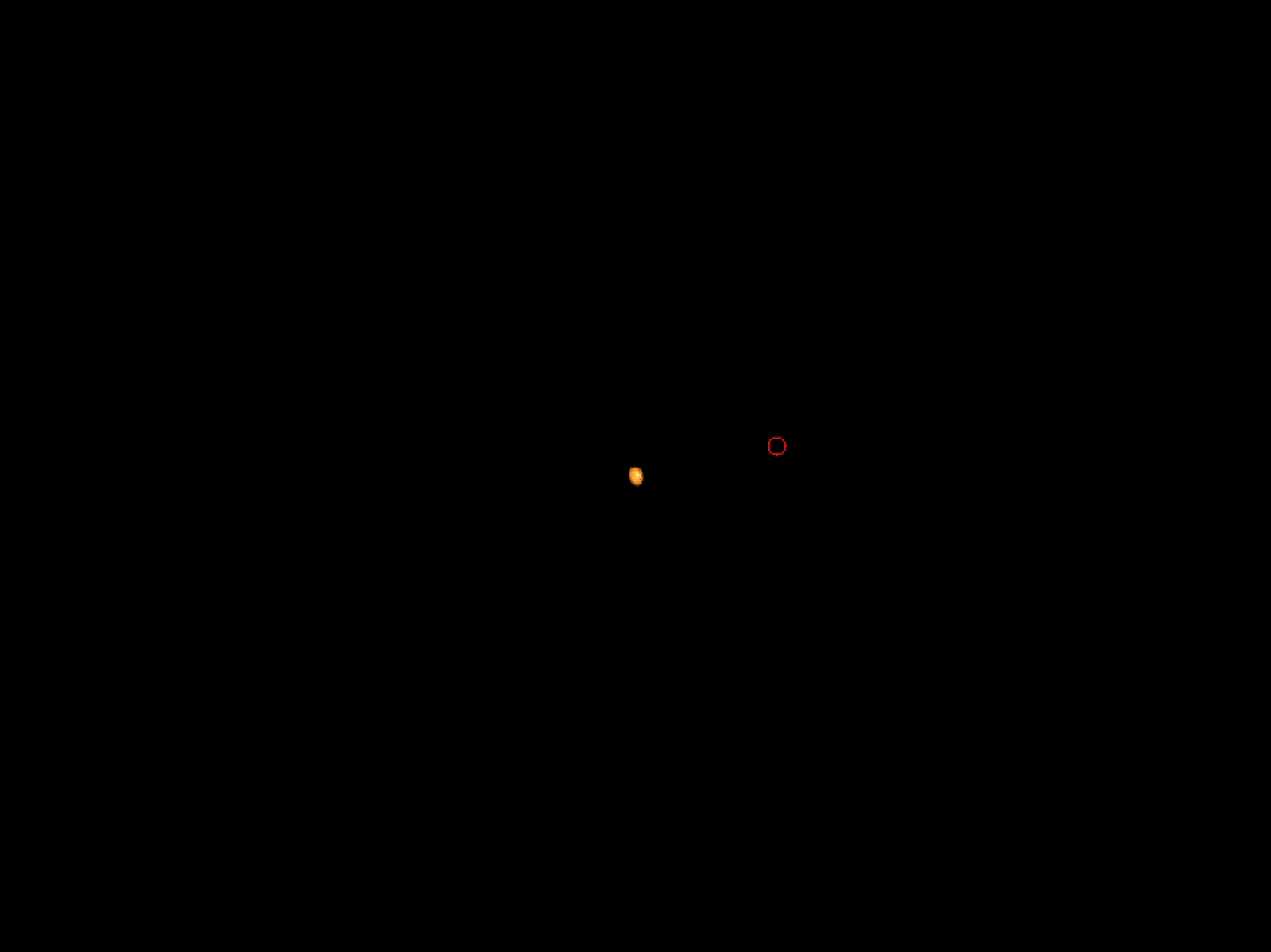


The source path (G giant) relative to the lens system (Planet + M star)

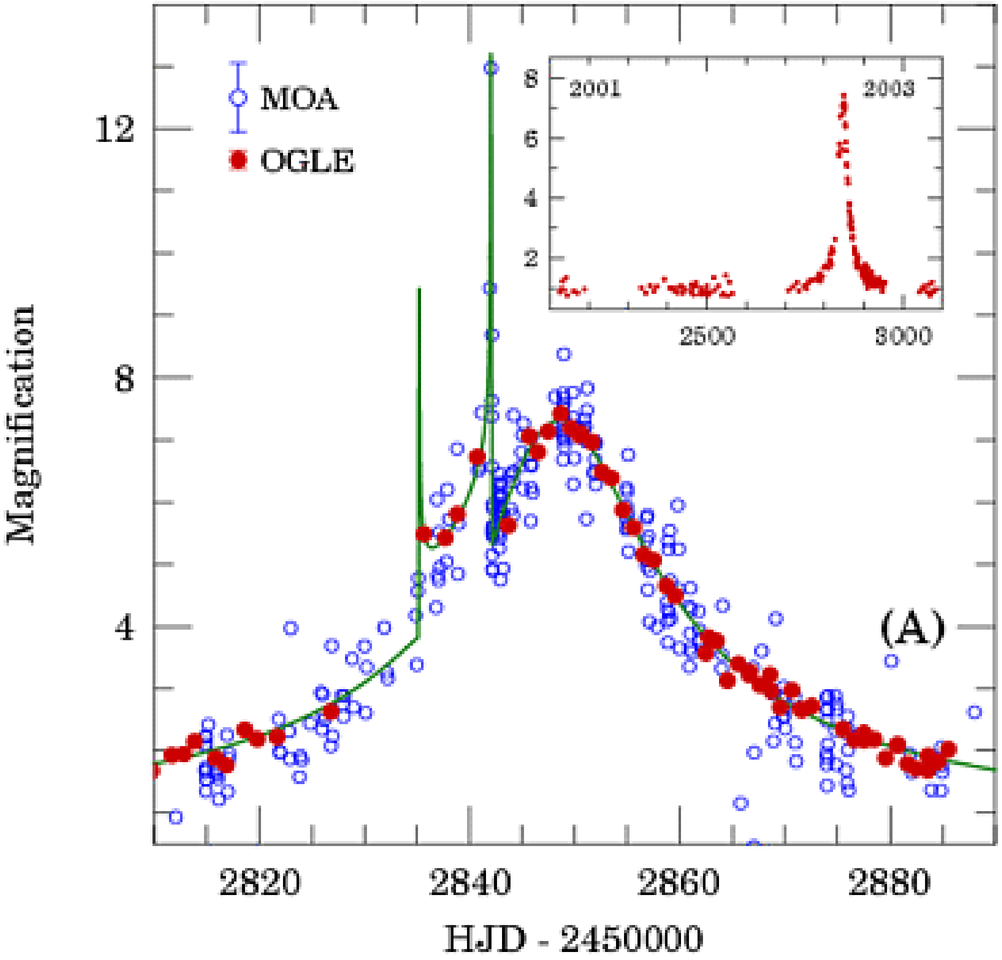
$$R_{*source} \Rightarrow m_P$$

$$m_p \approx 5 m_{Earth}$$





First planet detection using microlensing (MOA-2003-BLG-053 / OGLE-2003-BLG-235)



1.5 Jupiter mass planet

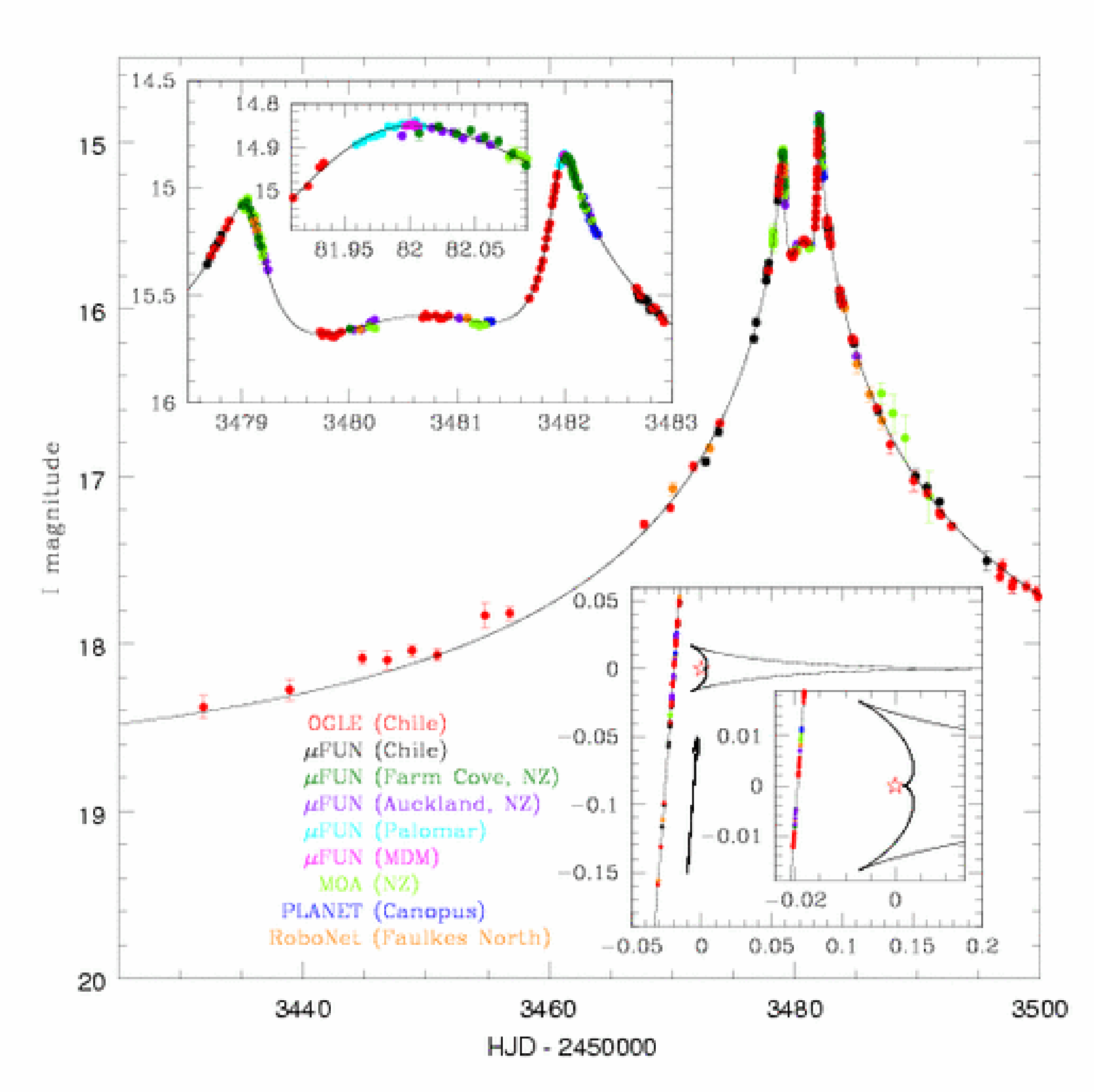
q=0.004

a=3 A.U.

D=5.2 kpc

Bond et al. (2004)

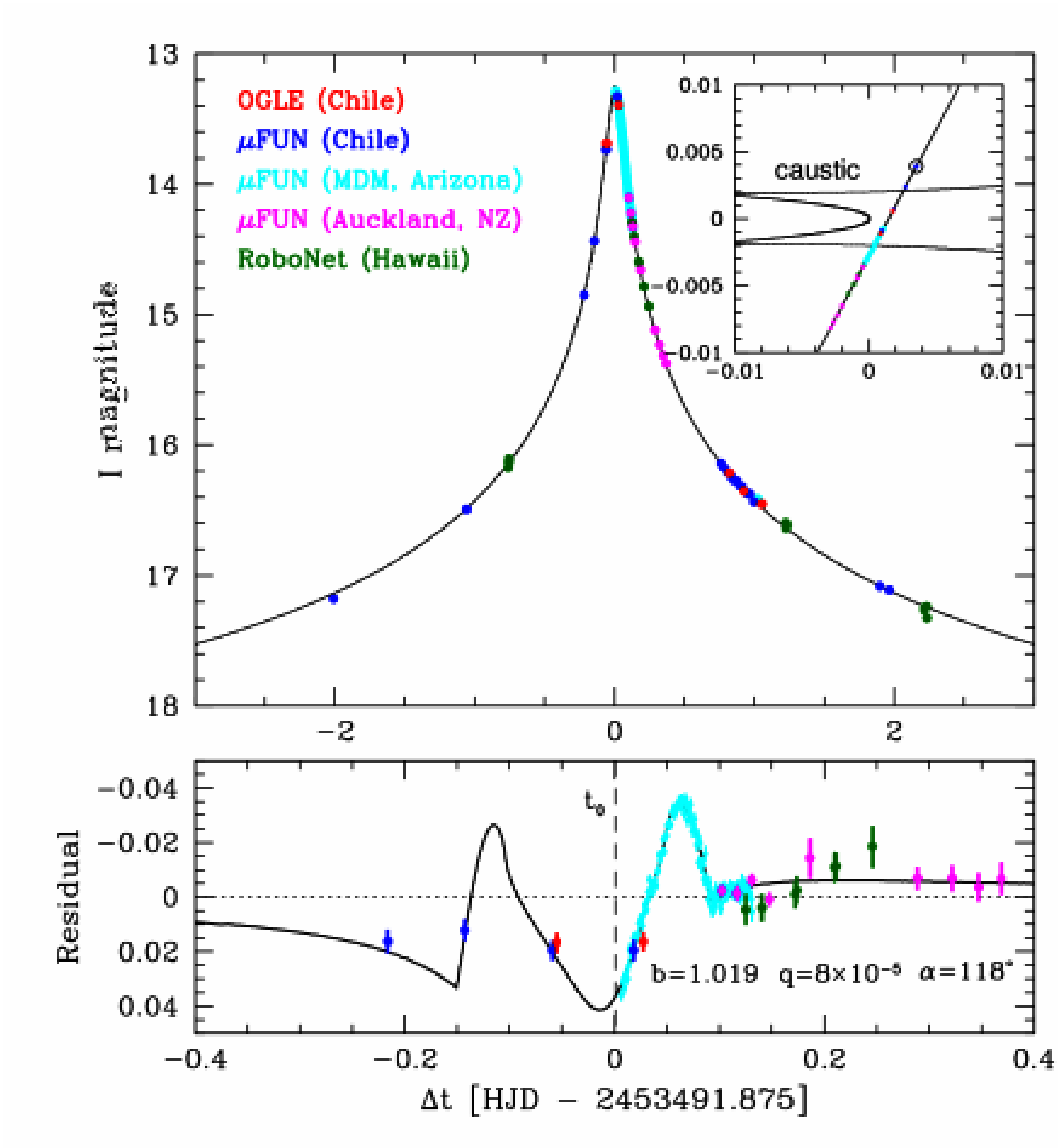
OGLE-2005-BLG-071 (#2)



several-Jupiter mass planet

Udalski et al. 2005

OGLE-2005-BLG-169Lb (#4)



Neptune mass
13 M(Earth)
q=8e-5

Gould et al. 2006

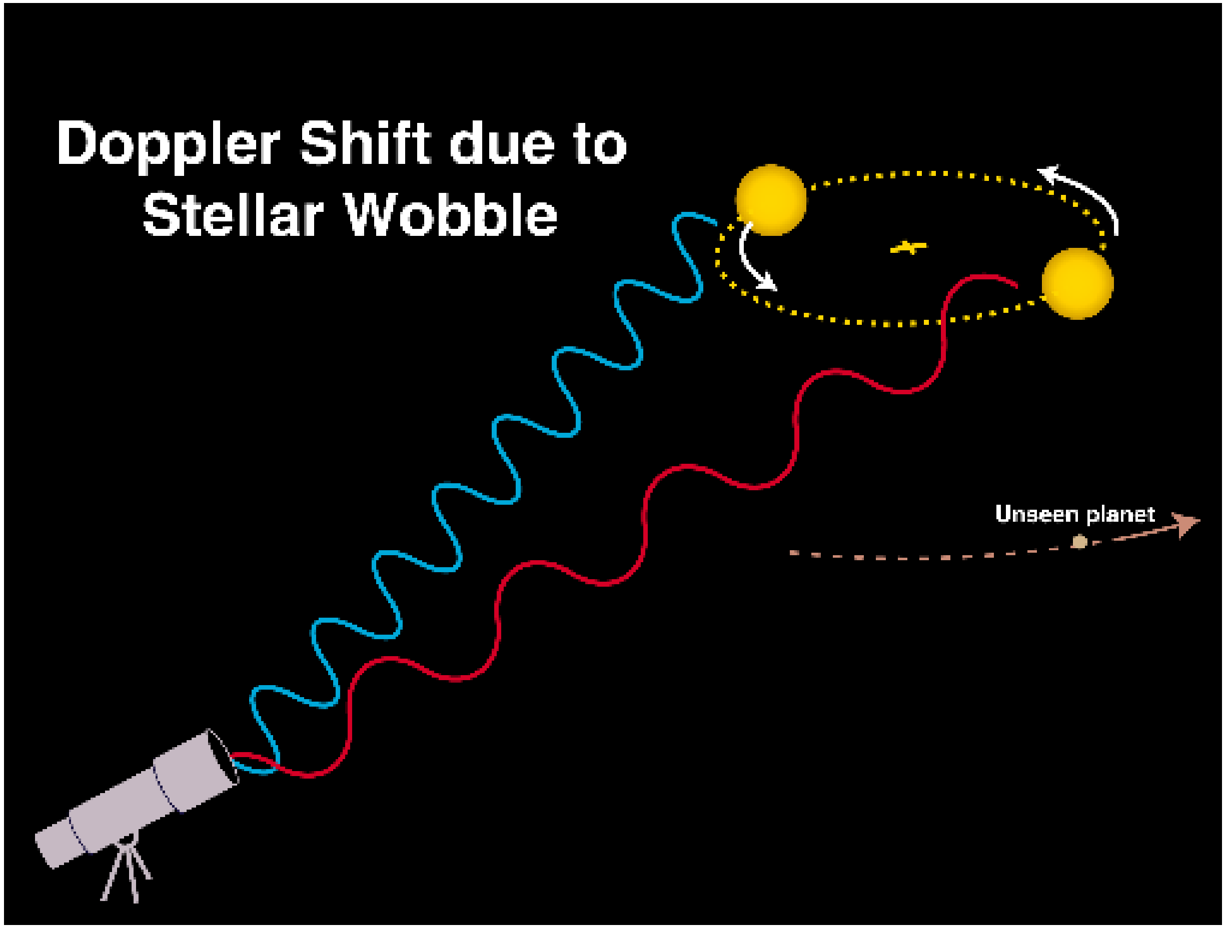
Methods for finding extrasolar planets

- 250 extrasolar planets discovered up to date (July 2007)

- **Radial velocities:** shifts in the stellar spectrum (the first exoplanet: 1995)
- **Astrometry:** very precise measuring of stellar positions (wobble due to the planet)

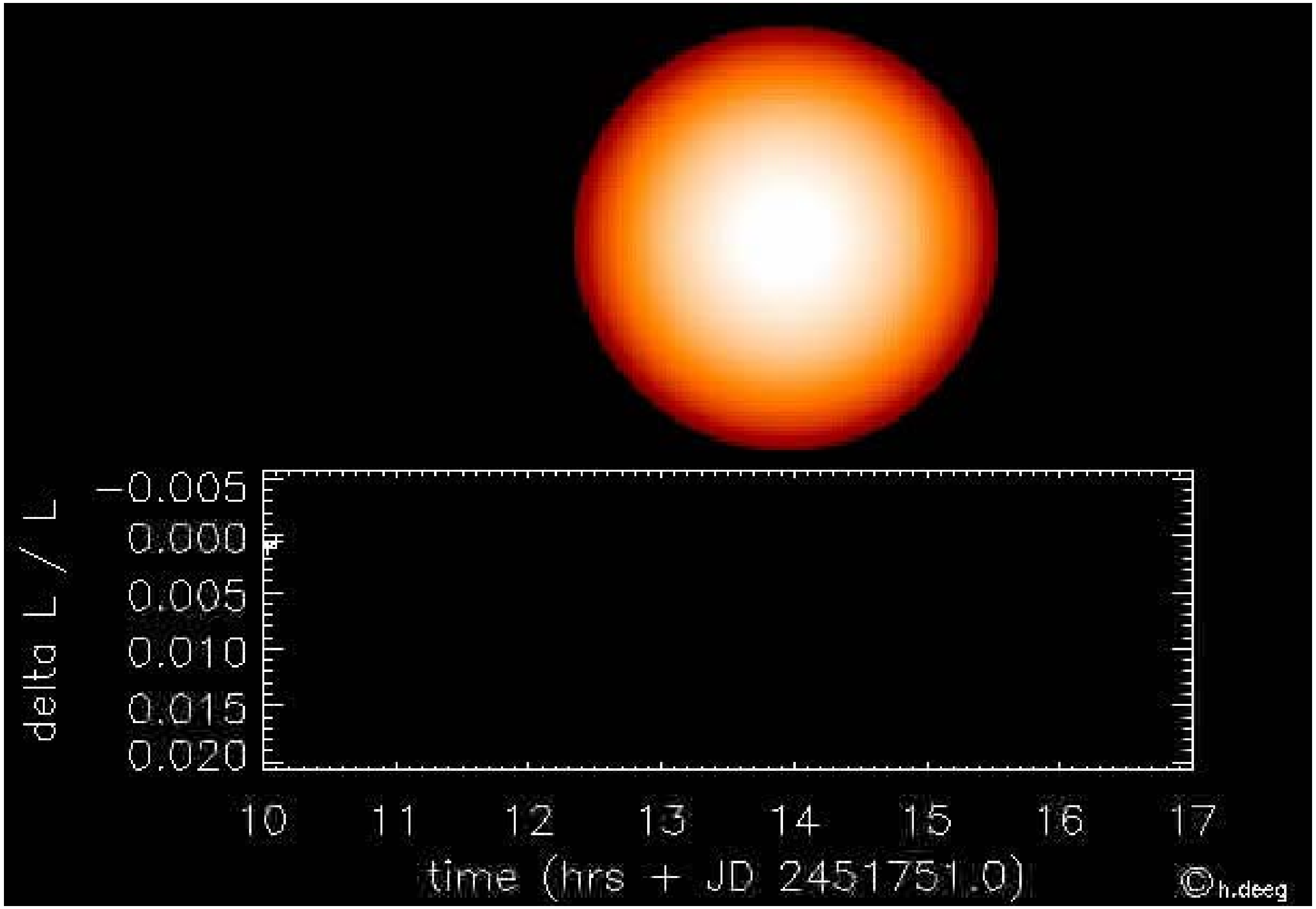
- **Direct imaging:** 4 planet candidates,
may be small stars (brown dwarfs)
- **Transits**:
large planets very close to their parent stars
- **Pulsar planets**
- **Gravitational microlensing**

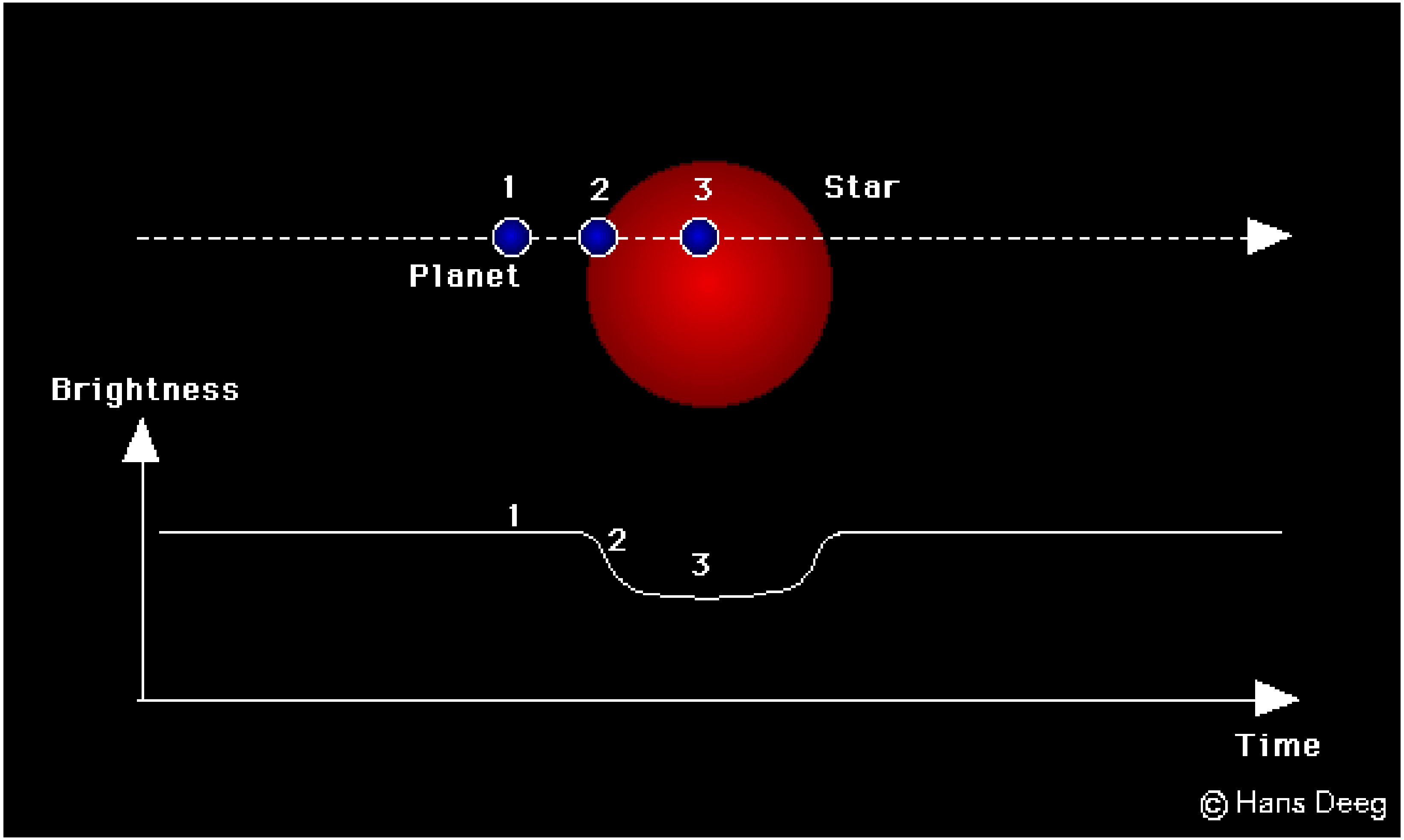
Radial velocities



Only the lower limit on the mass!

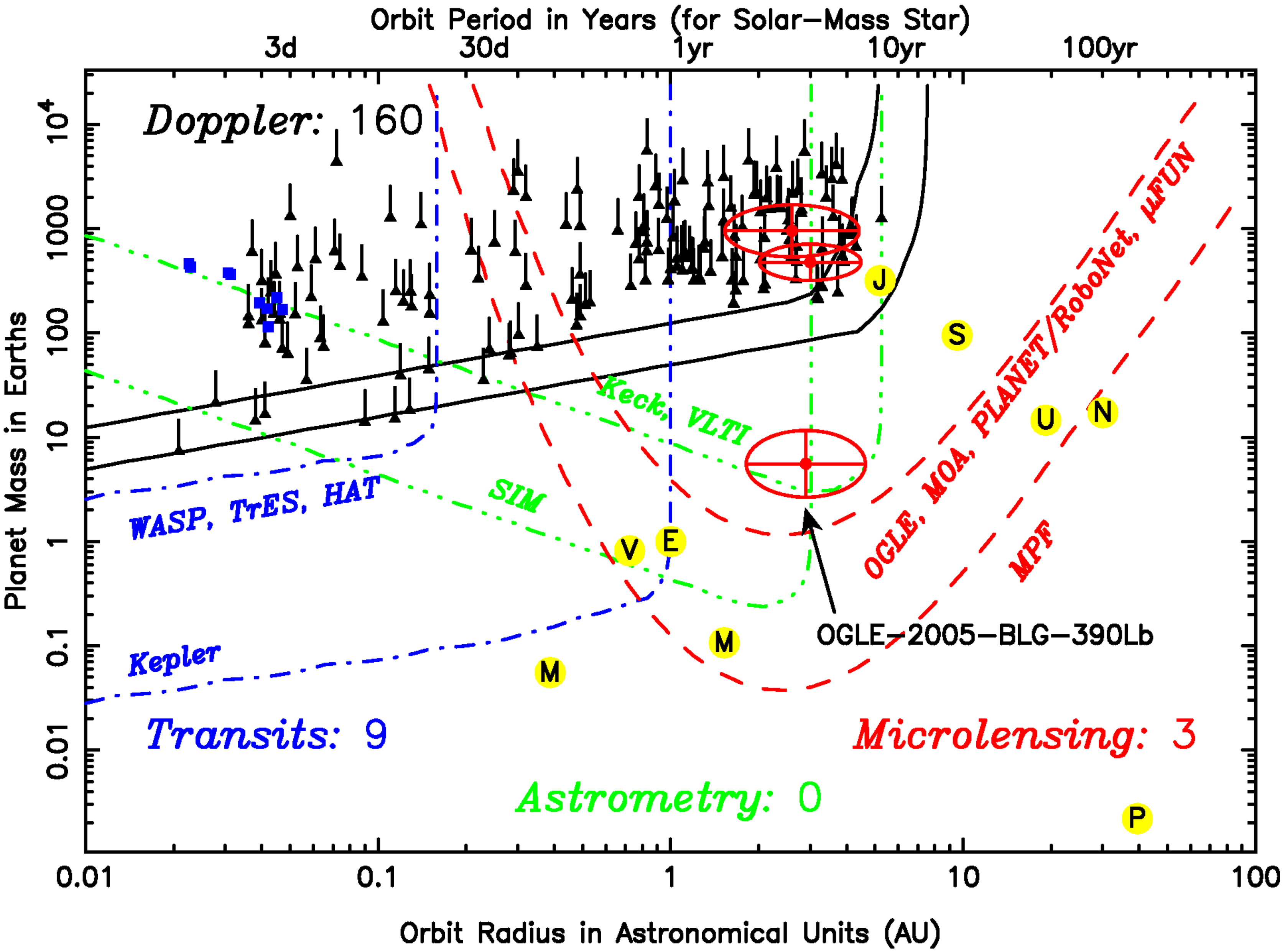
- **Transits**:

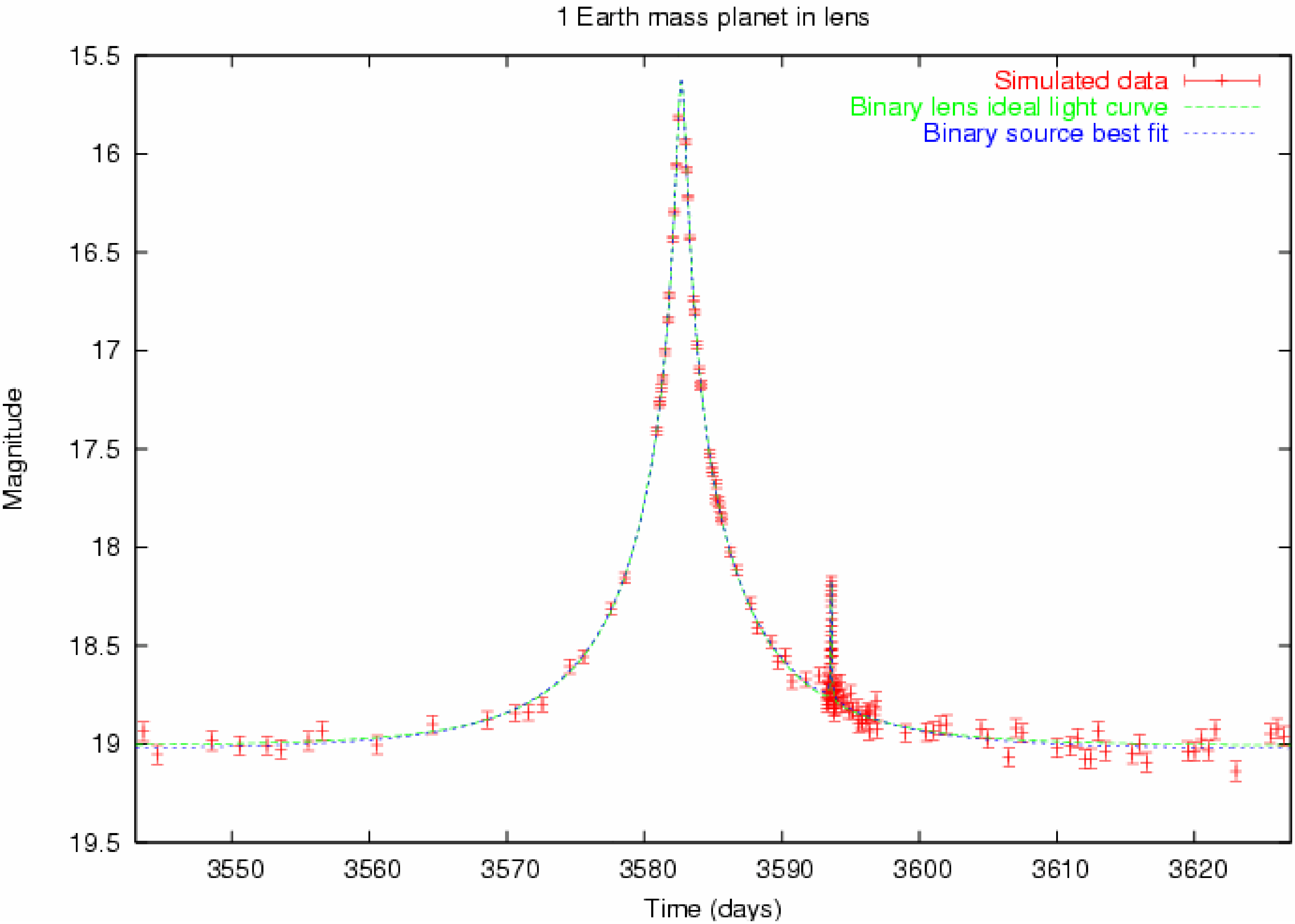

delta L / L
−0.005
0.000
0.005
0.010
0.015
0.020
10
11
12
13
14
15
16
17
time (hrs + JD 2451751.0)
©h.deeg

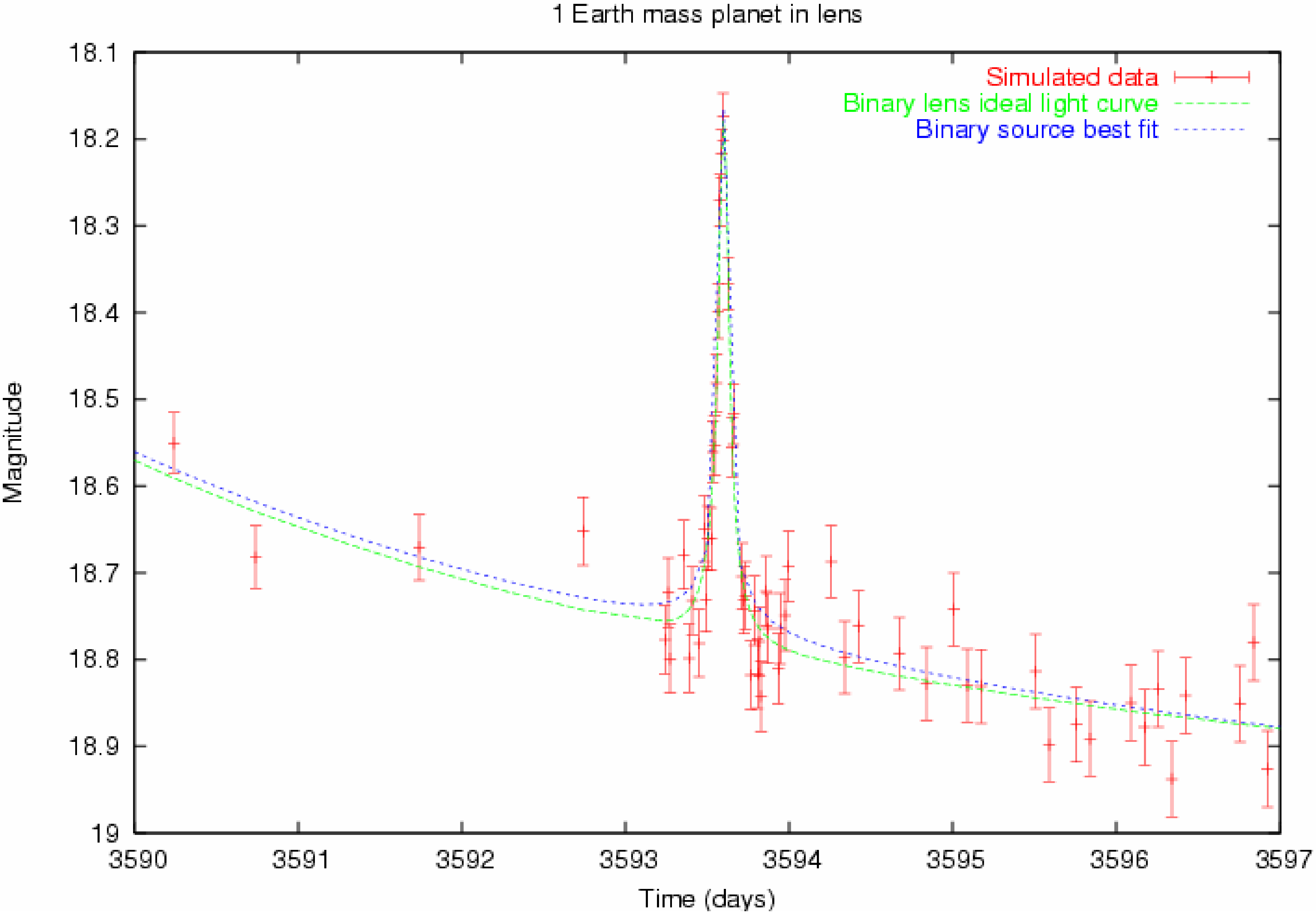


Water vapour detected in the atmosphere of a hot Jupiter transiting planet (Tinetti et al, July 2007)

Known Exoplanets: 9+160+3=172 (Jan 2006)

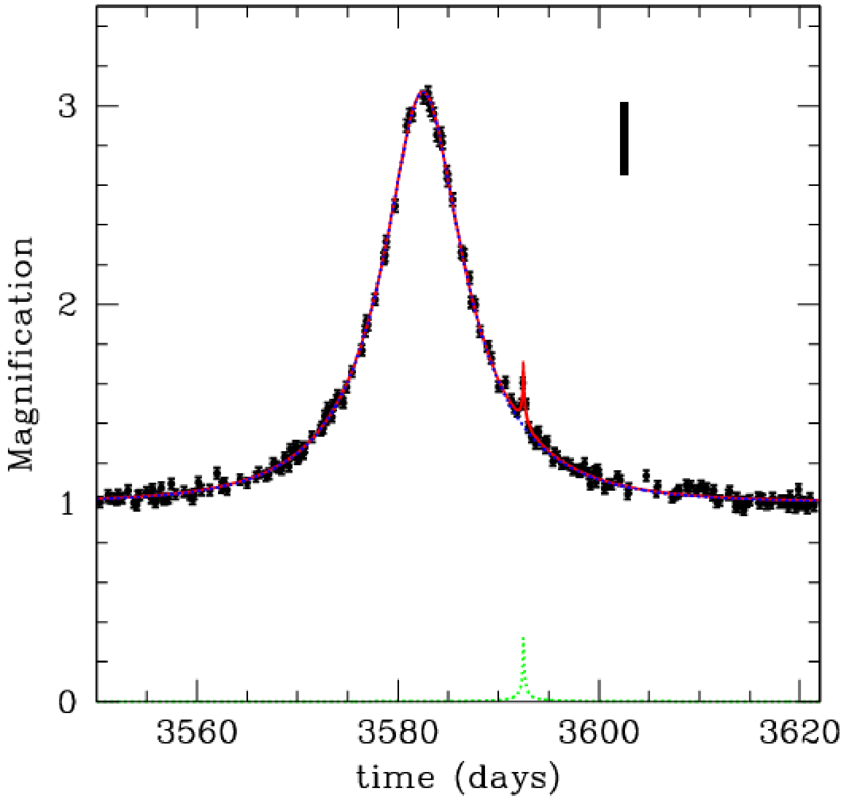


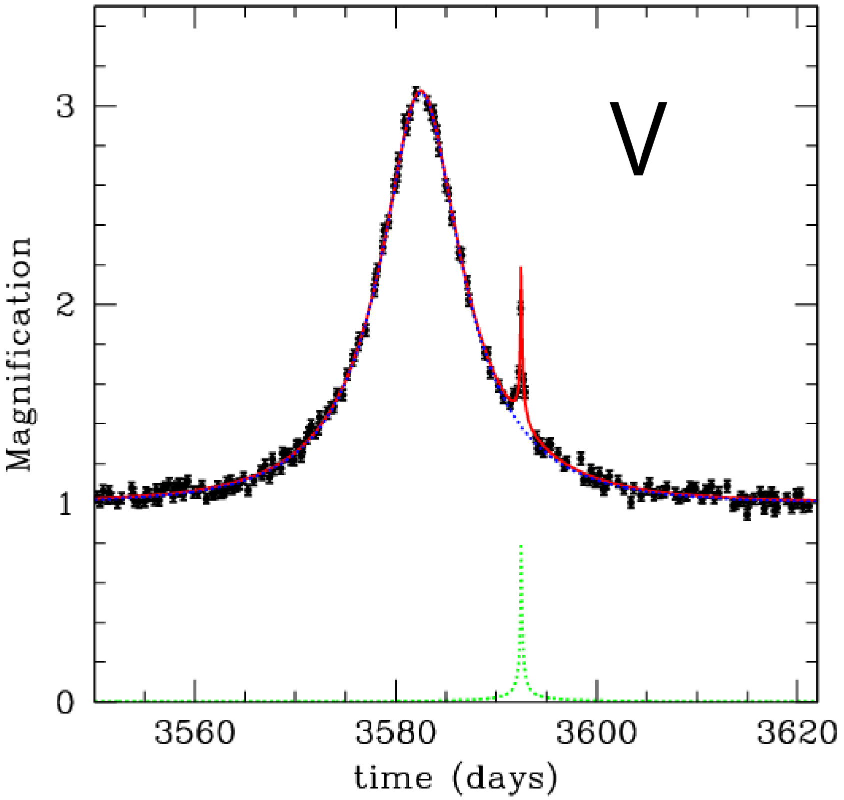

1 Earth mass planet in lens
Simulated data
Binary lens ideal light curve
Binary source best fit
Magnitude
15.5
16
16.5
17
17.5
18
18.5
19
19.5
3550
3560
3570
3580
3590
3600
3610
3620
Time (days)

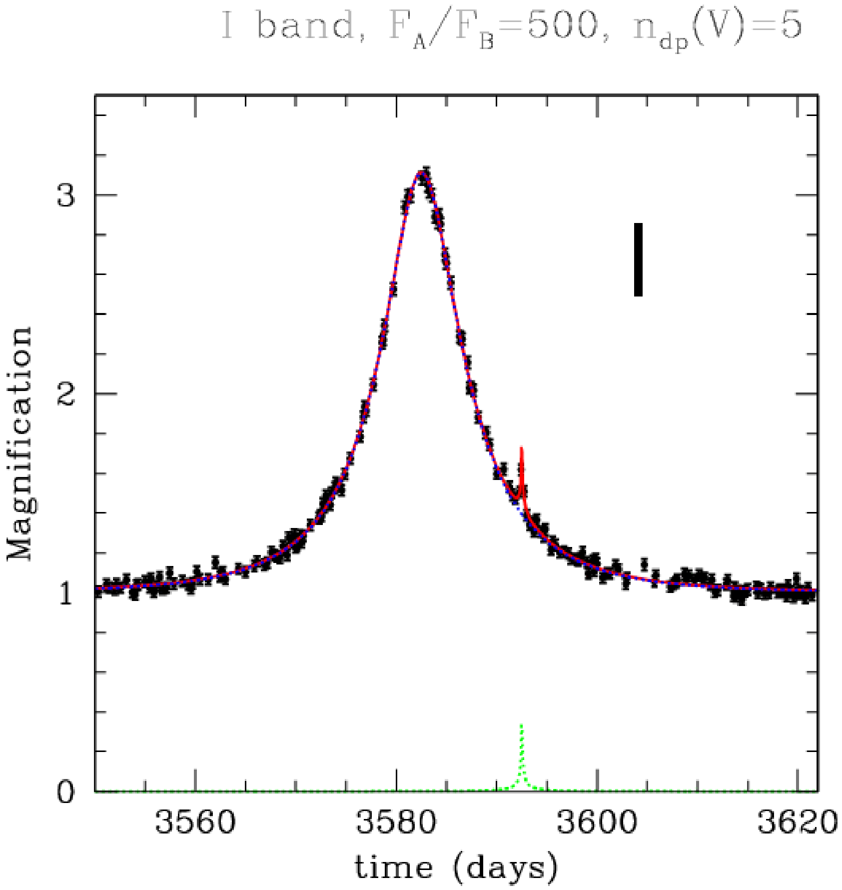

1 Earth mass planet in lens
Simulated data
Binary lens ideal light curve
Binary source best fit
Magnitude
18.1
18.2
18.3
18.4
18.5
18.6
18.7
18.8
18.9
19
3590
3591
3592
3593
3594
3595
3596
3597
Time (days)

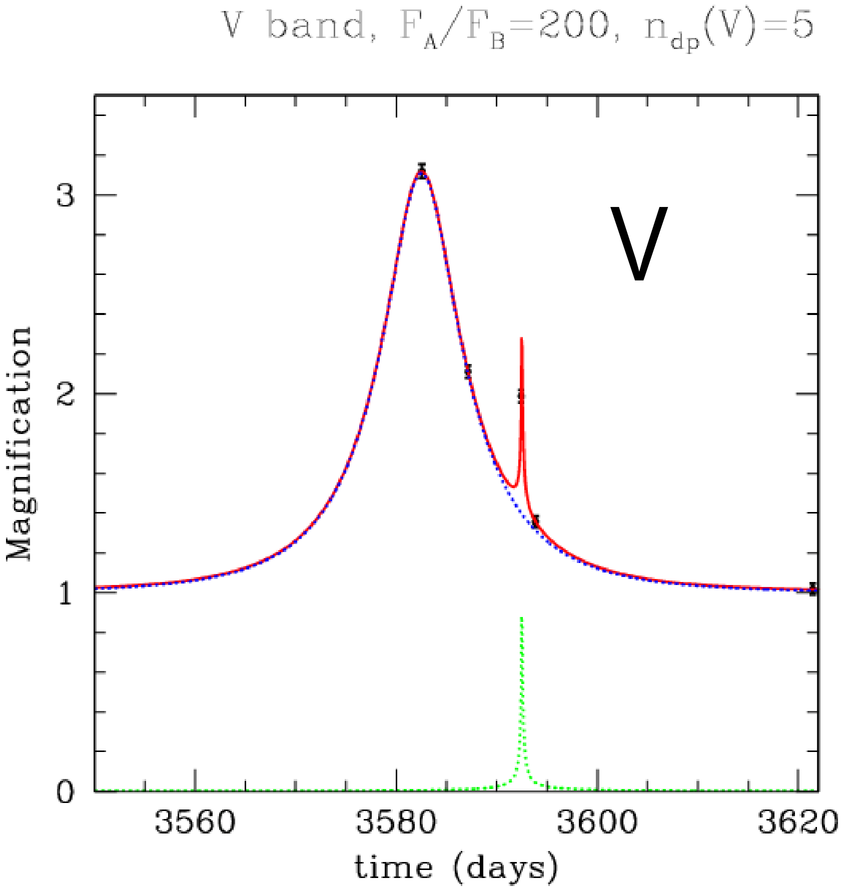
Flux Ratio Method

Binary source – single lens events: $$\frac{F_A(I)}{F_B(I)} \neq \frac{F_A(V)}{F_B(V)}$$


I band, $F_A/F_B=500$

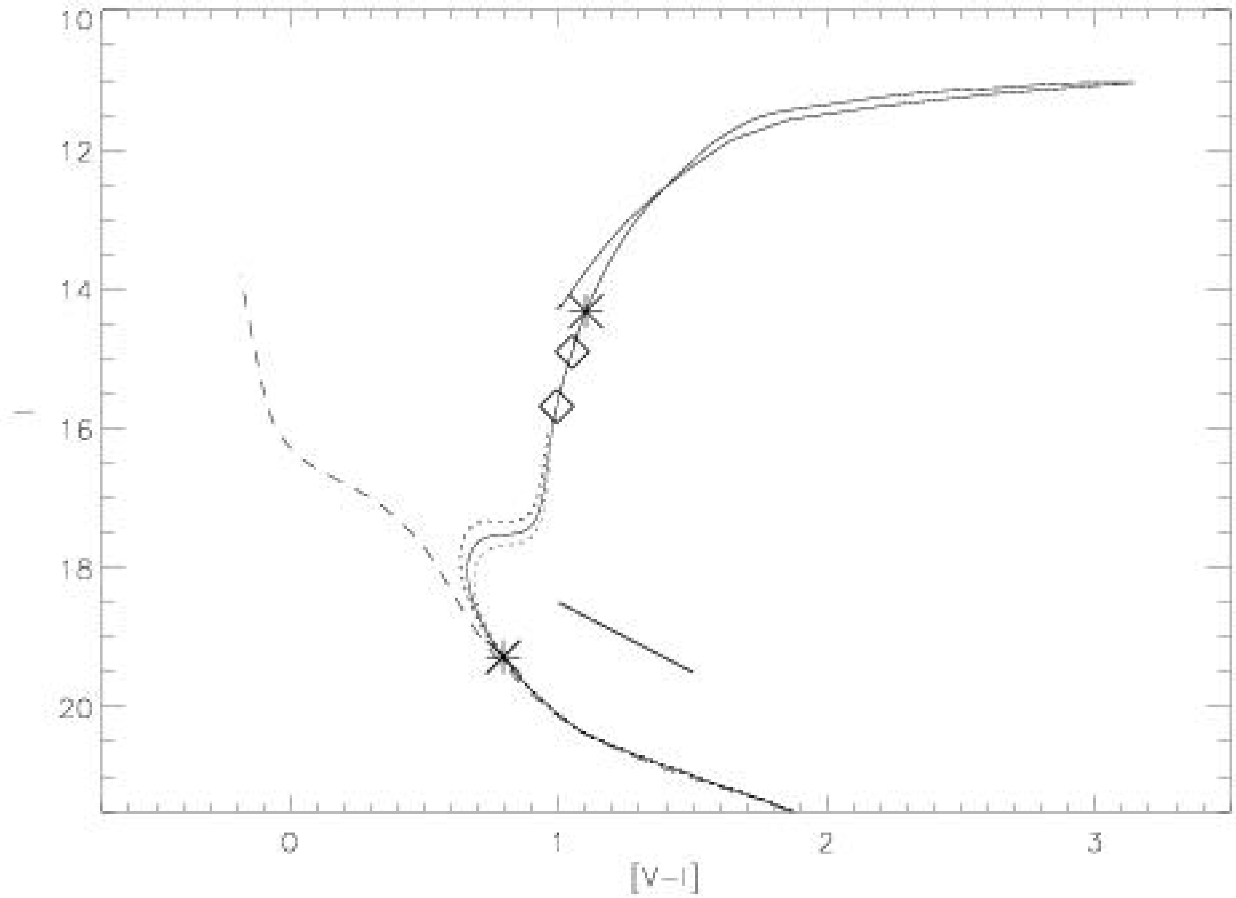

V band, $F_A/F_B=200$





Only few additional data points in V band may distinguish a ***binary source - single lens*** *event from a* ***planetary binary lens - single source*** *event !*

Isochrone for 10 Gyr (D=8 kpc)



I

(V-I)

Summary

- **Microlensing** is capable of detecting **Earth-like planets** (low-mass, rocky)
- Ambiguity between a **planetary binary lens** and a **binary source** light curve solutions of can be broken by:

- Very **dense data sampling** and **high data quality** (OGLE-2005-BLG-390)
- **Flux ratio method**

=> Detection of **low mass planets**!