GRAVITATIONAL LENSING

15 – PLANETARY MICROLENSING

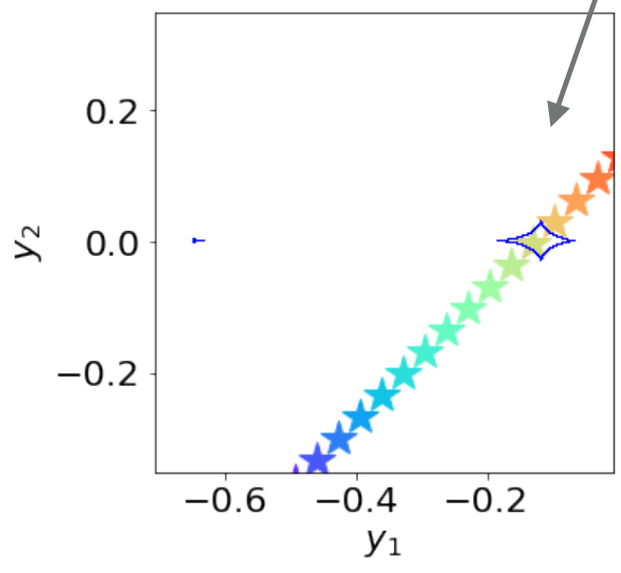
Massimo Meneghetti
AA 2017-2018

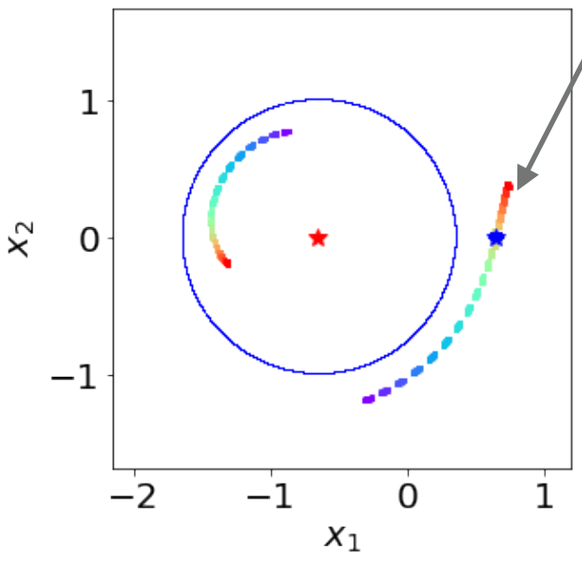
displaying material from S. Gaudi & Y. Shvartzvald (Sagan Workshop 2017)

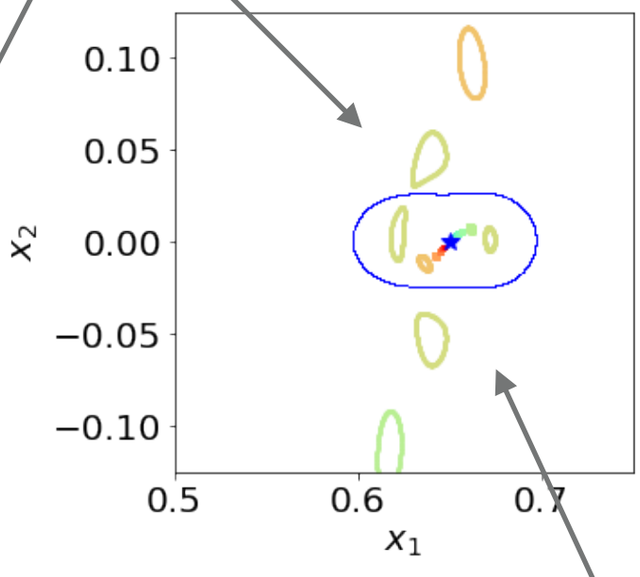
PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES

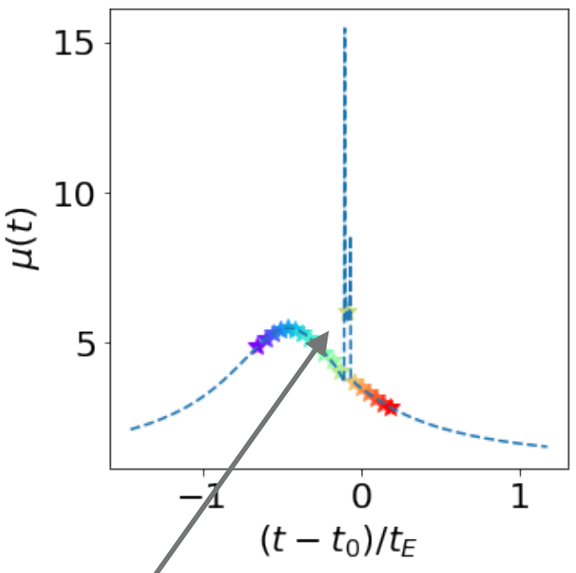
Planetary caustics

Planetary critical lines









magnified outer image

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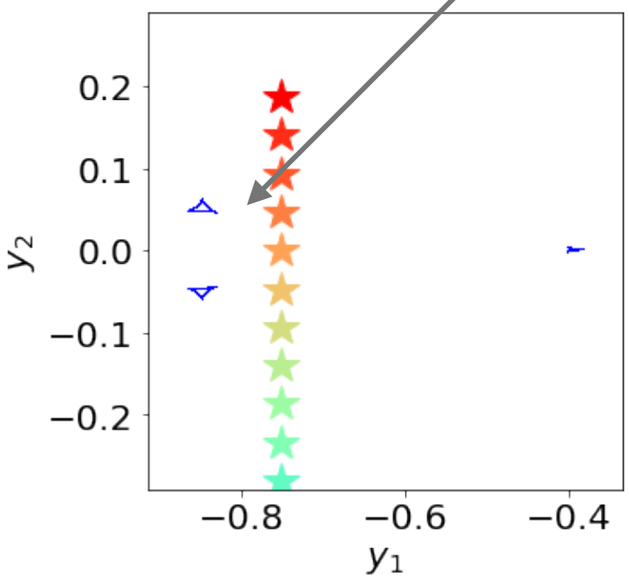
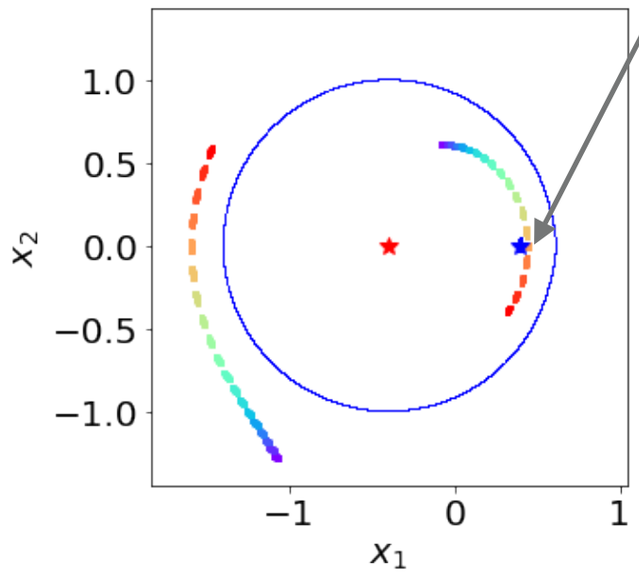
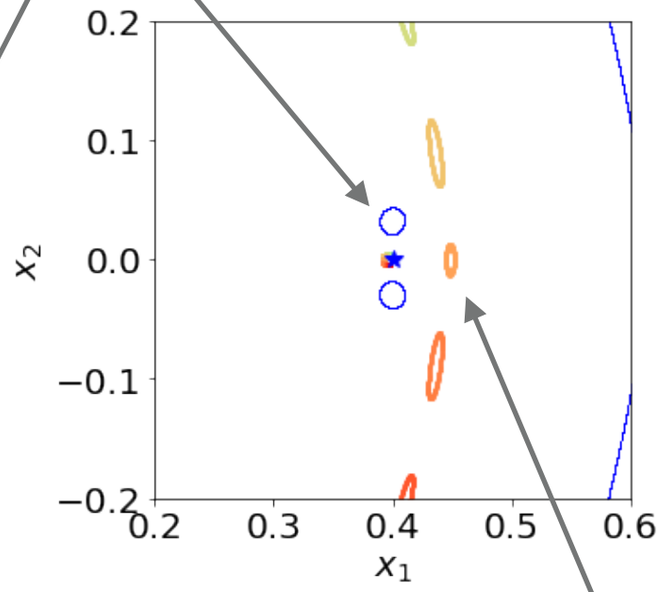
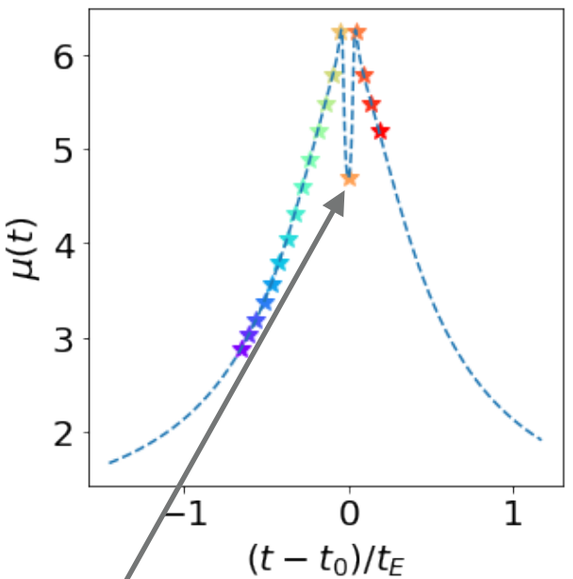
Planetary caustics

Planetary critical lines



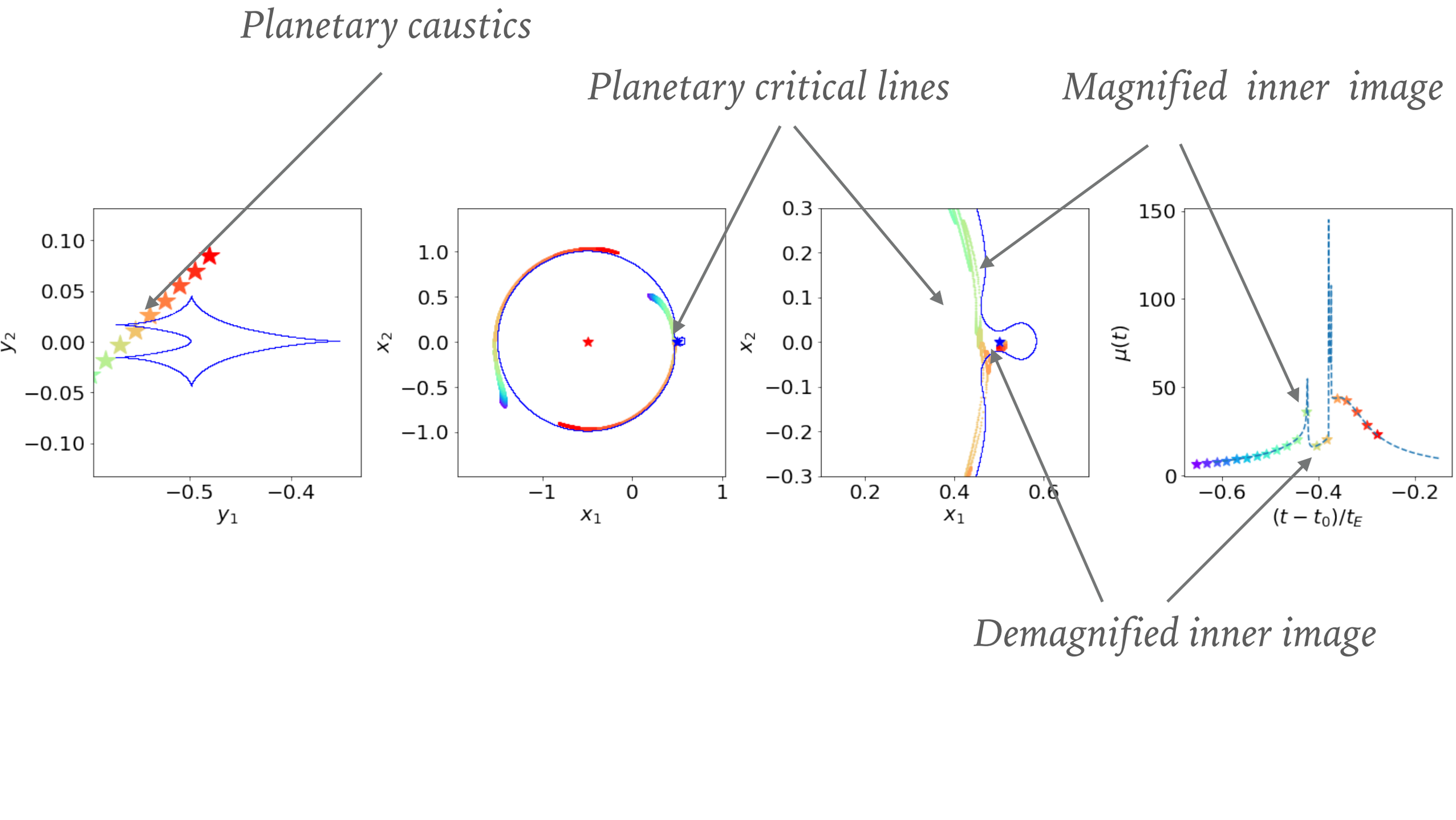






Demagnified inner image

PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES



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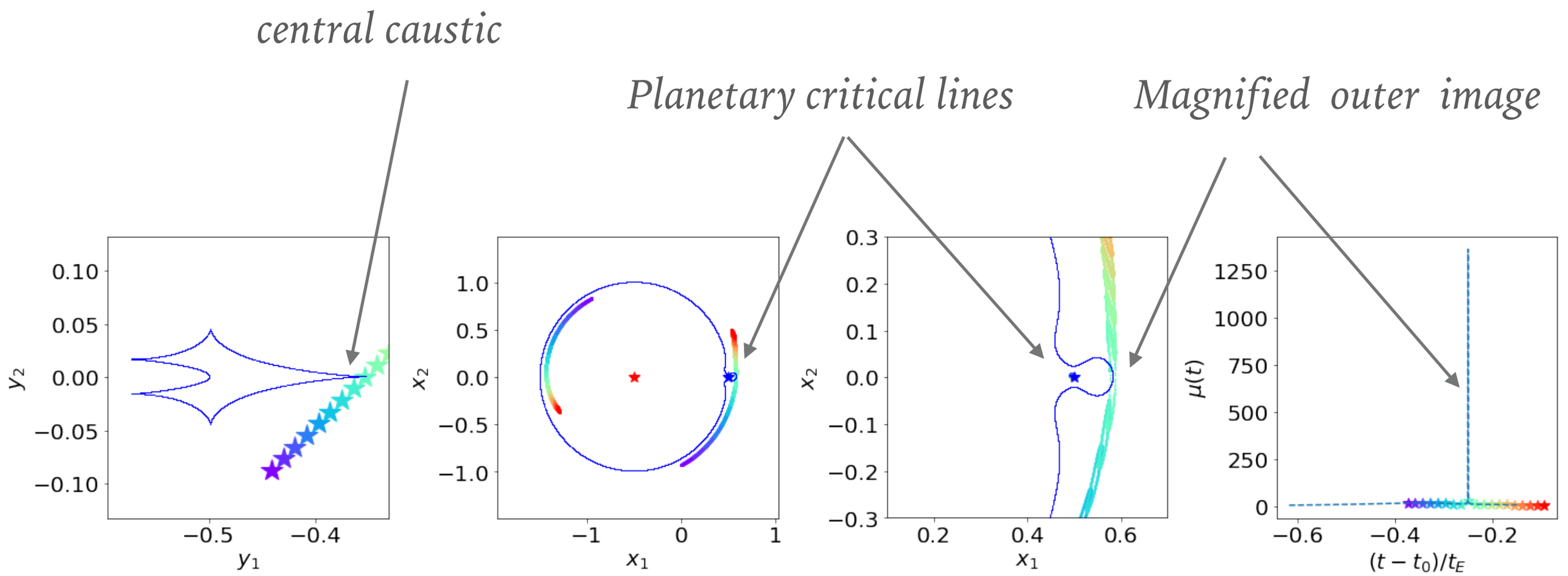
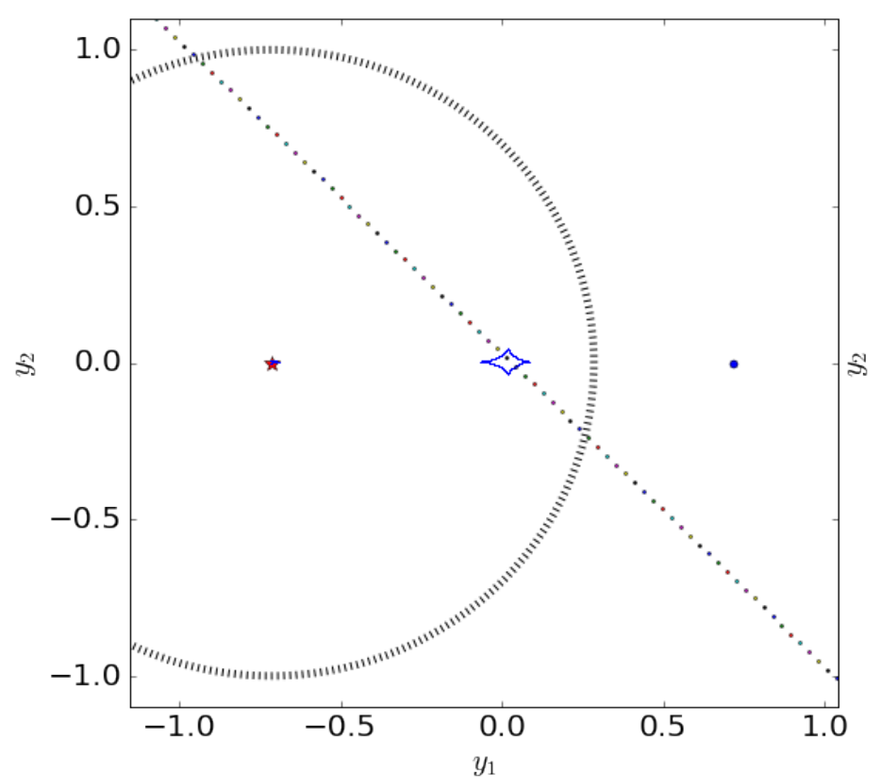
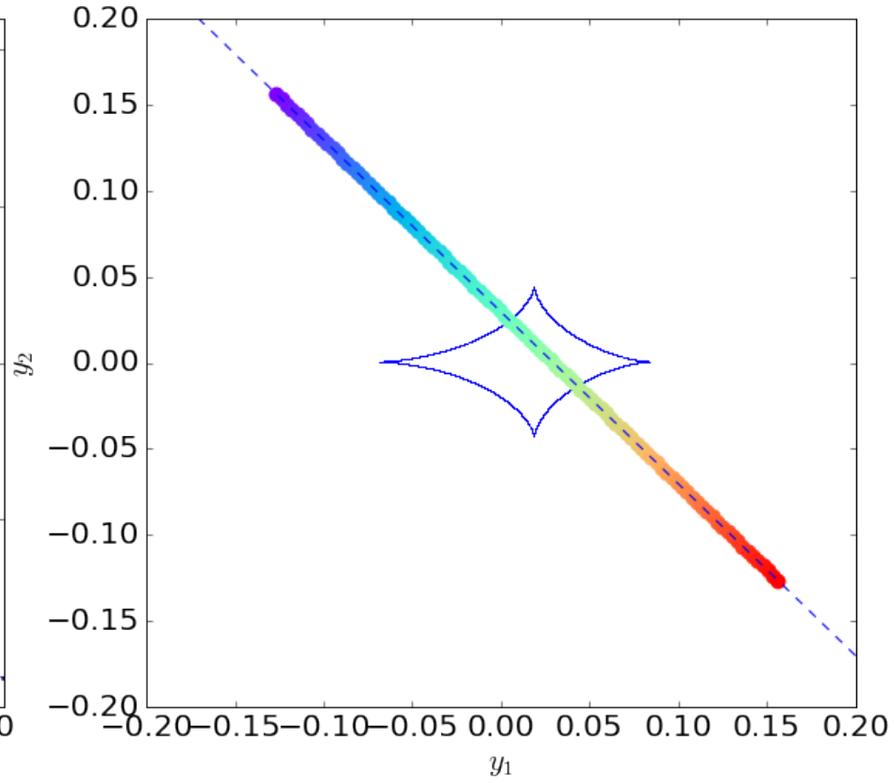
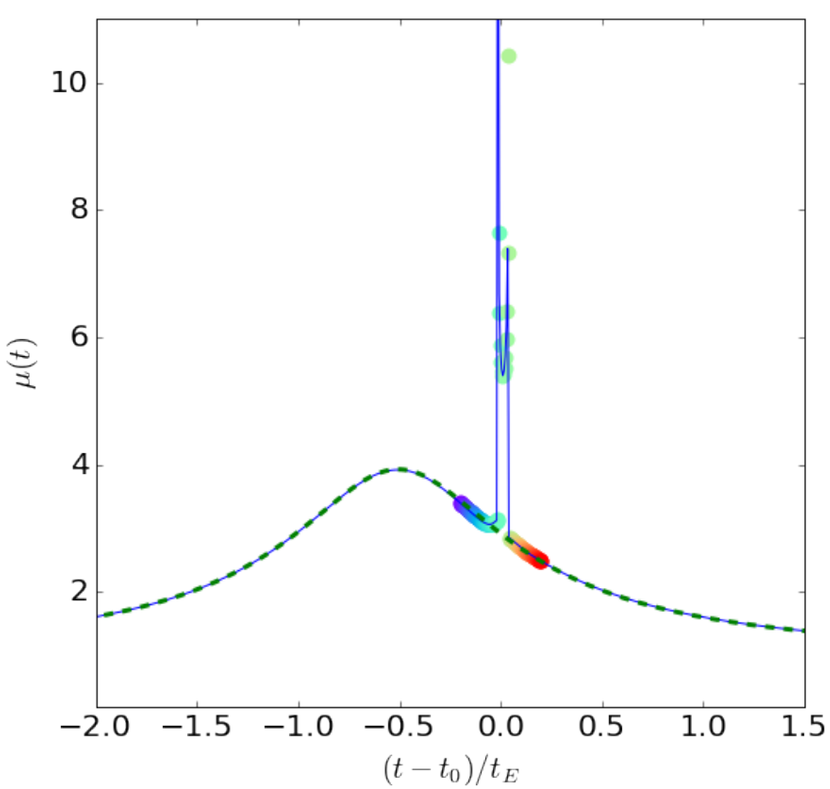


PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES

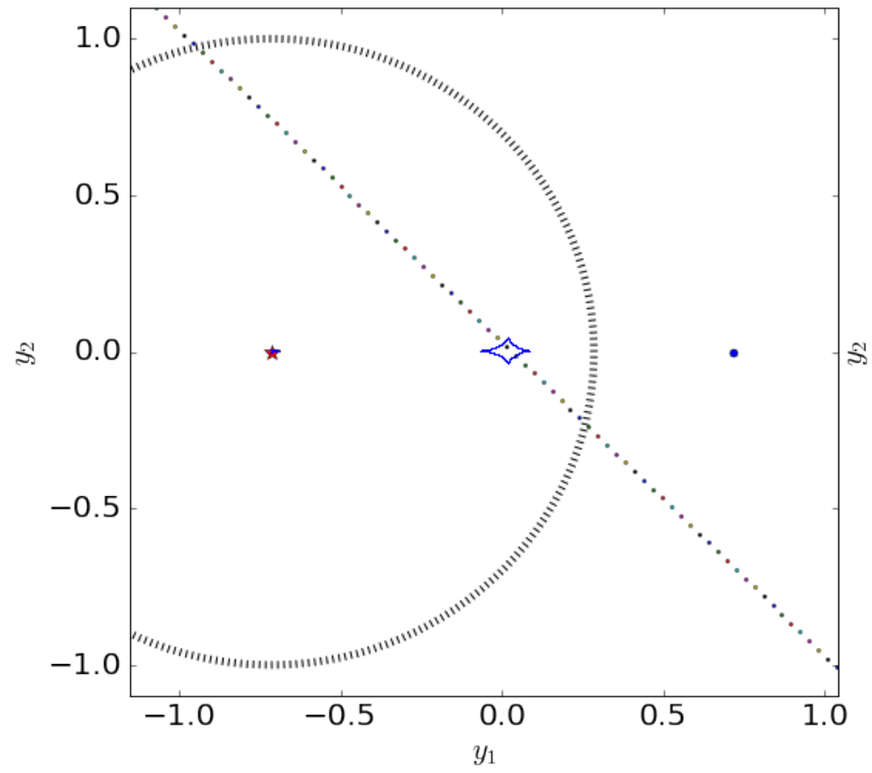


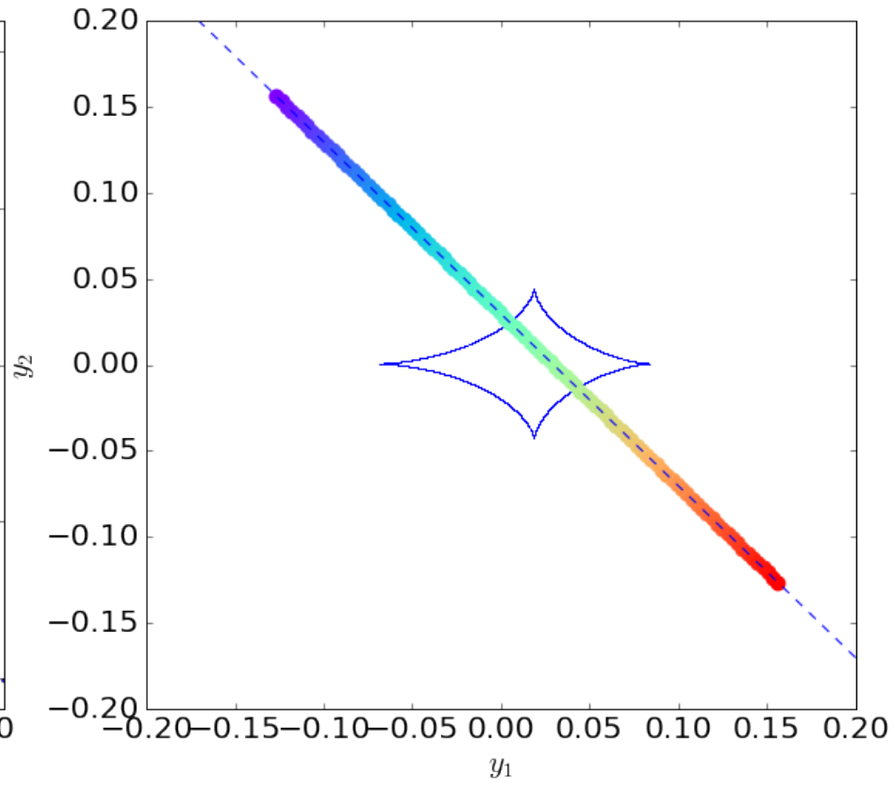


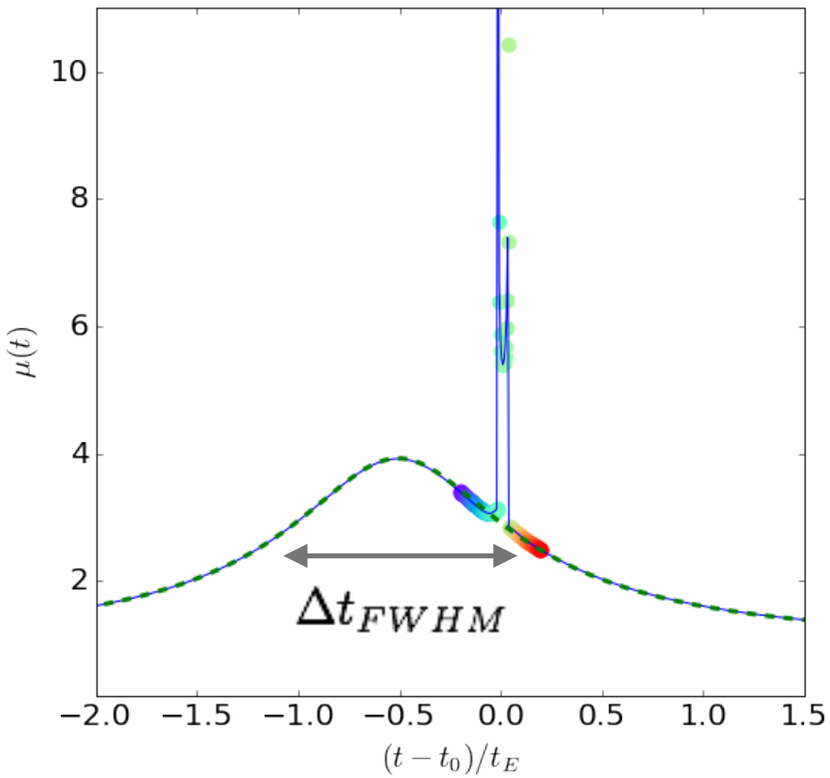


- primary event:
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

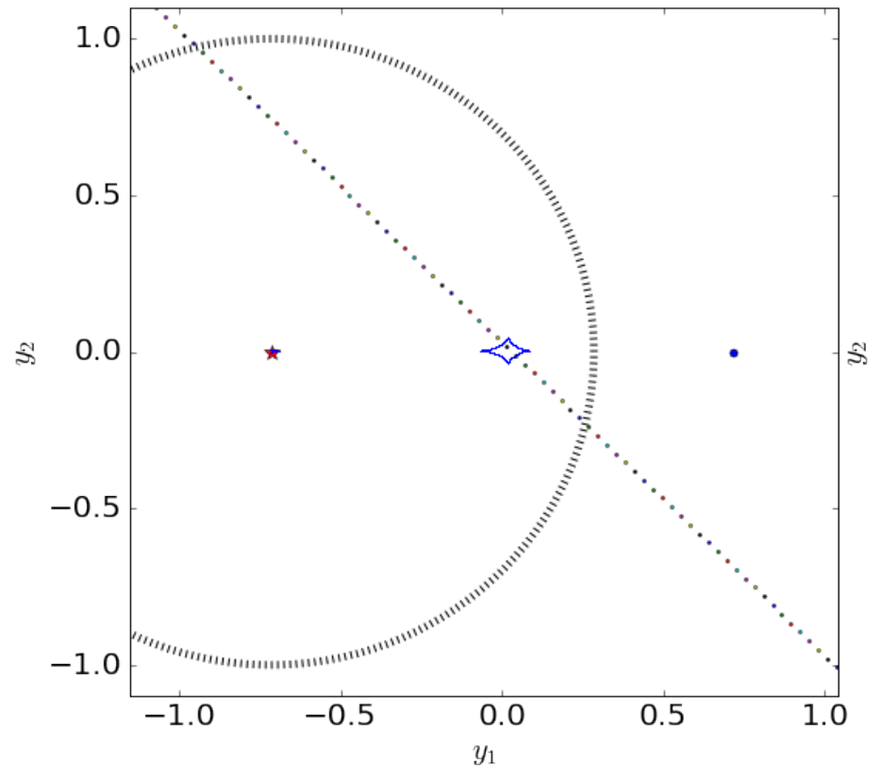


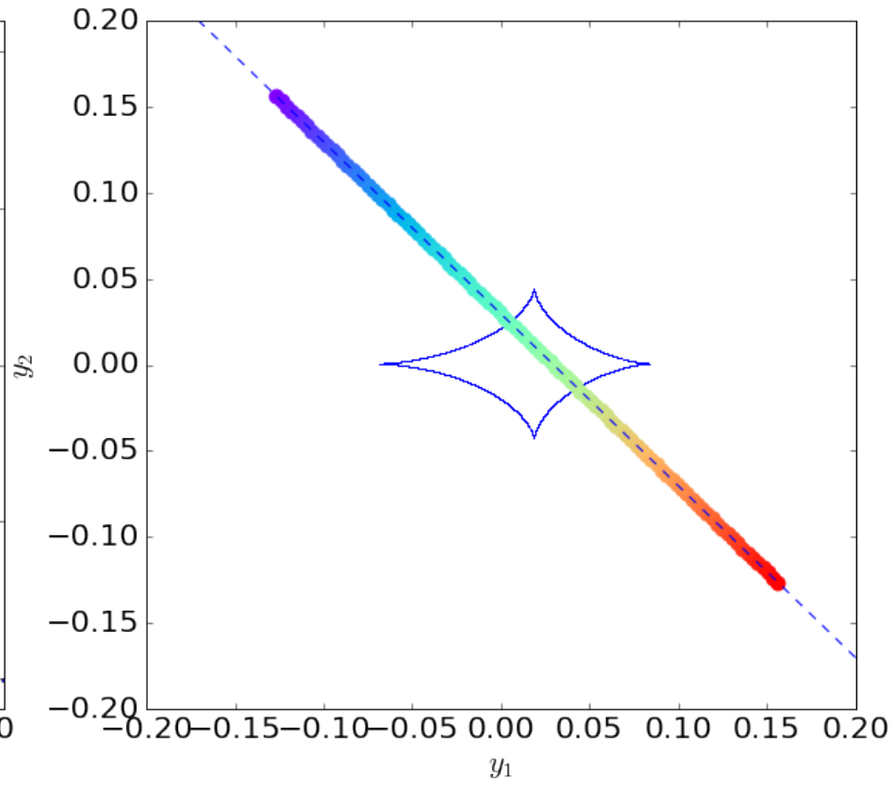


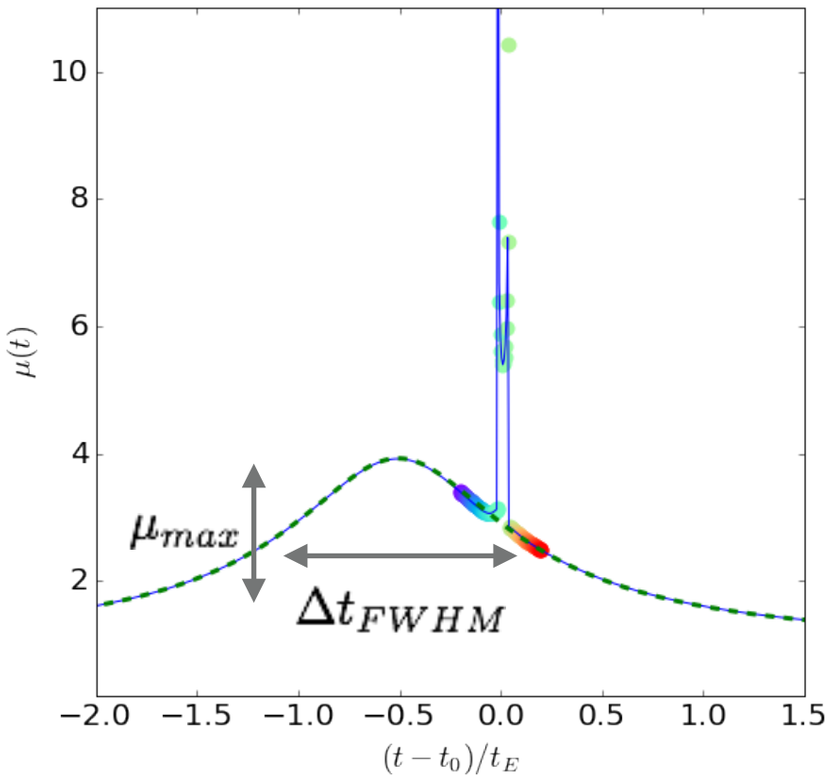


- primary event: Δt_{FWHM}
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

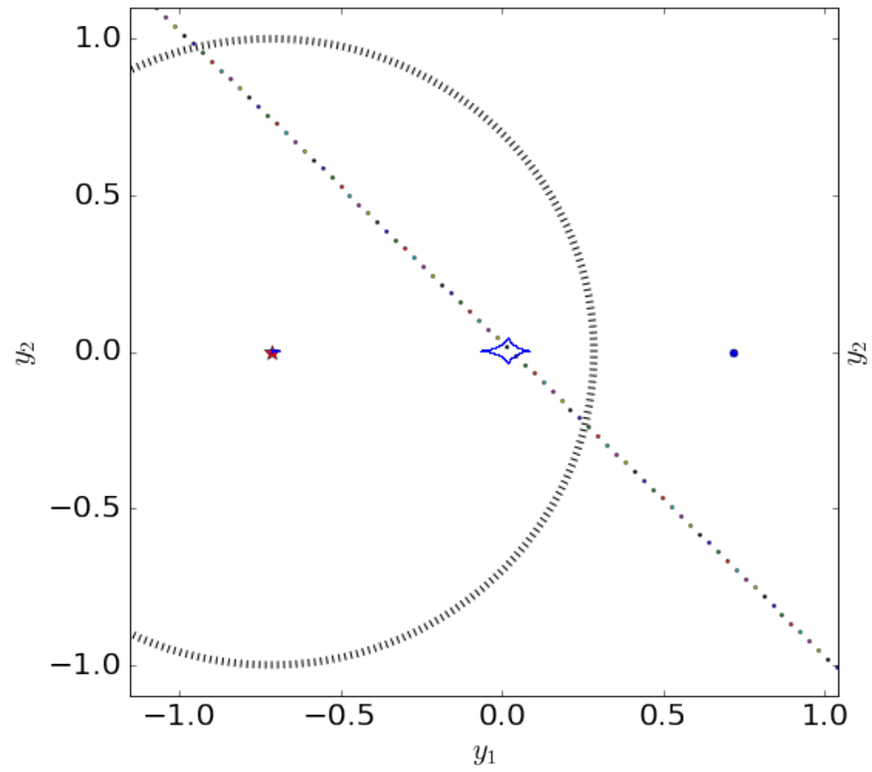


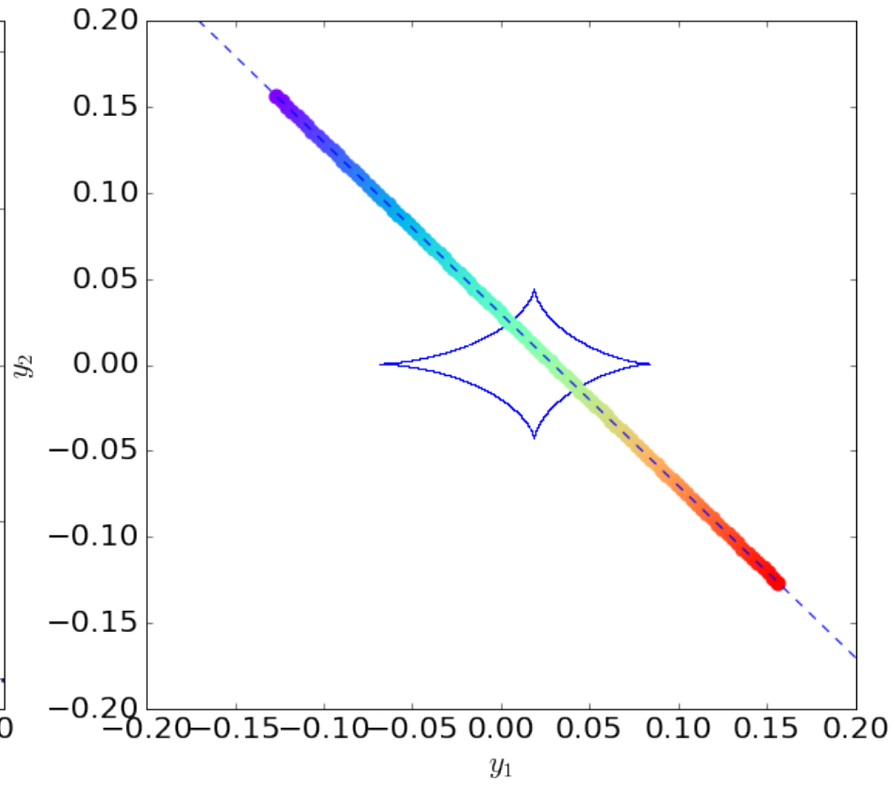


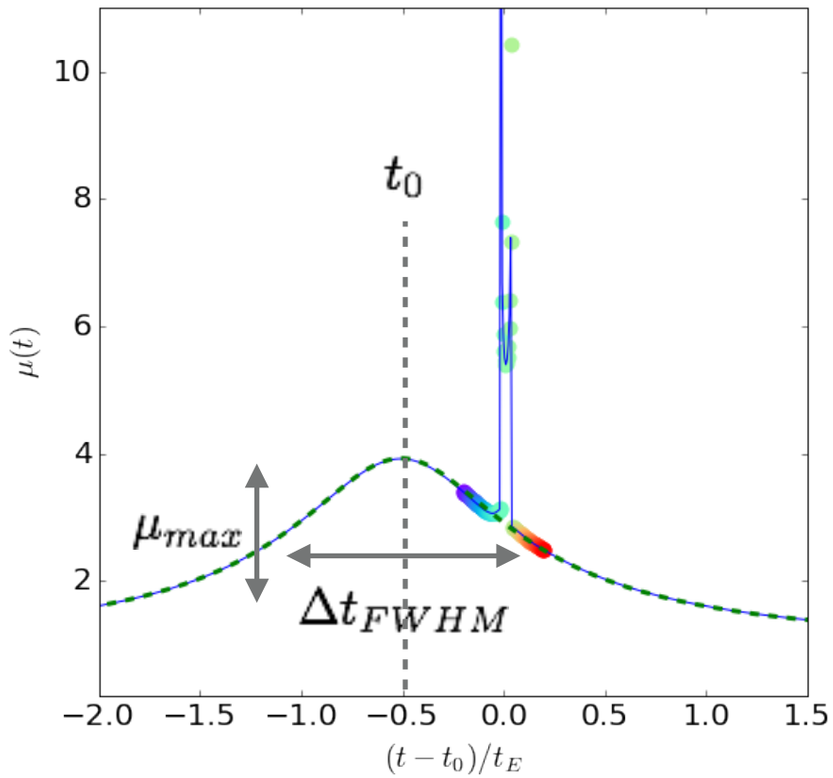


- primary event: Δt_{FWHM} μ_{max}
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES







- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation:

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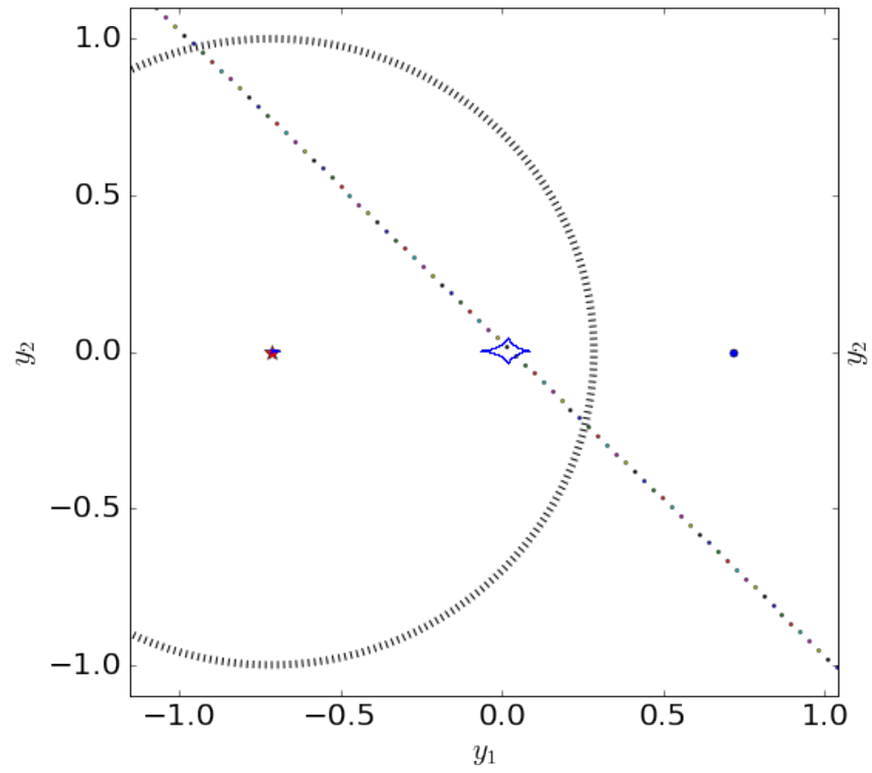

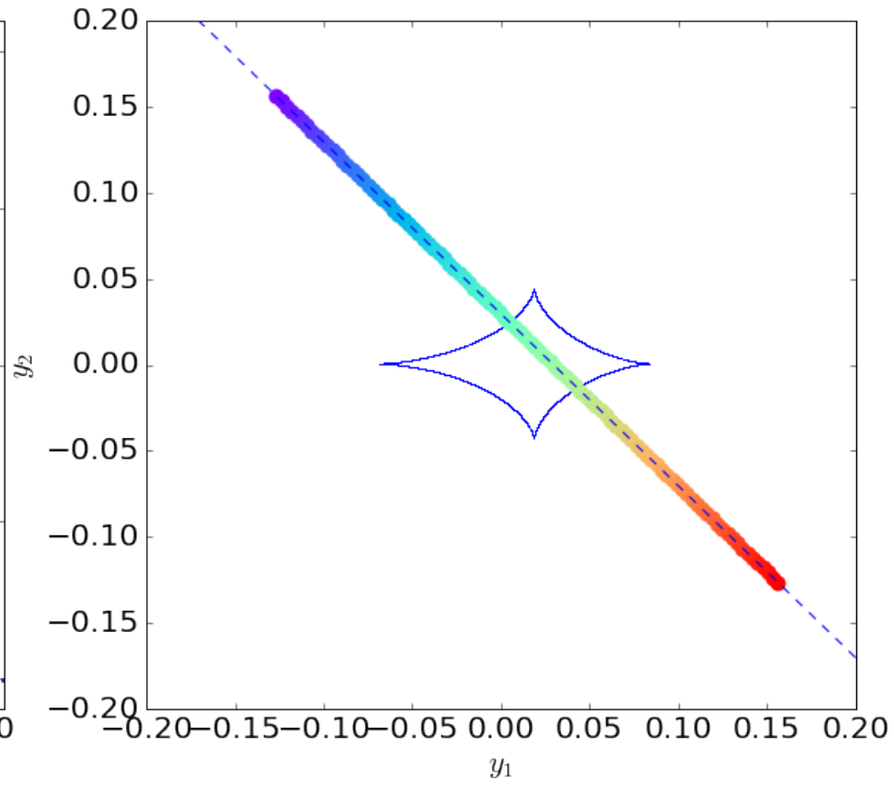

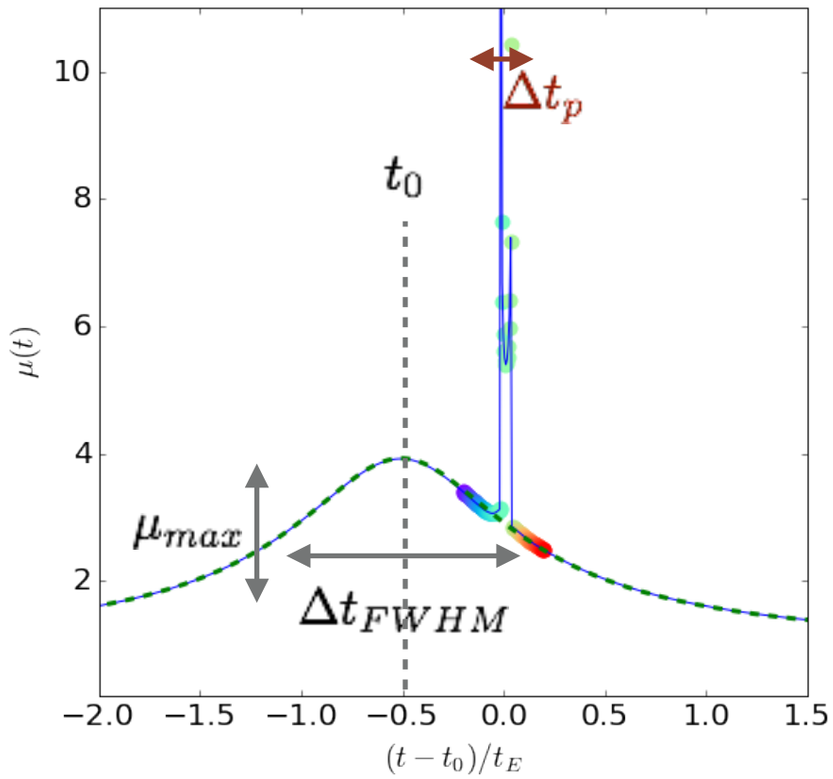

- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p

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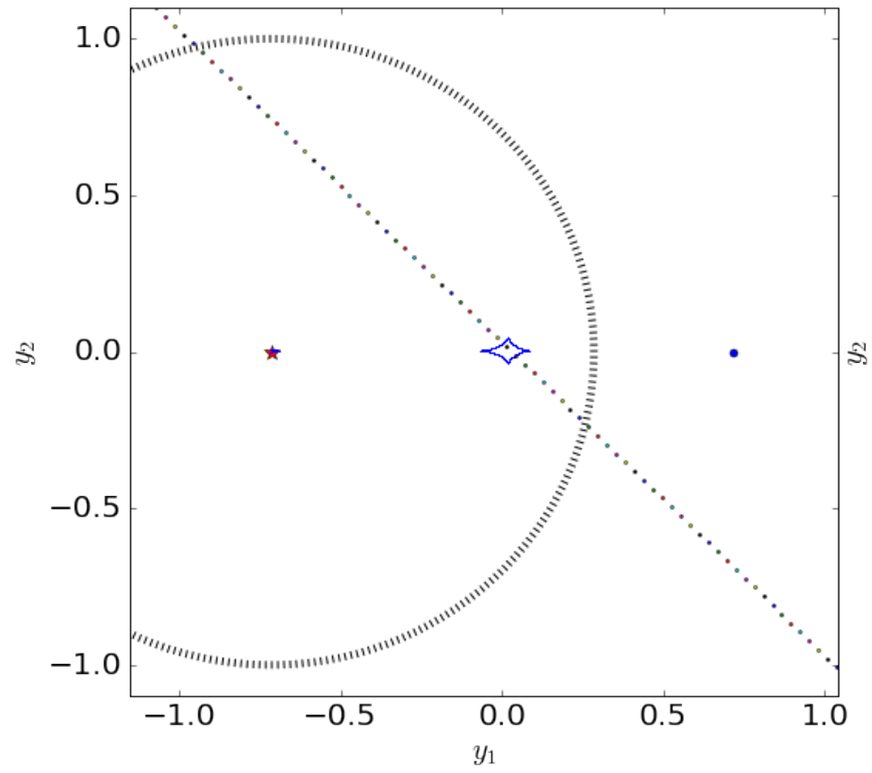
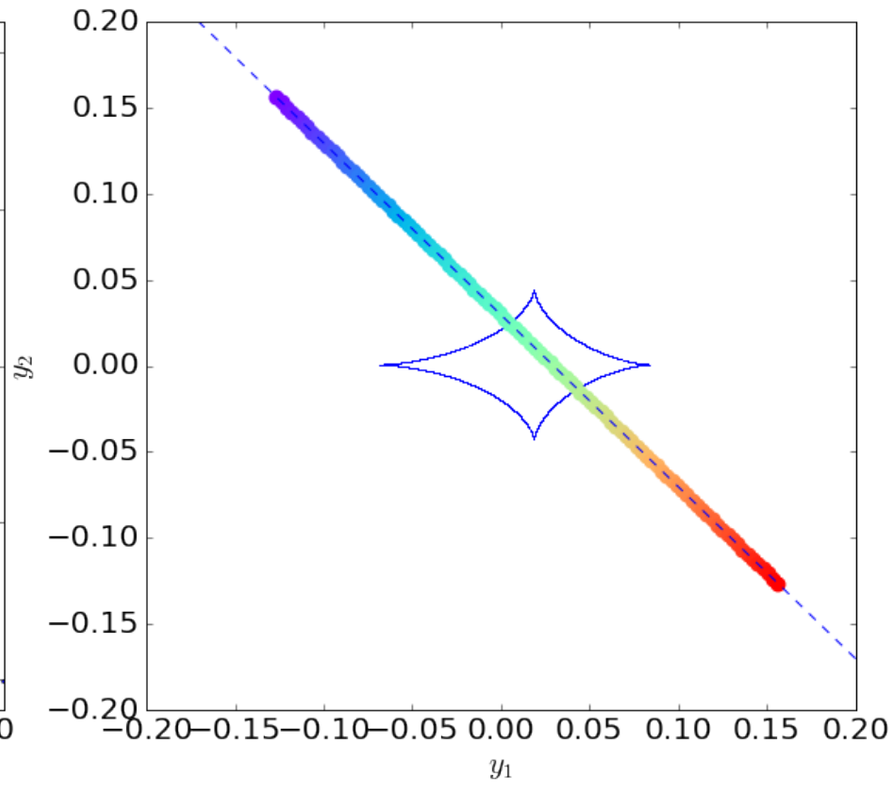
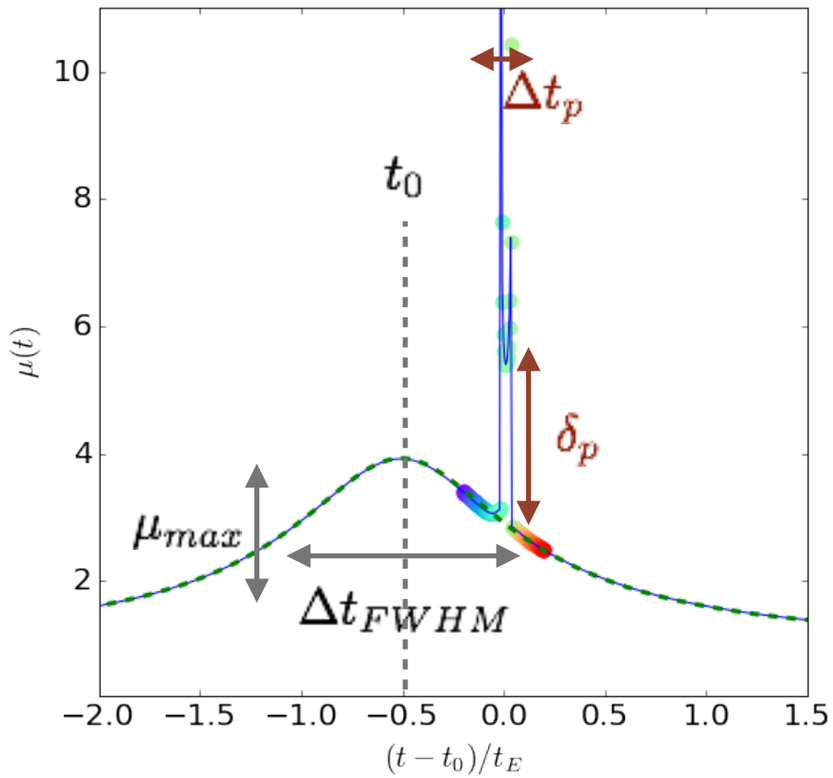
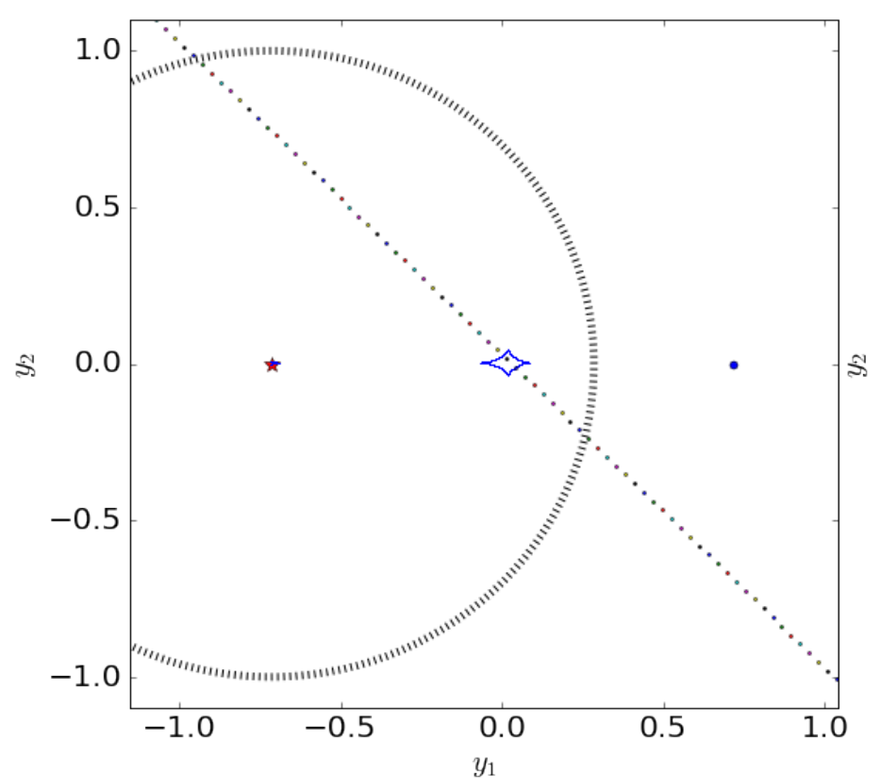


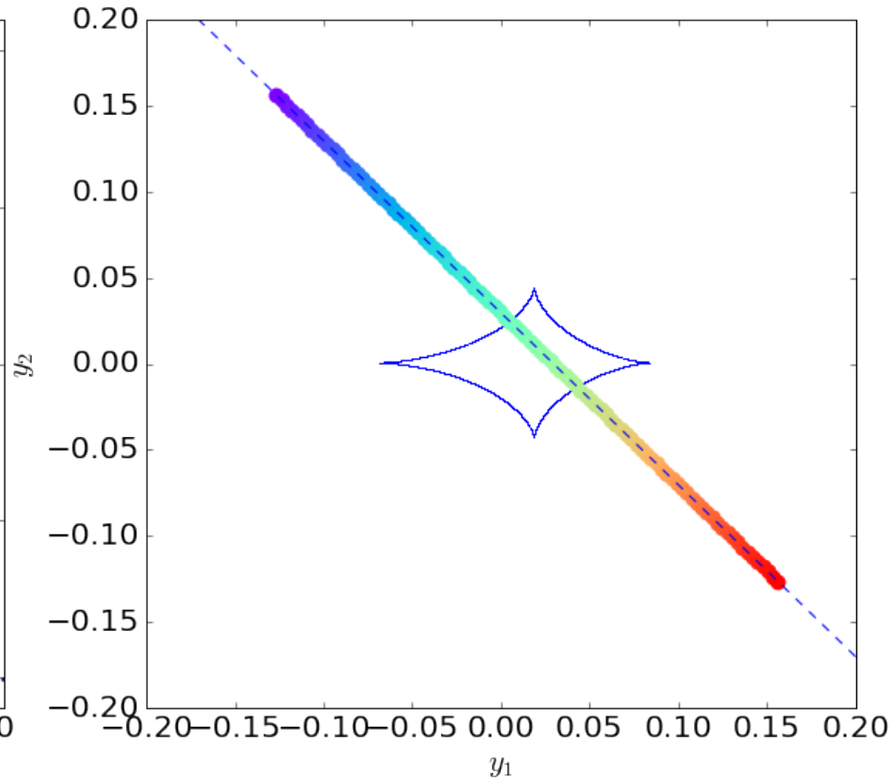


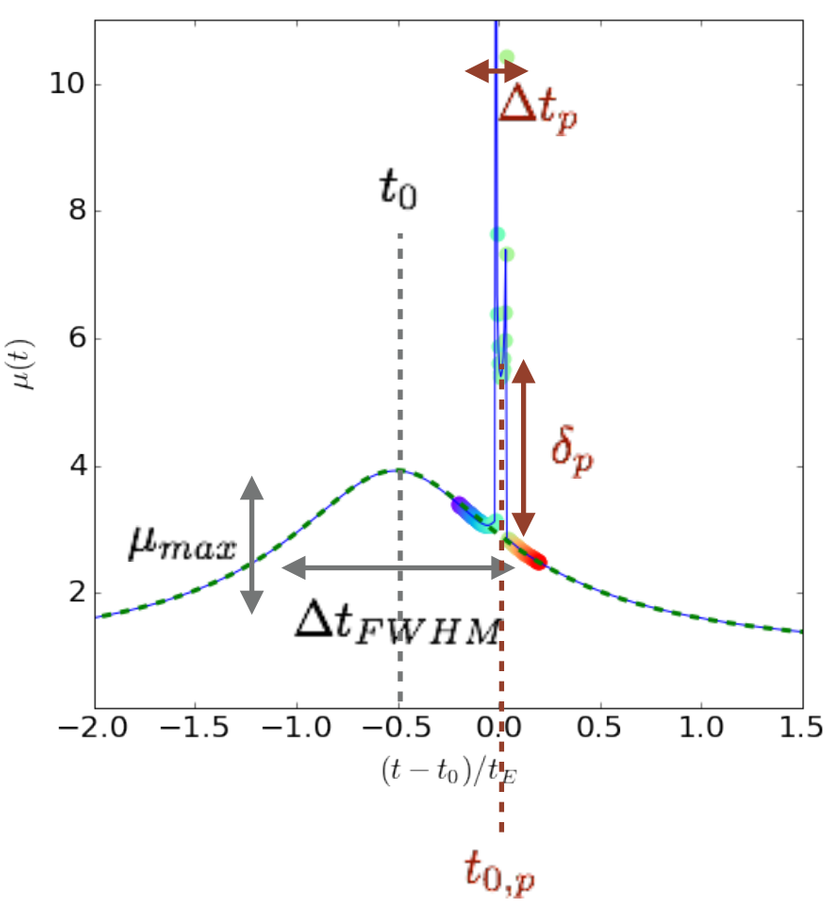


- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p δ_p

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

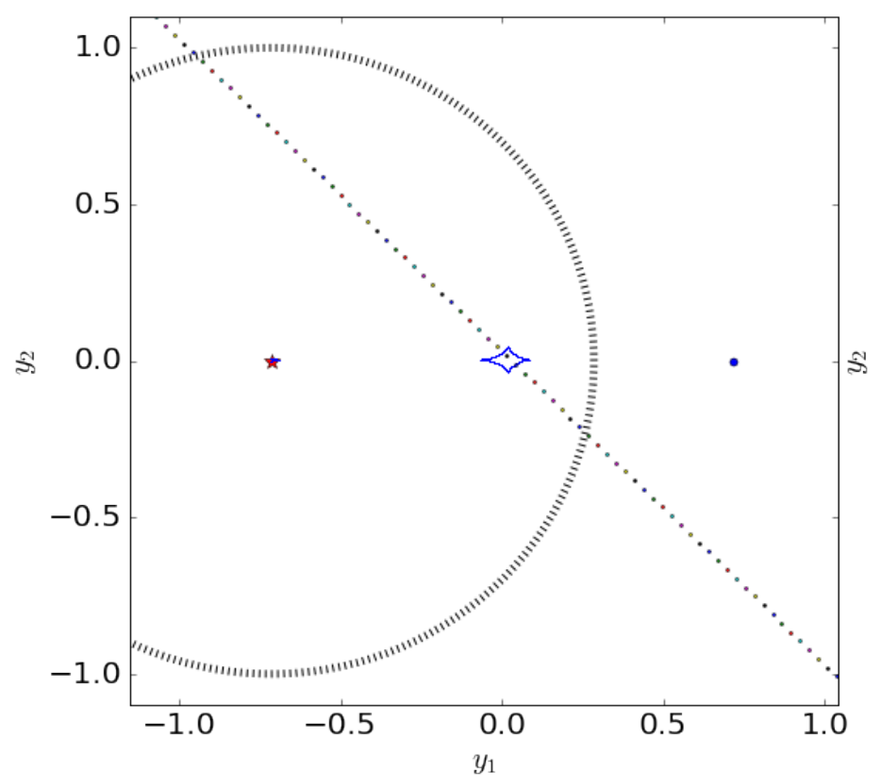


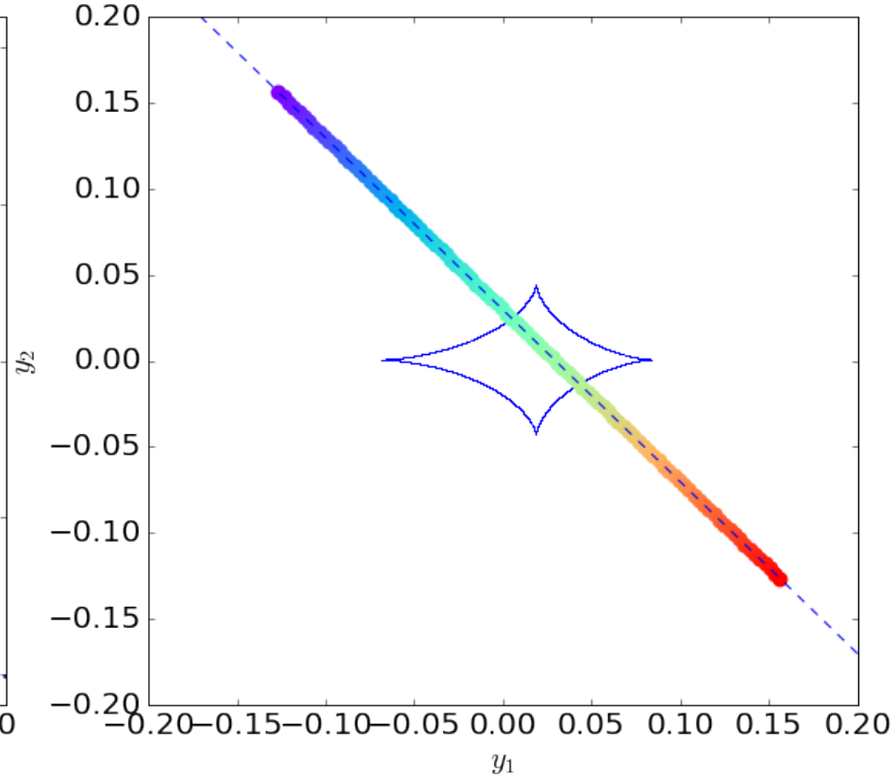


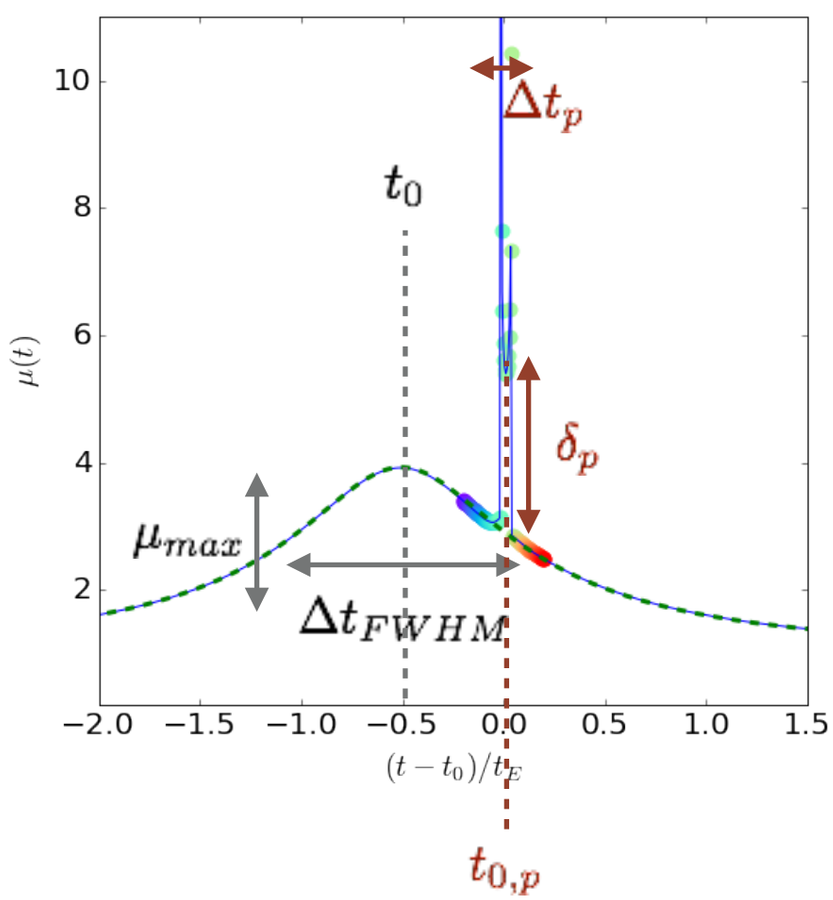


- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p δ_p $t_{0,p}$

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES







$$\Delta t_{FWHM},\ \mu_{max},\ t_0 \ \Rightarrow\ \mu(y) = \frac{y^2+2}{y\sqrt{y^2+4}} \qquad y(t) = \sqrt{y_0^2 + \left(\frac{t-t_0}{t_E}\right)^2}$$

$$\Rightarrow \quad y_0 \quad t_E$$

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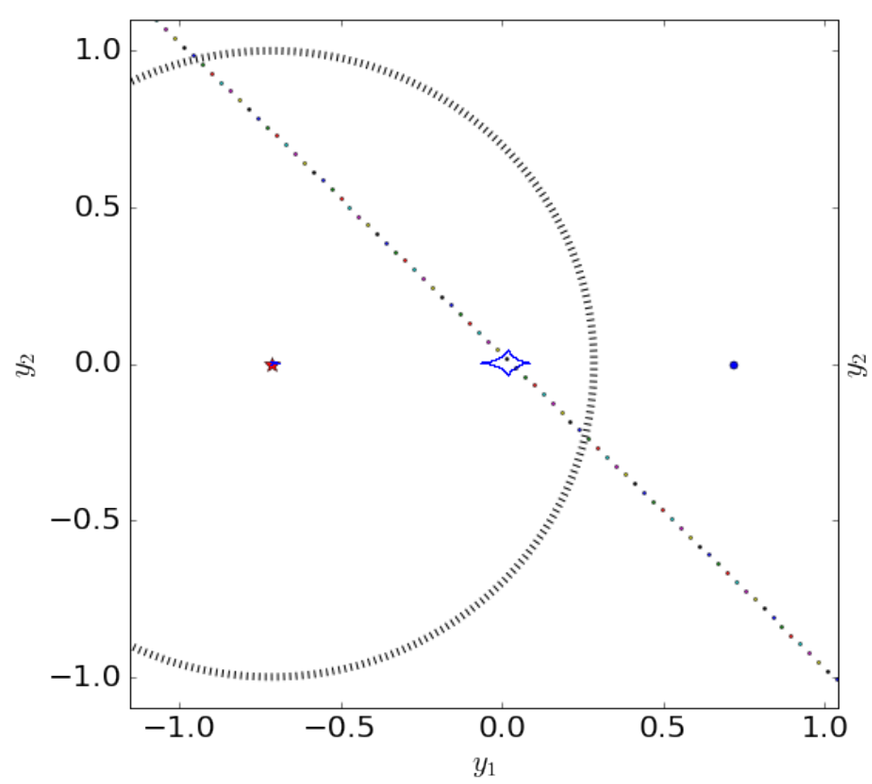
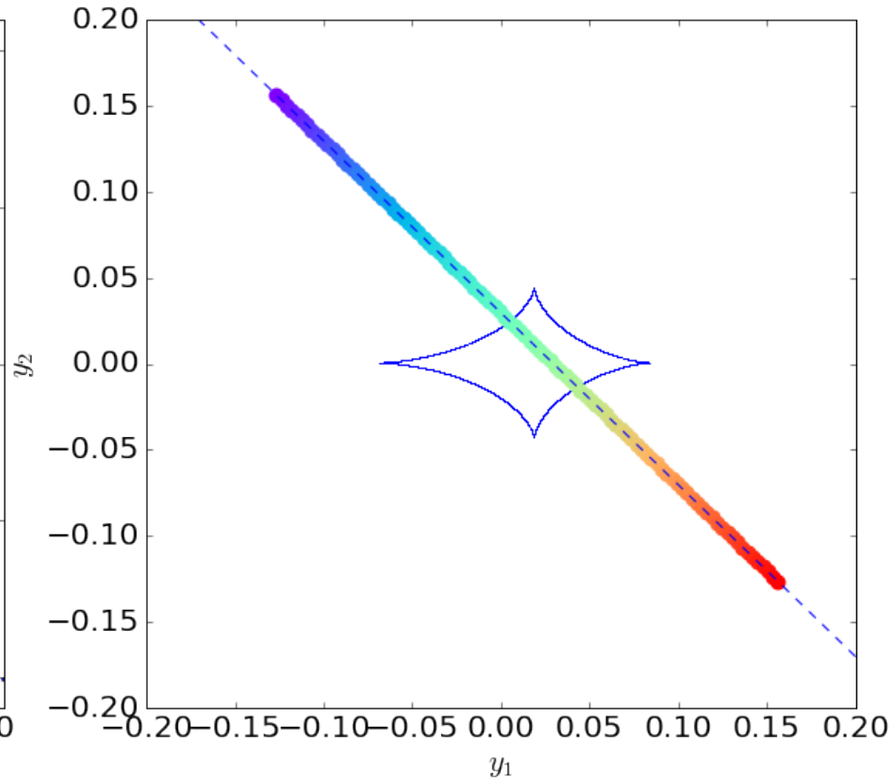
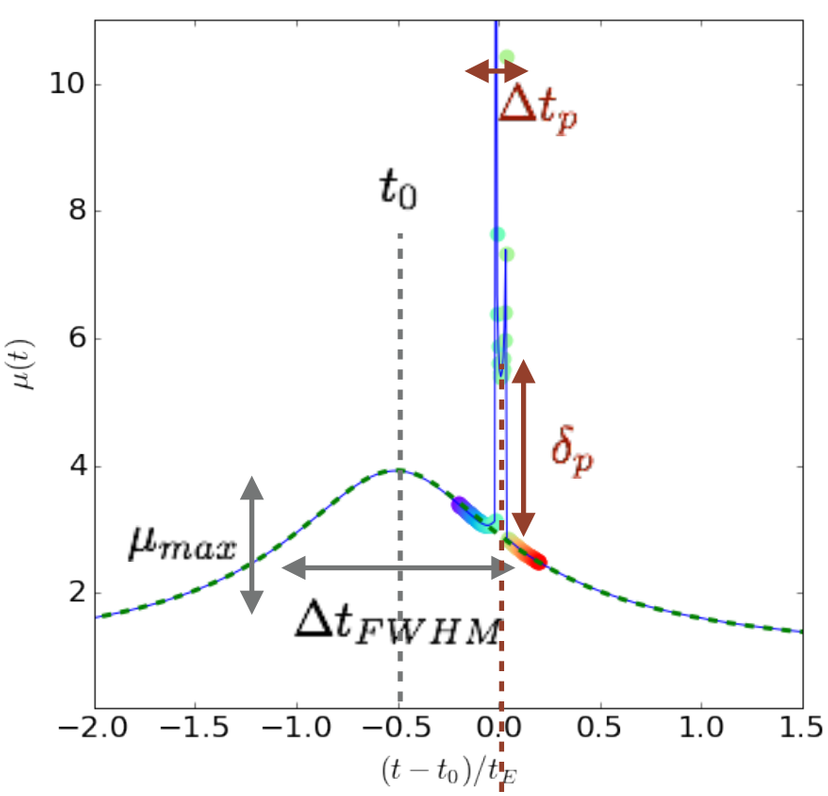
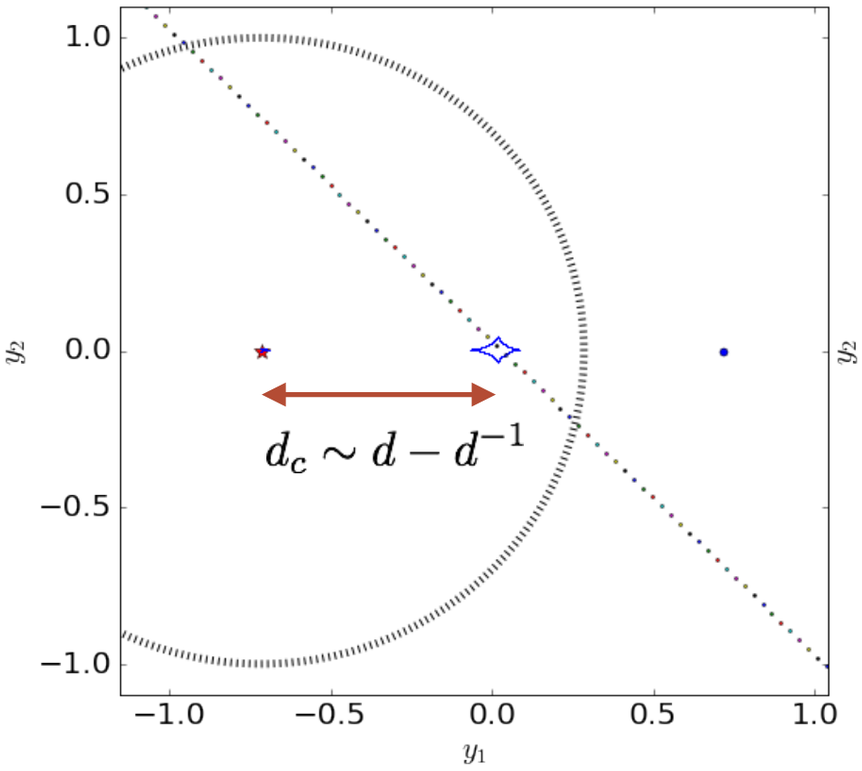


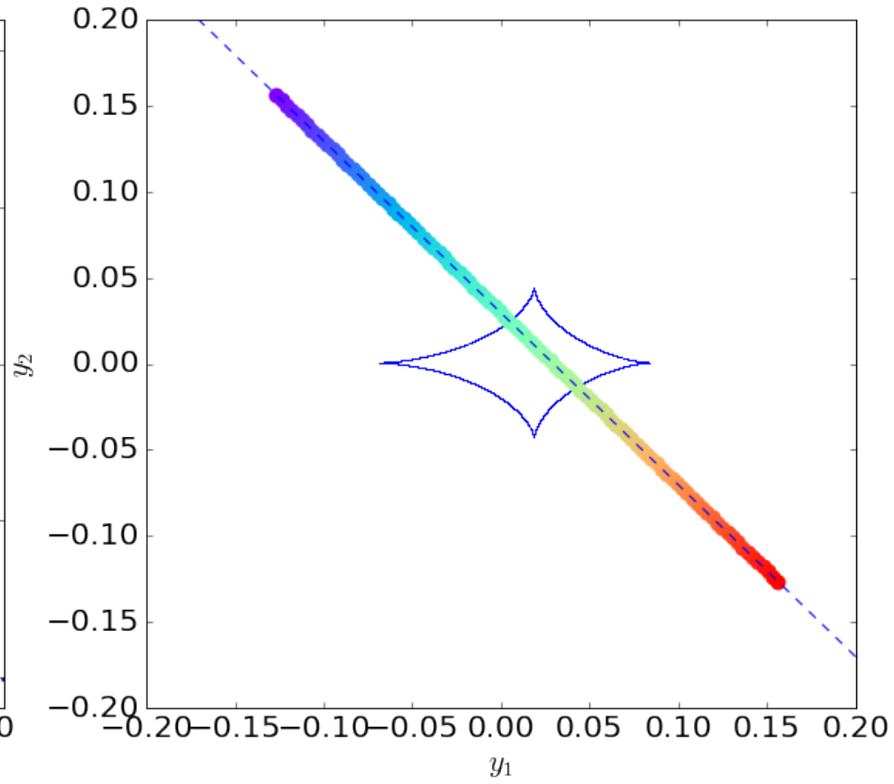


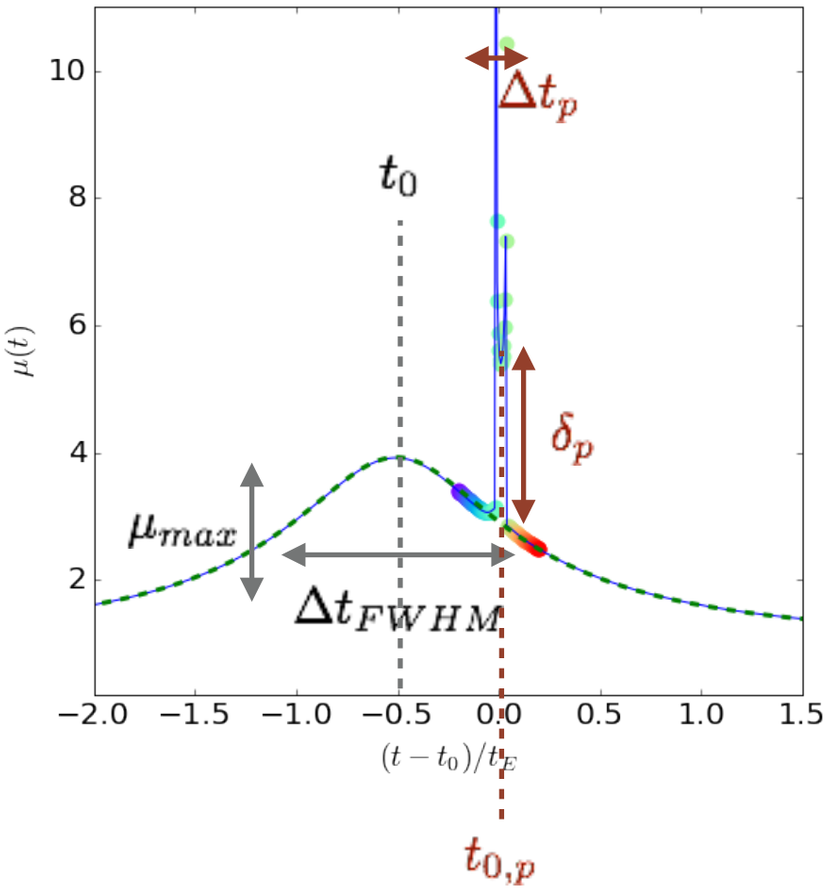


$$\Delta t_p \sim t_{E,p} \quad \Rightarrow t_E \Rightarrow \quad q = \left(\frac{t_{E,p}}{t_E} \right)^2$$

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES





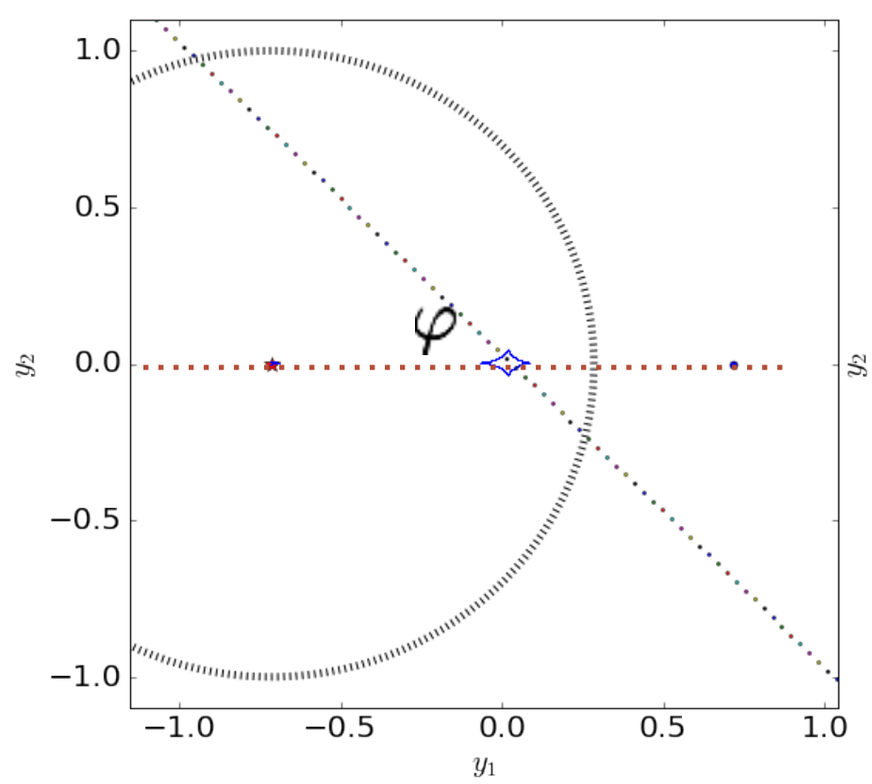


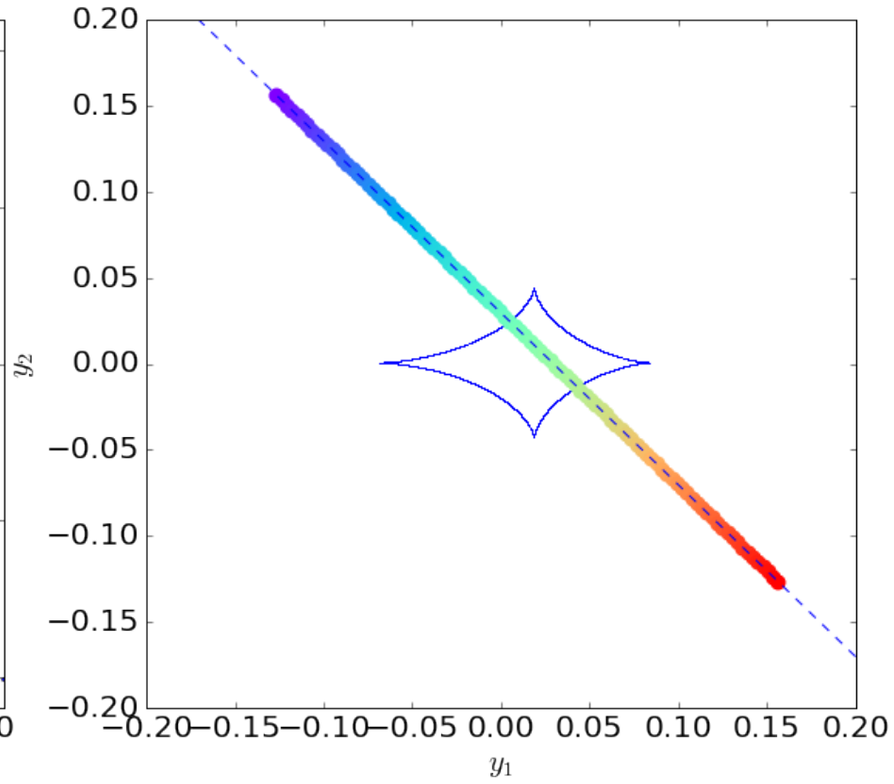
$$t_{0,p} \Rightarrow \; y_p = \sqrt{y_0^2 + \left(\frac{t_{0,p} - t_0}{t_E}\right)^2}$$

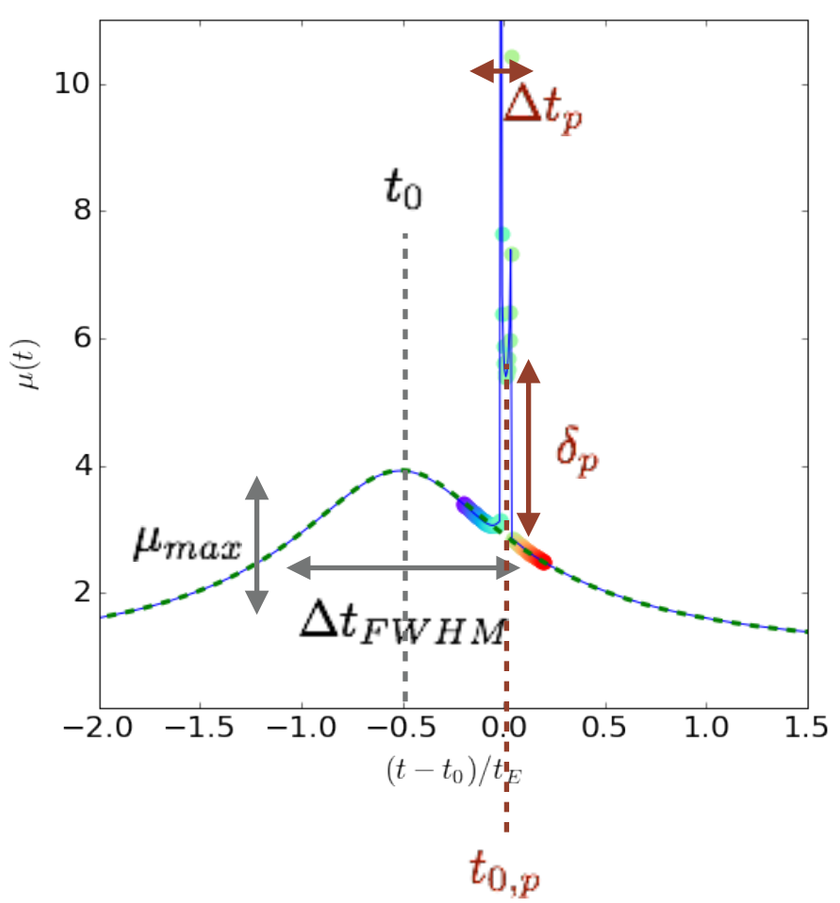
$$\Rightarrow d \sim \frac{y_p \pm \sqrt{y_p^2 + 4}}{2}$$

up to the degeneracy in d

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES





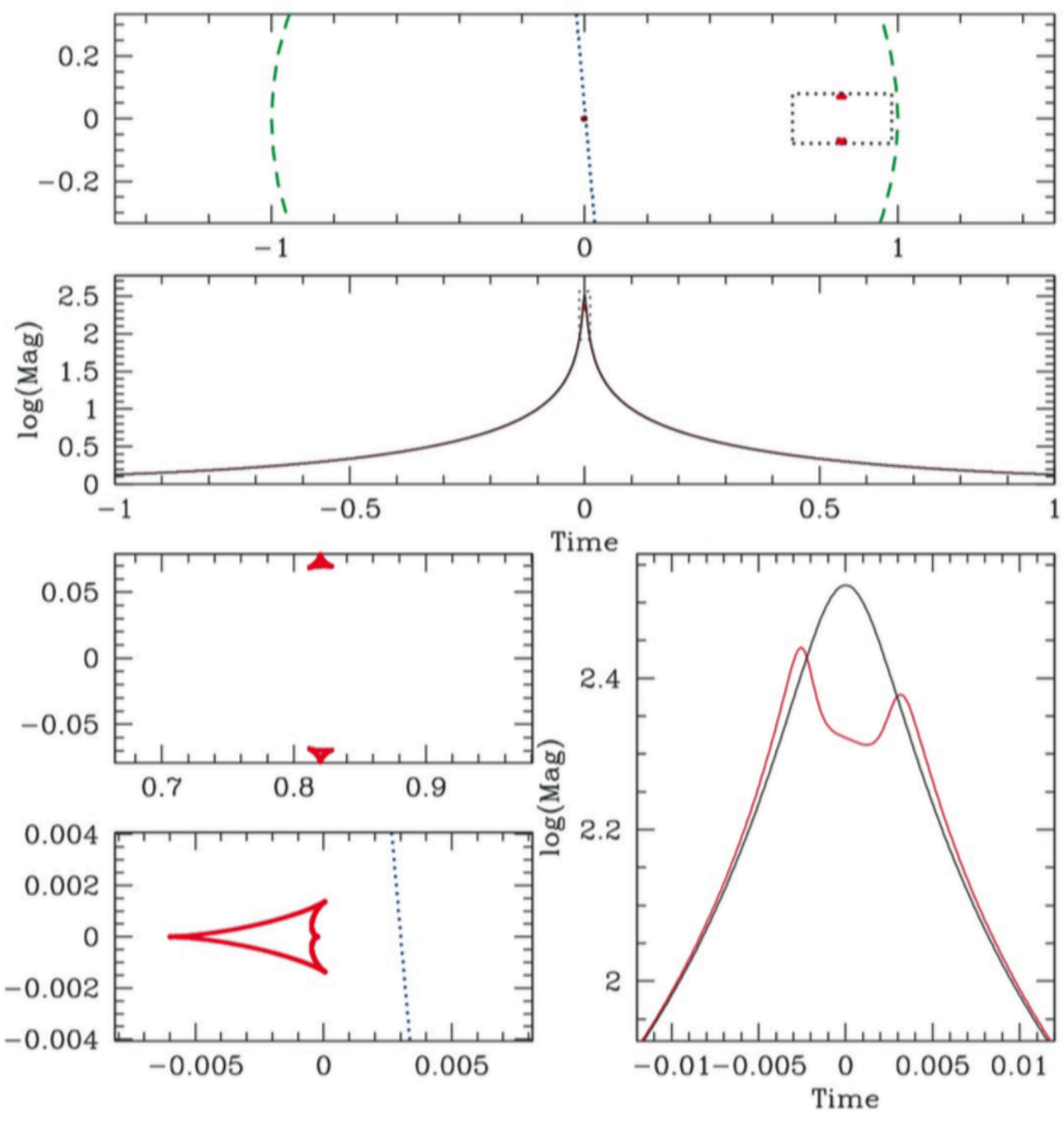


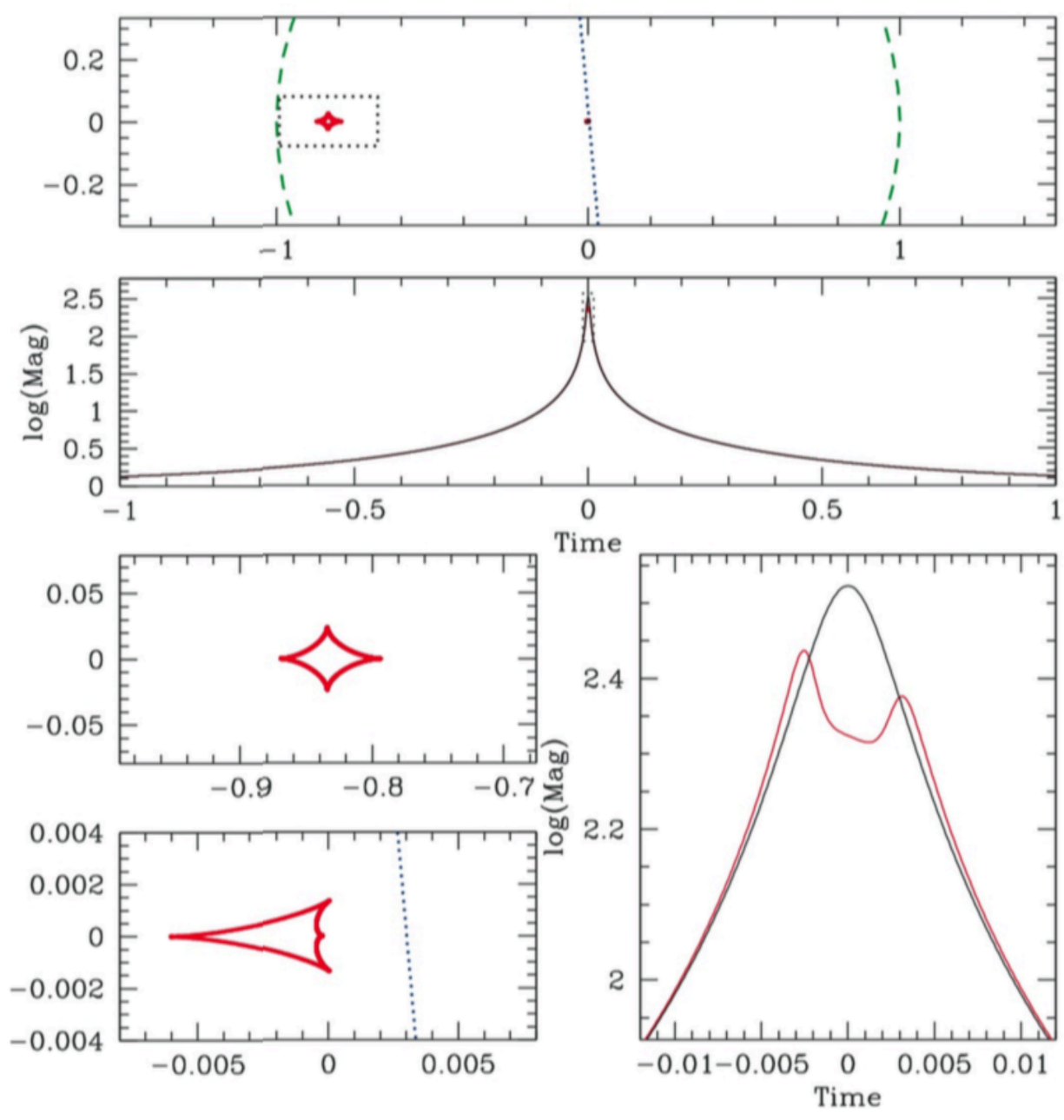
$$y_0, y_p \Rightarrow \varphi = \sin^{-1} \frac{y_0}{y_p}$$

TO SUMMARIZE

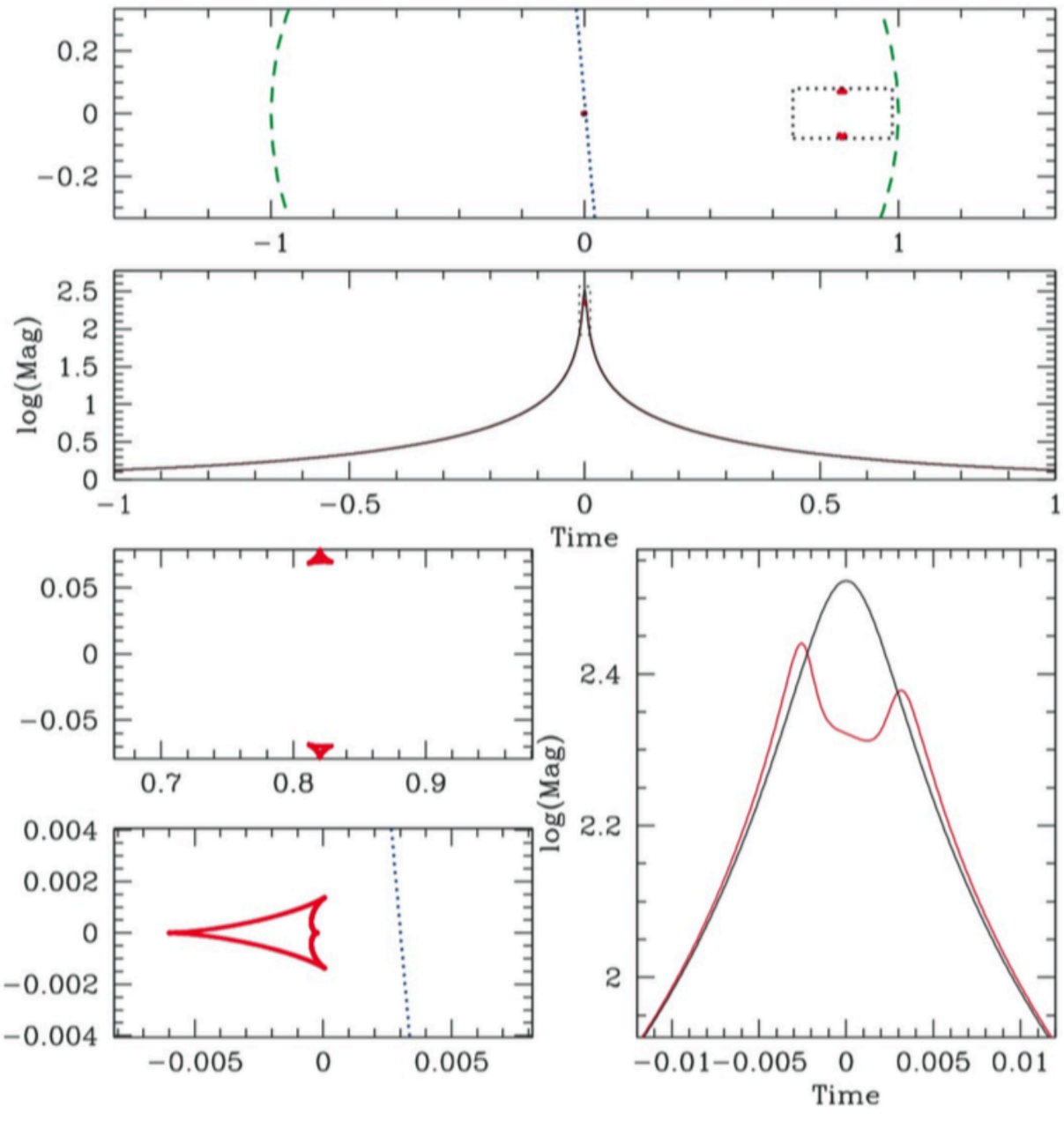
- different caustic topologies give rise to different kind of perturbations on the light curves
- planets can be detected in only a few qualitatively different ways:
  - at relatively low magnification of the primary, if the source crosses the planetary caustics from close or wide planets
  - near the peak of the light curve, if the source has a small impact parameter, in both cases of wide and close planets
  - at modest to high-magnification, through the perturbations from the resonant caustic.
  - in the case of free-floating planets, as single, short time-scale events.

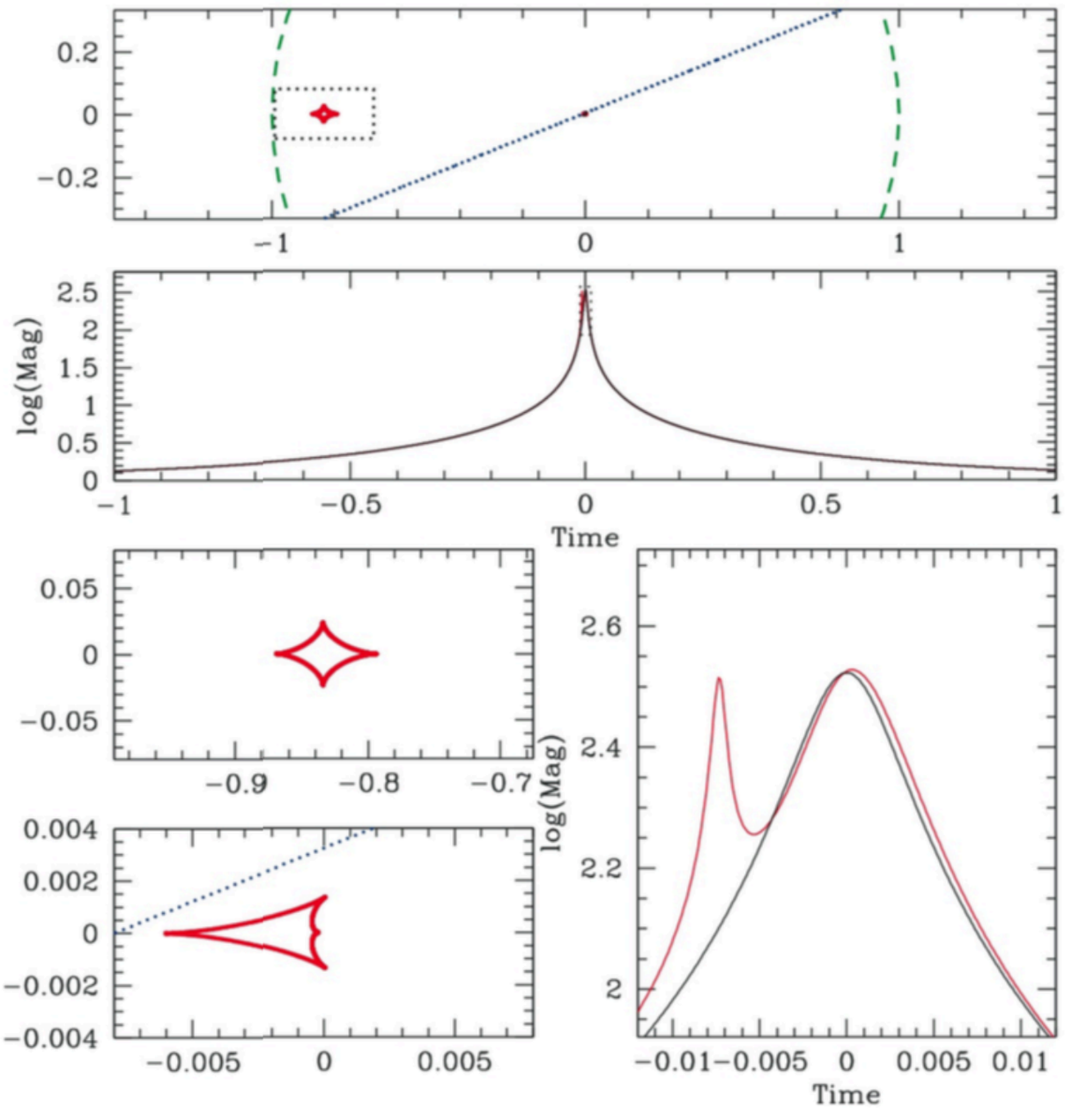
CLOSE–WIDE DEGENERACY





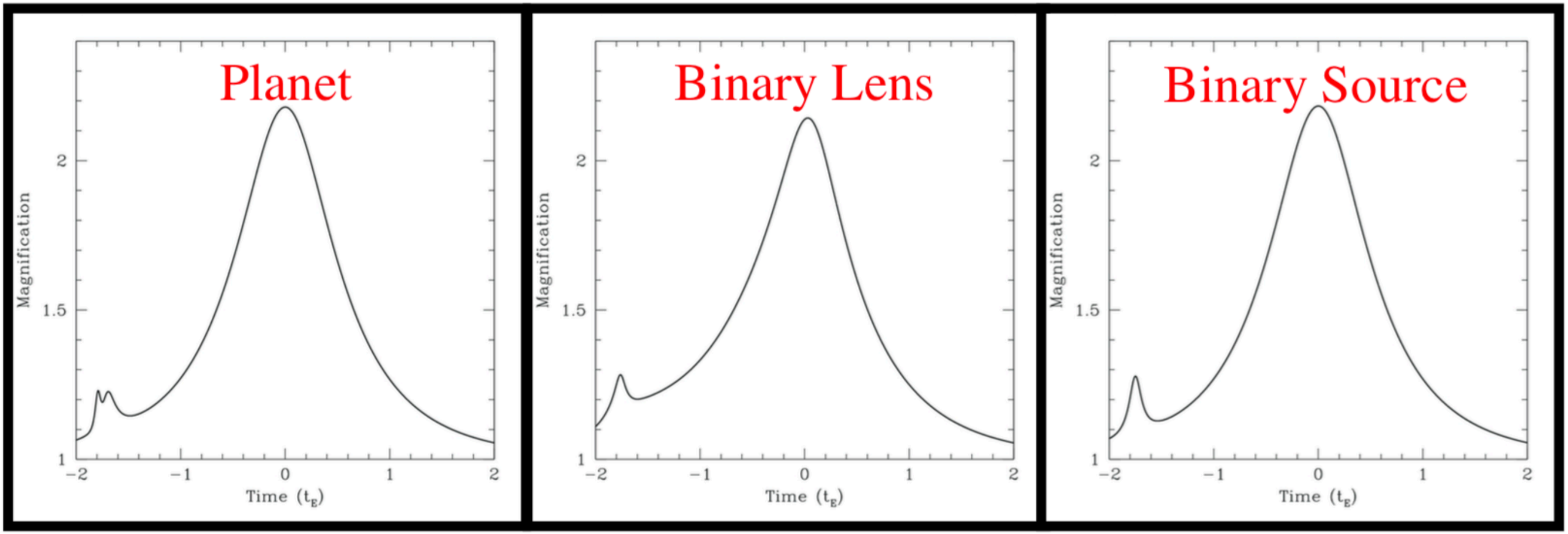
DOUBLE HORN OR BUMP





UNCERTAINTIES: SOME FEATURES CAN BE EXPLAINED IN DIFFERENT WAYS

Short duration deviations in the wings:



Can be caused by:

- *Planets*
- *close binary lenses*
- *extreme flux ratio binary sources (rare)*

Rule: negative deviations are exclusively planets

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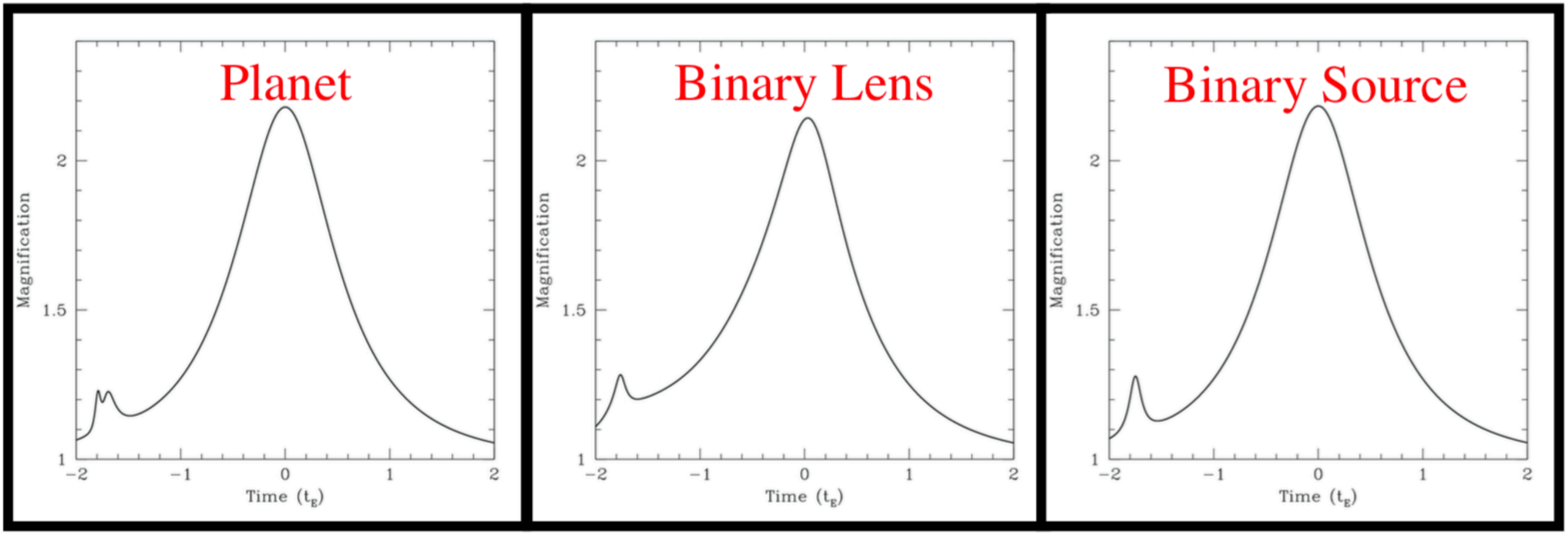

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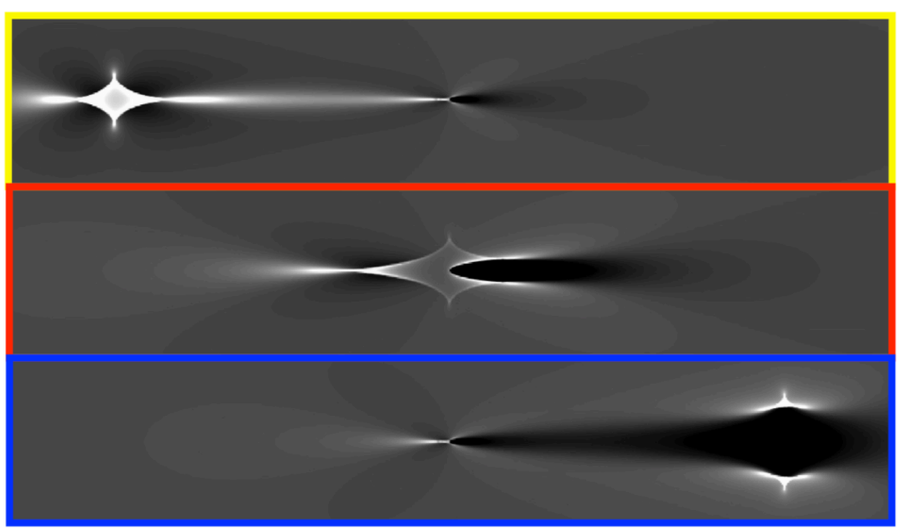

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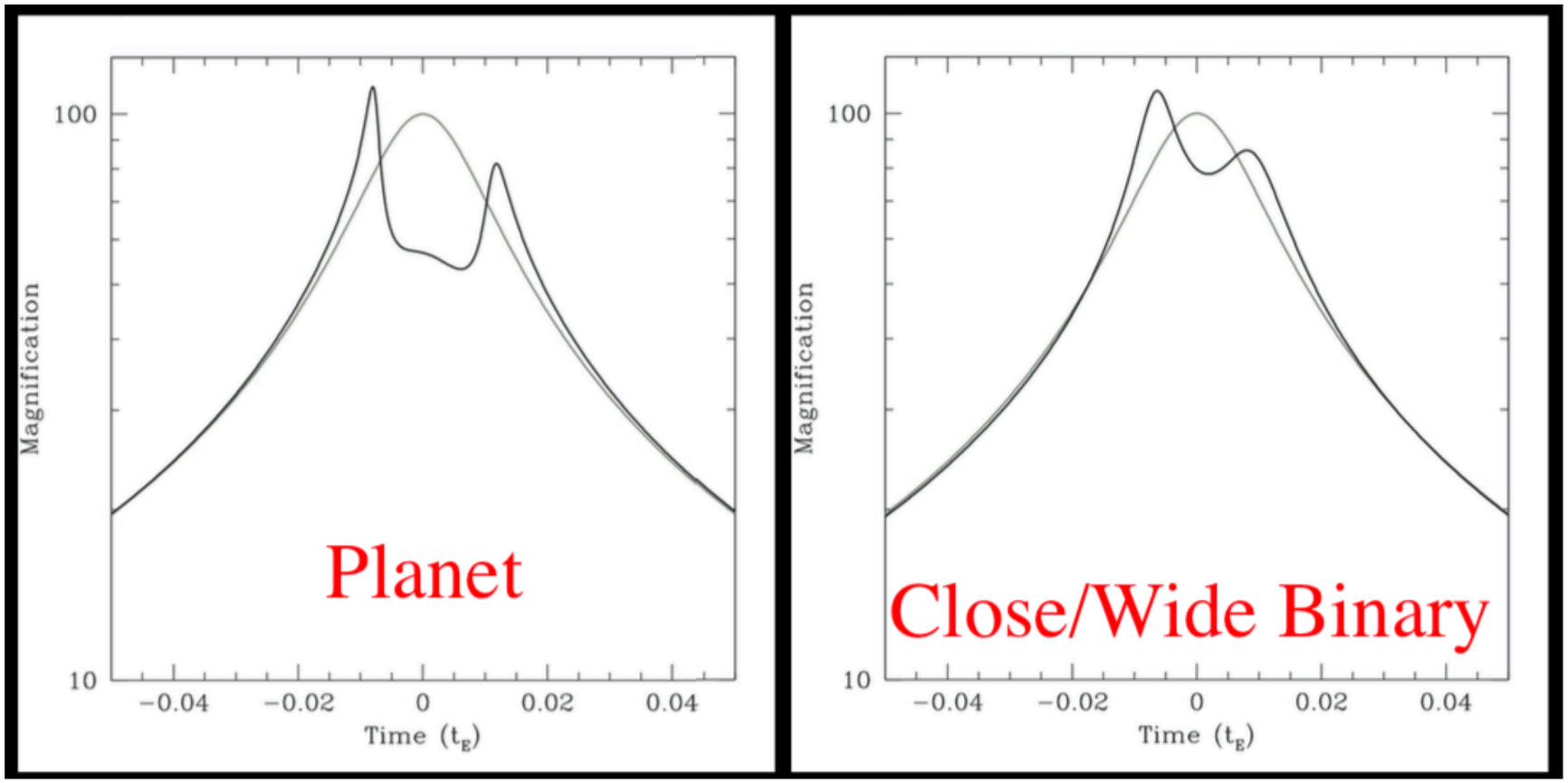
UNCERTAINTIES: SOME FEATURES CAN BE EXPLAINED IN DIFFERENT WAYS

Short duration deviations at the peak:

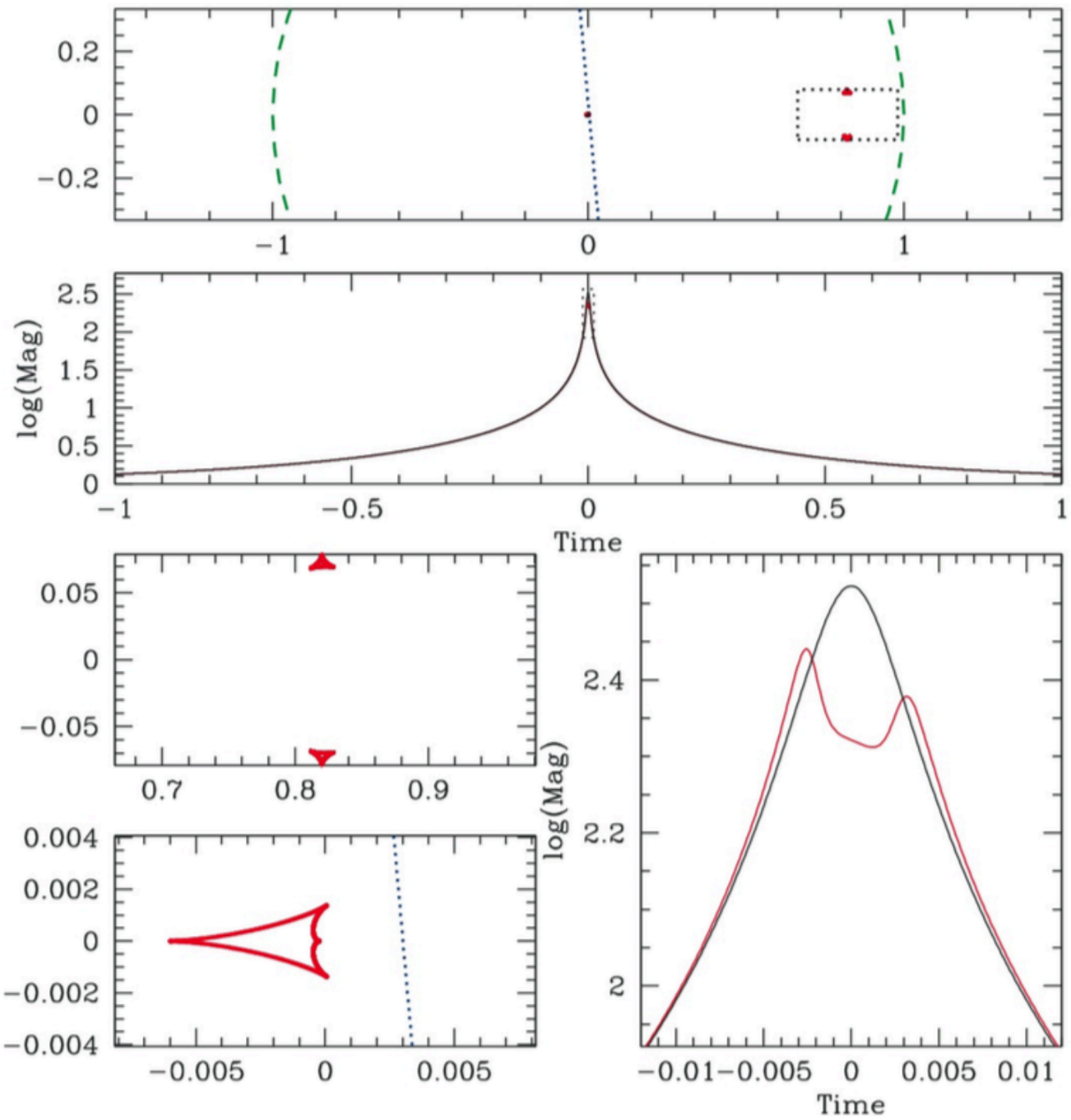


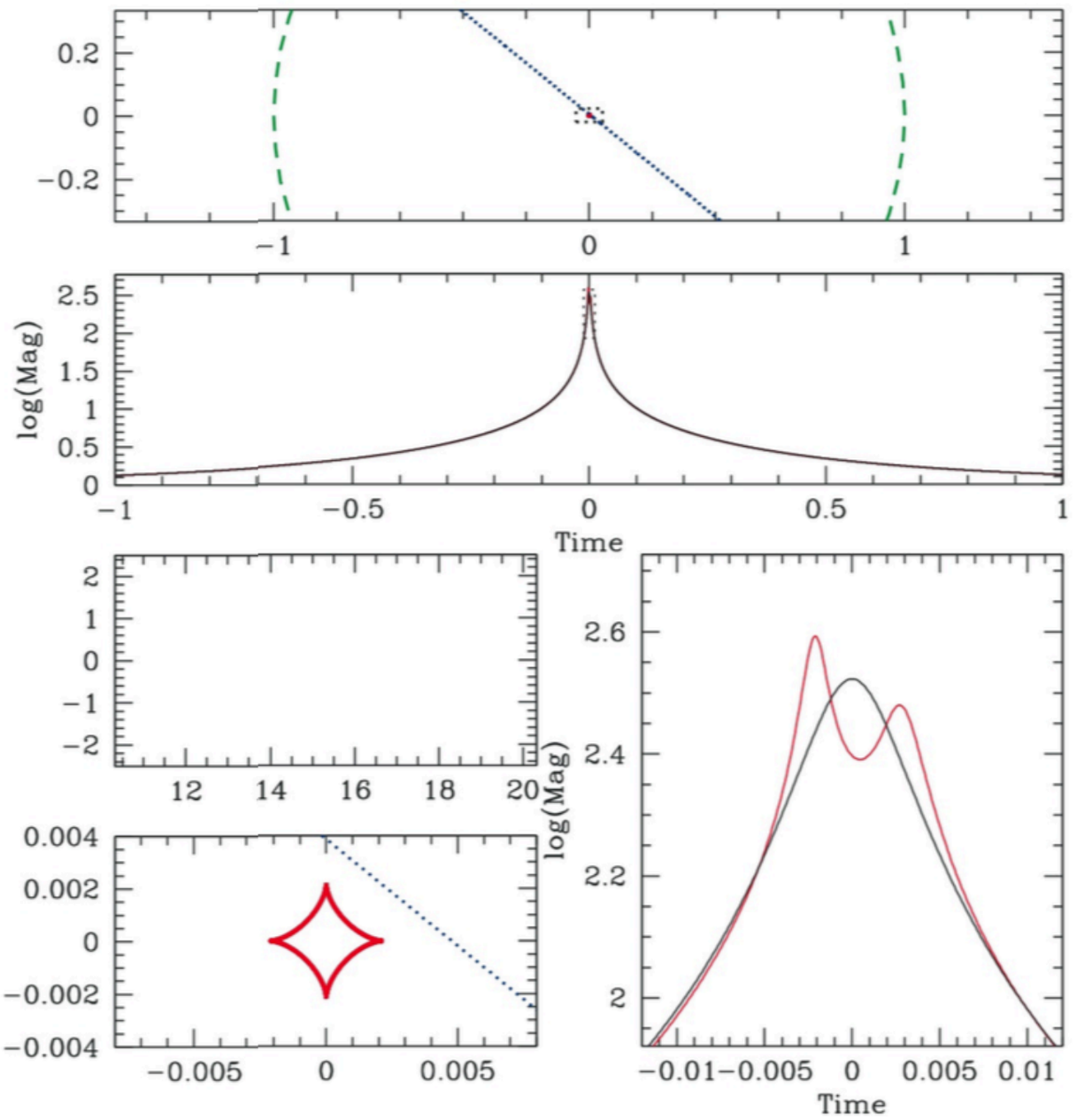
Can be caused by:

- *Planets*
- *very closer or very wide binary lenses*

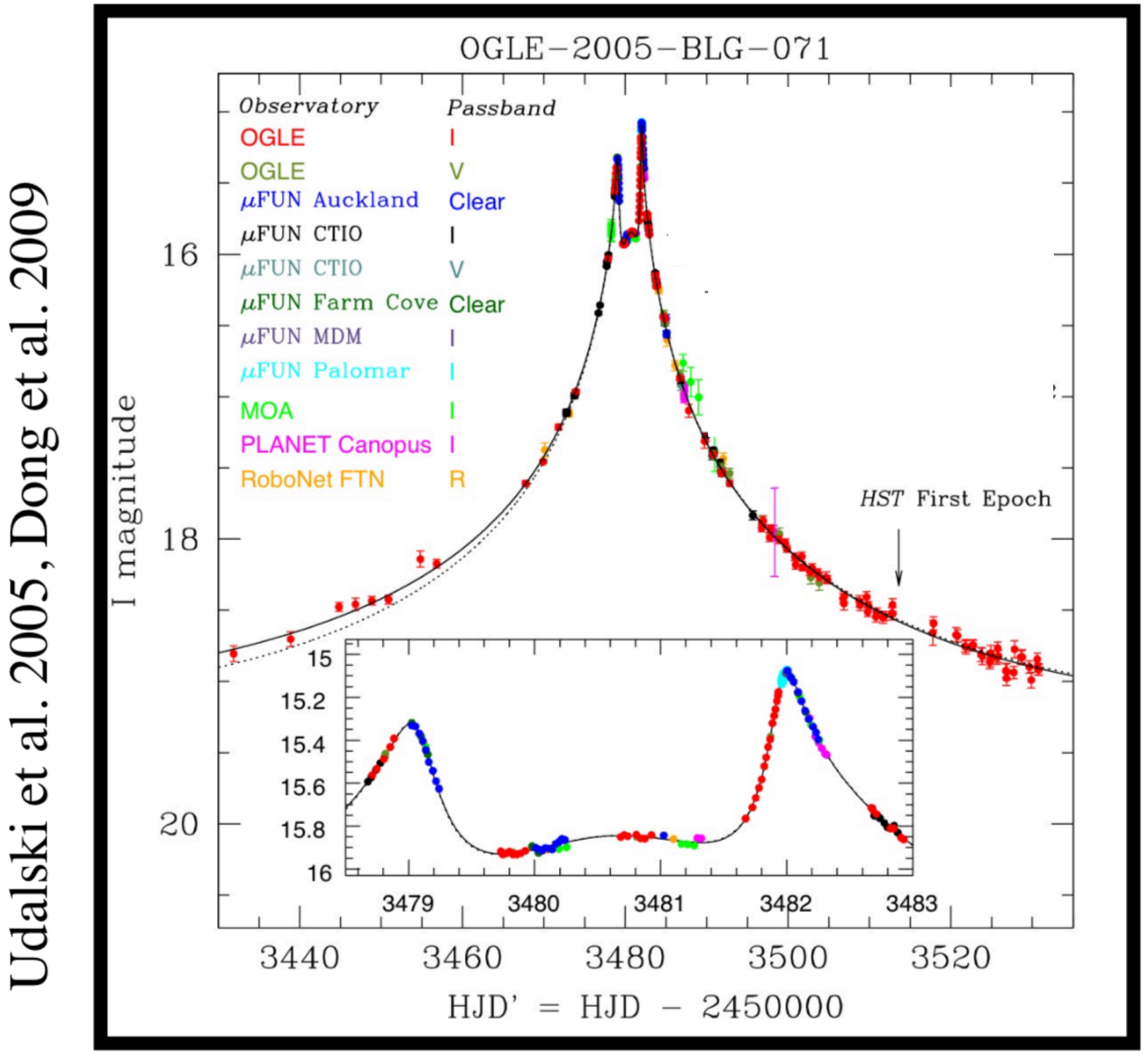
Rule: look for the central bump in the middle of the horns

CLOSE BINARIES VS PLANETS



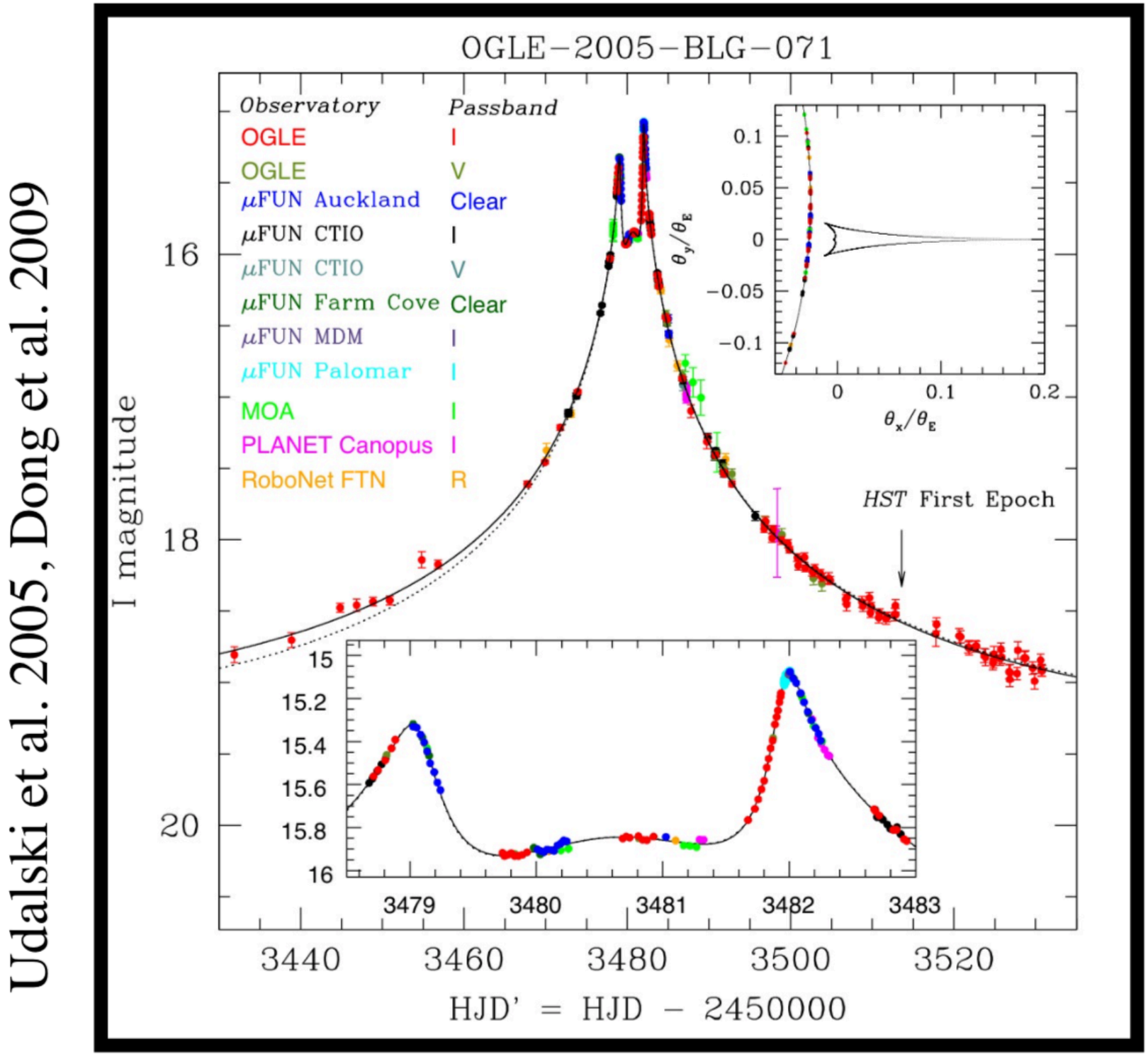


QUIZ



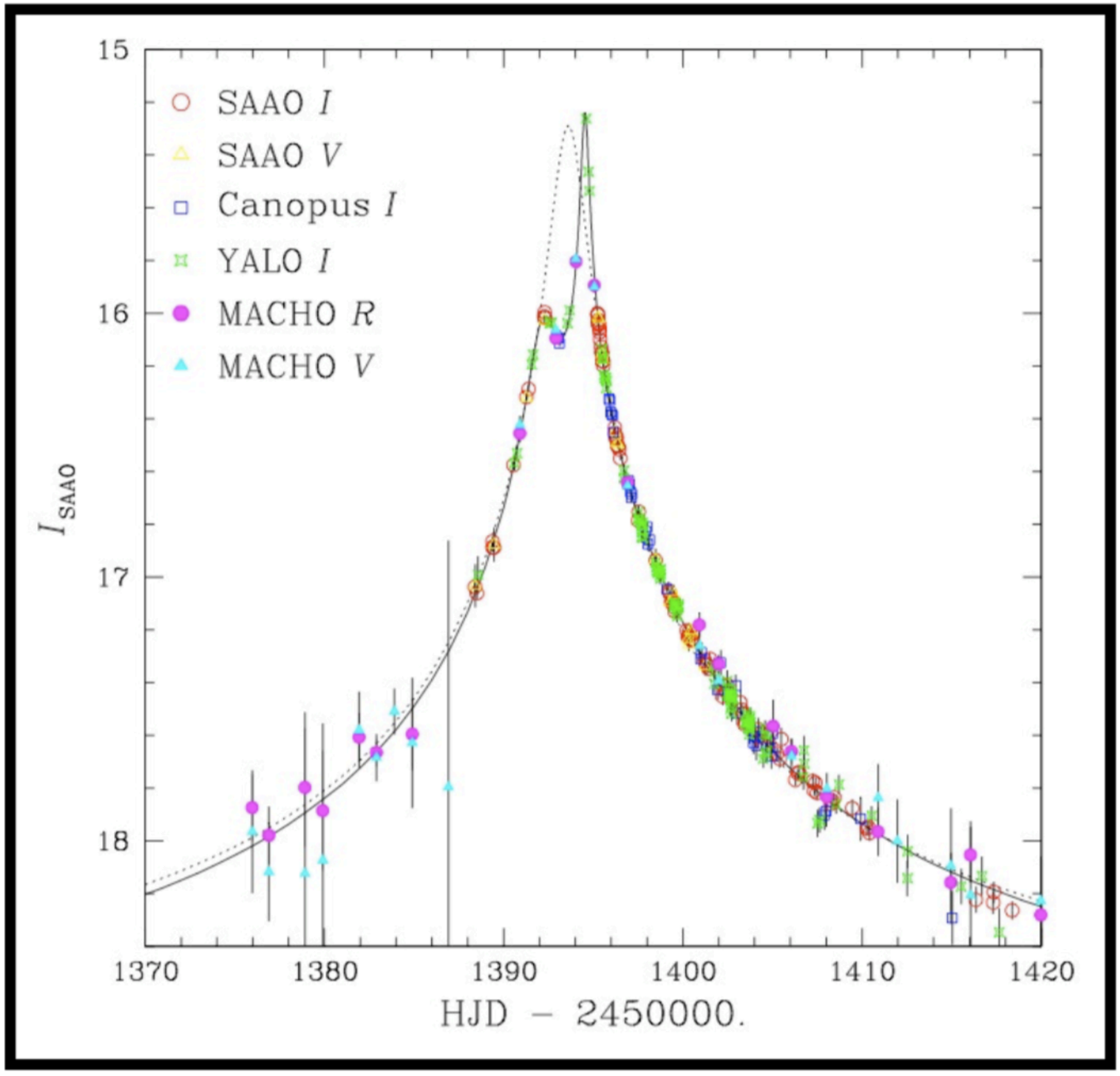
Udalski et al. 2005, Dong et al. 2009

QUIZ



Udalski et al. 2005, Dong et al. 2009

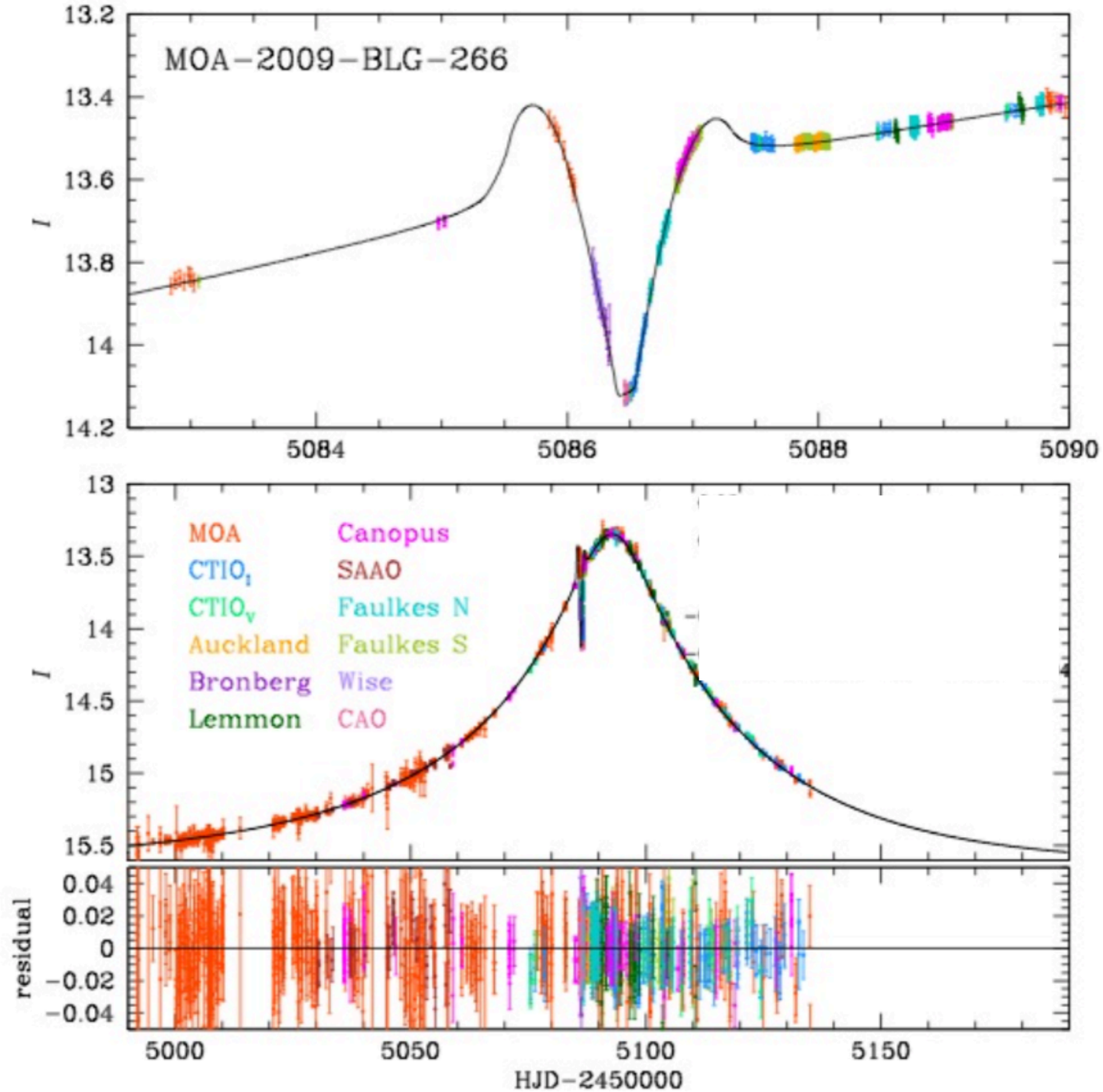
QUIZ



Albrow et al. 2002

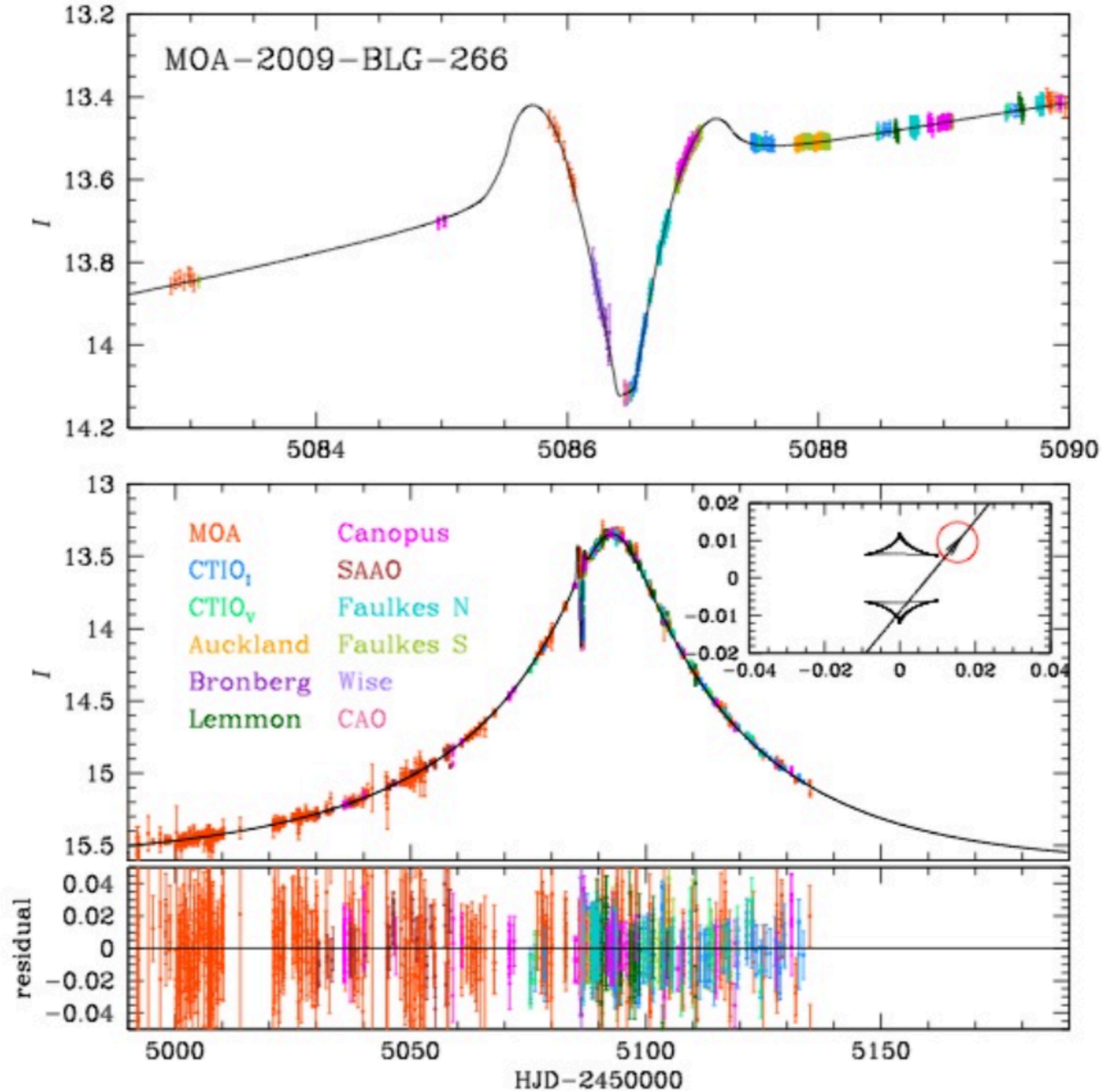
QUIZ

(Muraki et al. 2011)

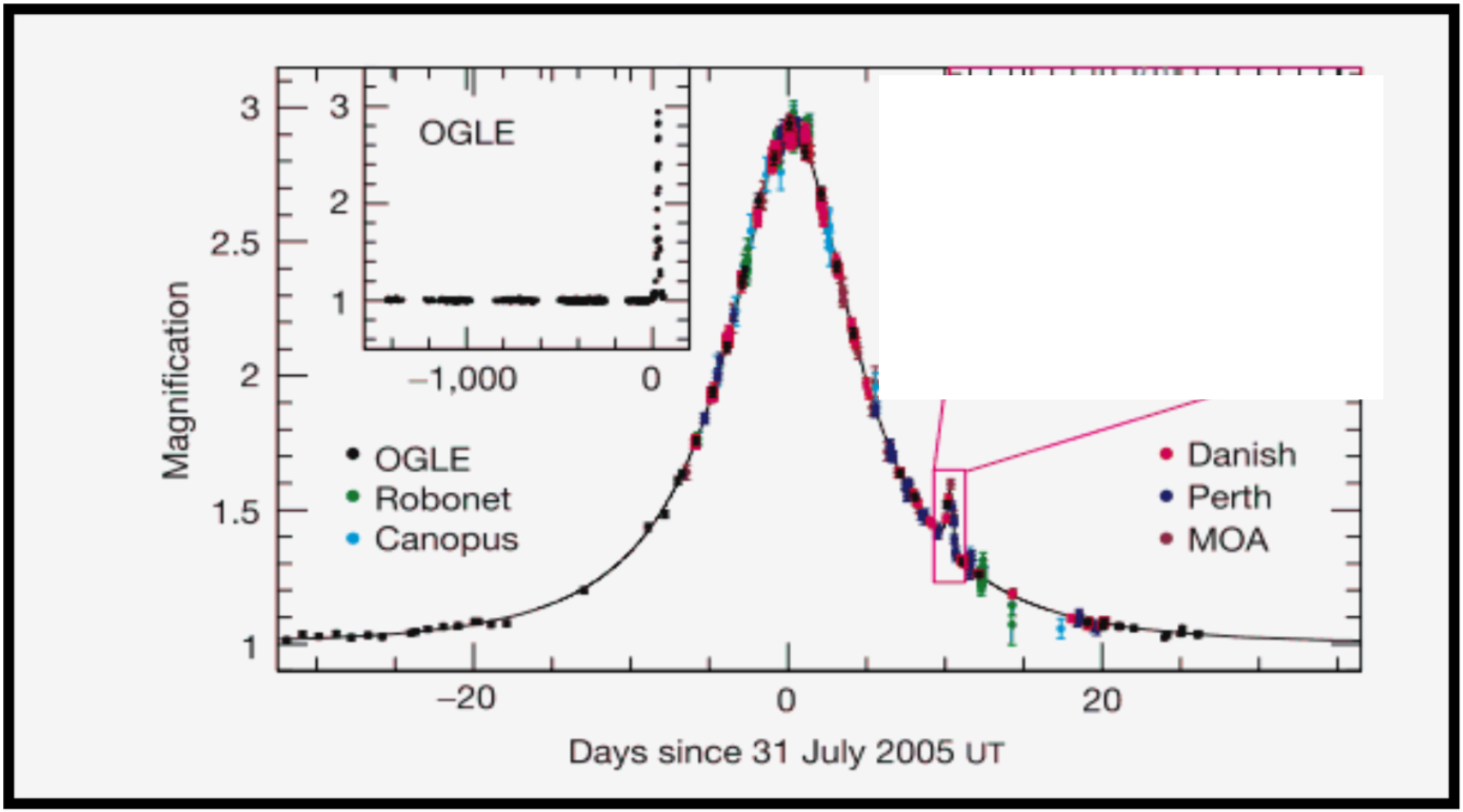


QUIZ

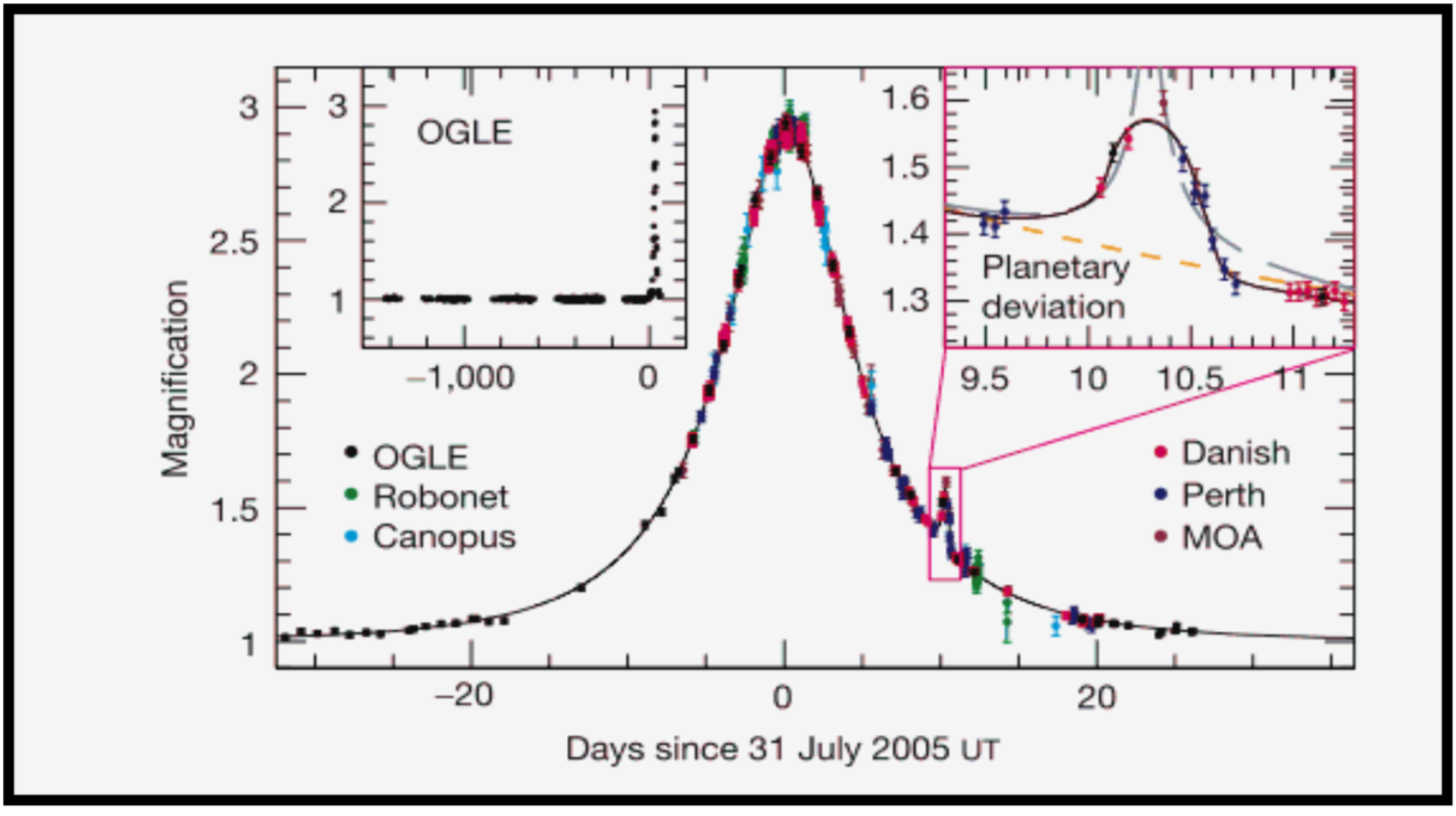
(Muraki et al. 2011)



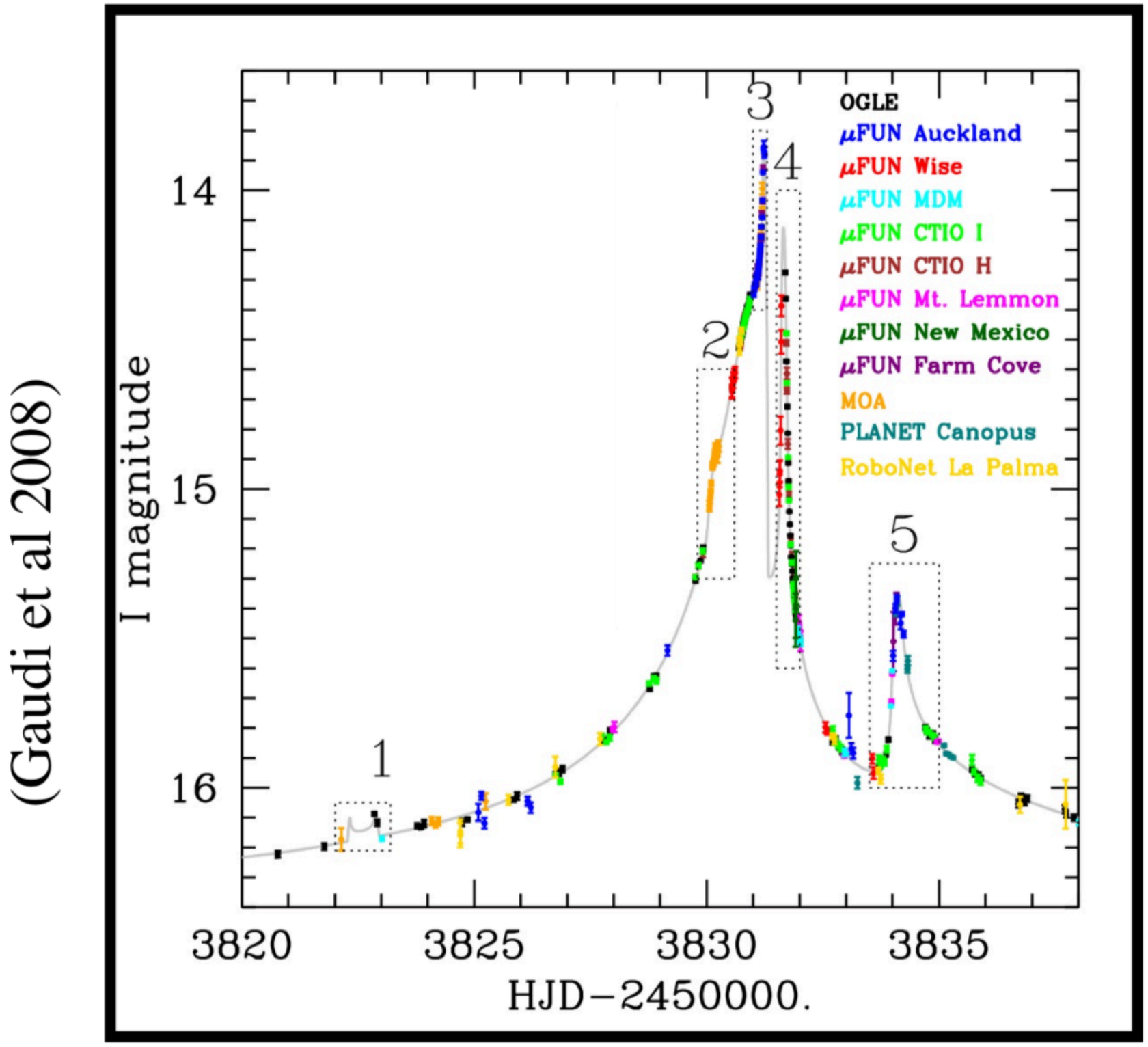
QUIZ


OGLE
−1,000
0
3
2
1
OGLE
Robonet
Canopus
Danish
Perth
MOA
Magnification
3
2.5
2
1.5
1
−20
0
20
Days since 31 July 2005 UT

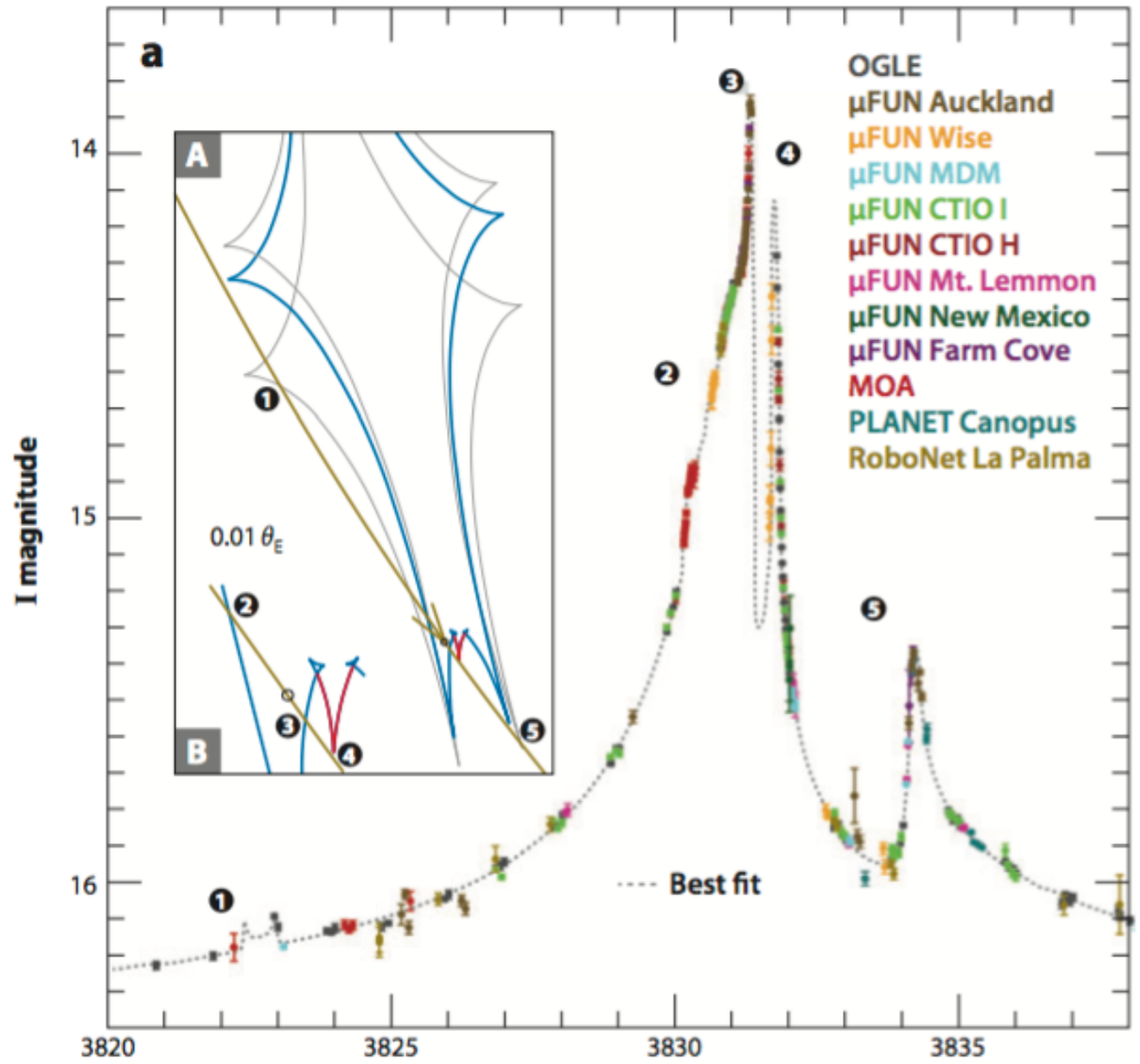
QUIZ


OGLE
Planetary
deviation
Magnification
OGLE
Robonet
Canopus
Danish
Perth
MOA
Days since 31 July 2005 UT

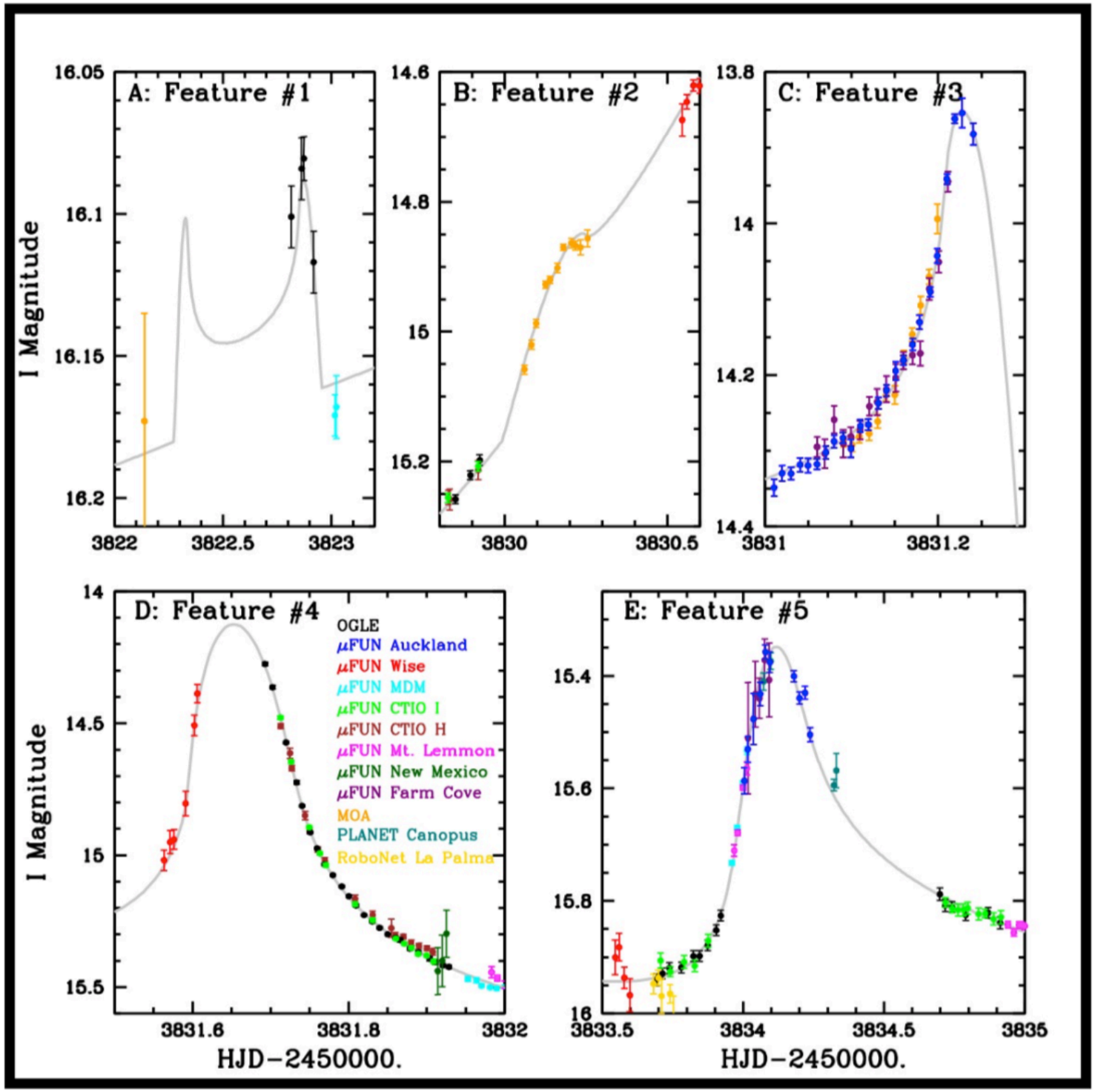
QUIZ

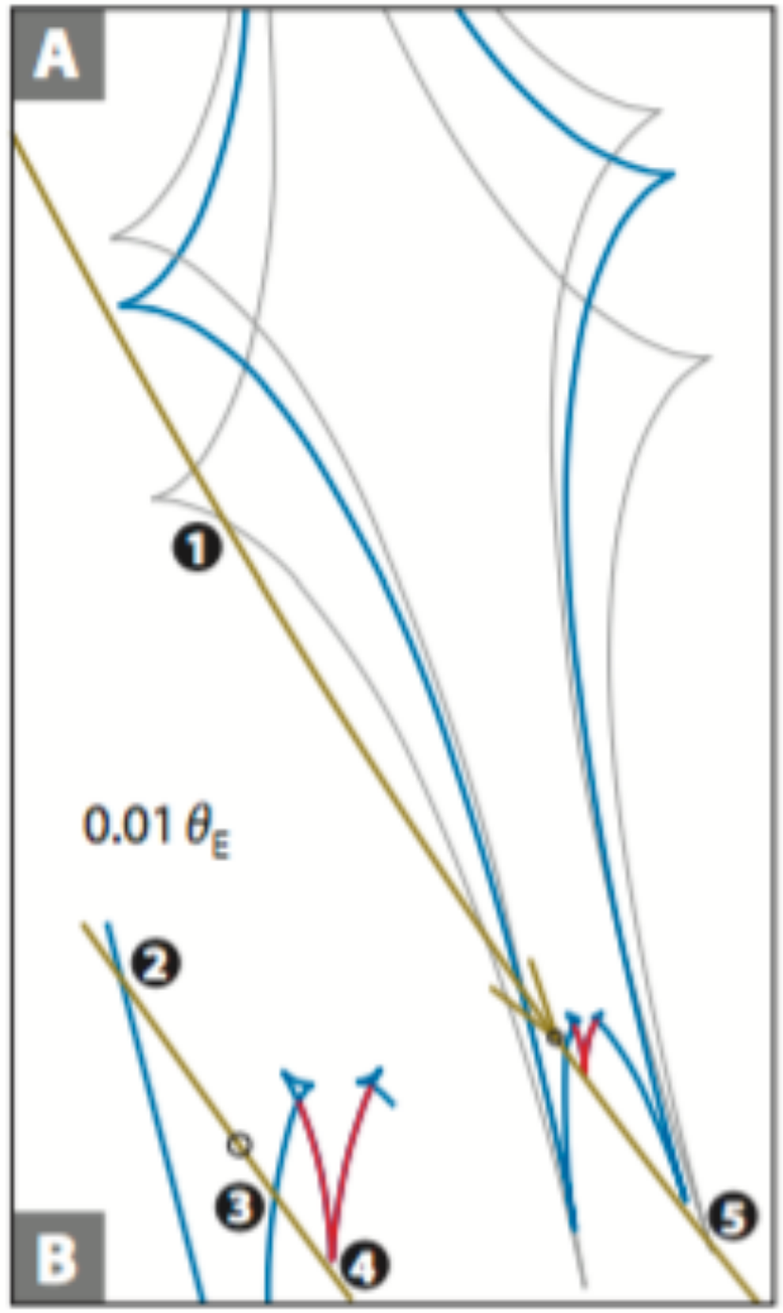

(Gaudi et al 2008)
I magnitude
HJD−2450000.
14
15
16
3820
3825
3830
3835
1
2
3
4
5
OGLE
μFUN Auckland
μFUN Wise
μFUN MDM
μFUN CTIO I
μFUN CTIO H
μFUN Mt. Lemmon
μFUN New Mexico
μFUN Farm Cove
MOA
PLANET Canopus
RoboNet La Palma

MULTIPLE PLANETS AND EVOLVING CAUSTIC

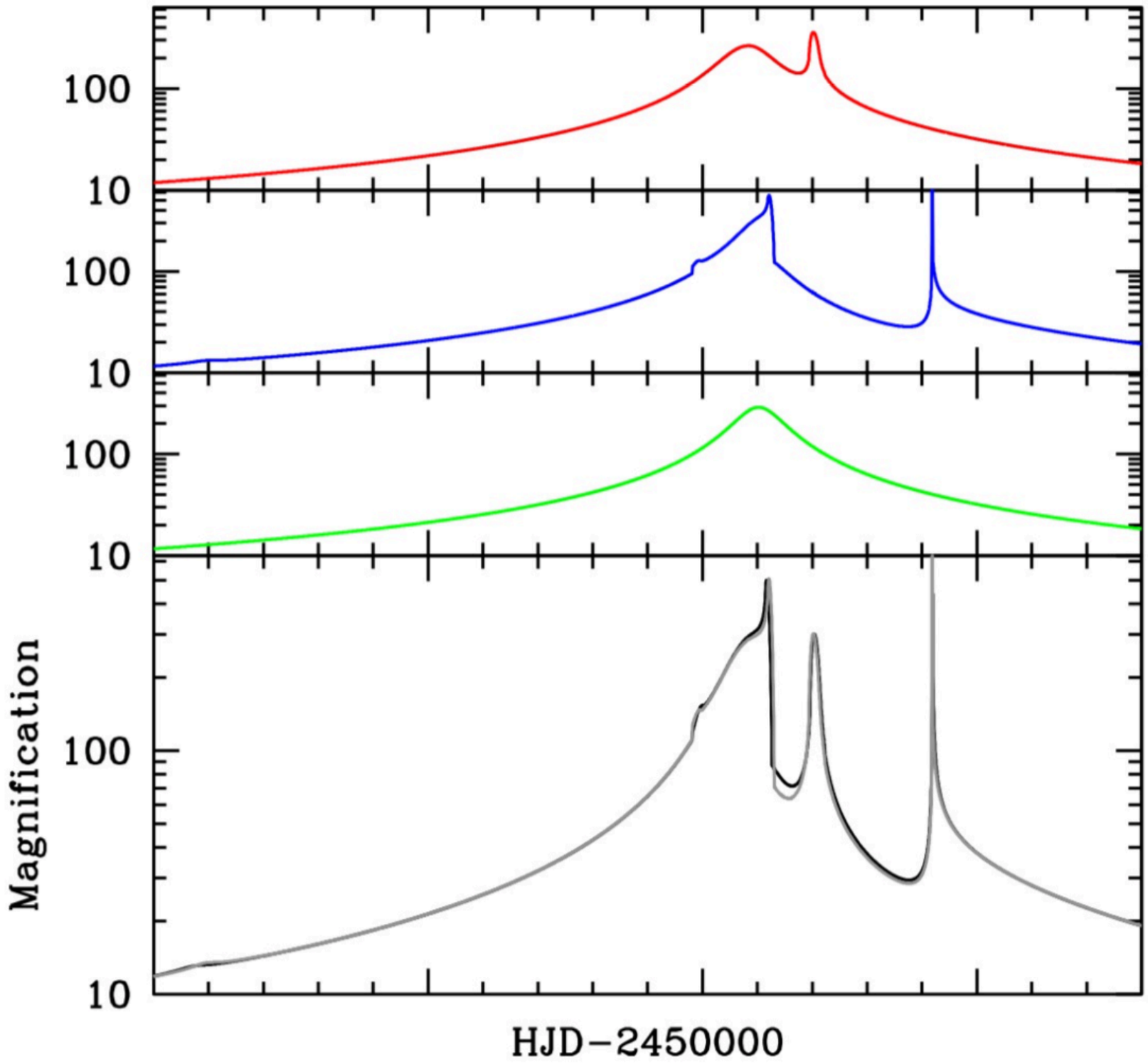


MULTIPLE PLANETS AND EVOLVING CAUSTIC





MULTIPLE PLANETS AND EVOLVING CAUSTIC



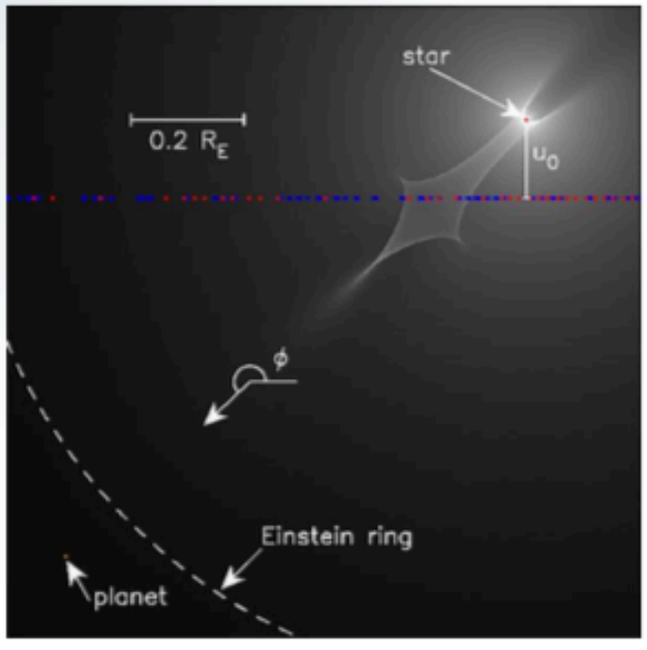
FIRST PLANET DISCOVERY

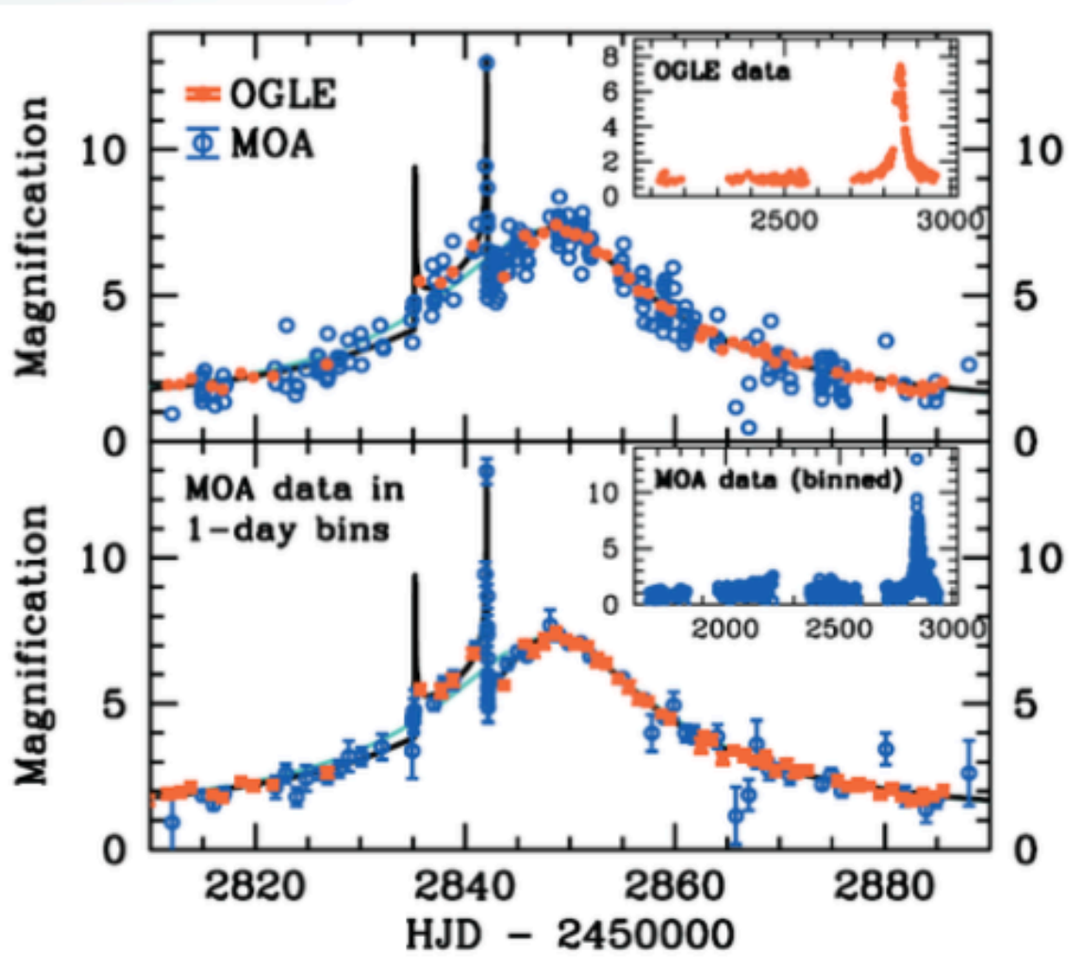
OGLE-2003-BLG-235/MOA-2003-BLG-53

Model parameters

t_E	$61.5 \pm 1.8\ [d]$
q	$3.9^{+1.1}_{-0.7} \times 10^{-3}$
s	1.120 ± 0.007

Resonant caustic





Bond et al. 2004

FIRST PLANET DISCOVERY

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

Model parameters

t_E	$61.5 \pm 1.8\ [d]$
q	$3.9^{+1.1}_{-0.7} \times 10^{-3}$
s	1.120 ± 0.007

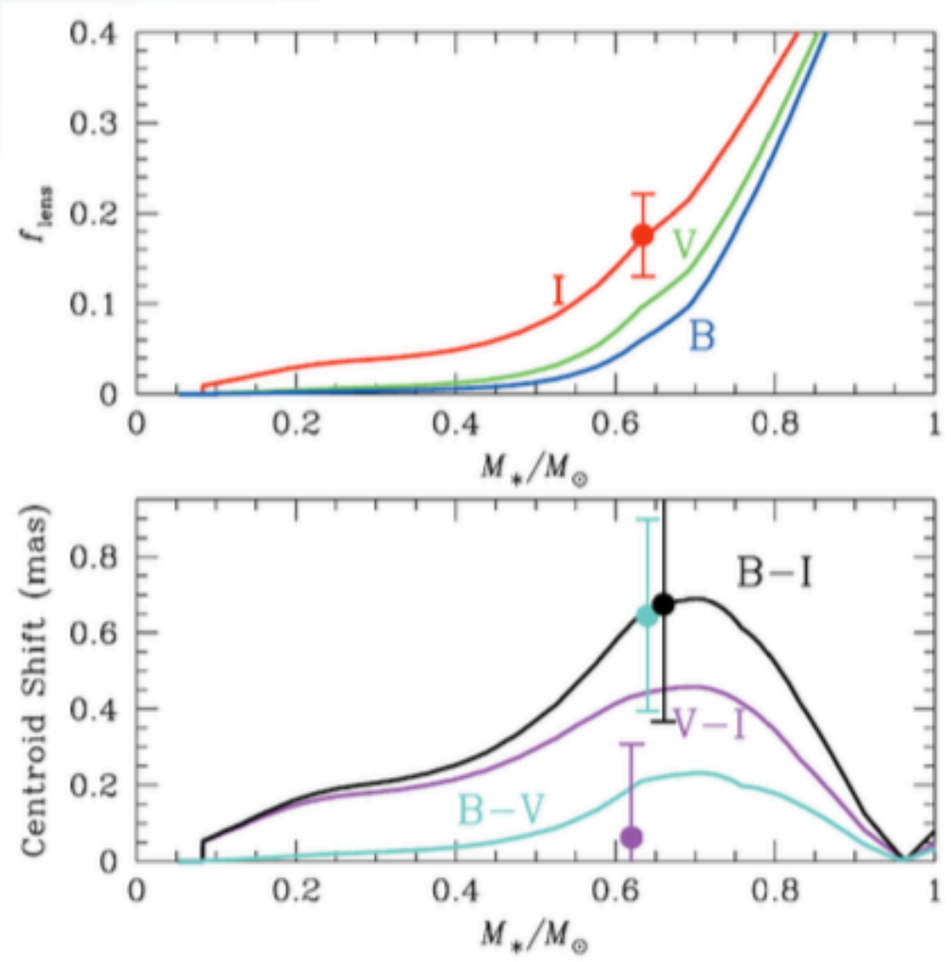
Bond et al. 2004

Physical properties

$m_{\rm planet}$	$2.6^{+0.8}_{-0.6}[M_J]$
$a_\perp$	$4.3^{+2.5}_{-0.8}[\rm AU]$
$M_{\rm host}$	$0.63^{+0.07}_{-0.09}[M_\odot]$

Bennett et al. 2006

Host star identification using *HST*



Bennett et al. 2006

SECOND PLANET DISCOVERY

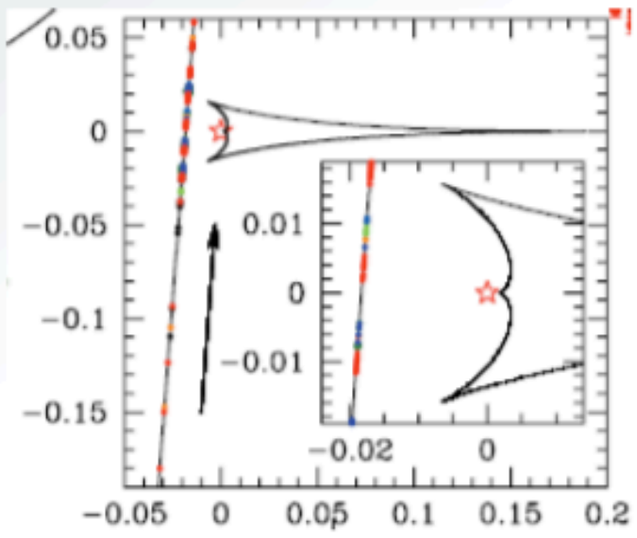
OGLE-2005-BLG-071

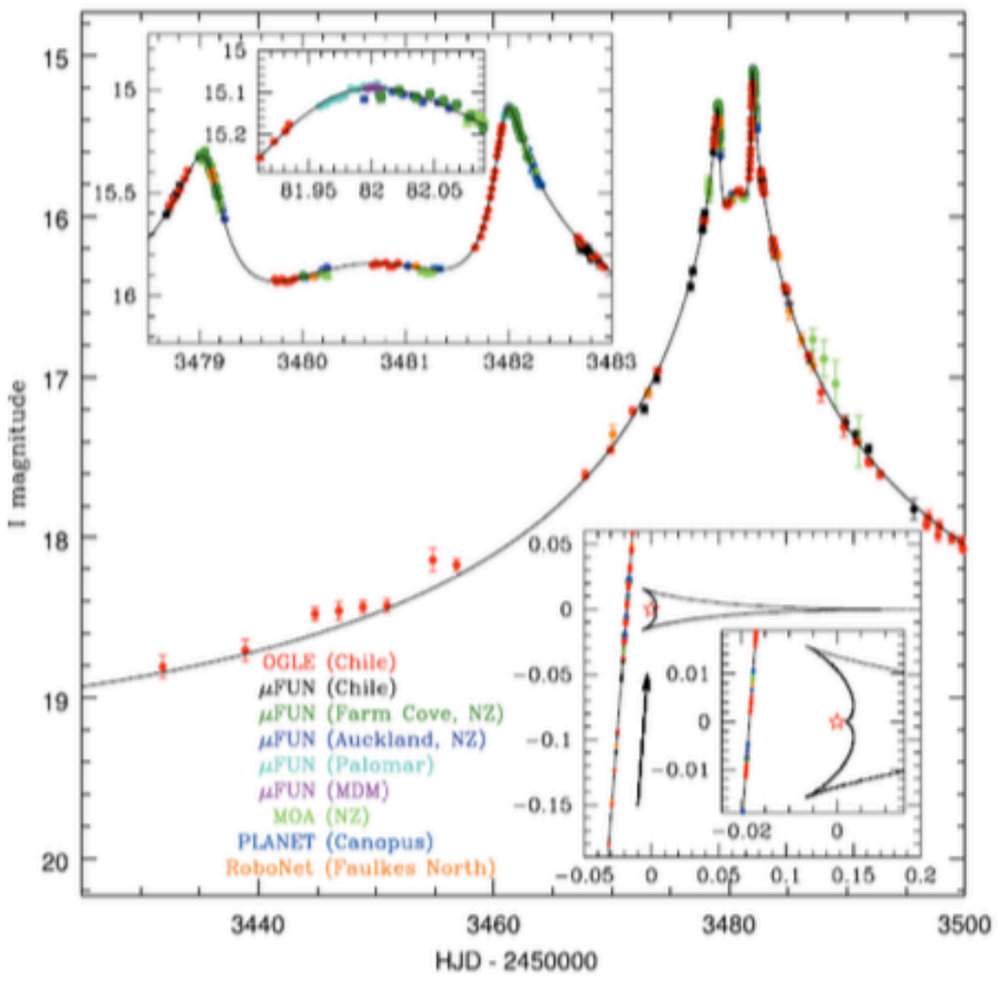
Model parameters

t_E	71 $[d]$
q	$7.1 \ / 6.7 \times 10^{-3}$
s	1.29 / 0.76

Wide / Close

Central caustic





Udalski et al. 2005

SECOND PLANET DISCOVERY

OGLE-2005-BLG-071

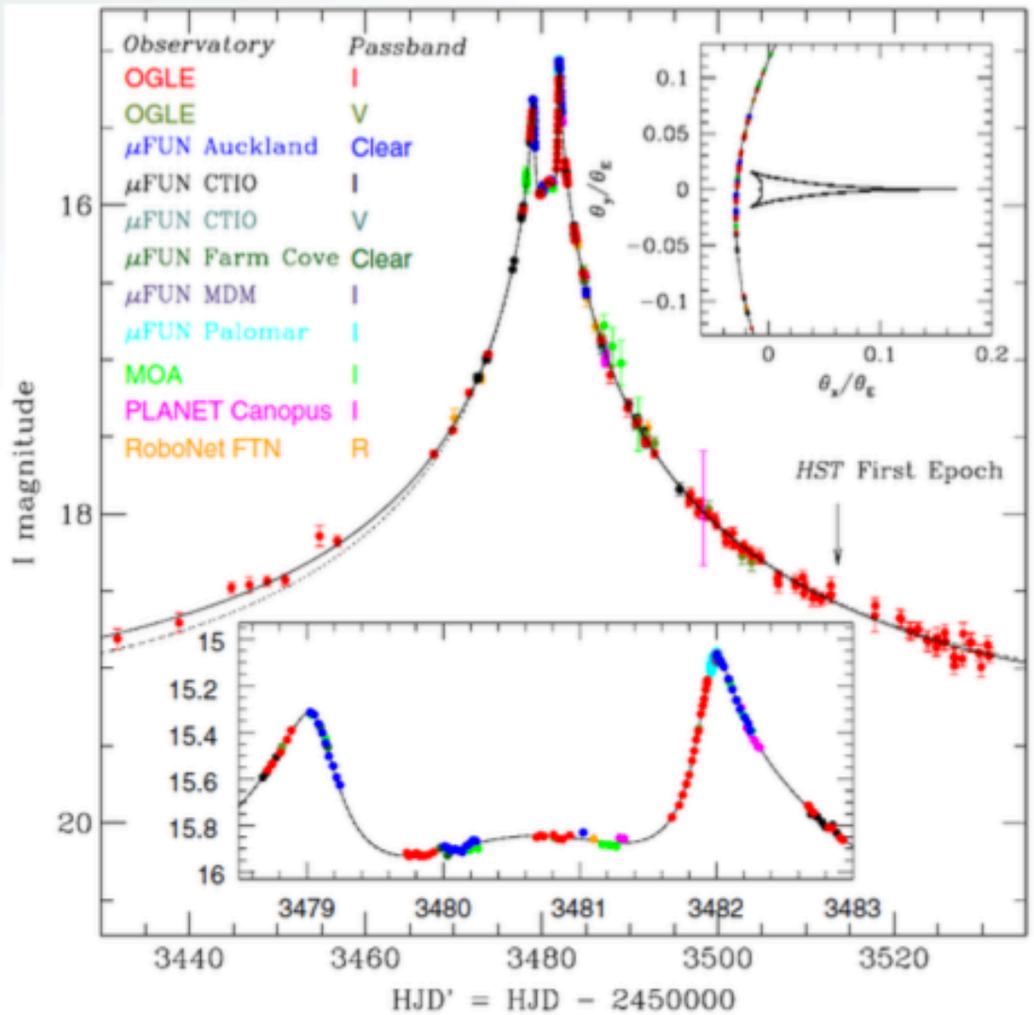
Model parameters

t_E	71 $[d]$
q	7.5 / 6.9×10^{-3}
s	1.31 / 0.76

Wide / Close

Physical properties

m_{planet}	3.8 / 3.4 $[M_J]$
$a_\perp$	3.6 / 2.1 [AU]
M_{host}	0.46 $[M_\odot]$



Dong et al. 2009

SUPER JUPITERS AROUND M-DWARFS

~20% of microlensing planet discoveries !!

Event	Host mass $[M_\odot]$	Planet mass $[M_J]$	Bayesian estimate?	Discovery Ref.
OGLE-2005-BLG-071	0.46 ± 0.04	3.8 ± 0.4		Udalski+(2005)
OGLE-2012-BLG-0406	0.44 ± 0.07	2.73 ± 0.43		Poleski+(2014)
MOA-2011-BLG-322	$0.39^{+0.45}_{-0.19}$	$11.6^{+13.4}_{-5.6}$	Yes	Shvartzvald+(2014)
OGLE-2008-BLG-355	$0.37^{+0.30}_{-0.17}$	$4.6^{+3.7}_{-2.2}$	Yes	Koshimoto+(2014)
OGLE-2015-BLG-0954	0.33 ± 0.12	3.9 ± 1.4		Shin+(2016)
MOA-2016-BLG-227	$0.29^{+0.23}_{-0.15}$	$2.8^{+2.2}_{-1.5}$	Partial	Koshimoto+(2017)
MOA-2009-BLG-387	$0.19^{+0.30}_{-0.12}$	$2.6^{+4.2}_{-1.6}$	Partial	Batista+(2011)
MOA-2010-BLG-073	0.16 ± 0.03	11.0 ± 2.0		Street+(2013)
OGLE-2013-BLG-0102	0.096 ± 0.013	12.6 ± 2.1		Jung+(2015)
OGLE-2012-BLG-0358	0.022 ± 0.002	1.85 ± 0.19		Han+(2013)

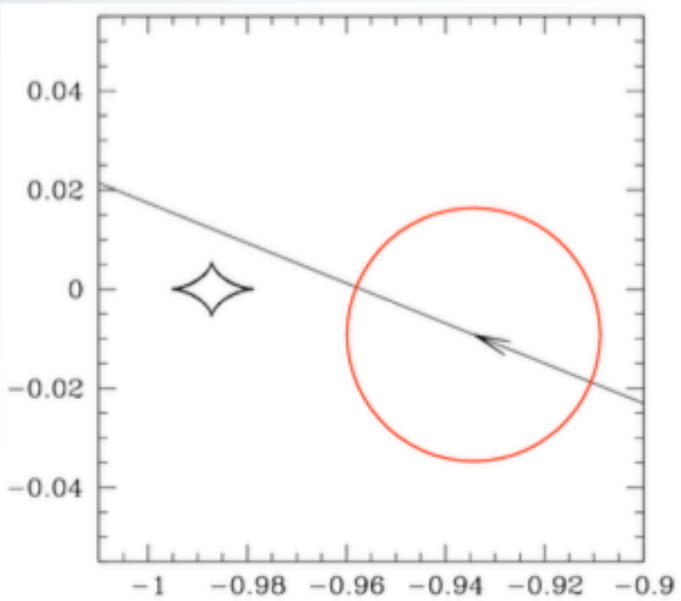
THIRD PLANET DETECTION

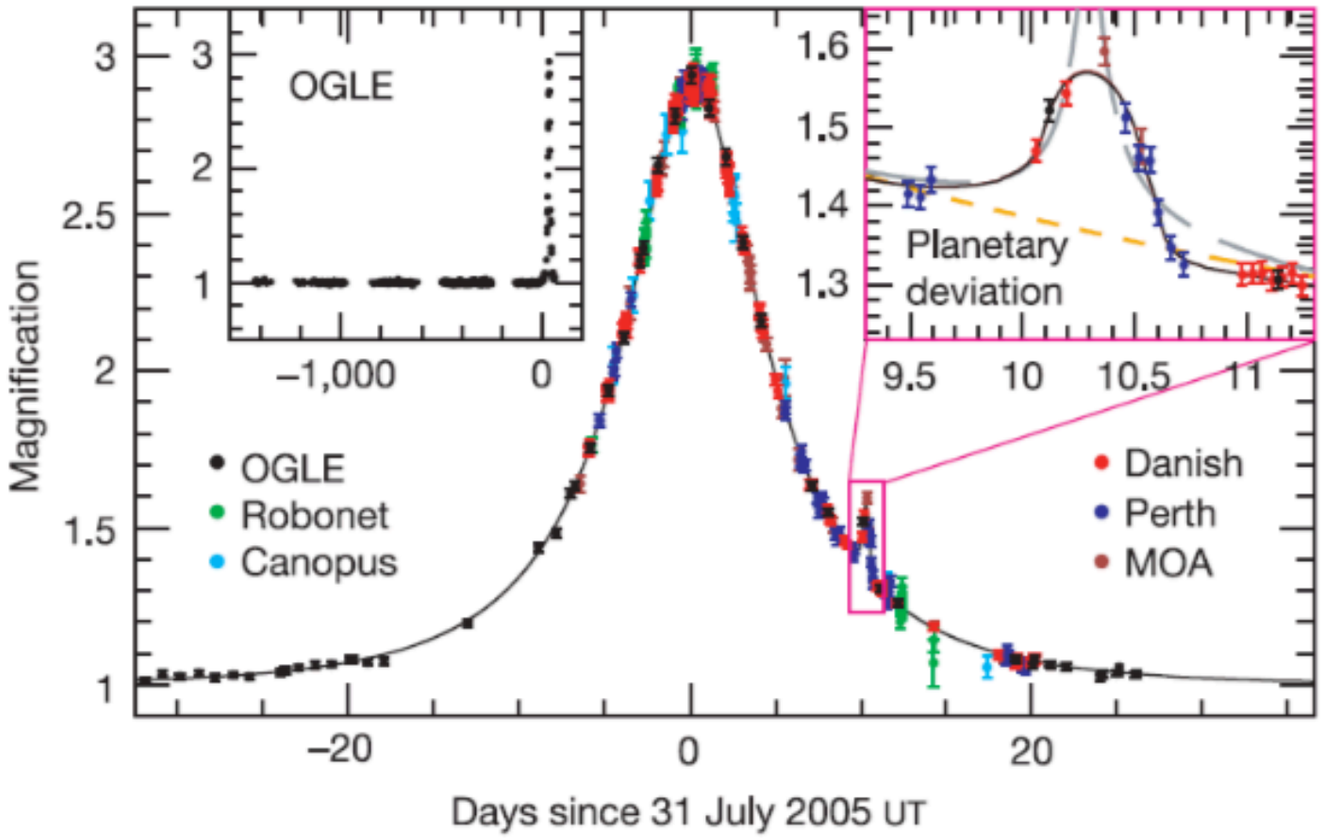
OGLE-2005-BLG-390

Model parameters

t_E	$11.0 \pm 0.1\,[d]$
q	$7.6 \pm 0.7 \times 10^{-5}$
s	1.61 ± 0.01

Planetary caustic





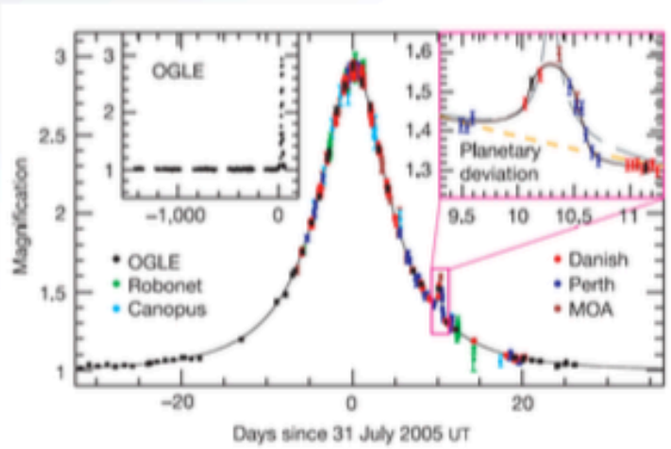
Beaulieu et al. 2006

THIRD PLANET DETECTION

OGLE-2005-BLG-390

Model parameters

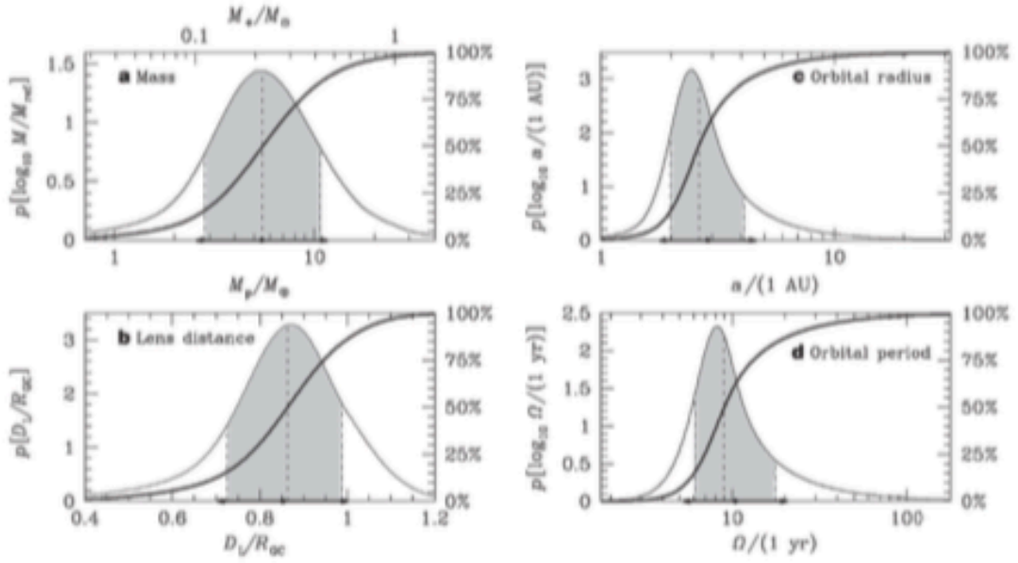
t_E	$11.0 \pm 0.1\ [d]$
q	$7.6 \pm 0.7 \times 10^{-5}$
s	1.61 ± 0.01



Physical properties

m_{planet}	$5.5^{+5.5}_{-2.7}\ [M_\oplus]$
$a_\perp$	$2.6^{+1.5}_{-0.6}$[AU]
M_{host}	$0.22^{+0.21}_{-0.11}\ [M_\odot]$

Bayesian analysis

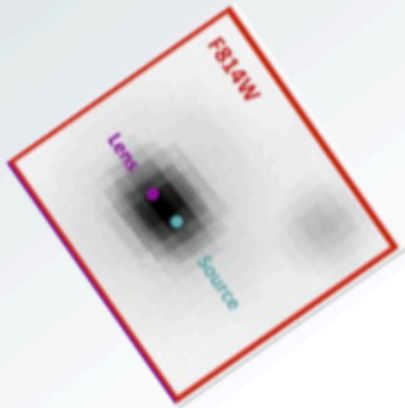


Beaulieu et al. 2006

FOURTH PLANET DETECTION

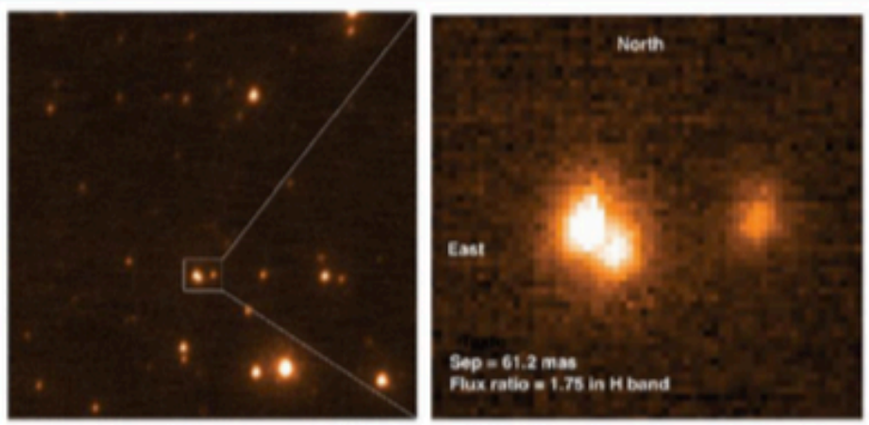
OGLE-2005-BLG-169

HST – 6.4 years after the event

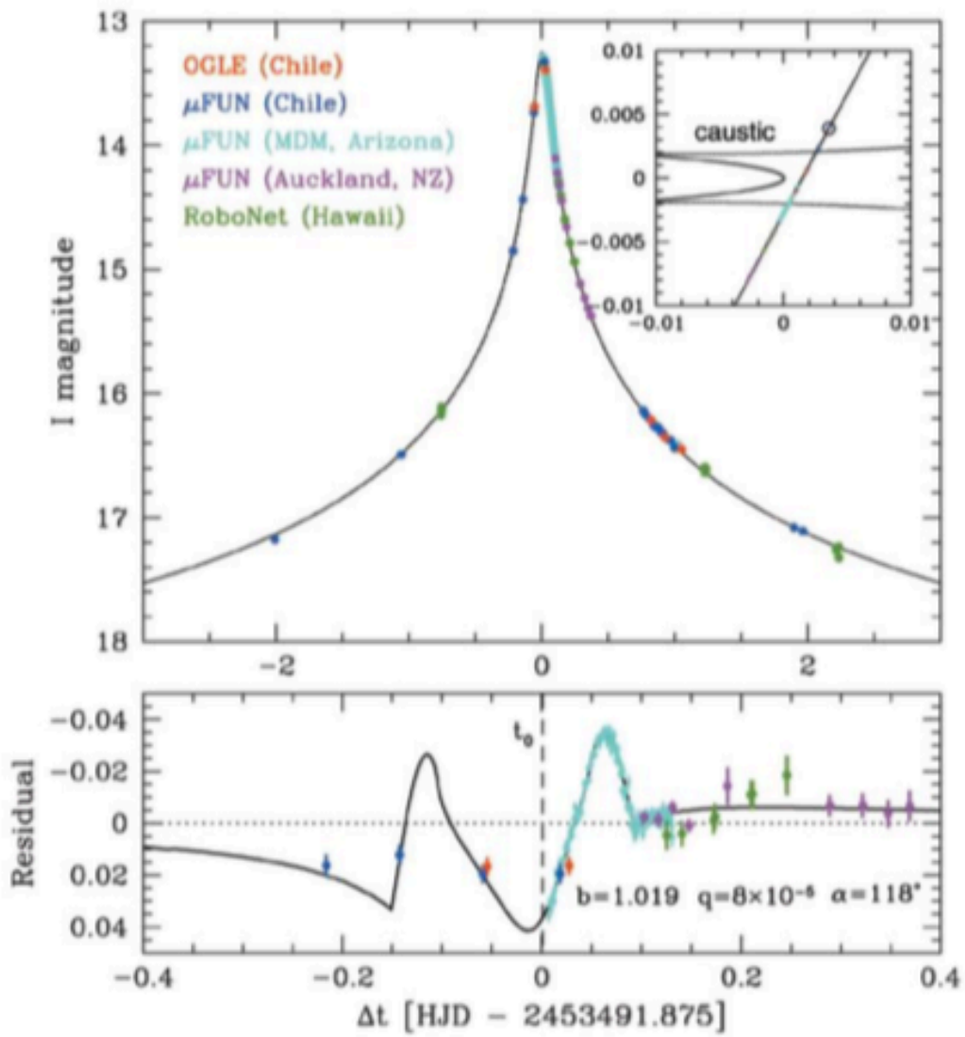


Bennett et al. 2015

Keck – 8.2 years after the event



Batista et al. 2015



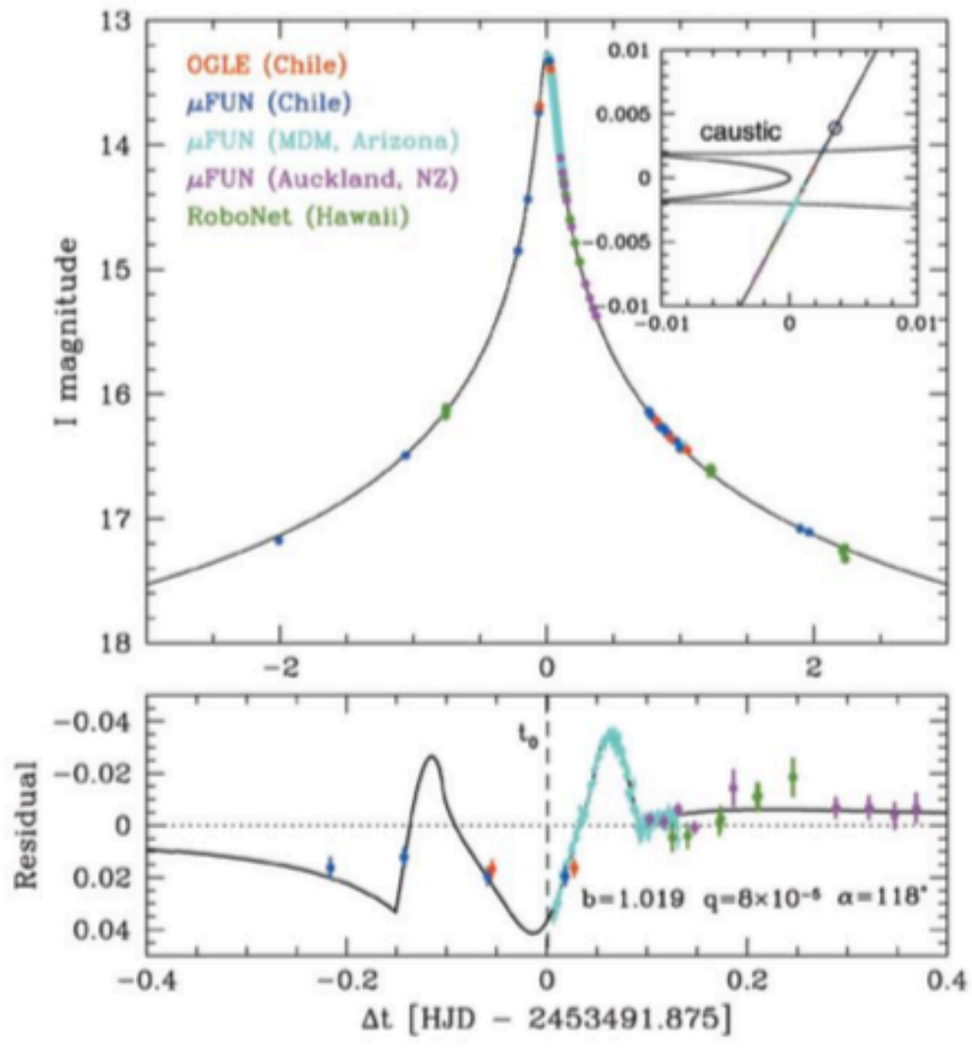
Gould et al. 2006

FOURTH PLANET DETECTION

OGLE-2005-BLG-169

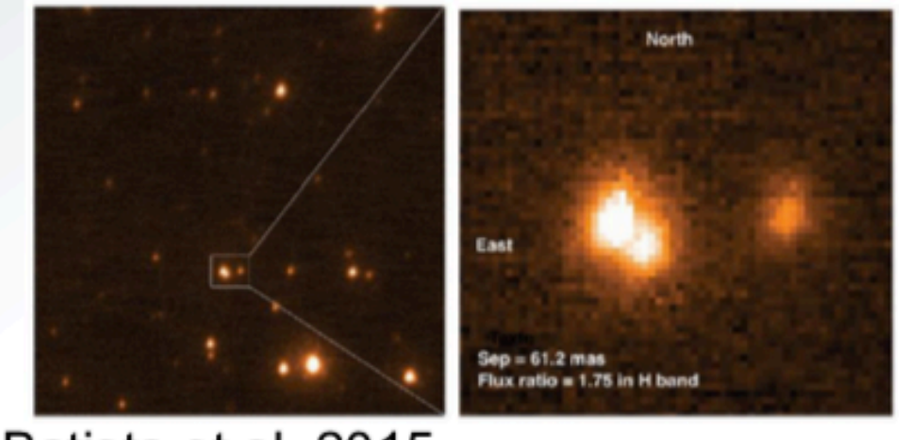
Physical properties

m_{planet}	$13.2 \pm 1.3[M_{\oplus}]$
$a_{\perp}$	$3.4 \pm 0.3[\text{AU}]$
M_{host}	$0.65 \pm 0.05[M_{\odot}]$



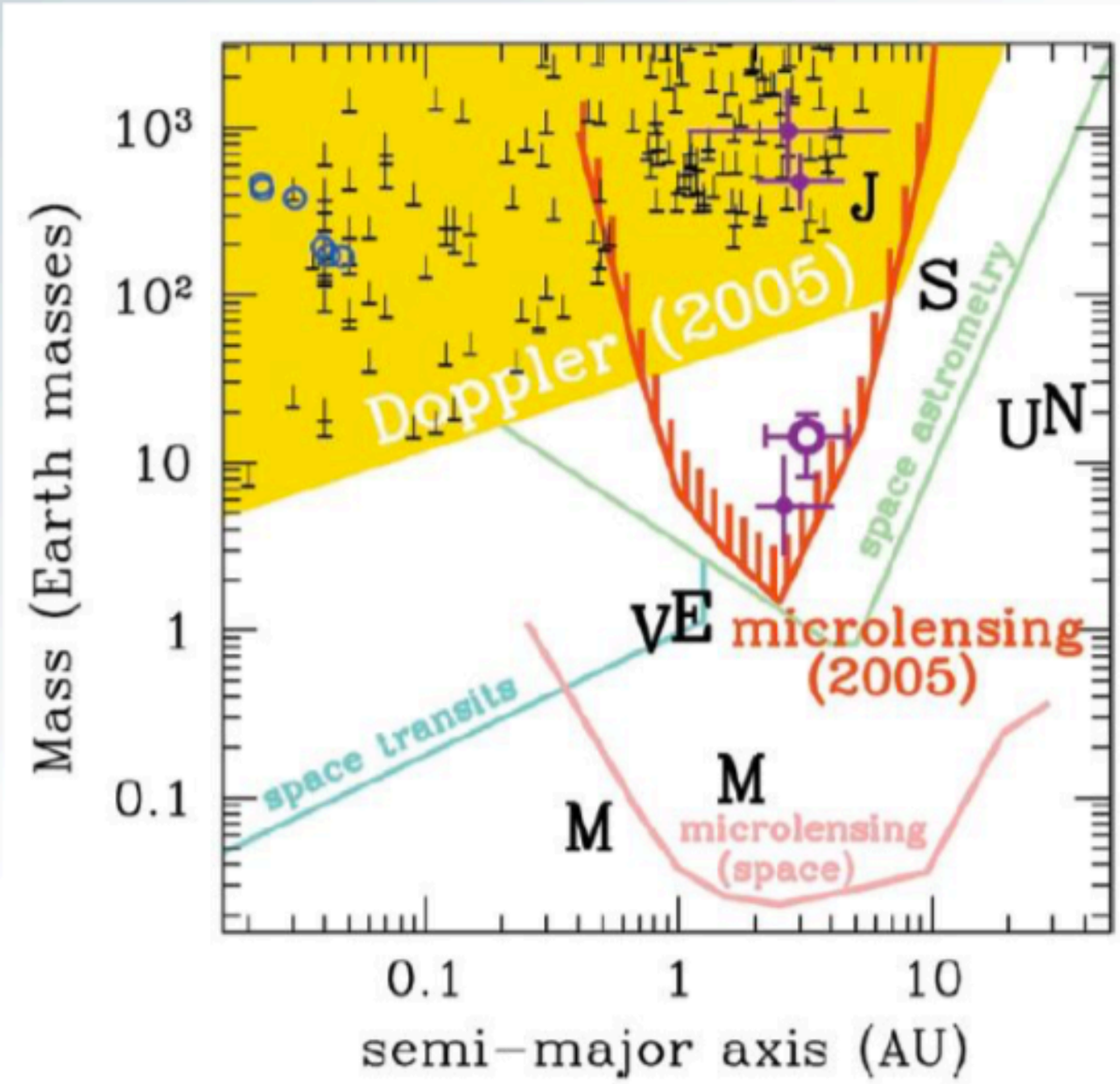
Gould et al. 2006

Keck – 8.2 years after the event



Batista et al. 2015

FOURTH PLANET DETECTION

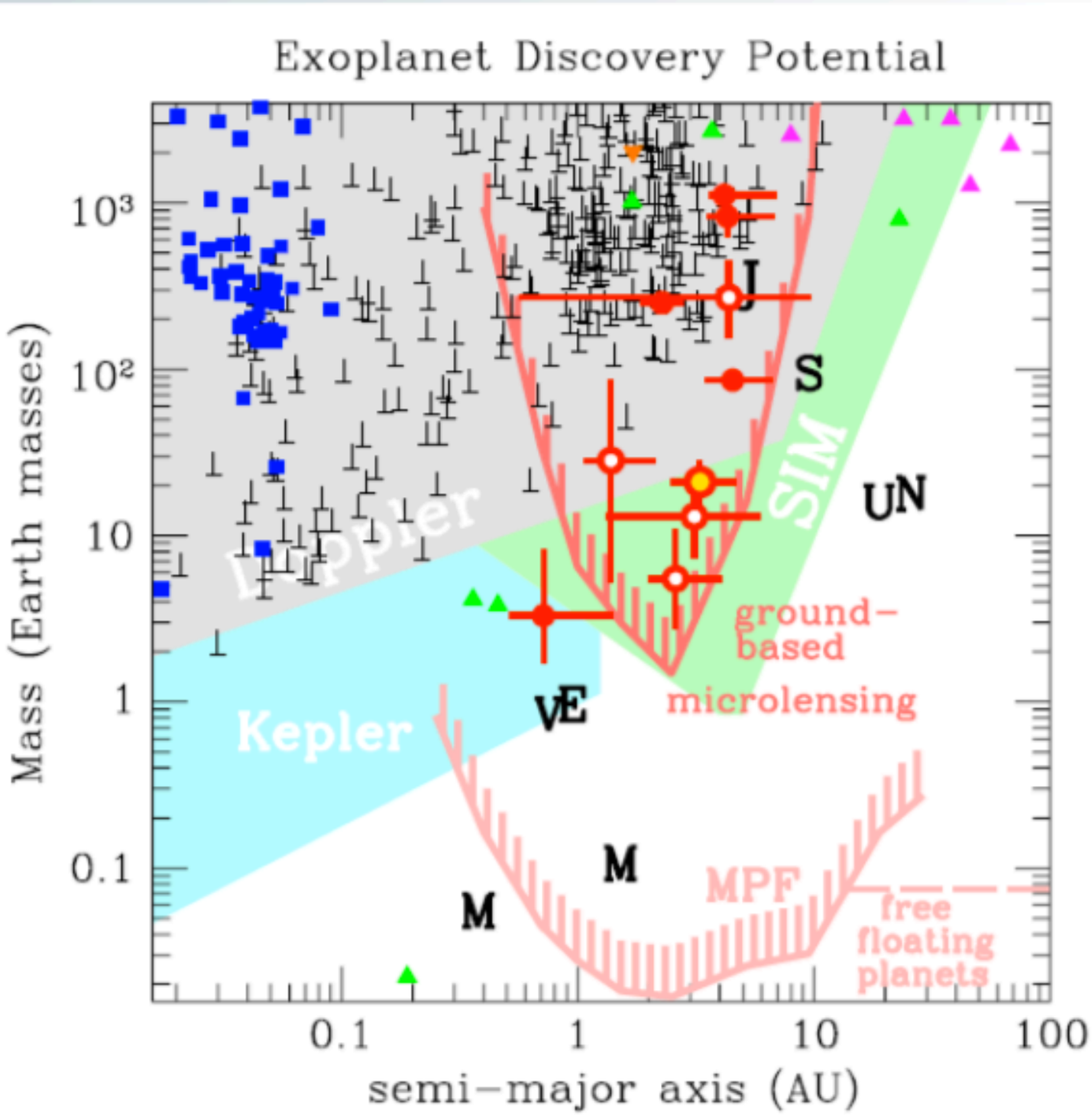


Super Jupiters are common…

…Neptunes even more!

Gould et al. 2006

. . . FIVE YEARS LATER . . .

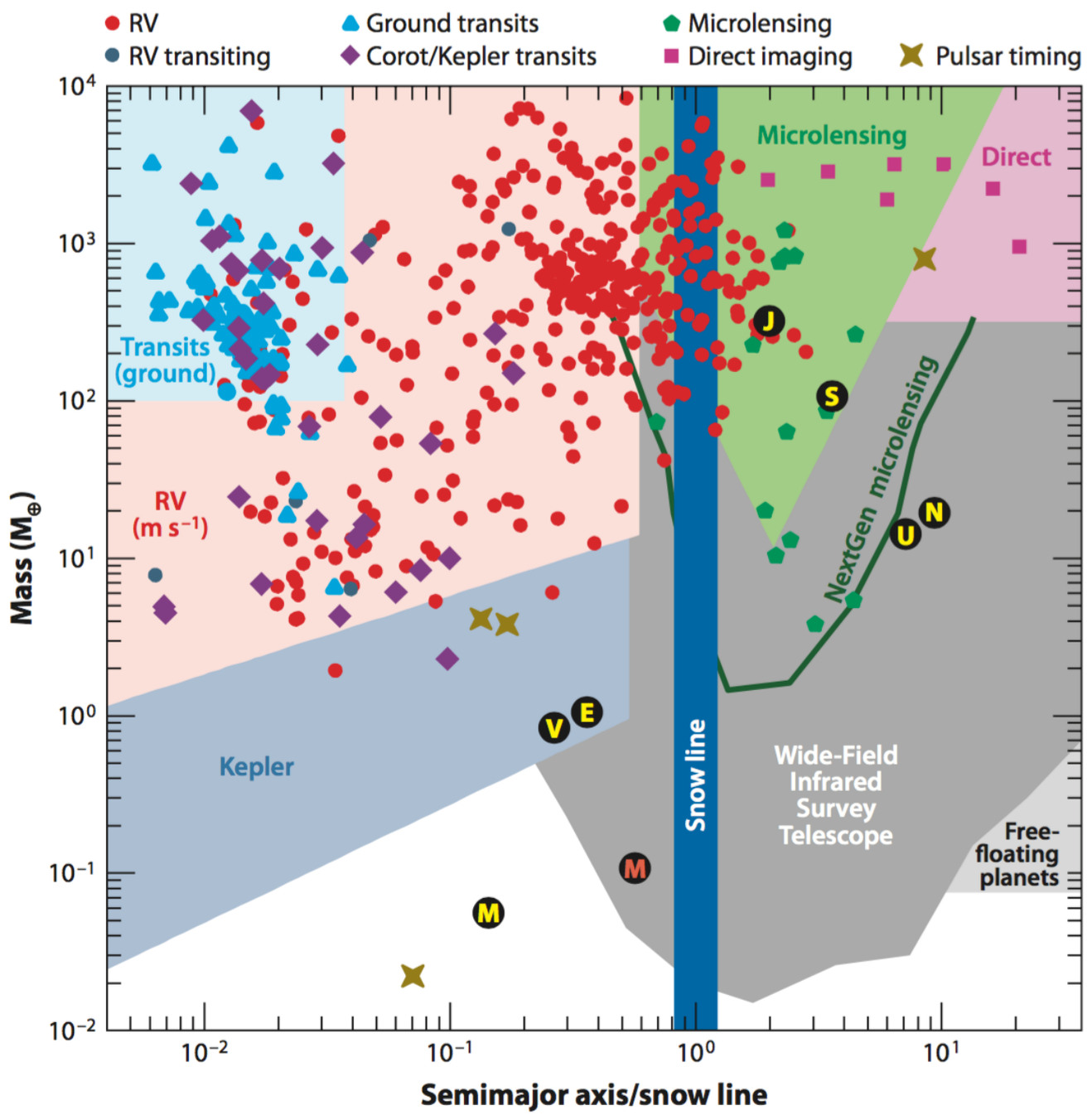


considering that Neptunes are harder to find: they are 3 times more common than Jupiters!

Sumi et al. 2010

ADVANTAGES OF USING MICROLENSING FOR PLANET SEARCHES

- ~60 planets discovered via microlensing so far
- d_{min}=0.66 AU
- bulk of planets at d~3 AU
- wide range of masses
- complementary technique to others that are most sensitive to planets near their host stars (transits, radial velocity)



ADVANTAGES OF USING MICROLENSING FOR PLANET SEARCHES

- planets are most easily identified when they are at a distance ~ER
- example: 1 mas at ~5kpc=5AU
- peak sensitivity beyond the snow line
- the snow line marks a very important region for planet formation! Giant planets can form only beyond the snow line.

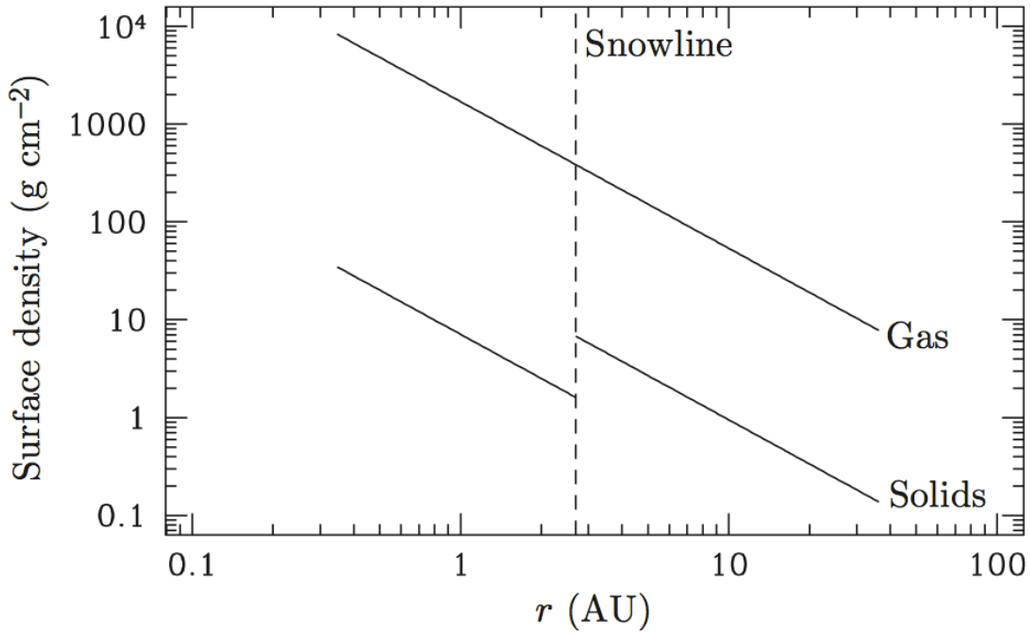
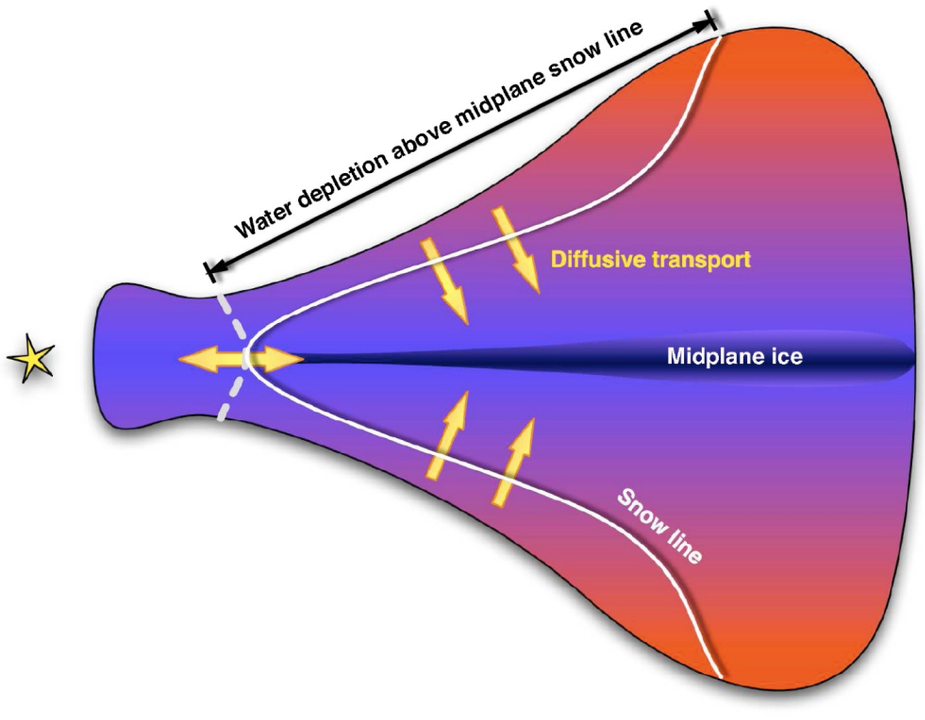


Fig. 1.1. The surface density in gas (upper line) and solids (lower broken line) as a function of radius in Hayashi's minimum mass Solar Nebula. The dashed vertical line denotes the location of the snowline.



OTHER ADVANTAGES...

- sensitivity to low-mass planets
- sensitivity to long period and free-floating planets
- sensitivity to a wide range of host stars over a wide range of galactocentric distances
- sensitivity to multiple planets

MULTIPLE PLANETS

A solar system analog!

OGLE-2006-BLG-109

Model parameters

m_b/M	1.35×10^{-3}
m_c/m_b	0.36
$a_{\perp,b}/a_{\perp,c}$	0.6

Solar system

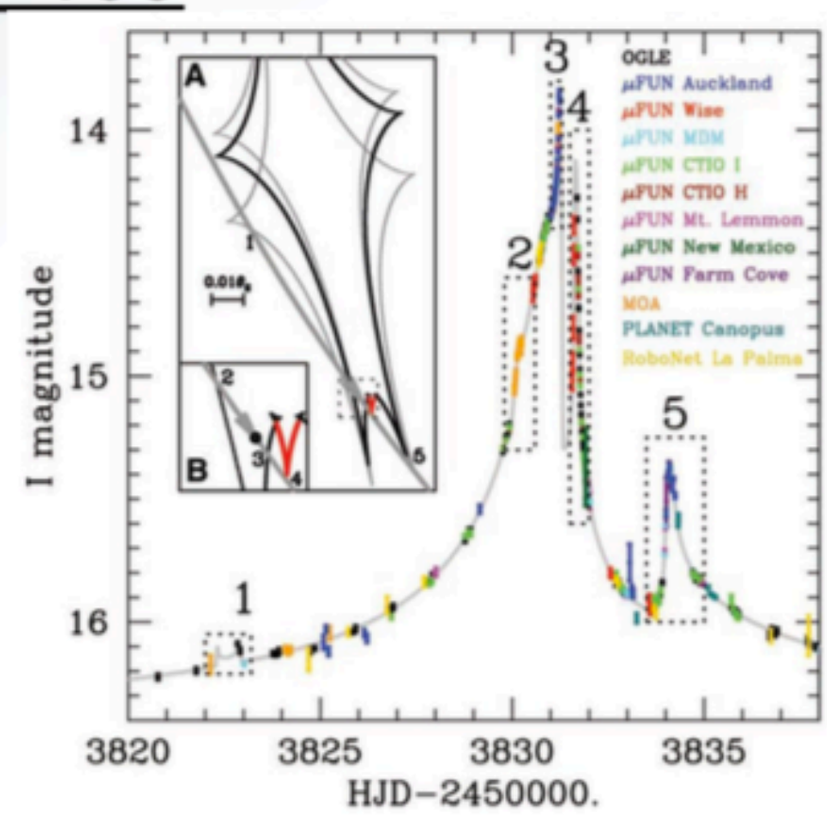
$m_j/M_\odot$	0.96×10^{-3}
m_s/m_j	0.30
a_j/a_s	0.5

Gaudi et al. 2008

Physical properties

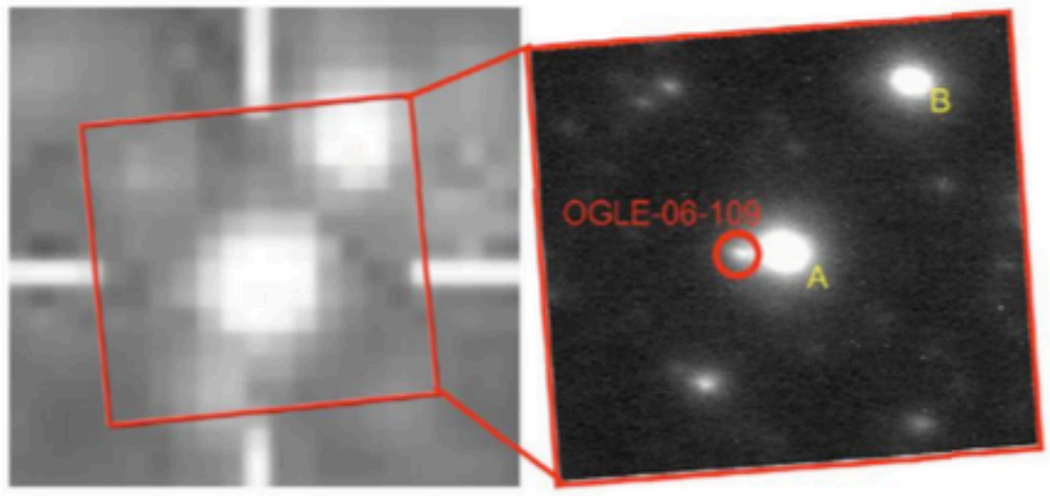
m_b	$0.73 \pm 0.06[M_{Jup}]$
$a_{\perp,b}$	2.3 ± 0.5[AU]
m_c	$0.75 \pm 0.06[M_{Sat}]$
$a_{\perp,c}$	$4.5^{+1.1}_{-1.0}$[AU]
M_{host}	$0.51^{+0.05}_{-0.04}\ [M_\odot]$

Bennett et al. 2010



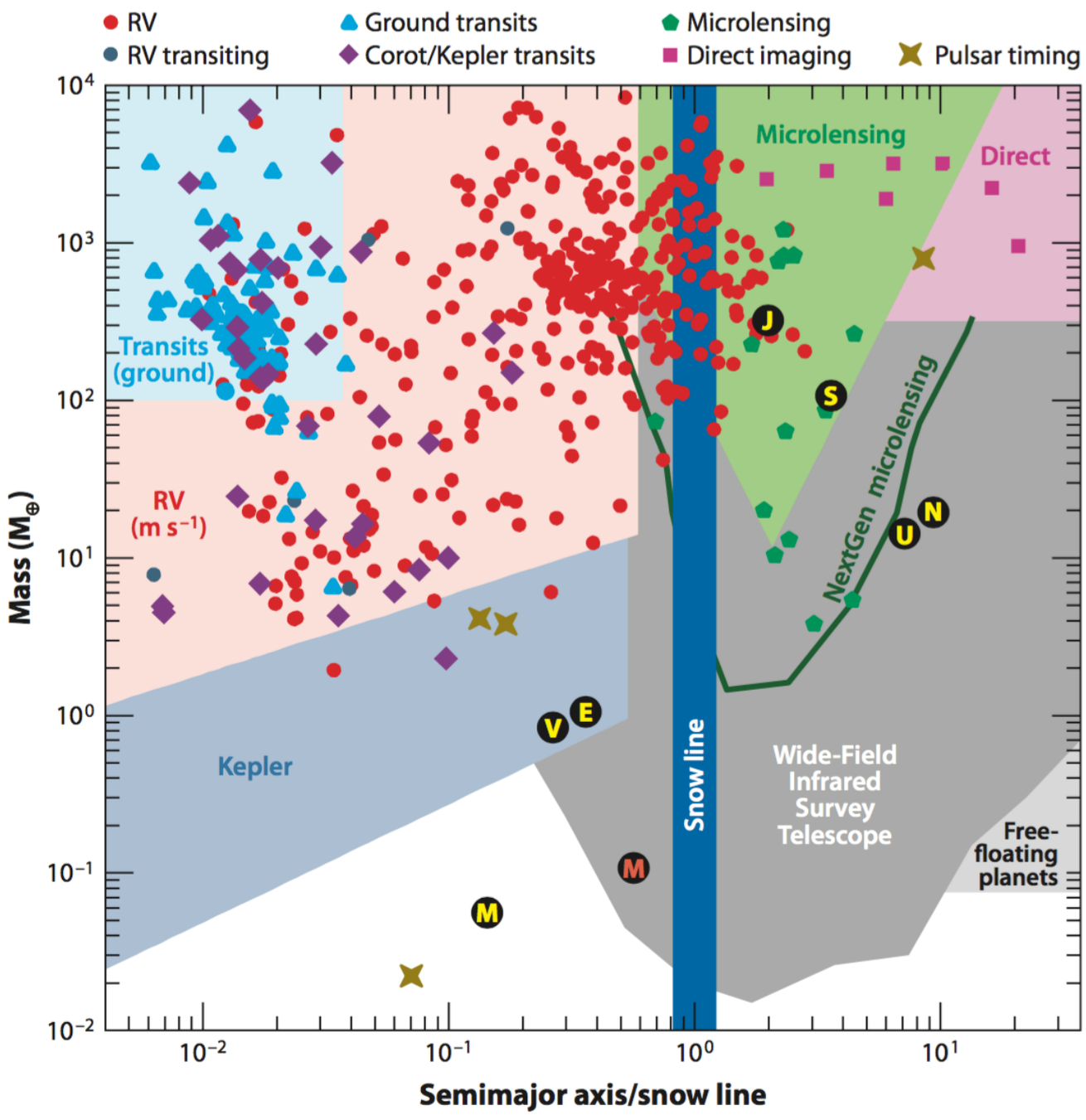
OGLE

Keck



. . . AND DISADVANTAGES

- small numbers compared to other methods (~2000 exoplanets confirmed to date)
- little sensitivity to the habitable zone
- faint and distant hosts
- limited information about the host and the planet



. . . AND DISADVANTAGES

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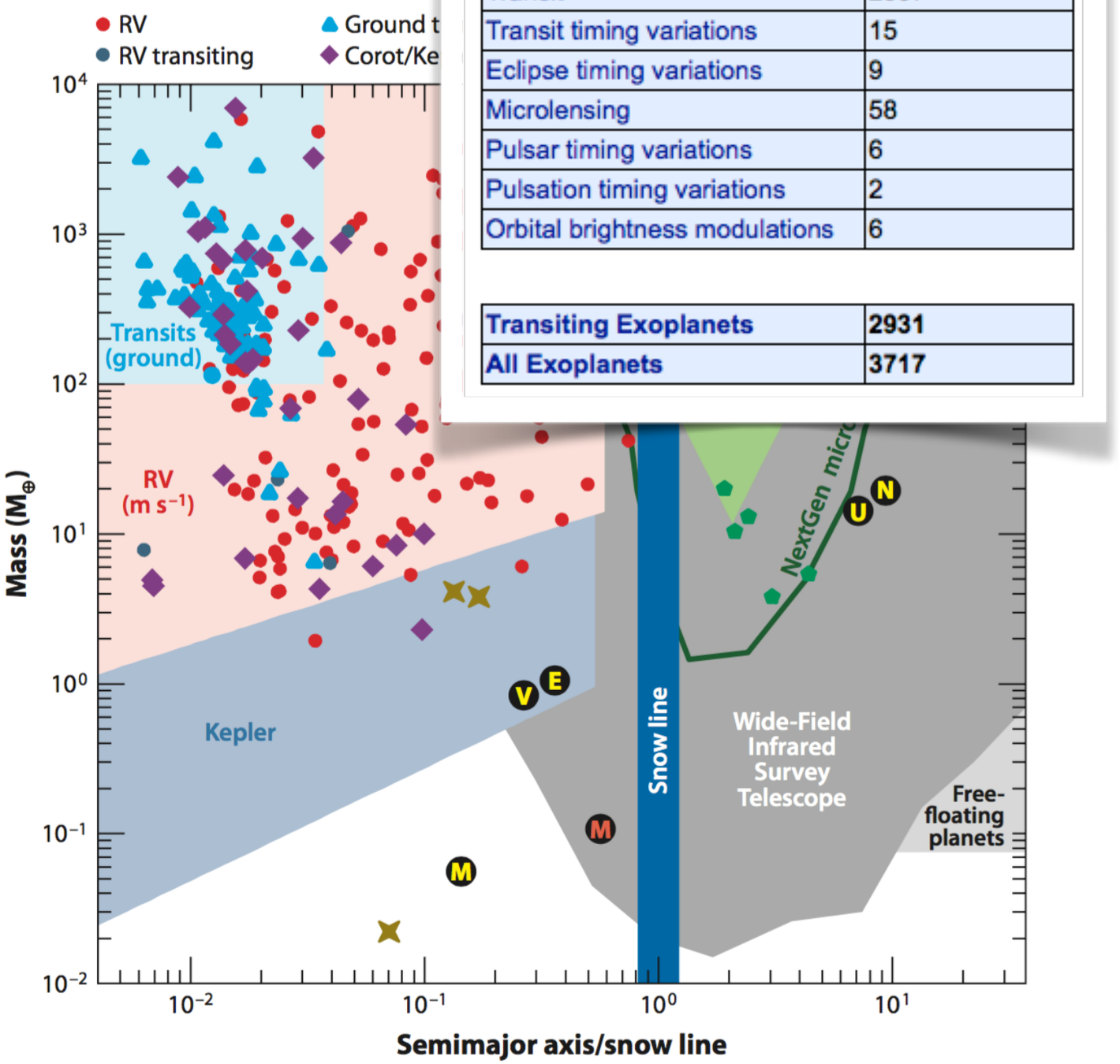
- little sensitivity to the habitable zone
- faint and distant hosts
- limited information about the host and the planet

Confirmed Exoplanet Statistics

Discovery Method	Number of Planets
Astrometry	1
Imaging	44
Radial Velocity	669
Transit	2907
Transit timing variations	15
Eclipse timing variations	9
Microlensing	58
Pulsar timing variations	6
Pulsation timing variations	2
Orbital brightness modulations	6

Transiting Exoplanets	**2931**
All Exoplanets	**3717**



HOW ARE PLANETS SEARCHED FOR?

- first generation of surveys: from MACHO searches to planets
- alert and follow-up
- survey teams (Optical Gravitational Lensing Experiment, OGLE; Microlensing Observations in Astrophysics, MOA) use medium size telescopes with relatively wide cameras to monitor the bulge or the MC with a cadence of few observations per day
- real-time data reduction and alerting in case of promising events
- follow-up teams (Probing Lensing Anomalies NETwork, PLANET; RoboNet; Microlensing Network for the Detection of Small Terrestrial planets, MiNDSTEp; Microlensing Follow-up Network, μFun) monitor on timescales of hours
- this strategy privileges intermediate-high-magnification events.
- likely to yield many central or resonant caustic events

CURRENT PLANET SEARCHES

- next generation surveys (after 2010)
- dedicated medium-small size telescopes (~1.5 m) observing with wide field cameras (FOV ~2 sq. degs.) large areas with a cadence of ~20 mins
- greater ability to observe planetary caustic events, in particular wide separation planets
- free-floating planets
- MOA-II (New Zealand, 1.8m, 2.2 sq. deg.), OGLE-IV (Chile, 1.3m, 1.4 sq. deg.), WISE Observatory (Israel, 1 m, 1 sq. deg)
- currently monitoring a common area of 8 sq. deg in the bulge