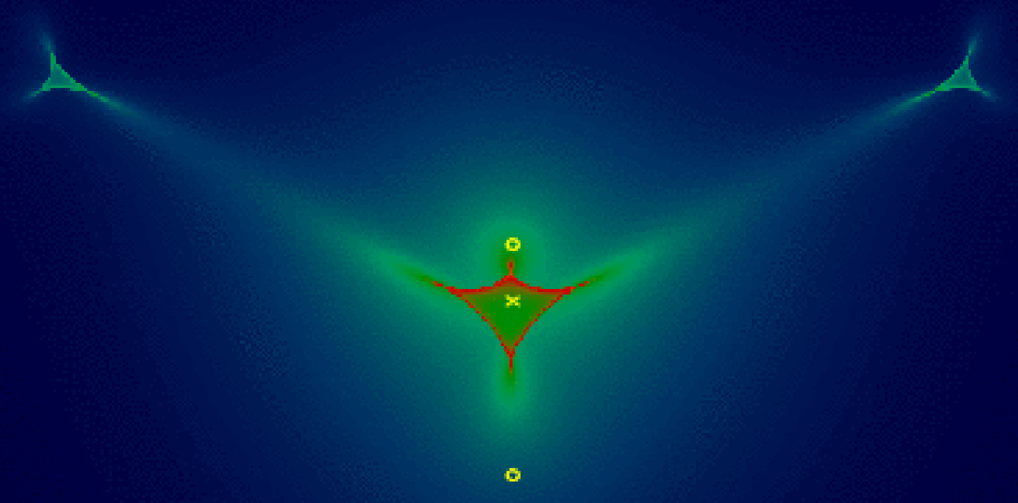
# Searching for extrasolar planets using microlensing



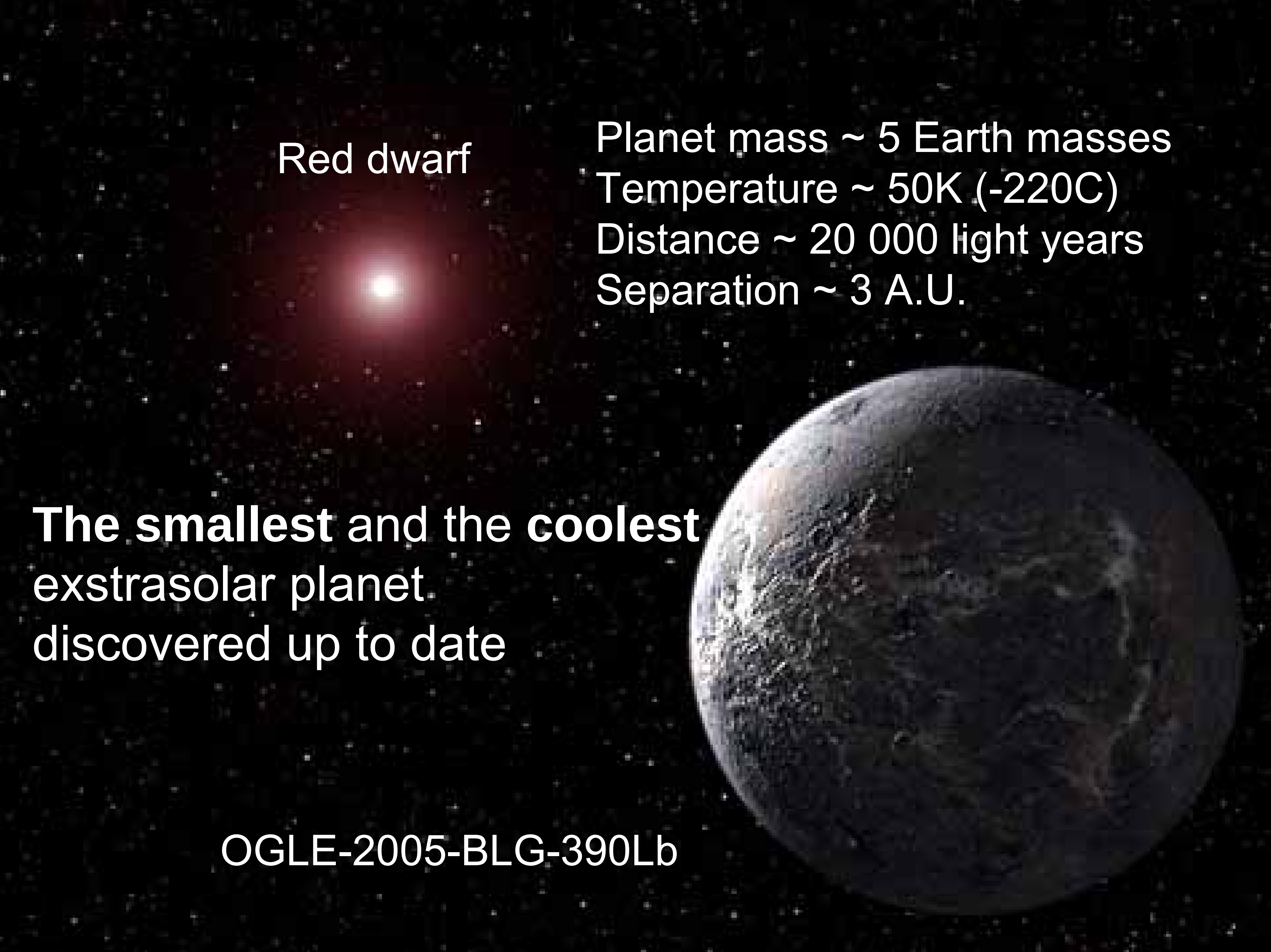
Dijana Dominis Prester

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)

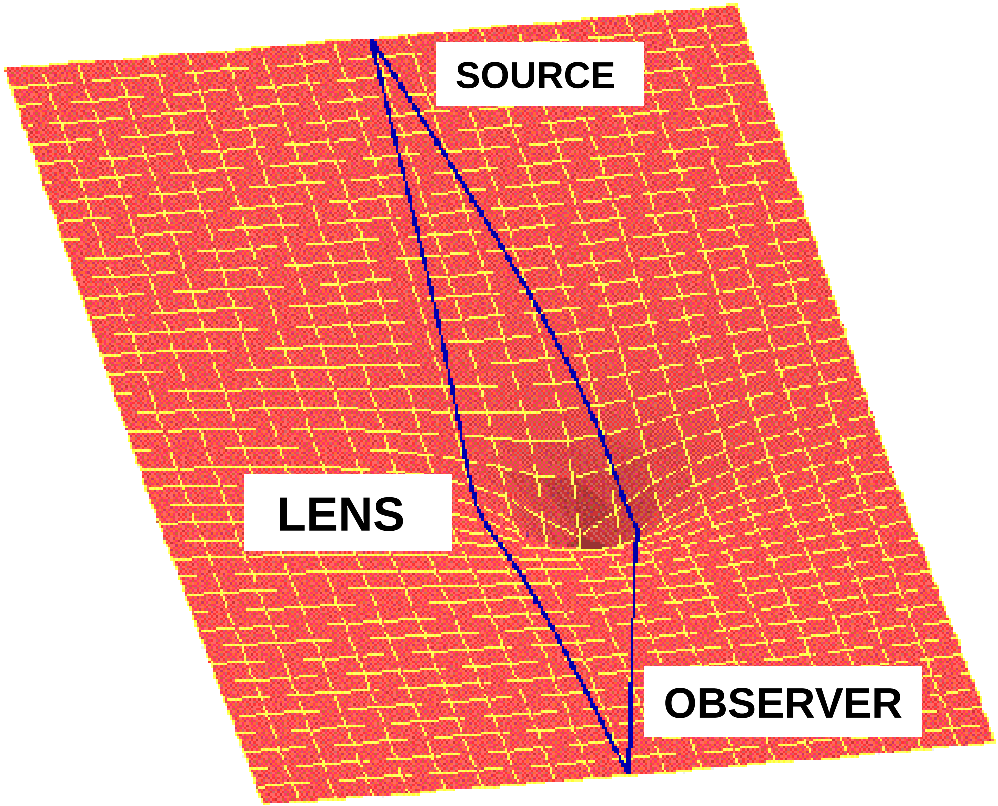
=> **microlensing**


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

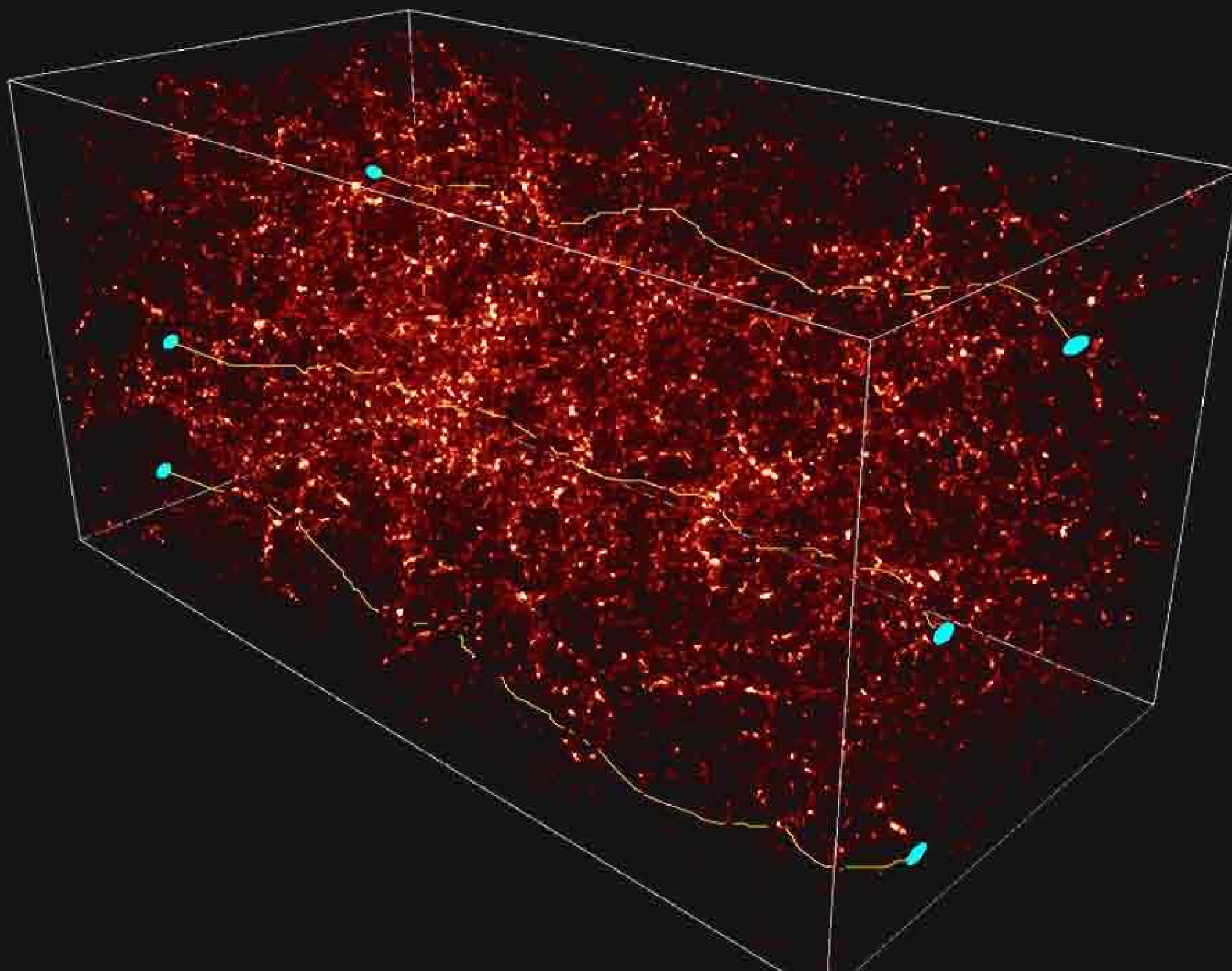
1. Gravitational lensing and microlensing
2. Single and binary lenses and sources
3. Discovery of OGLE-2005-BLG-390Lb
4. Other methods for finding extrasolar planets
5. Modeling techniques (synthetic data, optimization, genetic algorithm)

# Gravitational lensing



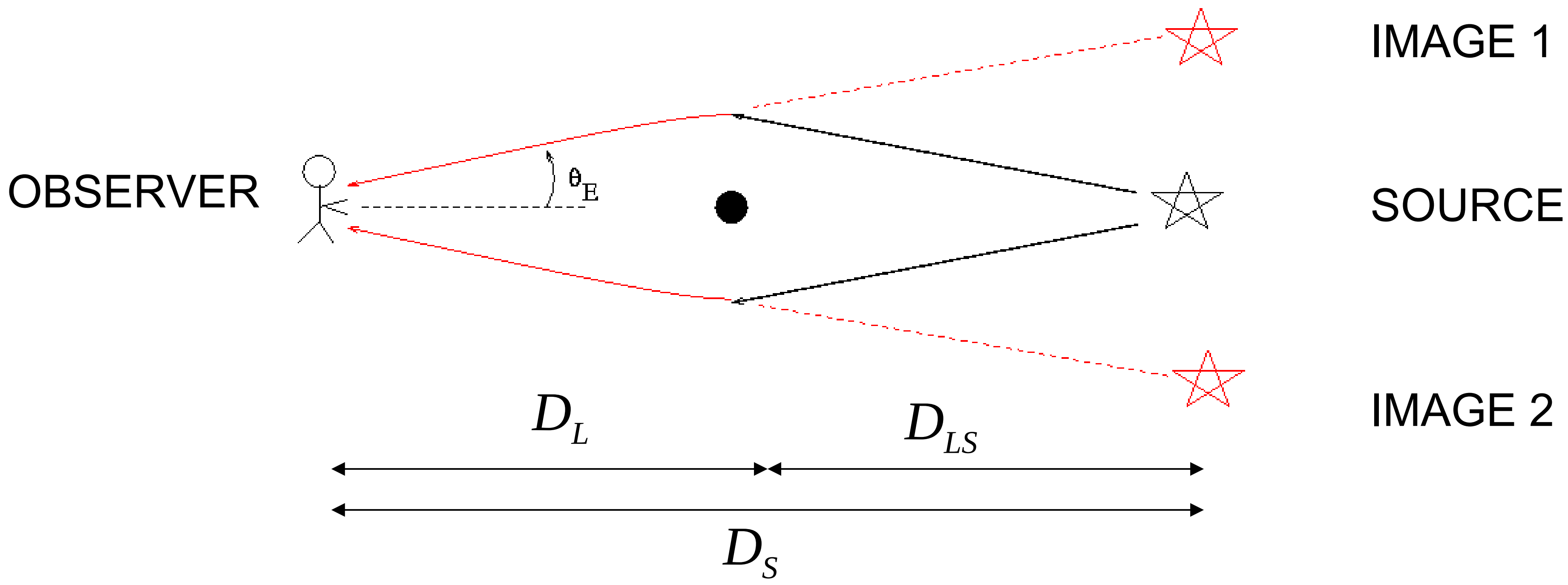

- Gravitational field
- Mass – deflects the light ray
- Larger mass => larger deflection angle

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



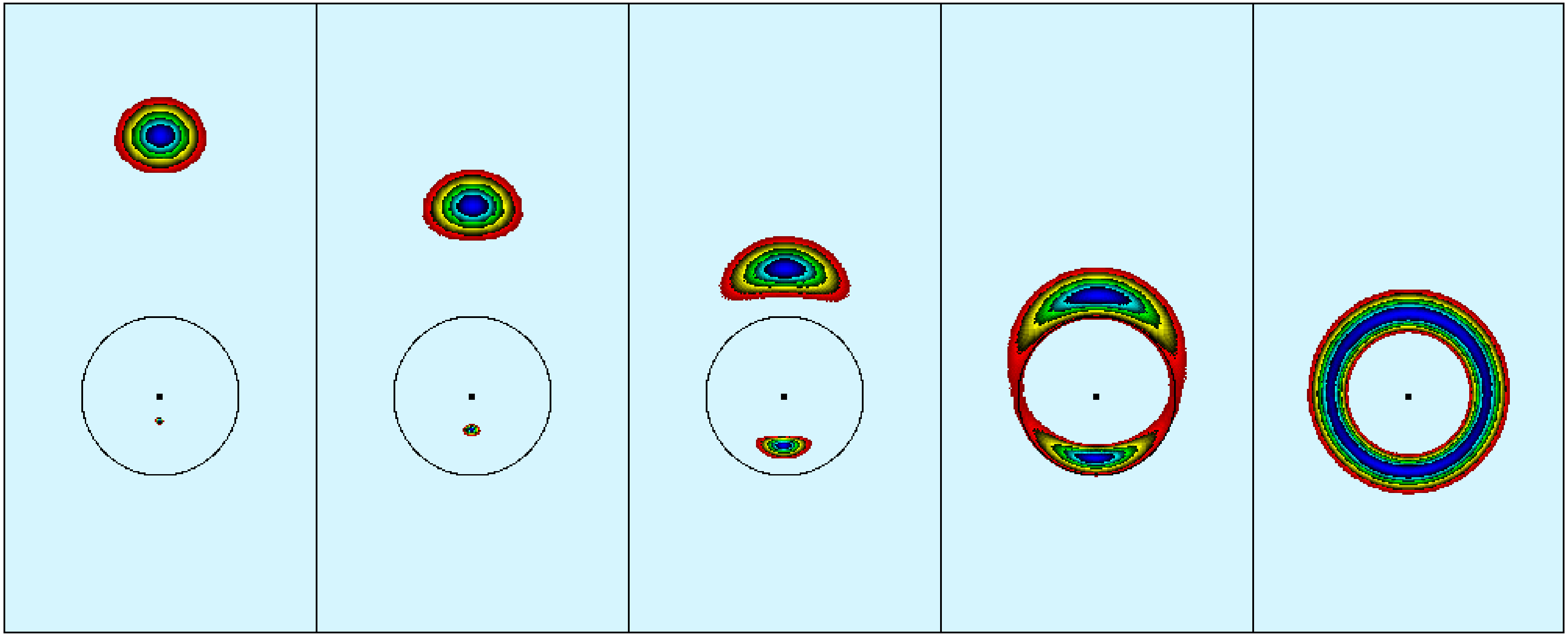
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

# Single Point Mass Lens

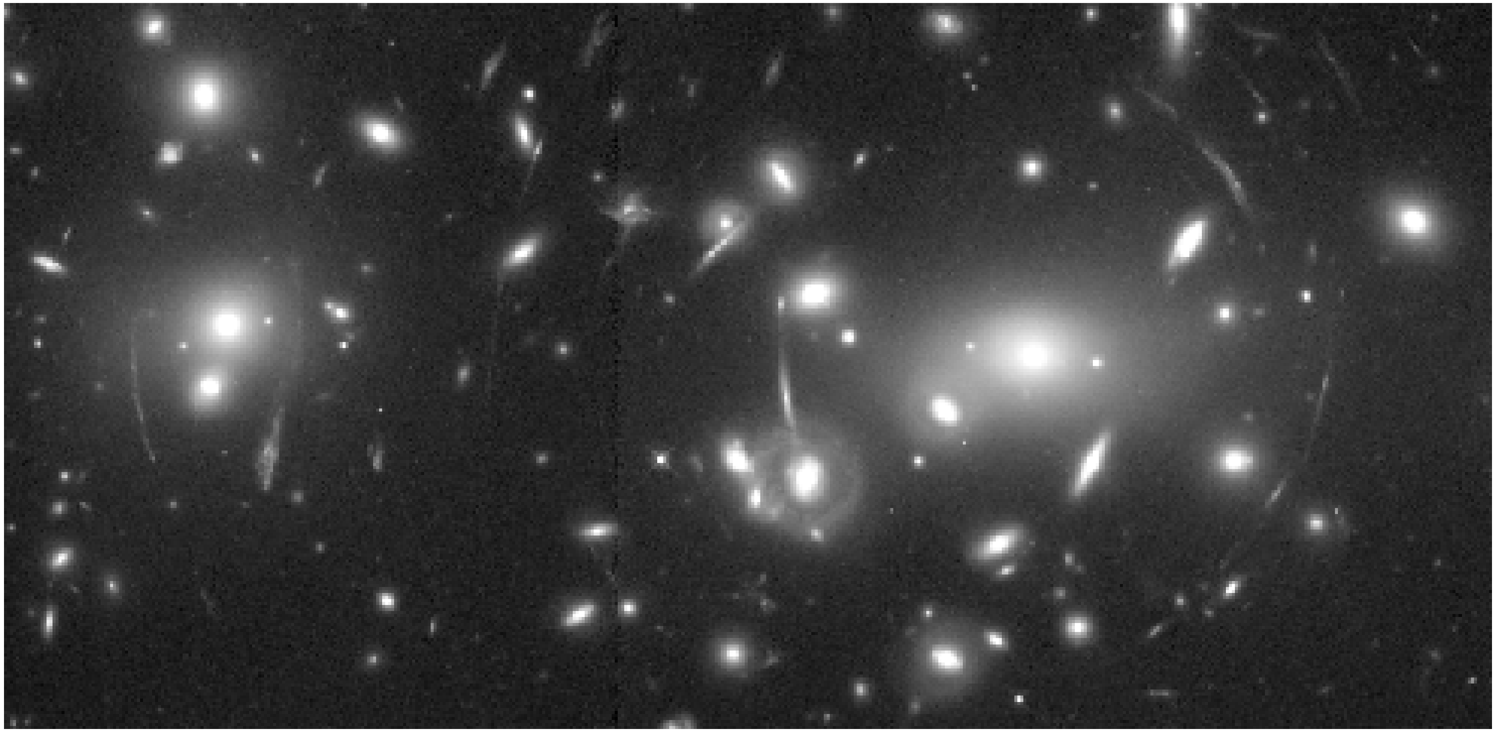


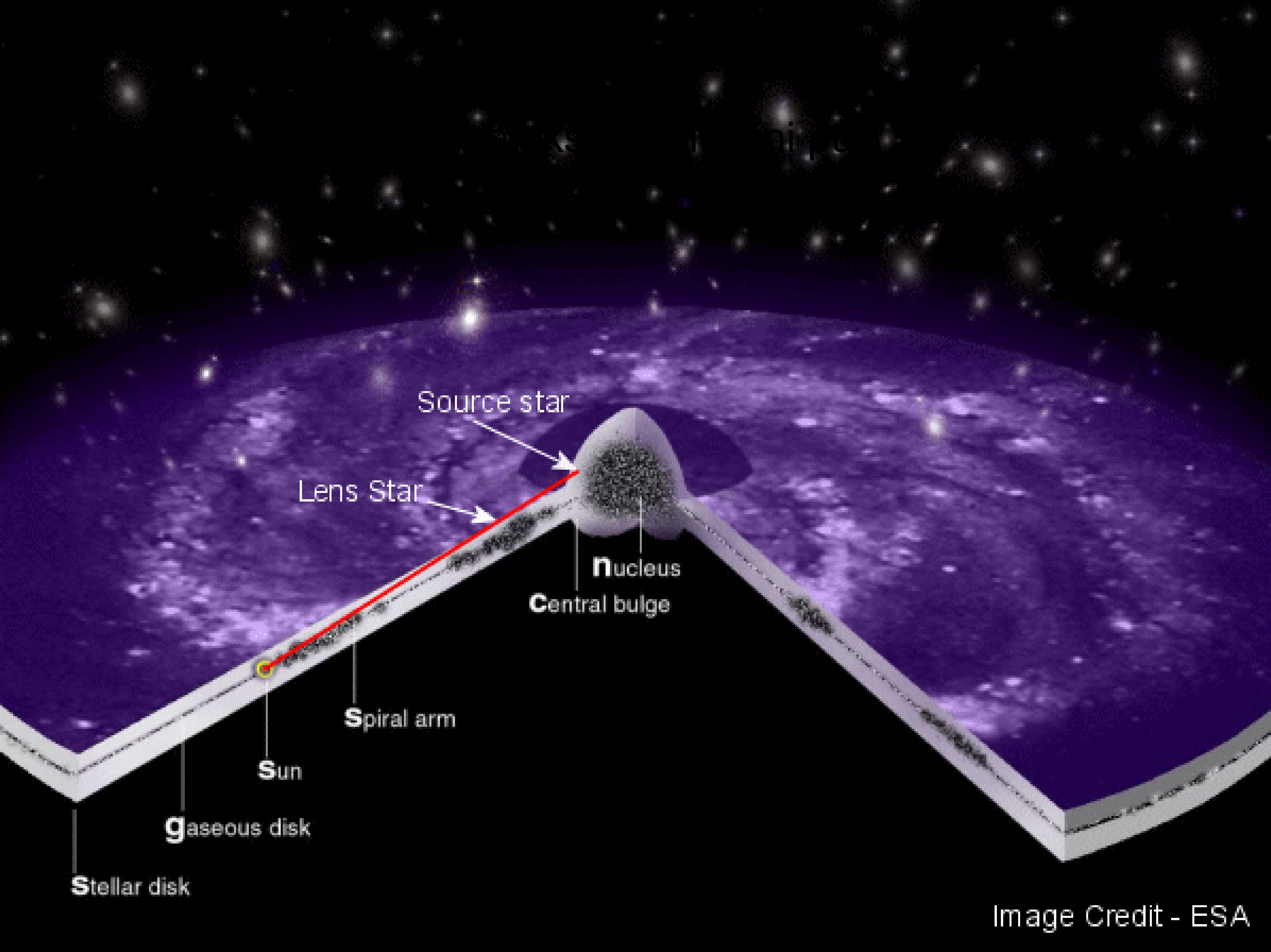

Einstein radius: $$R_0 = \sqrt{\frac{4GM_{tot}D_{LS}}{c^2 D_L D_S}}$$

# Einstein ring



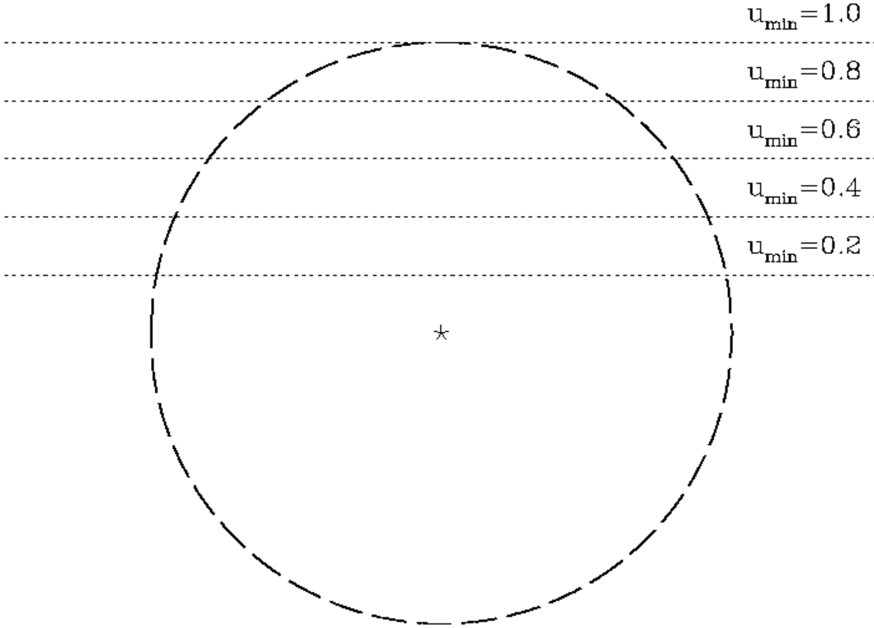
# Cluster of galaxies Abell 2218 as a gravitational lens




Source star
Lens Star
nucleus
Central bulge
Spiral arm
Sun
gaseous disk
Stellar disk
Image Credit - ESA

# Microlensing

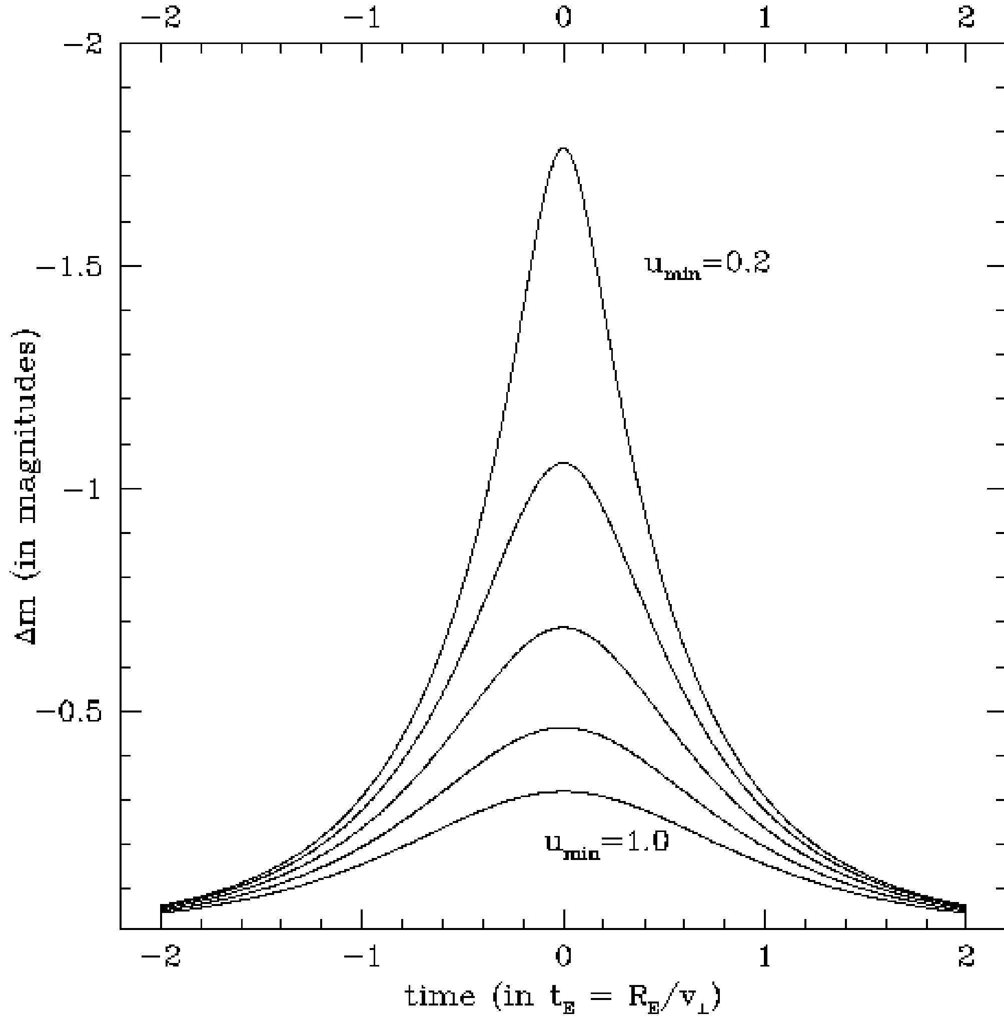
- the source and the images cannot be resolved
 (resolution of the image is larger than the Einstein ring)
- image fluxes are added to the source flux
- **Magnification** (amplification)




Magnification:

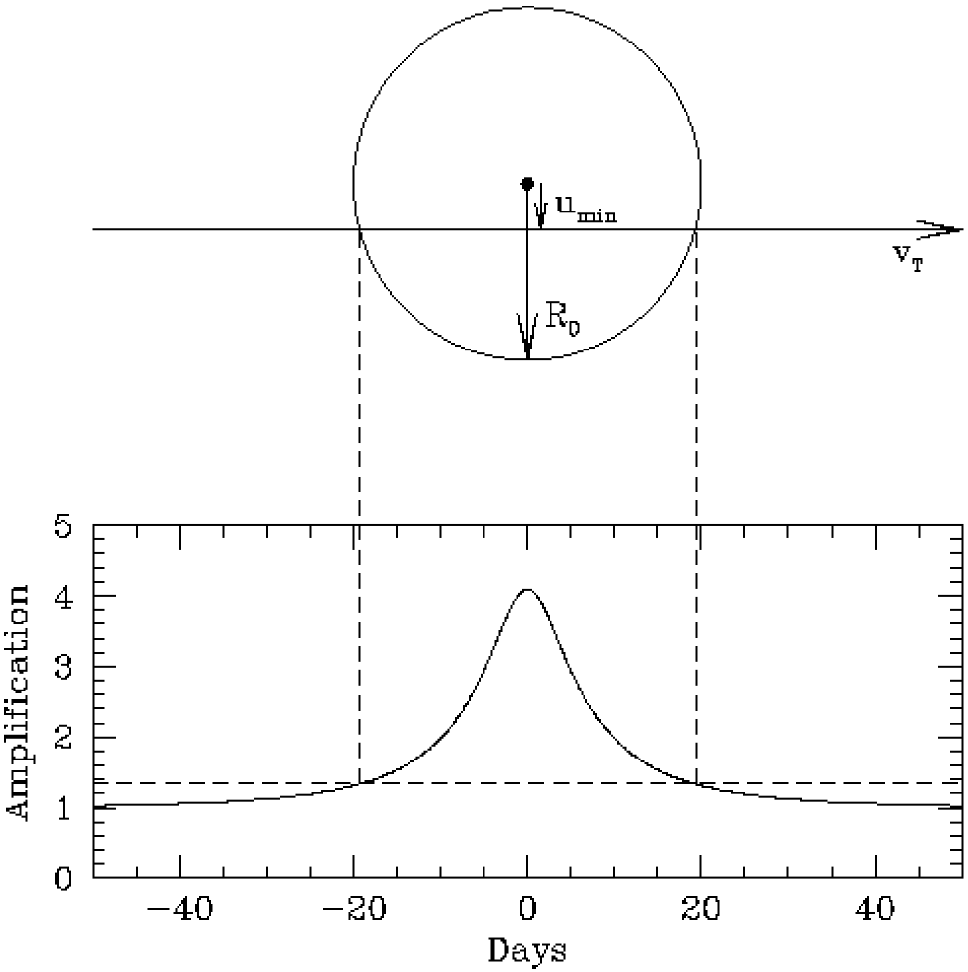
$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

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




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

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

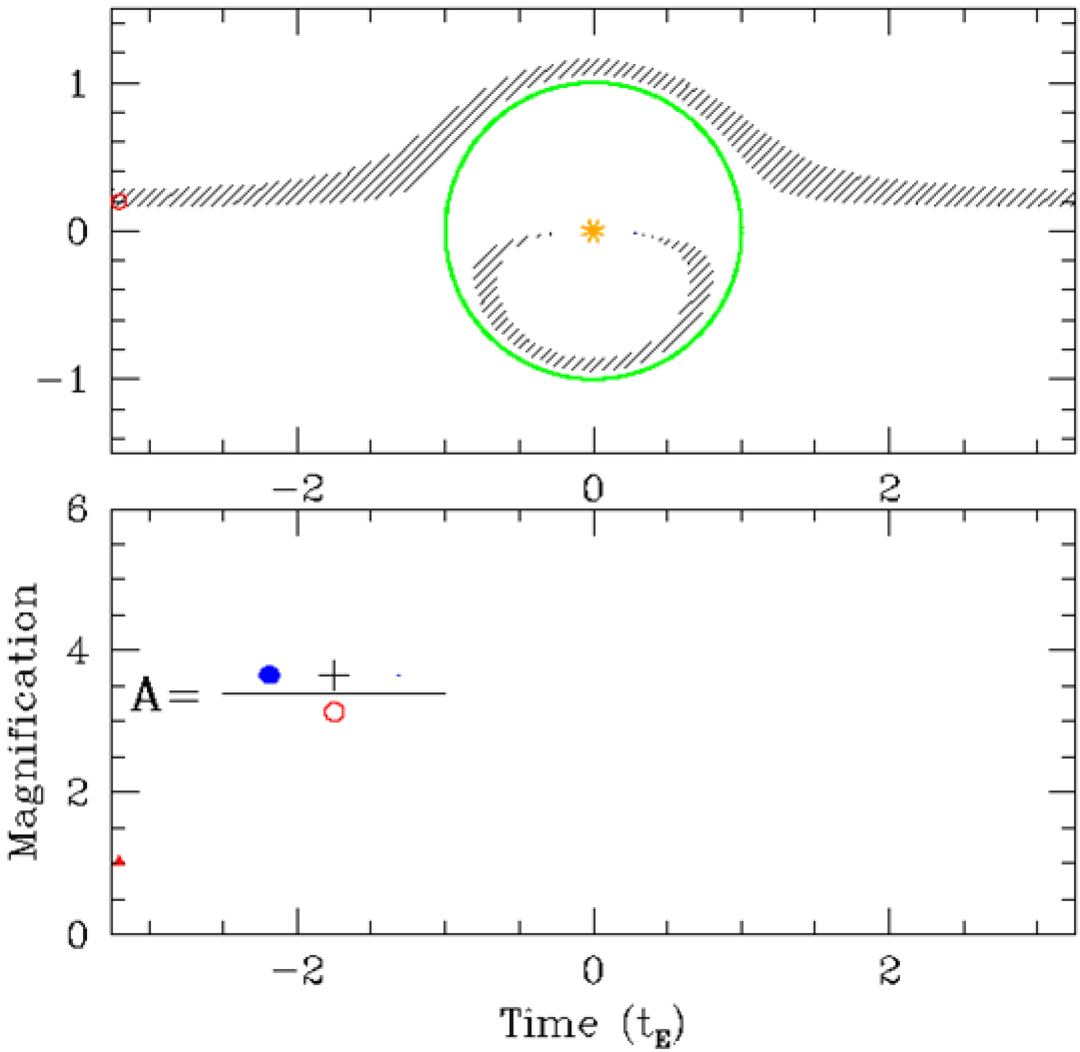



Einstein crossing time:

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

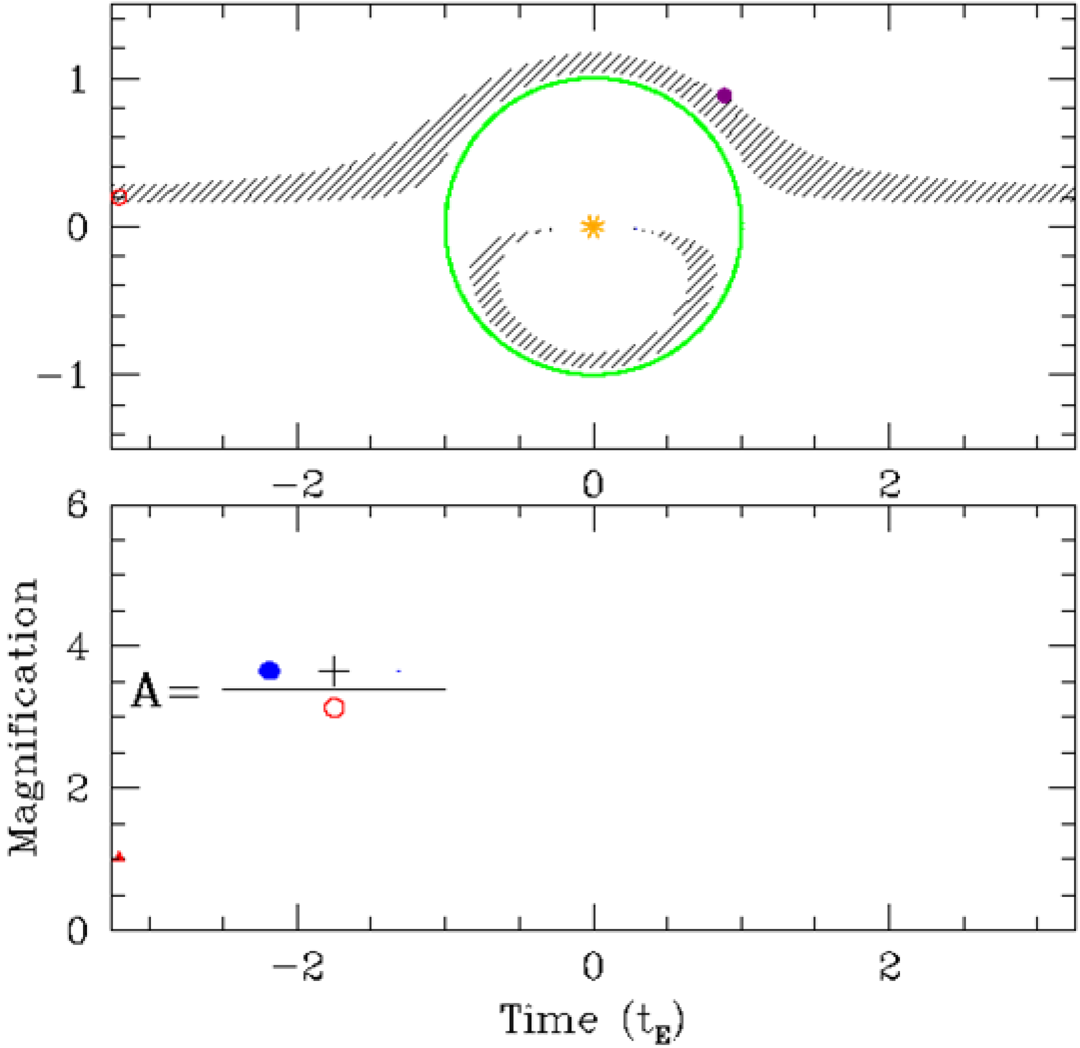
Light curve:
change of brightness with time

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

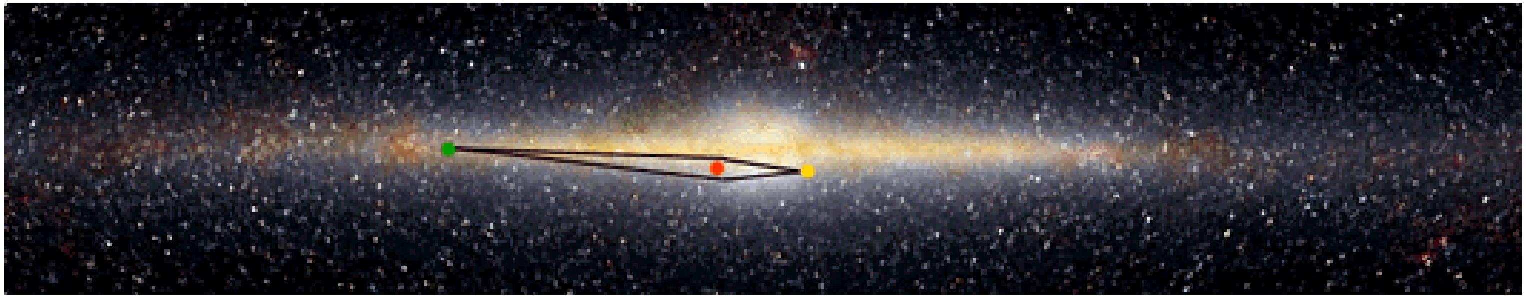



**Animation: © Scott Gaudi**

***Source*** **– 1 star**
***Lens*** **– star + planet**



# Microlensing towards the Galactic Bulge



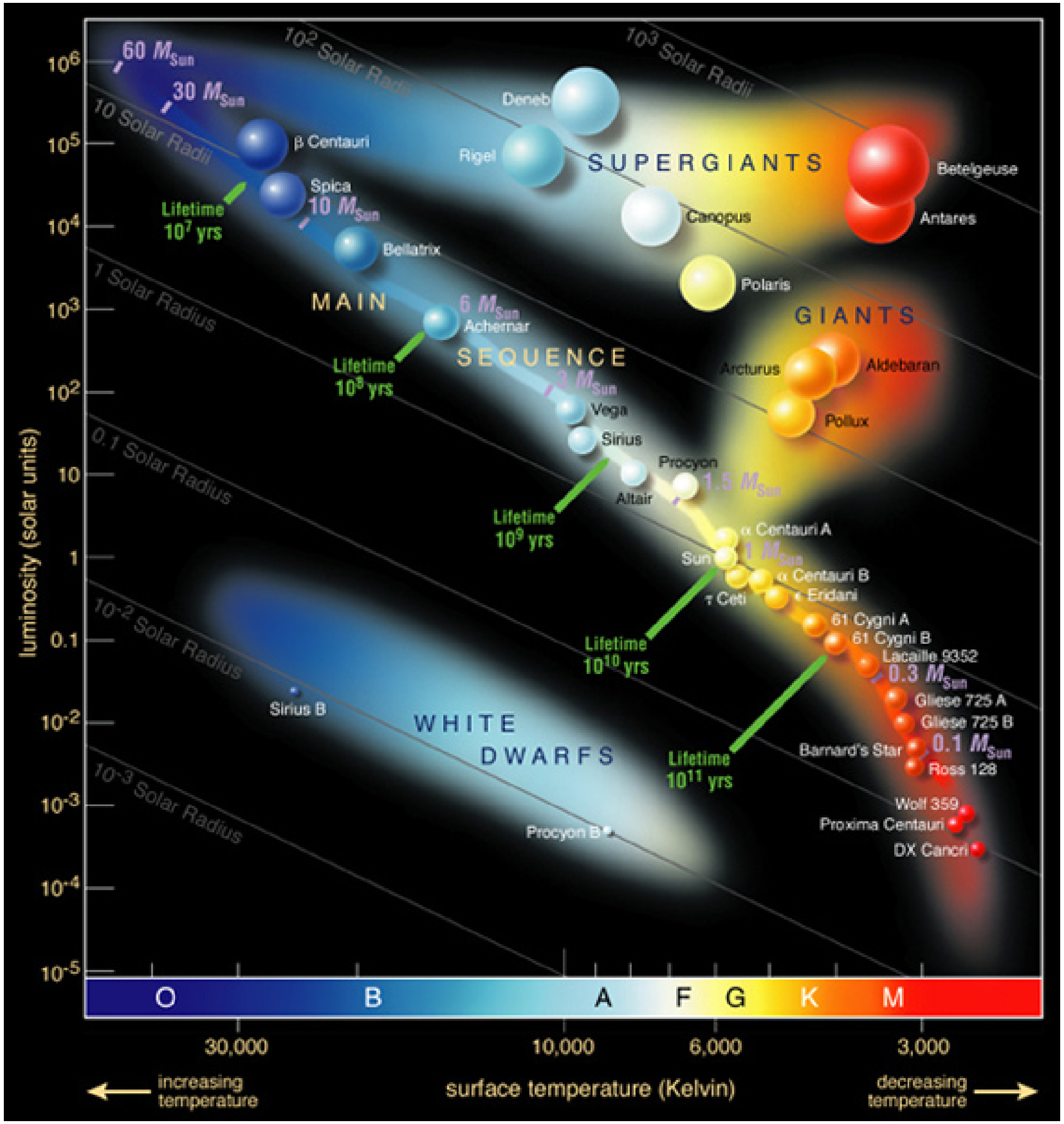
- Paczynski: monitoring stars in LMC (detection of brown dwarfs or Jupiter like objects)

- Monitoring the Galactic Bulge – known population

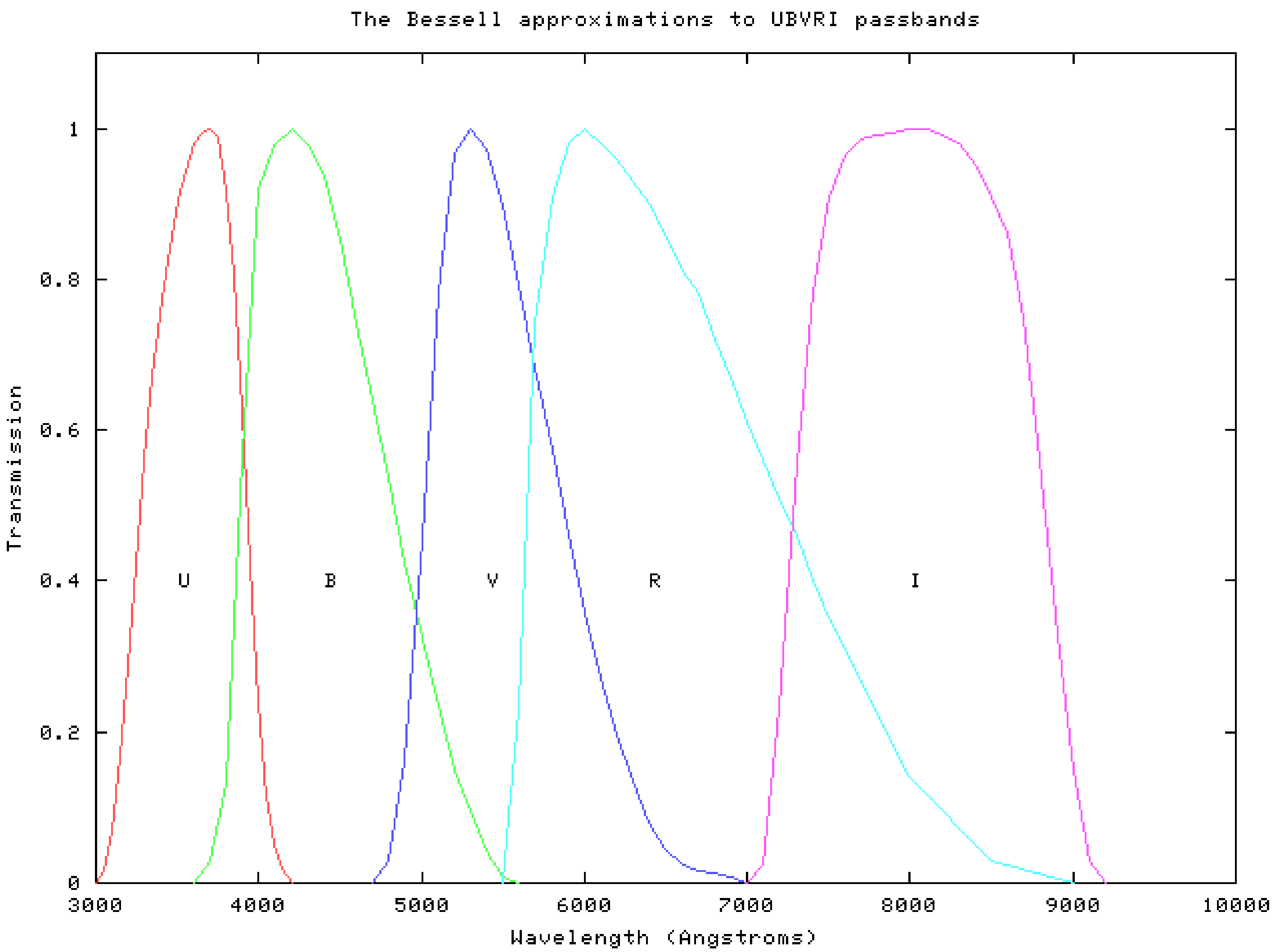
$$D_L \approx 5.0 - 6.0 kpc, D_S \approx 6.0 - 8.5 kpc$$

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

# HR diagram (spectral types)



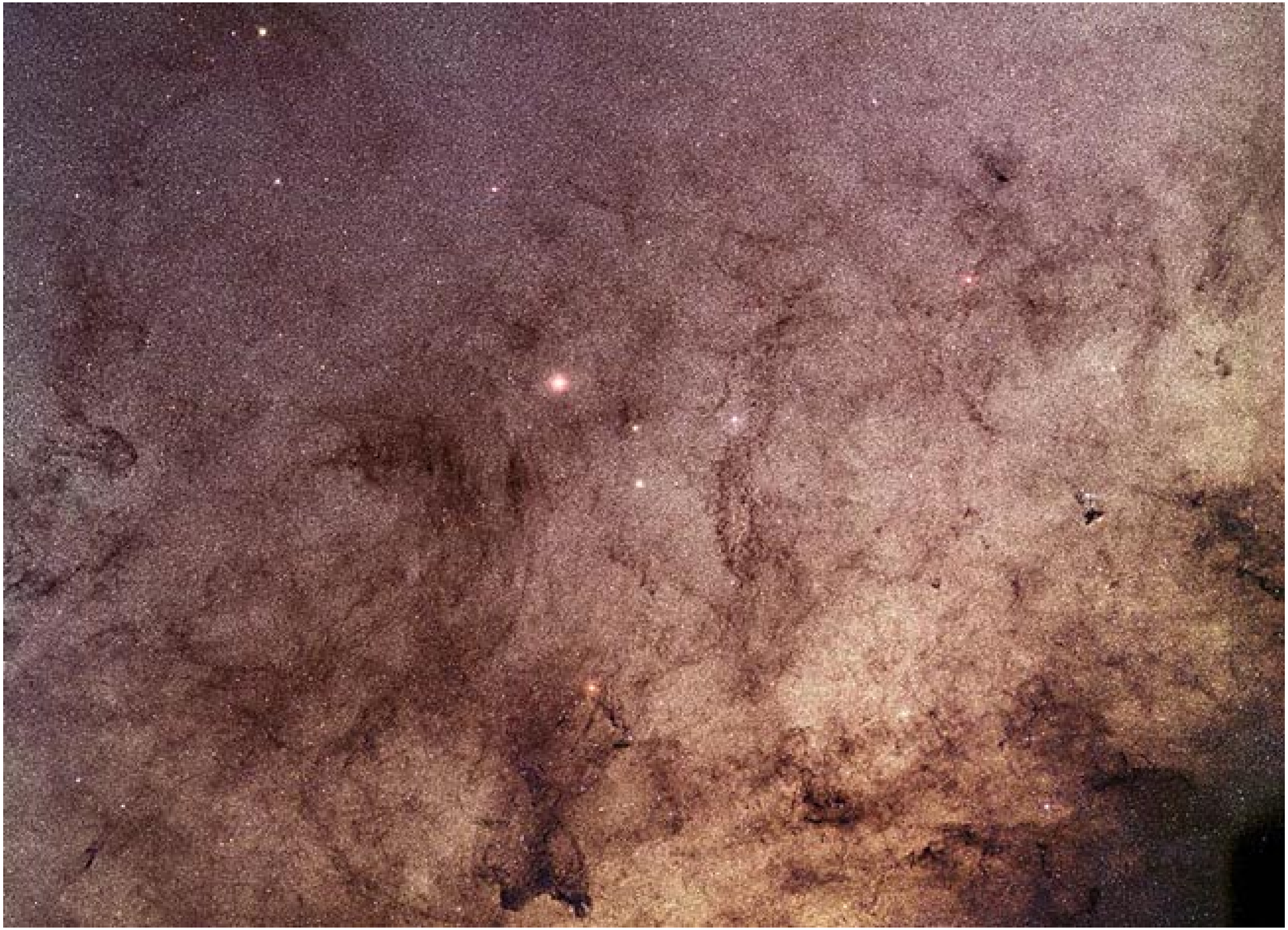
# Photometric system UBVRI



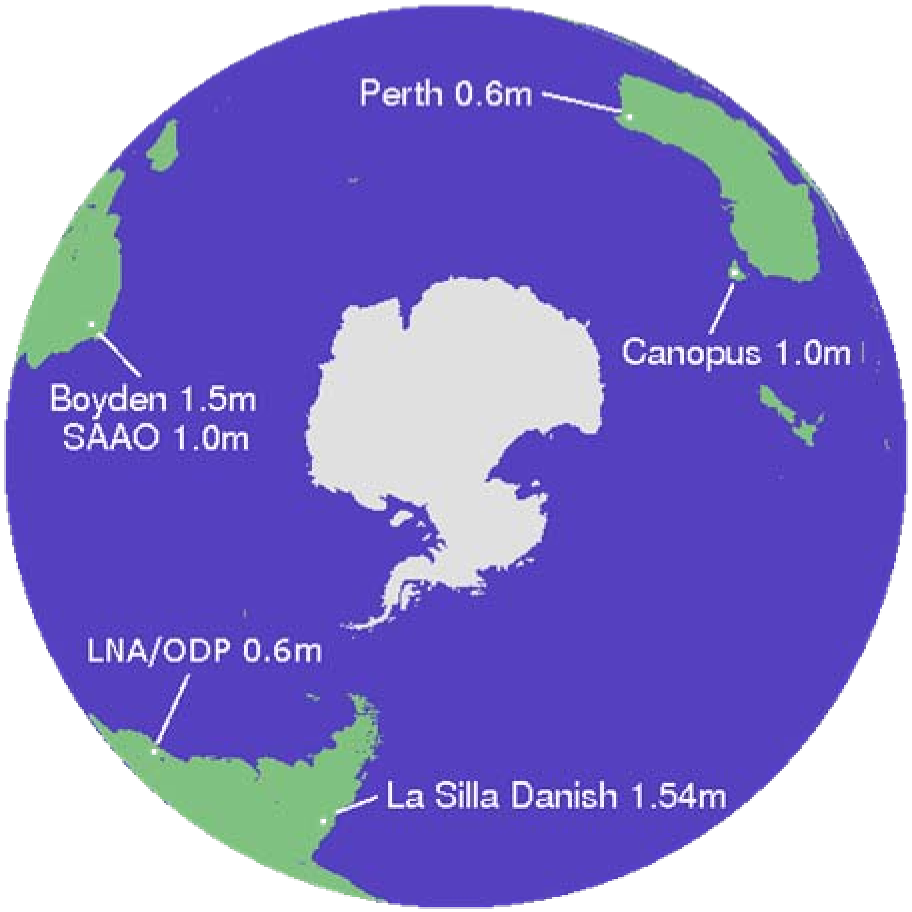
# Galactic center

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

# Baade's window



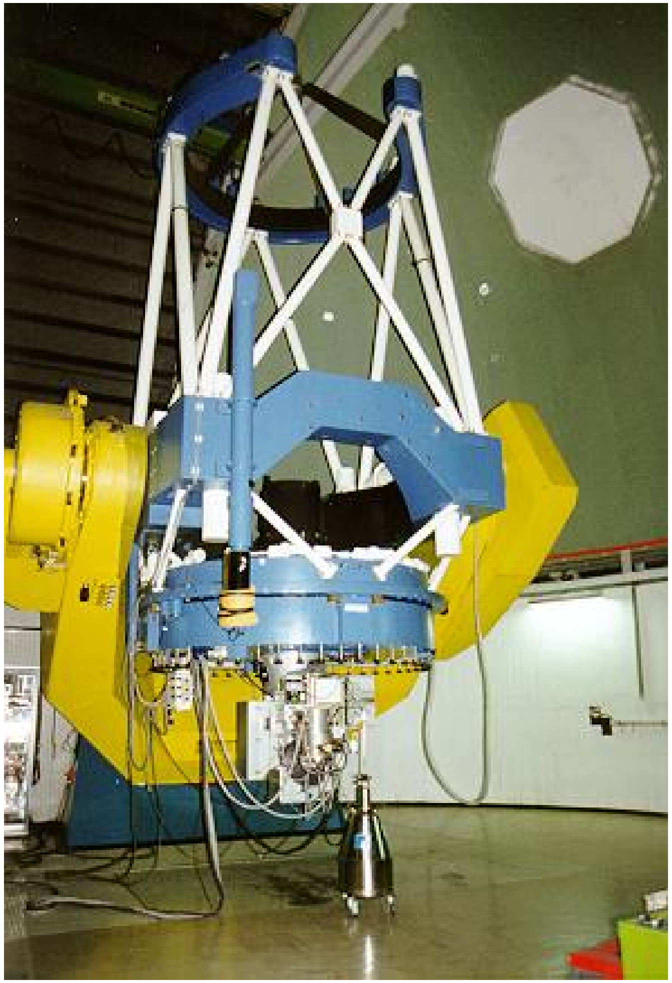
# Microlensing surveys



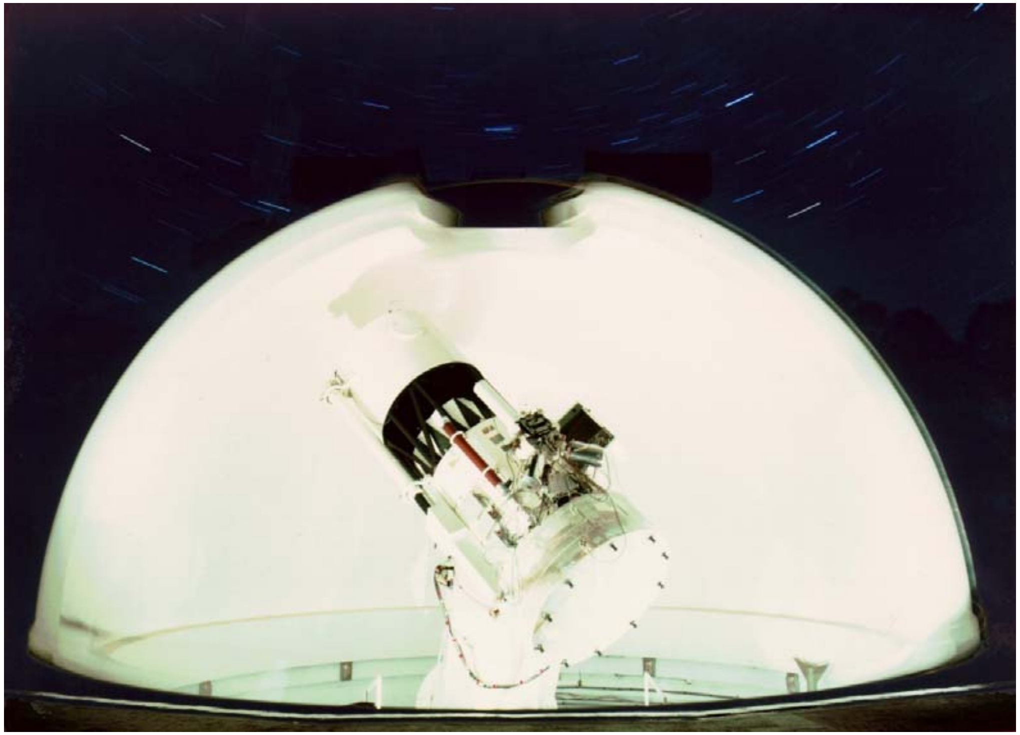

**OGLE** and **MOA:**
Wide-field monitoring, alerts

**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



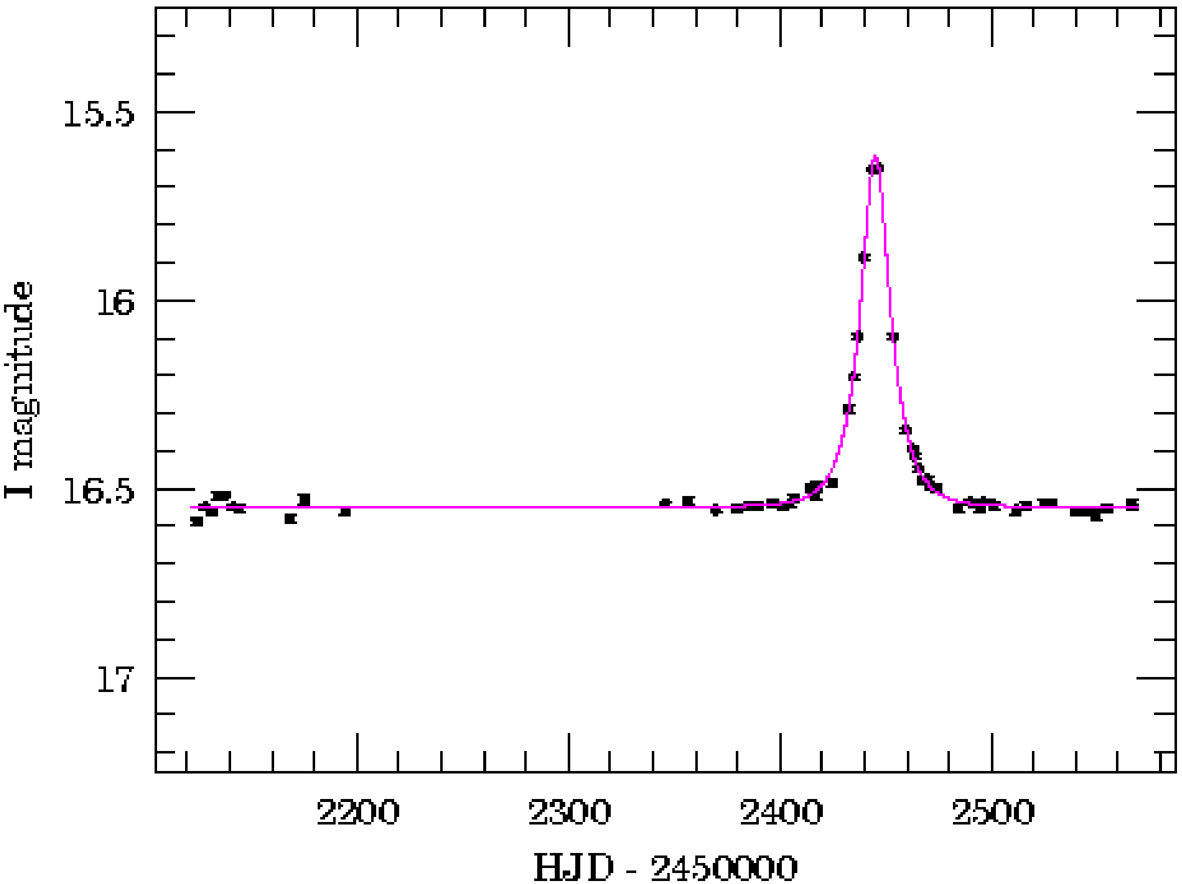
Tasmania (Australia): 1.0 m

La Silla Observatory(Chile)

2400m

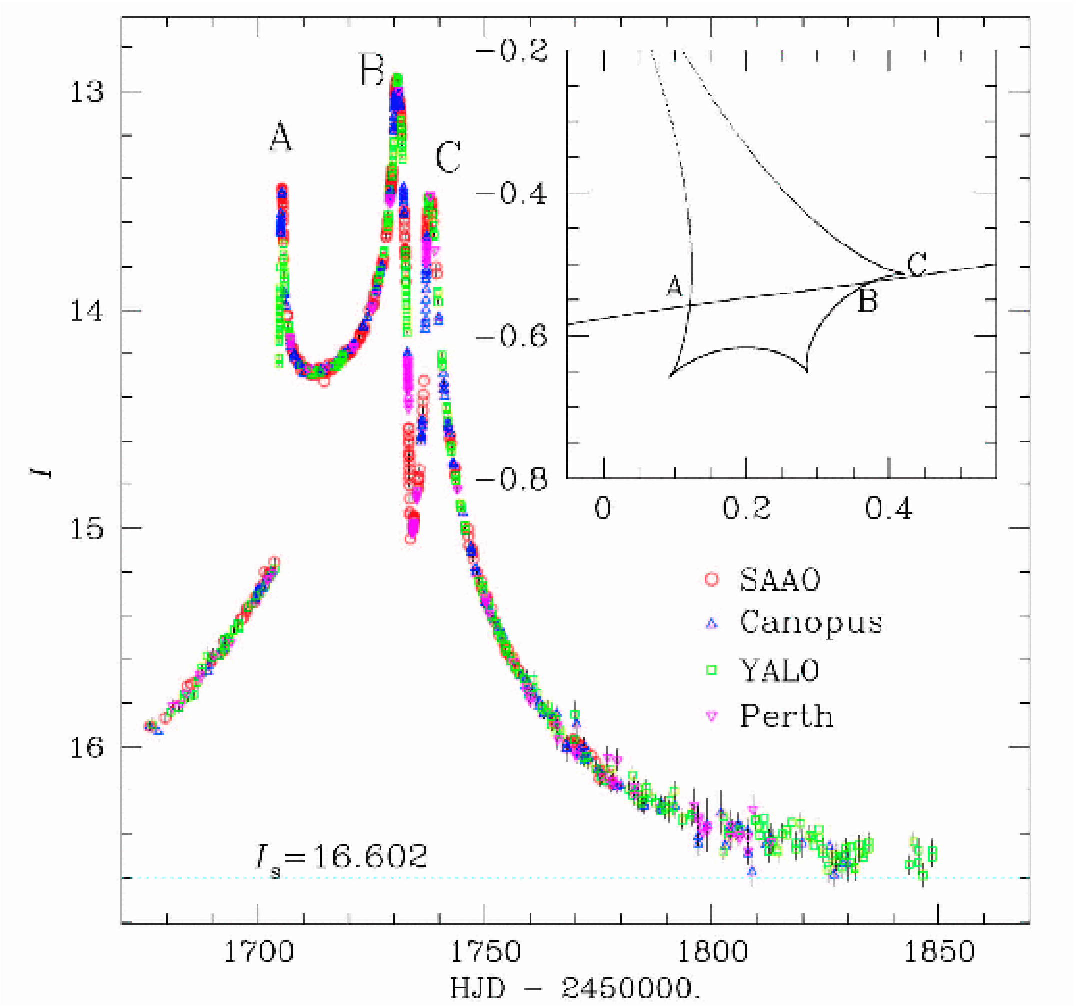
Atacama desert (less problems due to the Earth‘s atmosphere)

# Single lens – single source light curve




OGLE-2002-BLG-192

# Binary lens – single source light curve

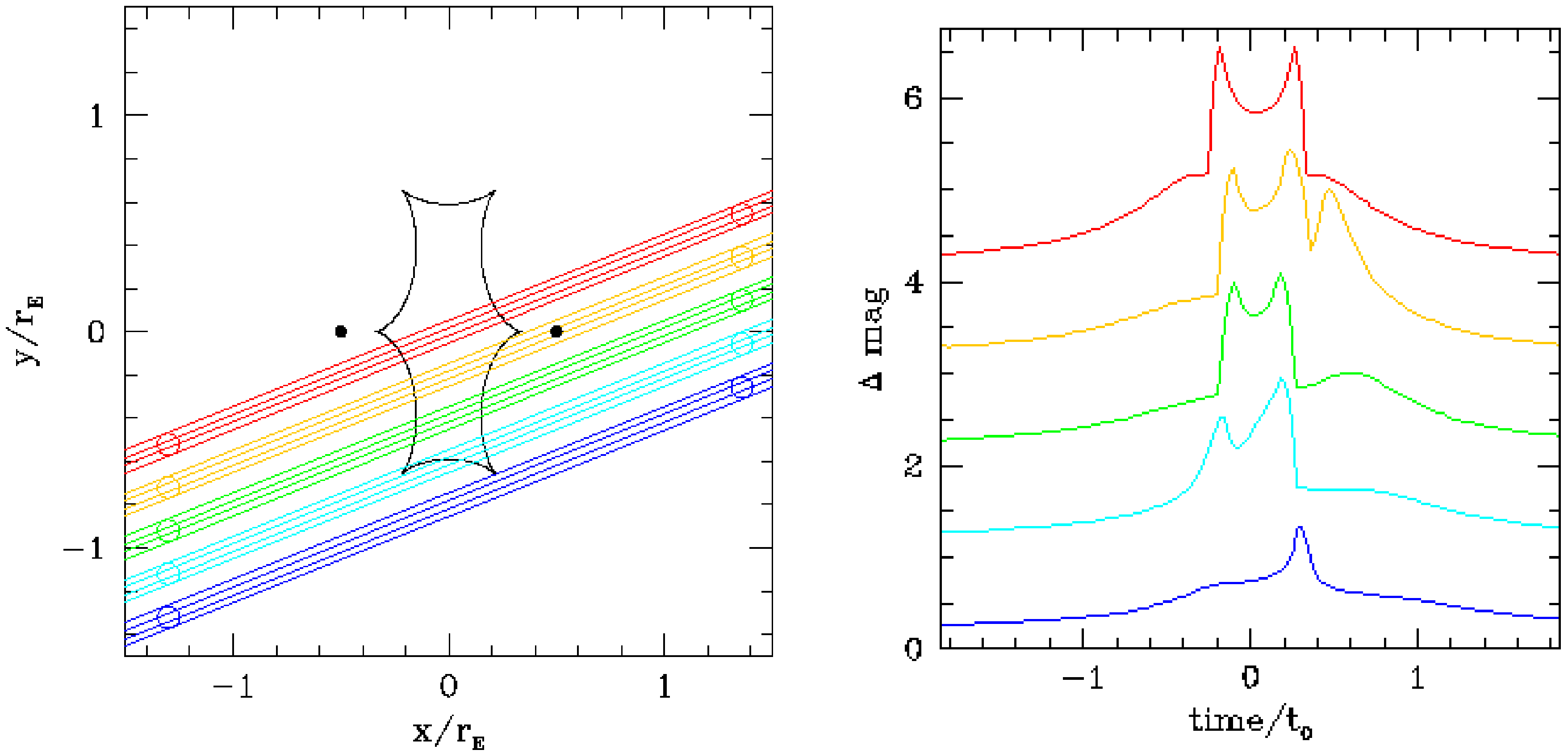



CAUSTIC:

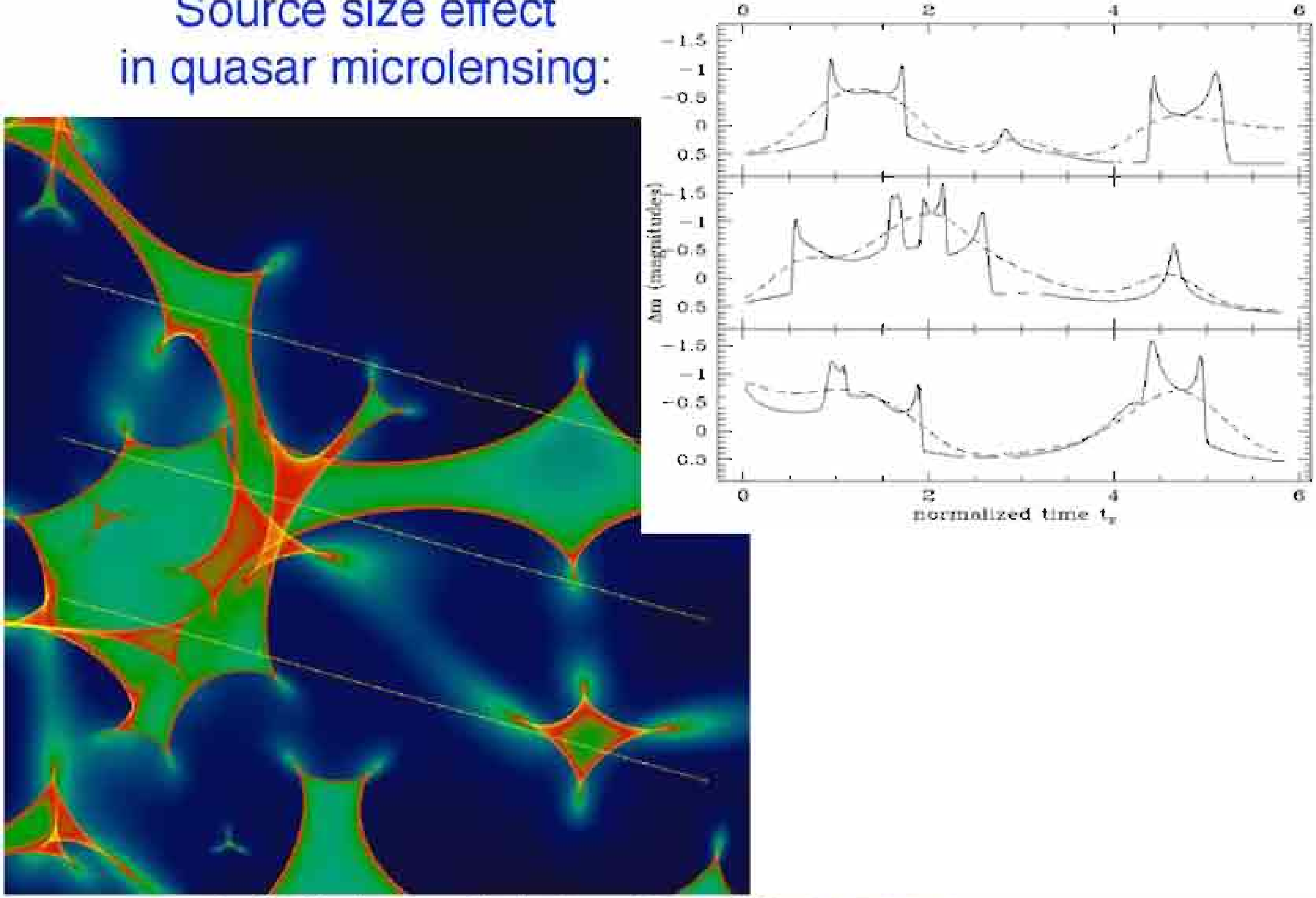
very large magnification

EROS-BLG-2000-5

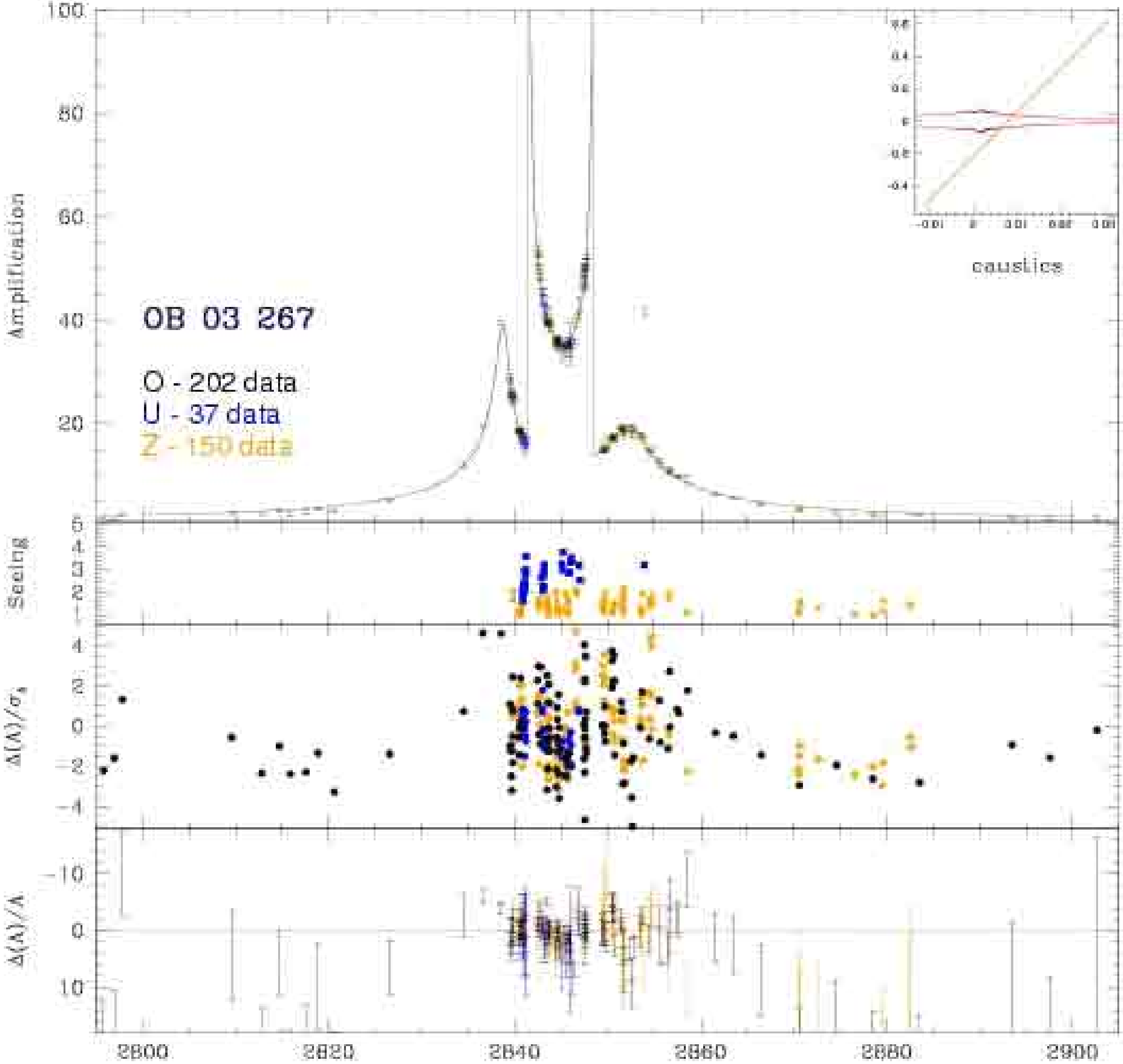
# Binary lens



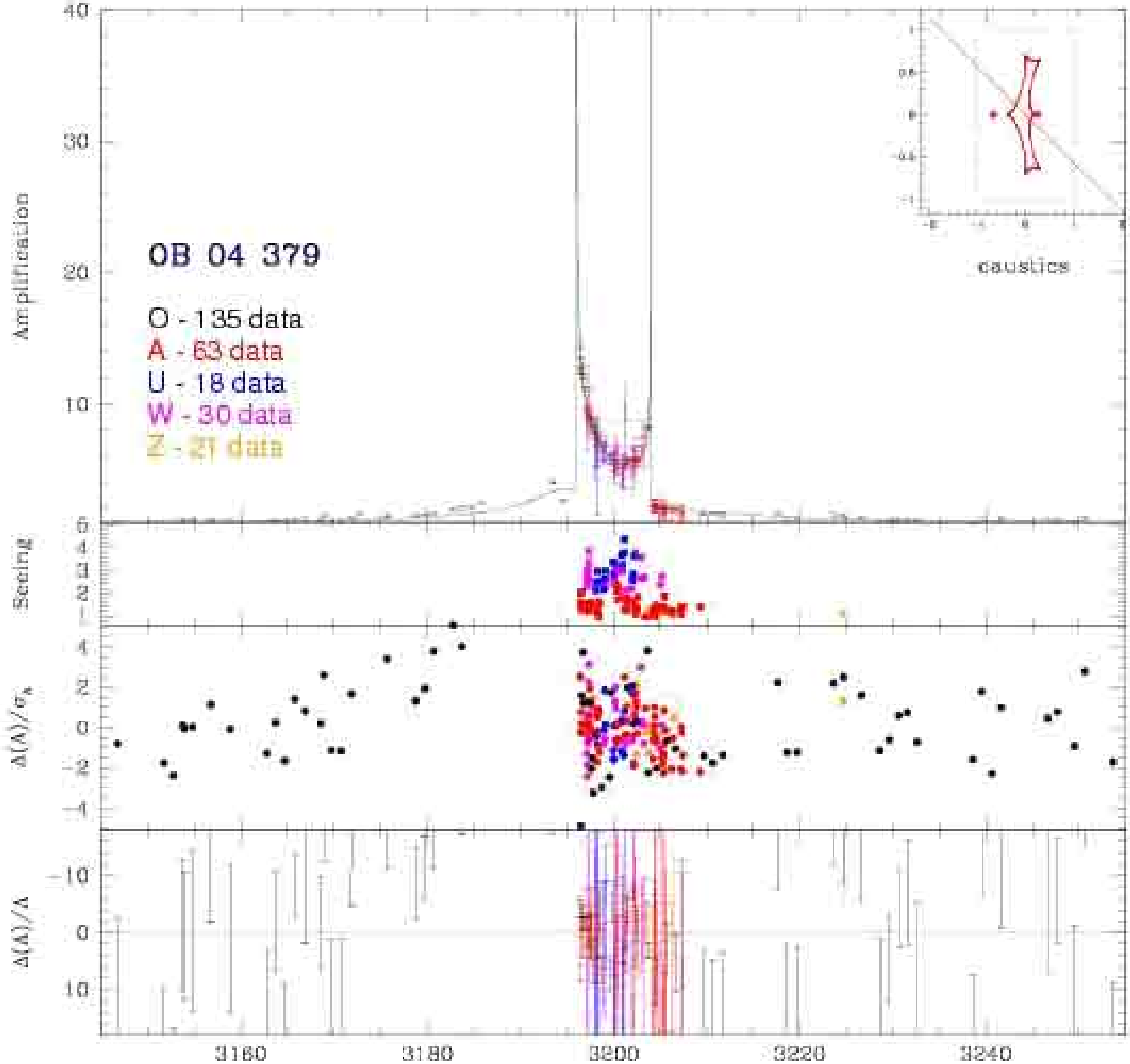
# Source size effect in quasar microlensing:



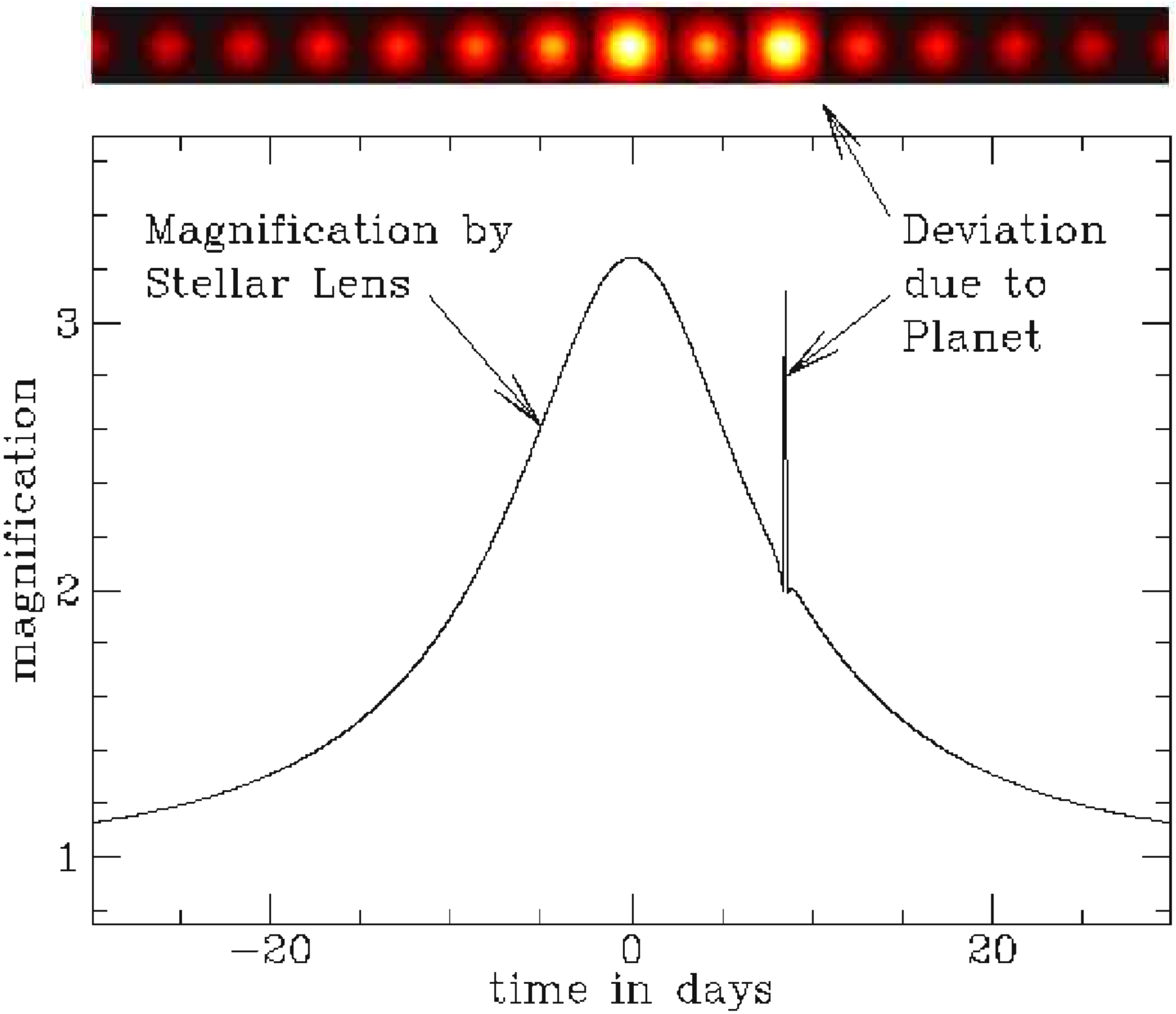

Joachim Wambsganss: "Microlensing and Compact Objects in Galaxies"
at: "Applications of Gravitational Lensing", KITP, Santa Barbara, October 4, 2006



OB 03 267
O - 202 data
U - 37 data
Z - 150 data
Amplification
caustics
Seeing
$\Delta(A)/\sigma_A$
$\Delta(A)/A$



OB 04 379
O - 135 data
A - 63 data
U - 18 data
W - 30 data
Z - 21 data
caustics
Amplification
Seeing
Δ(A)/σA
Δ(A)/A

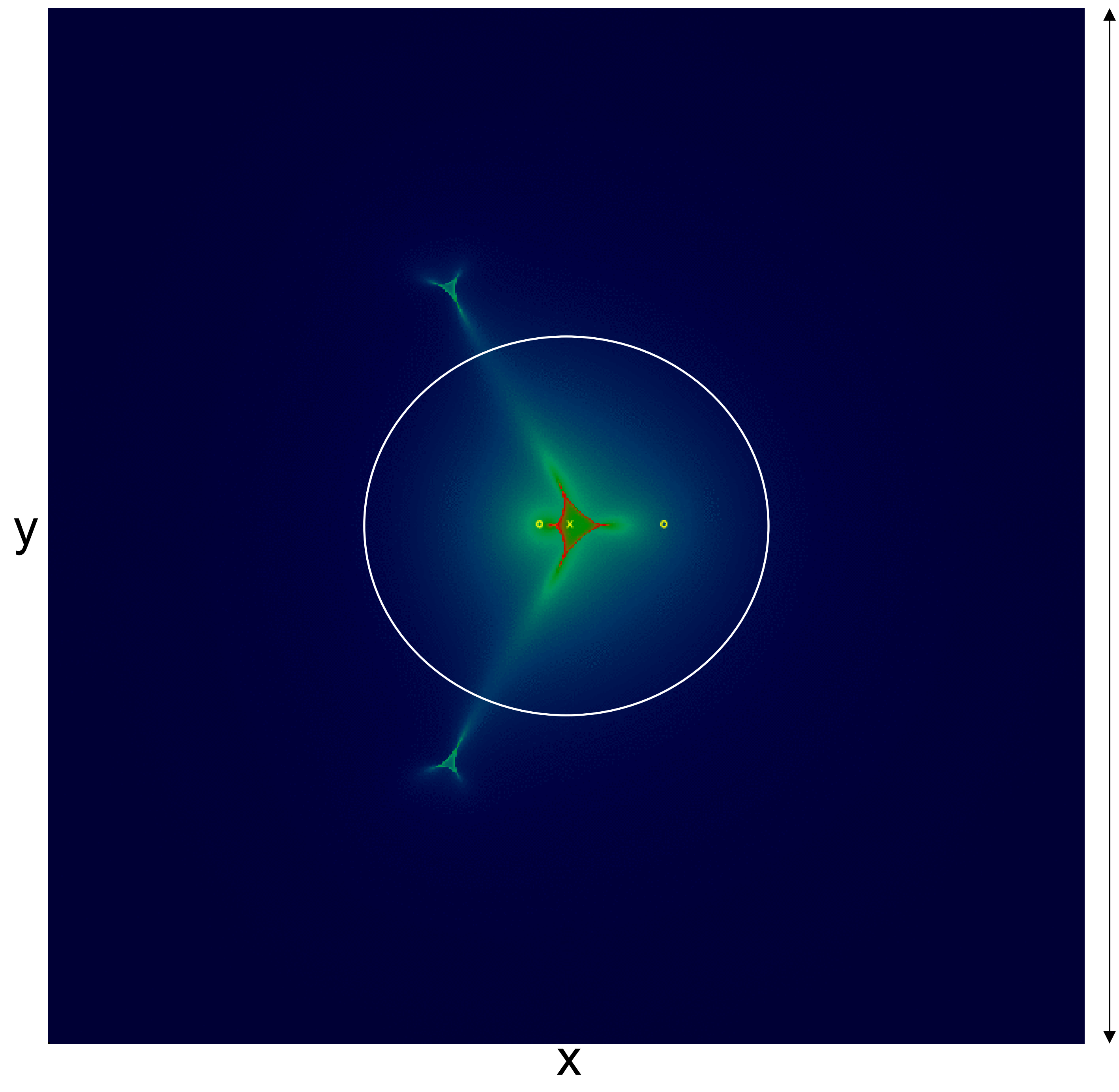


Magnification by
Stellar Lens
Deviation
due to
Planet
magnification
3
2
1
−20
0
20
time in days

# Modeling orbiting binary lenses

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

=> **Magnification patterns**




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

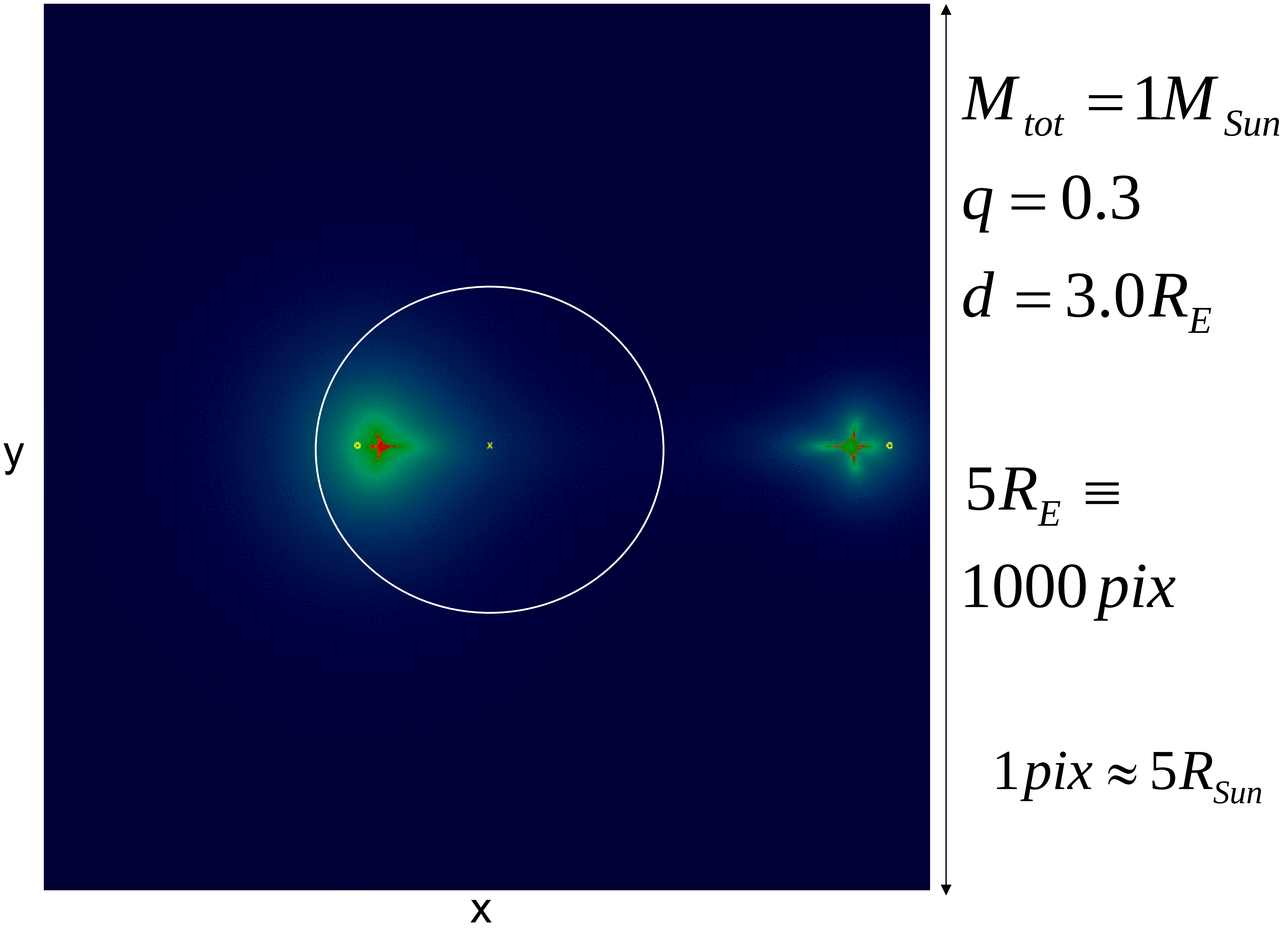
$q = 0.3$

$d = 0.6R_E$

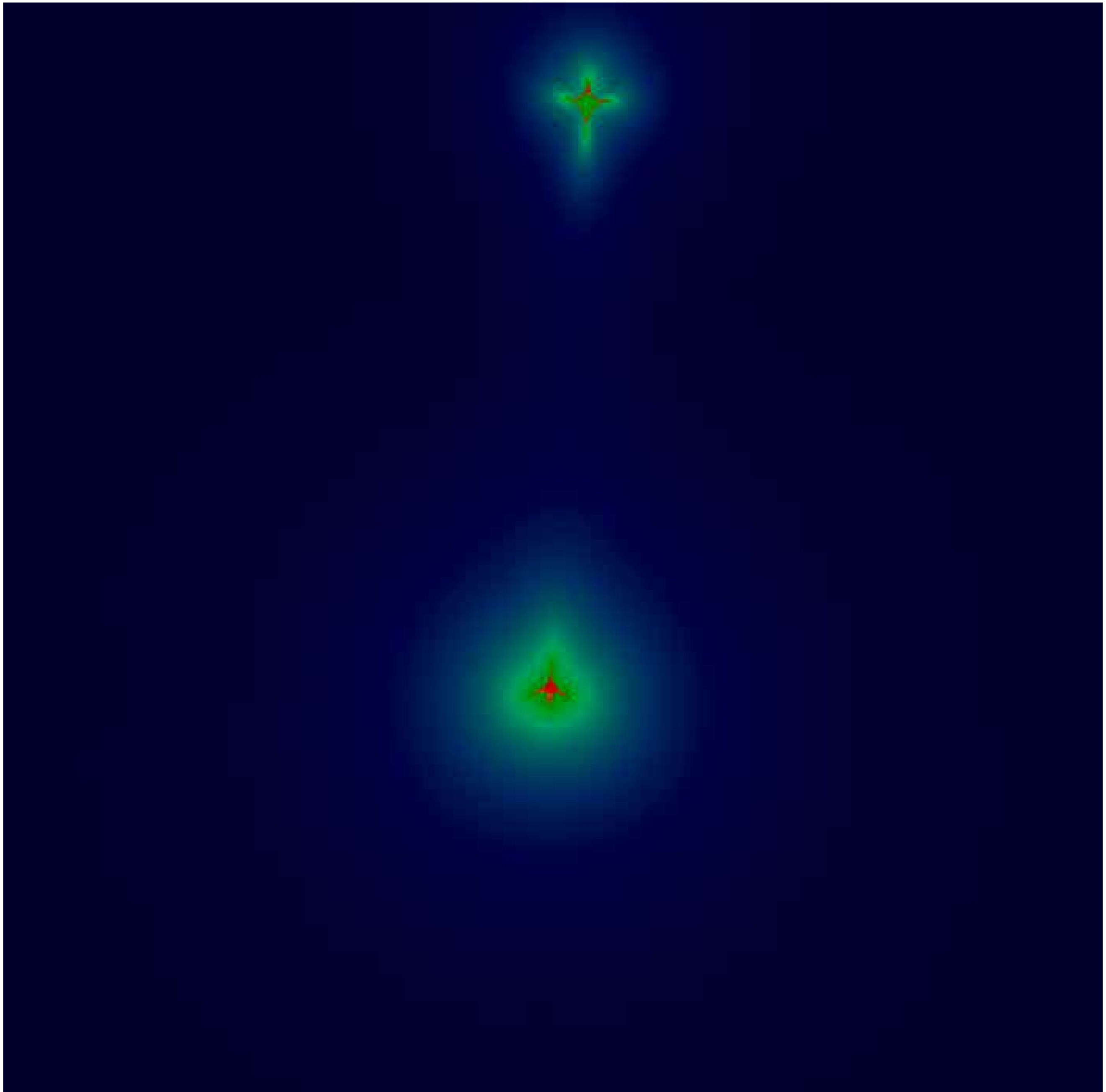
$5R_E \equiv$

$1000\,pix$

$1pix \approx 5R_{Sun}$



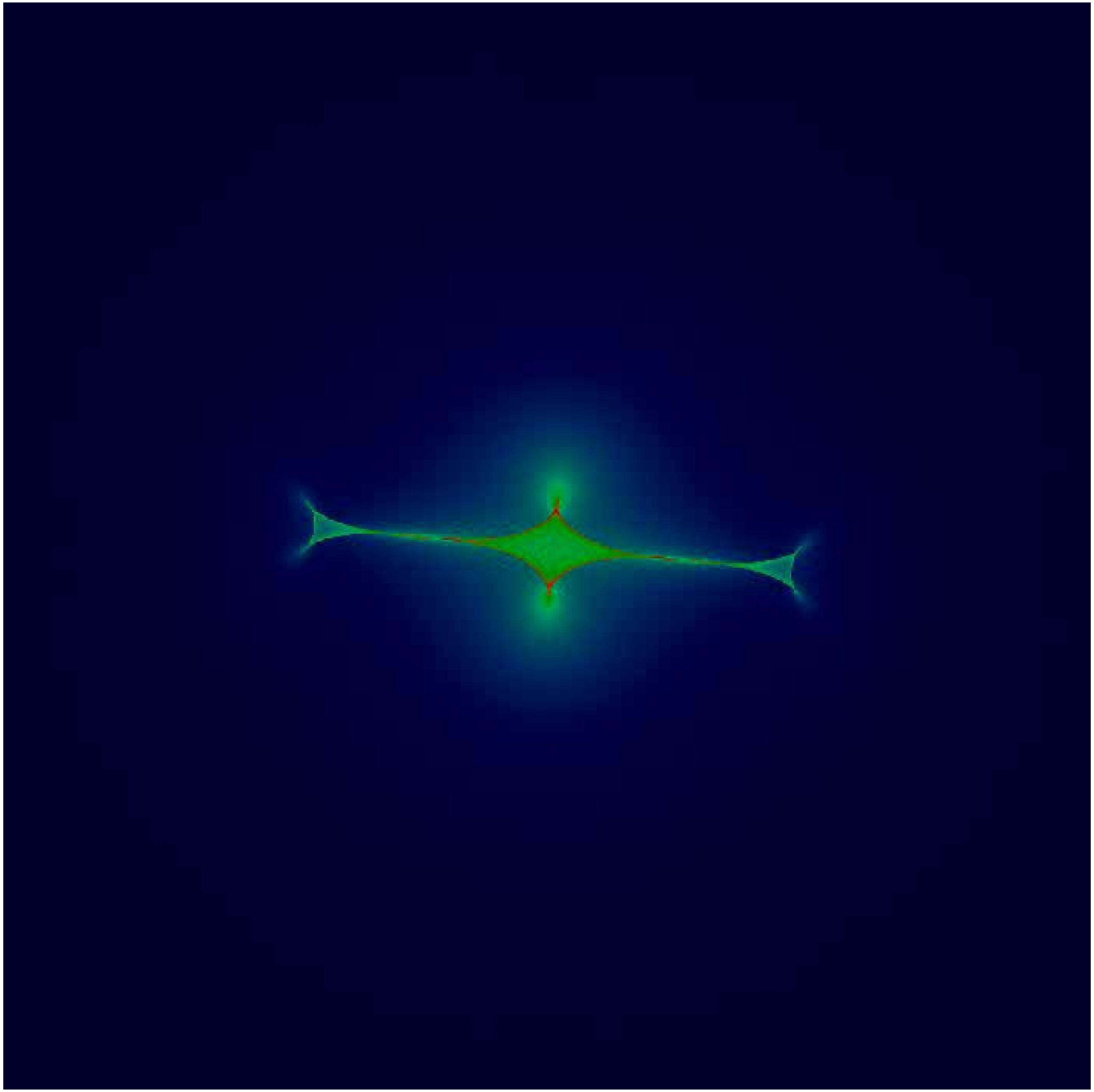
$M_{tot} = 1 M_{Sun}$
$q = 0.3$
$d = 3.0 R_E$
$5 R_E \equiv$
$1000\, pix$
$1 pix \approx 5 R_{Sun}$
y
x



$q = 0.3$

$i = 90^o$

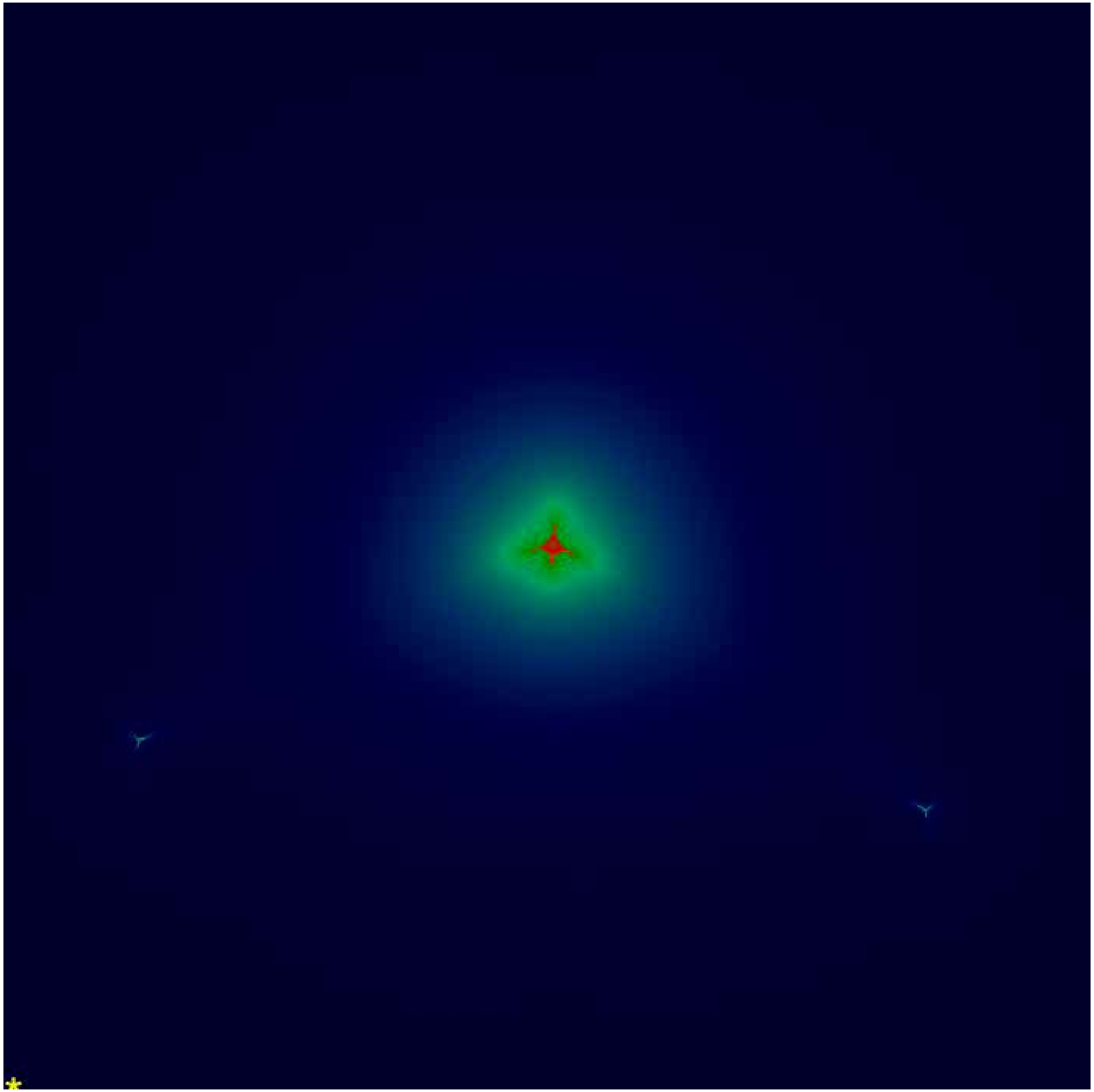
$d = 3R_E$



$q = 1.0$

$i = 45^{\circ}$

$d = 1R_E$



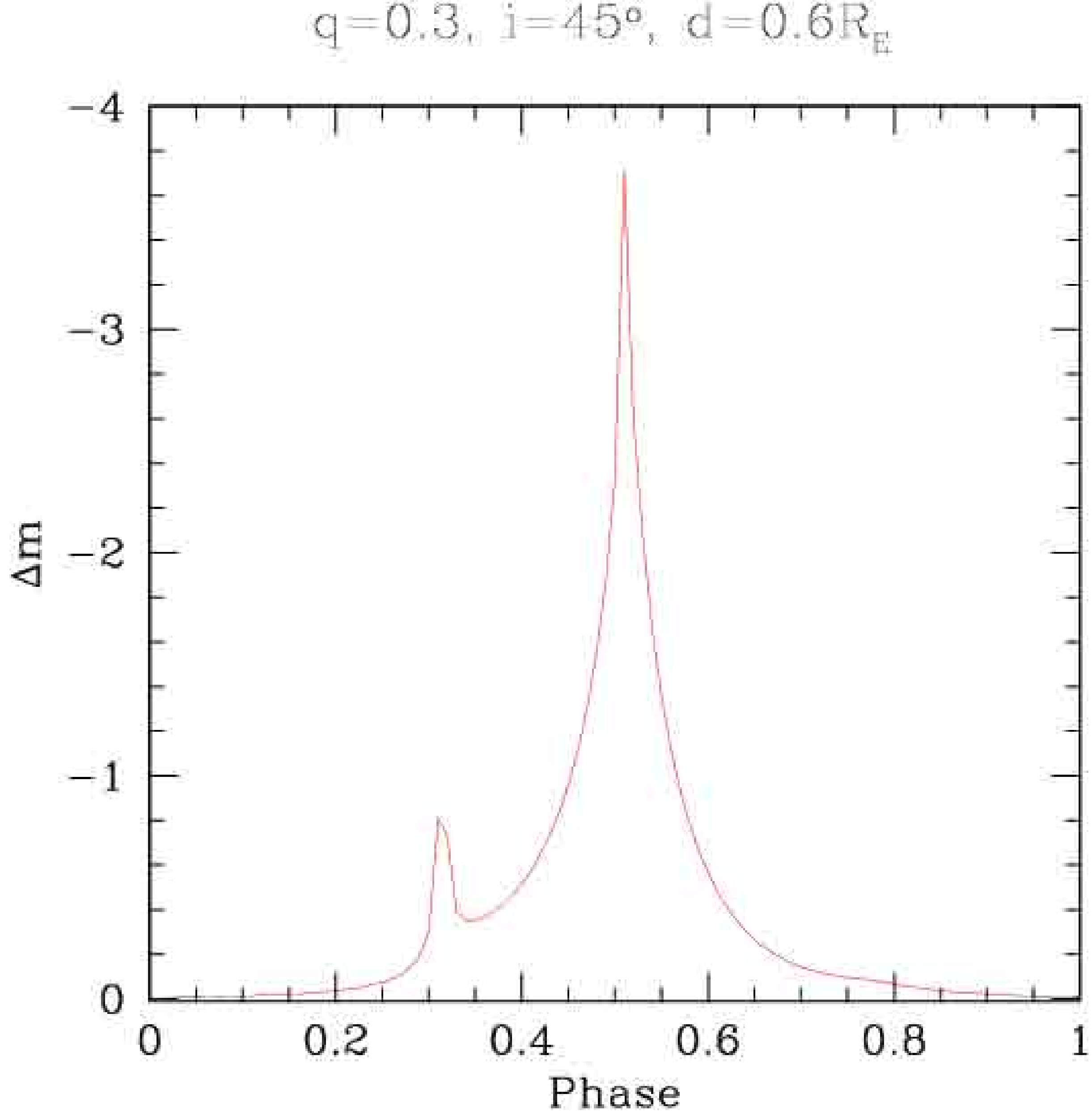
$q = 0.3$

$i = 45^o$

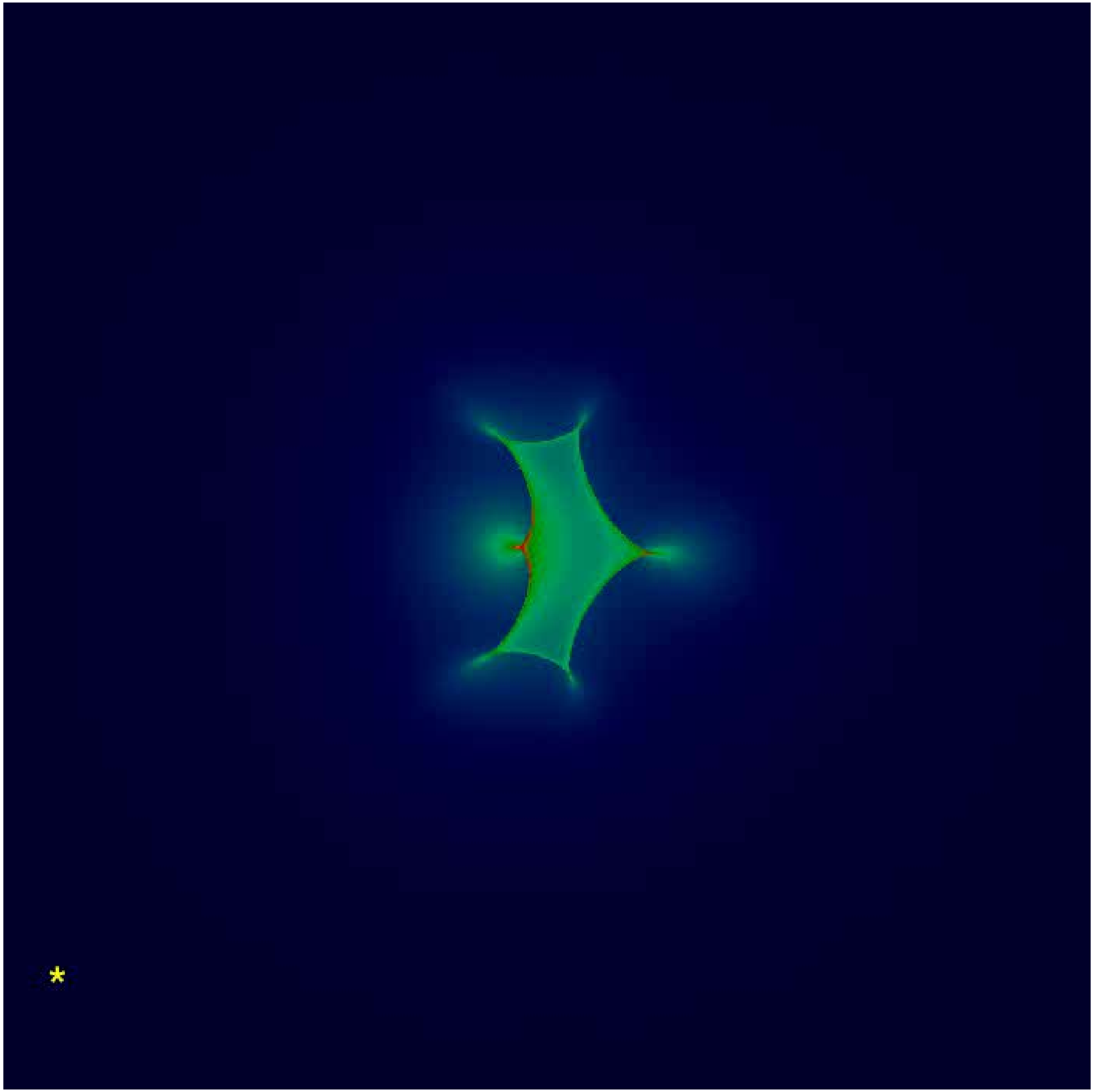
$d = 0.6 R_E$

$P \approx 100 d$

$R_* \approx 10 R_{Sun}$



q=0.3, i=45°, d=0.6R_E
−4
−3
−2
−1
0
Δm
0
0.2
0.4
0.6
0.8
1
Phase



$q = 0.3$

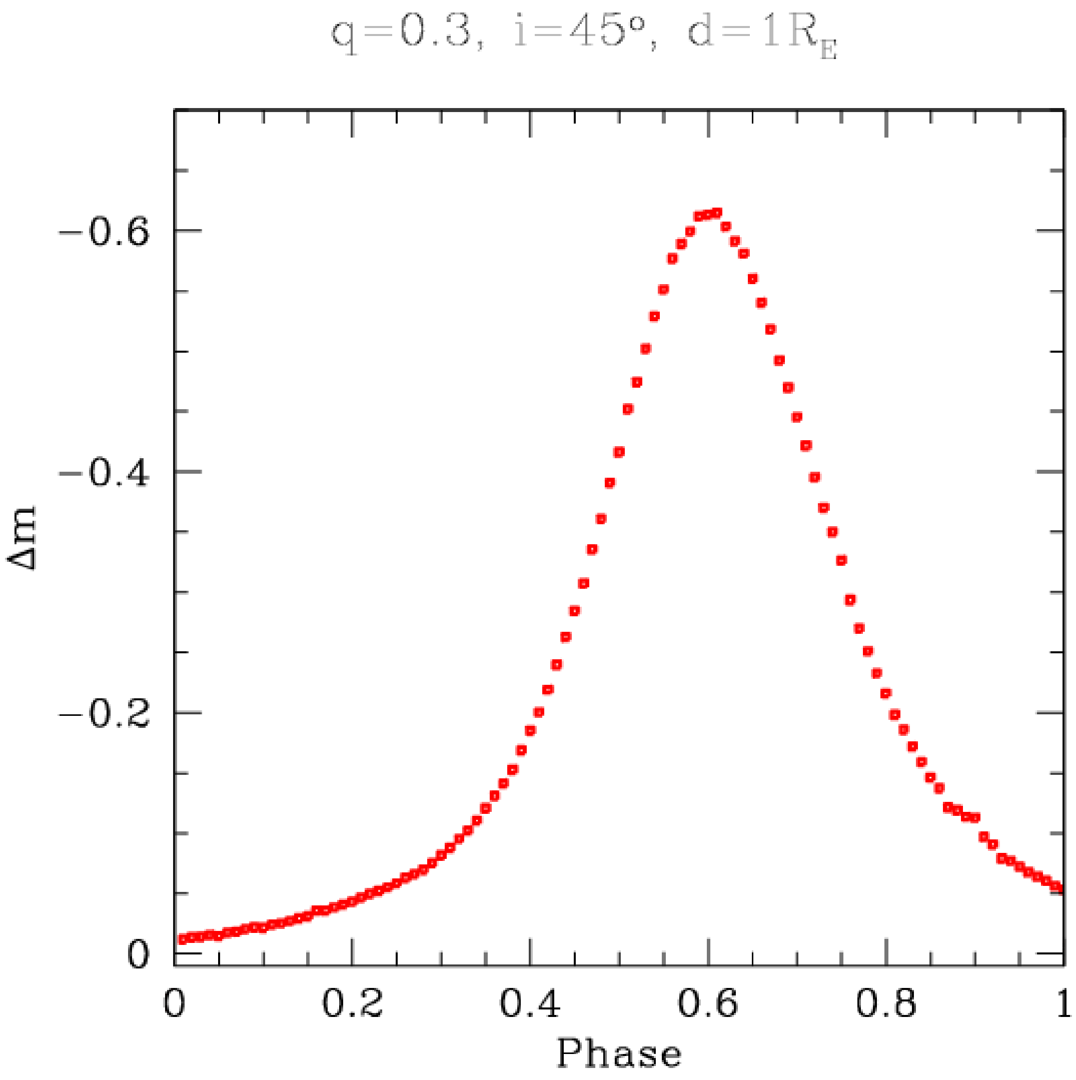
$i = 45^o$

$d = 1R_E$

$P \approx 1year$

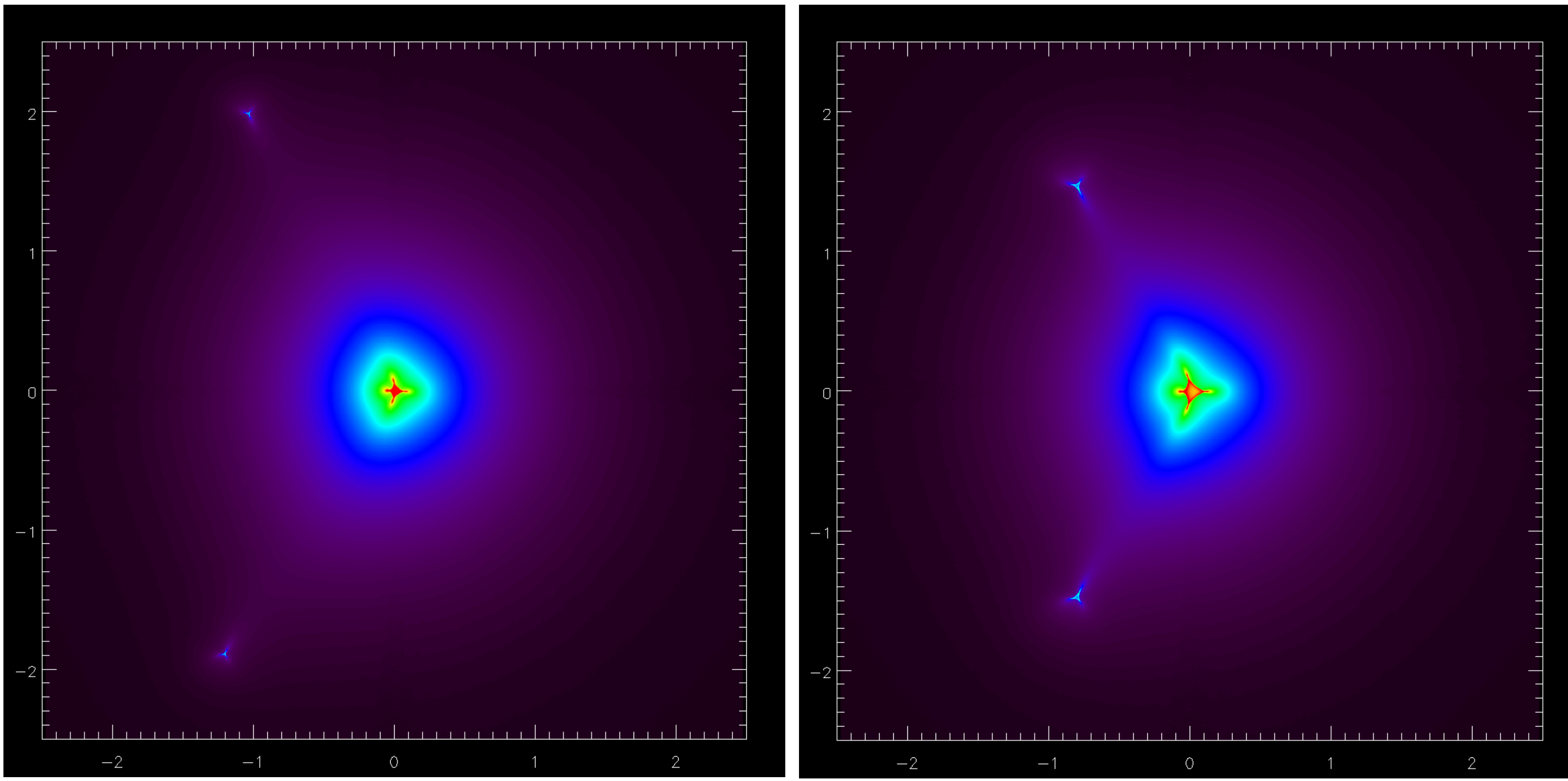
$R_* \approx 10R_{Sun}$

# „Ideal“ synthetic light curve



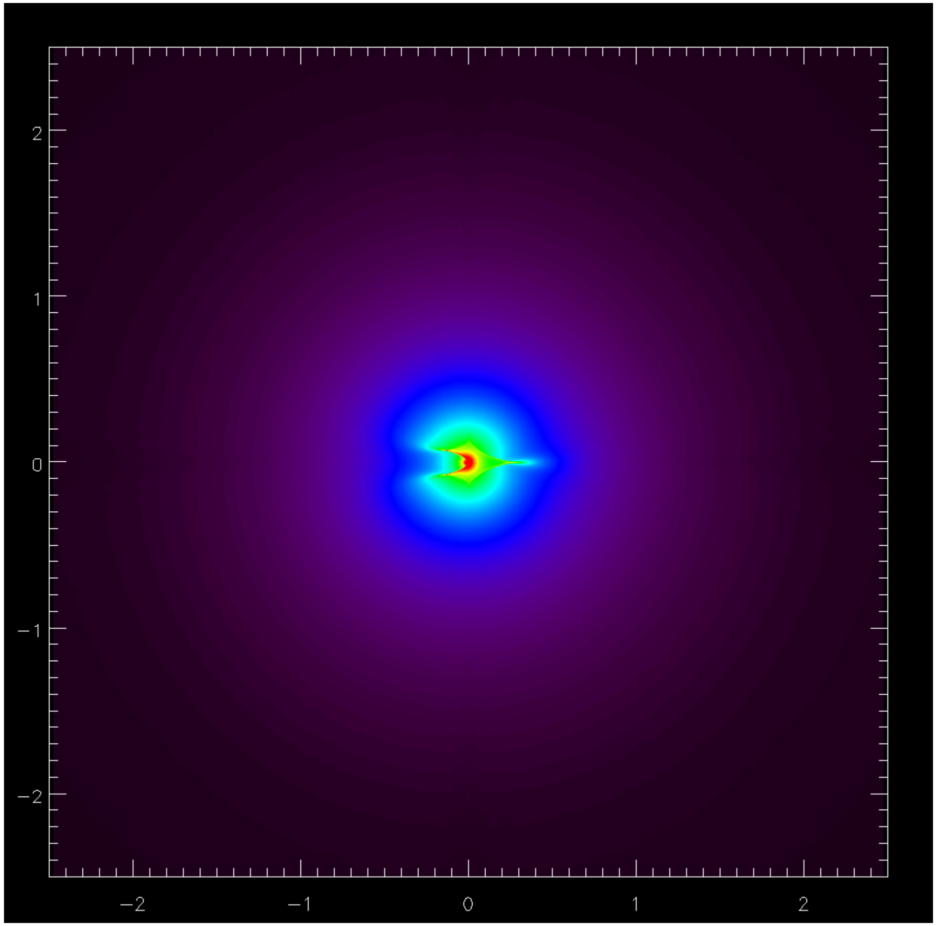

P~1year

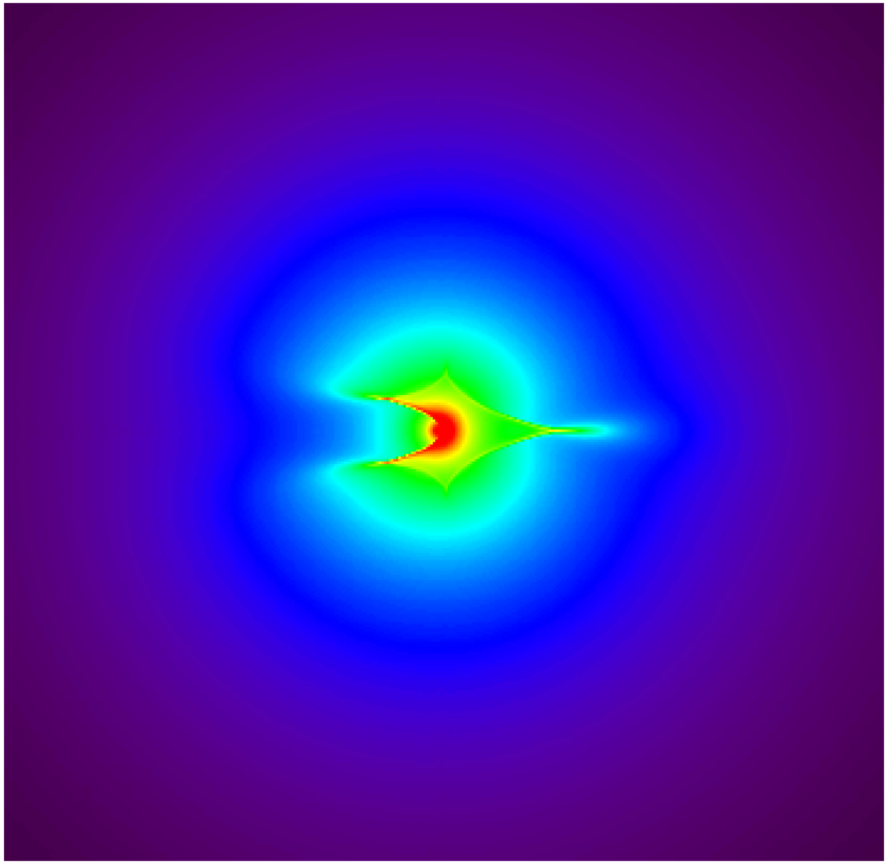
$d = 0.4R_E$ $d = 0.5R_E$



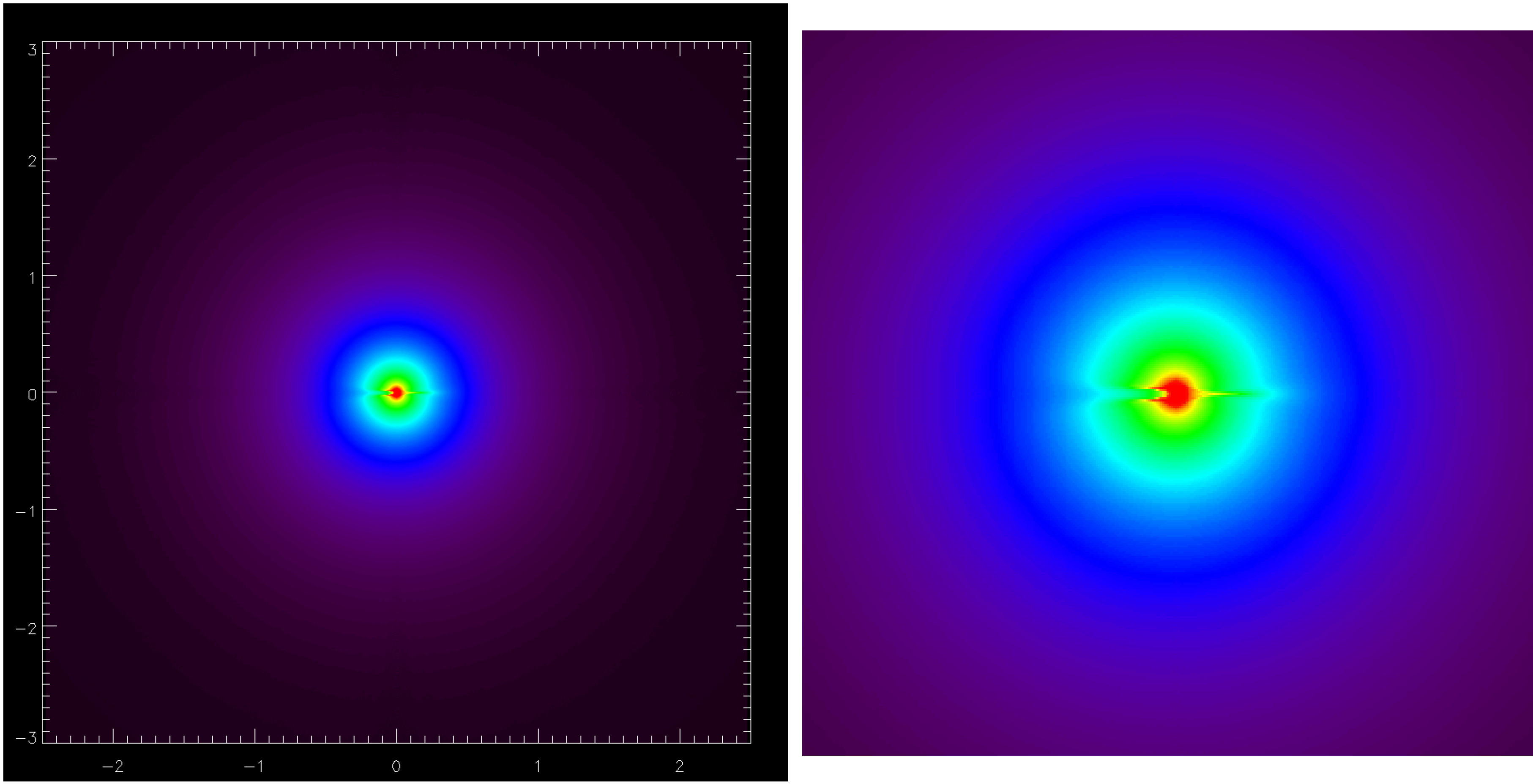

$q$=0.3

# Mass ratio *q=0.01*

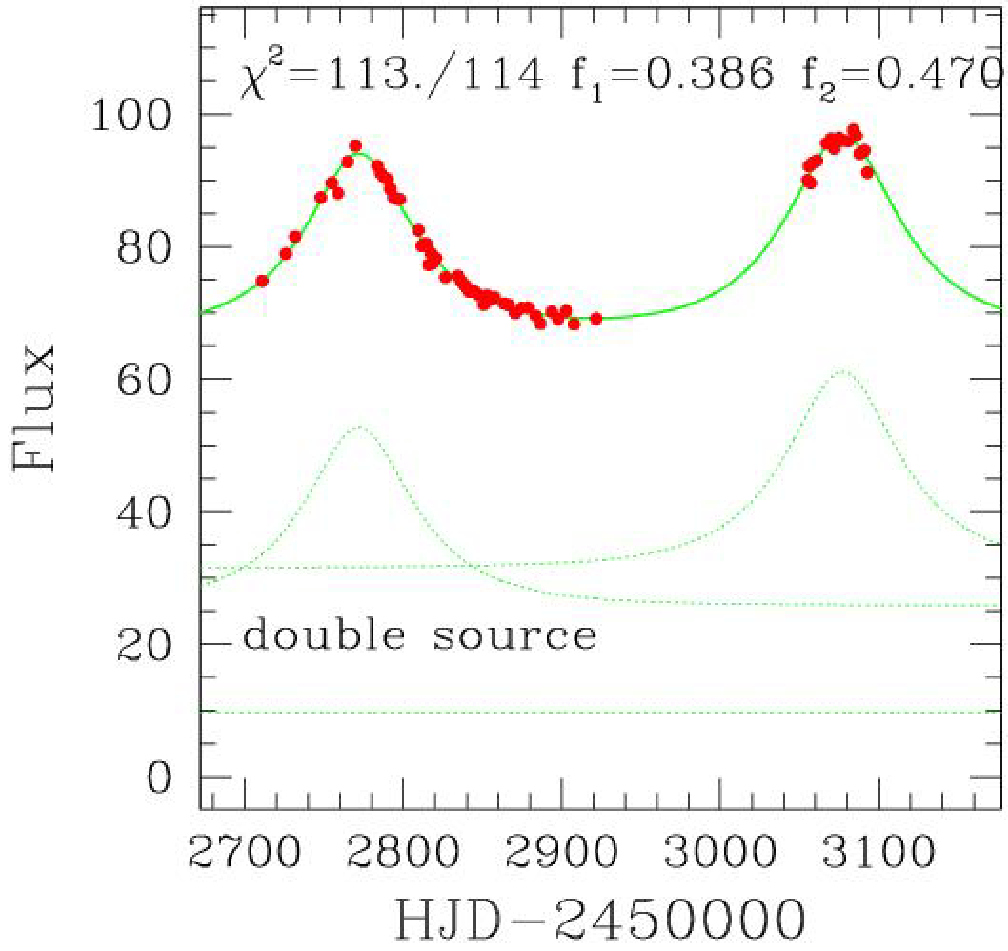


# Mass ratio *q=0.001*

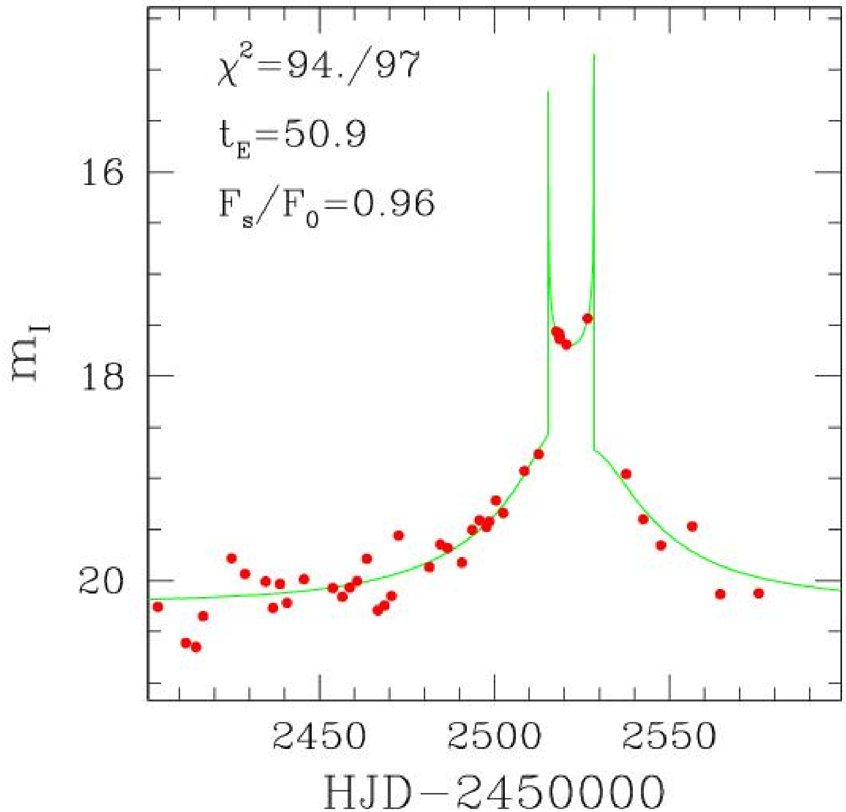


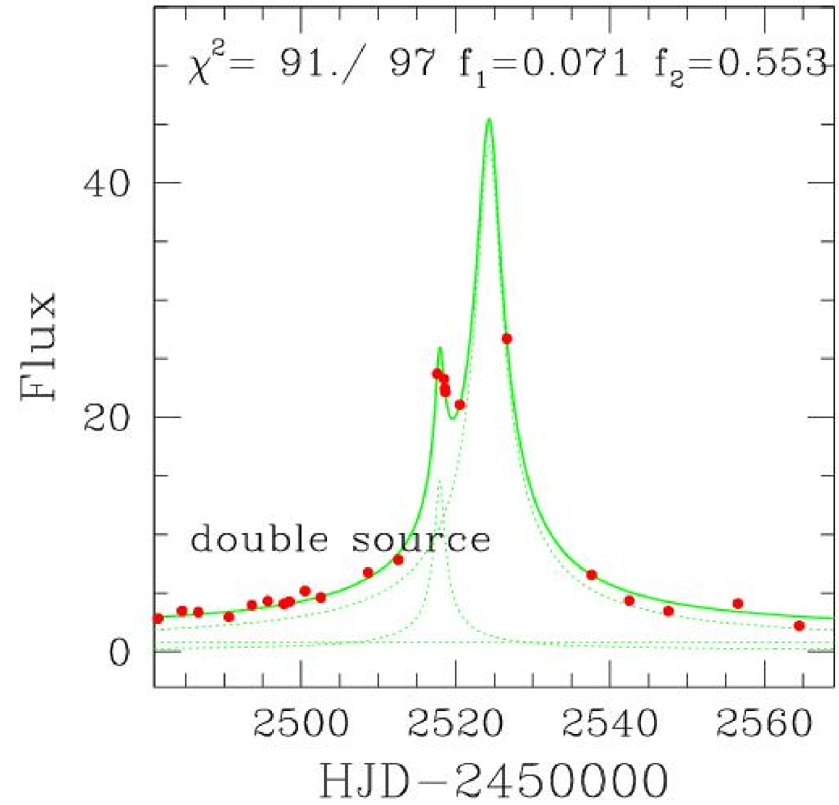
# Binary source – single lens light curve




OGLE-2003-BLG-067

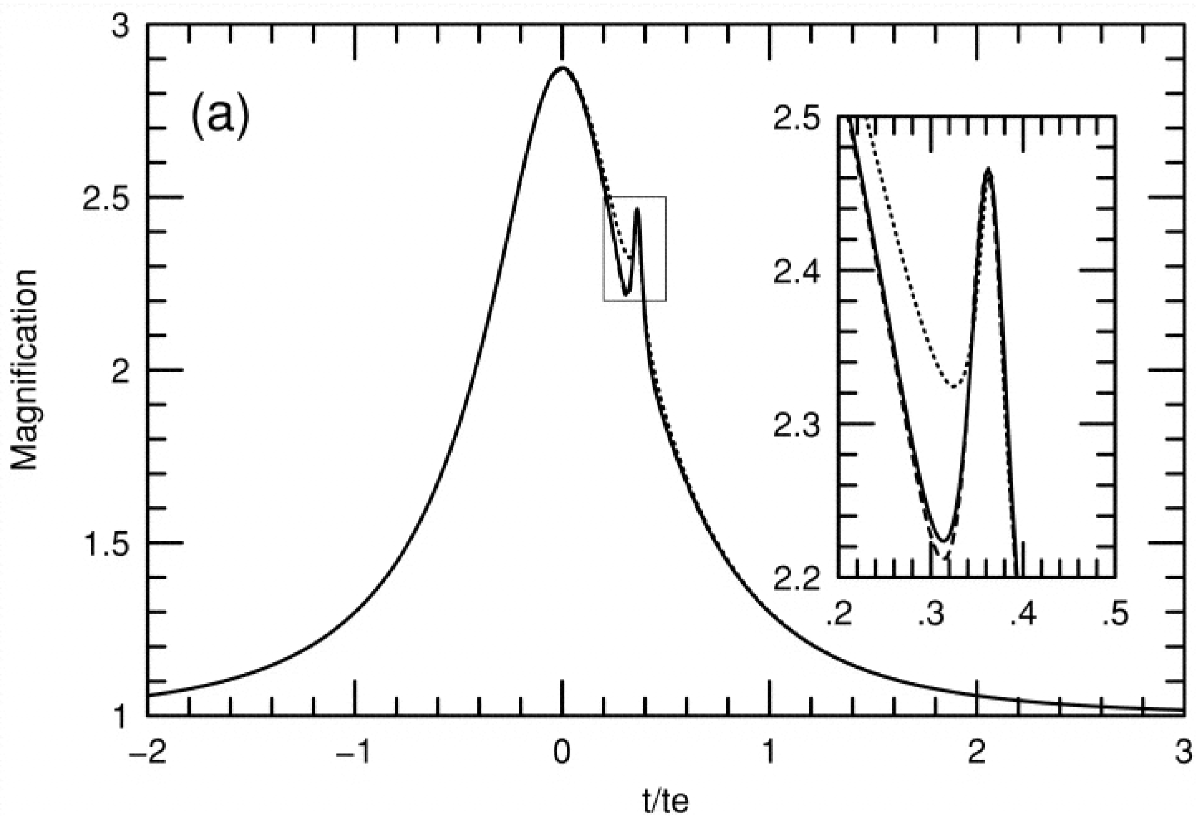
# Stellar binary lens – binary source degeneracy




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

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




Gaudi (1998)

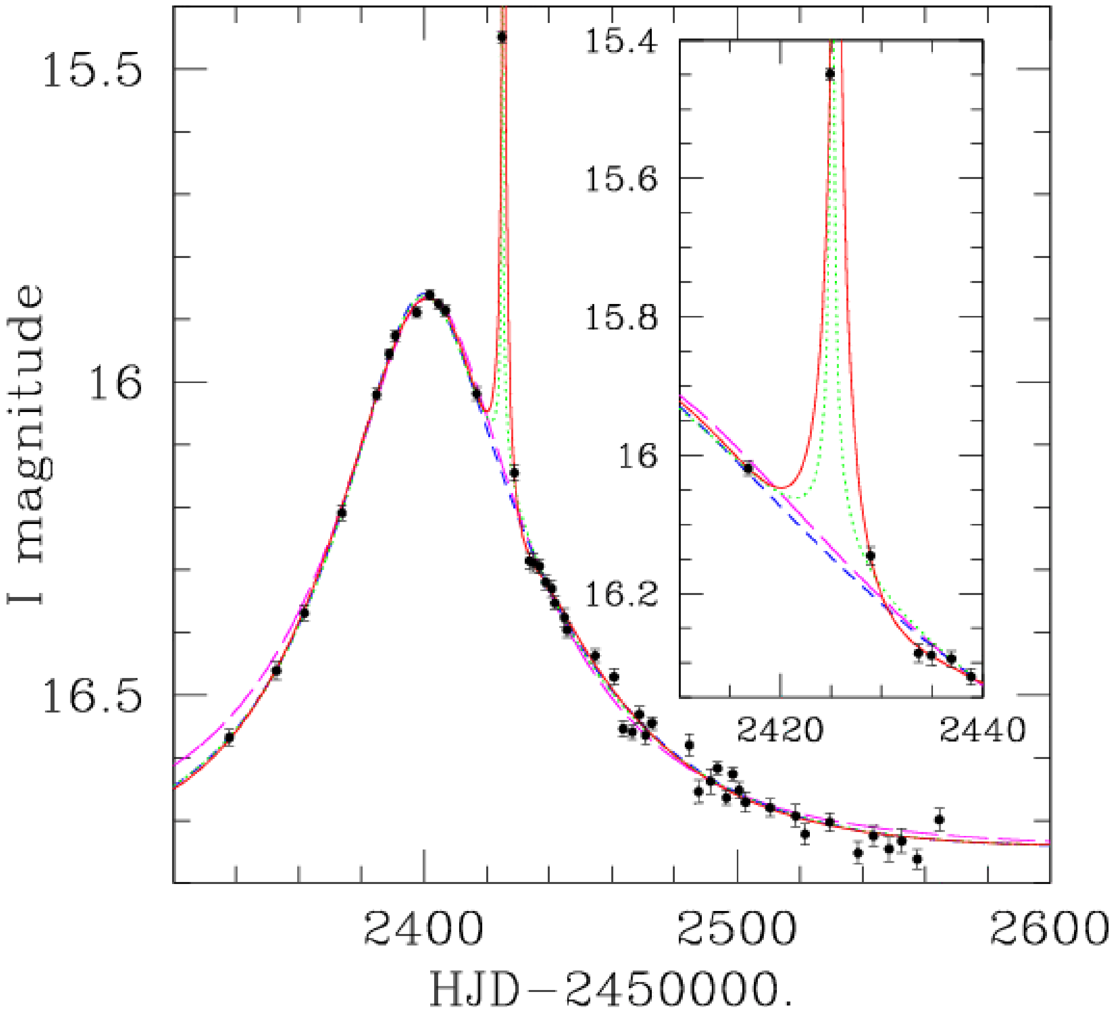
Solid line:
Binary lens

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

$$d = 1.3 R_E$$

Short-dashed line:
Binary source

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




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

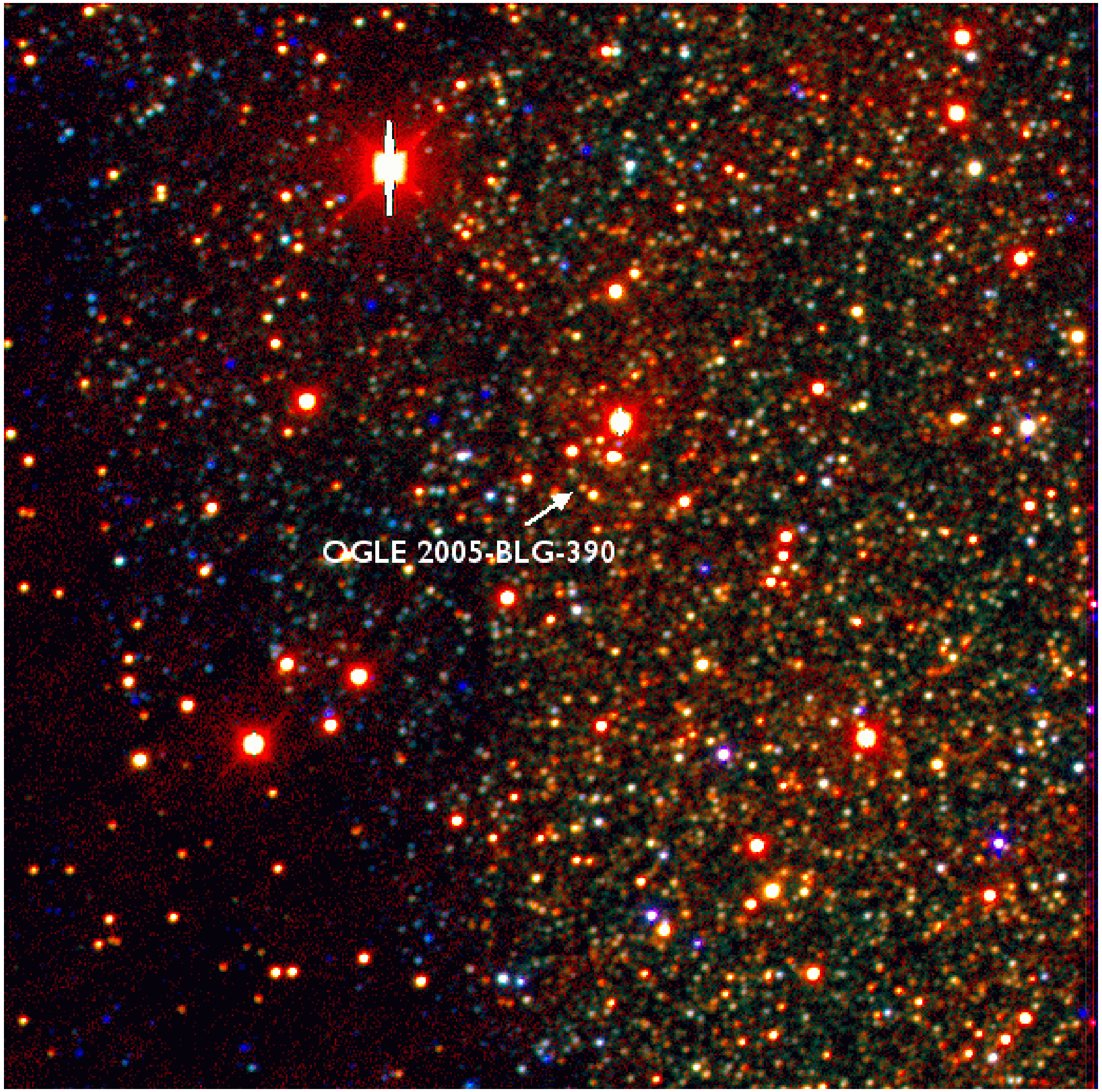
# OGLE-2005-BLG-390

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

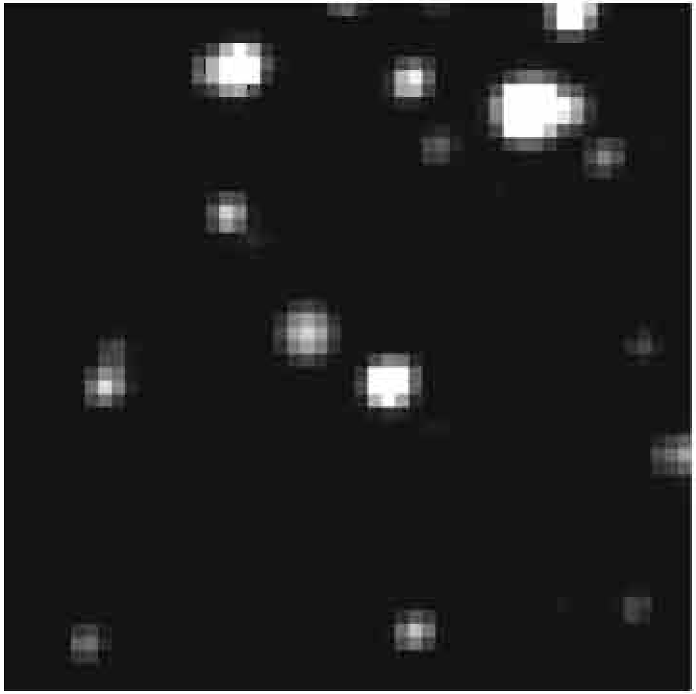
$I$ photom. band

**G4III** type source star

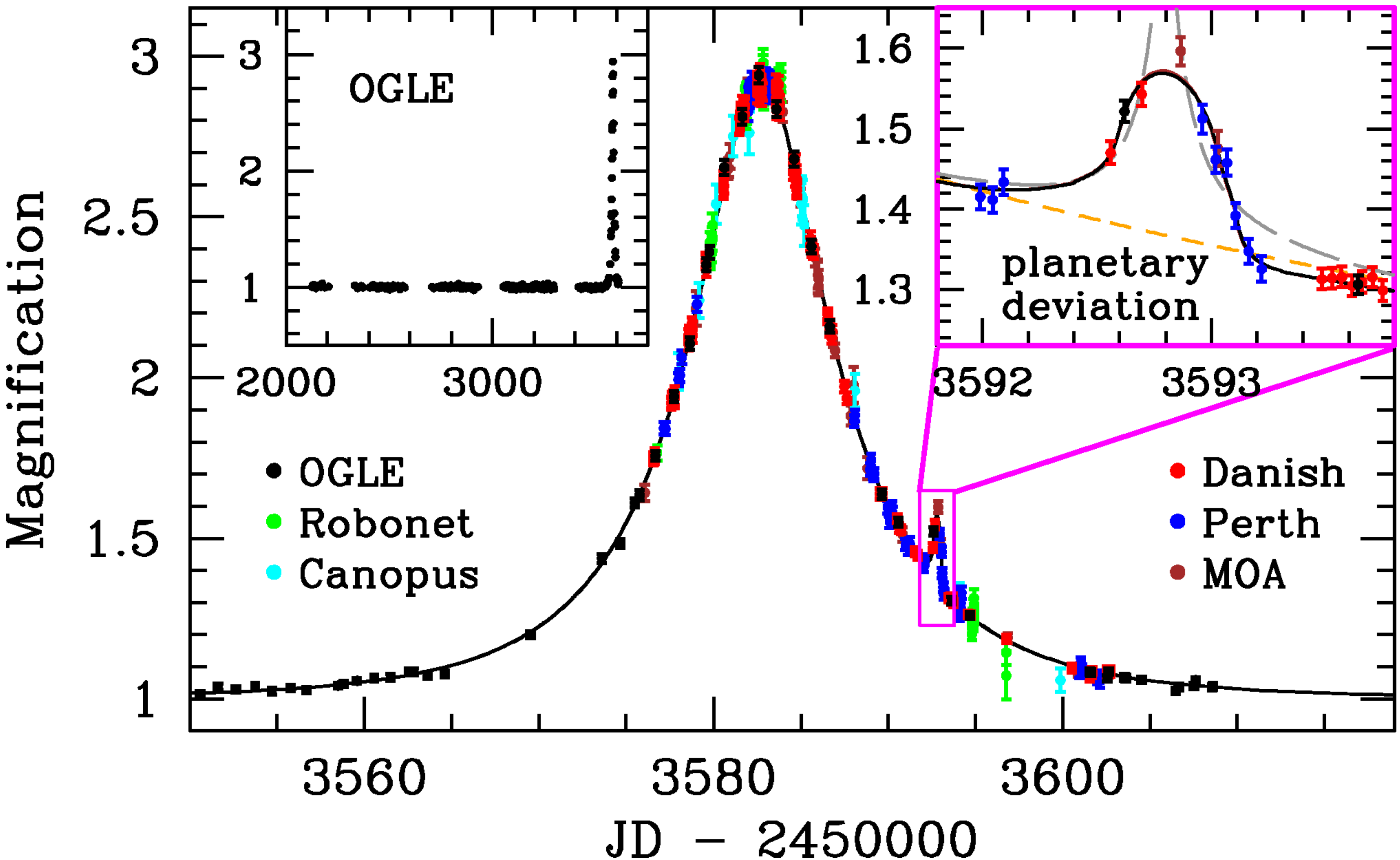
$R_{G*} \sim 10 R_{Sun}$
$T_{G*} \sim 5200K$




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**

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

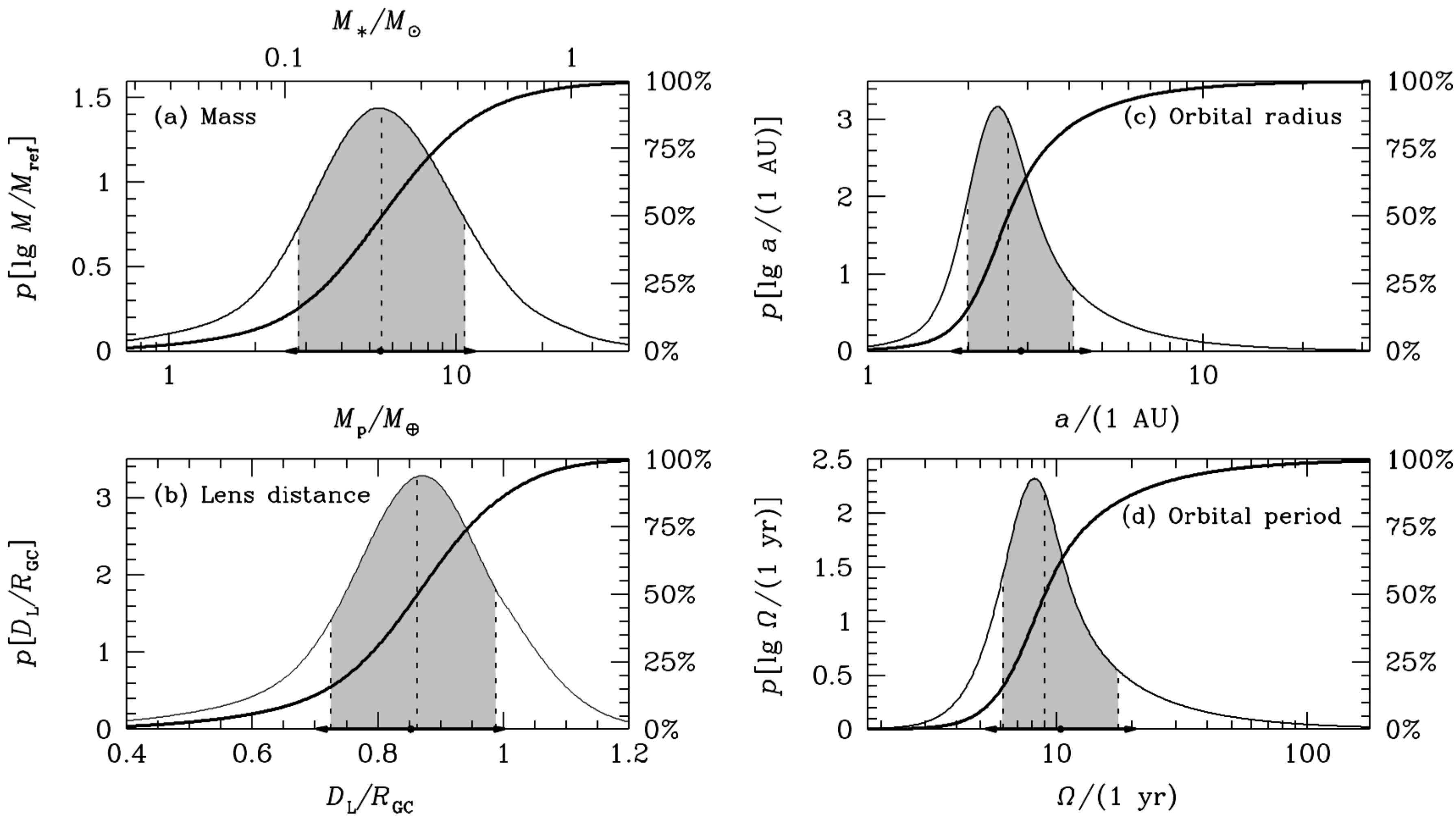
$$u_0 = (0.359 \pm 0.005)R_E$$

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

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

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

# Determining system parameters using probability distributions



# Solution

## (OGLE-2005-BLG-390)

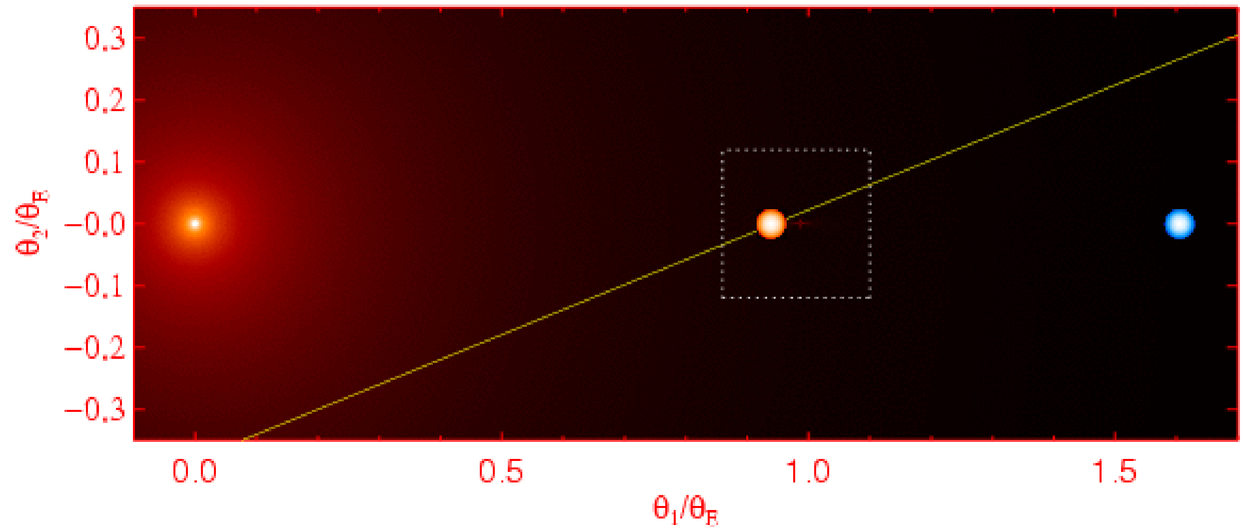
- Planet mass: $M_P = 5.5^{+5.5}_{-2.7} M_{Earth}$
- Host star mass: $M_{M*} = 0.22^{+0.21}_{-0.11} M_{Sun}$
- Separation:

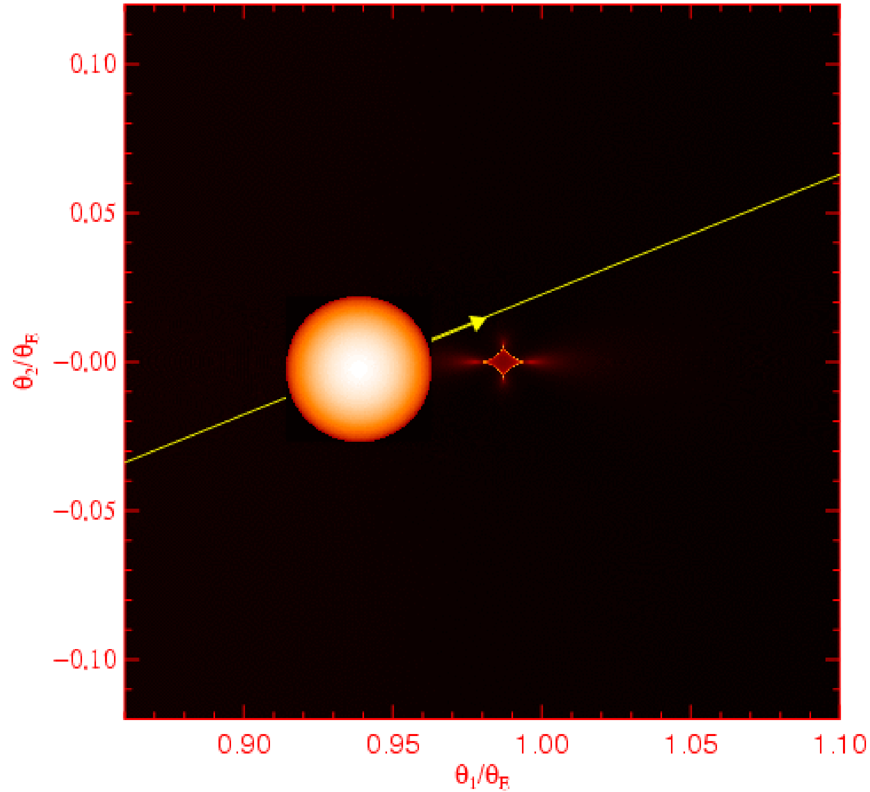
$$d_P = 2.7^{+1.5}_{-0.6} A.U.$$

- 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)



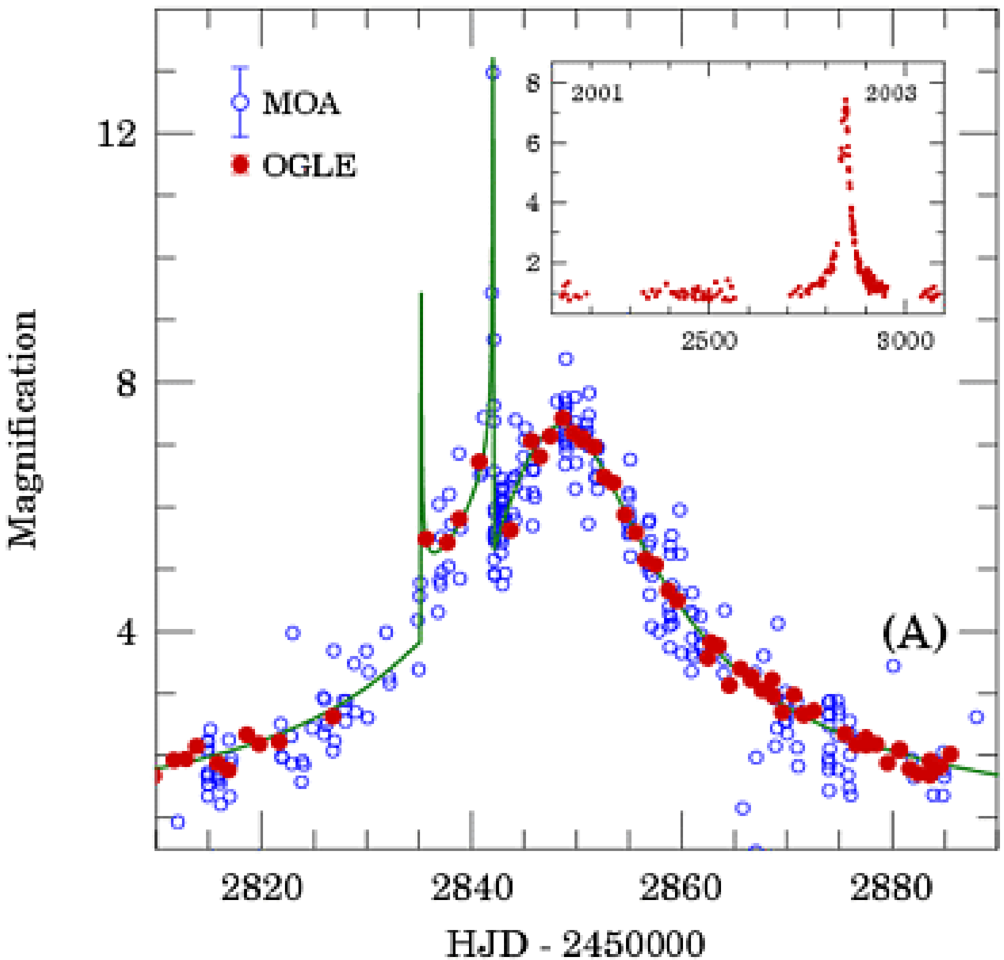




The source path (G giant) relative to the lens system (Planet + M star)

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

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

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




1.5 Jupiter mass planet

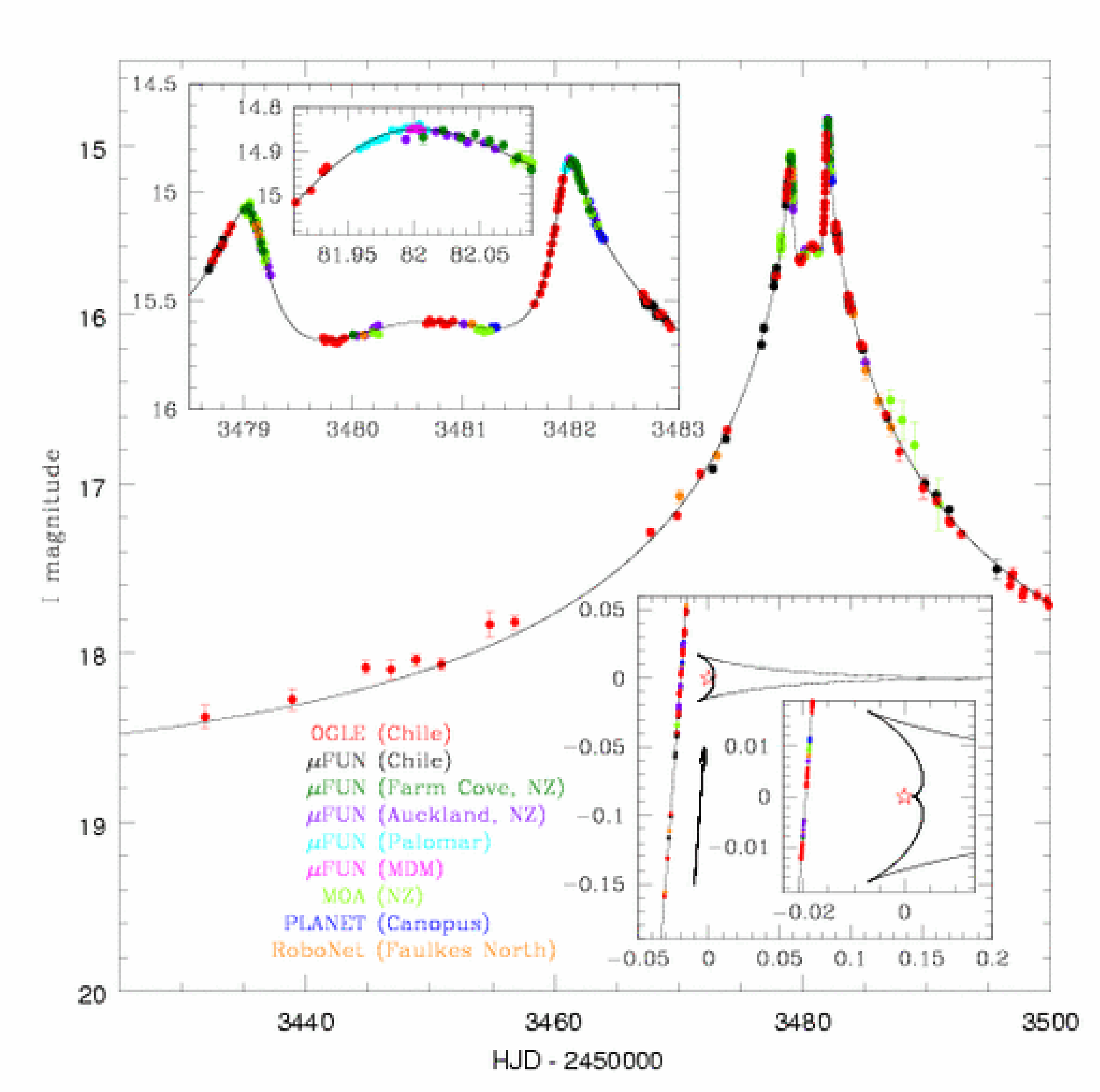
q=0.004

a=3 A.U.

D=5.2 kpc

Bond et al. (2004)

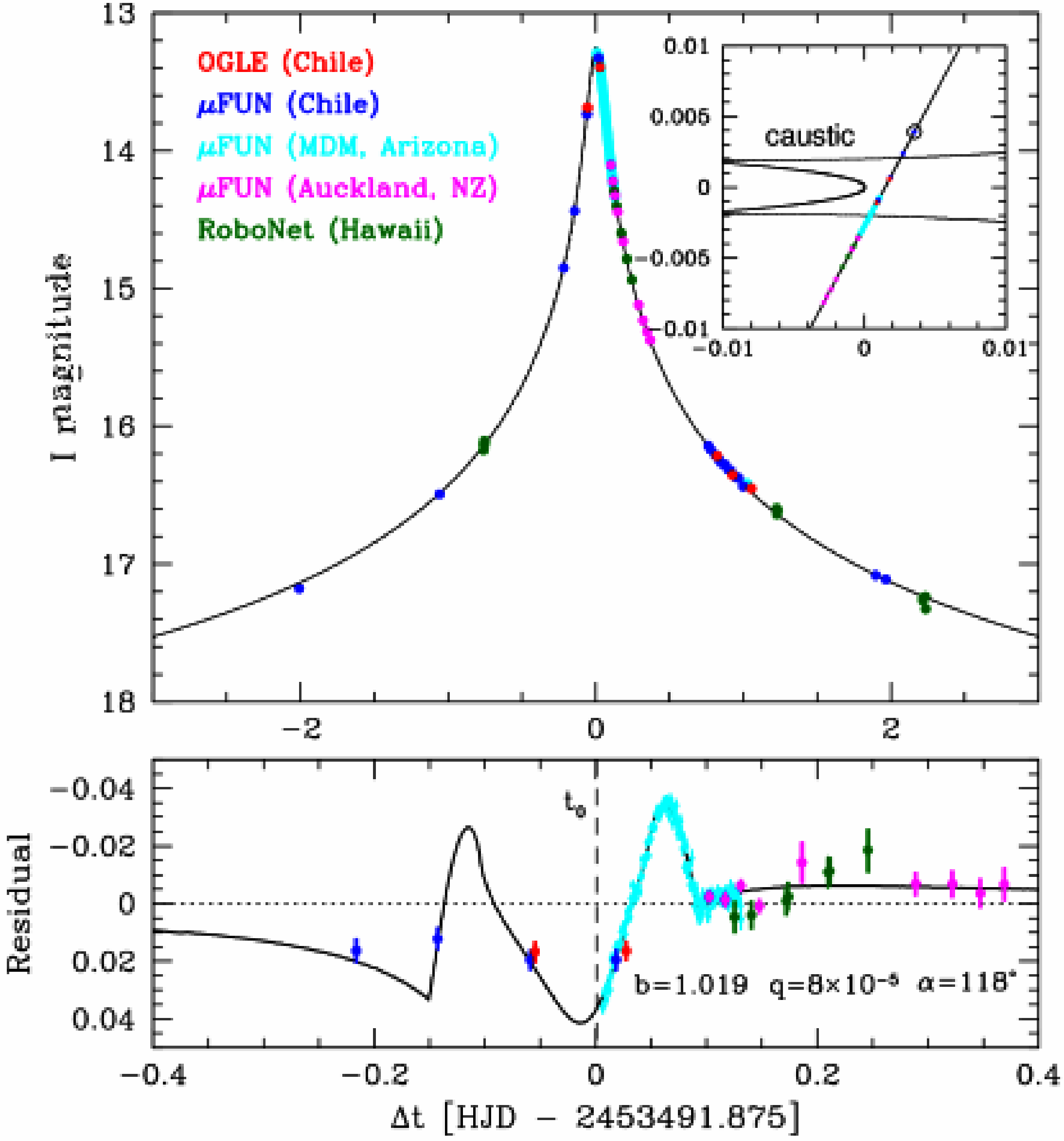
# OGLE-2005-BLG-071 (#2)




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

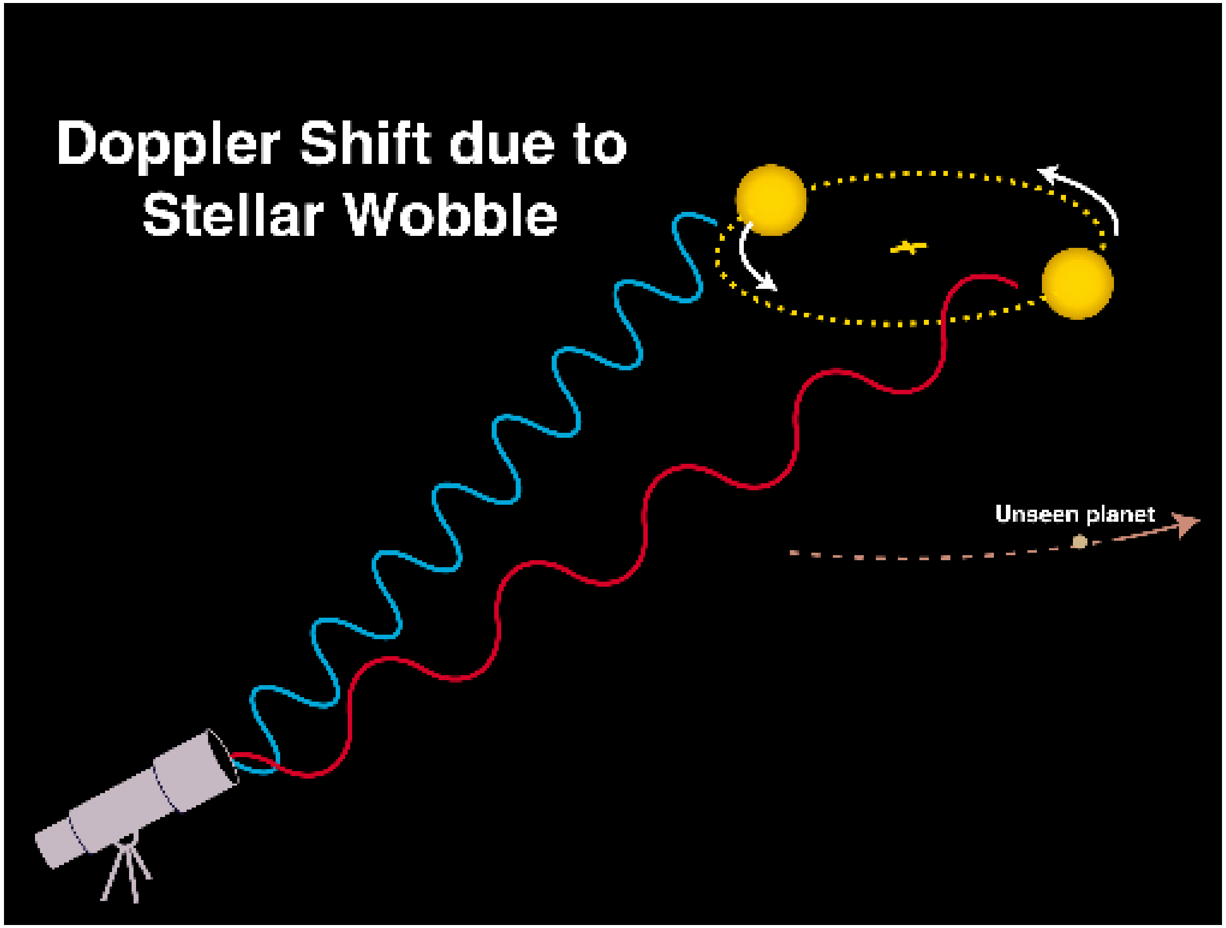
# Methods for finding extrasolar planets

- 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)

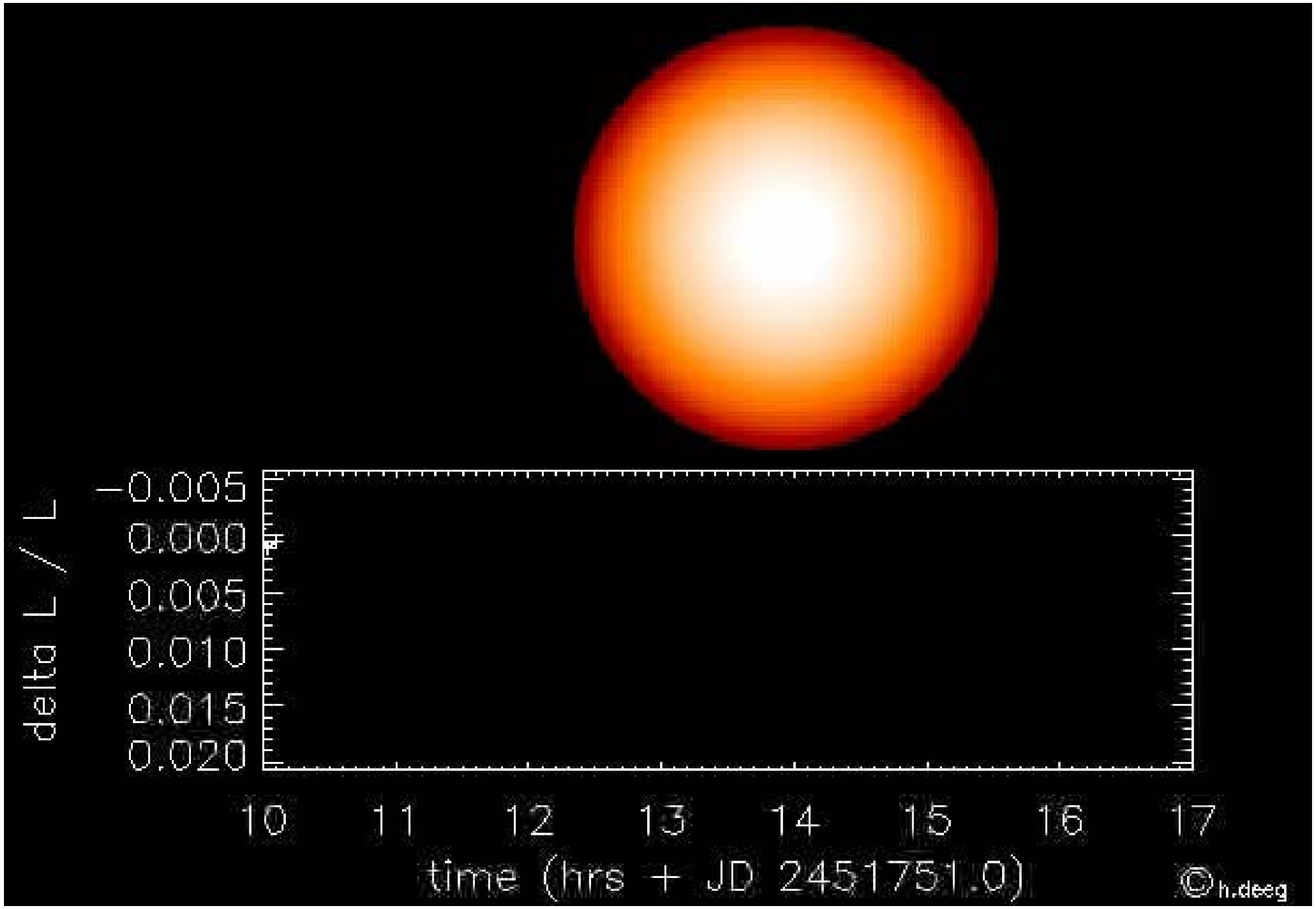
- **Direct imaging:** 4 planet candidates, may be small stars (brown dwarfs)
- **Transits**: large planets very close to their parent stars
- **Pulsar planets**
- **Gravitational microlensing**

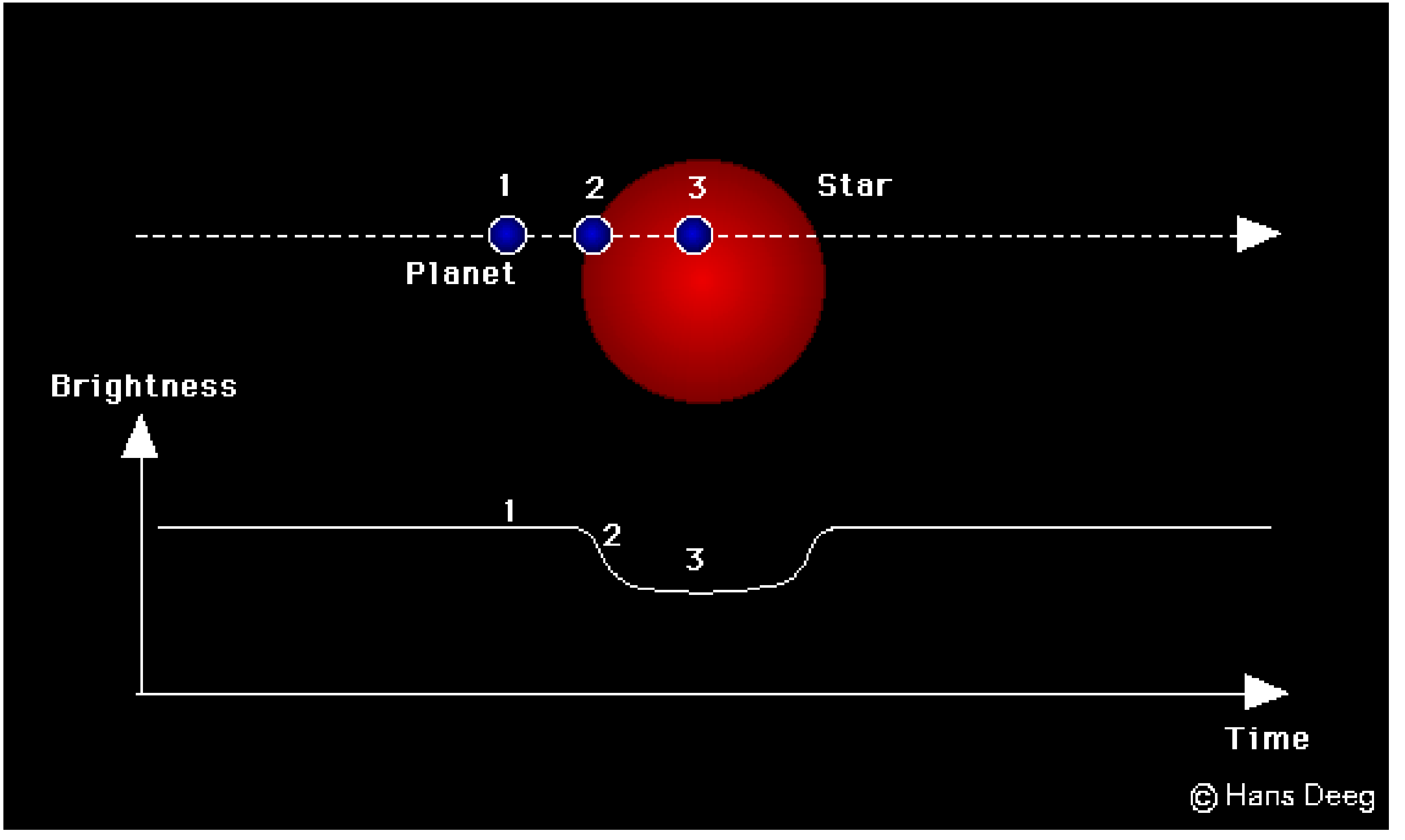
# Radial velocities



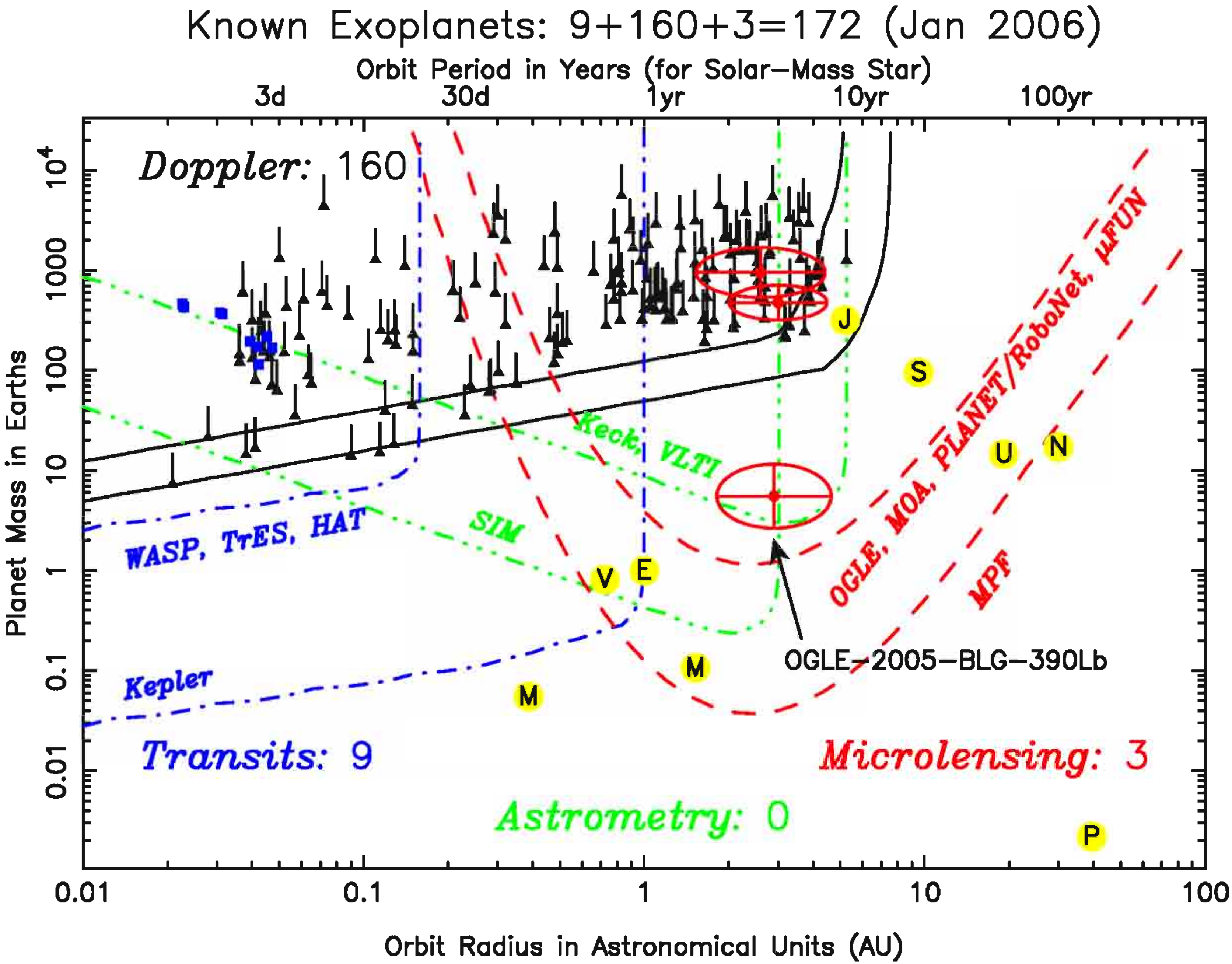

Only the lower limit on the mass!

## - **Transits**:

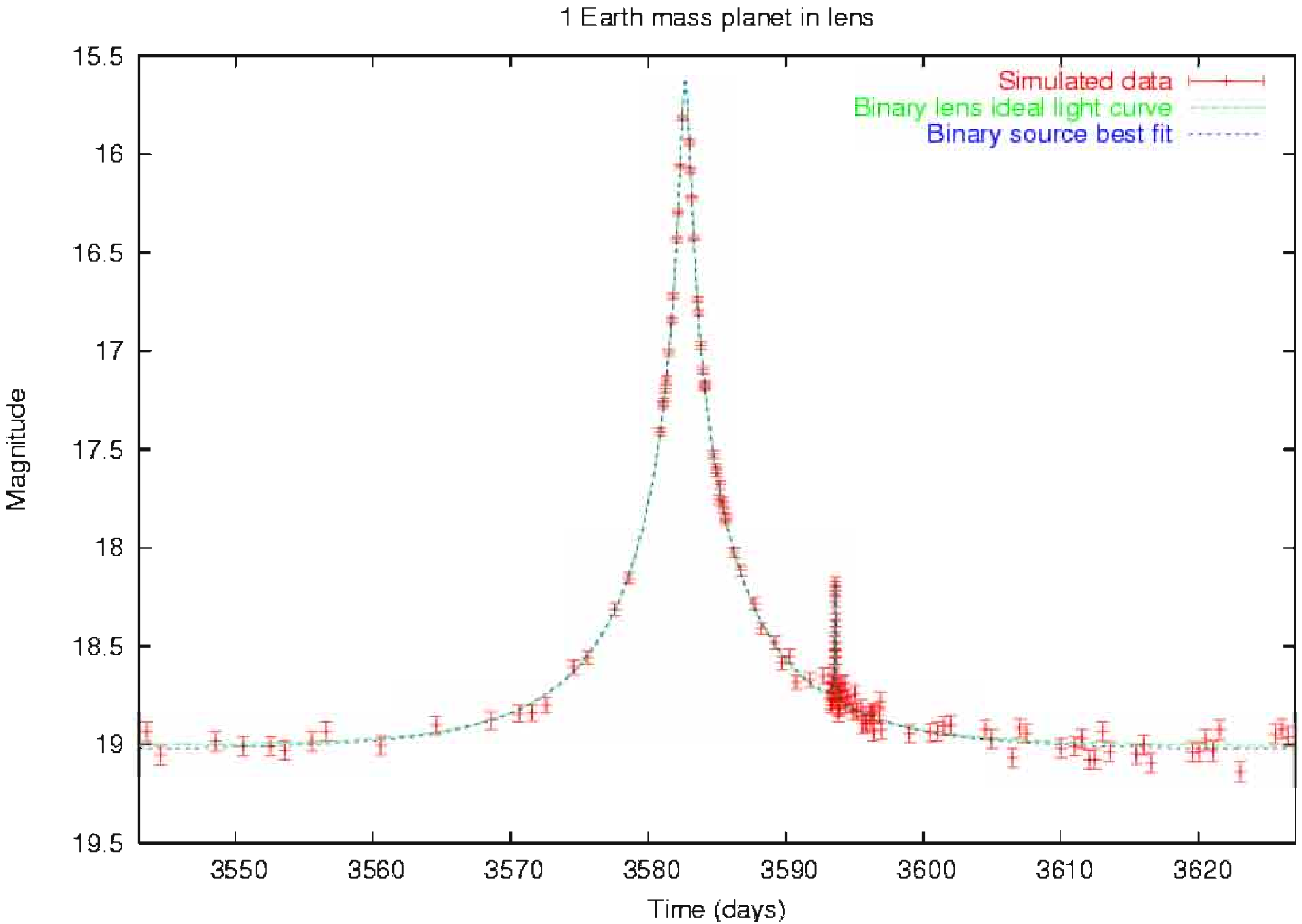

−0.005
0.000
0.005
0.010
0.015
0.020
delta L / L
10
11
12
13
14
15
16
17
time (hrs + JD 2451751.0)
©h.deeg



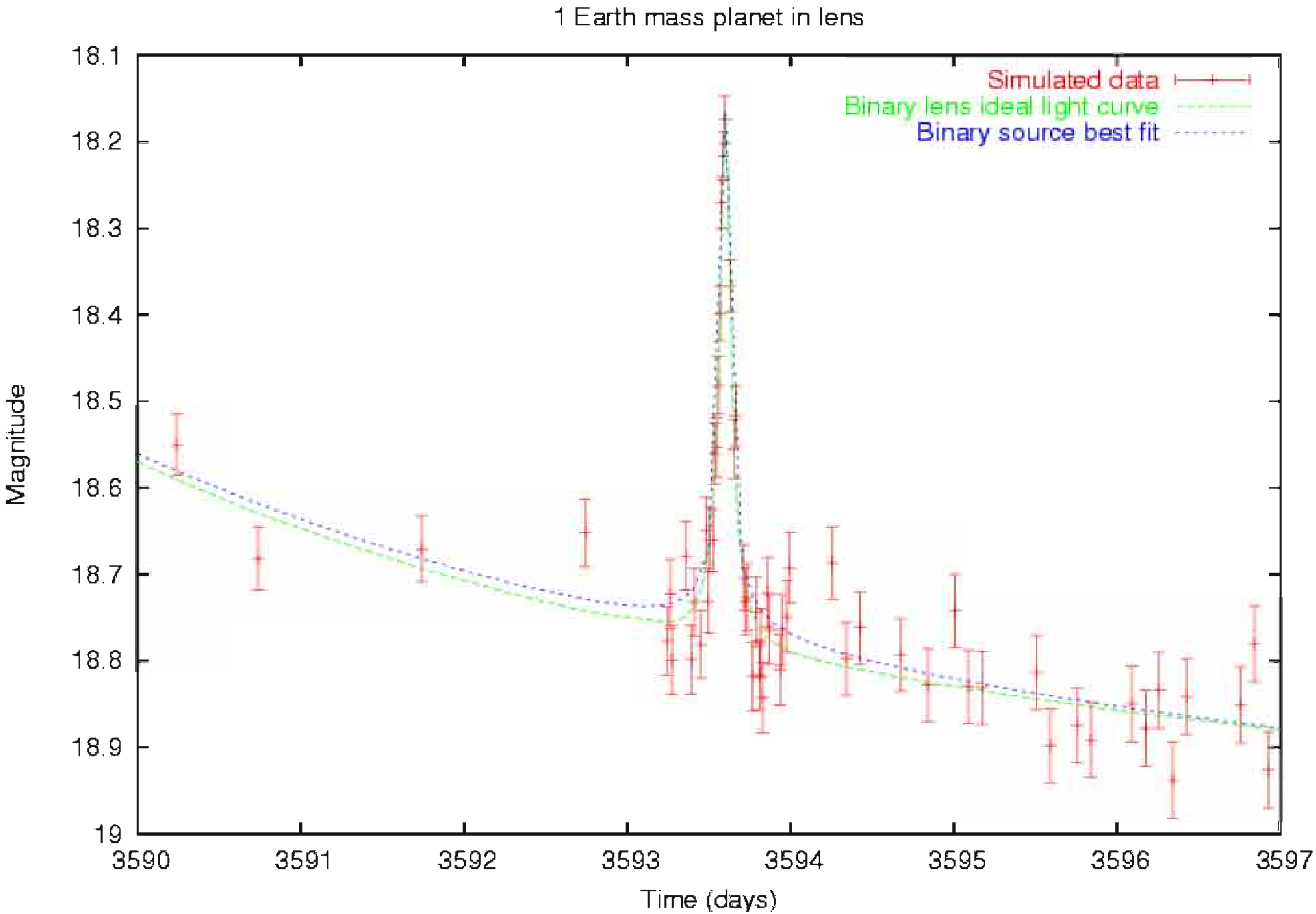

Water vapour detected in the atmosphere of a hot Jupiter transiting planet (Tinetti et al, July 2007)



Known Exoplanets: 9+160+3=172 (Jan 2006)
Orbit Period in Years (for Solar-Mass Star)
3d
30d
1yr
10yr
100yr
Doppler: 160
Planet Mass in Earths
Keck, VLTI
SIM
WASP, TrES, HAT
Kepler
OGLE, MOA, PLANET/RoboNet, μFUN
MPF
OGLE-2005-BLG-390Lb
J
S
U
N
V
E
M
M
P
Transits: 9
Microlensing: 3
Astrometry: 0
Orbit Radius in Astronomical Units (AU)

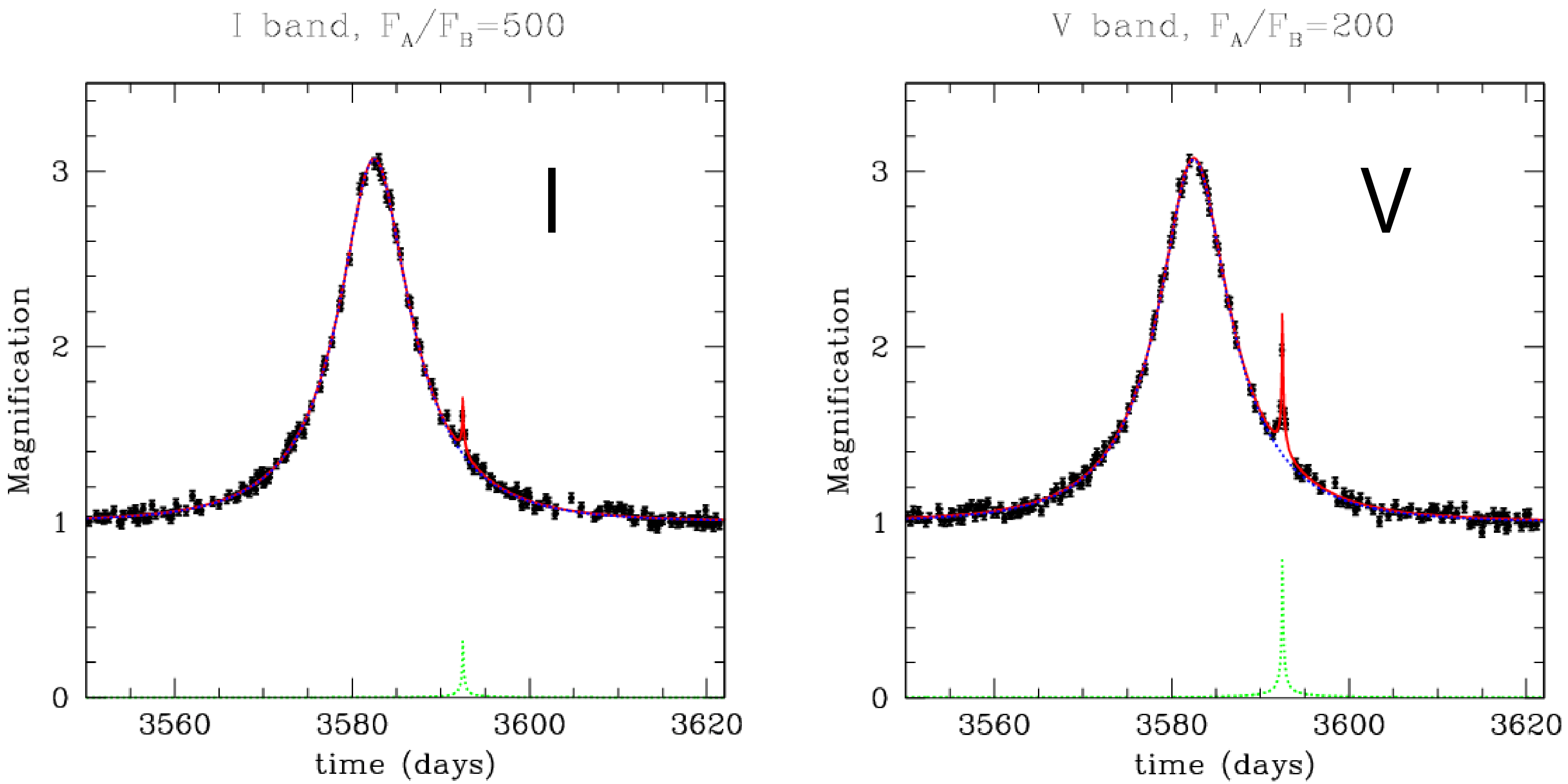


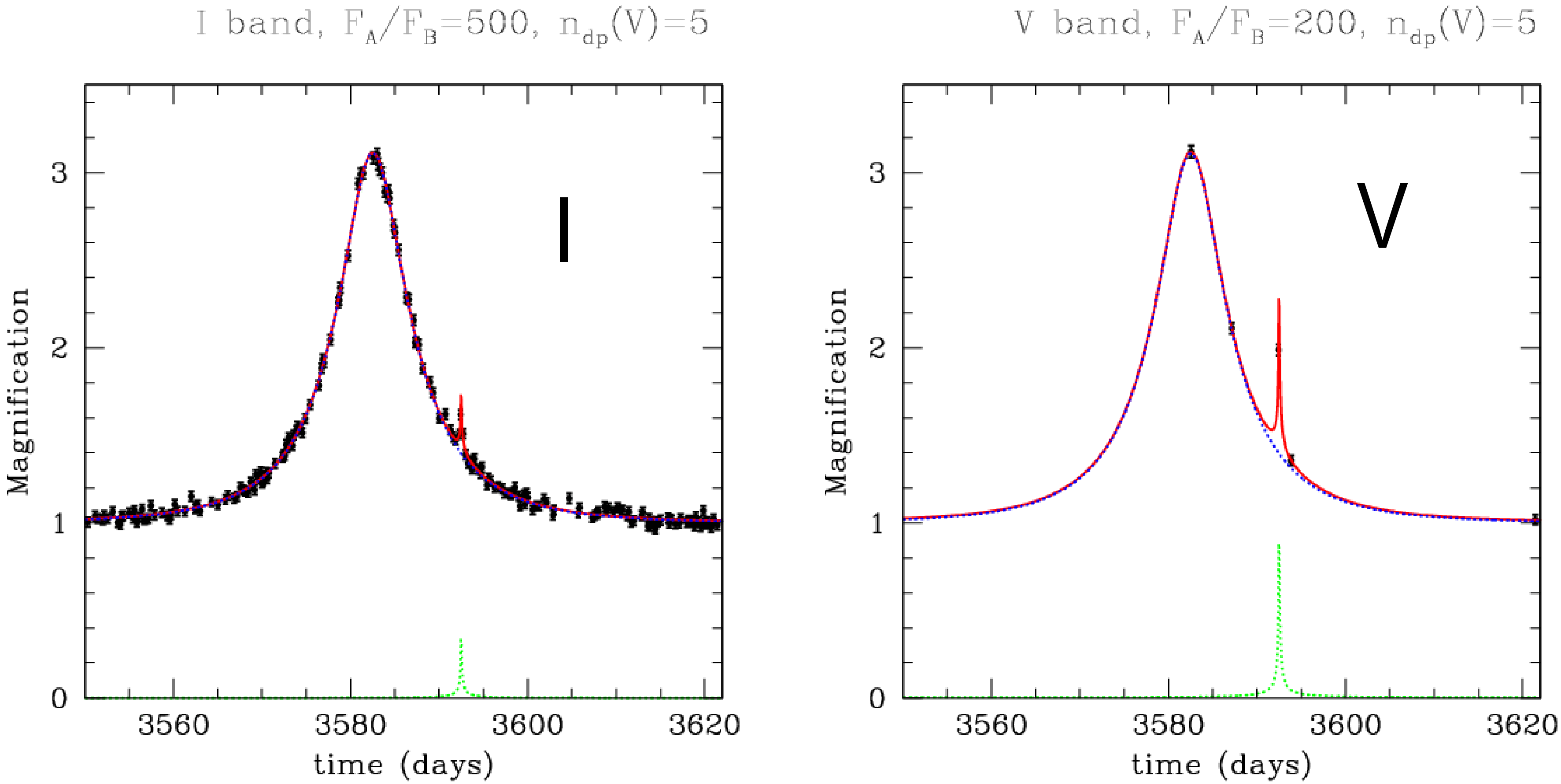
1 Earth mass planet in lens
Simulated data
Binary lens ideal light curve
Binary source best fit
Magnitude
Time (days)
15.5
16
16.5
17
17.5
18
18.5
19
19.5
3550
3560
3570
3580
3590
3600
3610
3620


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

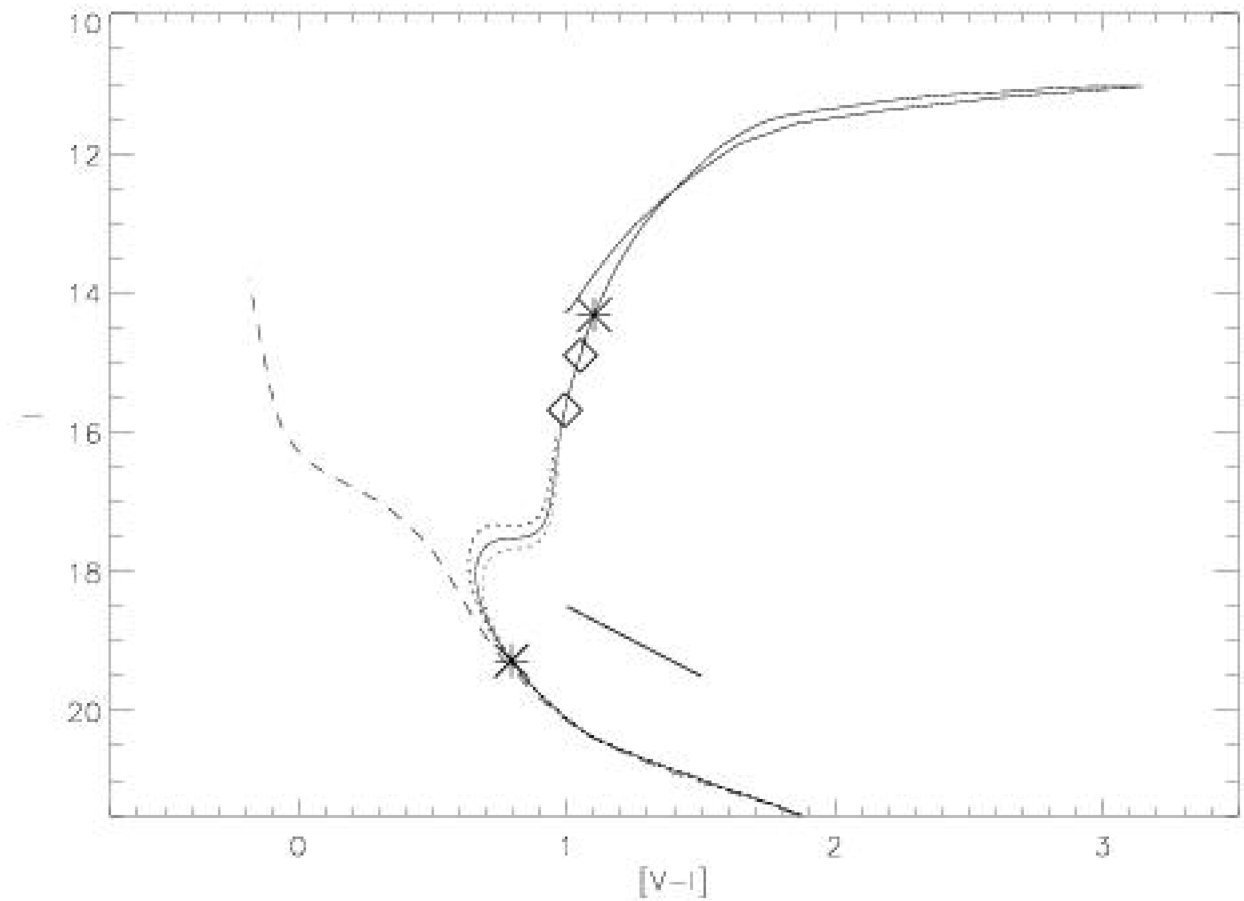
Binary source – single lens events: $$\frac{F_A(I)}{F_B(I)} \neq \frac{F_A(V)}{F_B(V)}$$






*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**!