GRAVITATIONAL LENSING

17 – BINARY LENSES: PLANETARY MICROLENSING

Massimo Meneghetti
AA 2018-2019

a

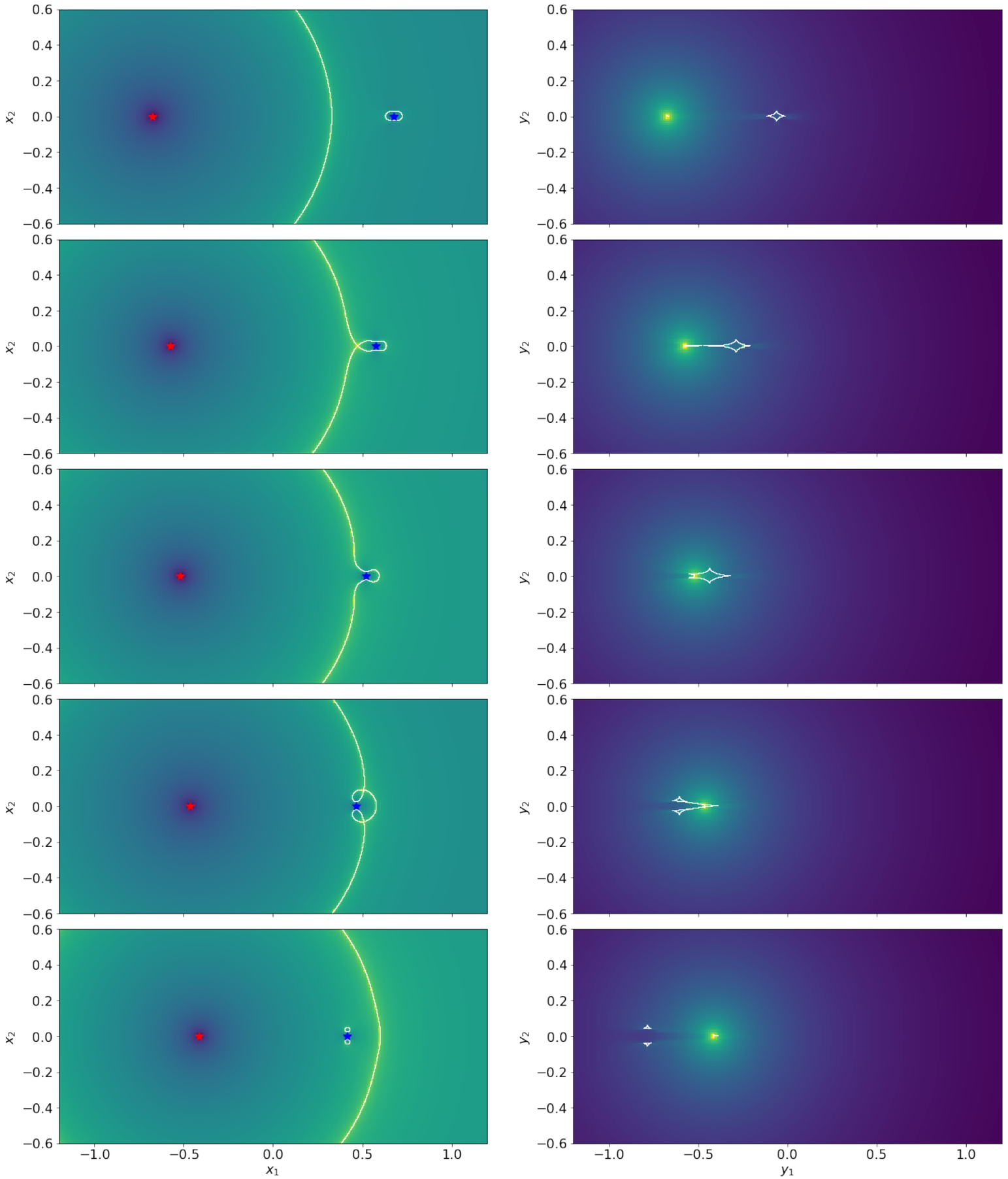
b

β_y (θ_E)

β_x (θ_E)

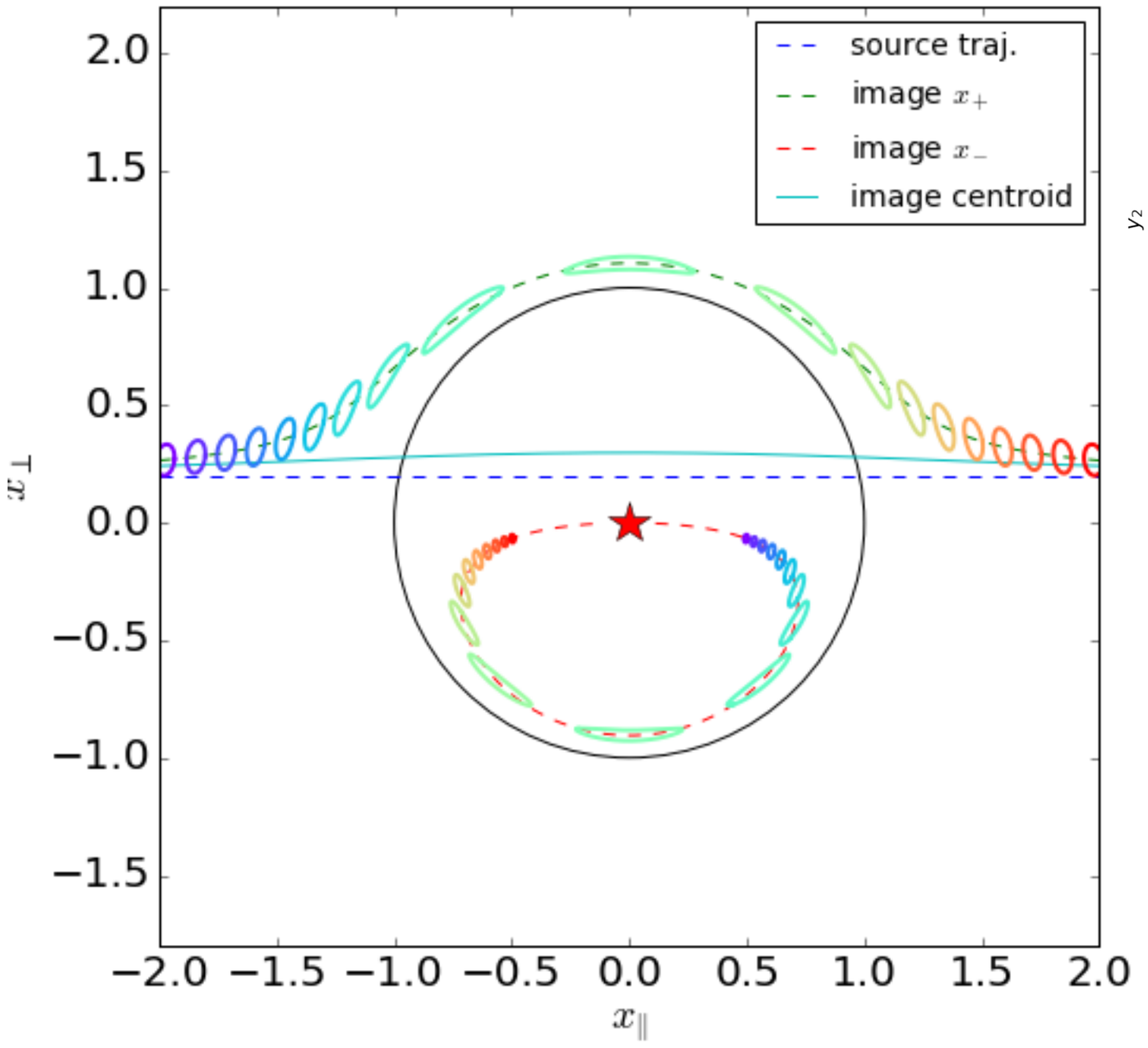
Caustics: Intermediate, Wide, Close

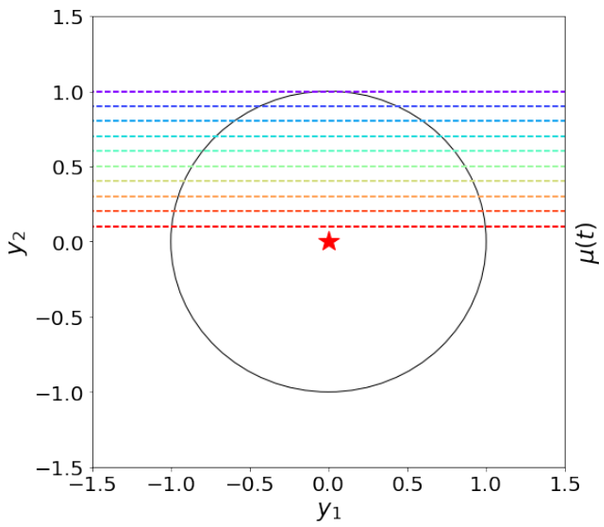
Gaudi 2013

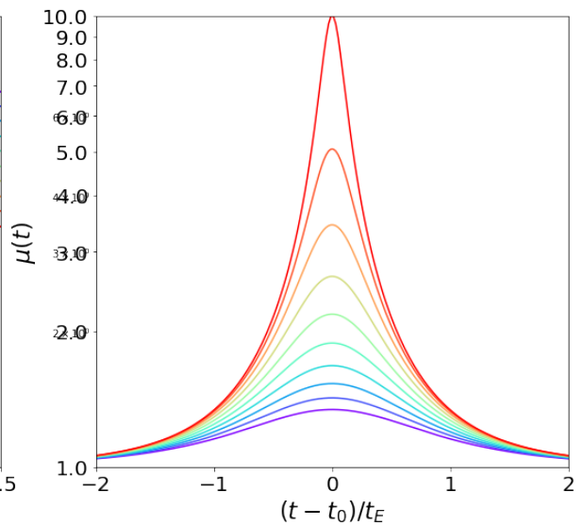

0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
x_2
y_2
−1.0
−0.5
0.0
0.5
1.0
x_1
y_1

ANOTHER WAY TO LOOK AT THE LIGHT CURVES: POINT MASS LENS

Lensing of an extended circular source







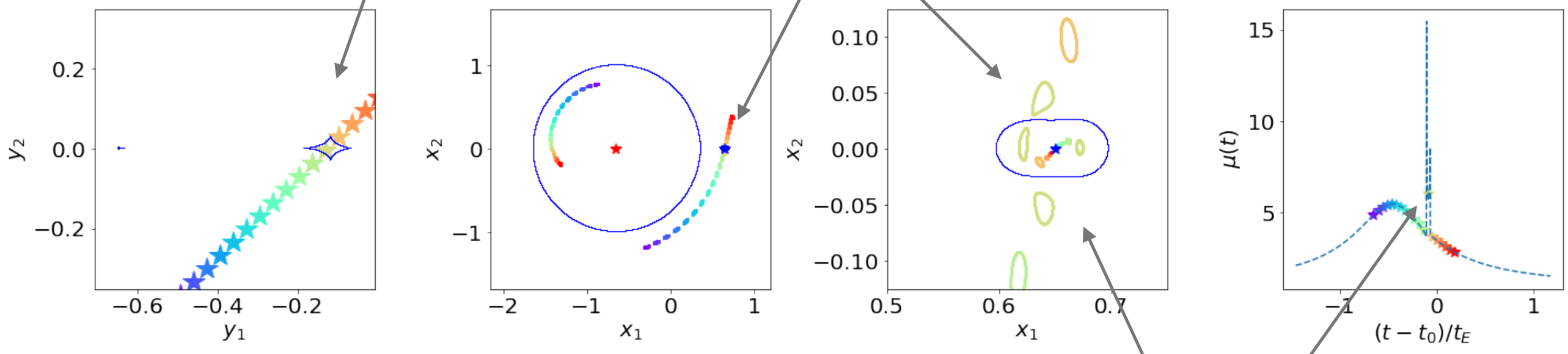
$$x_\pm = \frac{1}{2}\left[y \pm \sqrt{y^2 + 4}\right]$$

Always two images, largest magnifications near t_0

PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES

Planetary caustics

Planetary critical lines



magnified outer image

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Planetary caustics

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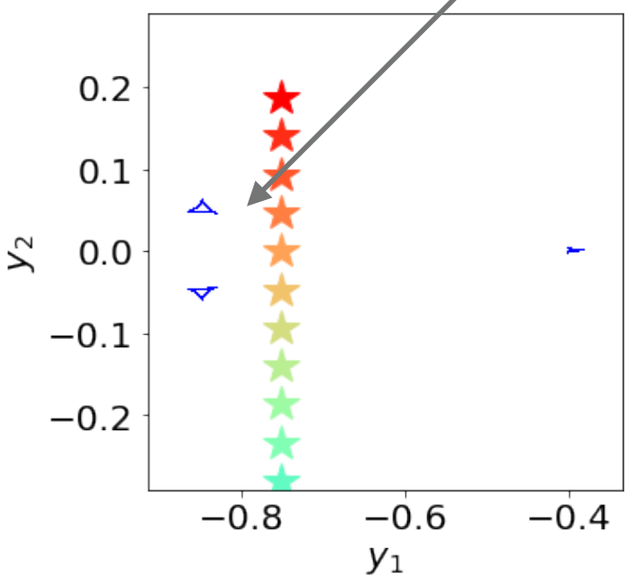
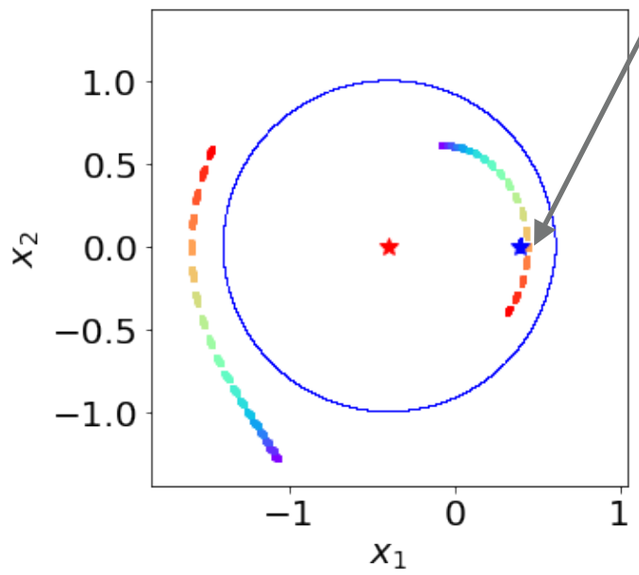
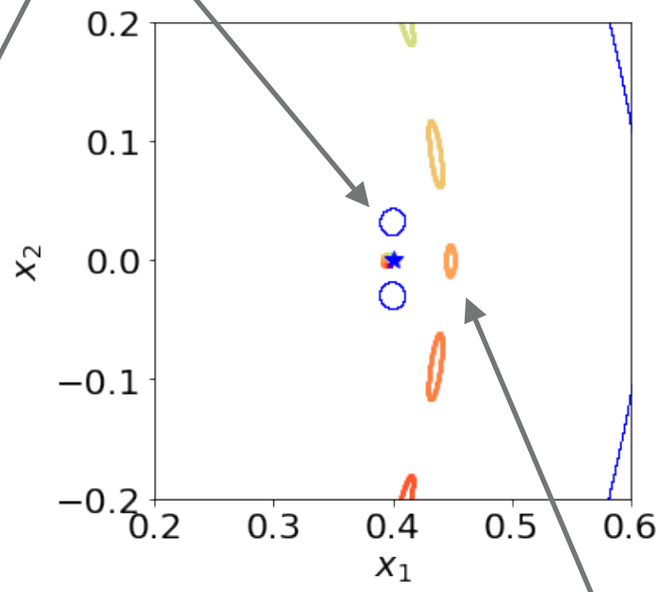
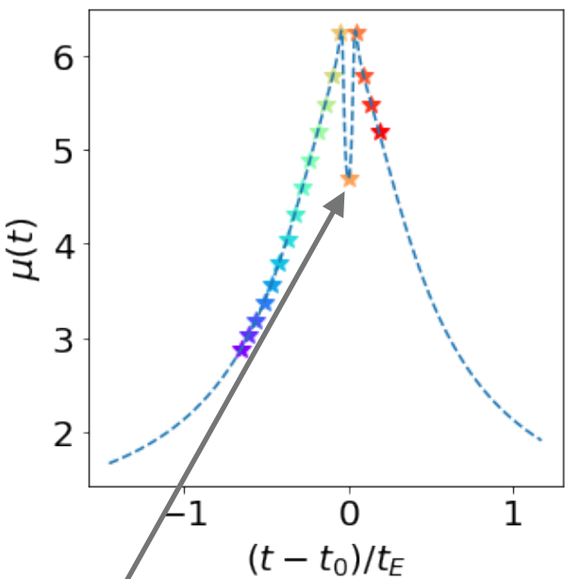


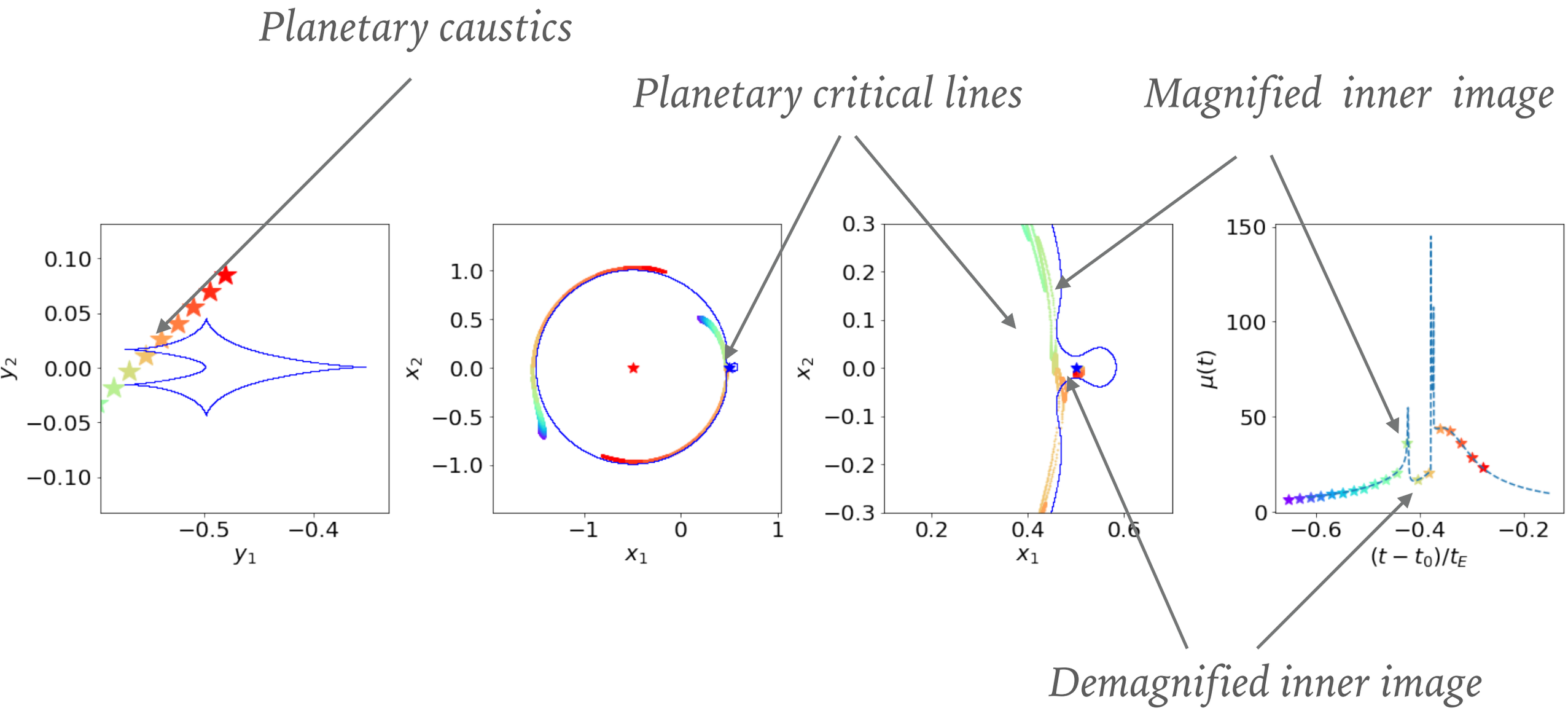




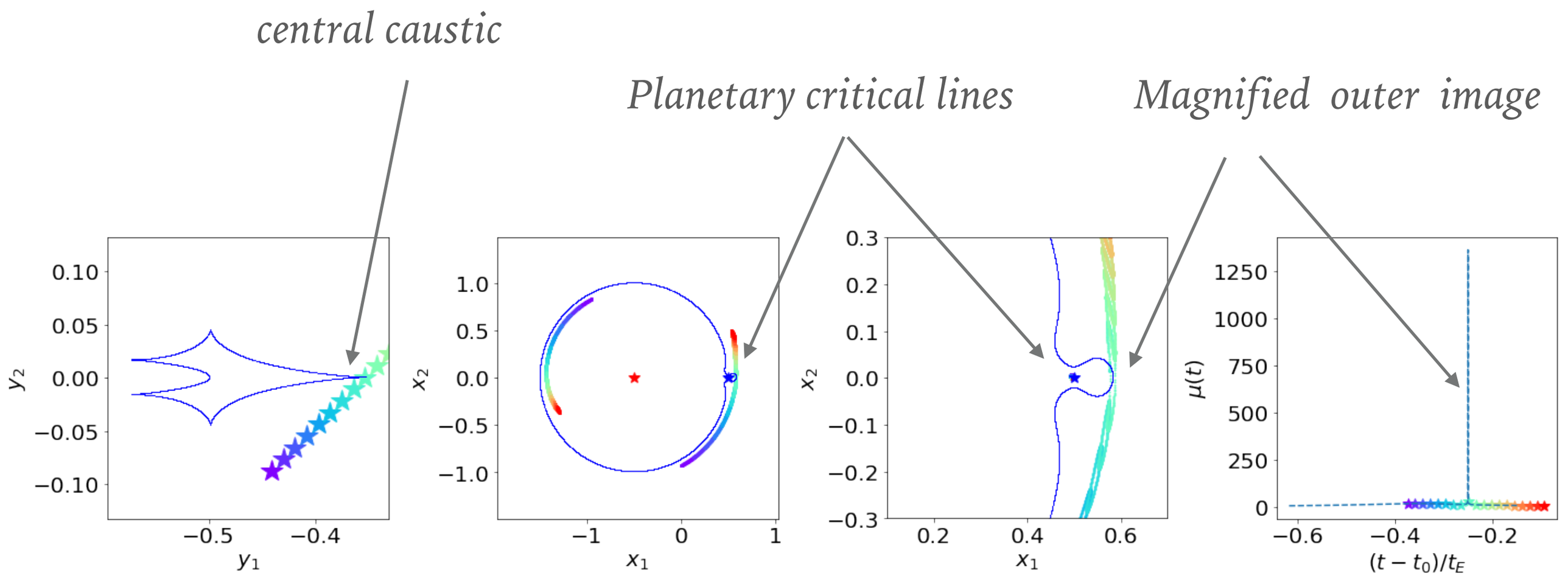


Demagnified inner image

PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES



PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES



INTERPRETING THE LIGHT CURVES

If we notice a planetary caustic perturbation, it means that the planet is located at the position of one of the images:

$$|x_{\pm}| = d$$

Consequently the caustic which is being crossed has a position which can be derived from the lens equation (which is satisfied by the images)

$$x_{\pm} = \frac{1}{2}\left[y \pm \sqrt{y^2 + 4}\right]$$

INTERPRETING THE LIGHT CURVES

If we notice a planetary caustic perturbation, it means that the planet is located at the position of one of the images:

$$|x_{\pm}| = d \qquad\qquad x_{\pm} = \frac{1}{2}\left[y \pm \sqrt{y^2+4}\right]$$

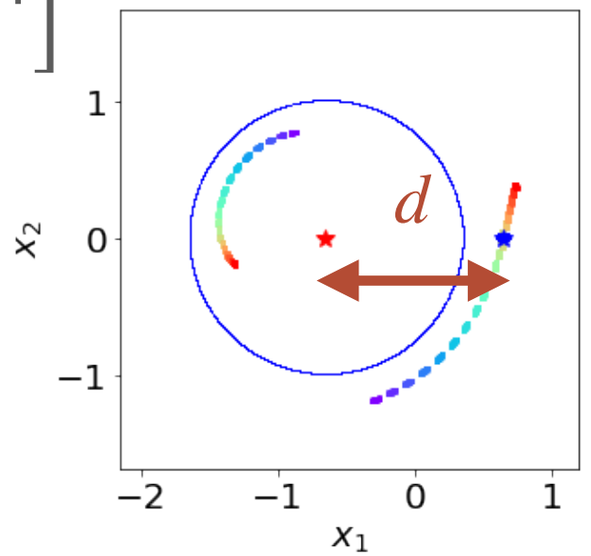
Case 1: perturbation of the outer image ($x_+ > 0$):

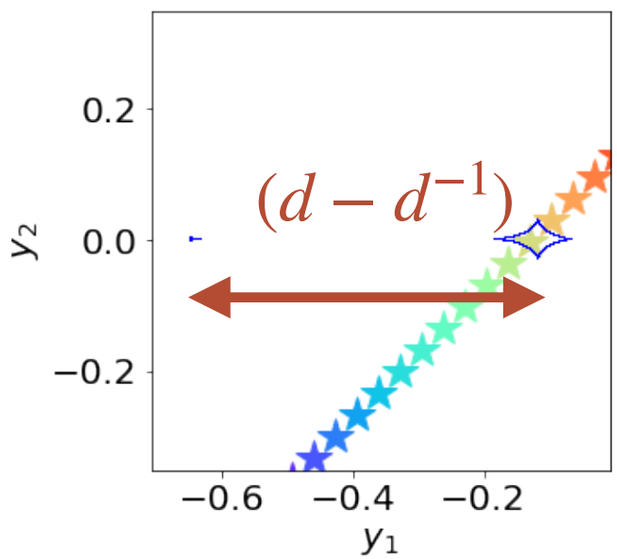
$$d = \frac{1}{2}y + \frac{1}{2}\sqrt{y^2+4}$$

$$\frac{1}{2}\sqrt{y^2+4} = \left(d - \frac{1}{2}y\right)$$

$$y^2 + 4 = 4\left(d^2 + \frac{y^2}{4} - yd\right) \Rightarrow yd = d^2 - 1$$

$$y = (d - d^{-1})$$





INTERPRETING THE LIGHT CURVES

If we notice a planetary caustic perturbation, it means that the planet is located at the position of one of the images:

$$|x_{\pm}| = d \qquad\qquad x_{\pm} = \frac{1}{2}\left[y \pm \sqrt{y^2+4}\right]$$

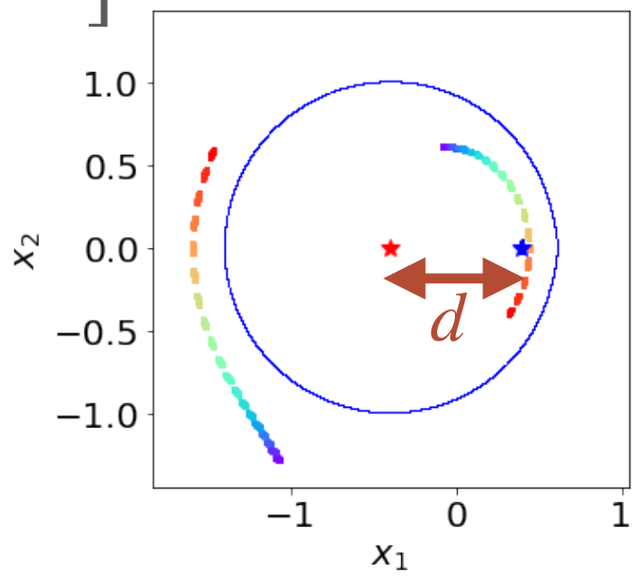
Case 2: perturbation of the inner image ($x_-<0$):

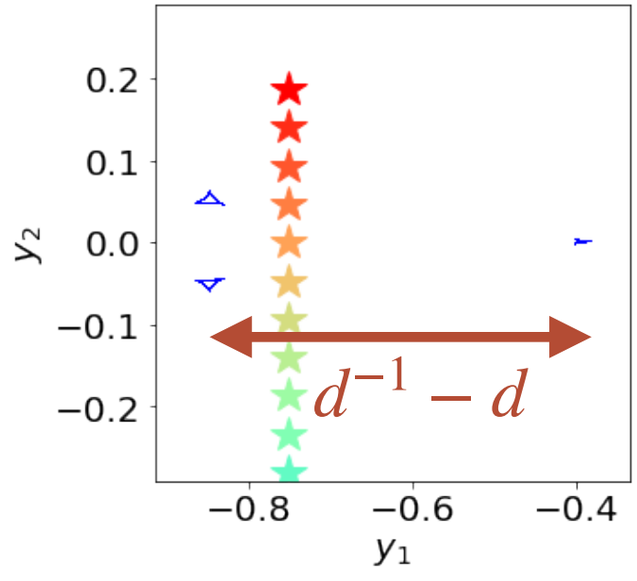
$$d = -\left(\frac{1}{2}y - \frac{1}{2}\sqrt{y^2+4}\right)$$

$$\frac{1}{2}\sqrt{y^2+4} = \left(\frac{1}{2}y + d\right)$$

$$y^2 + 4 = 4\left(\frac{y^2}{4} + yd + d^2\right) \Rightarrow yd = 1 - d^2$$

$$y = (d^{-1} - d)$$

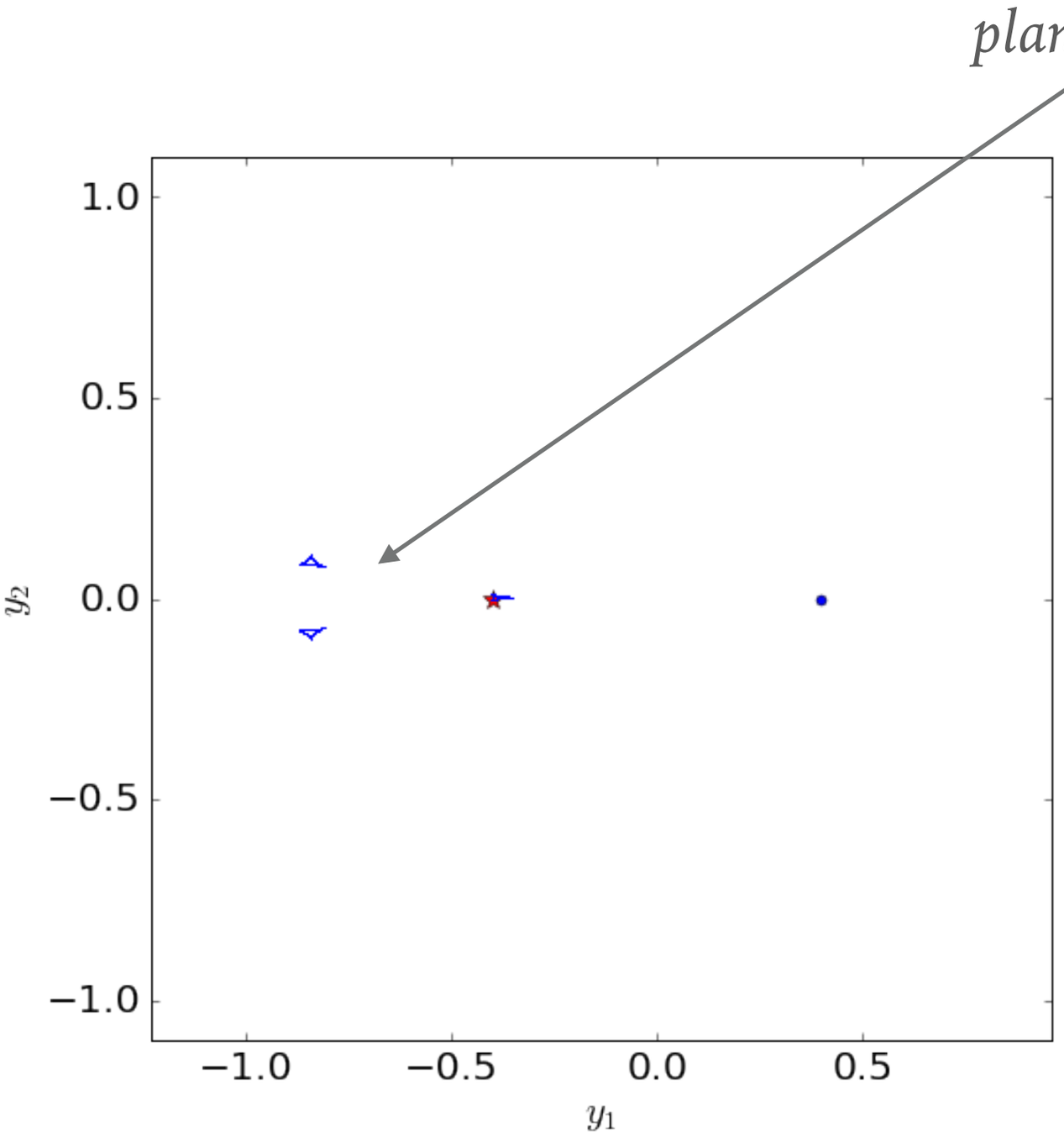


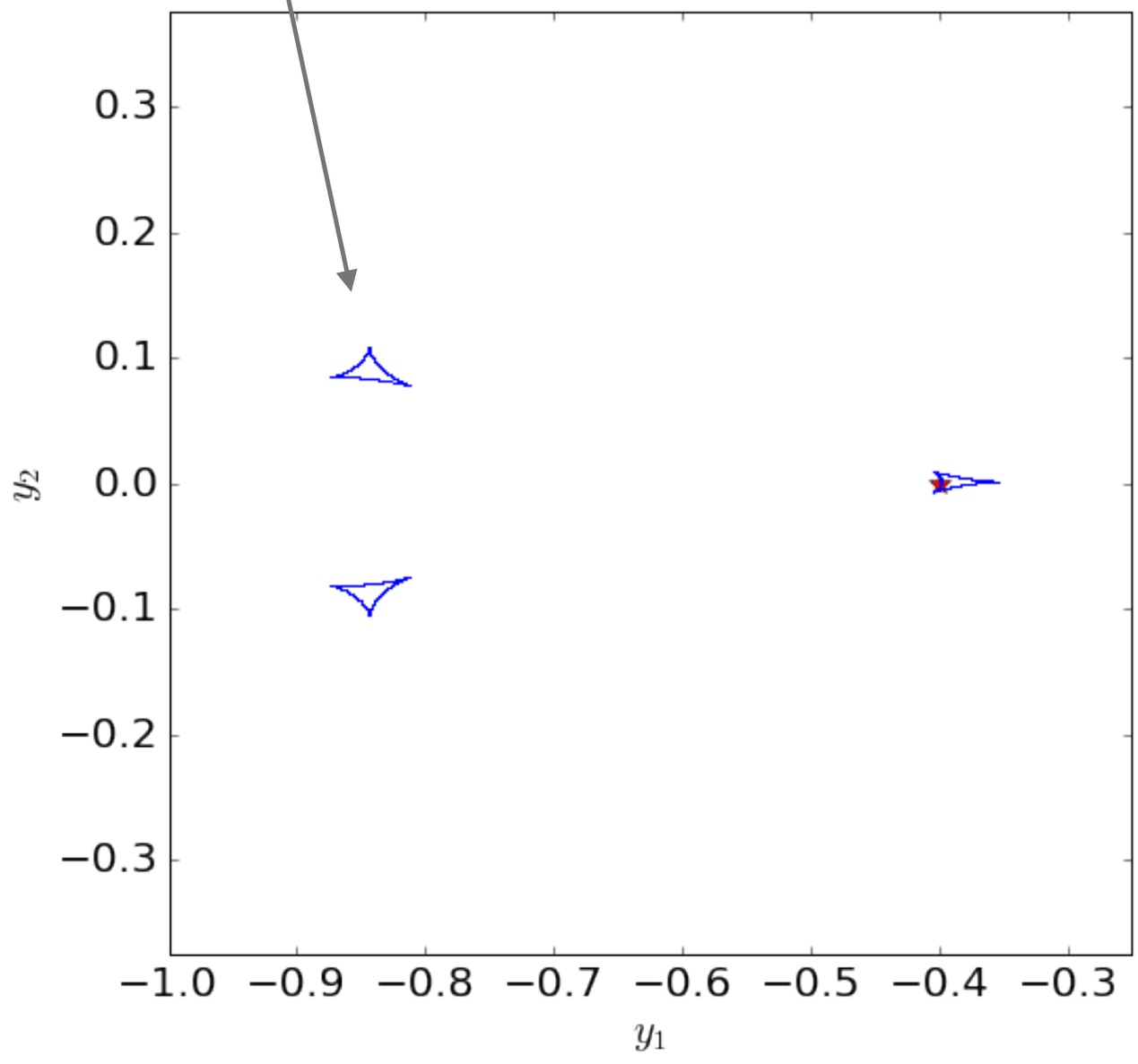


PLANETARY CAUSTICS IN CLOSE TOPOLOGIES

planetary caustics

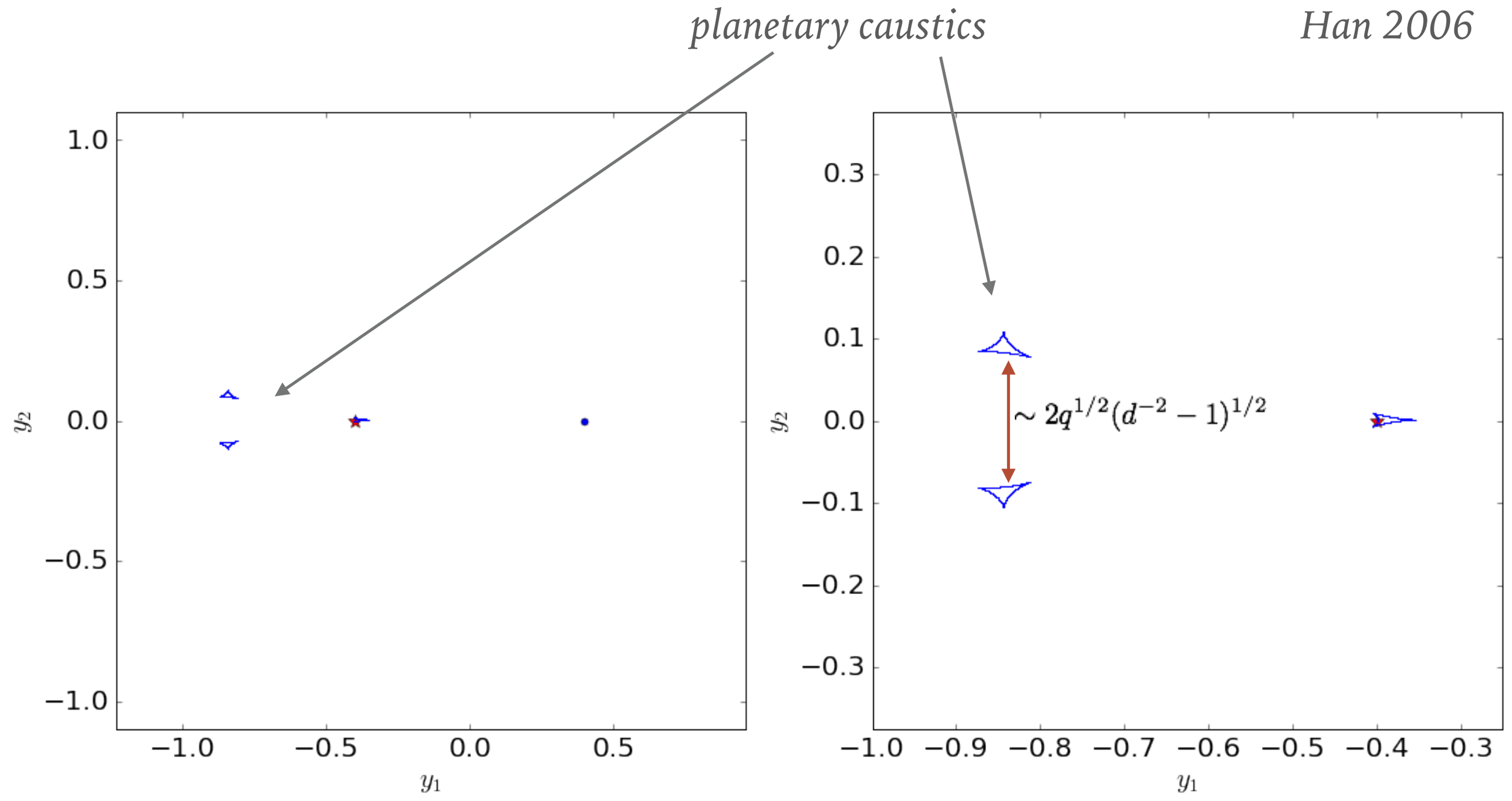
Han 2006





Recommended reading: Han, C., 2006, ApJ, 638, 1080

PLANETARY CAUSTICS IN CLOSE TOPOLOGIES



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PLANETARY CAUSTICS IN CLOSE TOPOLOGIES

planetary caustics

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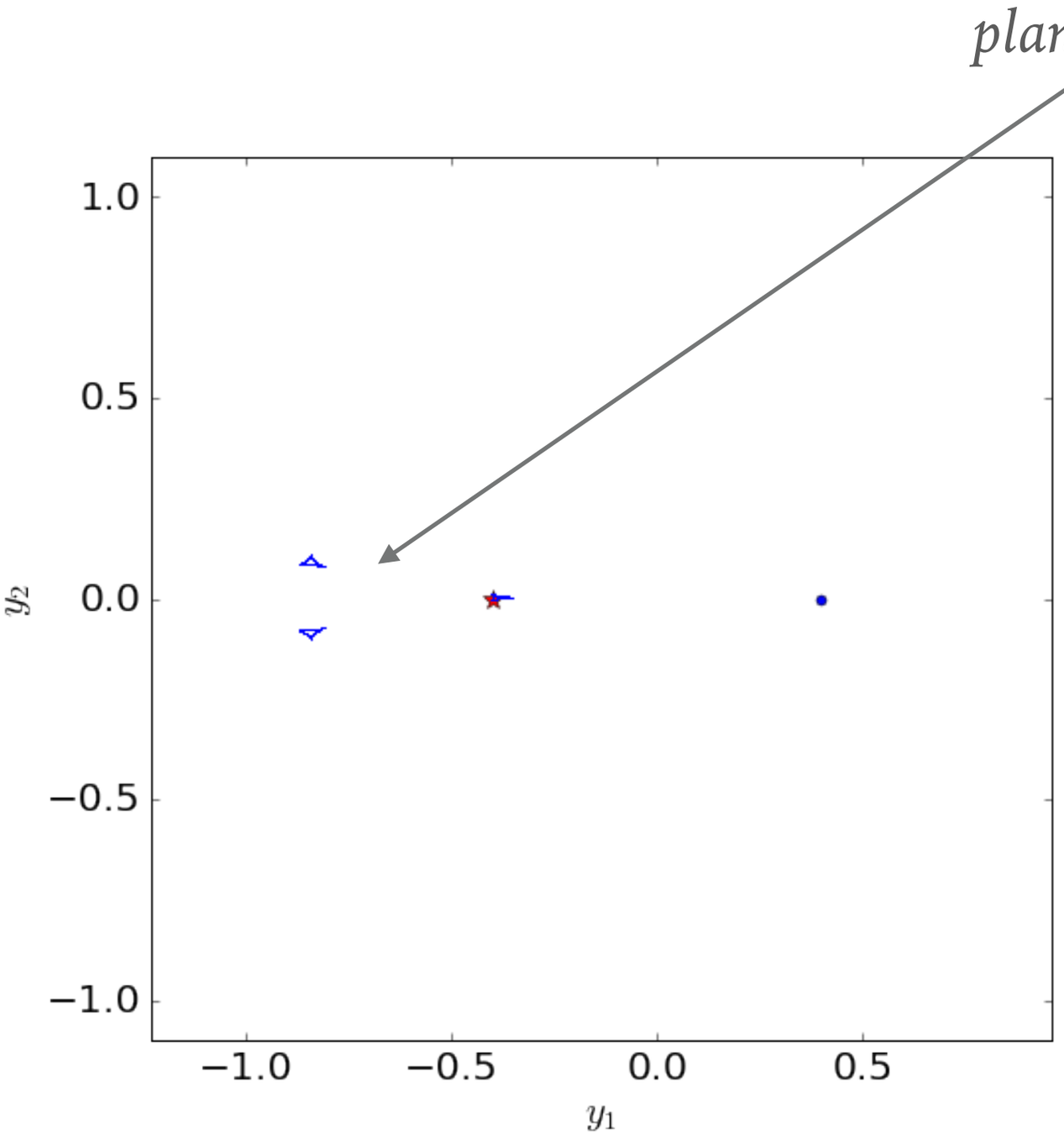

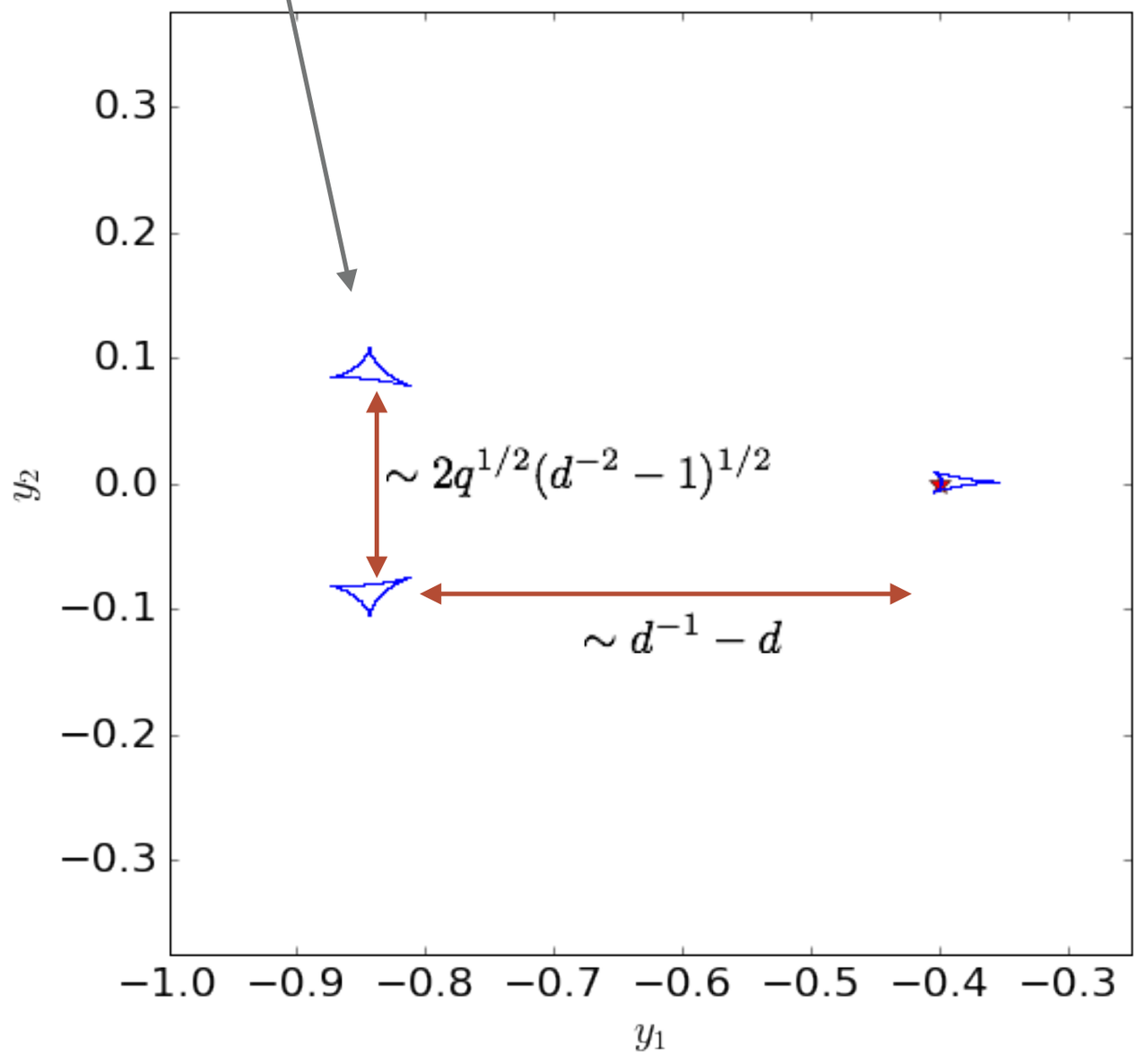

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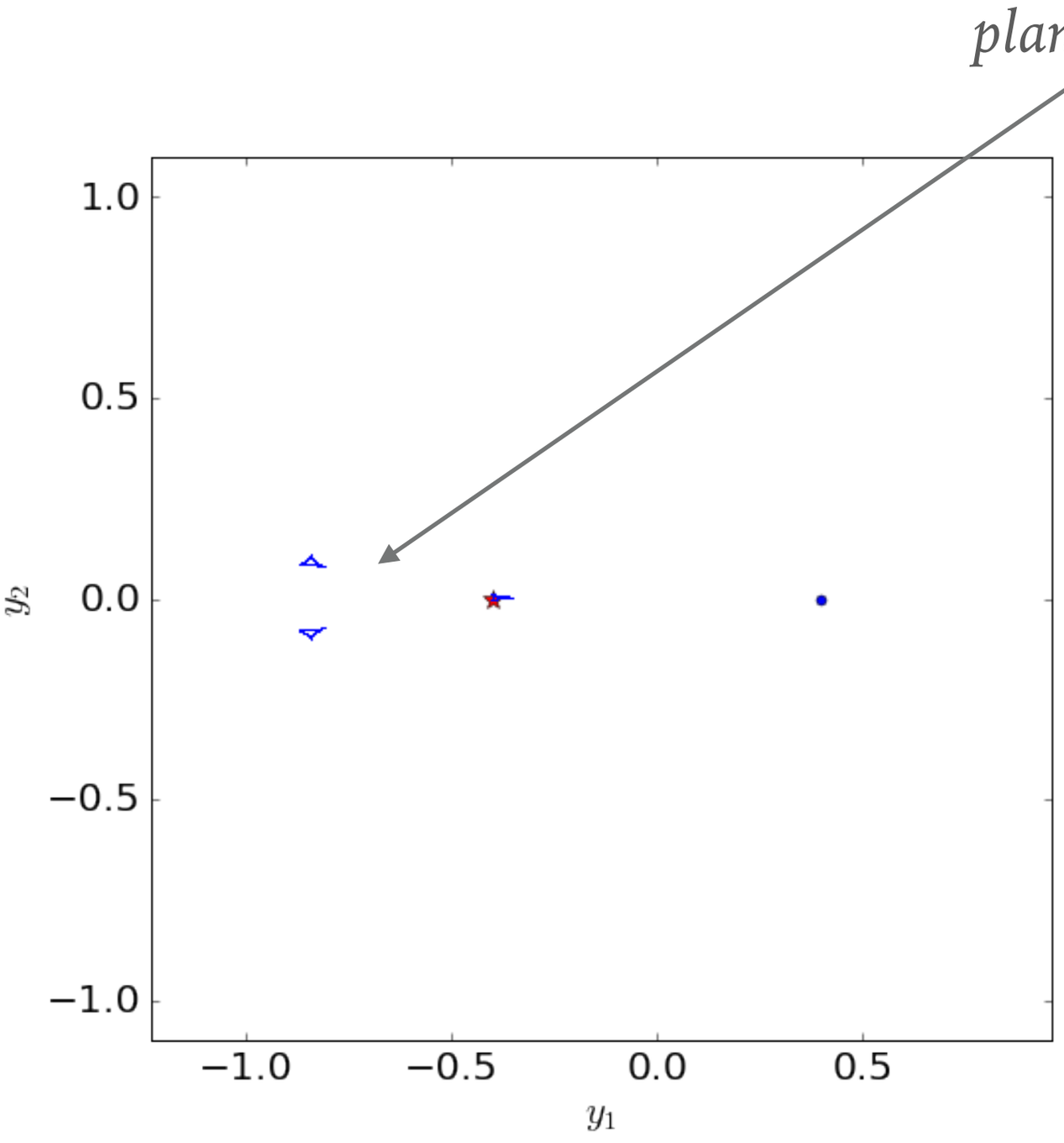
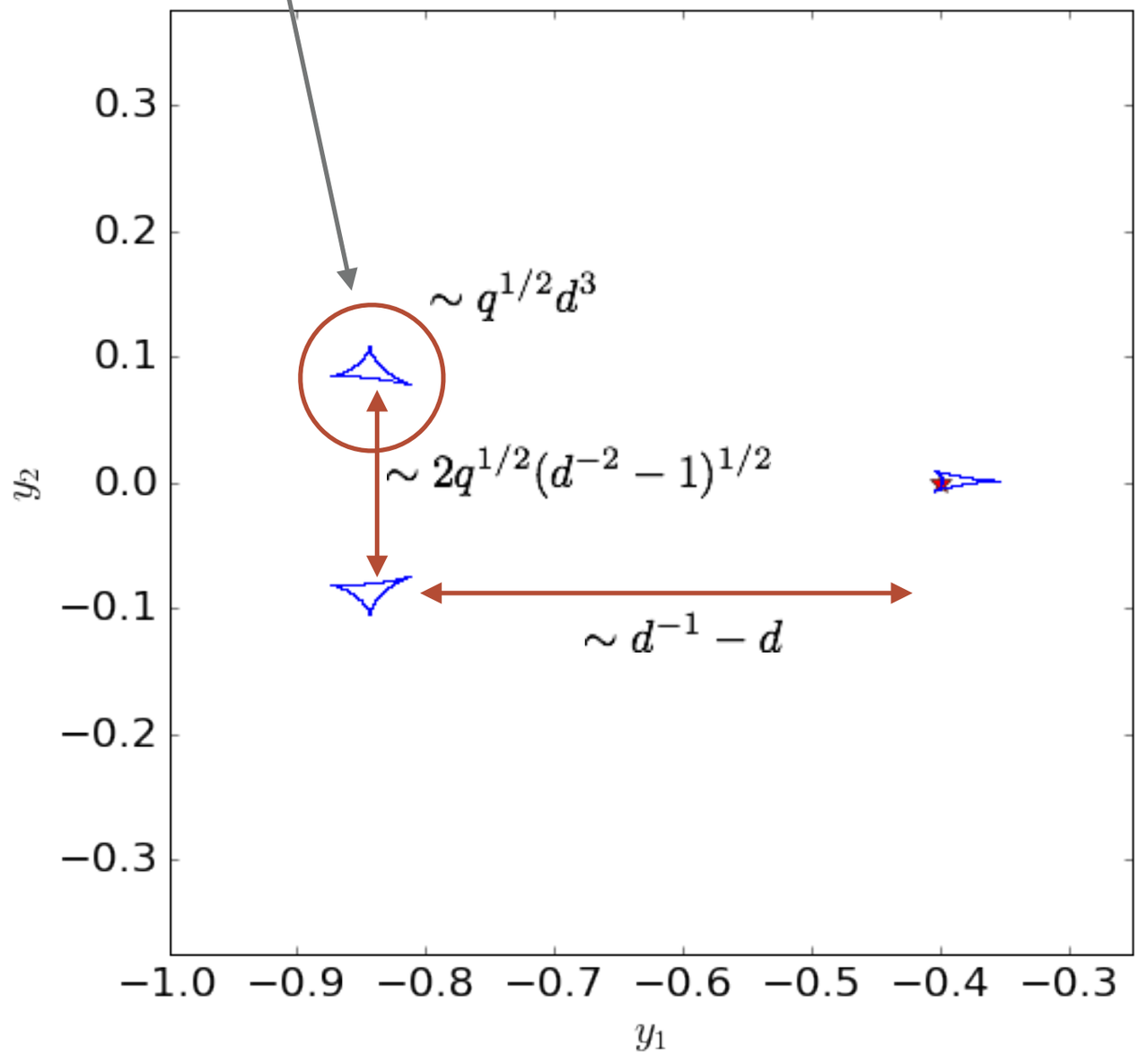
PLANETARY CAUSTICS IN CLOSE TOPOLOGIES

planetary caustics

Han 2006





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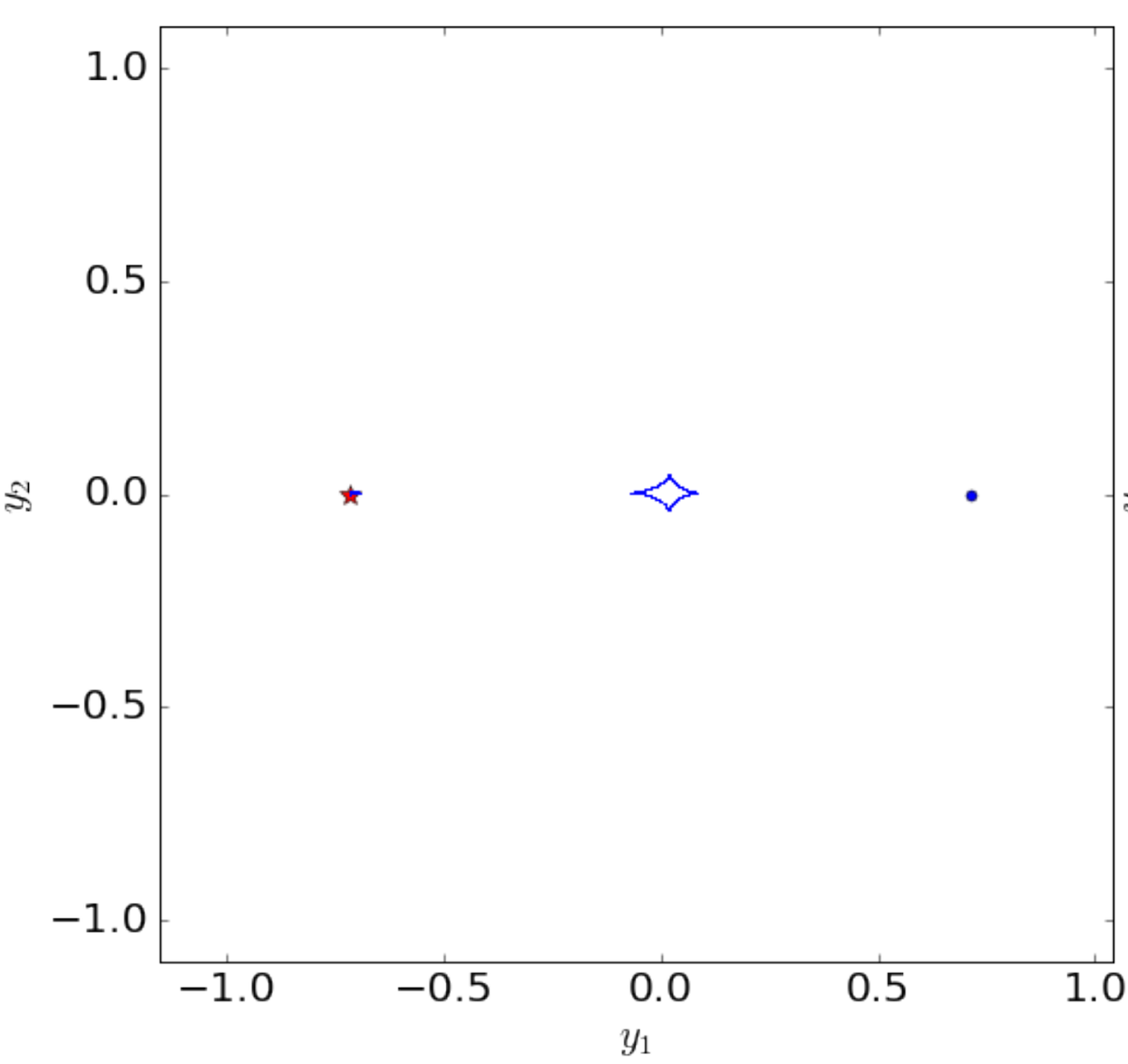
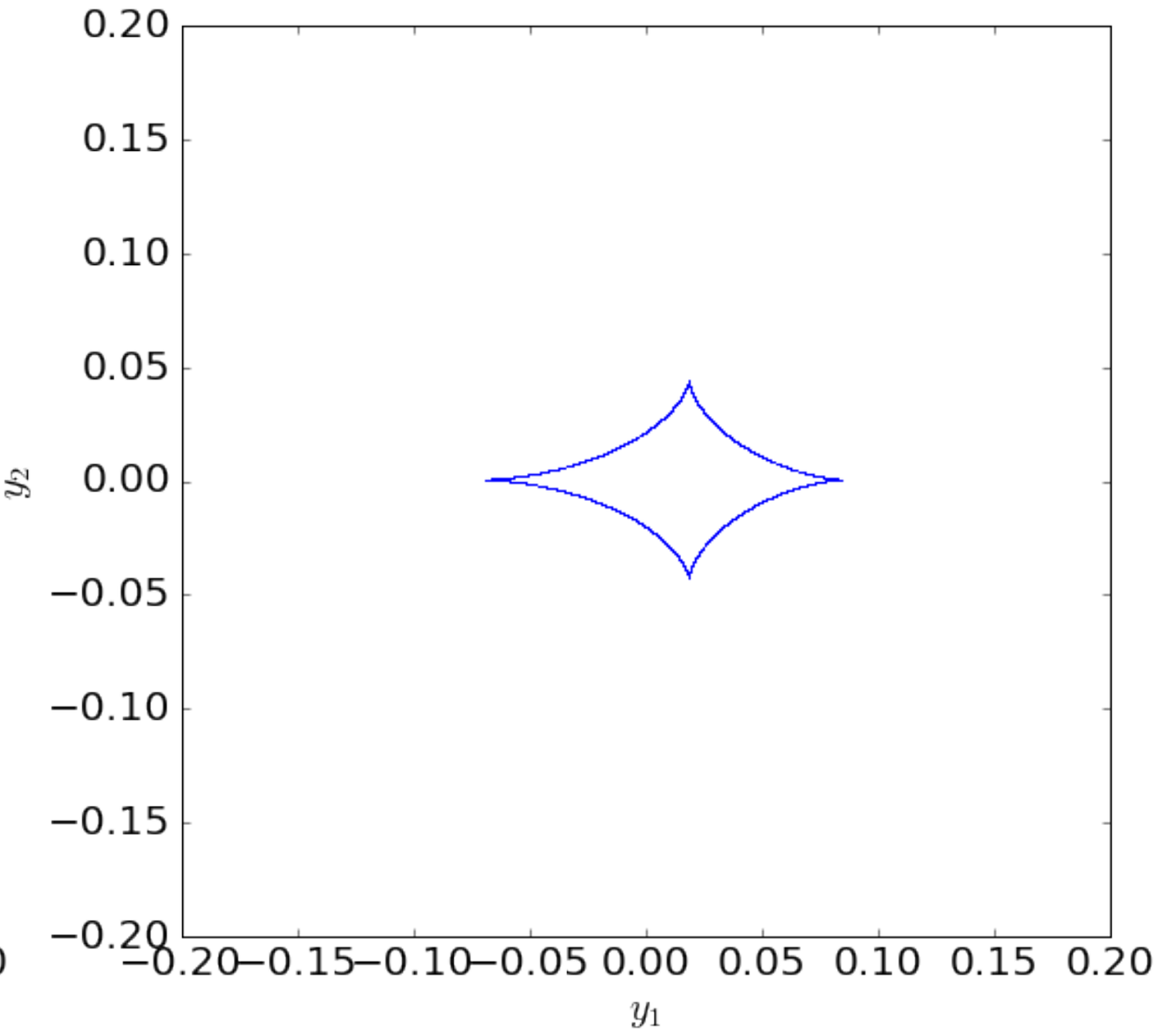
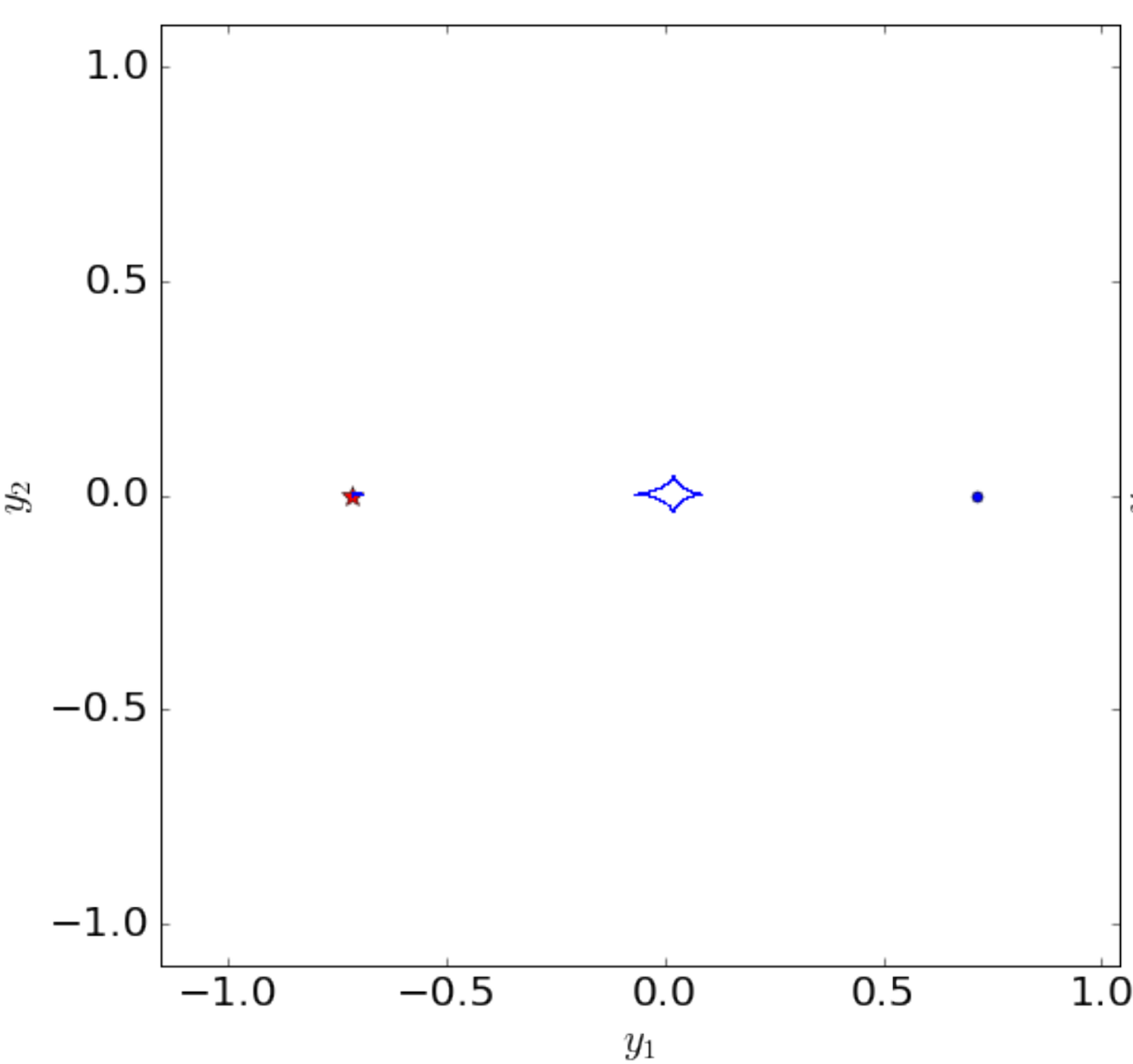
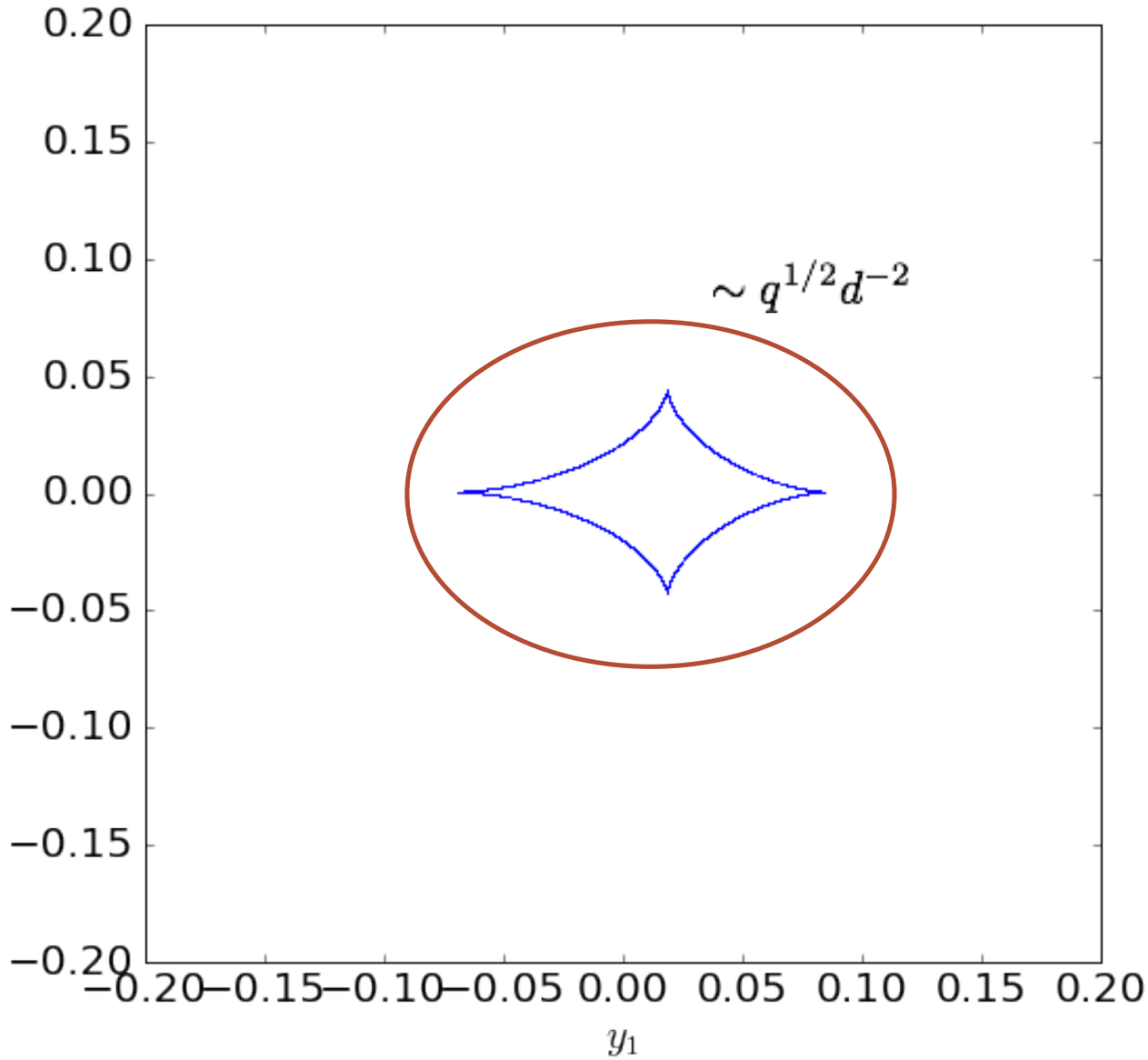
PLANETARY CAUSTICS IN WIDE TOPOLOGIES



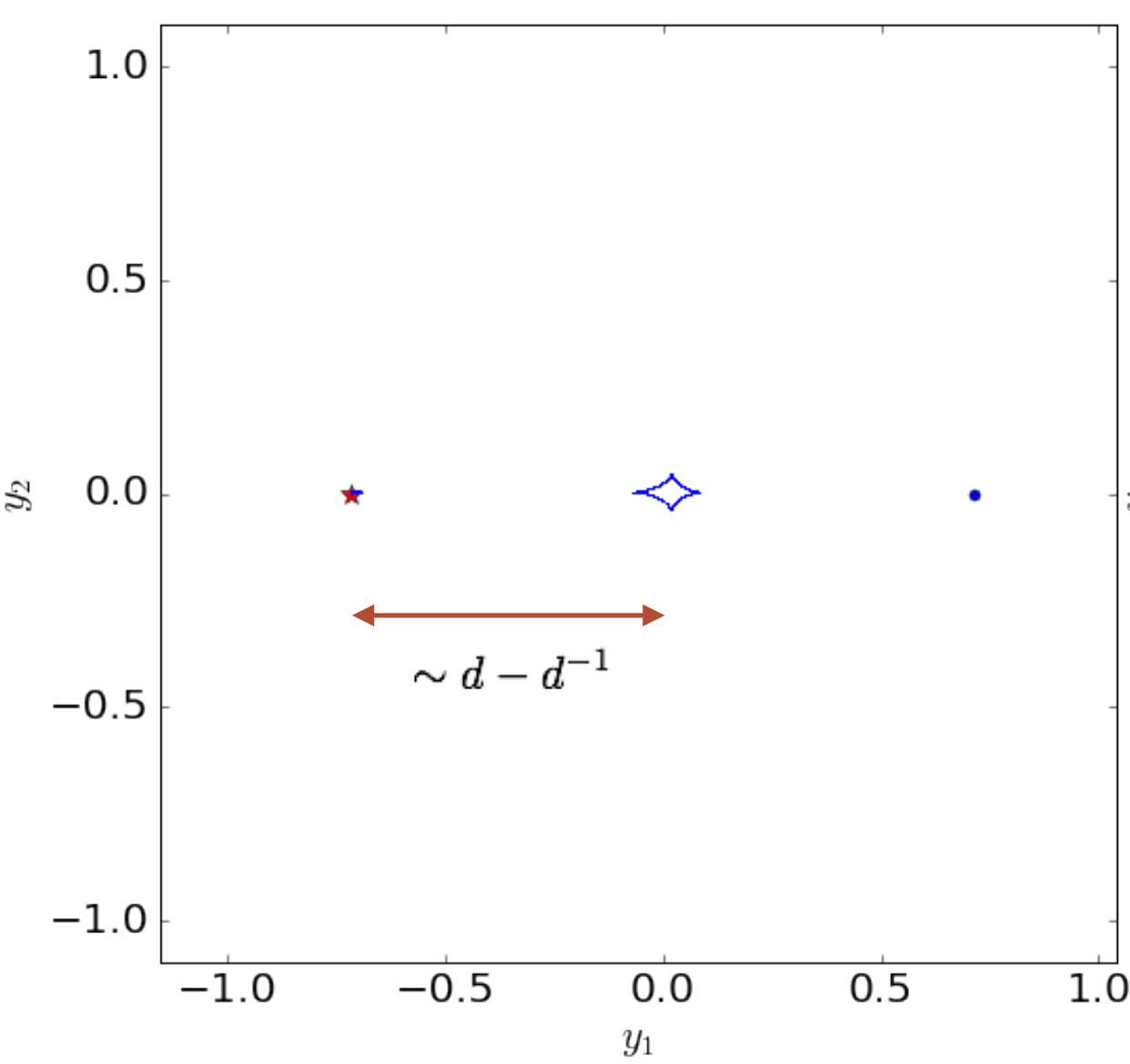


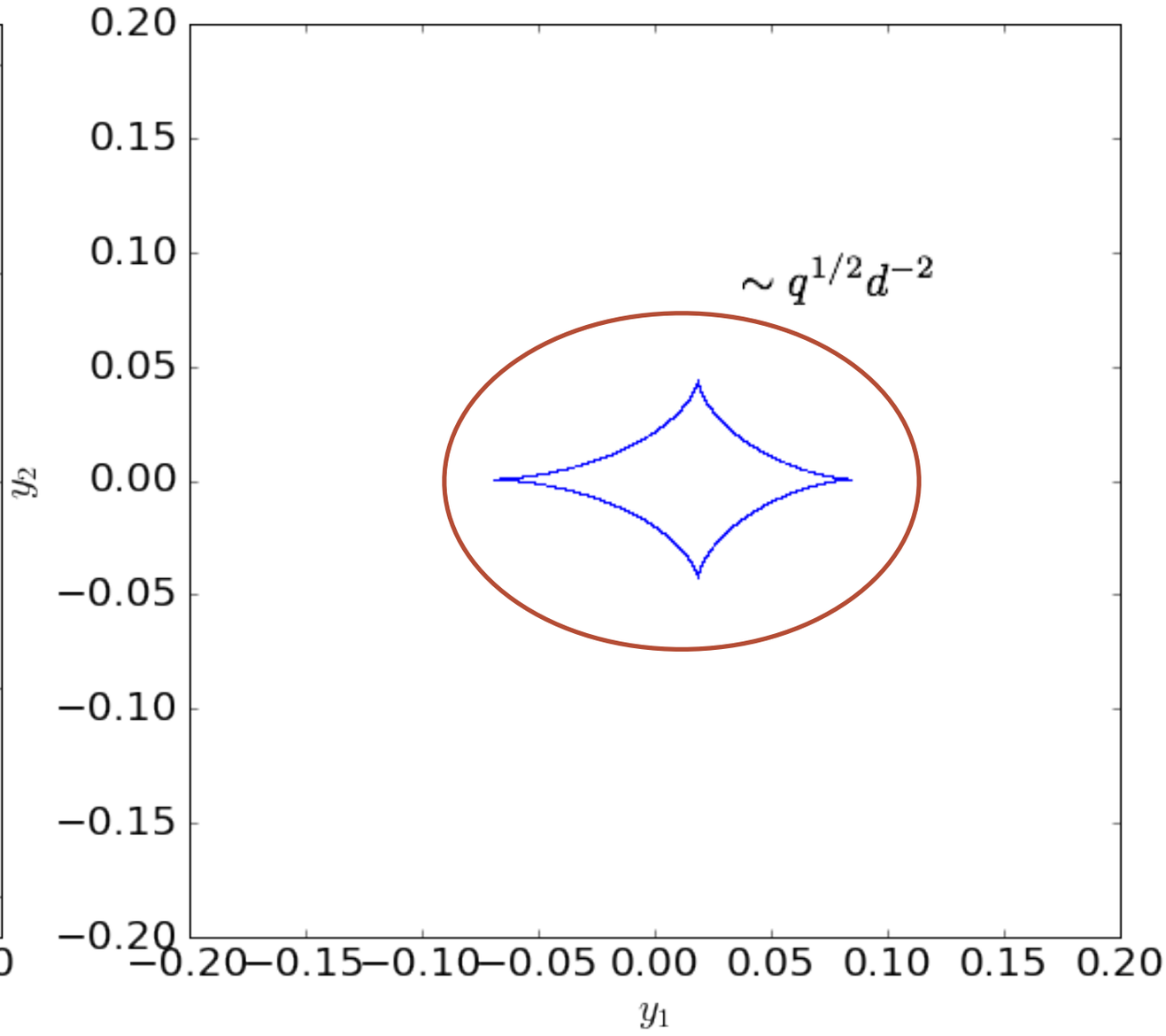
PLANETARY CAUSTICS IN WIDE TOPOLOGIES



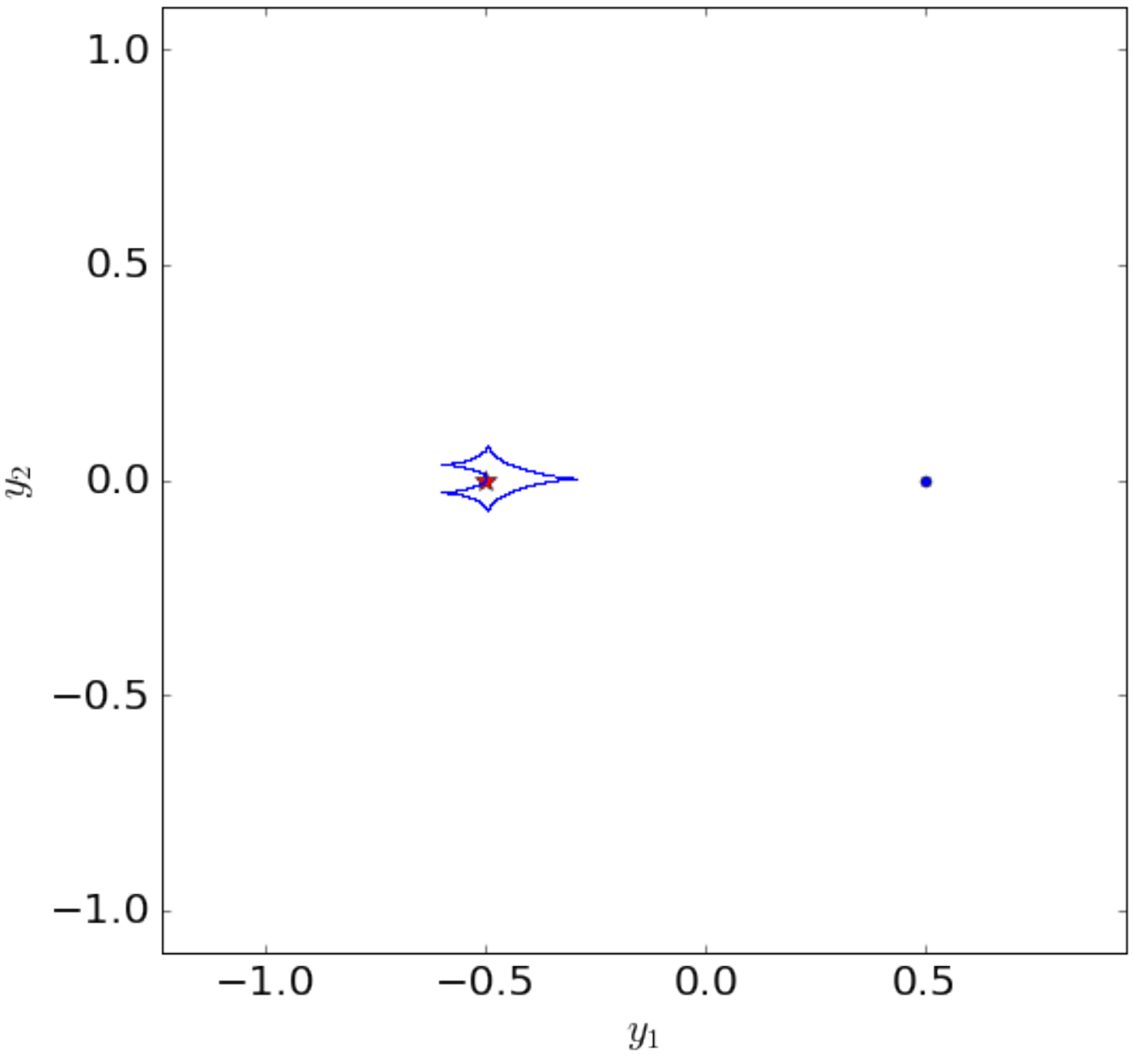


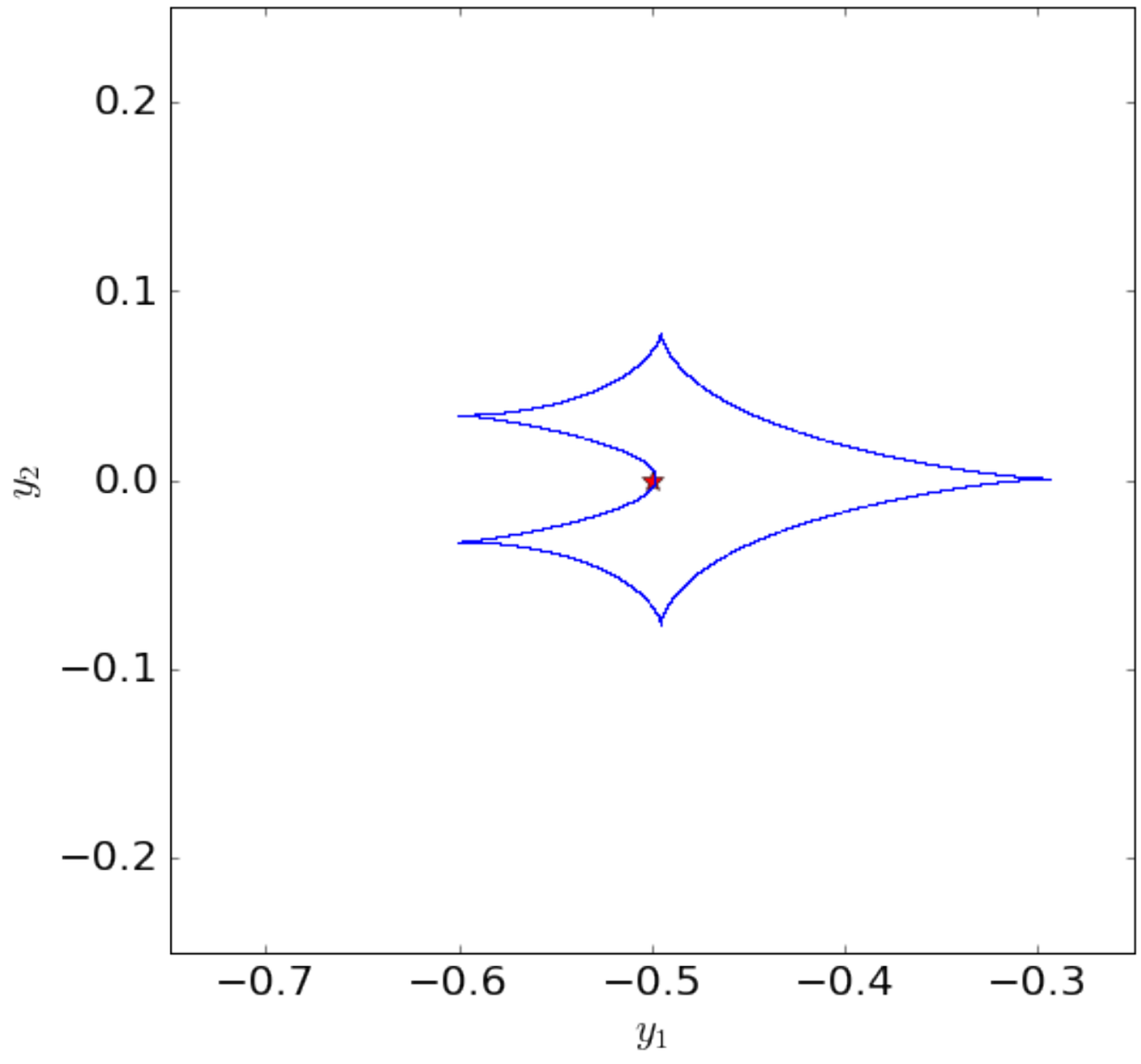
PLANETARY CAUSTICS IN WIDE TOPOLOGIES



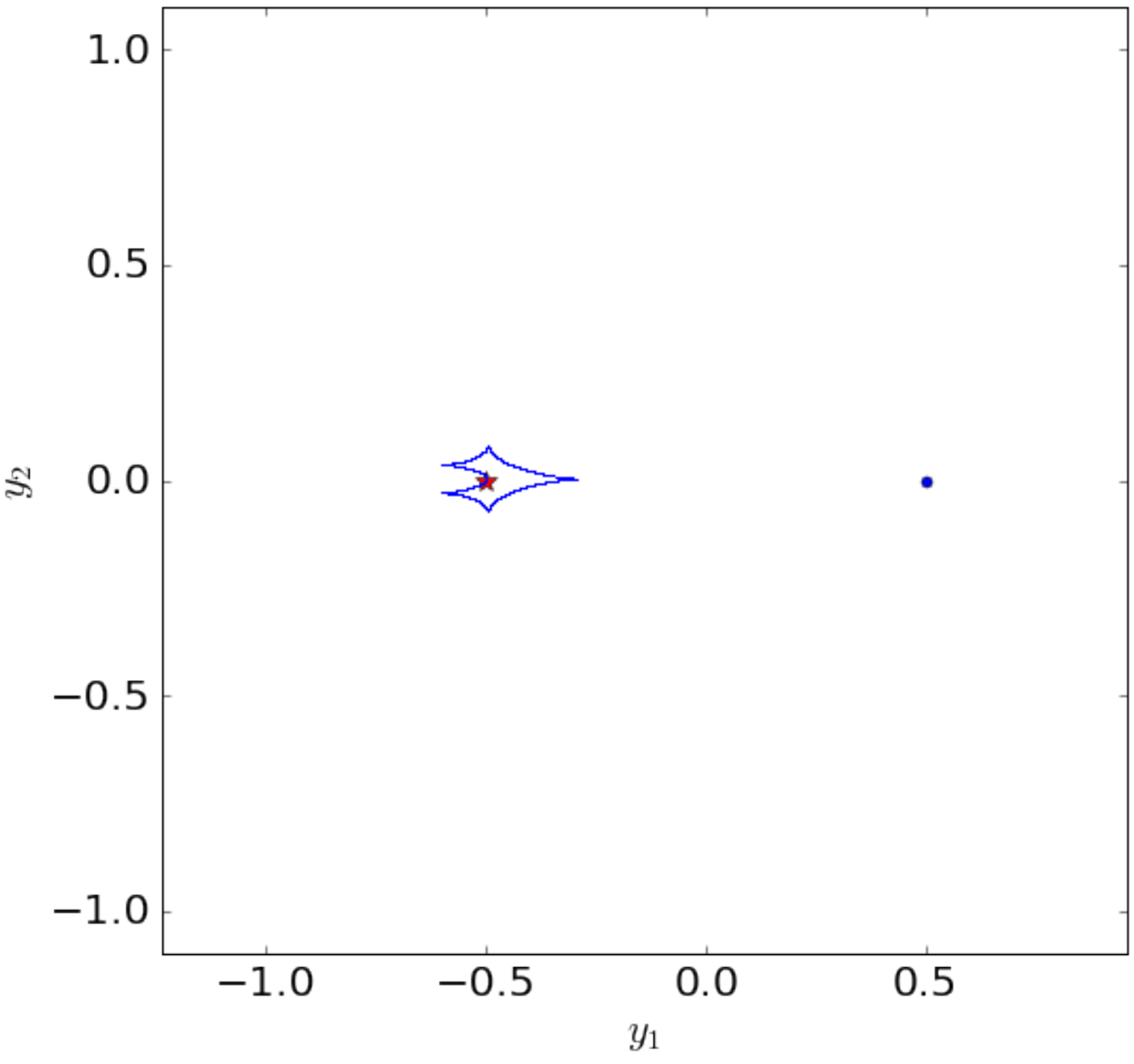


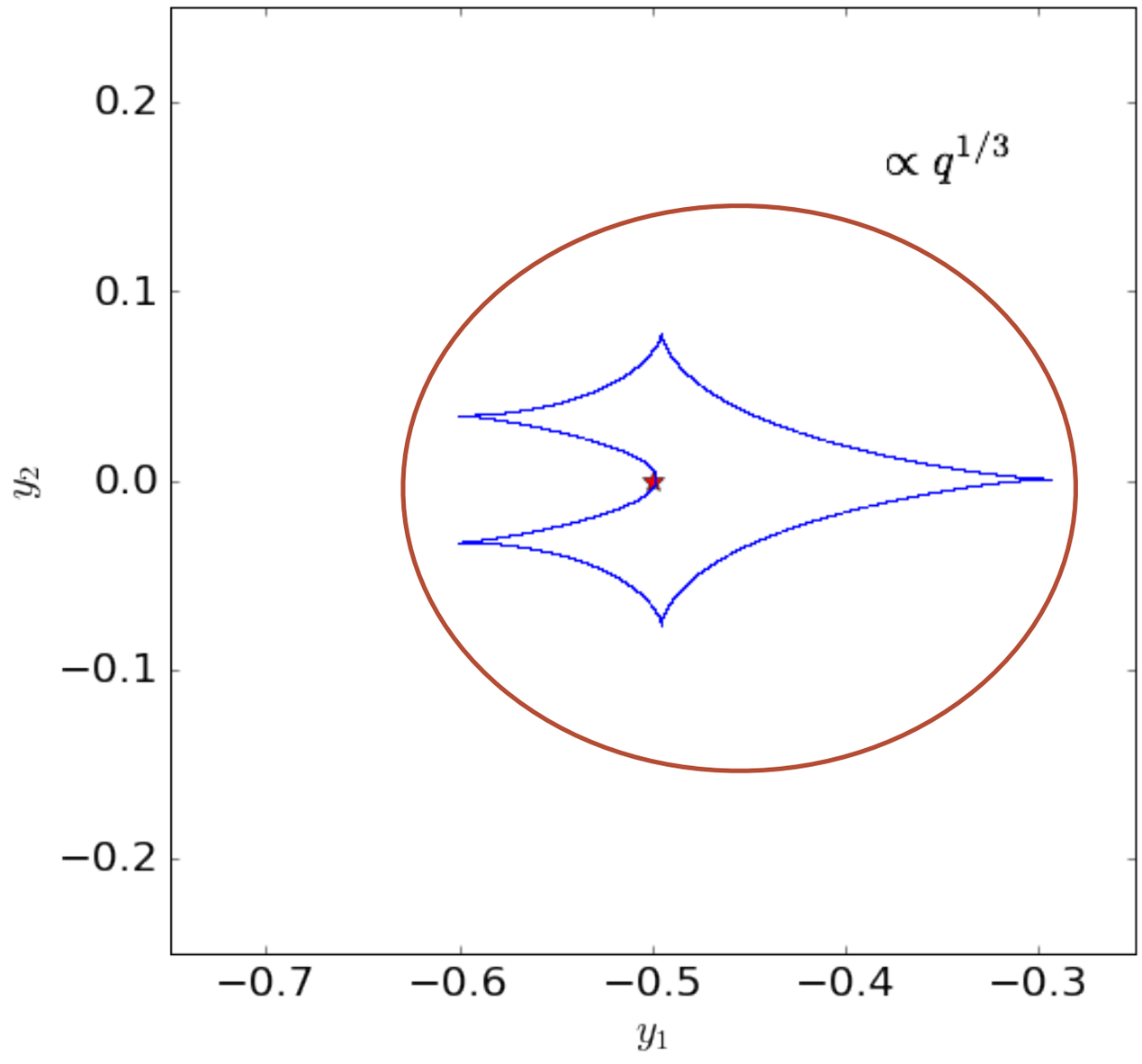
PLANETARY CAUSTICS IN INTERMEDIATE TOPOLOGIES



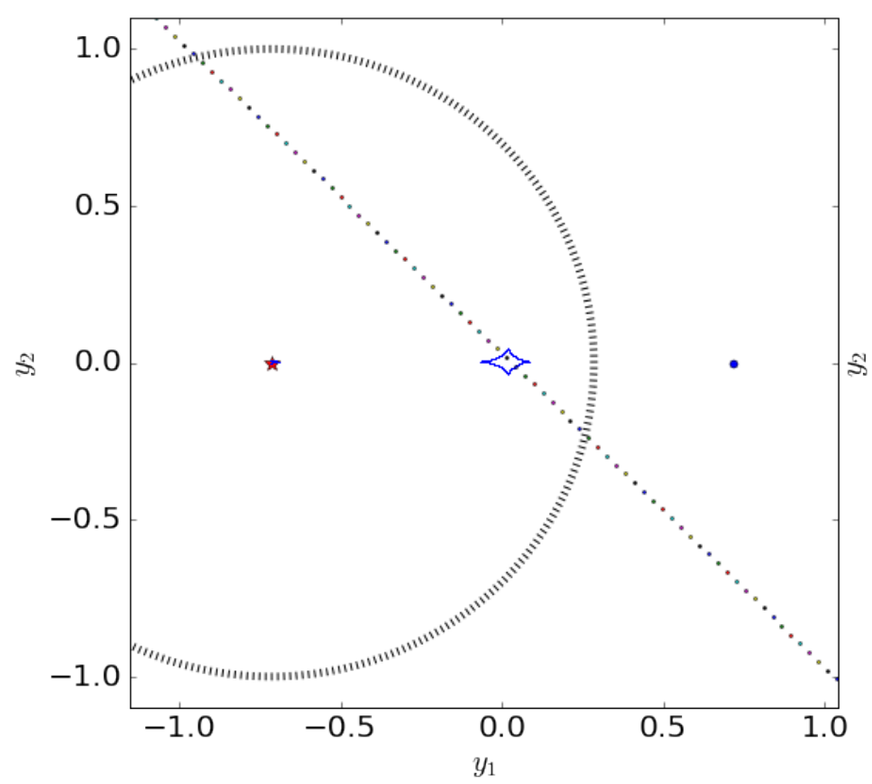


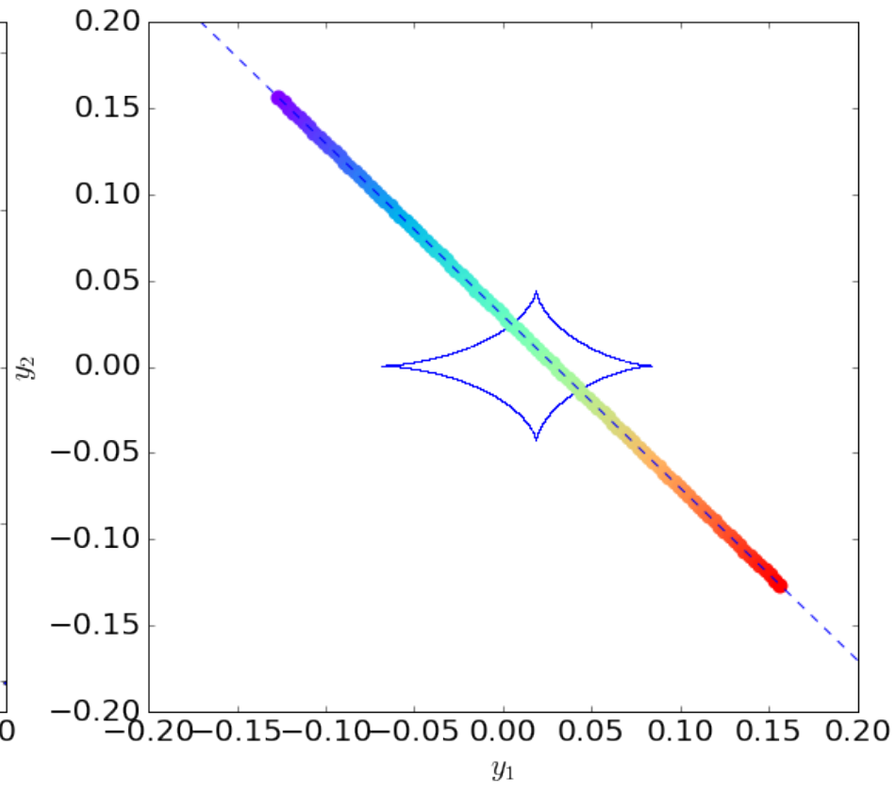
PLANETARY CAUSTICS IN INTERMEDIATE TOPOLOGIES

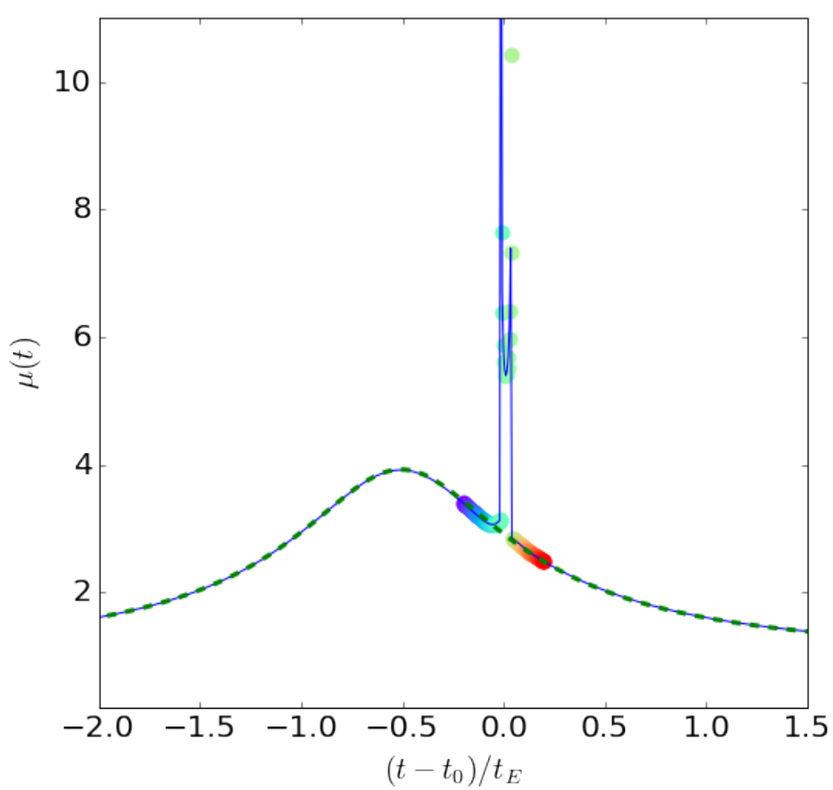




PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES

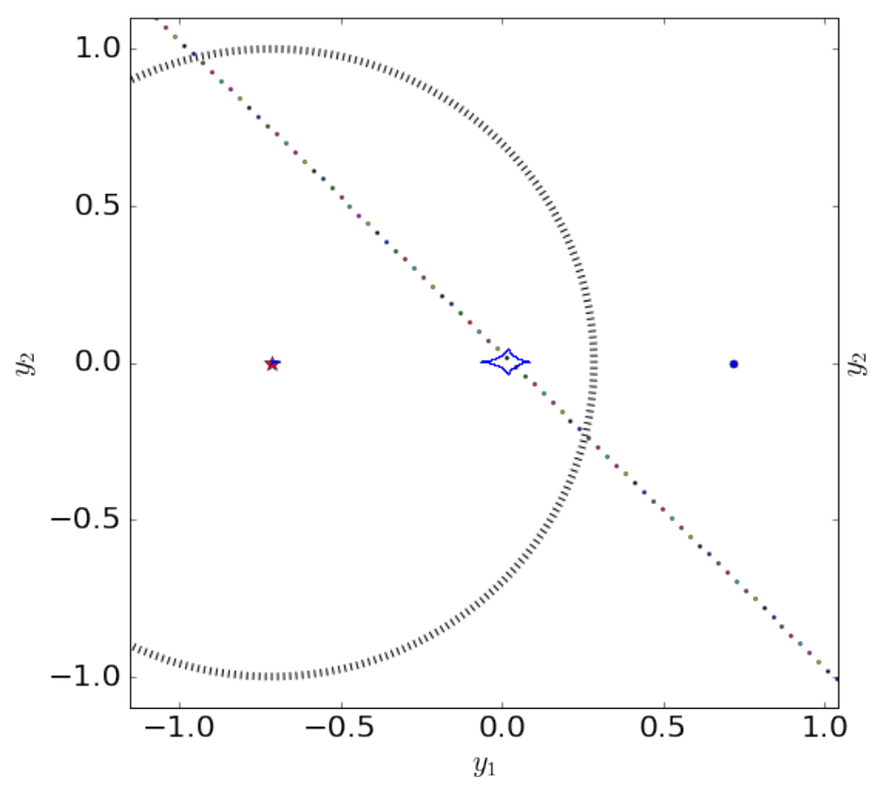


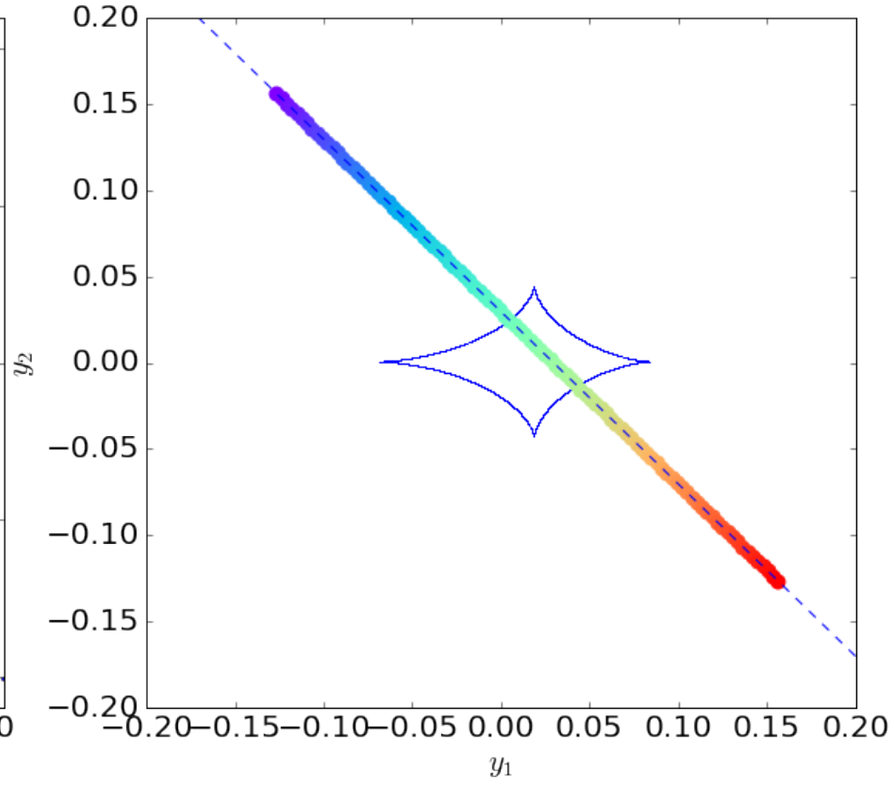


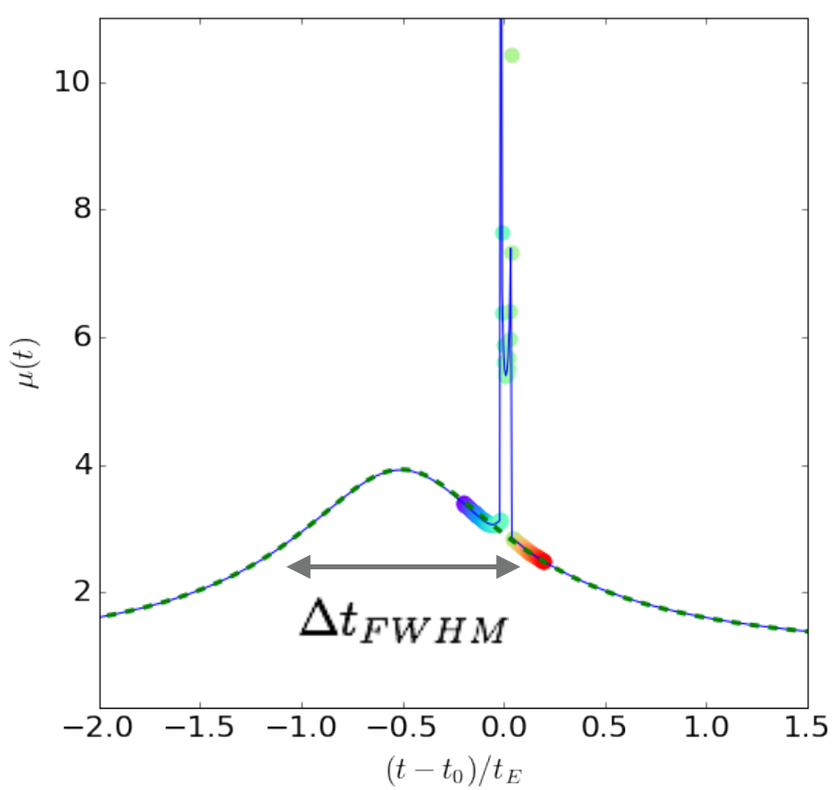


- primary event:
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

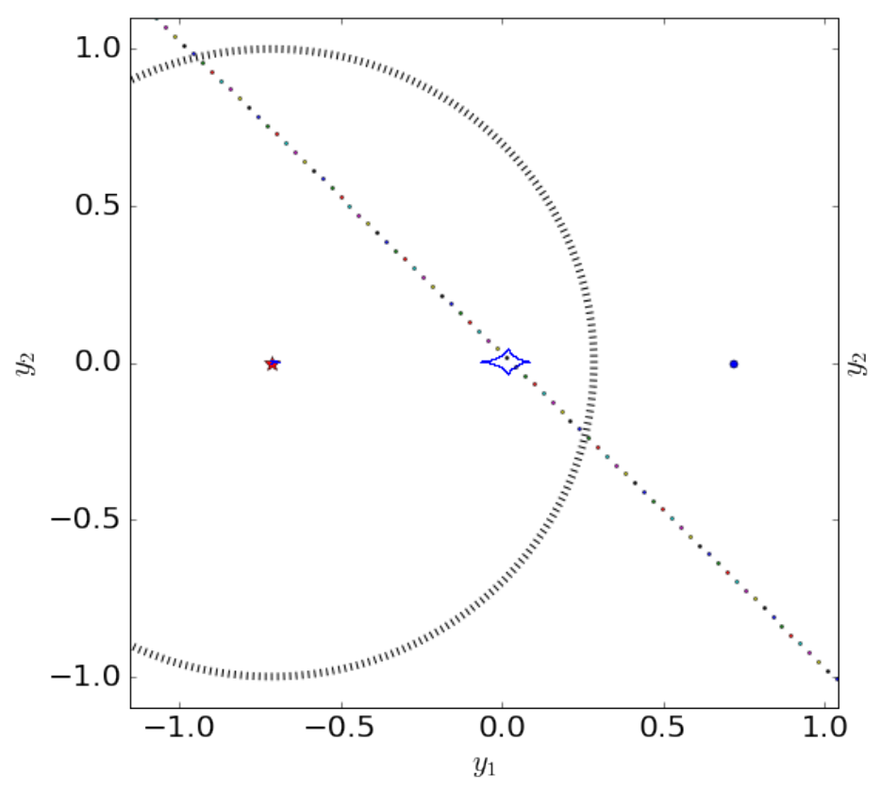


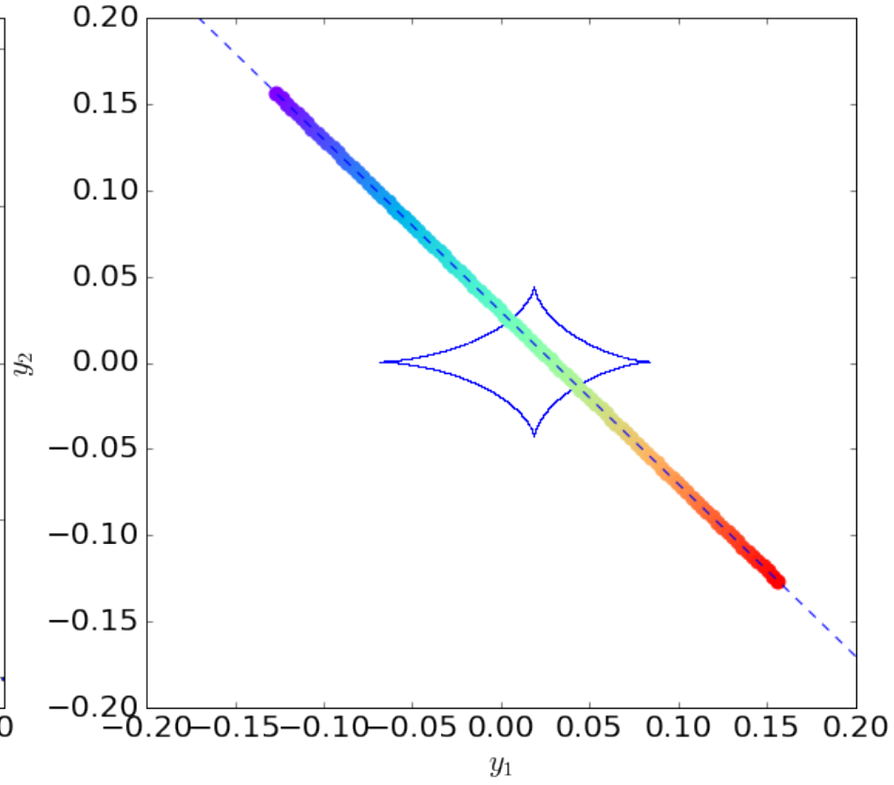


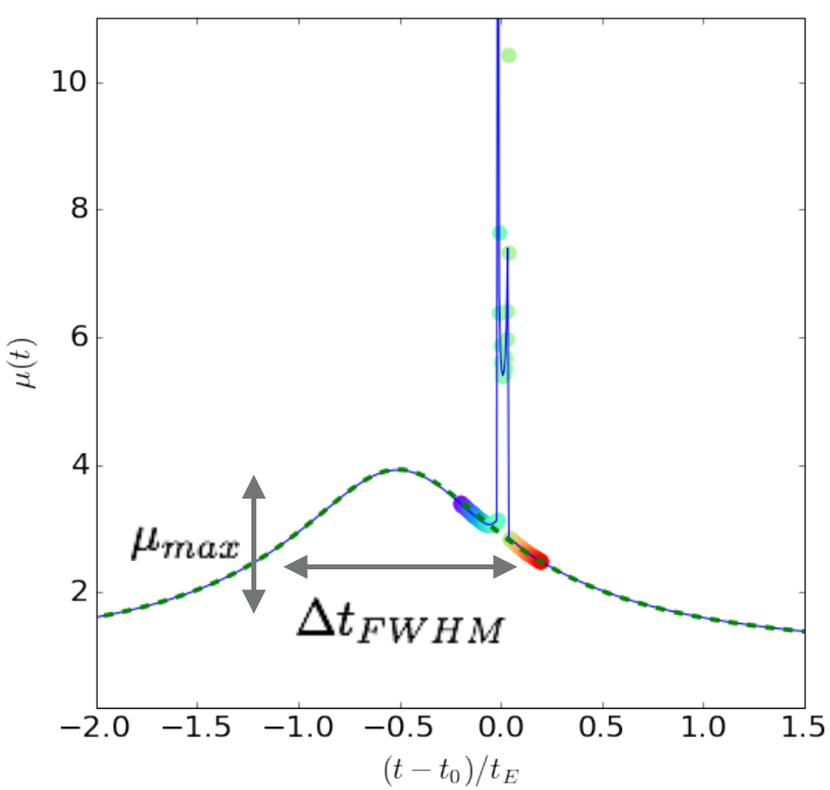


- primary event: Δt_{FWHM}
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

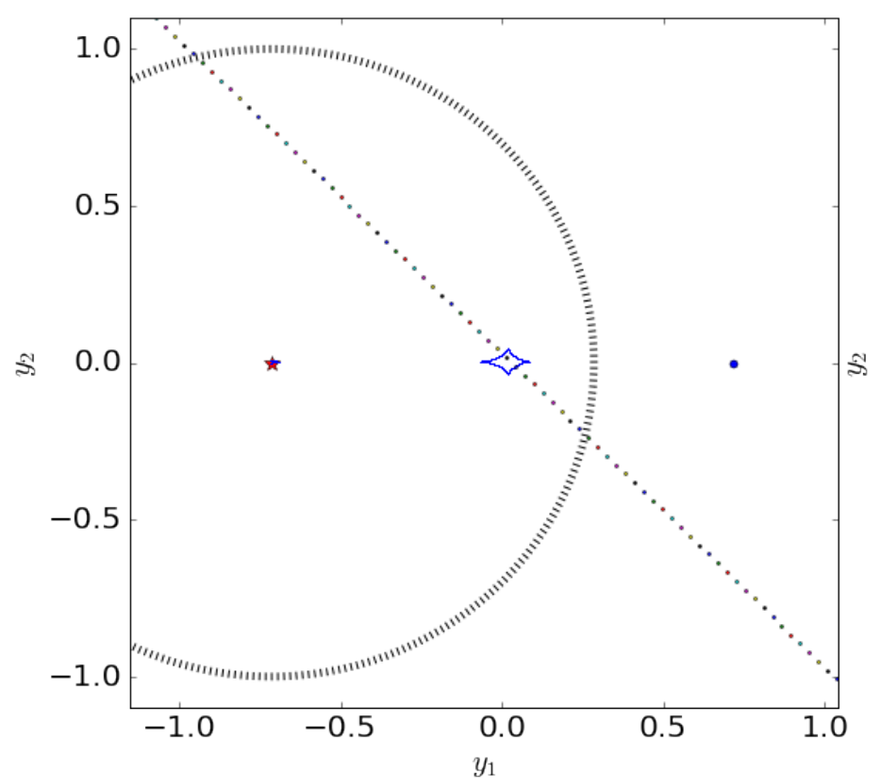


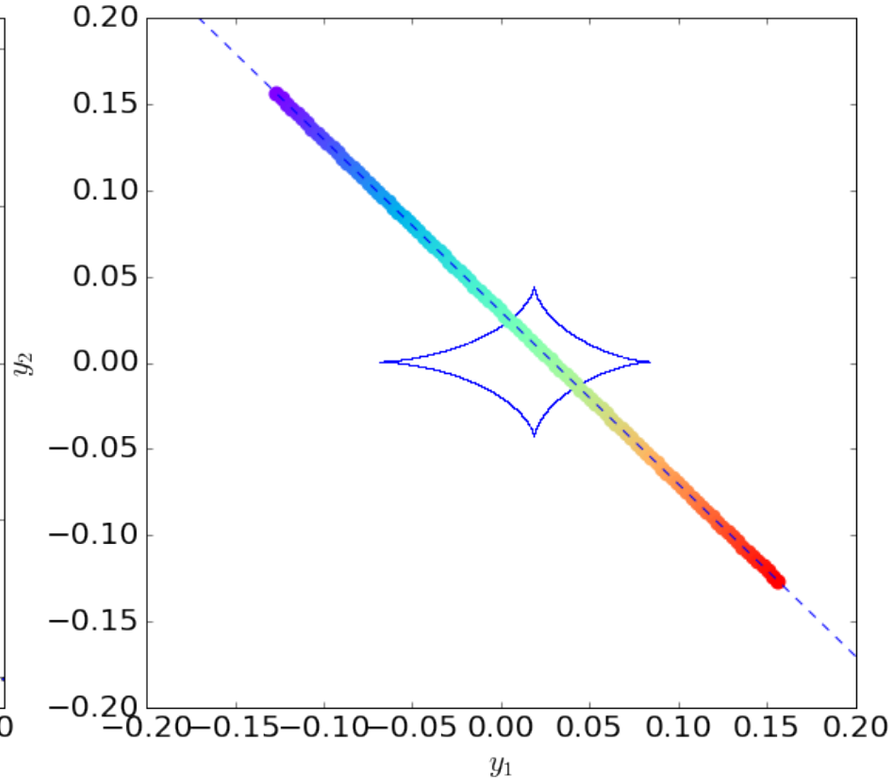


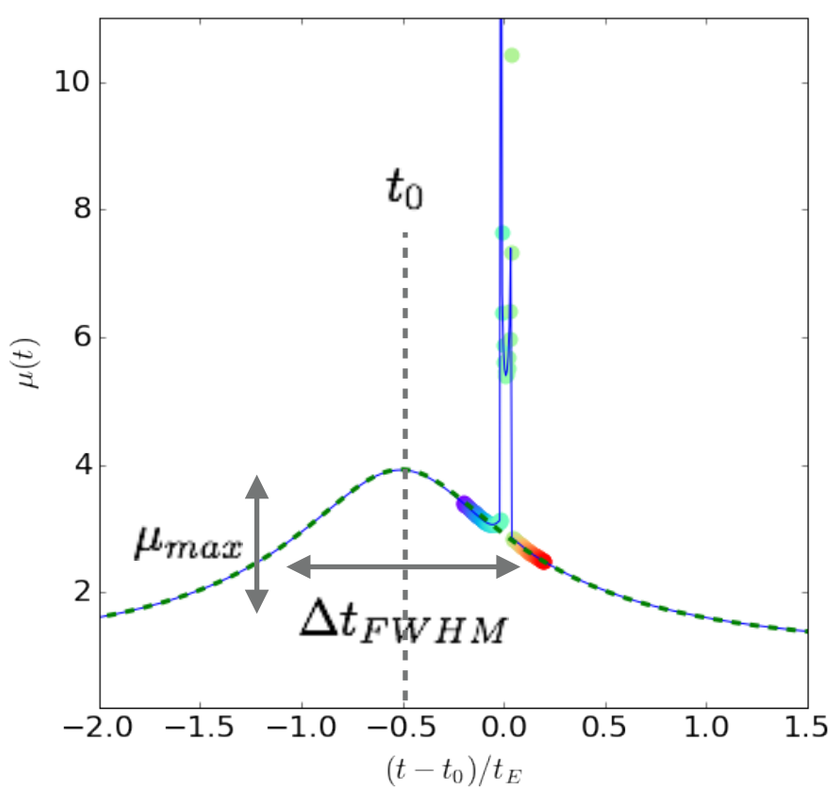


- primary event: Δt_{FWHM} μ_{max}
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

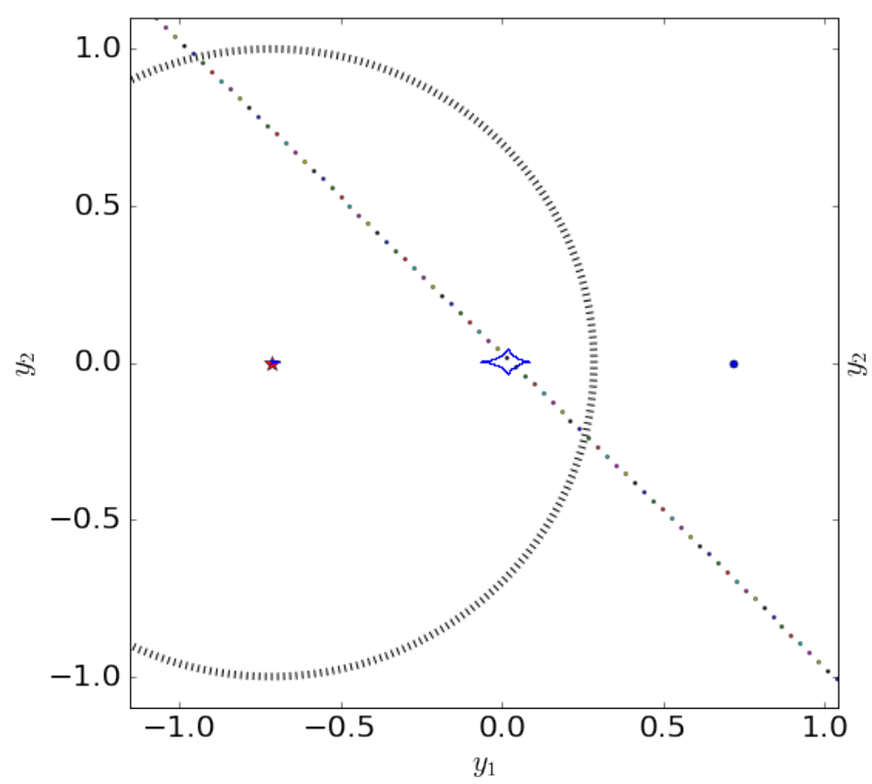


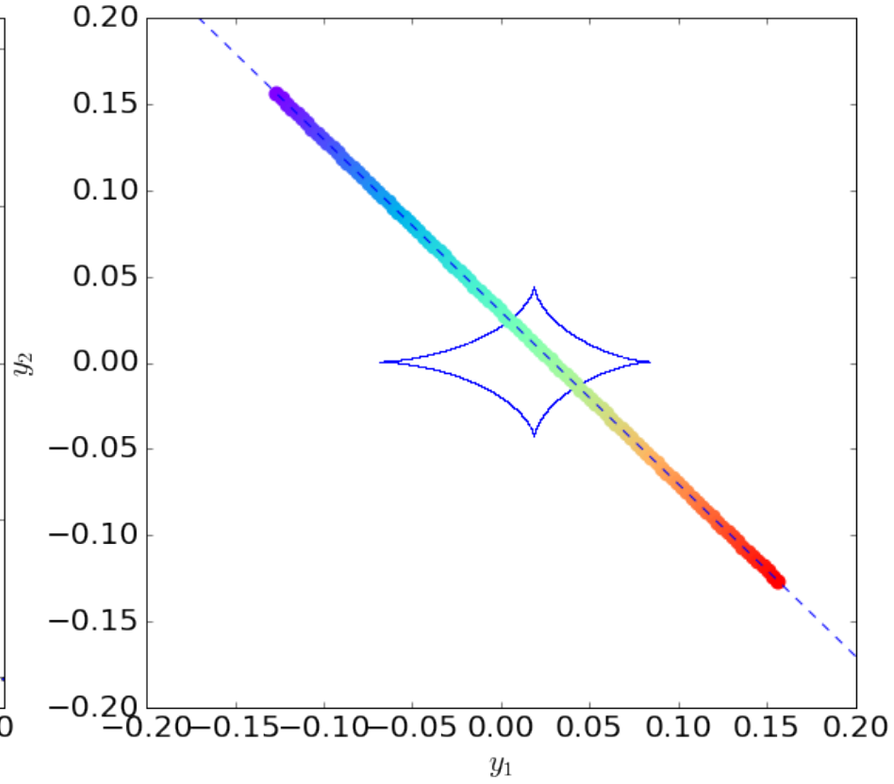


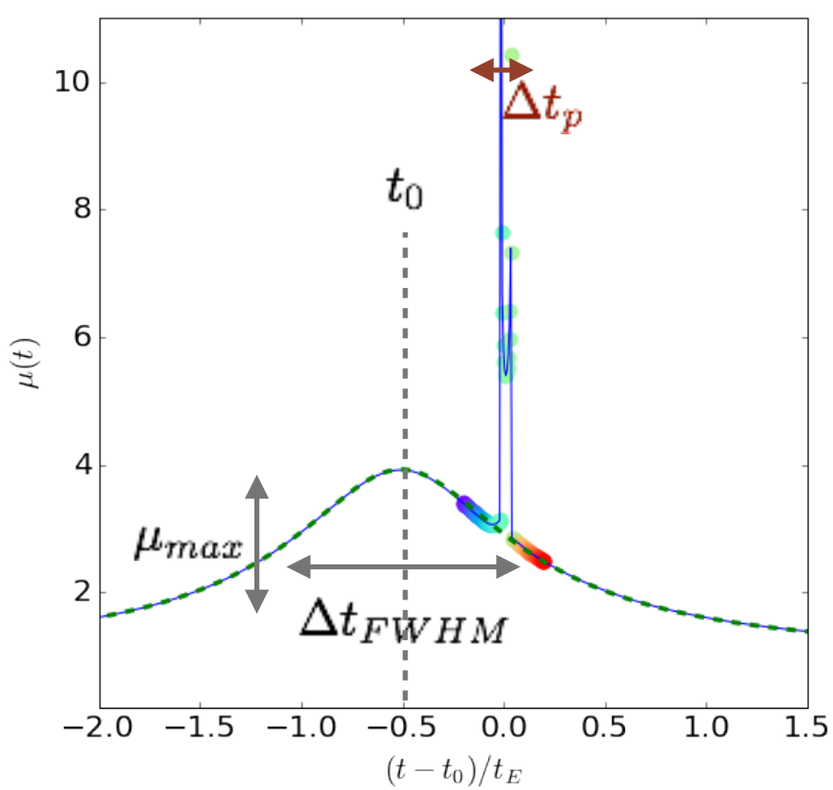


- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

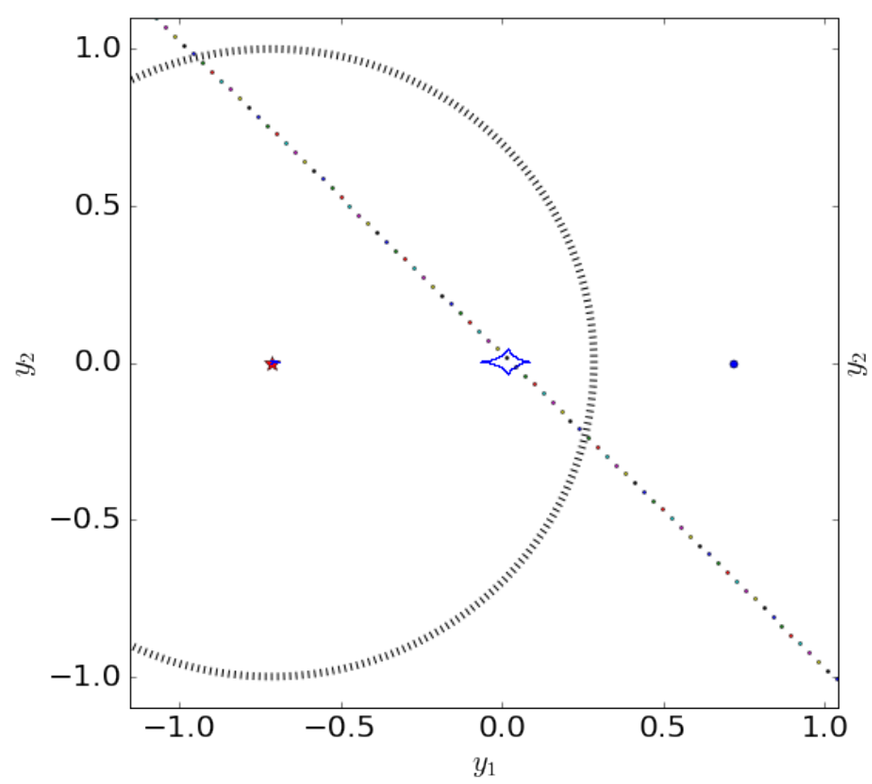


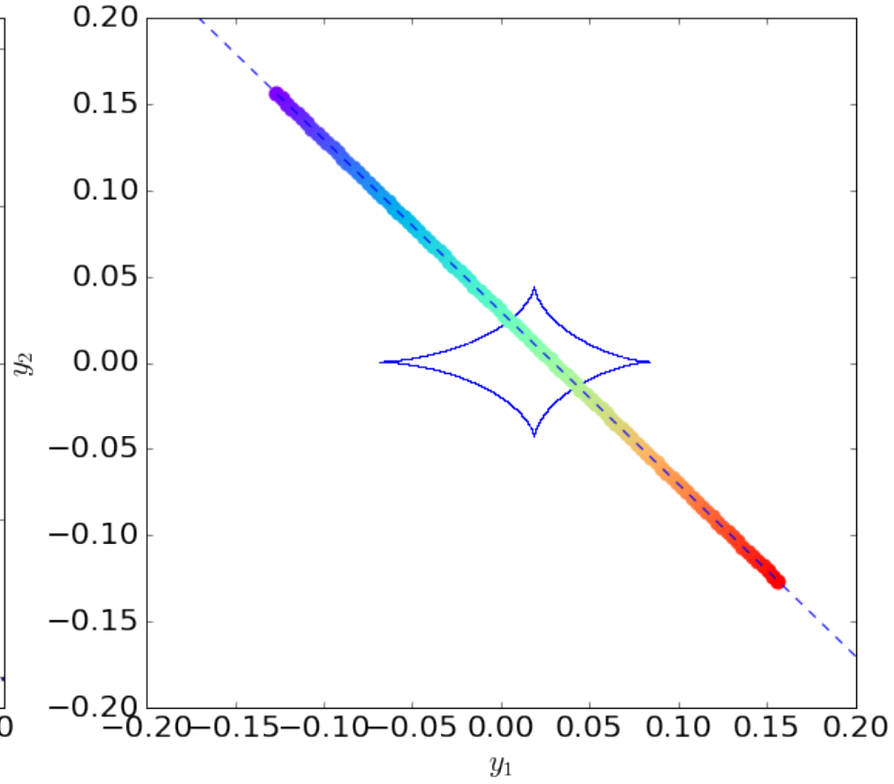


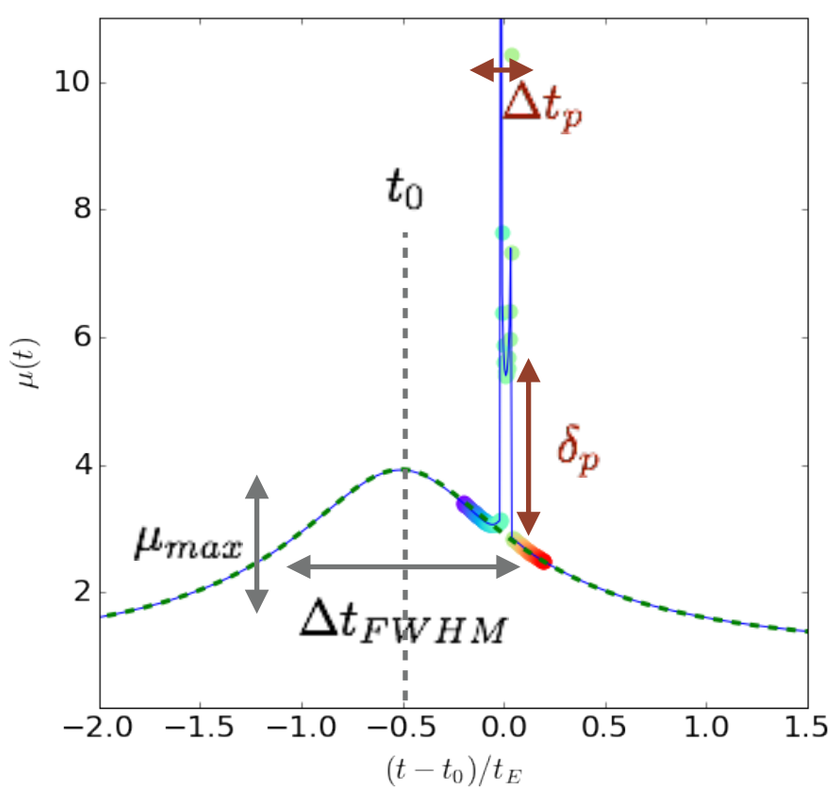


- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

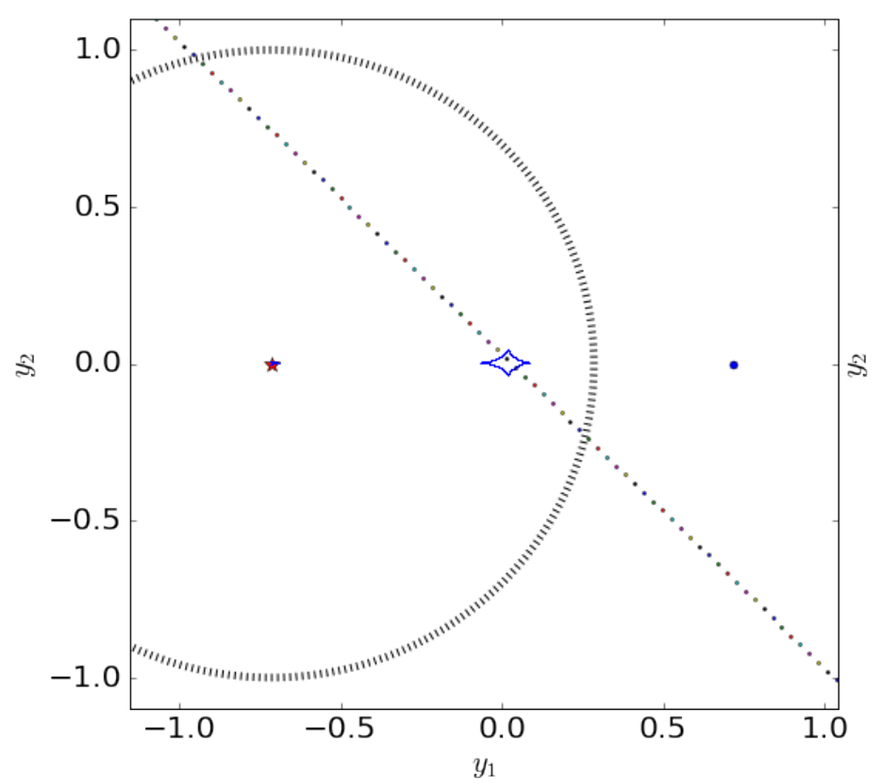


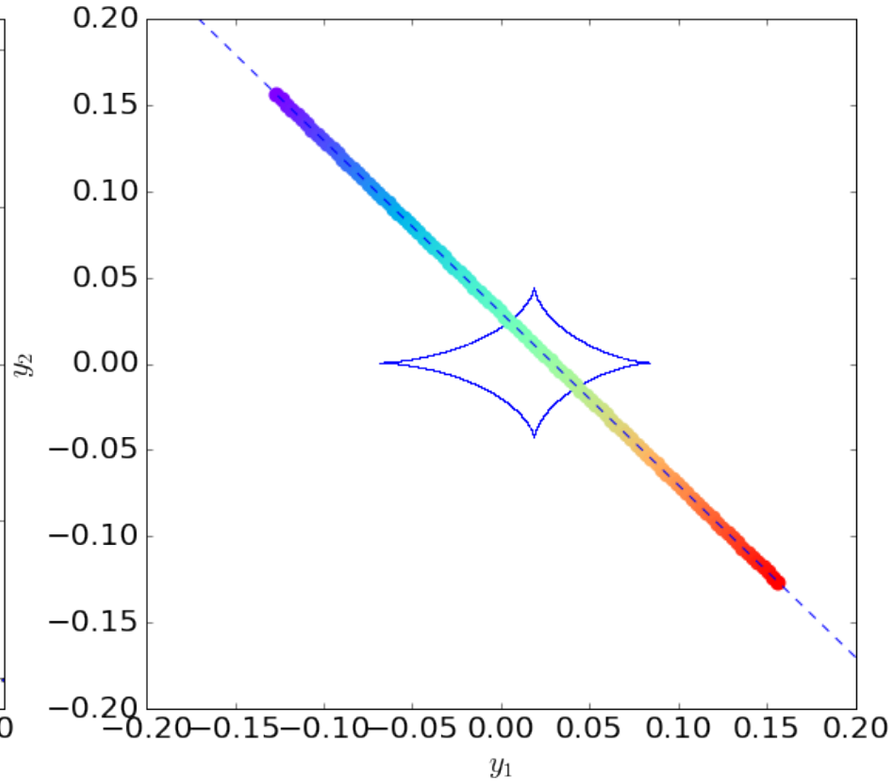


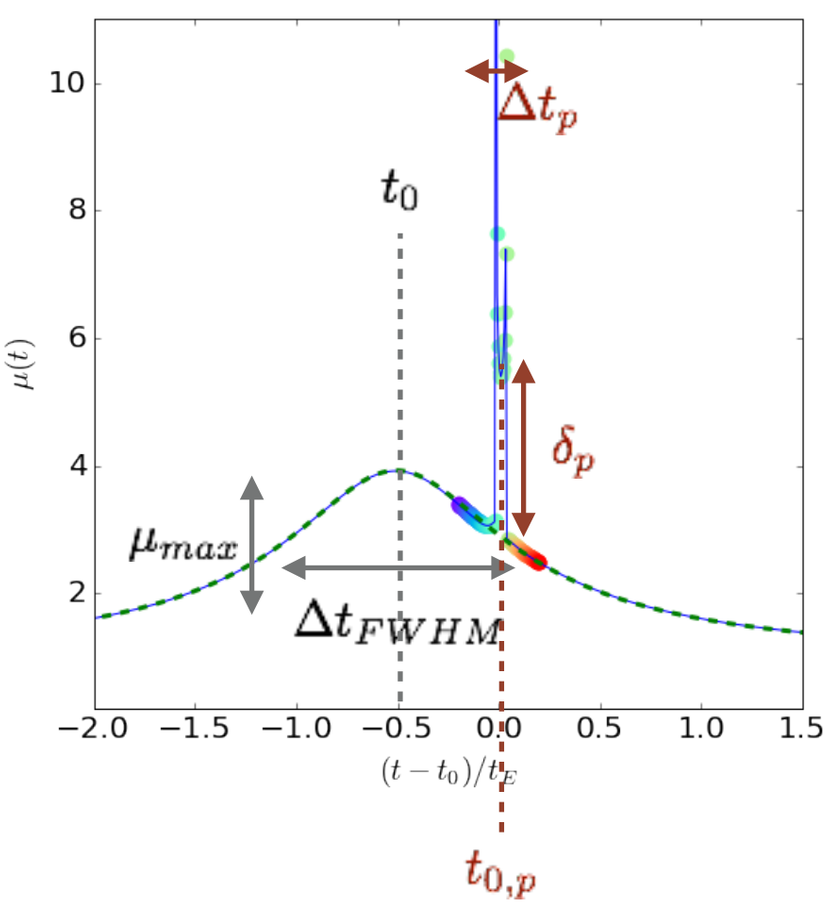


- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p δ_p

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

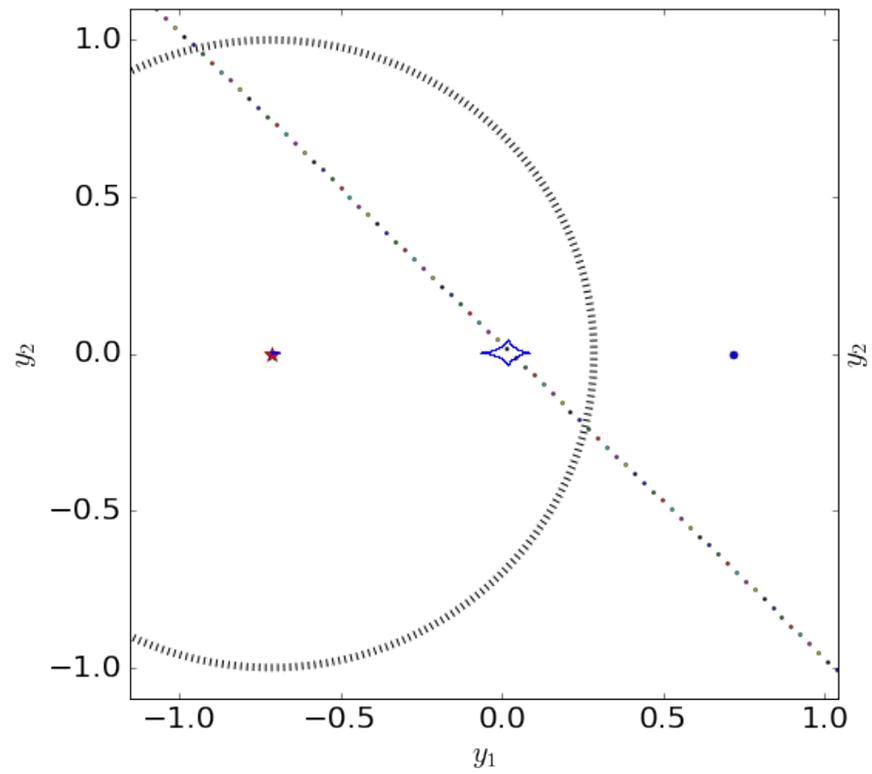


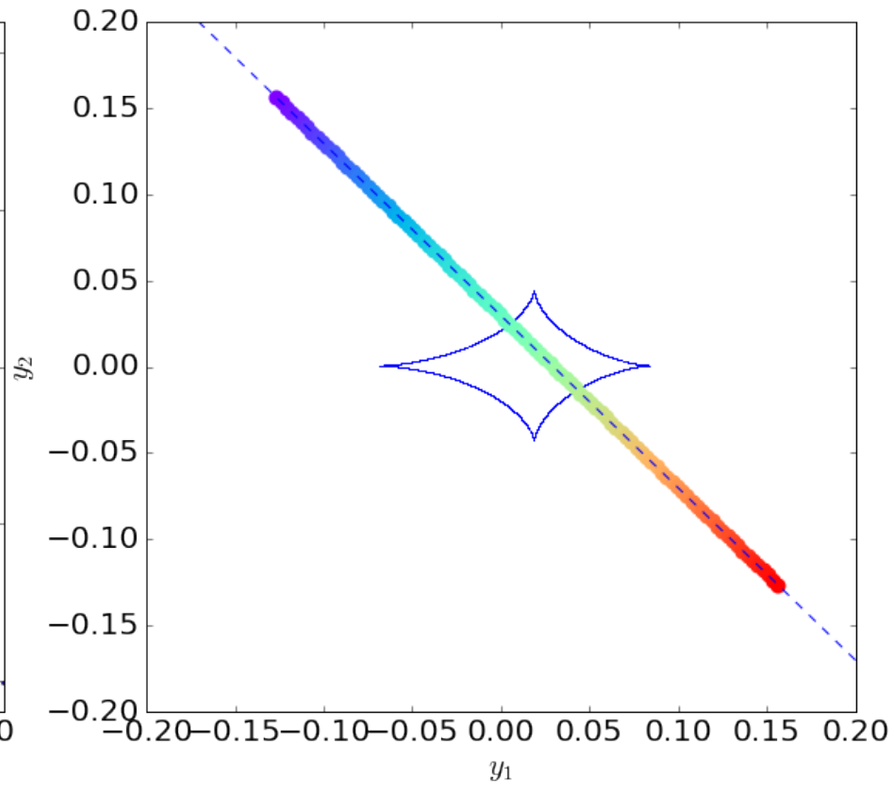


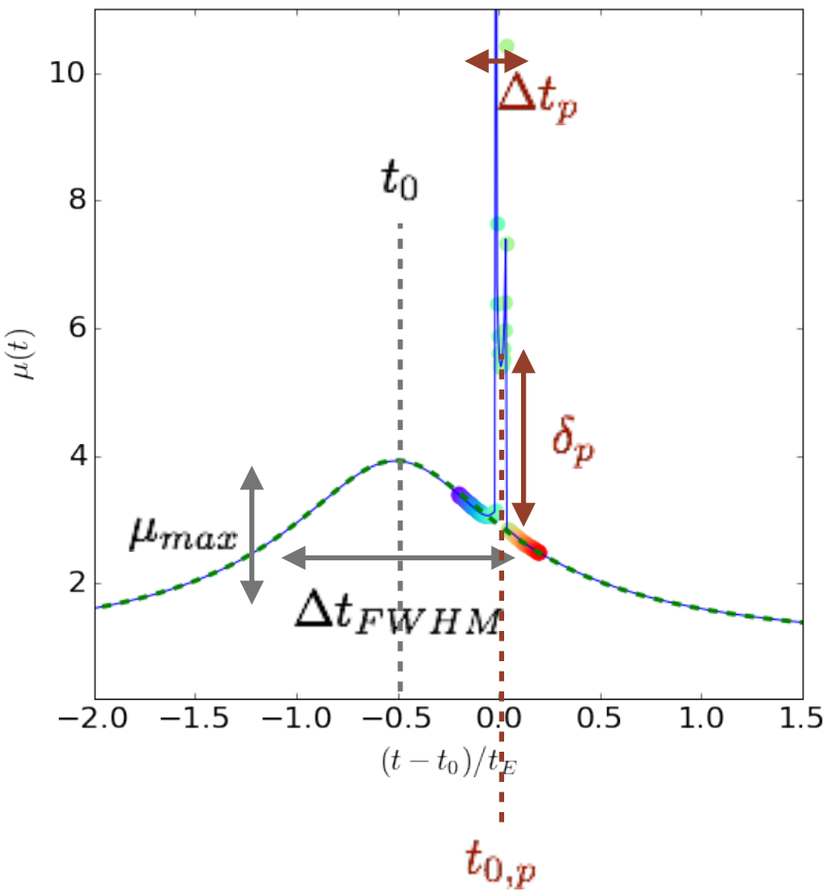


- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p δ_p $t_{0,p}$

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



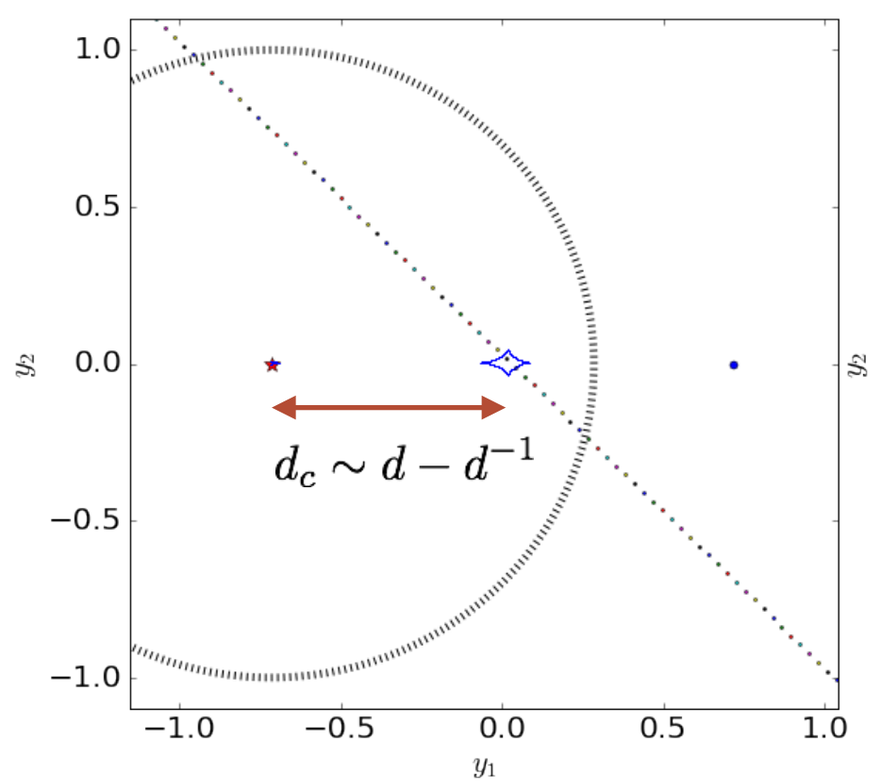


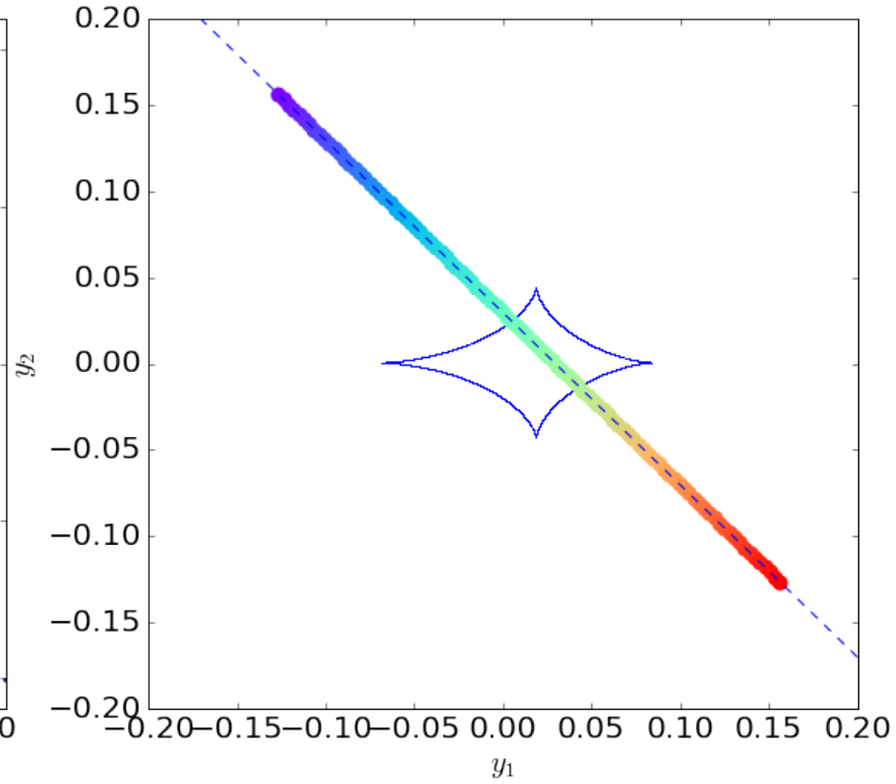


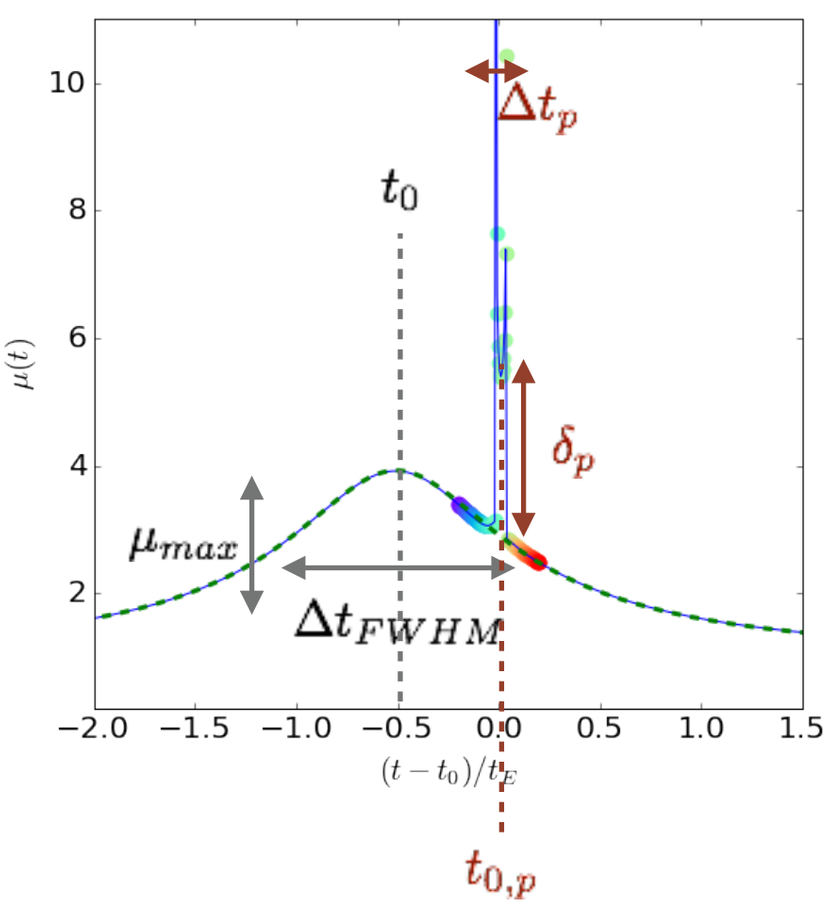
$$\Delta t_{FWHM},\ \mu_{max},\ t_0 \ \Rightarrow\ \mu(y) = \frac{y^2+2}{y\sqrt{y^2+4}} \qquad y(t) = \sqrt{y_0^2 + \left(\frac{t-t_0}{t_E}\right)^2}$$

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

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



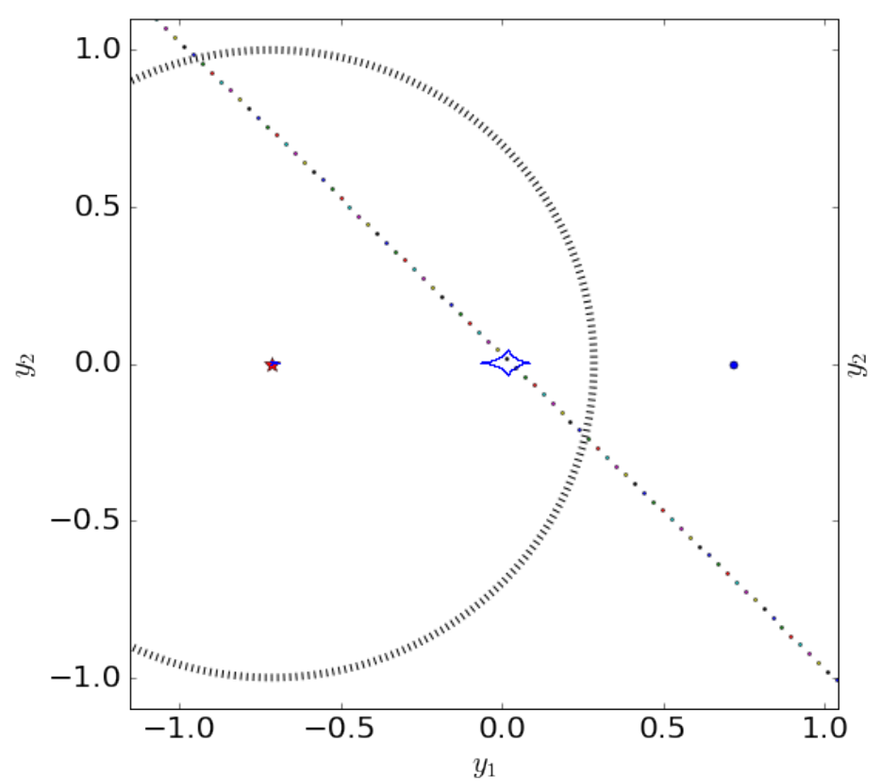


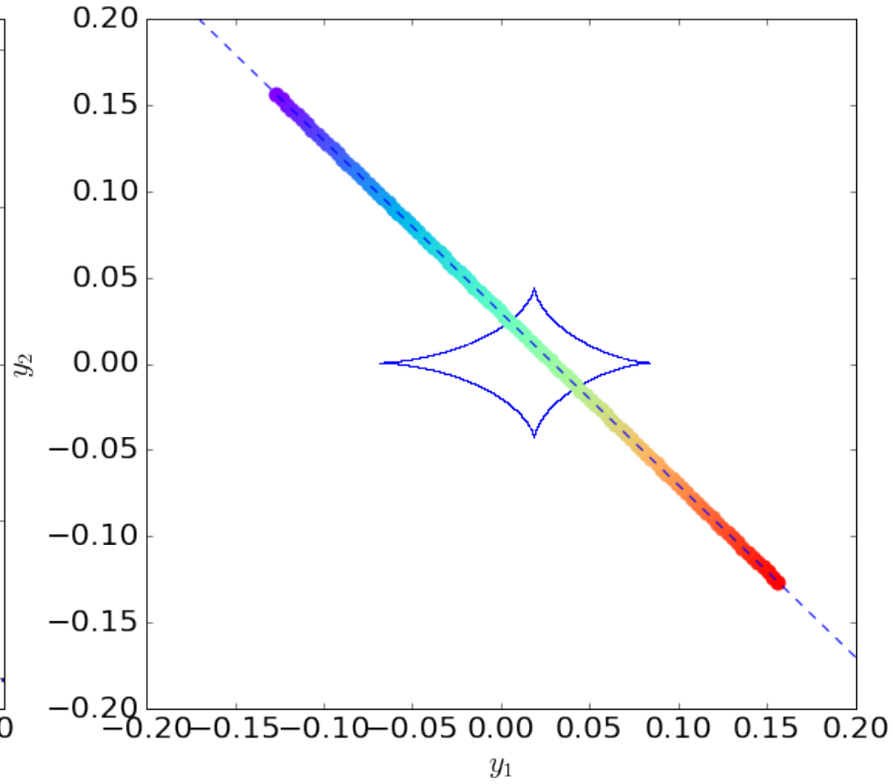


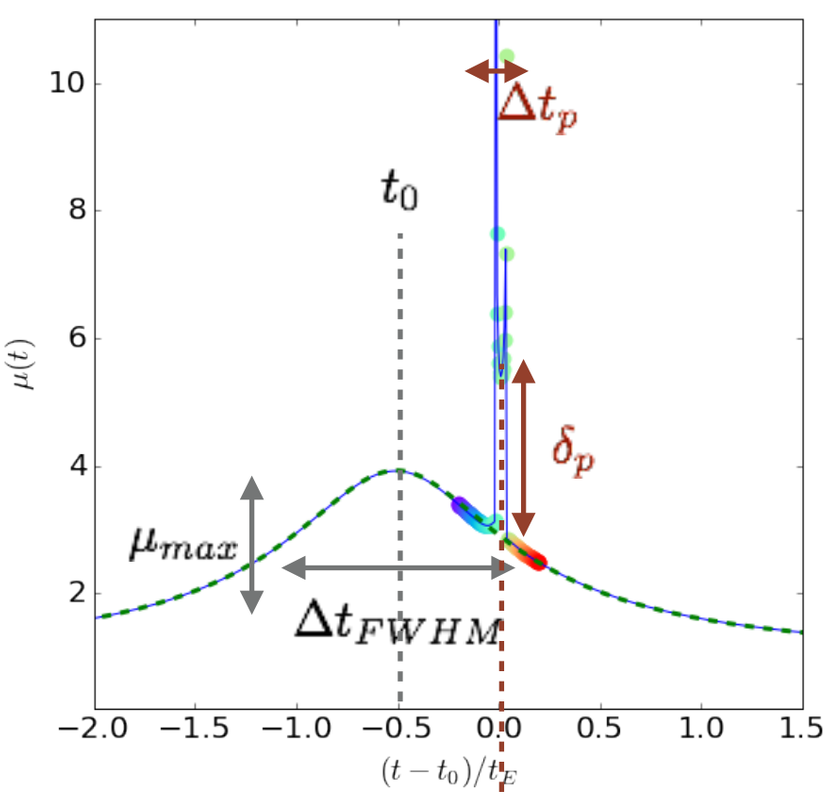
$$t_{0,p} \Rightarrow \; y_p = \sqrt{y_0^2 + \left(\frac{t_{0,p} - t_0}{t_E}\right)^2}$$

$$\Rightarrow d \sim \frac{1}{2}\left(y_p + \sqrt{y_p^2 + 4}\right)$$

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

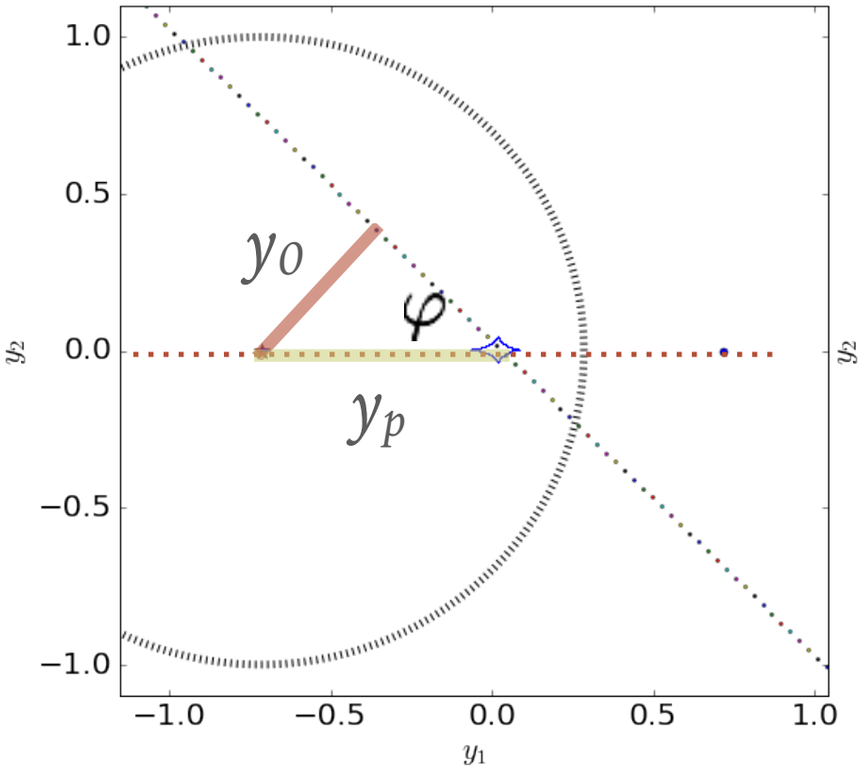


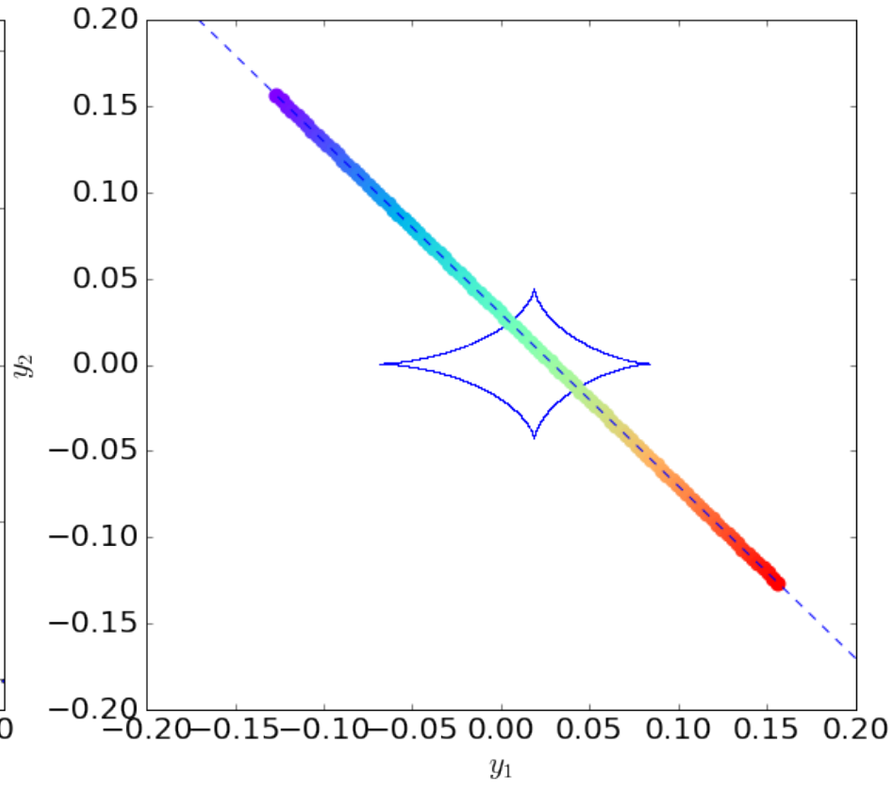


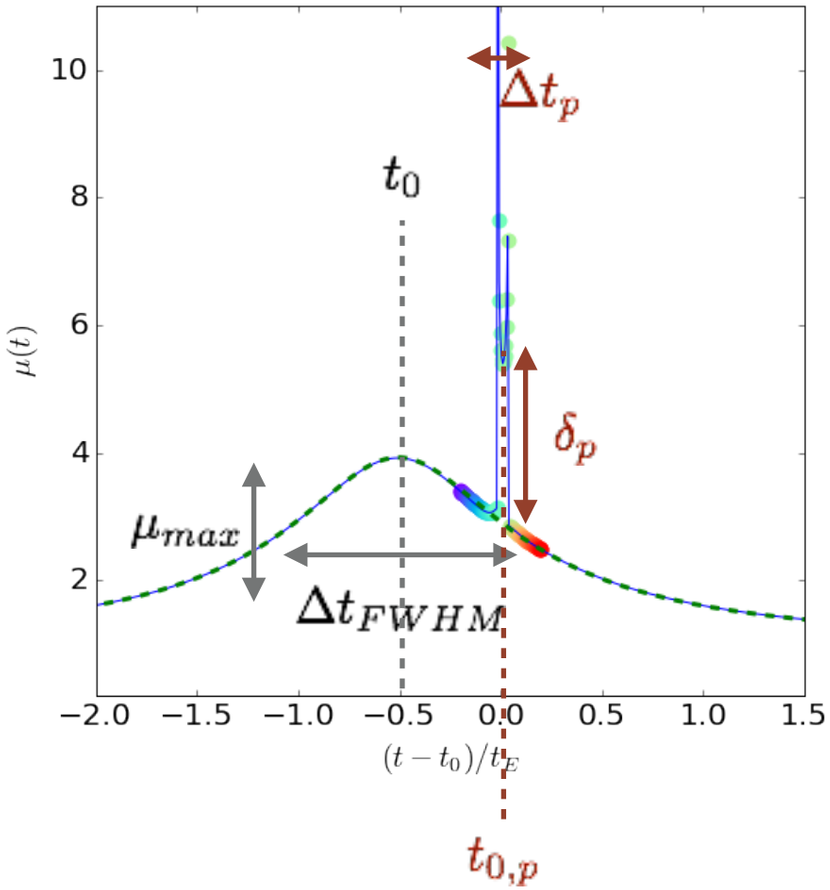


$$\Delta t_p \sim t_{E,p} \quad \Rightarrow t_E \Rightarrow \quad q = \left(\frac{t_{E,p}}{t_E} \right)^2$$

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES





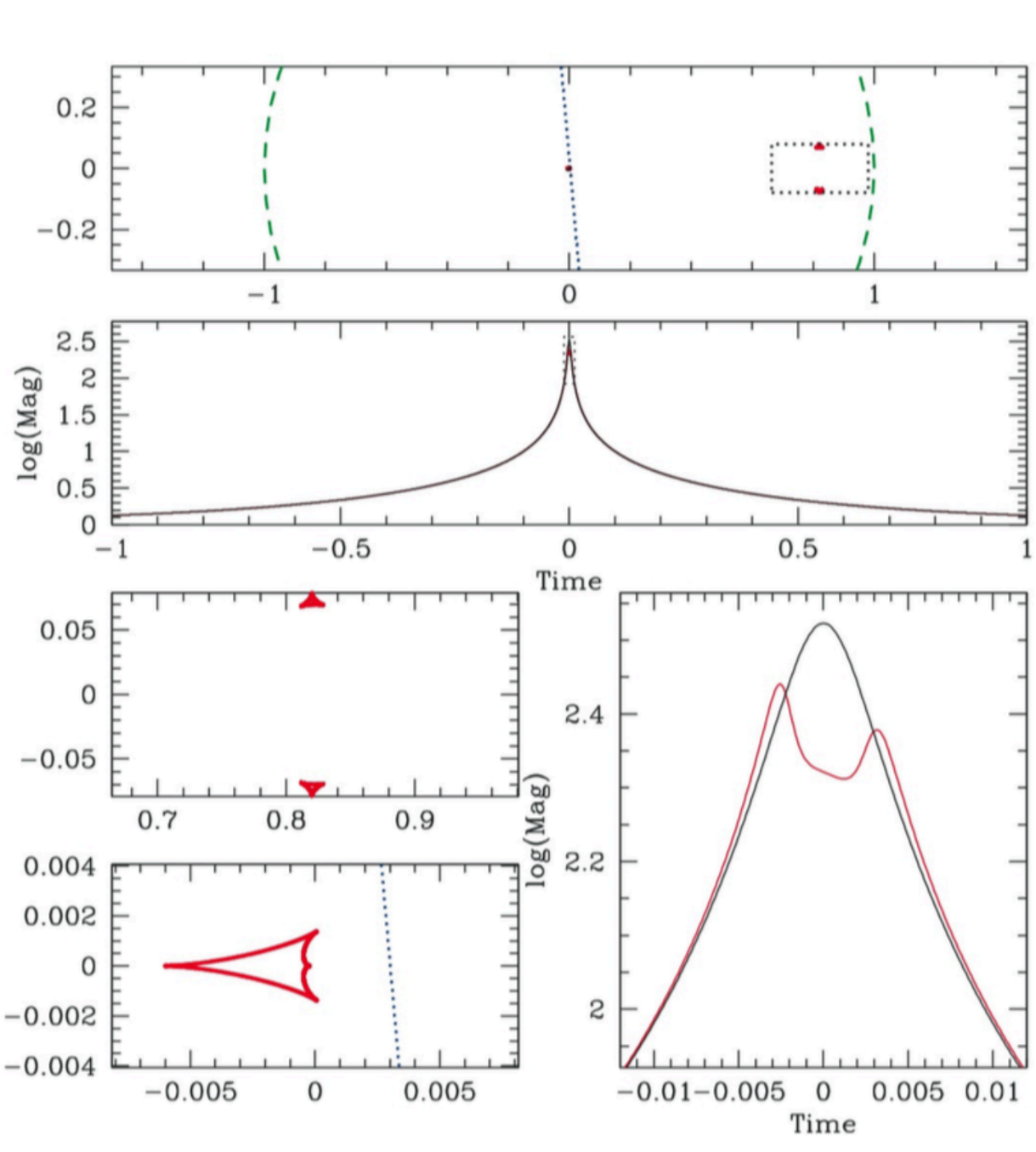


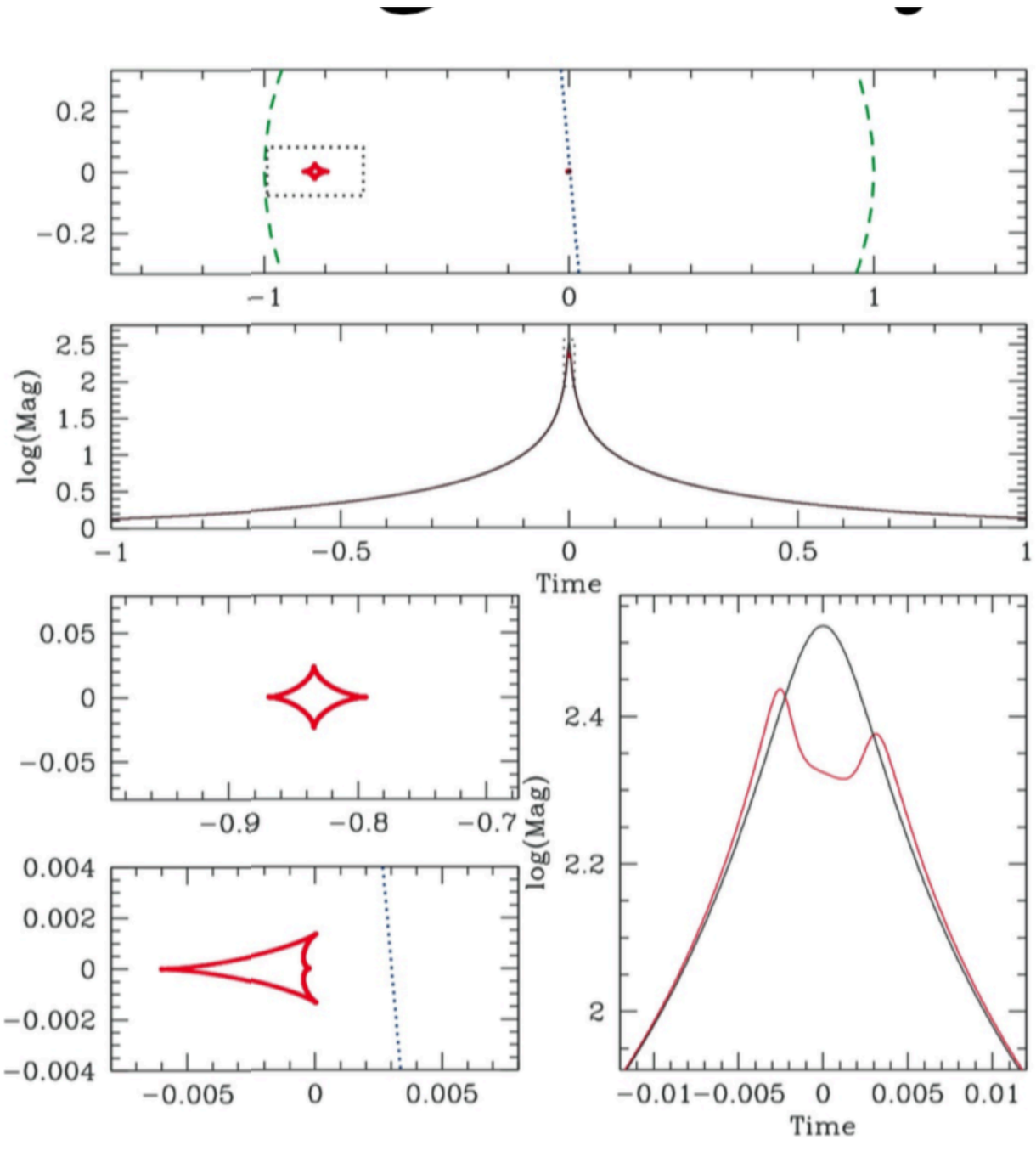
$$y_0, y_p \Rightarrow \varphi = \sin^{-1} \frac{y_0}{y_p}$$

TO SUMMARIZE

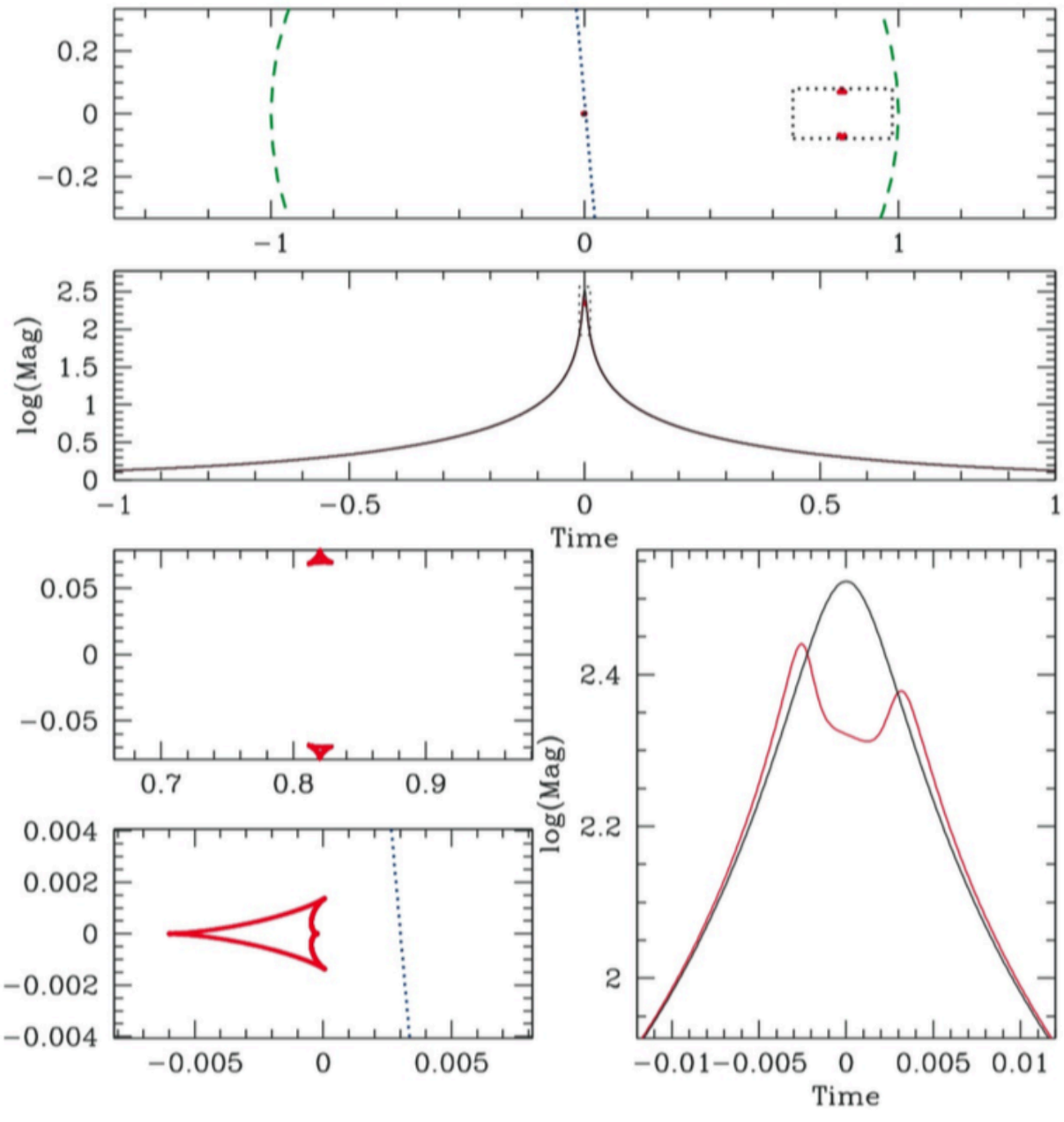
- different caustic topologies give rise to different kind of perturbations on the light curves
- planets can be detected in only a few qualitatively different ways:
  - at relatively low magnification of the primary, if the source crosses the planetary caustics from close or wide planets
  - near the 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.
- Light curves can be used to extract parameters of the primary and of the planet
- As seen for single point masses, degeneracies can be broken (finite source effects, microlensing parallax)
- Some cases are more difficult than others…

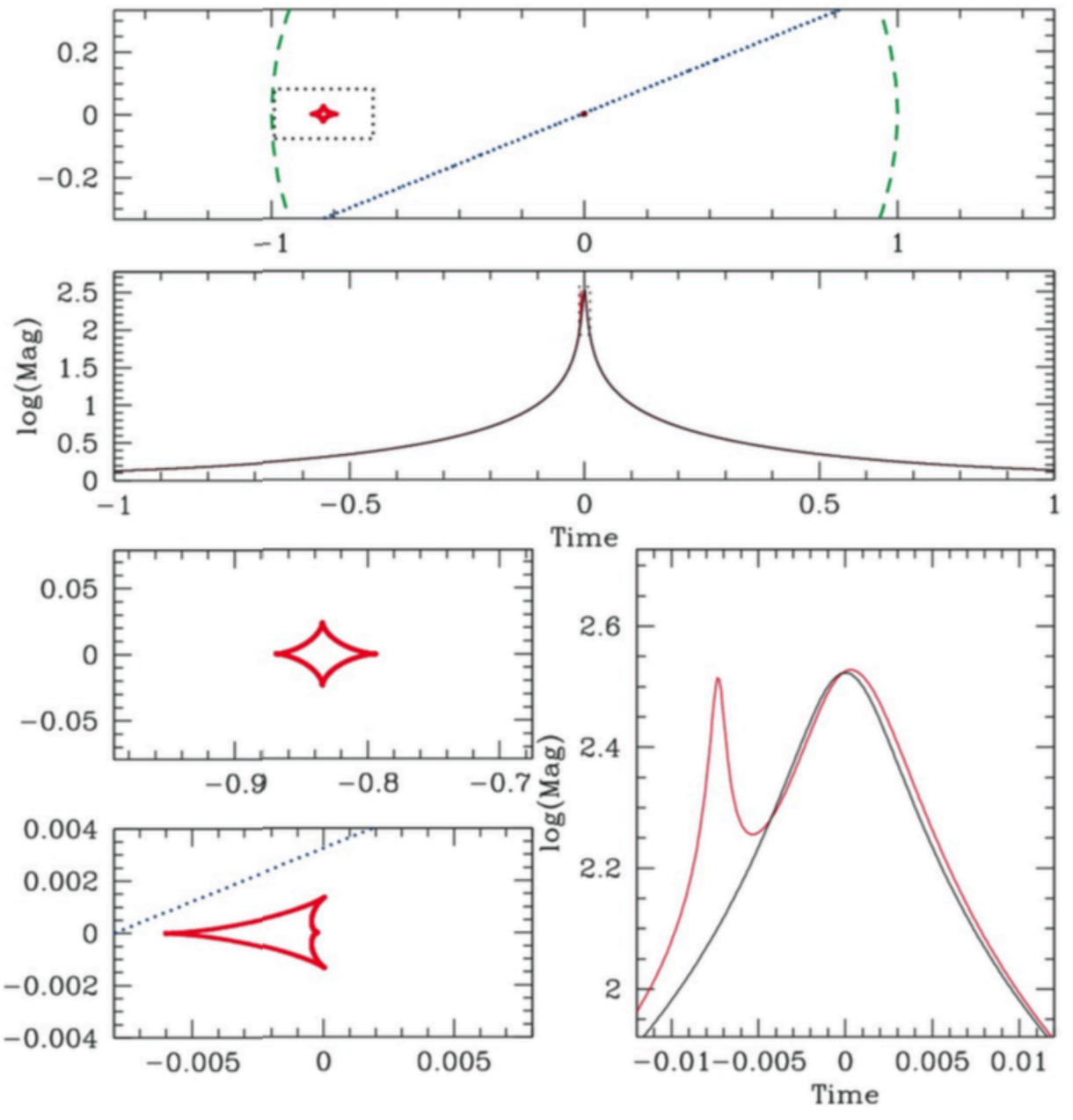
CLOSE–WIDE DEGENERACY





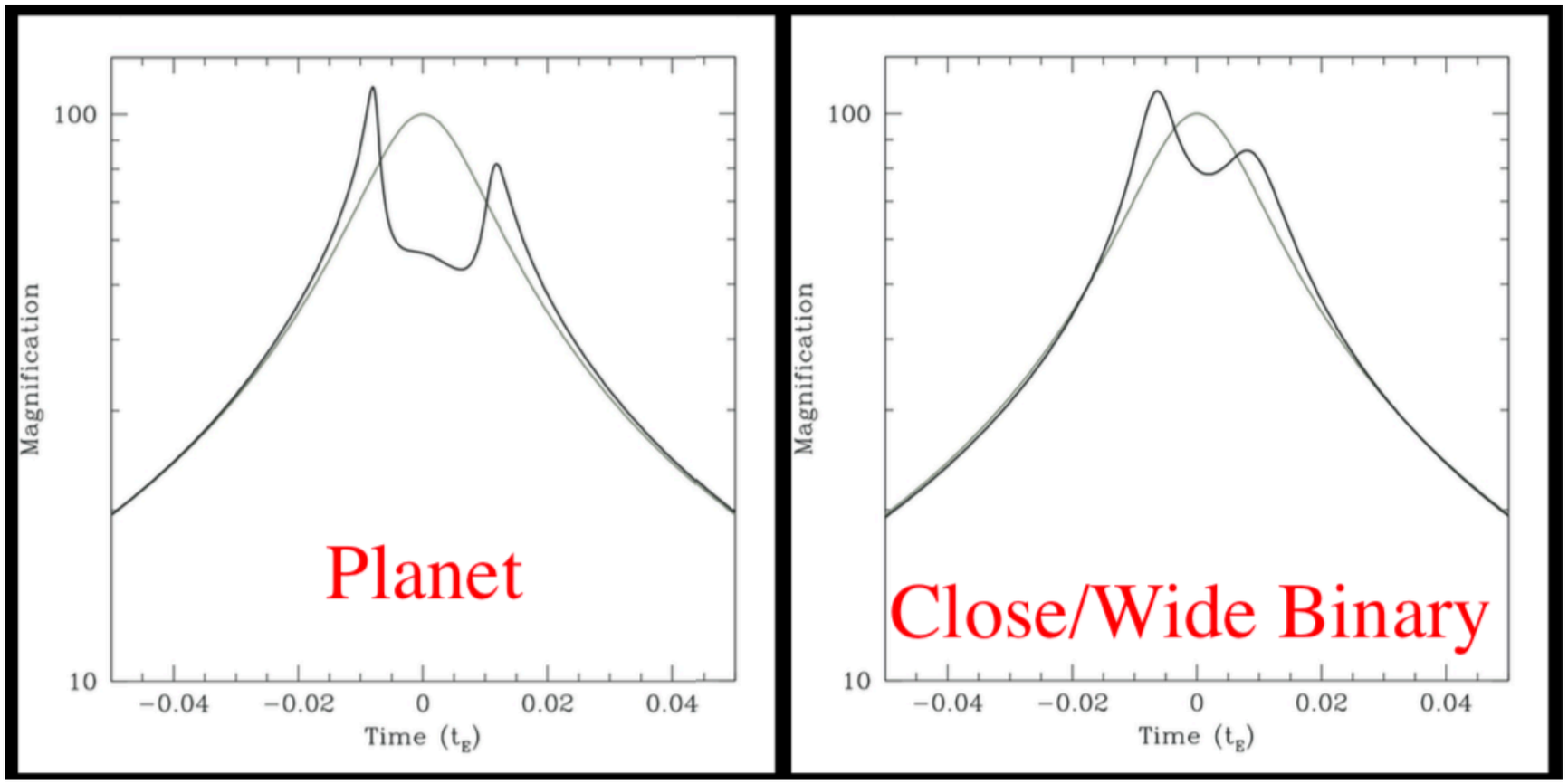
DOUBLE HORN OR BUMP





UNCERTAINTIES: SOME FEATURES CAN BE EXPLAINED IN DIFFERENT WAYS

Short duration deviations at the peak:

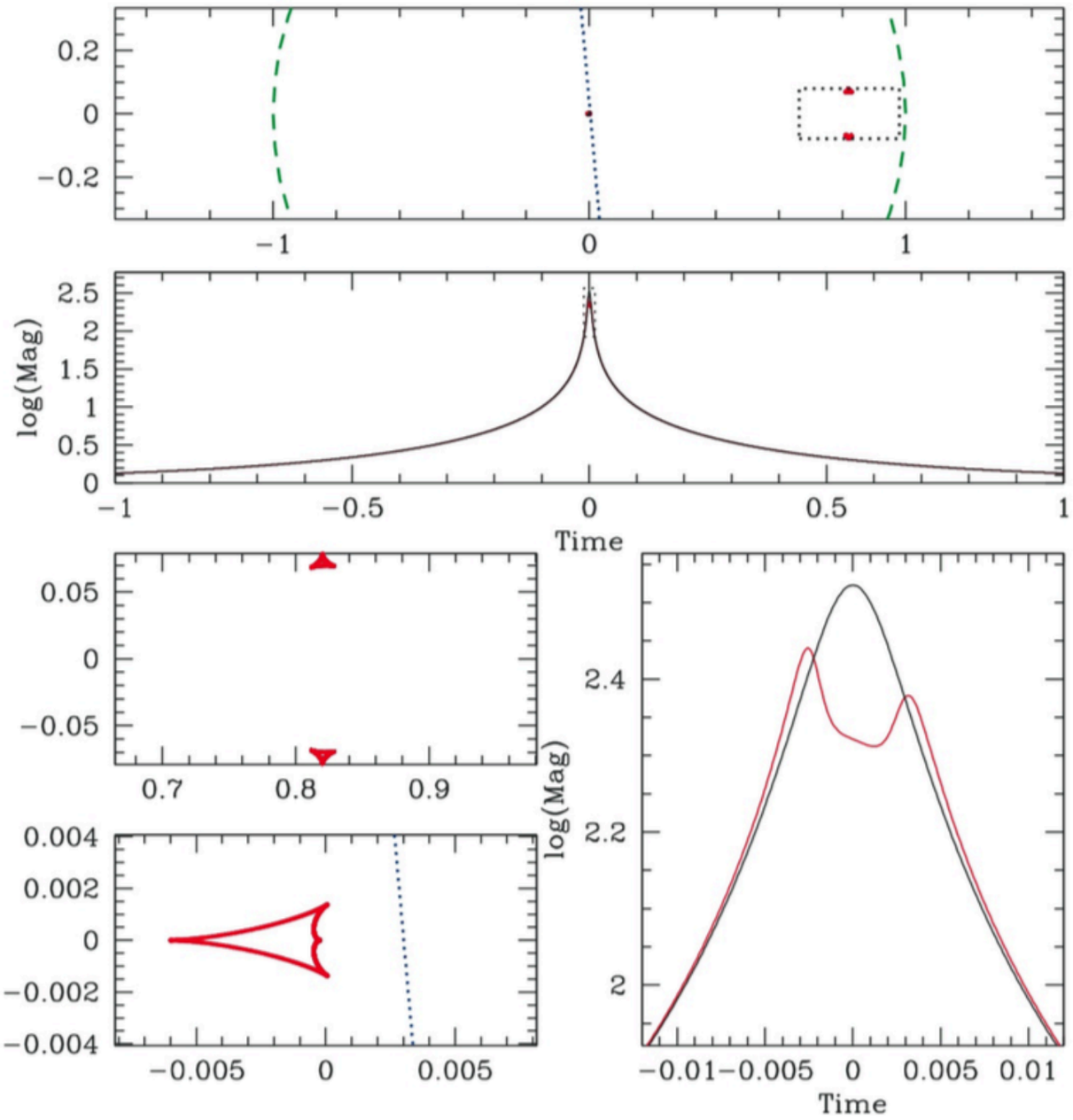


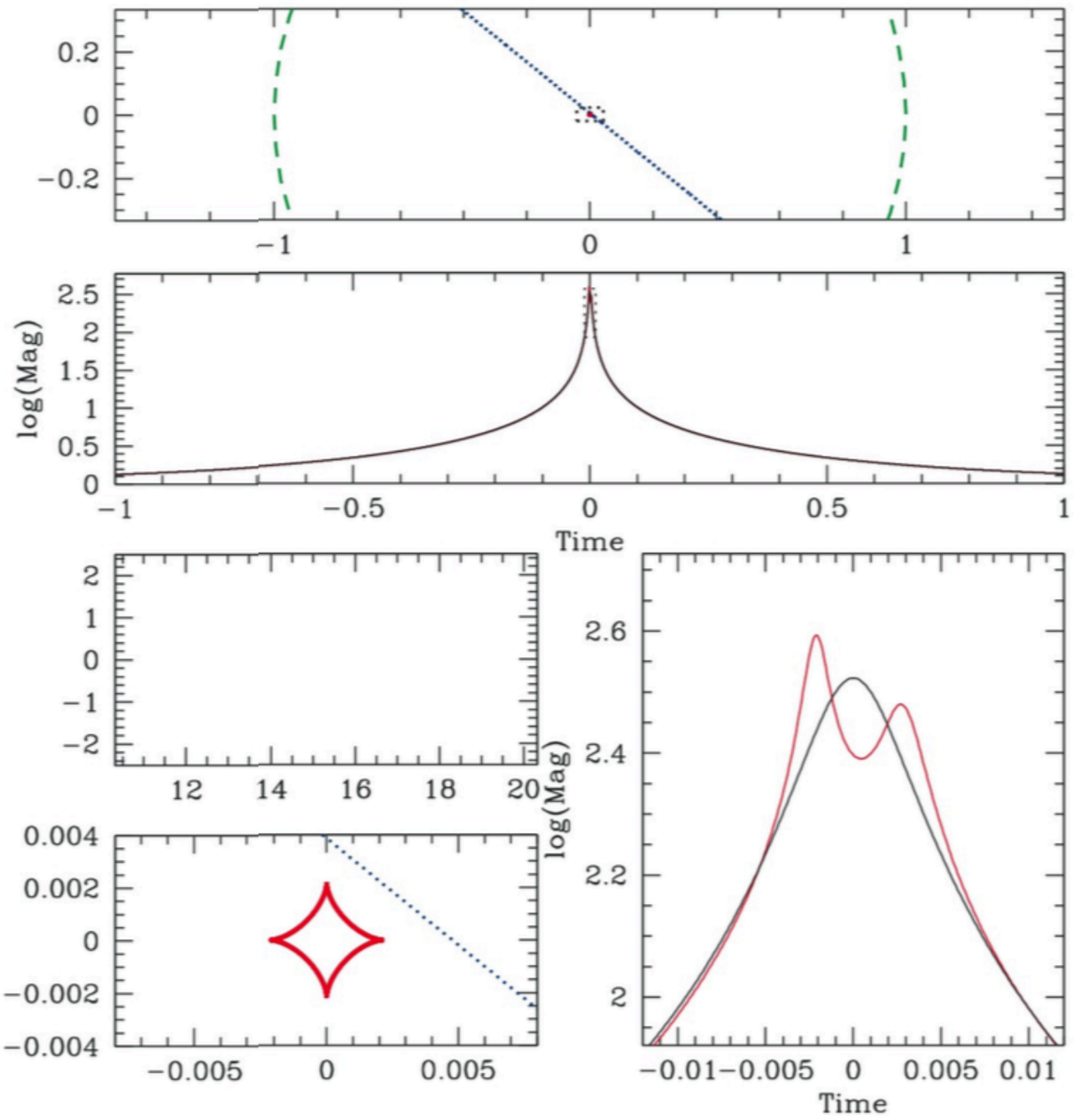
Can be caused by:

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

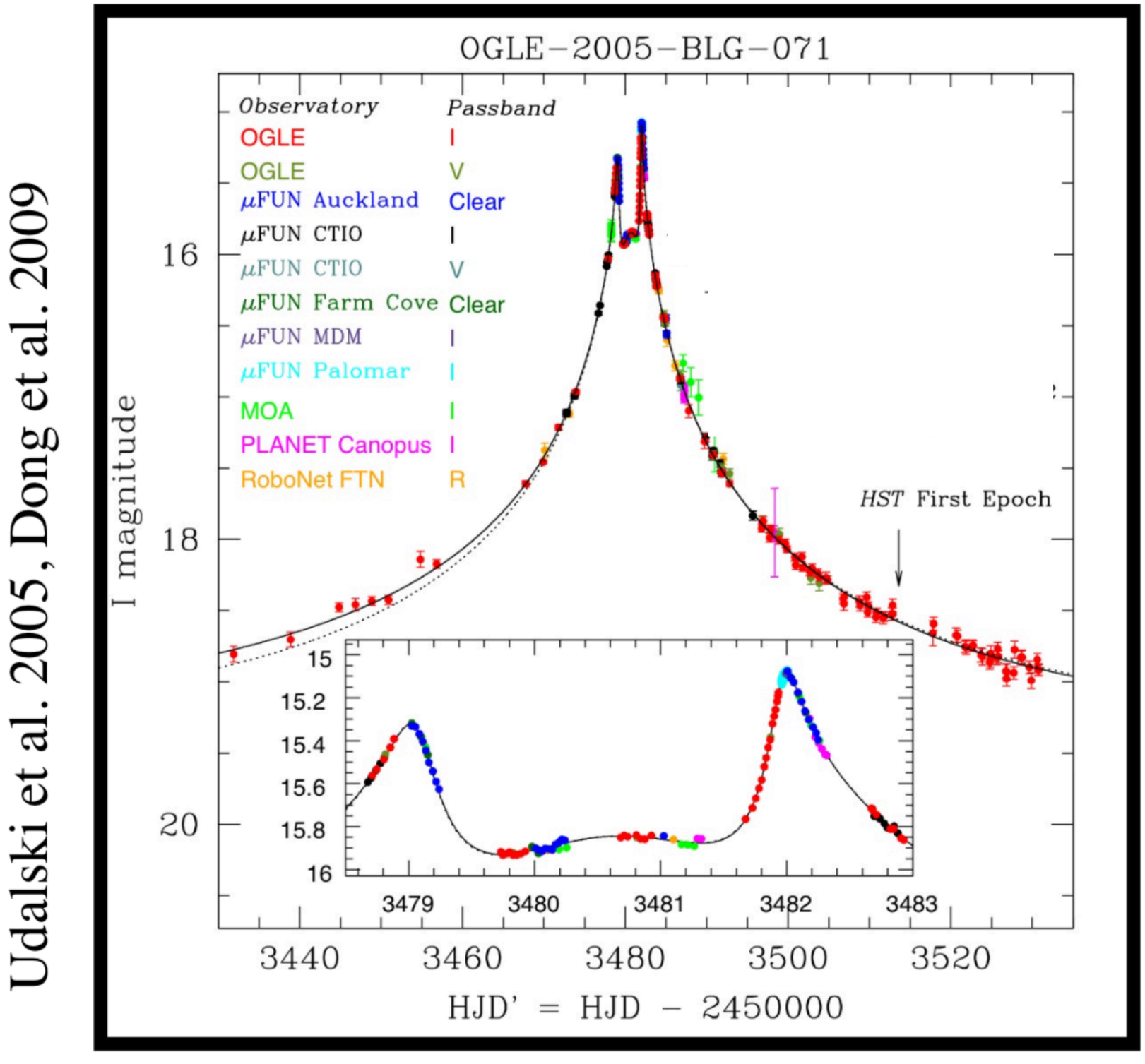
Rule: look for the central bump in the middle of the horns

CLOSE BINARIES VS PLANETS



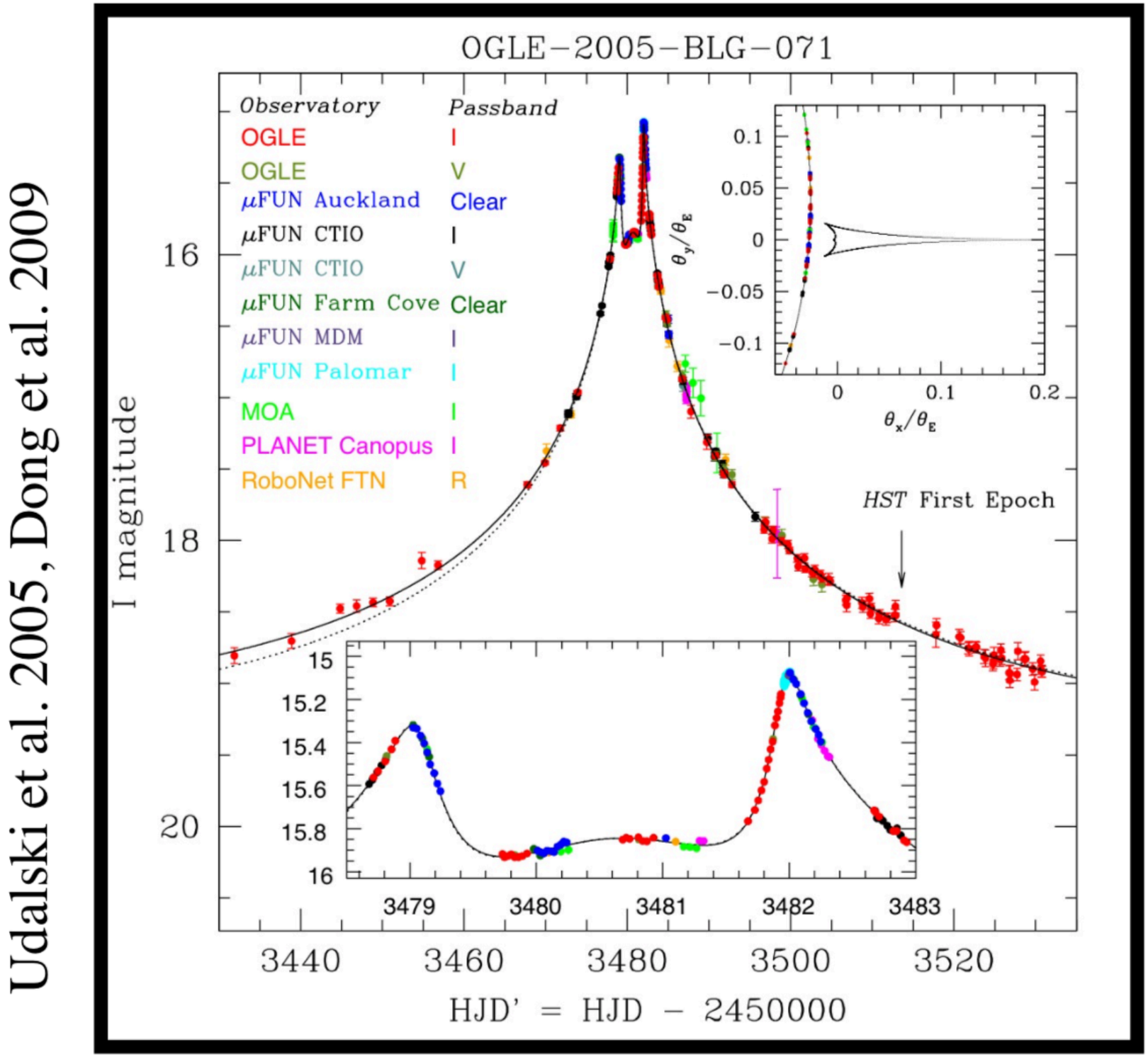


QUIZ



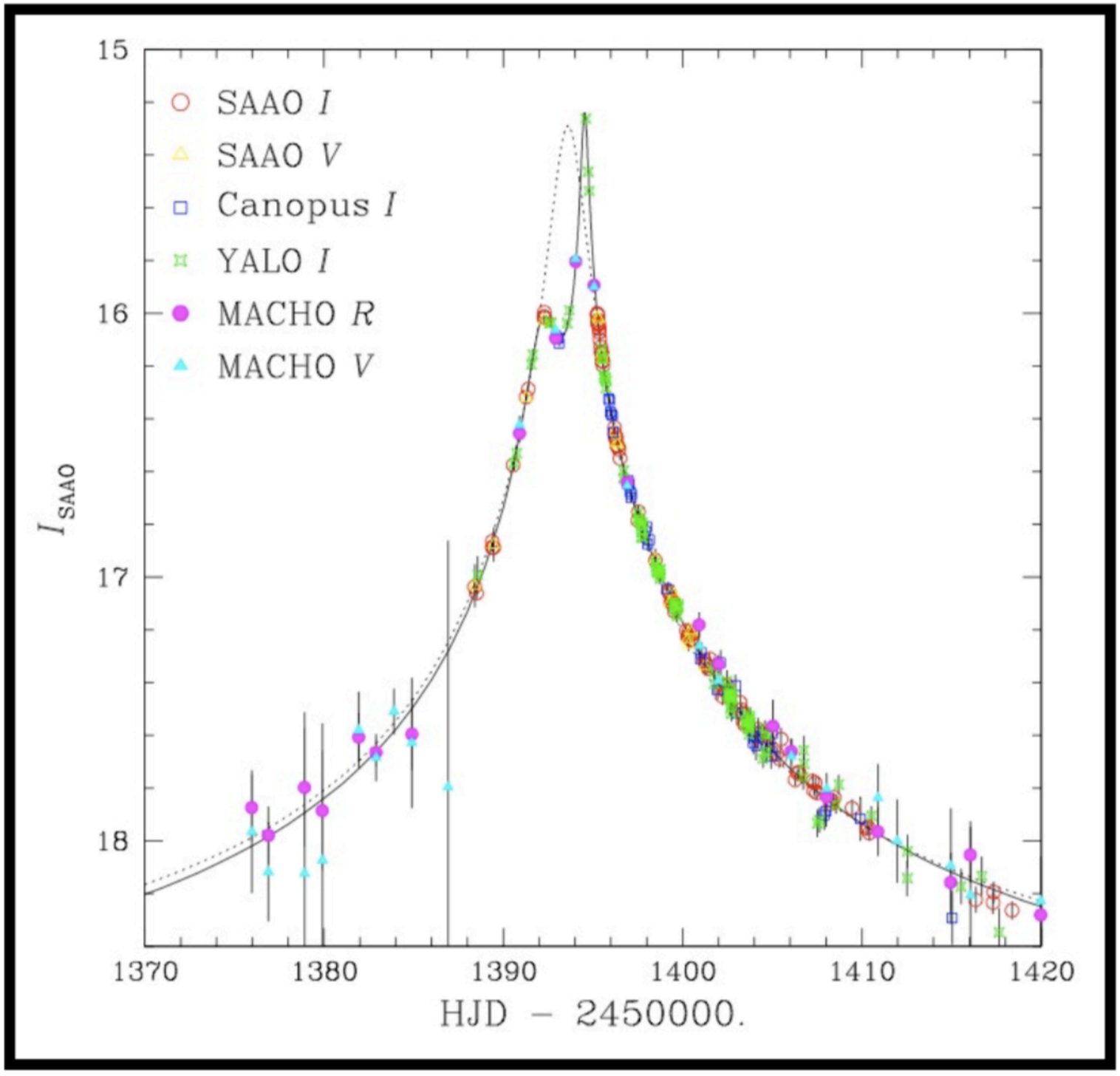
Udalski et al. 2005, Dong et al. 2009

QUIZ



Udalski et al. 2005, Dong et al. 2009

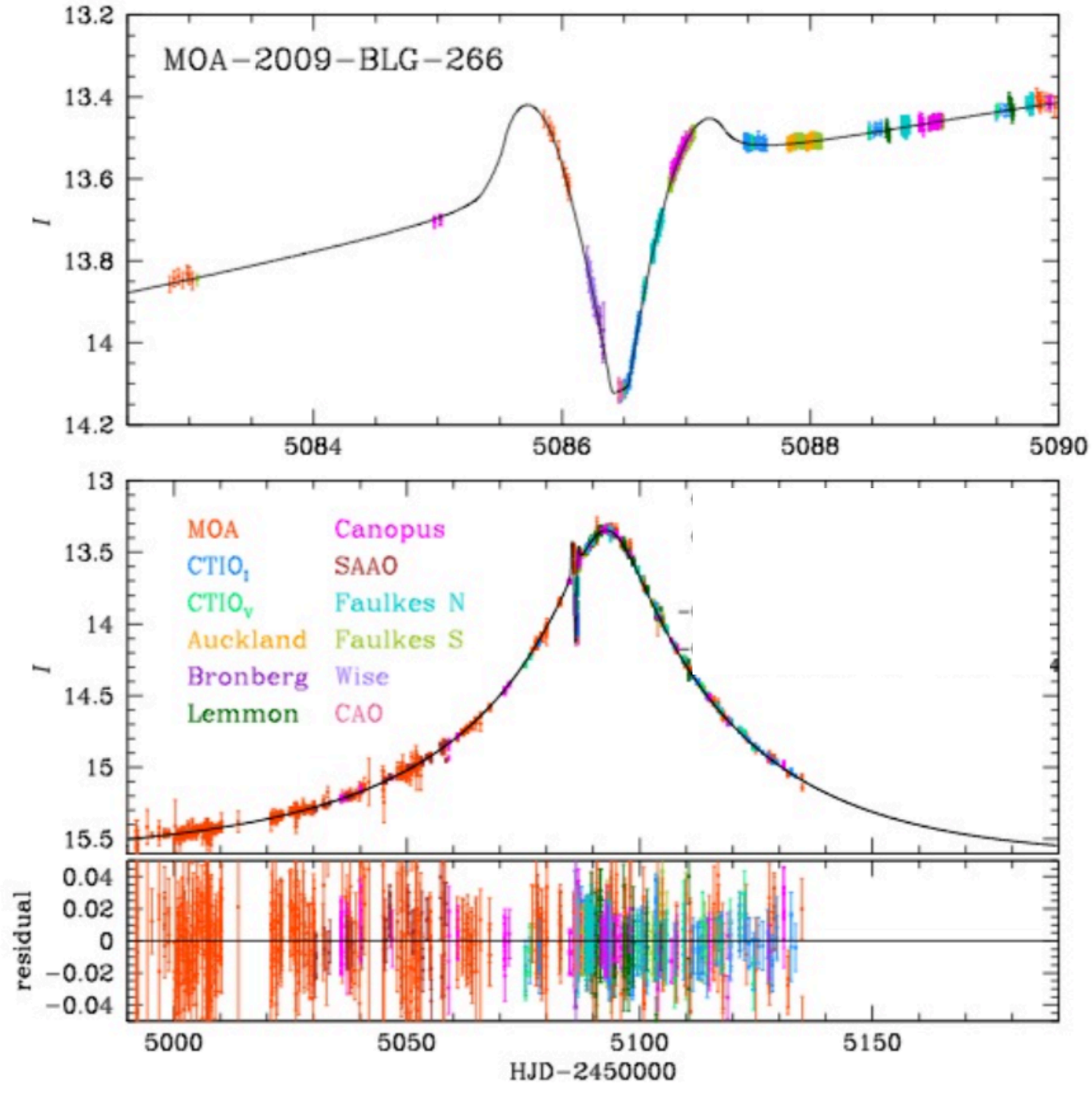
QUIZ



Albrow et al. 2002

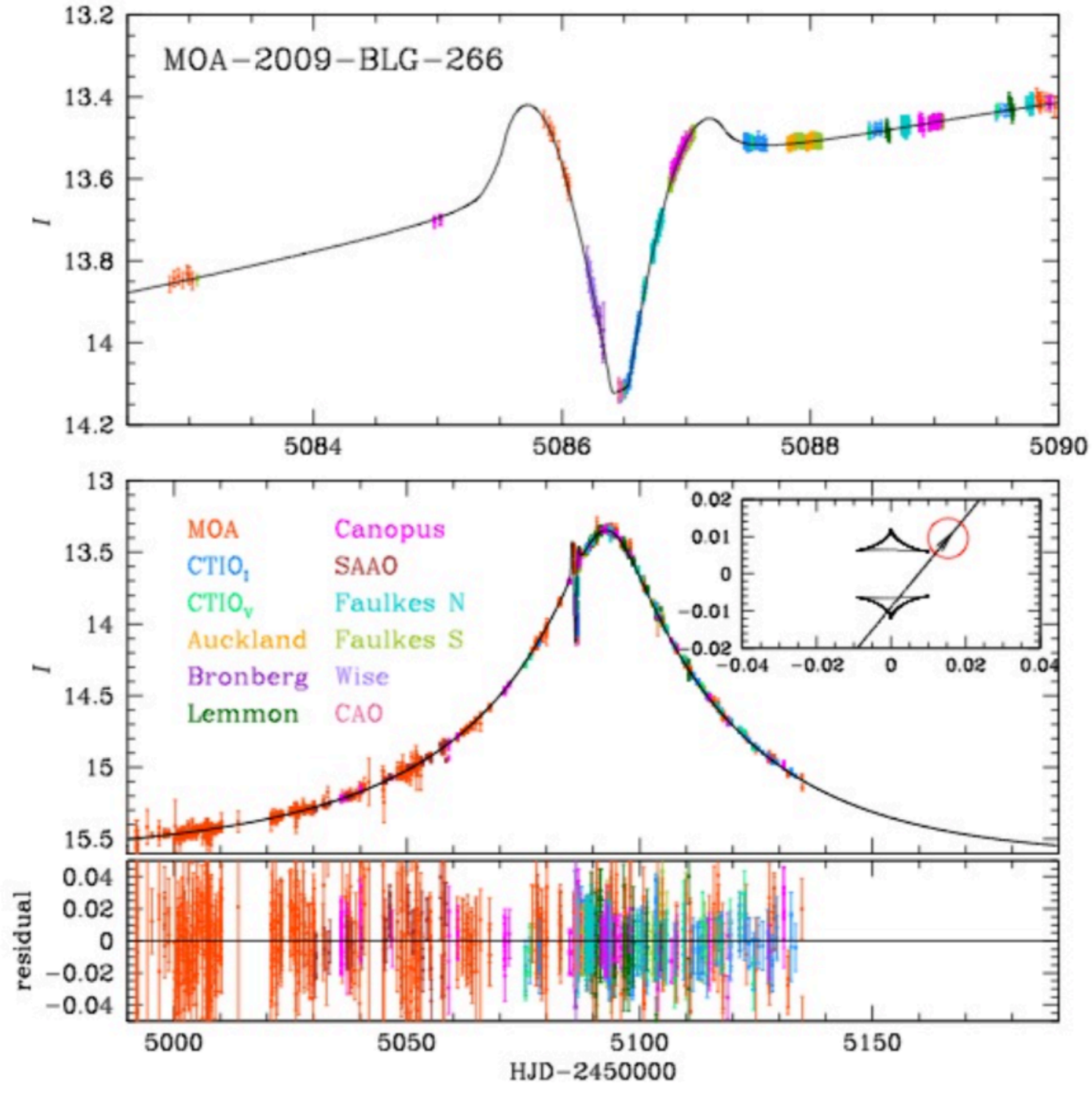
QUIZ

(Muraki et al. 2011)

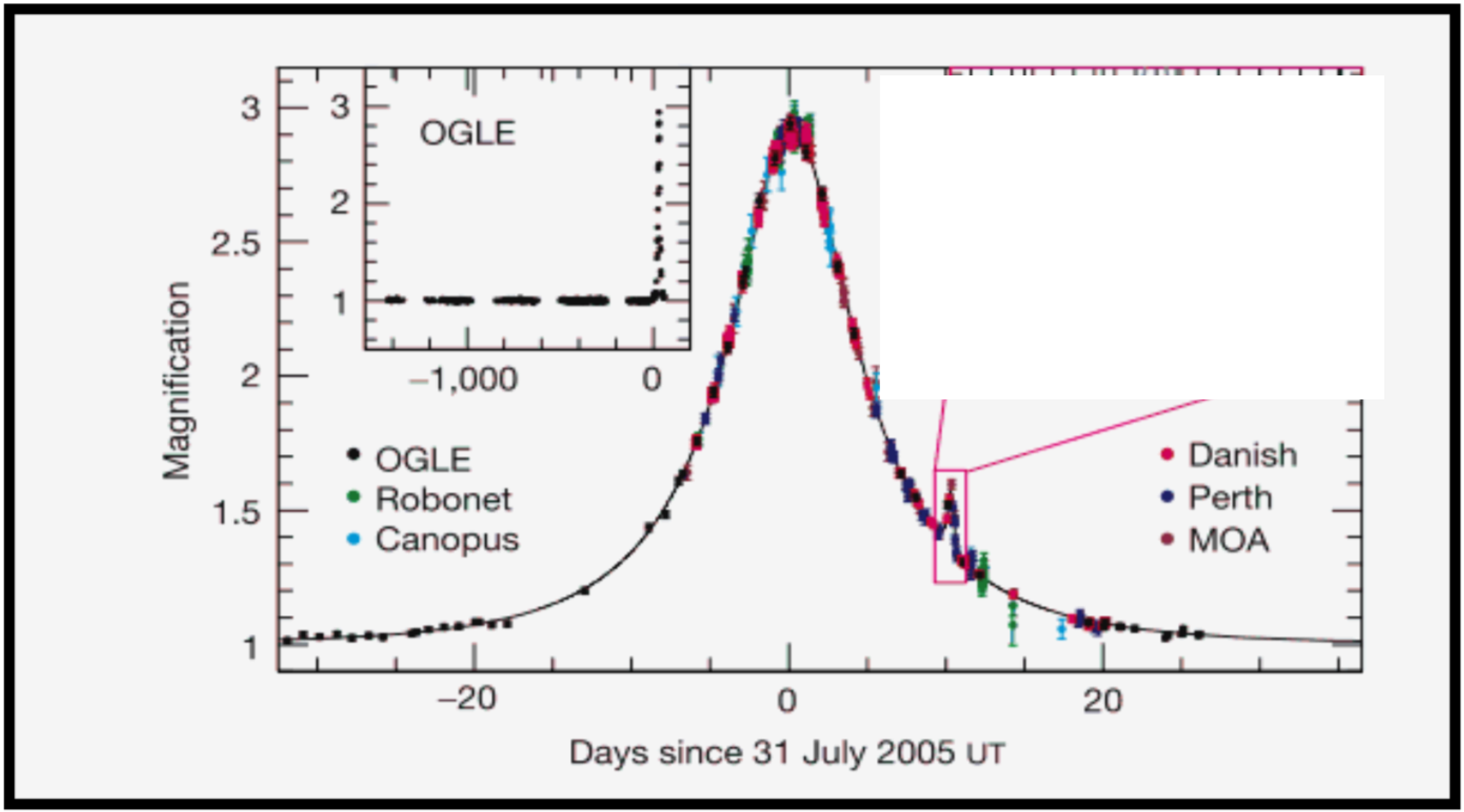


QUIZ

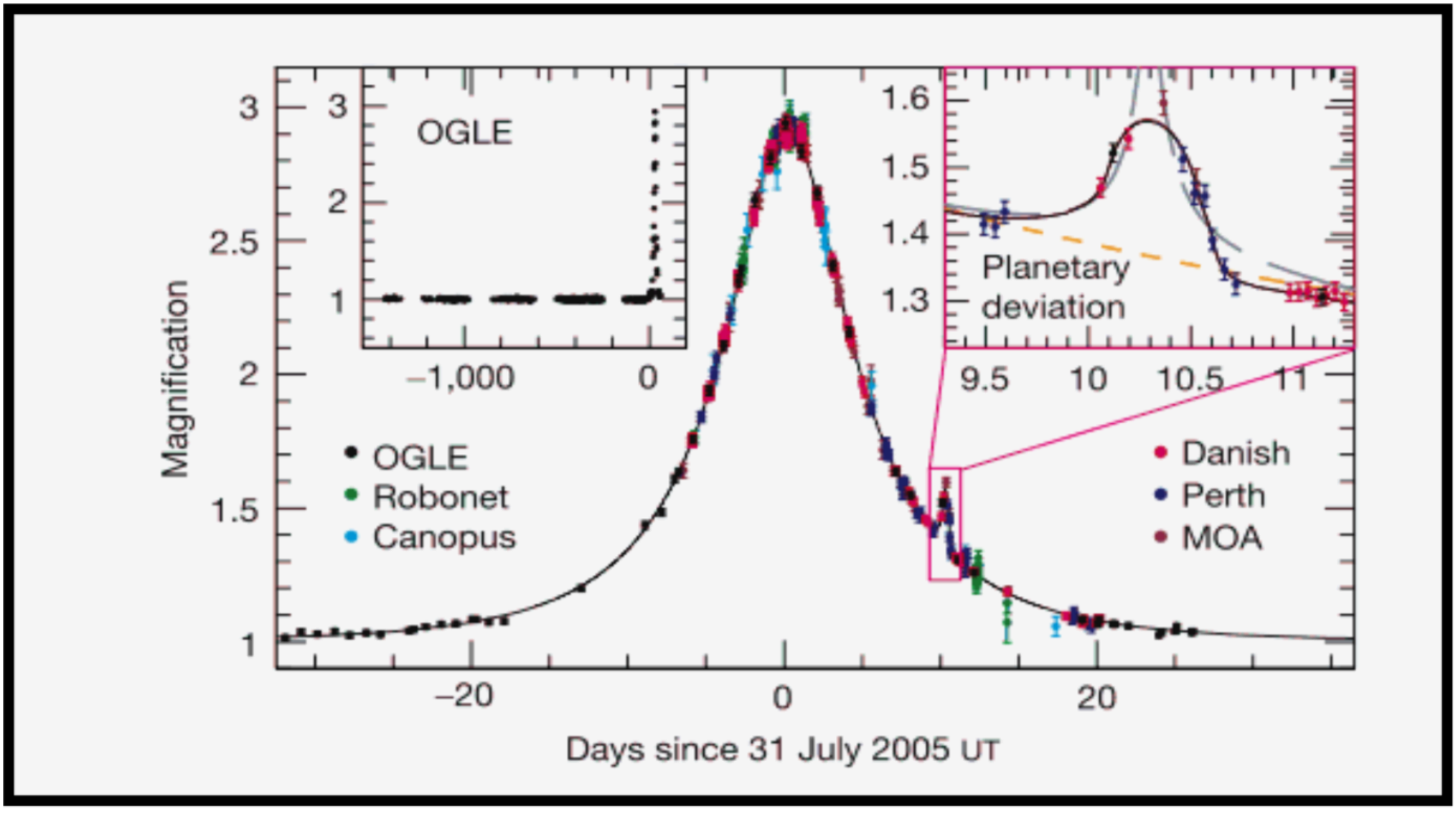
(Muraki et al. 2011)



QUIZ

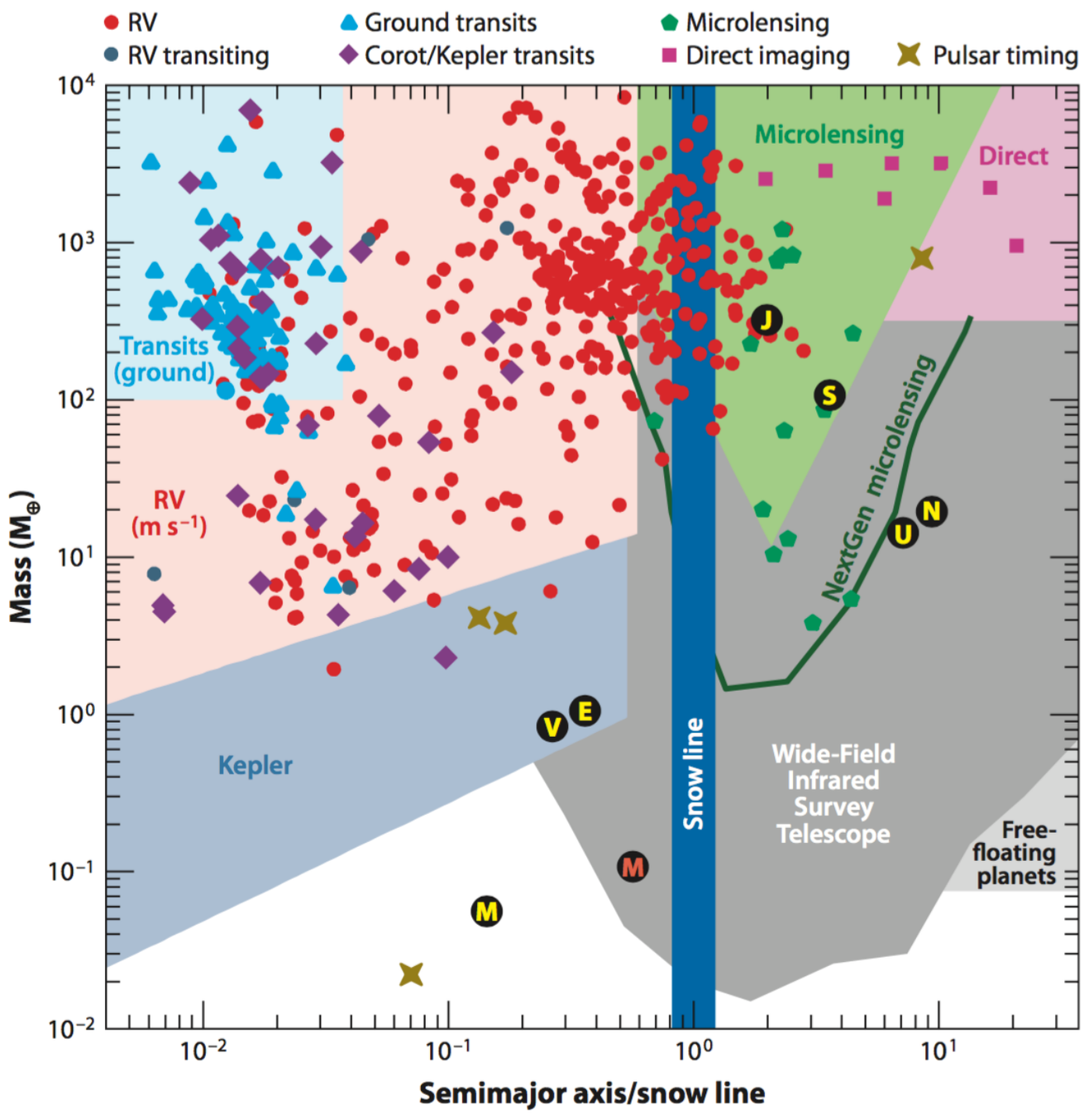

OGLE
−1,000
0
3
2
1
OGLE
Robonet
Canopus
Danish
Perth
MOA
Magnification
3
2.5
2
1.5
1
−20
0
20
Days since 31 July 2005 UT

QUIZ


OGLE
Planetary deviation
Magnification
Days since 31 July 2005 UT
OGLE
Robonet
Canopus
Danish
Perth
MOA
3
2.5
2
1.5
1
–20
0
20
1.6
1.5
1.4
1.3
9.5
10
10.5
11
–1,000
0

ADVANTAGES OF USING MICROLENSING FOR PLANET SEARCHES

- ~90 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.

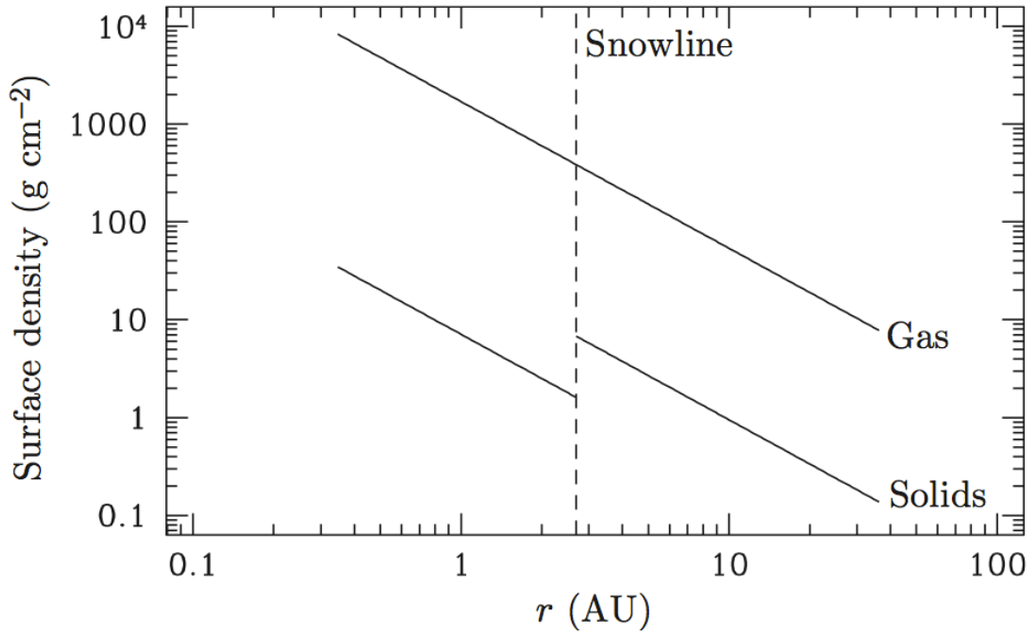
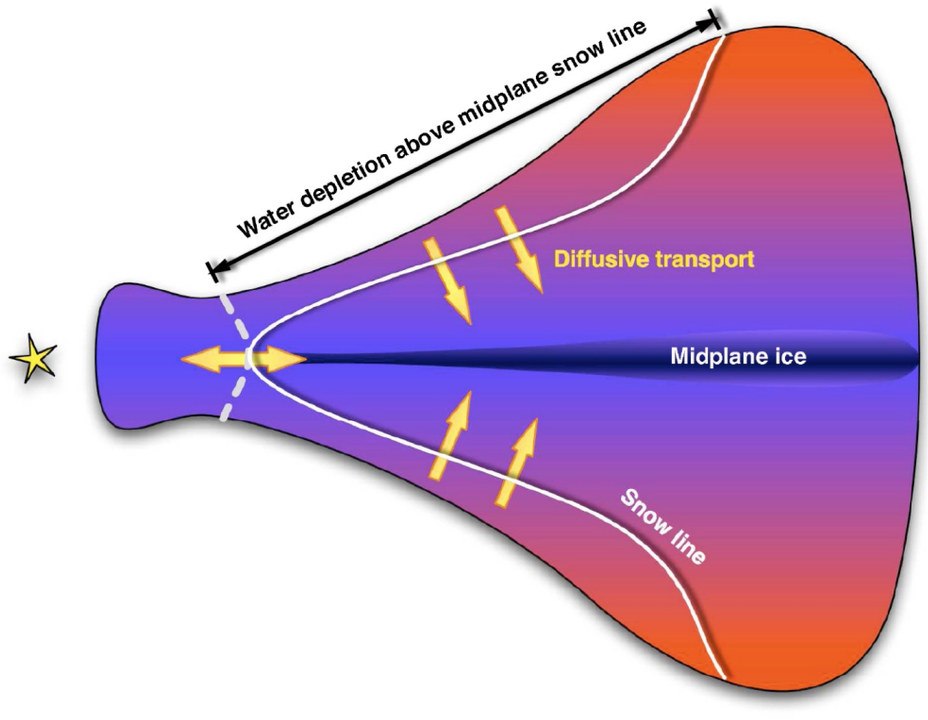


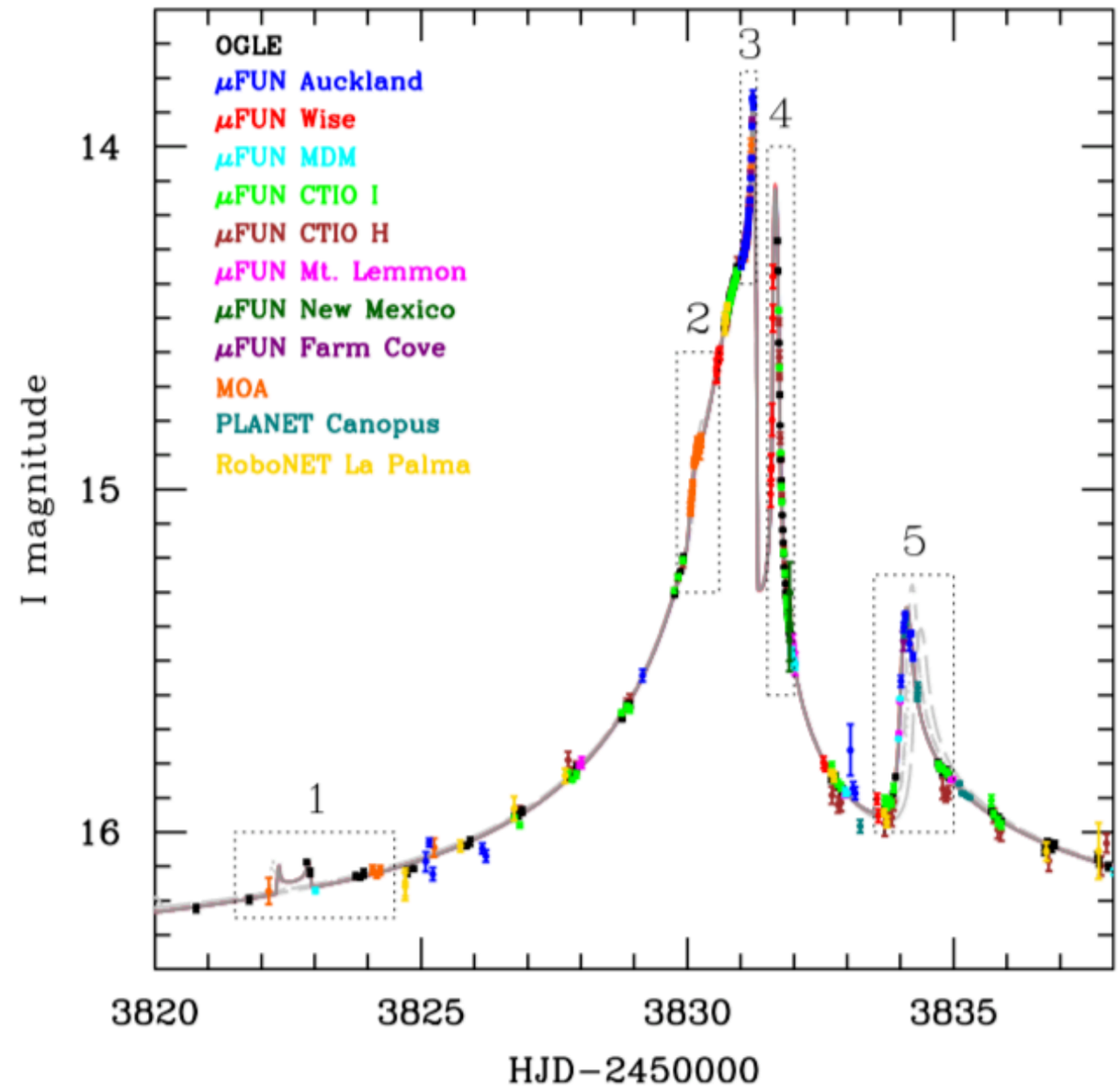
Fig. 1.1. The surface density in gas (upper line) and solids (lower broken line) as a function of radius in Hayashi's minimum mass Solar Nebula. The dashed vertical line denotes the location of the snowline.

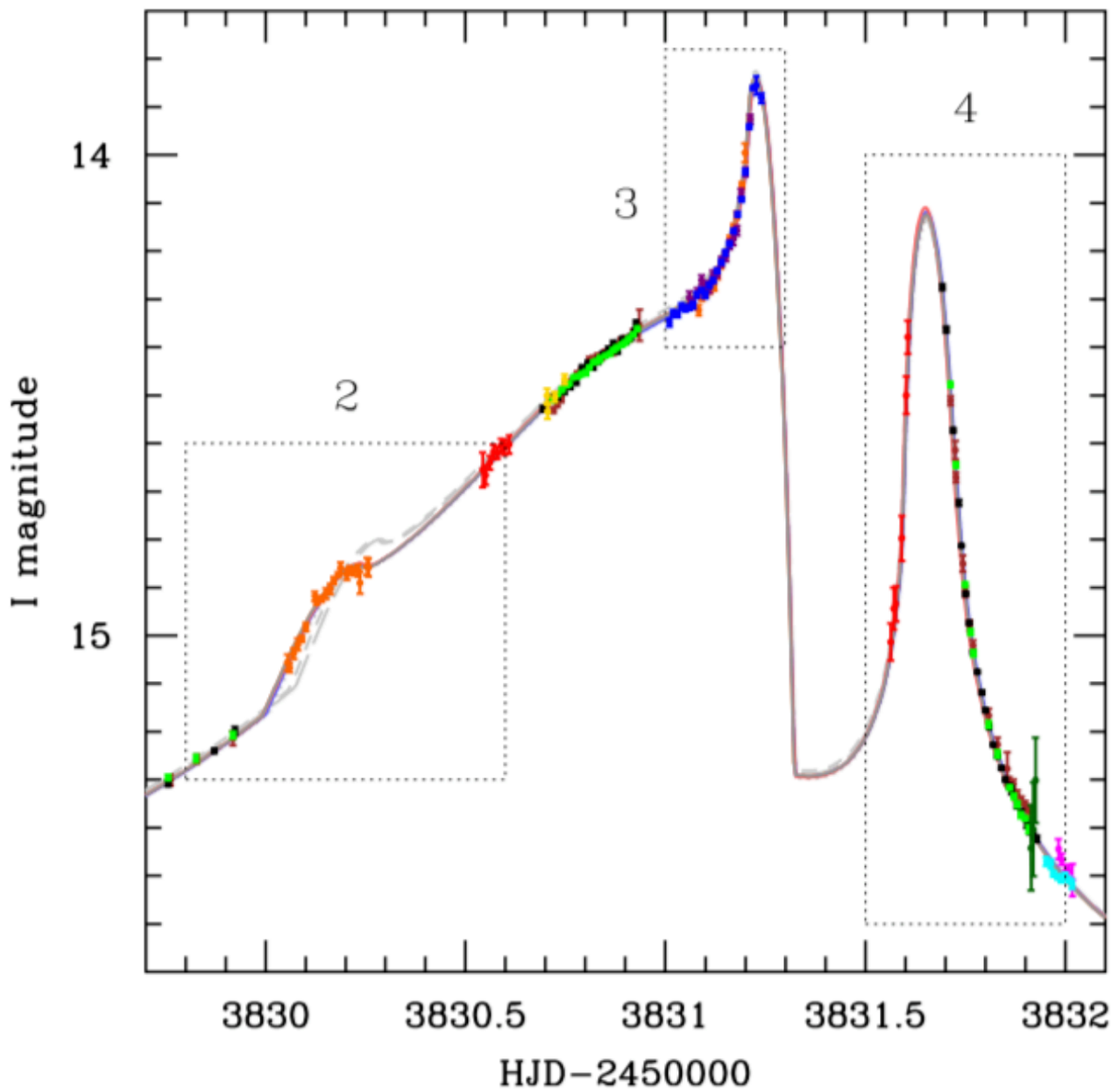


OTHER ADVANTAGES...

- 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 and orbital parameters...

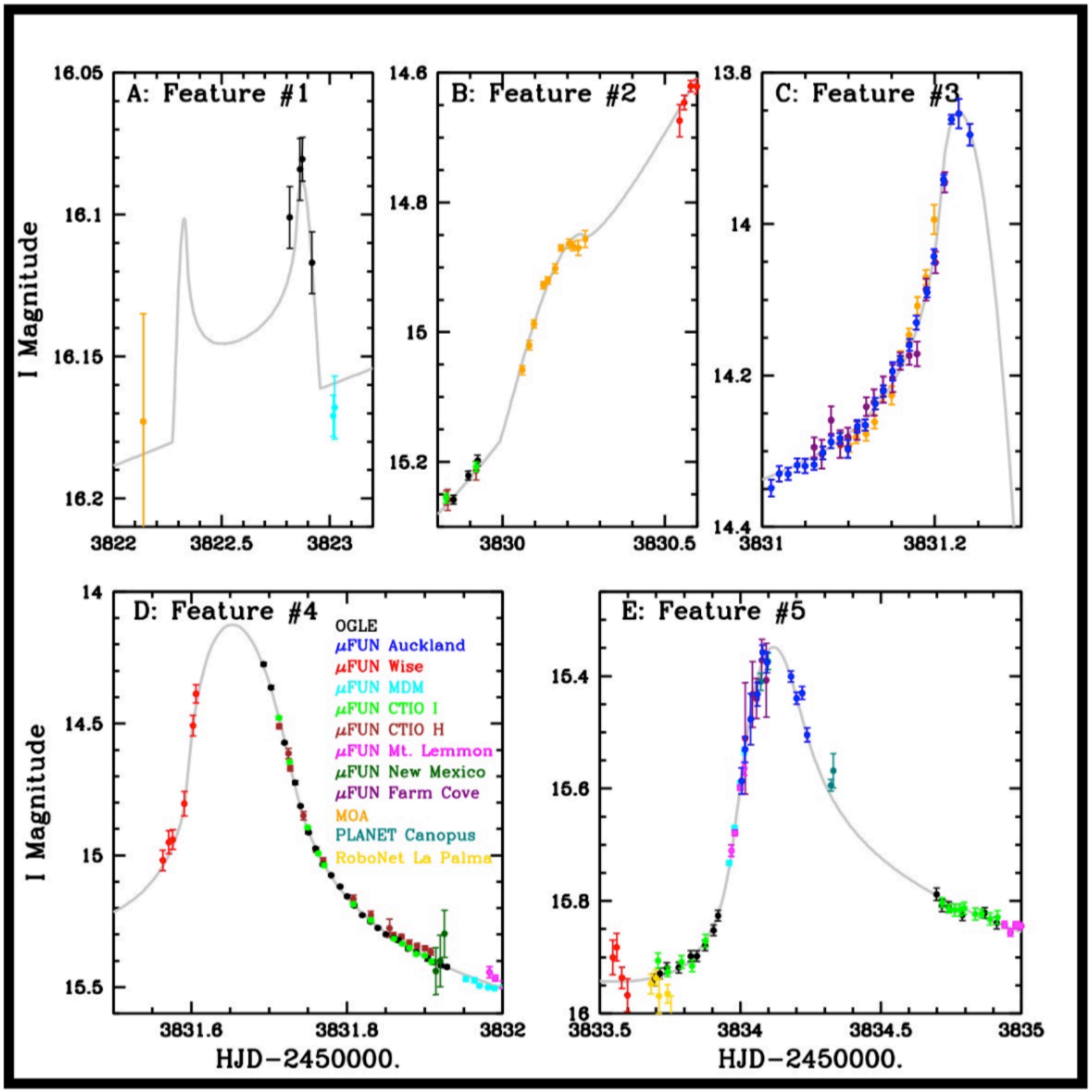
QUIZ

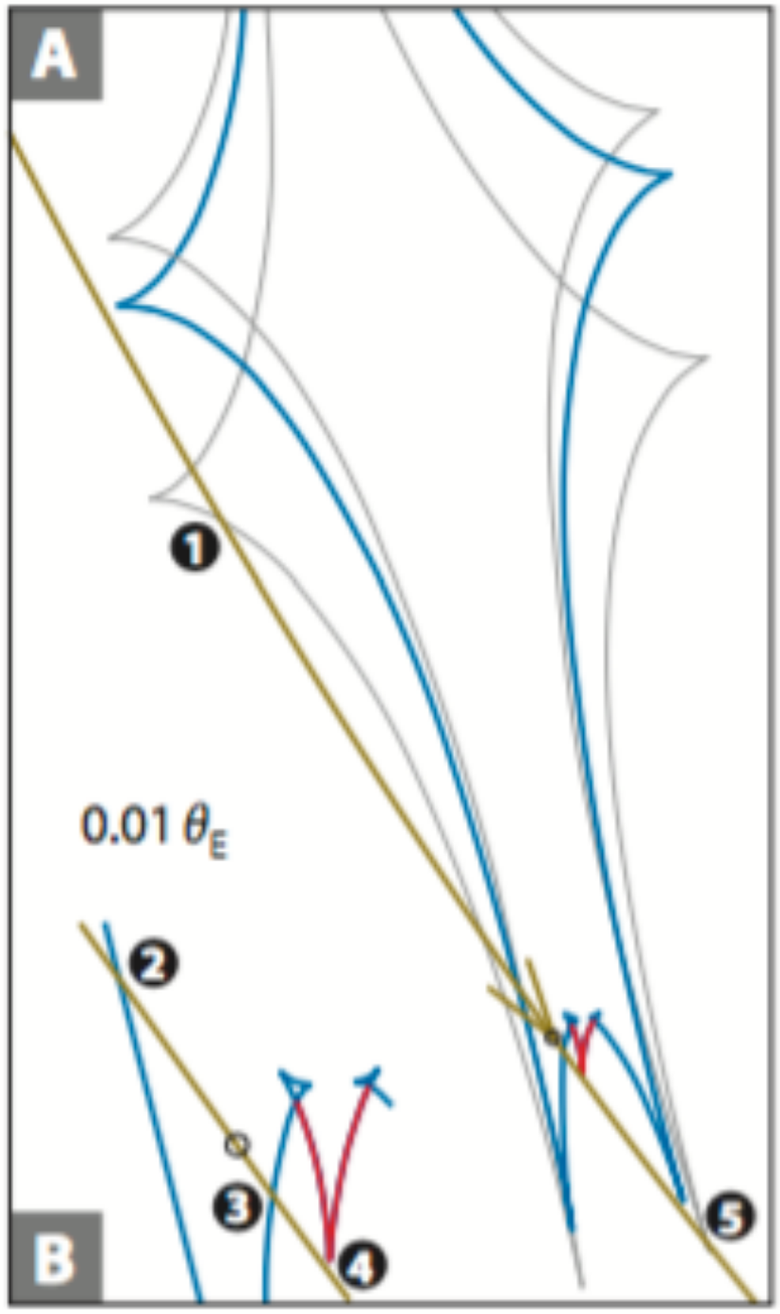




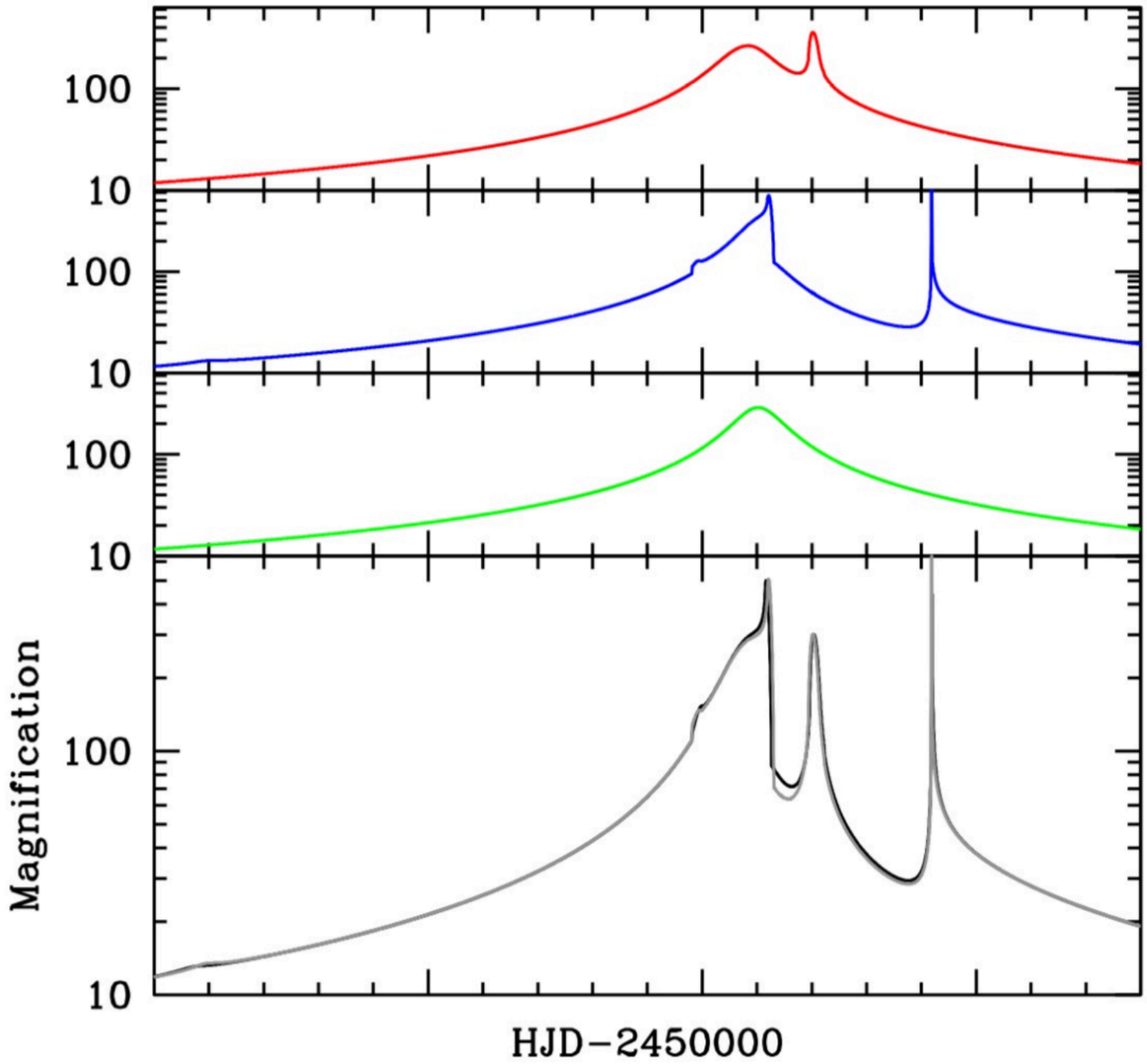
Gaudi et al. 2008, Bennett et al. 2010 — OGLE-2006-BLG-109

MULTIPLE PLANETS AND EVOLVING CAUSTIC



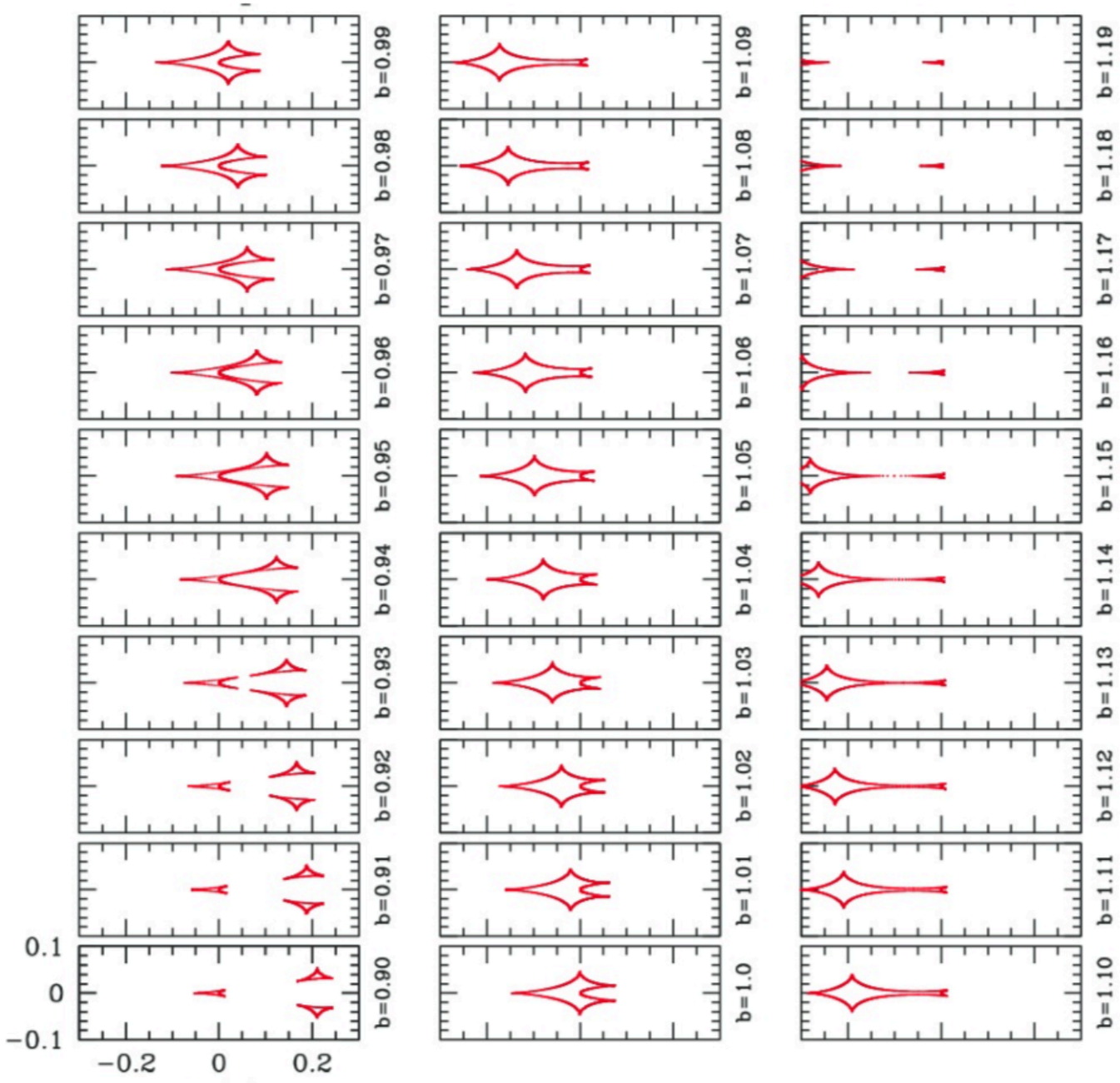


MULTIPLE PLANETS AND EVOLVING CAUSTIC



SHAPE OF THE RESONANT CAUSTIC VS D: SENSITIVITY TO ORBITAL MOTION

$$q = 0.001,\ s = 0.90 - 1.19,\ \Delta s = 0.29$$



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

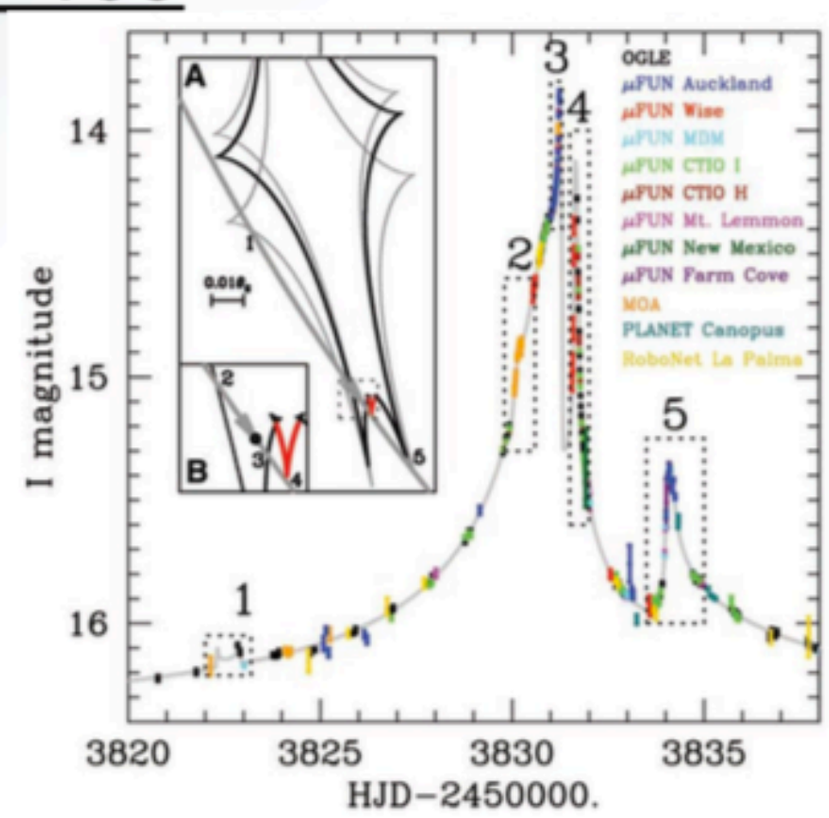
$m_j/M_\odot$	0.96×10^{-3}
m_s/m_j	0.30
a_j/a_s	0.5

Gaudi et al. 2008

Physical properties

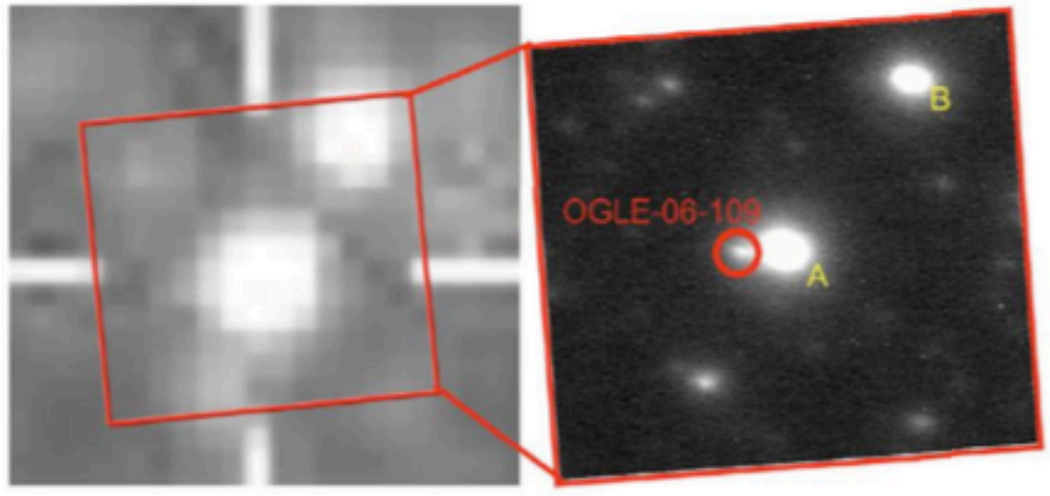
m_b	$0.73 \pm 0.06[M_{Jup}]$
$a_{\perp,b}$	2.3 ± 0.5[AU]
m_c	$0.75 \pm 0.06[M_{Sat}]$
$a_{\perp,c}$	$4.5^{+1.1}_{-1.0}$[AU]
M_{host}	$0.51^{+0.05}_{-0.04}\ [M_\odot]$

Bennett et al. 2010



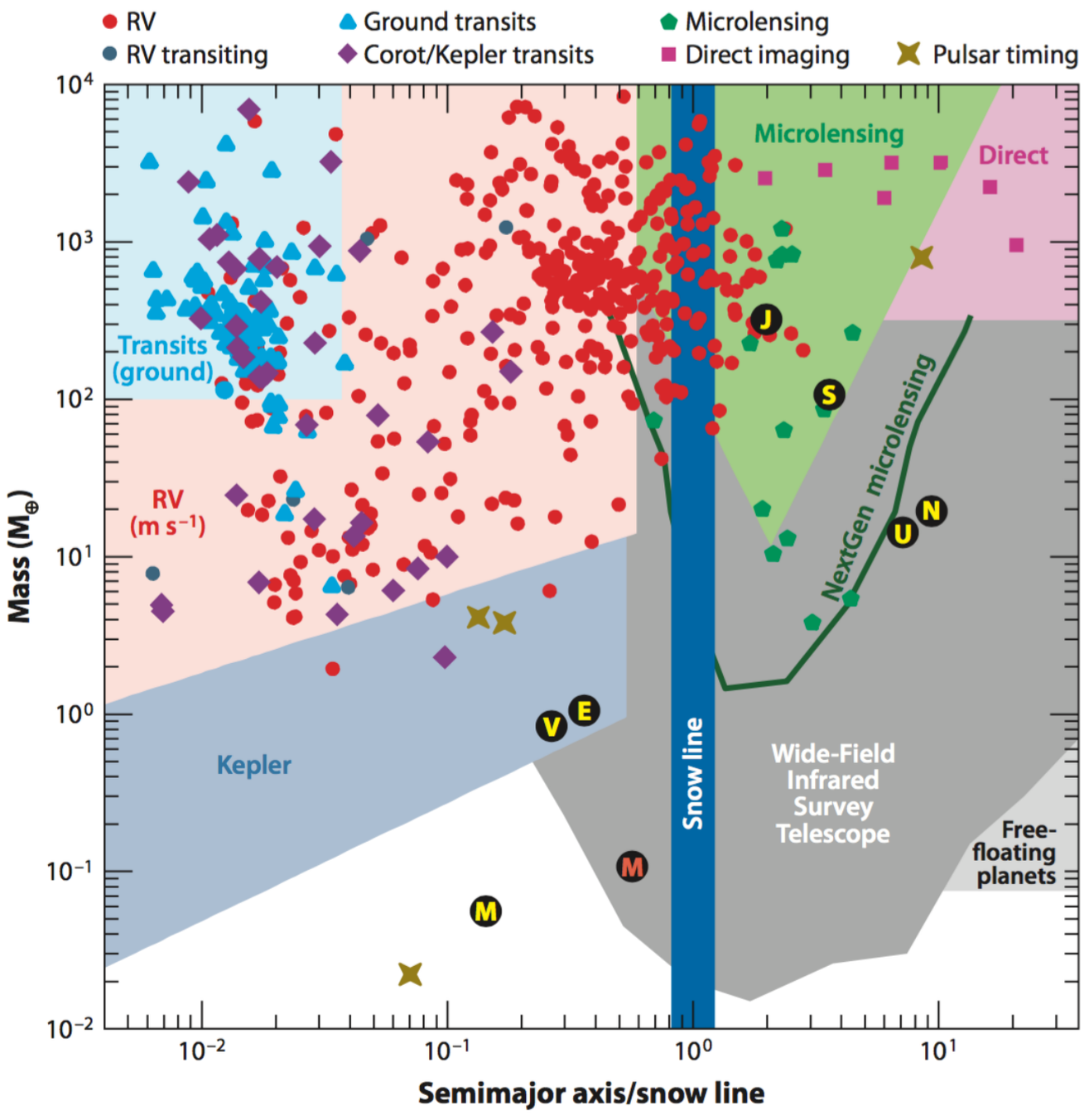
OGLE

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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Confirmed Exoplanet Statistics *(2017)*

Discovery Method	Number of Planets
Astrometry	1
Imaging	44
Radial Velocity	669
Transit	2907
Transit timing variations	15
Eclipse timing variations	9
Microlensing	58 *~90*
Pulsar timing variations	6
Pulsation timing variations	2
Orbital brightness modulations	6

Transiting Exoplanets	**2931**
All Exoplanets	**3717** *~4000*