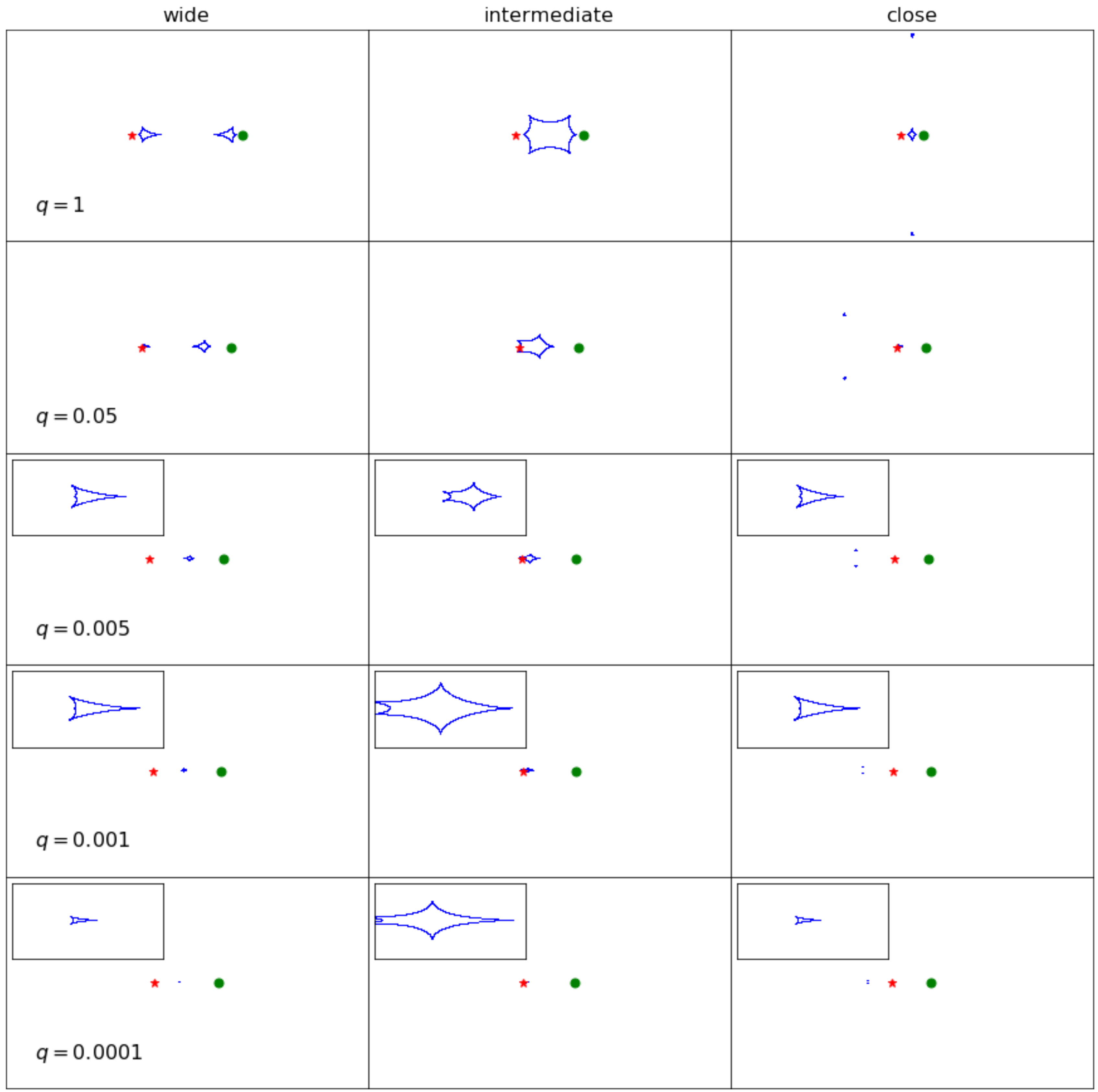
GRAVITATIONAL LENSING

LECTURE 18

Docente: Massimo Meneghetti

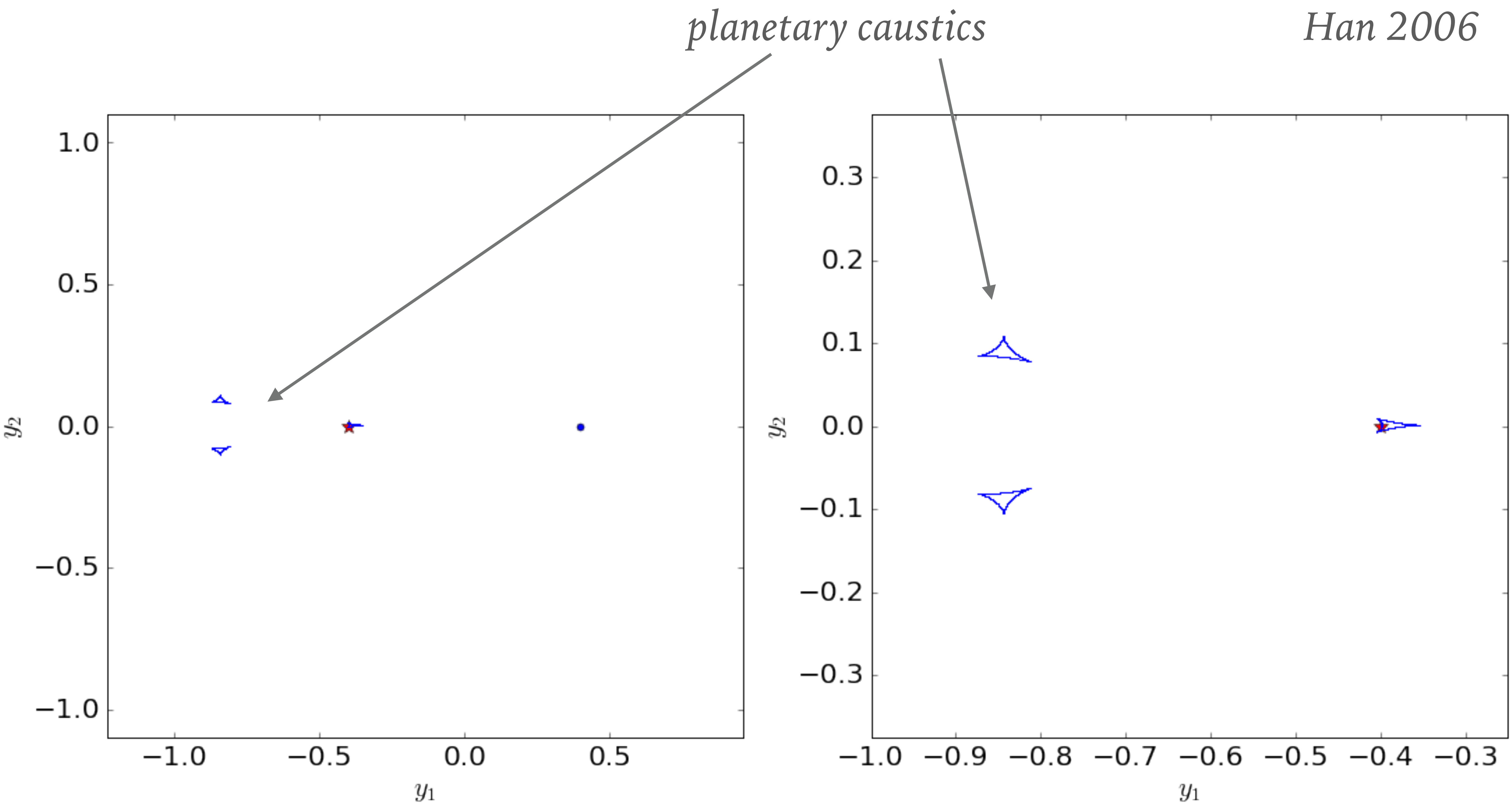
AA 2016-2017

CAUSTICS CONFIGURATIONS IN PLANETARY MICROLENSING



PLANETARY CAUSTICS IN CLOSE TOPOLOGIES

Han 2006



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

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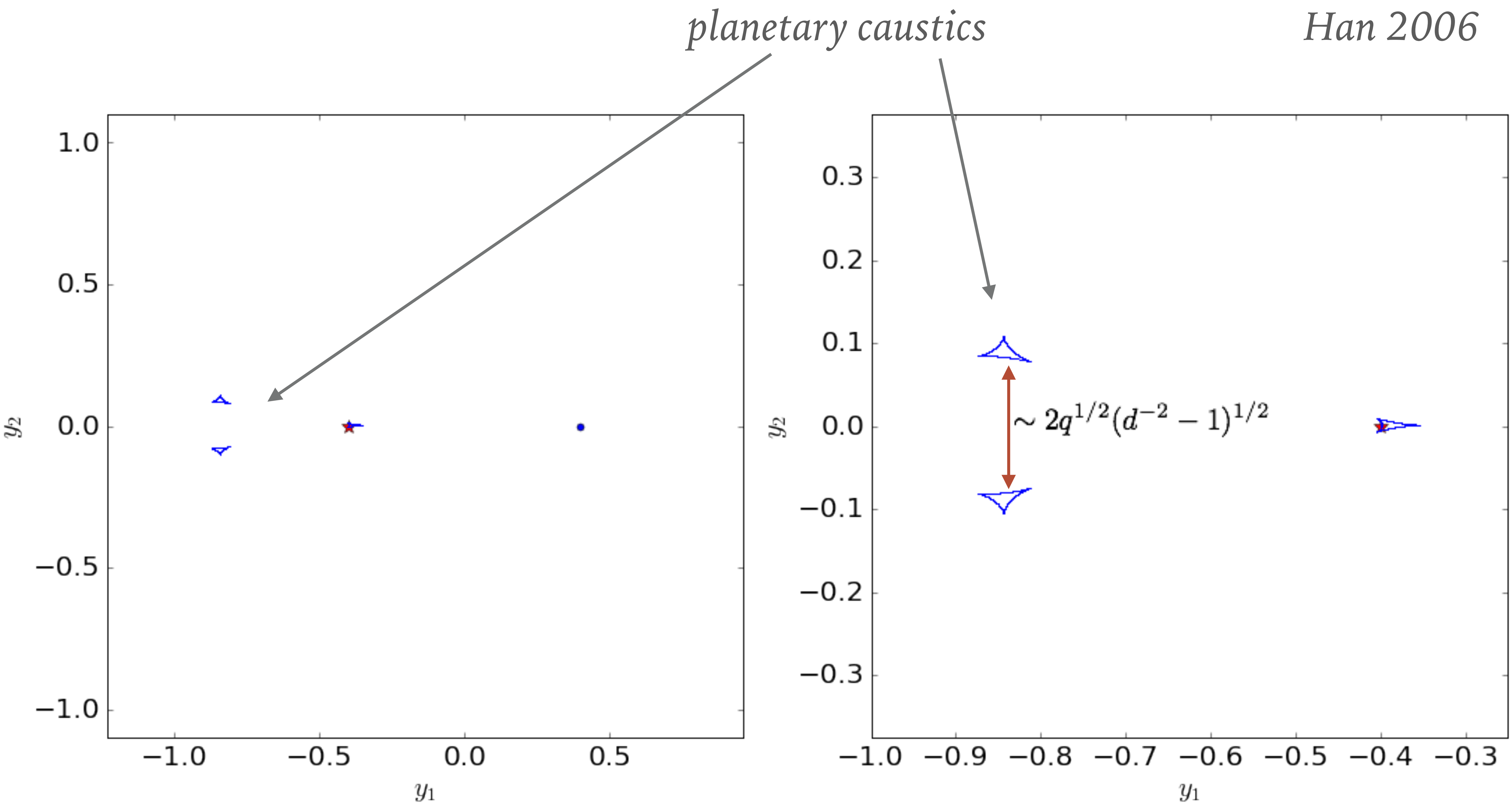

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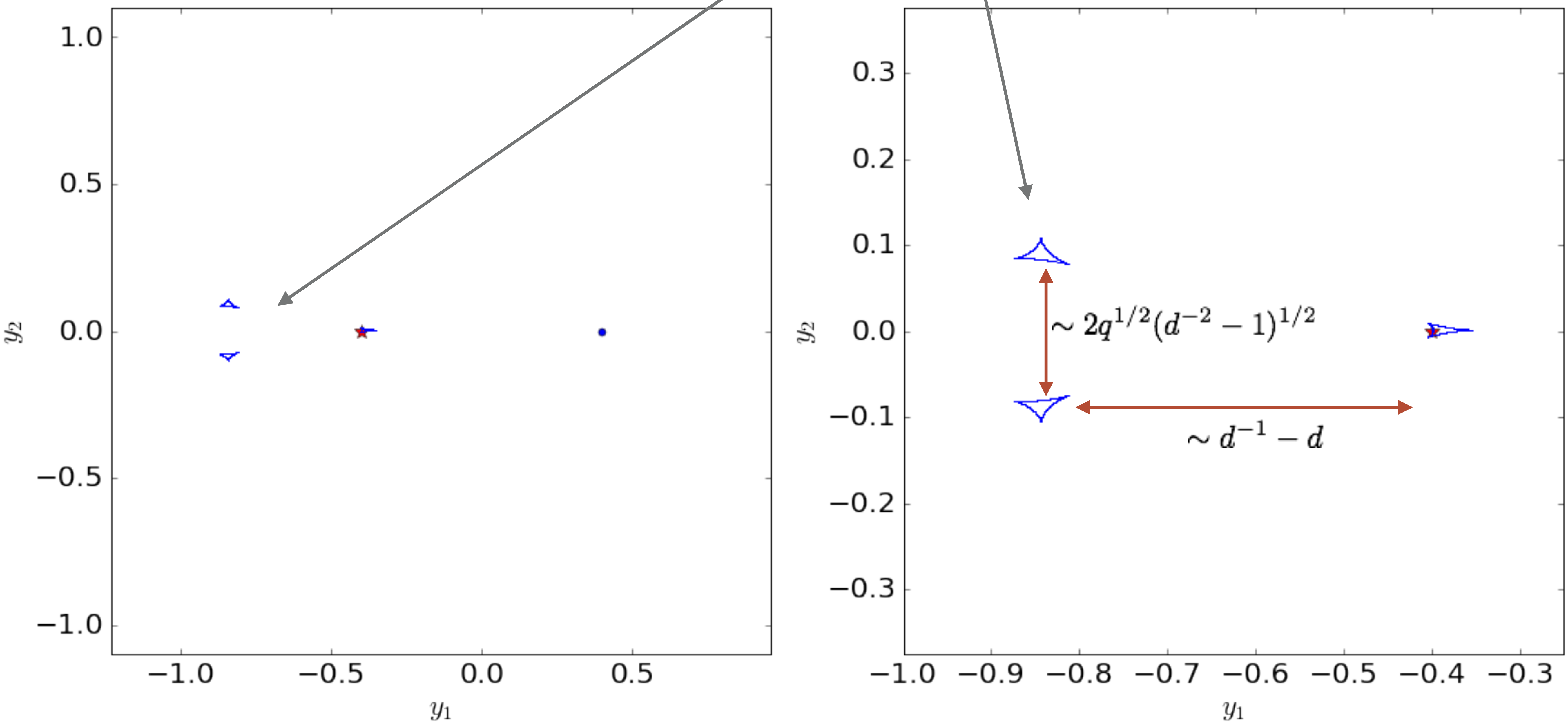
PLANETARY CAUSTICS IN CLOSE TOPOLOGIES

planetary caustics

Han 2006



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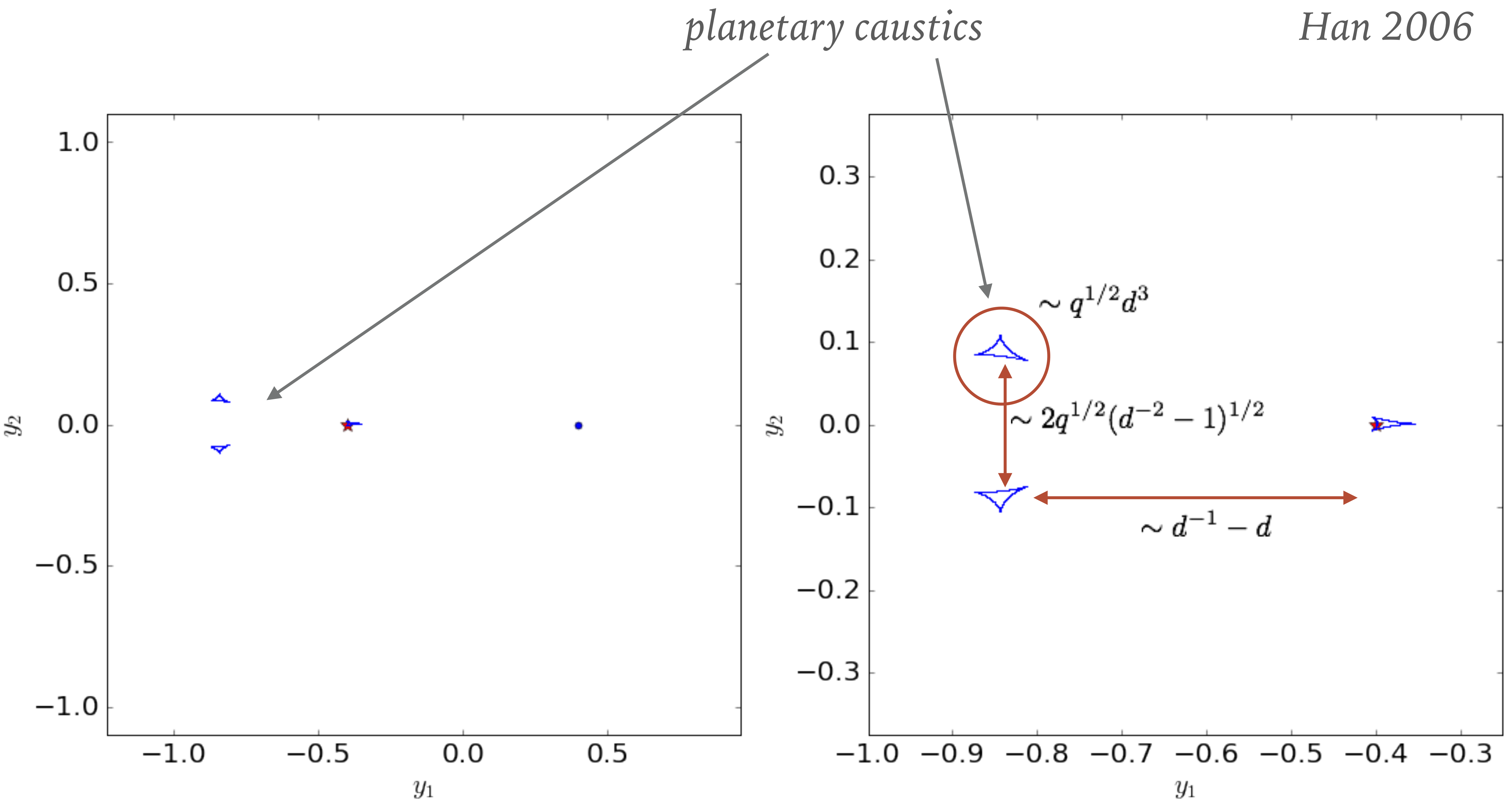

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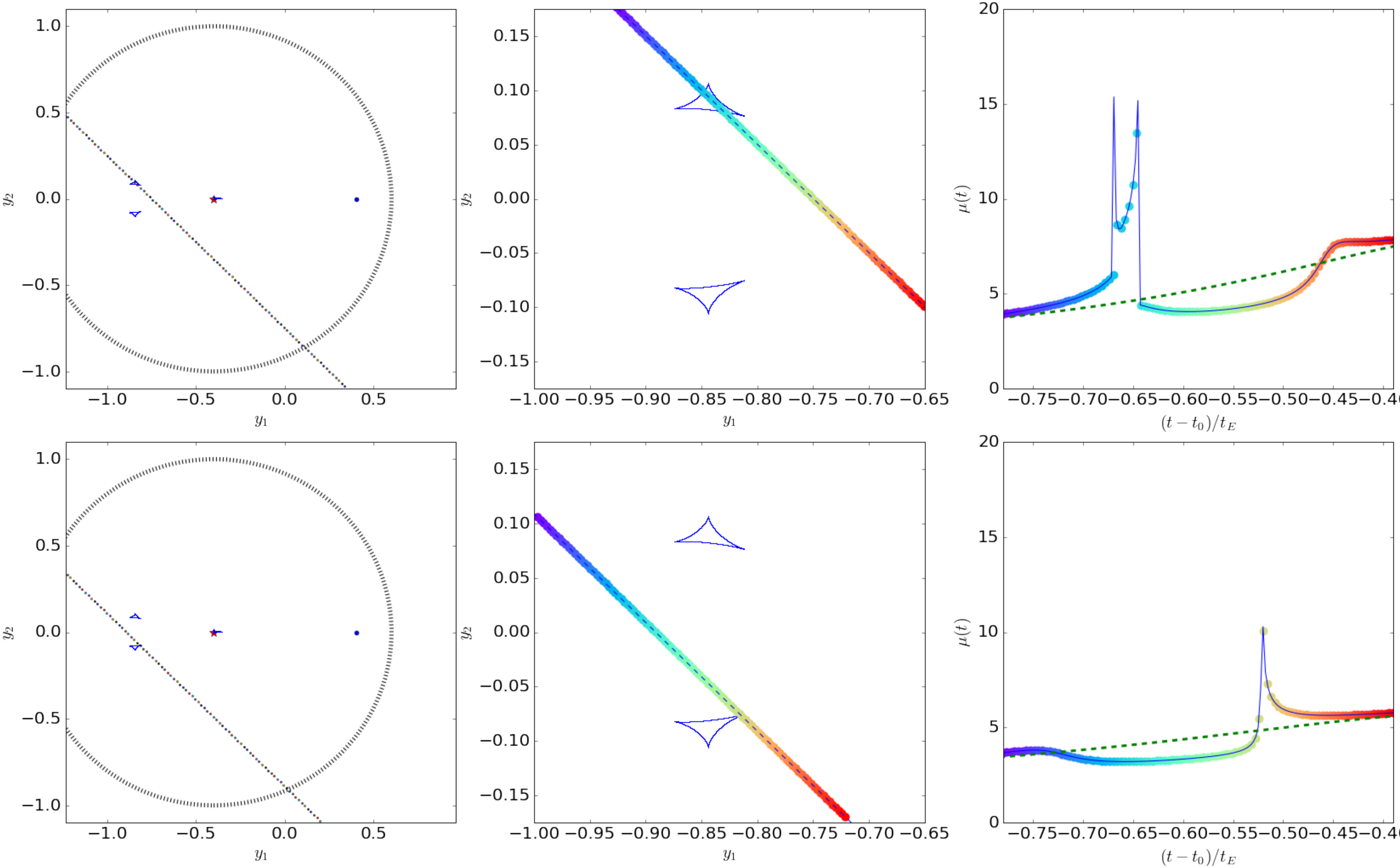
PLANETARY CAUSTICS PERTURBATIONS IN CLOSE TOPOLOGIES



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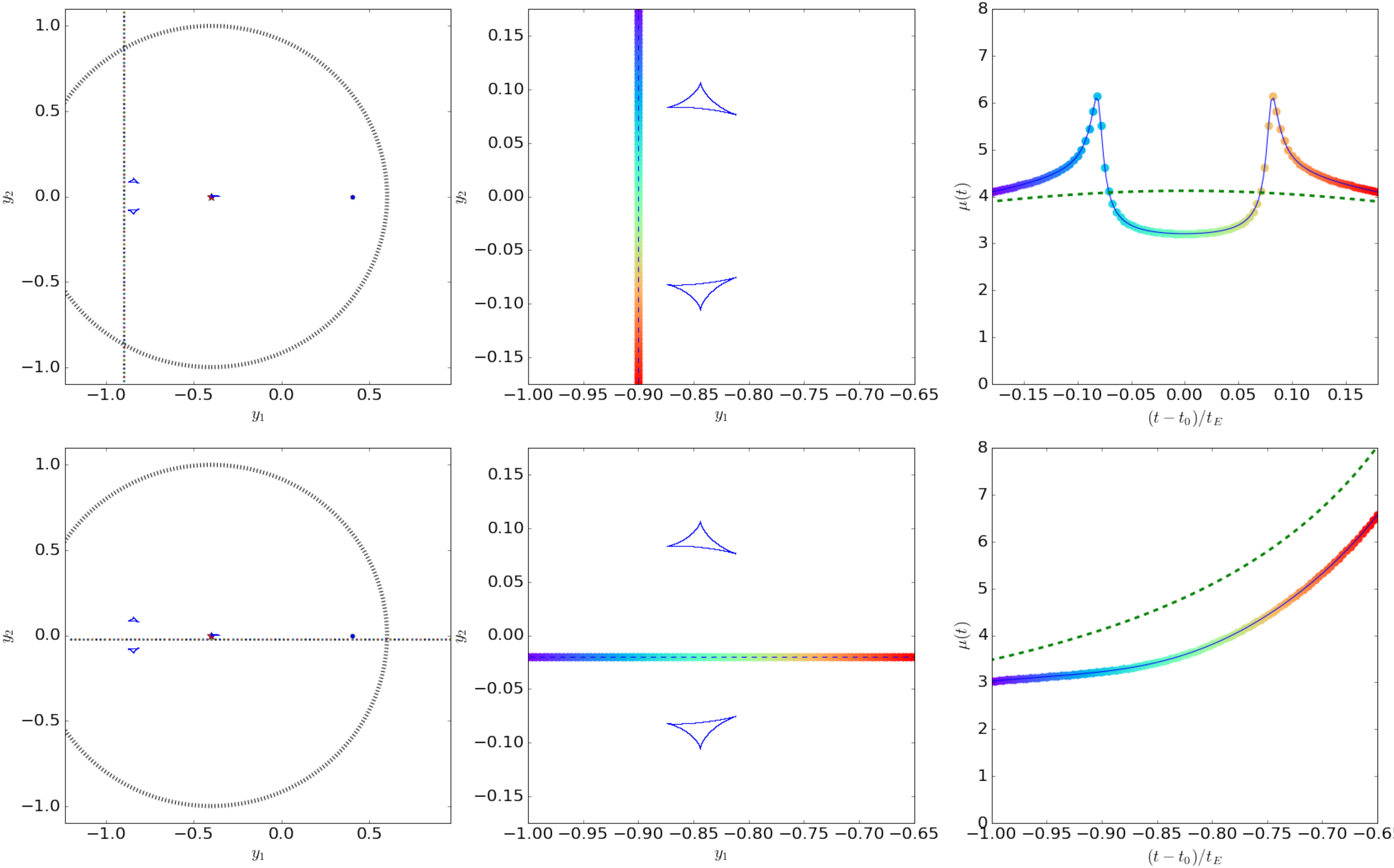
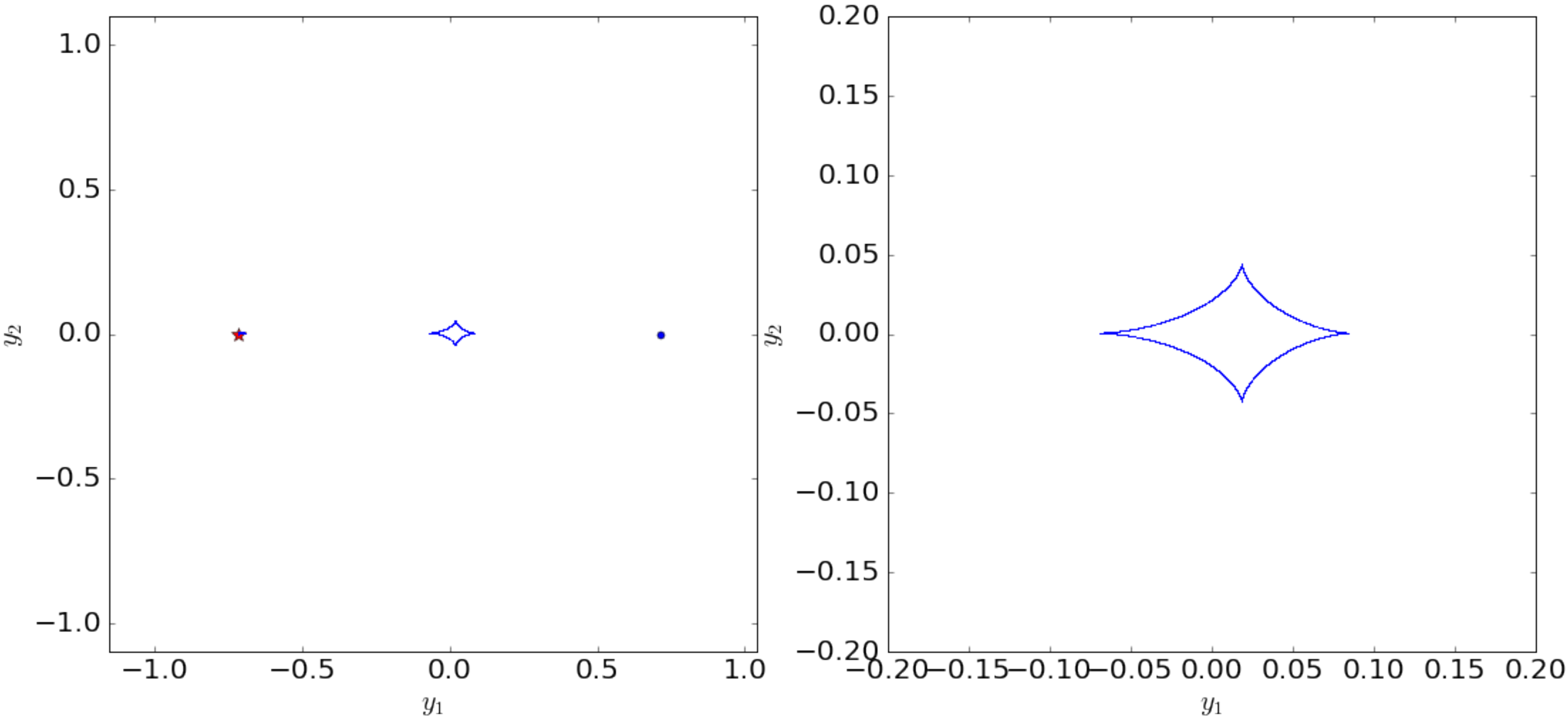


PLANETARY CAUSTICS IN WIDE TOPOLOGIES



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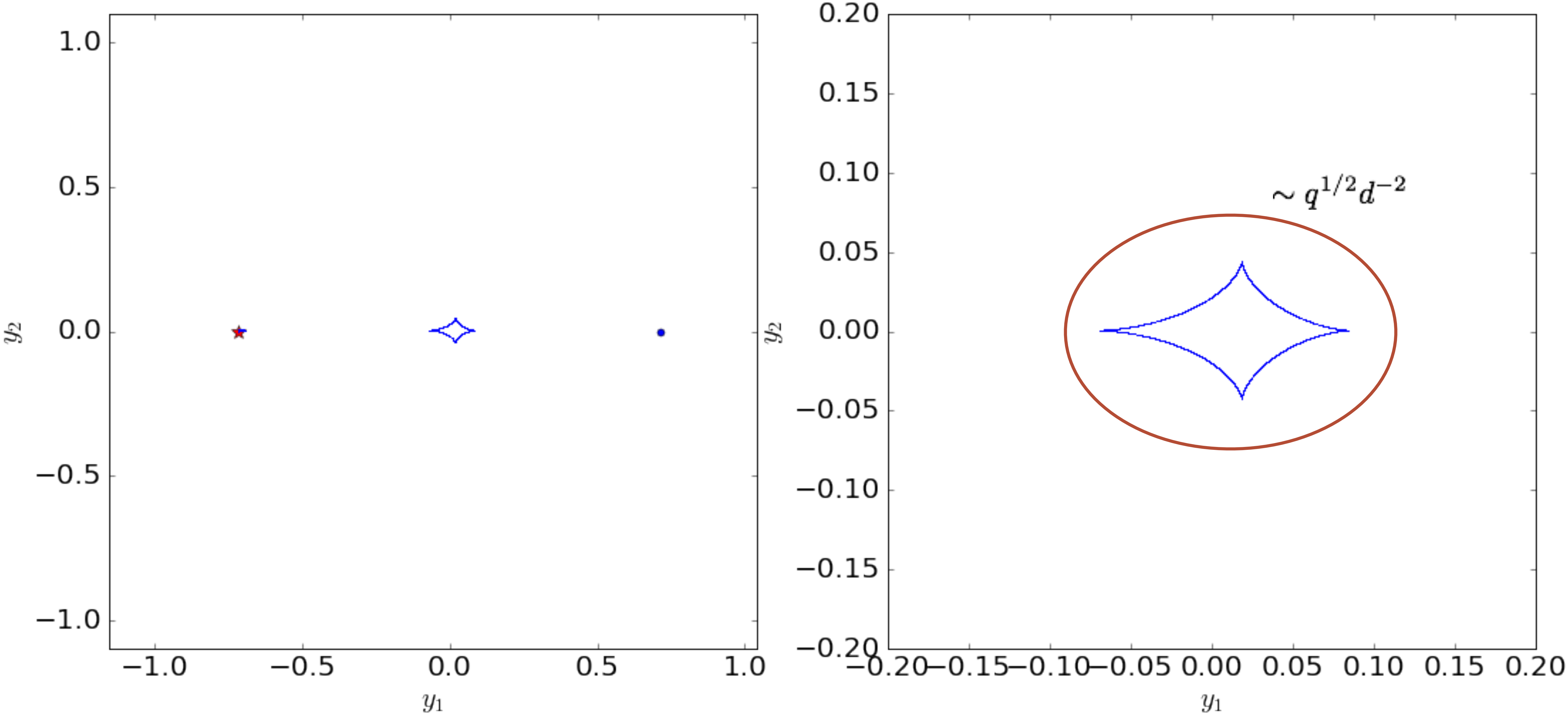

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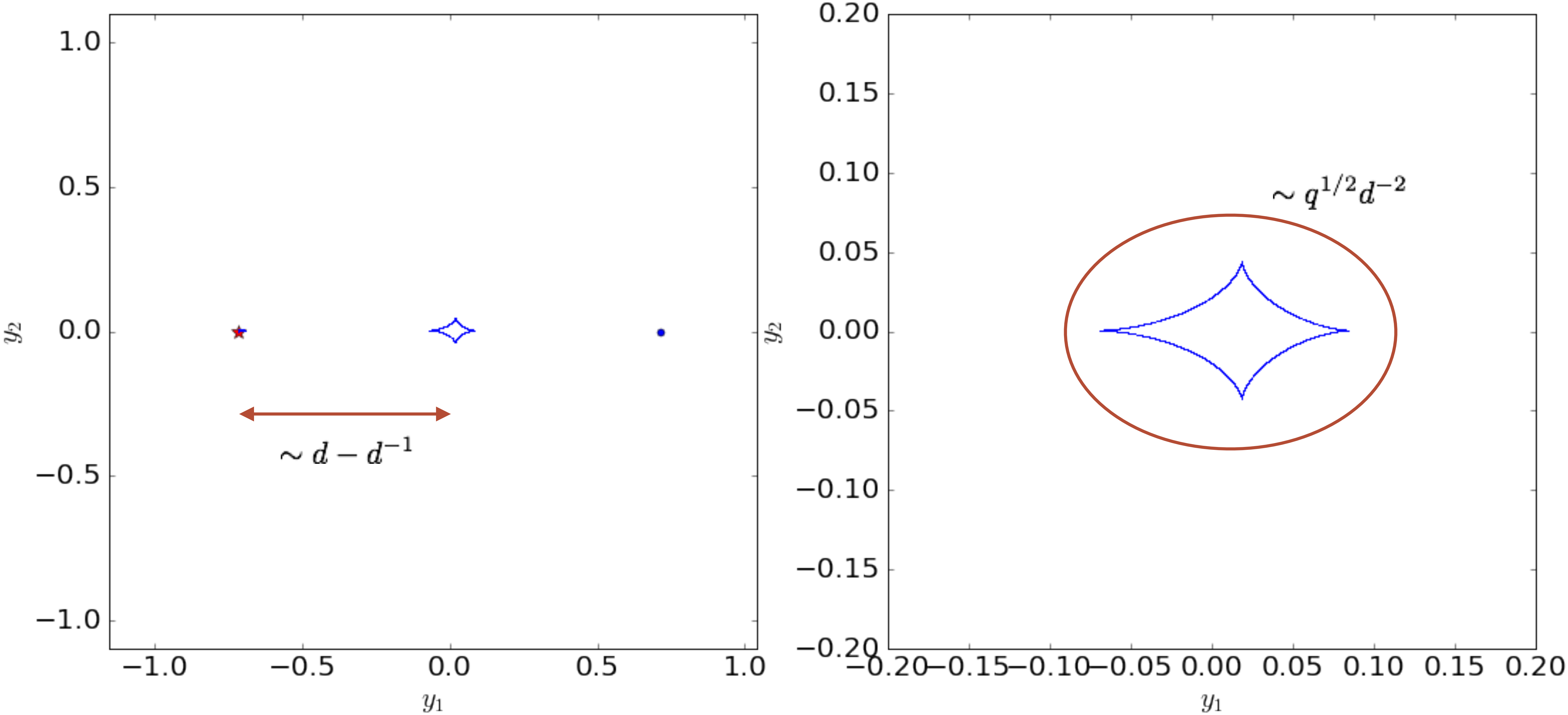

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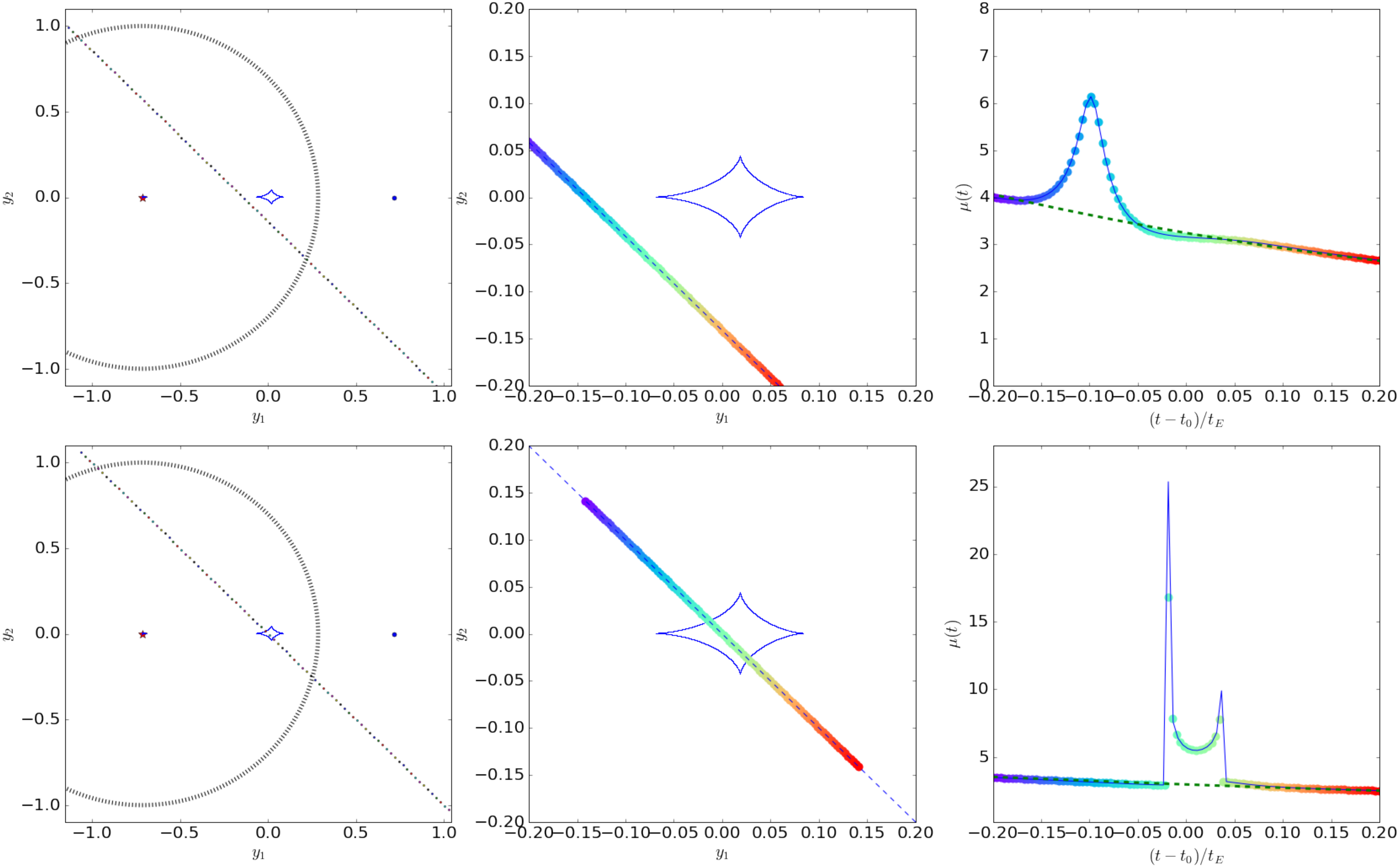

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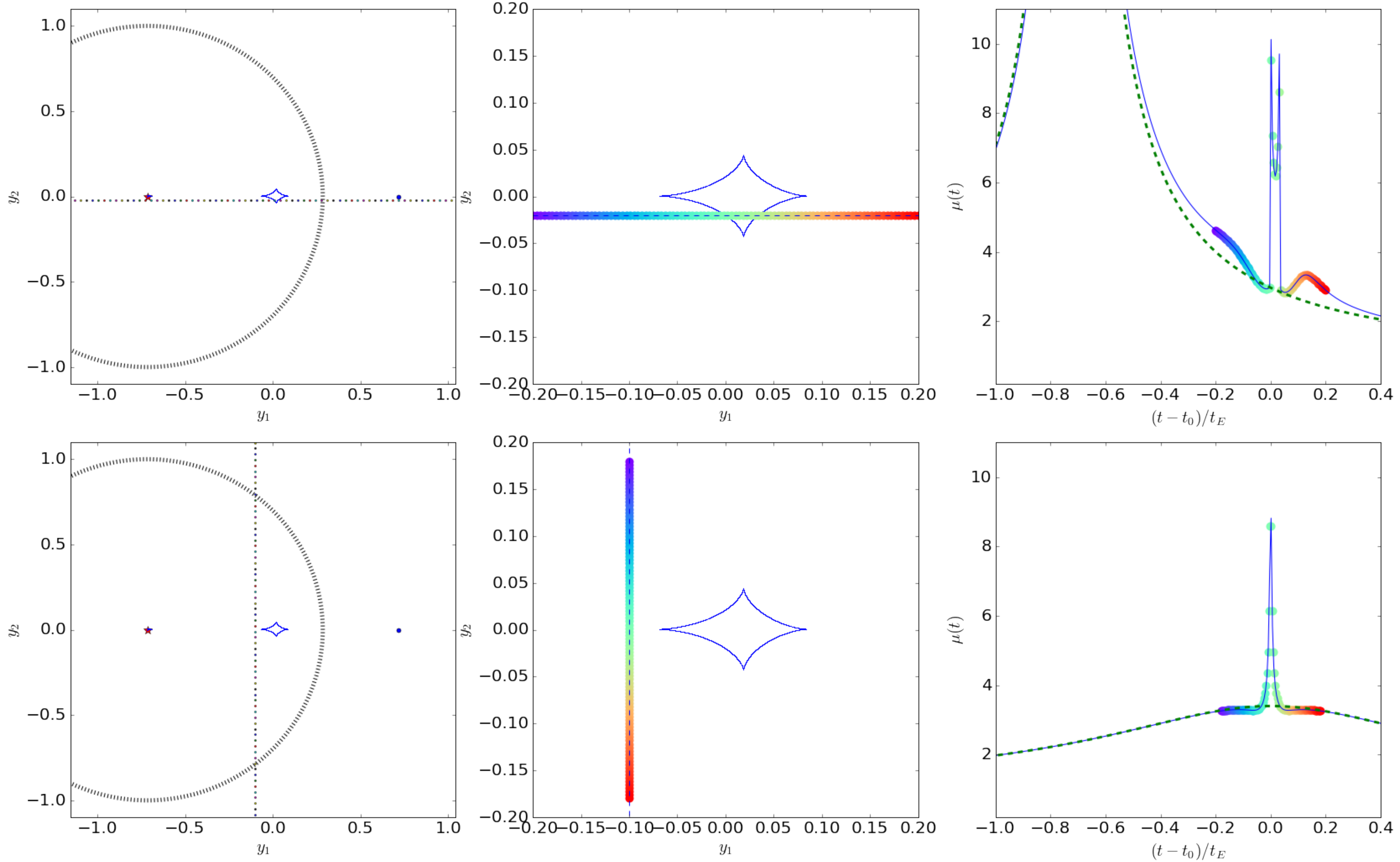
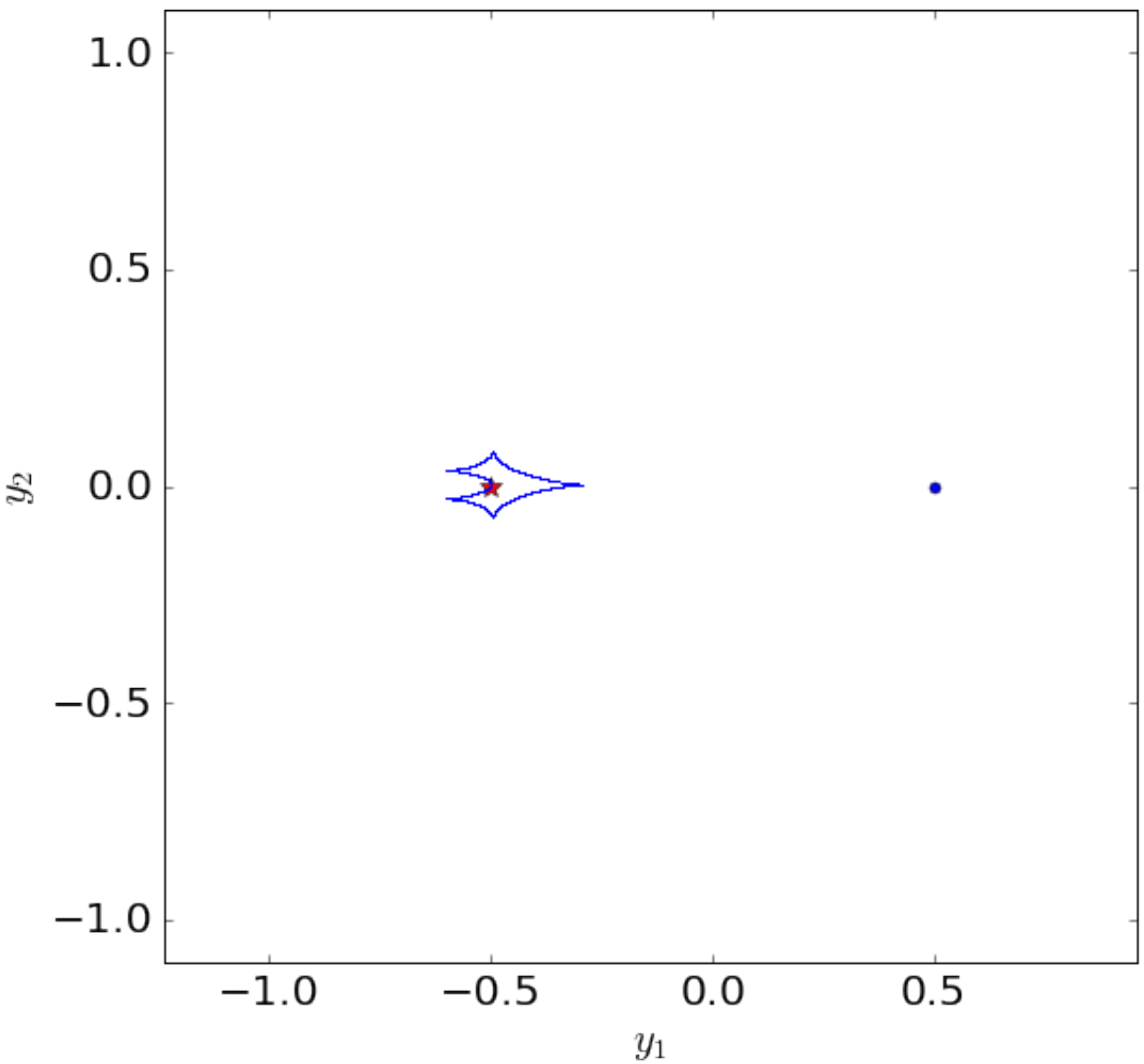
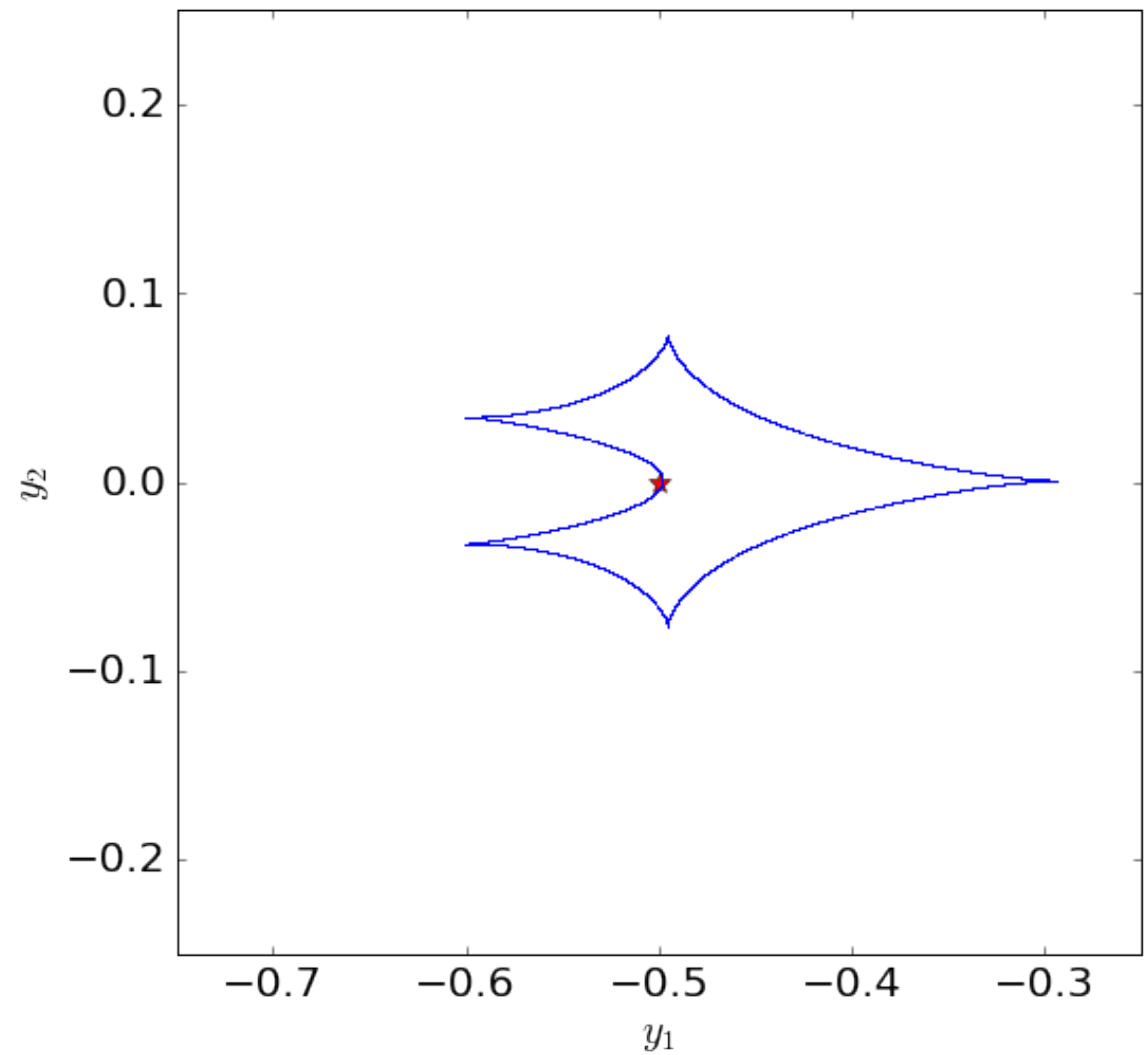


PLANETARY CAUSTICS IN INTERMEDIATE TOPOLOGIES





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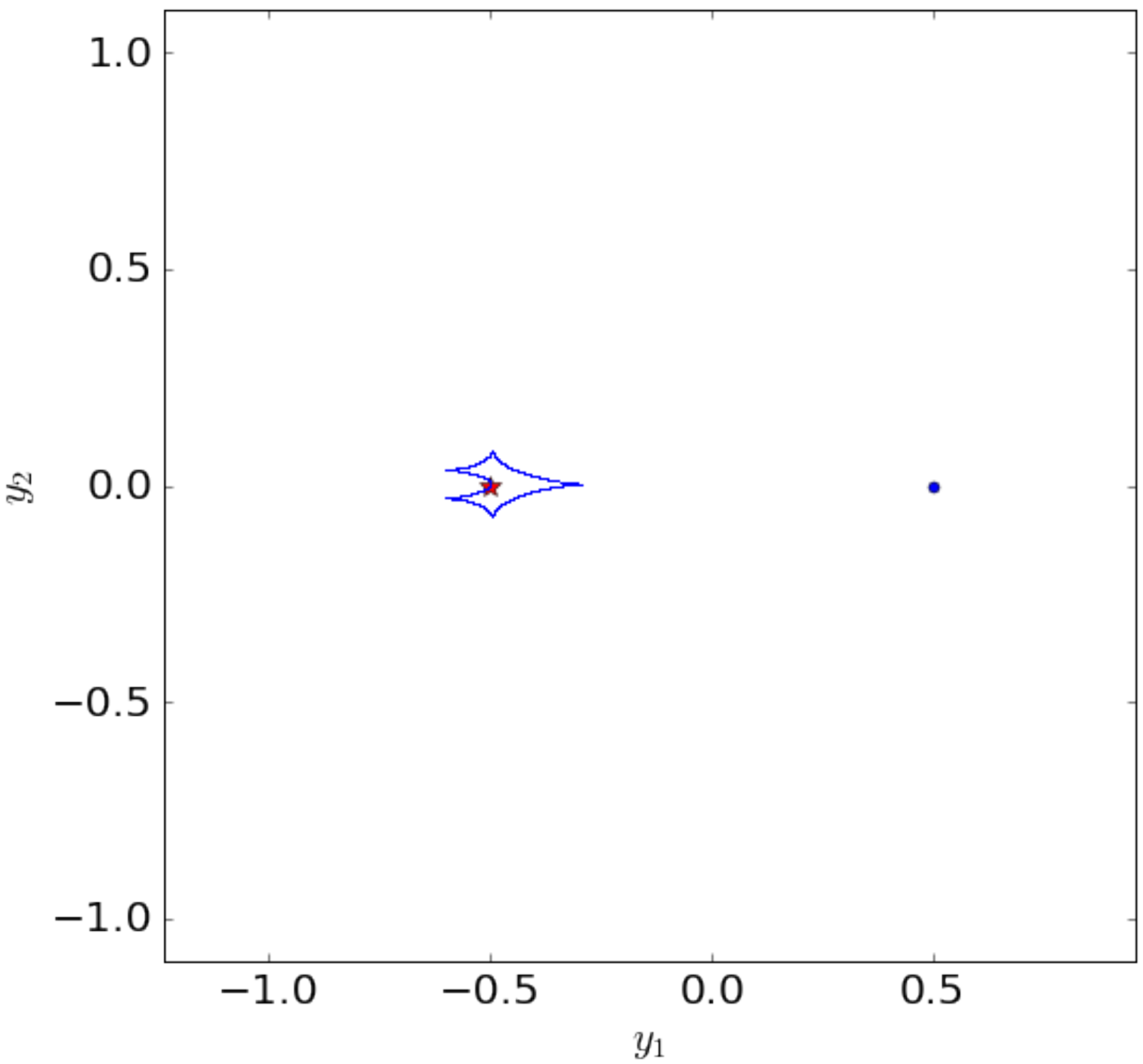

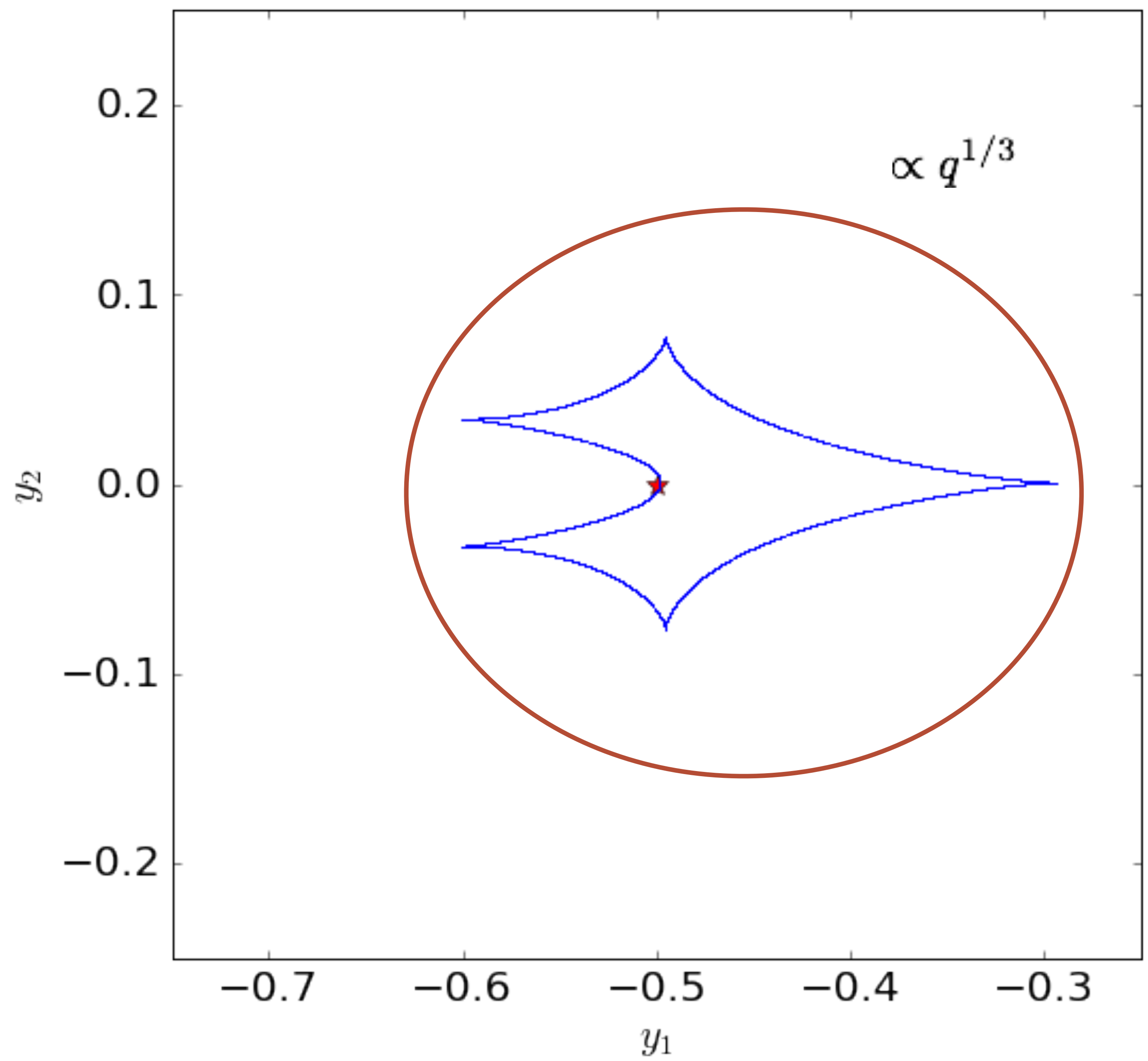

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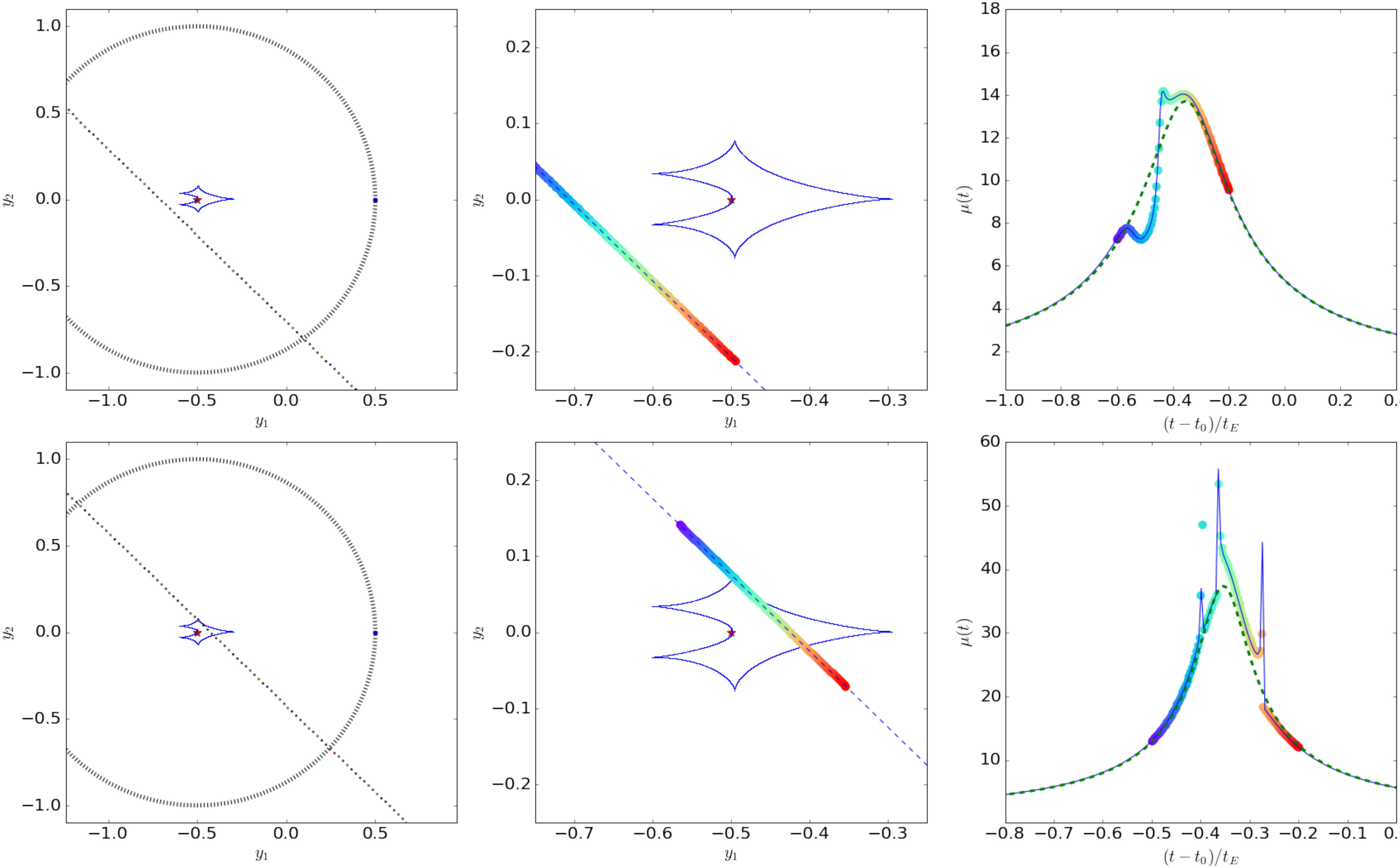

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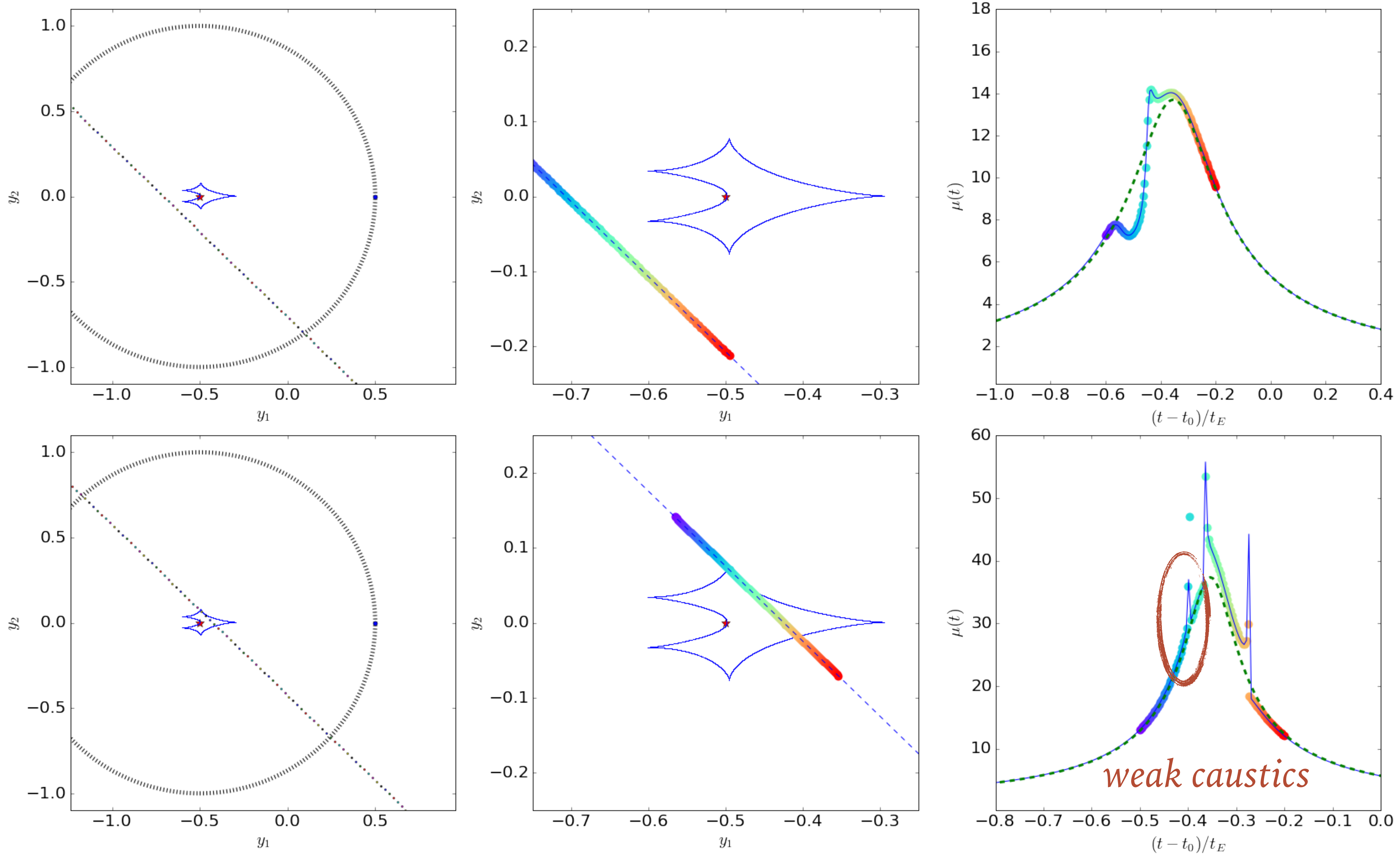

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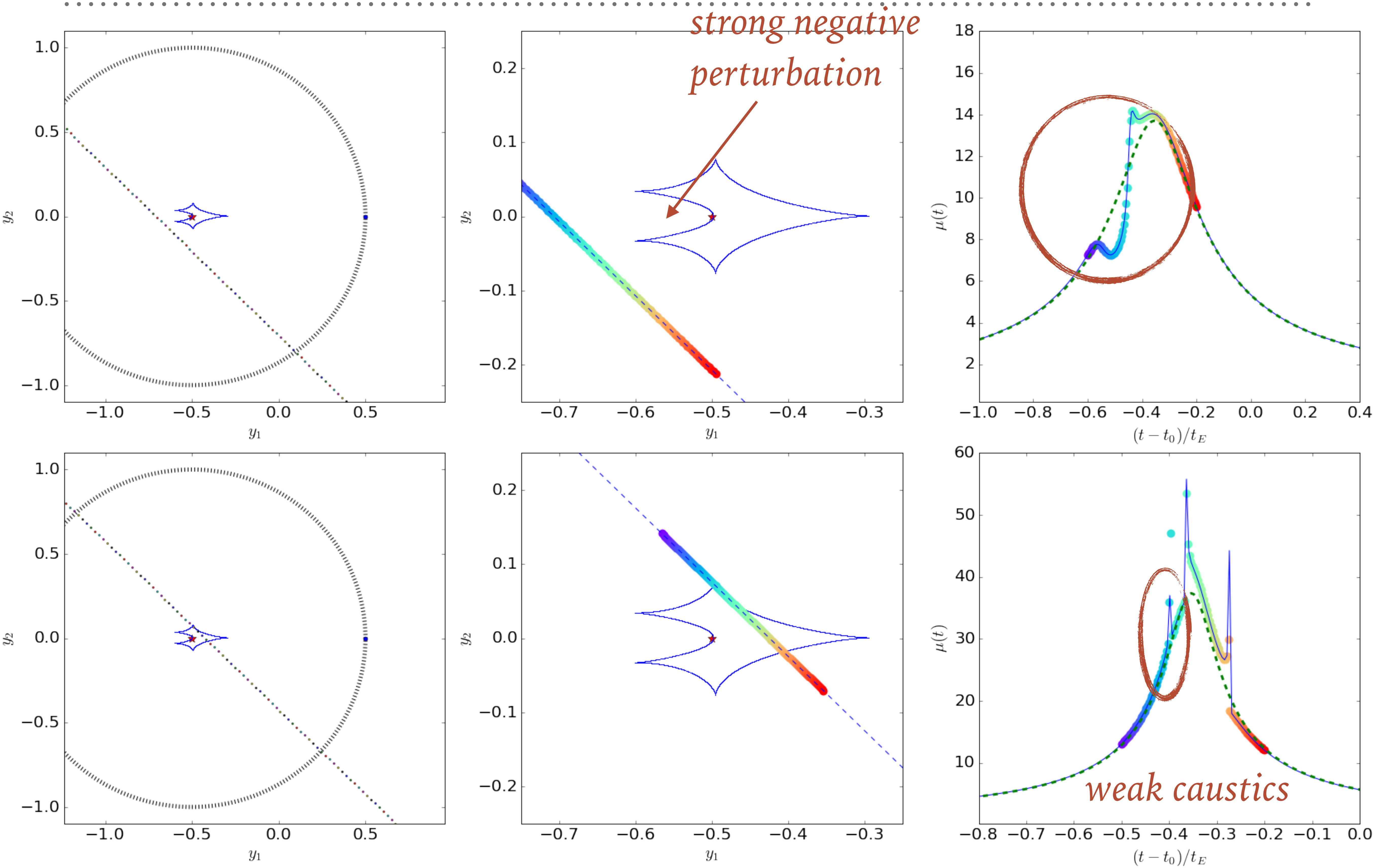

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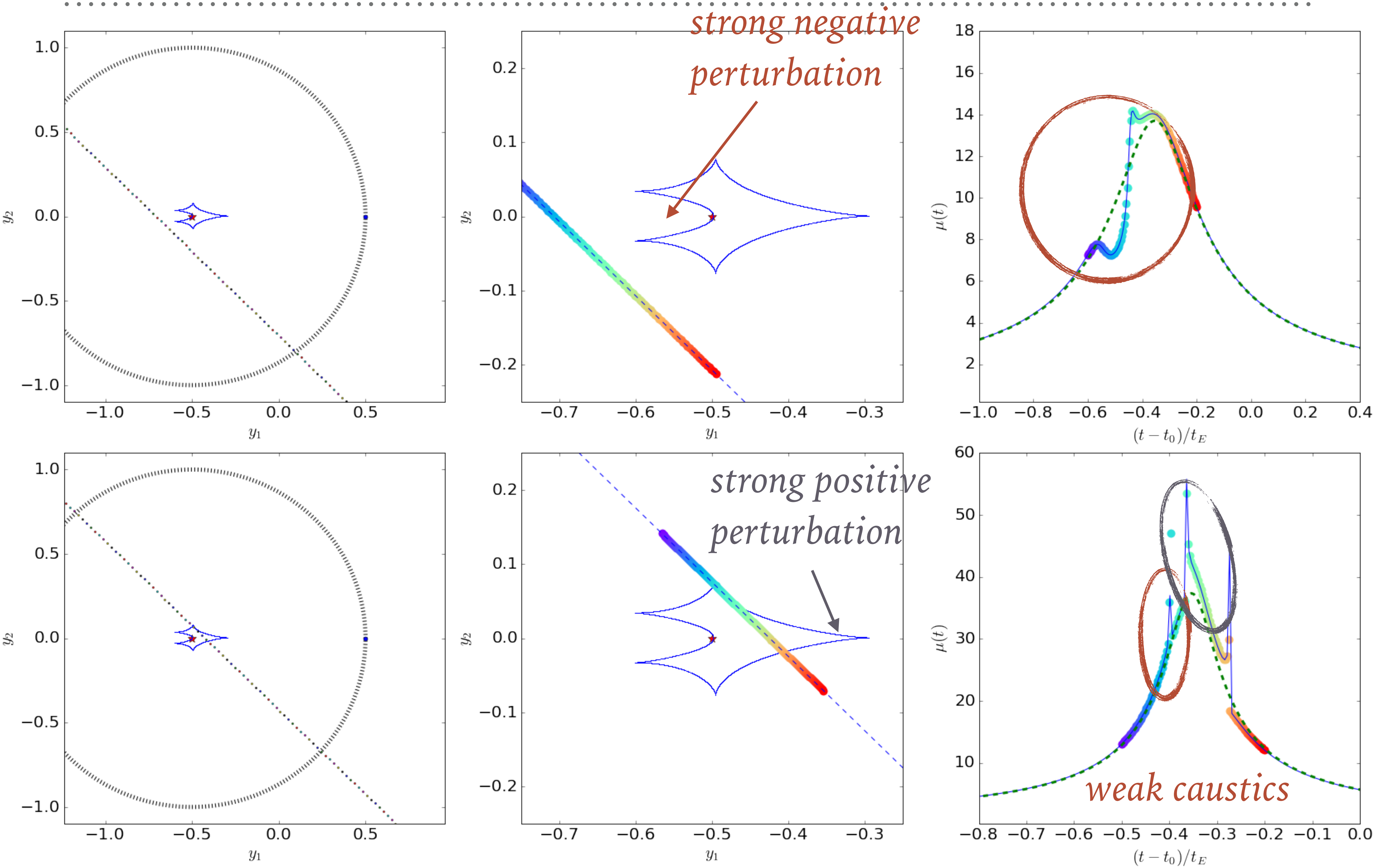


TO SUMMARIZE

- 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.

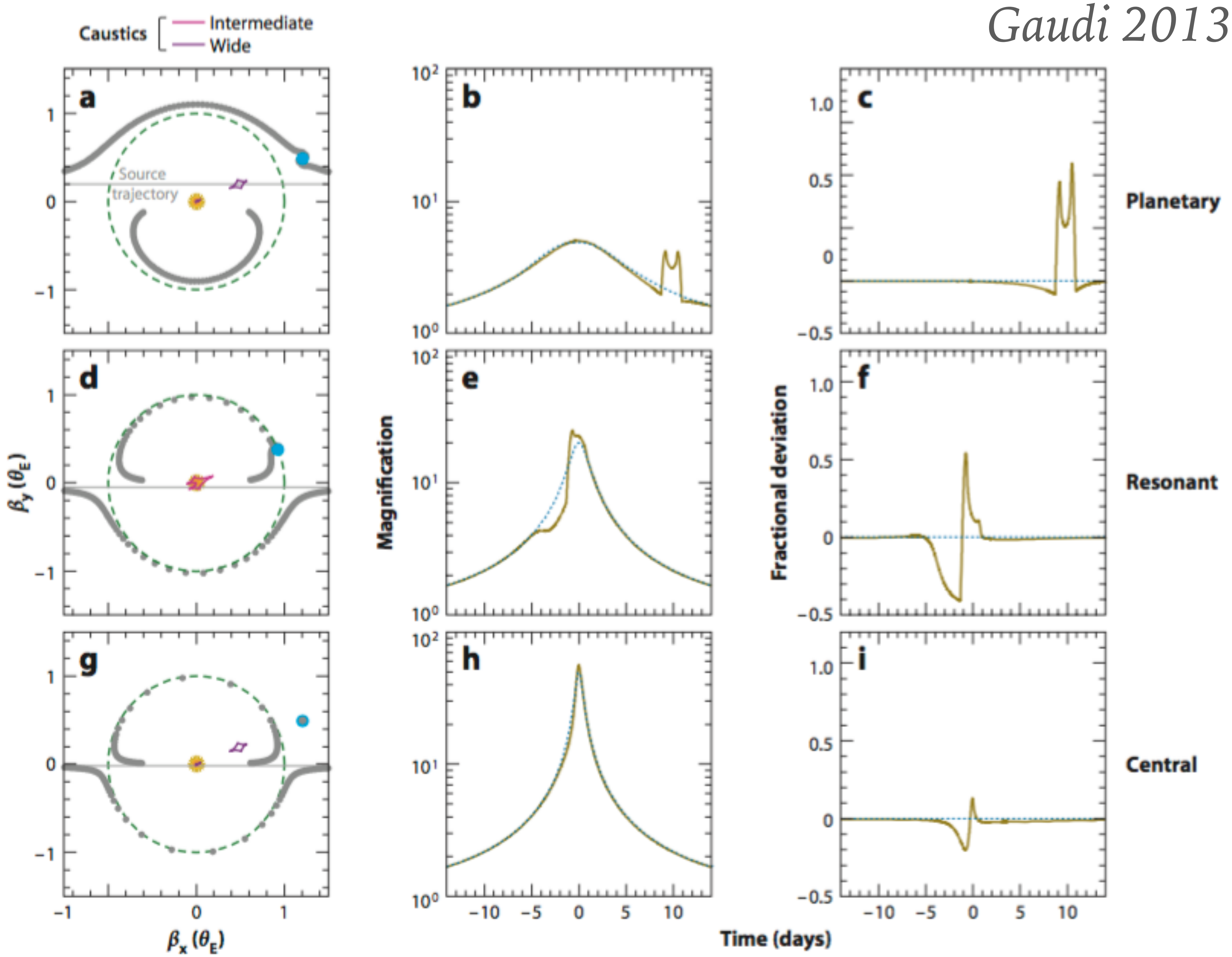
OF COURSE…

- there is also an astrometric perturbation…

The planet can be detected when it perturbs one of the two images of the source!

This tells us that microlensing is sensitive to planets at distances of the order of the star Einstein radius.

Gaudi 2013



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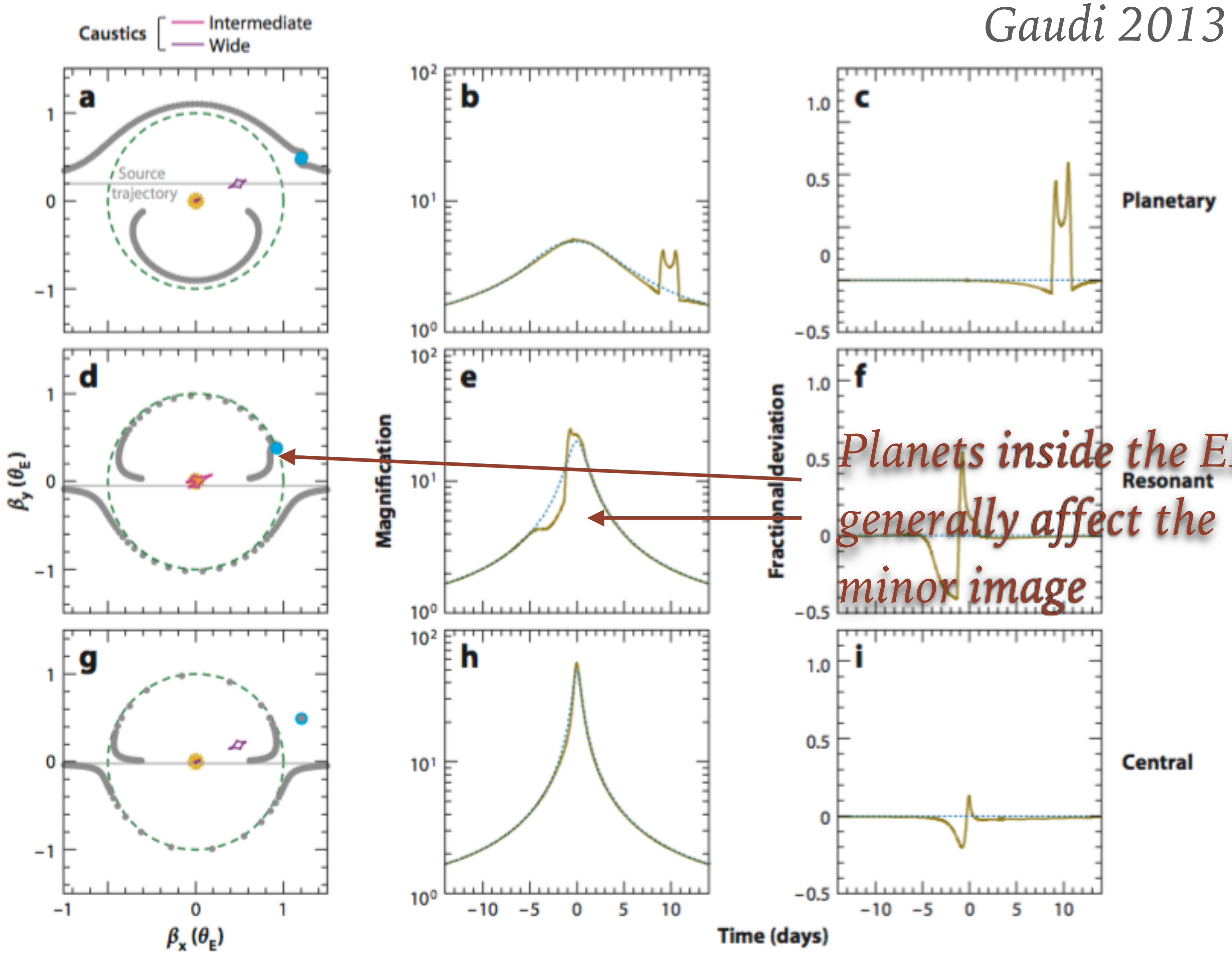

Planets inside the ER generally affect the minor image

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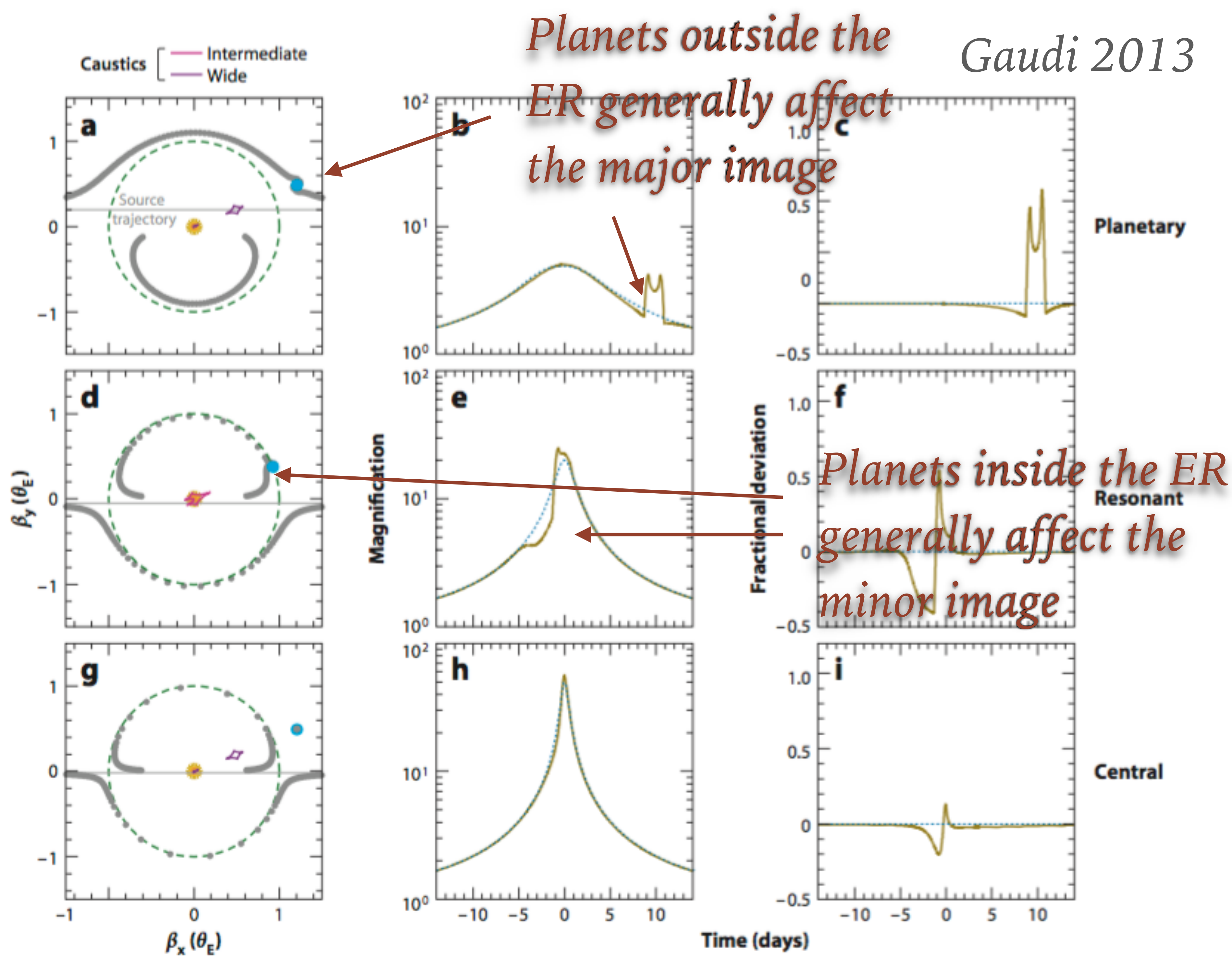

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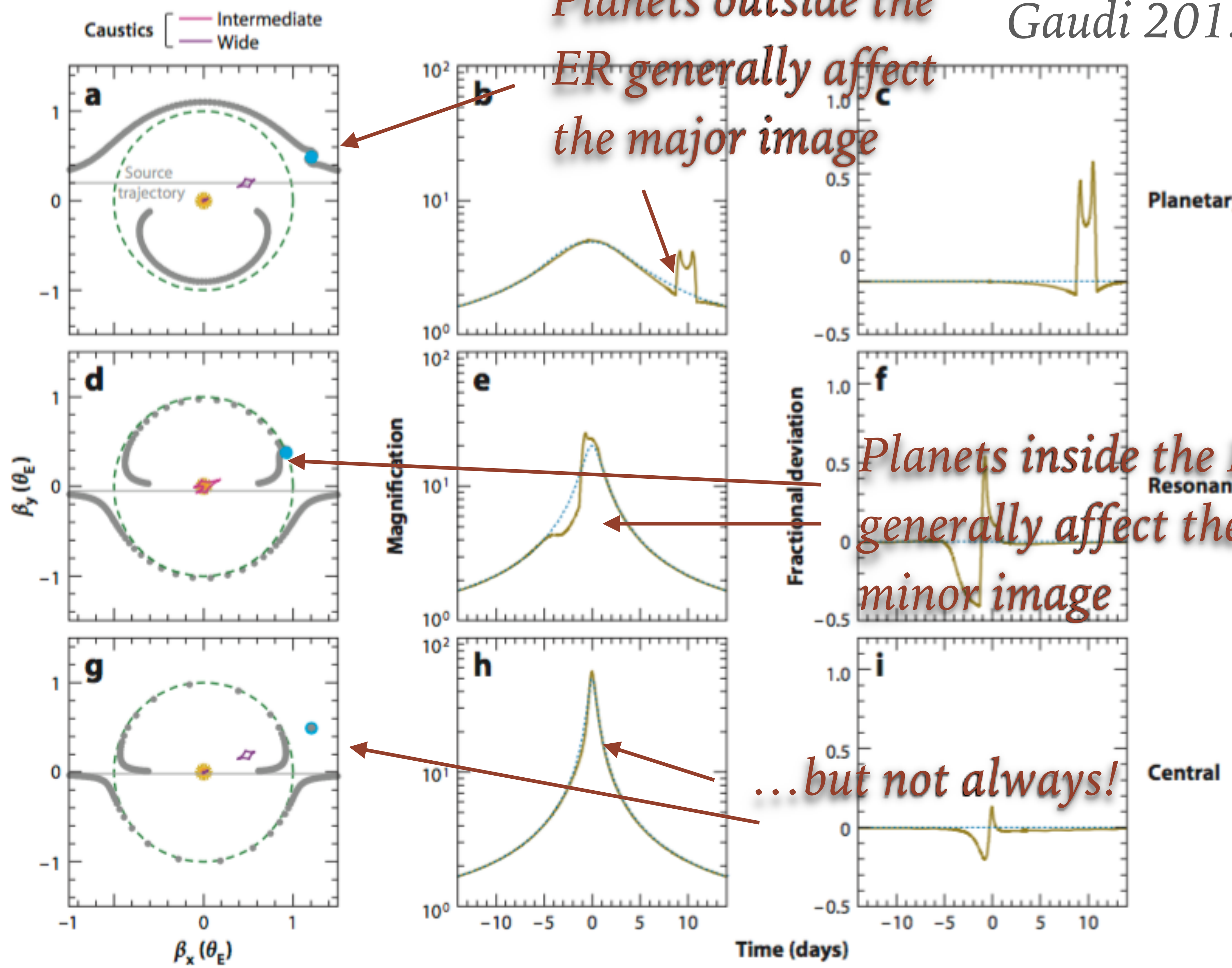
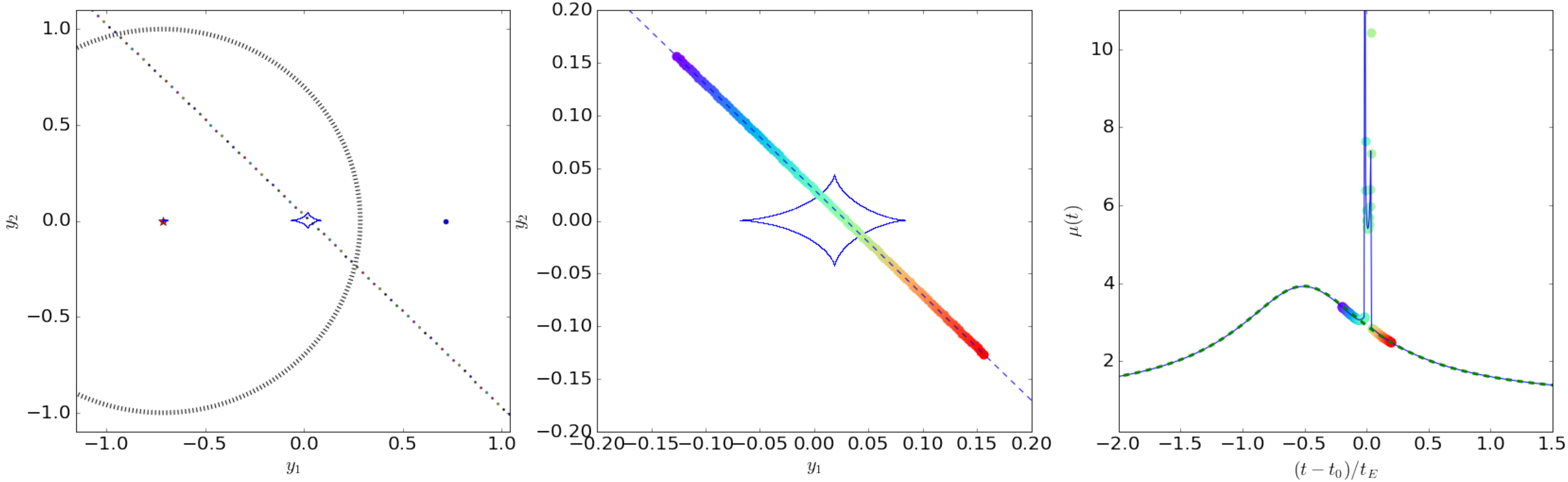


Planets outside the ER generally affect the major image

Planets inside the ER generally affect the minor image

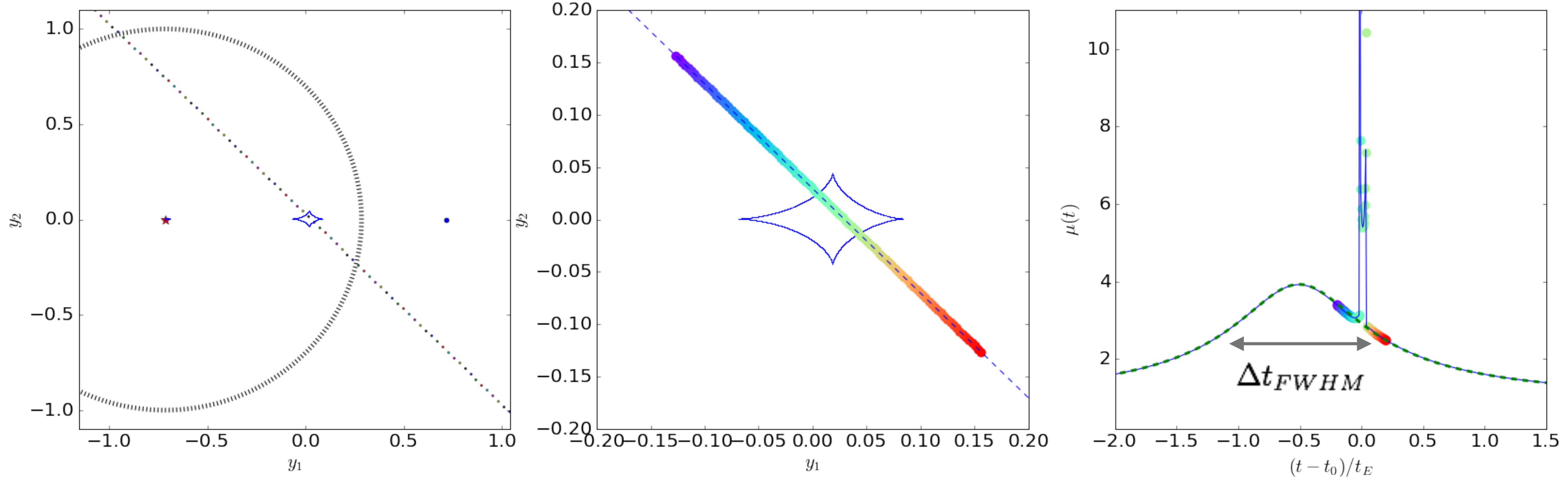
…but not always!

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



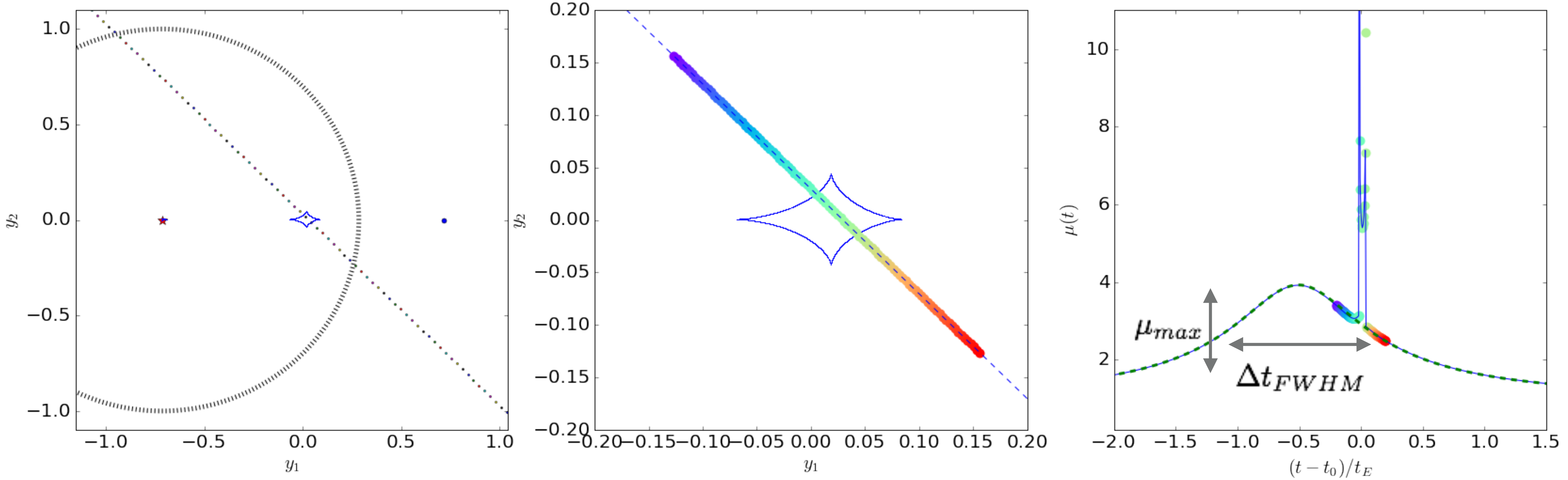
- primary event:
- planetary perturbation:

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



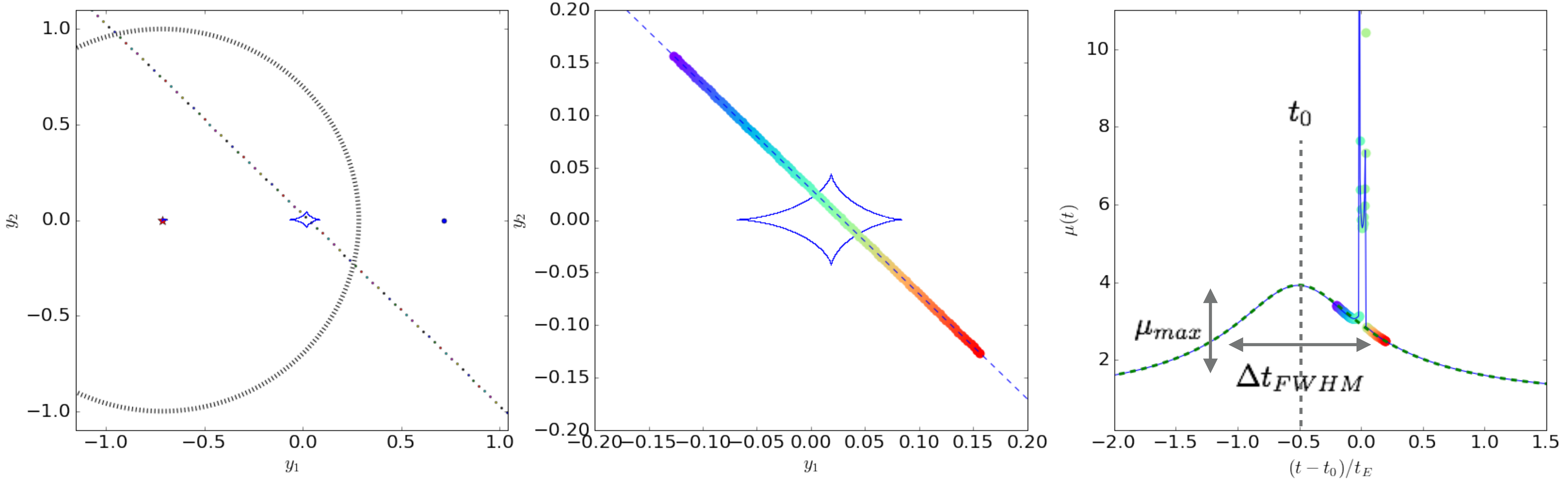
- primary event: Δt_{FWHM}
- planetary perturbation:

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



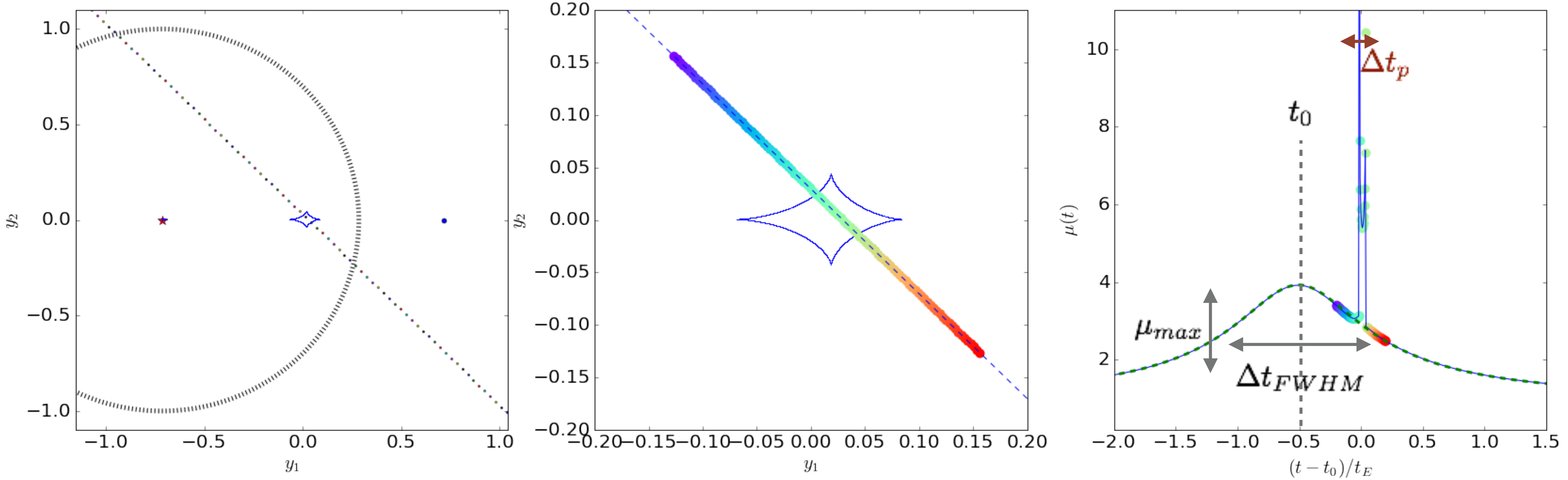
- primary event: Δt_{FWHM} μ_{max}
- planetary perturbation:

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



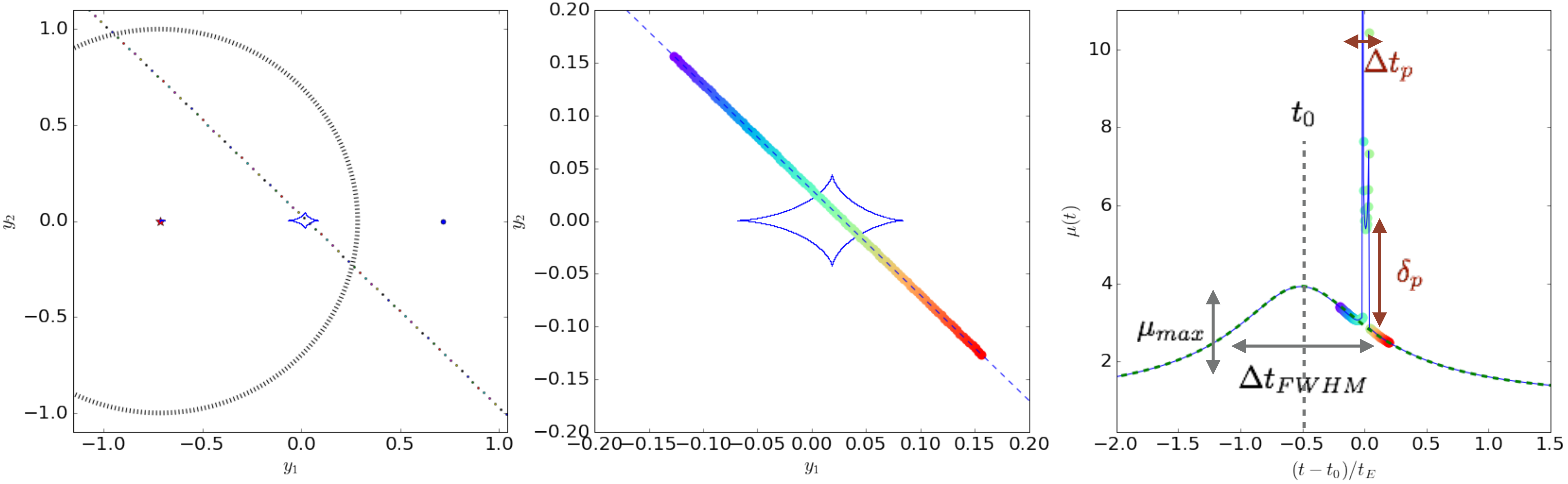
- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation:

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



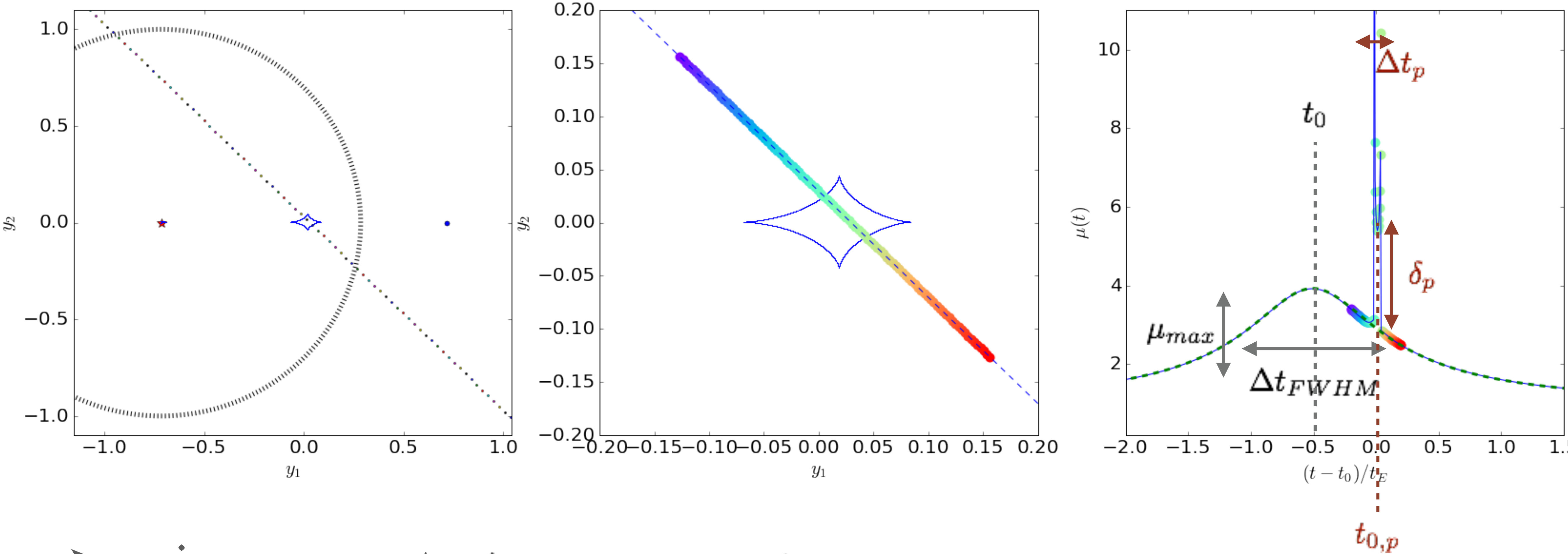
- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



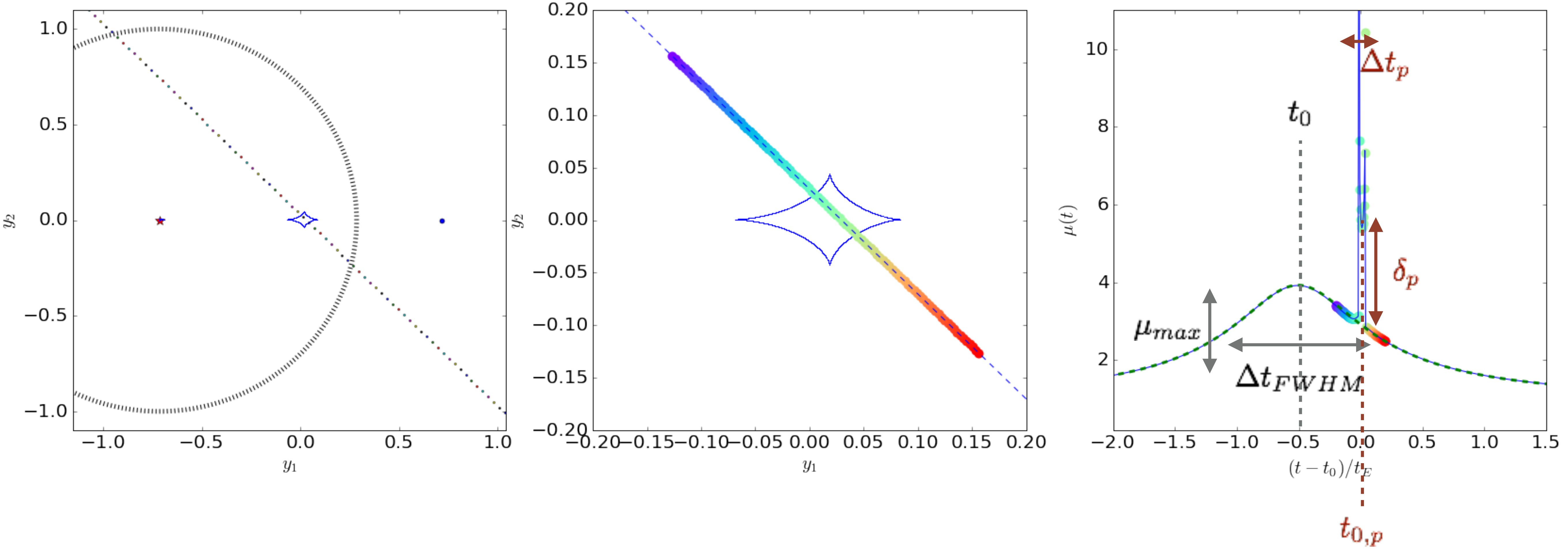
- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p δ_p

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



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

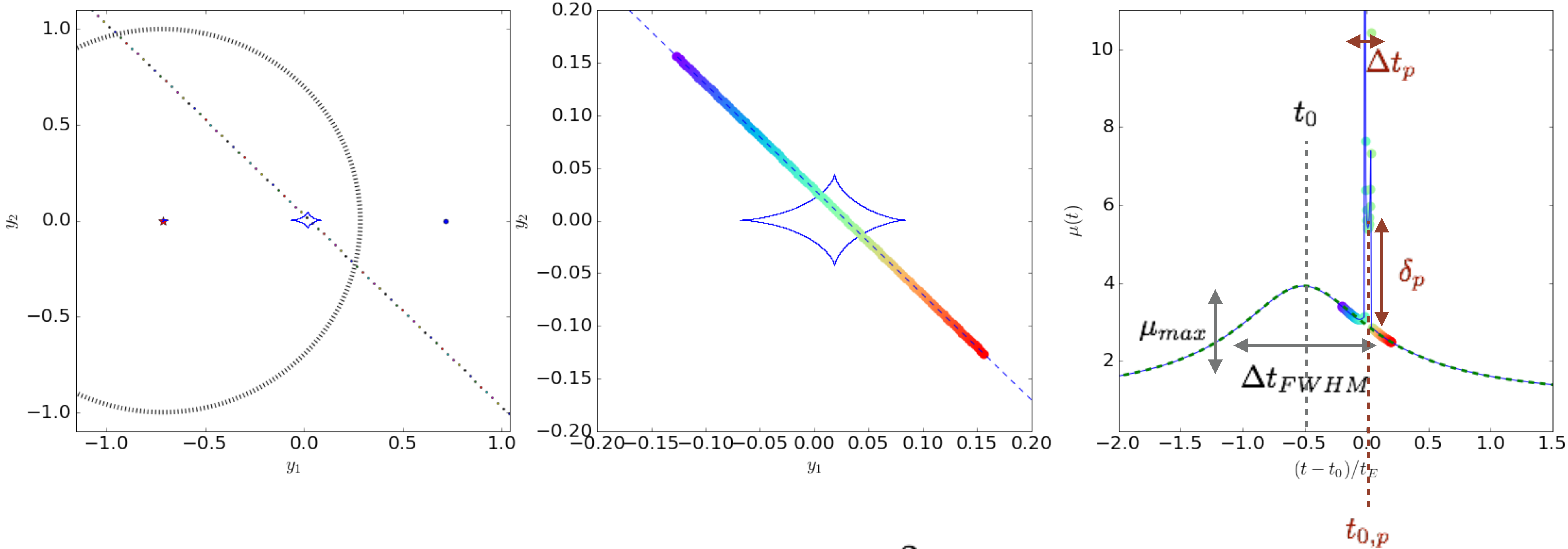
PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



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

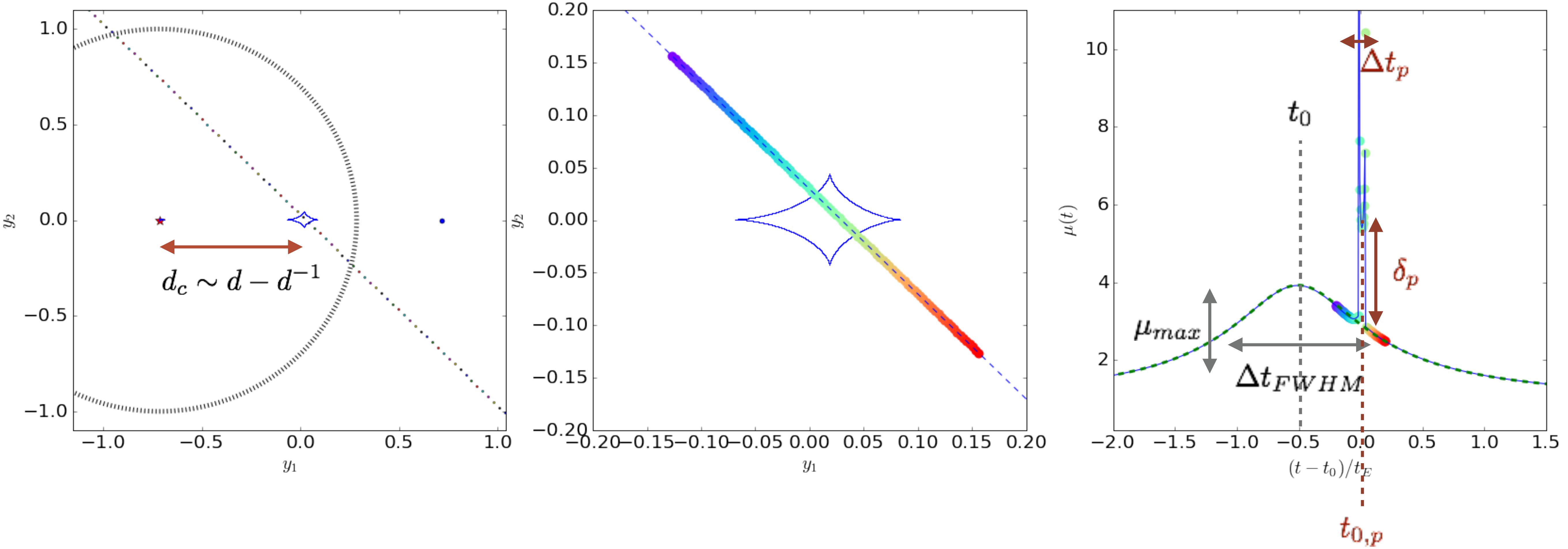
$$\Rightarrow \quad y_0 \quad t_E$$

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



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

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES

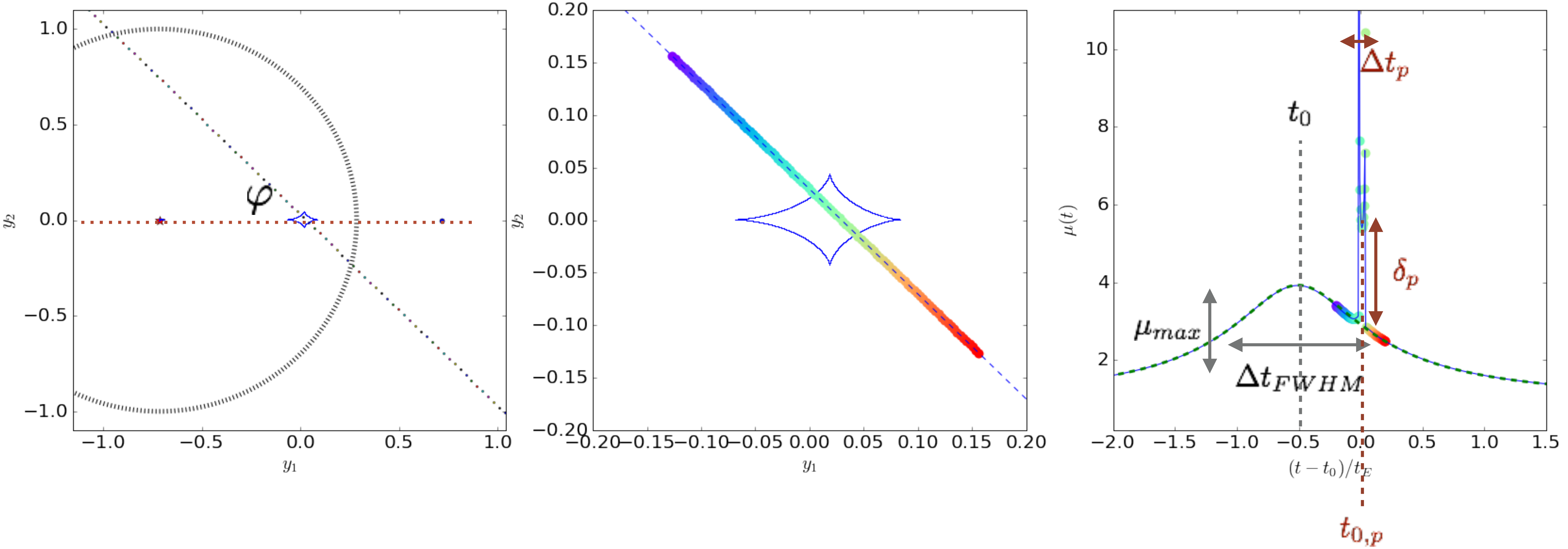


$$\delta_p,\ t_{0,p} \Rightarrow\ y_p = \sqrt{y_0^2 + \left(\frac{t_{0,p} - t_0}{t_E}\right)^2}$$

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

up to the degeneracy in d

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



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

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.

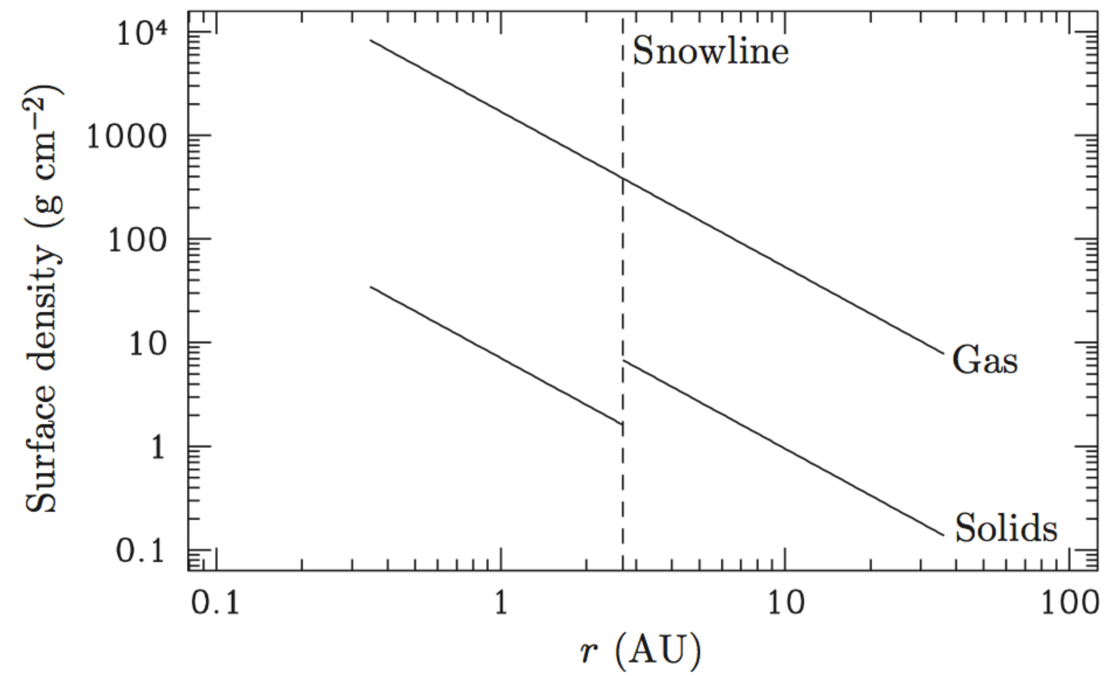
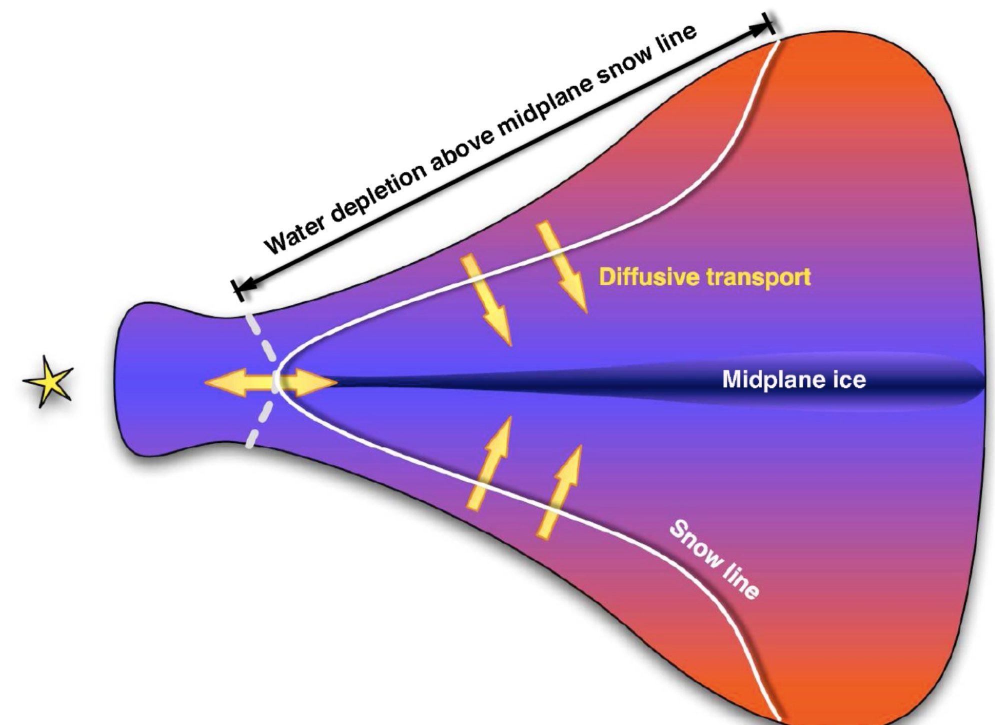
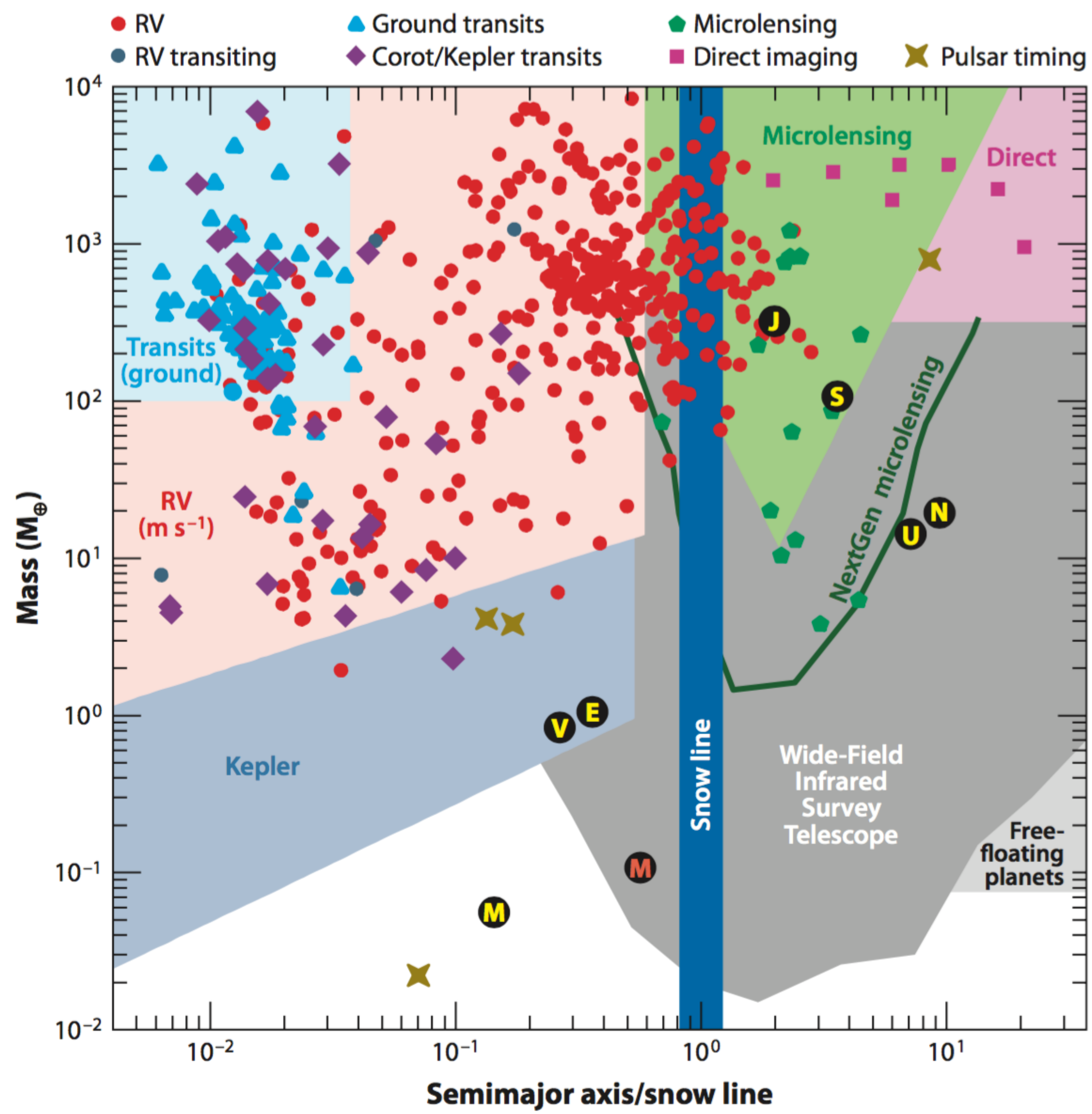


Fig. 1.1. The surface density in gas (upper line) and solids (lower broken line) as a function of radius in Hayashi's minimum mass Solar Nebula. The dashed vertical line denotes the location of the snowline.



ADVANTAGES OF USING MICROLENSING FOR PLANET SEARCHES

- ~40 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)

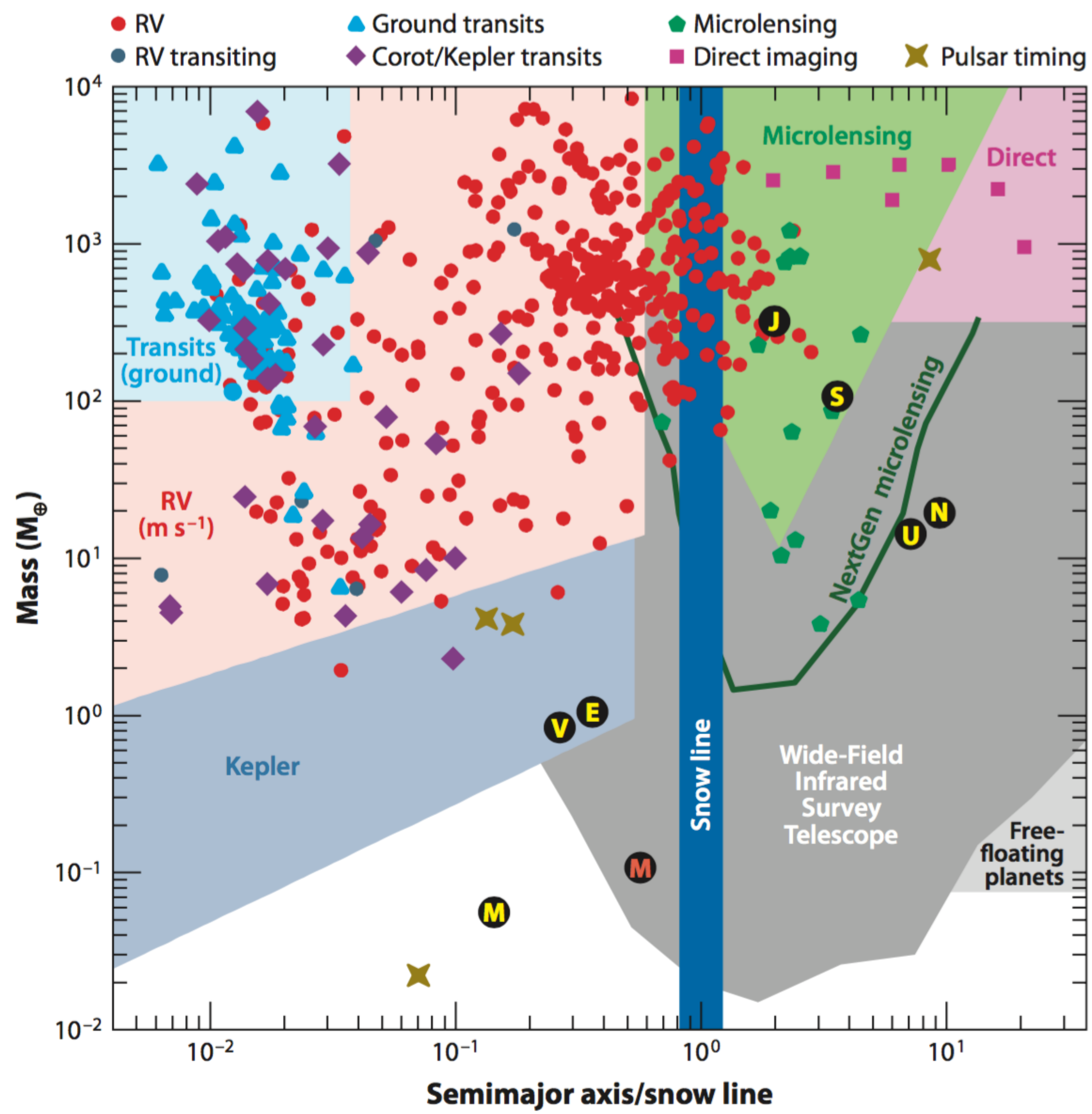


OTHER ADVANTAGES…

- 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 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



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

LIST OF MICROLENSING PLANETS (BEFORE 2013)

Table 3
List of All Published Microlensing Planets and How We Classify Them

Name	$A_{\max}$	$q(10^{-4})$	Caustic. Type (s)	Caustic Crossing?	References	Comment
OGLE-2009-BLG-151b/ MOA-2009-232b	5	4190	R	Yes	Choi et al. (2013)	A brown dwarf, but listed as planet at http://exoplanet.eu
OGLE-2011-BLG-0420b	40	3770	C	Yes	Choi et al. (2013)	A brown dwarf, but listed as planet at http://exoplanet.eu
OGLE-2012-BLG-358Lb	10	800	P	Yes	Han et al. (2013b)	The host star has mass 0.02 $M_{\odot}$
MOA-2011-BLG-322Lb	21	280	C	No	Shvartzvald et al. (2014)	
MOA-2009-BLG-387Lb	11	132	R	Yes	Batista et al. (2011)	
OGLE-2005-BLG-071Lb	42	71	C	No	Udalski et al. (2005)	
MOA-2008-BLG-379Lb	167	68.5	R	Yes	Suzuki et al. (2014)	
OGLE-2012-BLG-406Lb	2	62.6	P	Yes	Poleski et al. (2014)	
MOA-2011-BLG-293Lb	286	53	C	Yes	Yee et al. (2012)	
MOA-bin-1b	1.1	49	P	Yes	Bennett et al. (2012)	The planet has a large separation from the star
OGLE-2003-BLG-235Lb	8	39	R	Yes	Bond et al. (2004)	
MOA-2007-BLG-400Lb	628	25	C	Yes	Dong et al. (2009b)	Same for close/wide solutions
MOA-2010-BLG-477Lb	294	21.81	R	Yes	Bachelet et al. (2012)	
OGLE-2011-BLG-251Lb	18	19.2	C	No	Kains et al. (2013)	Four solutions, D is favored
OGLE-2006-BLG-109Lb	289	13.5	R	Yes	Gaudi et al. (2008)	
OGLE-2012-BLG-0026Lc	109	7.84	R	Yes	Han et al. (2013a)	Four solutions, D is favored
OGLE-2006-BLG-109Lc	289	4.86	C	Yes	Gaudi et al. (2008)	
MOA-2011-BLG-262Lb	80	4.7	C	Yes	Bennett et al. (2014)	An alternate model leads to a host mass of $\sim 4 M_{\mathrm{J}}$
MOA-2009-BLG-319Lb	167	3.95	R	Yes	Miyake et al. (2011)	
MOA-2008-BLG-310Lb	400	3.3	C	Yes	Janczak et al. (2010)	
MOA-2010-BLG-328Lb	14	2.6	P	Yes	Furusawa et al. (2013)	
OGLE-2012-BLG-0026Lb	109	1.30	C	Yes	Han et al. (2013a)	Four solutions, D is favored
OGLE-2007-BLG-368Lb	13	0.95	P	Yes	Sumi et al. (2010)	
OGLE-2005-BLG-169Lb	800	0.9	R	Yes	Gould et al. (2006)	
OGLE-2005-BLG-390Lb	3	0.76	P	Yes	Beaulieu et al. (2006)	
MOA-2009-BLG-266Lb	8	0.563	P	Yes	Muraki et al. (2011)	
MOA-2007-BLG-192Lb	~ 270	...	...	...	Bennett et al. (2008)	Too few data points to constrain the planet

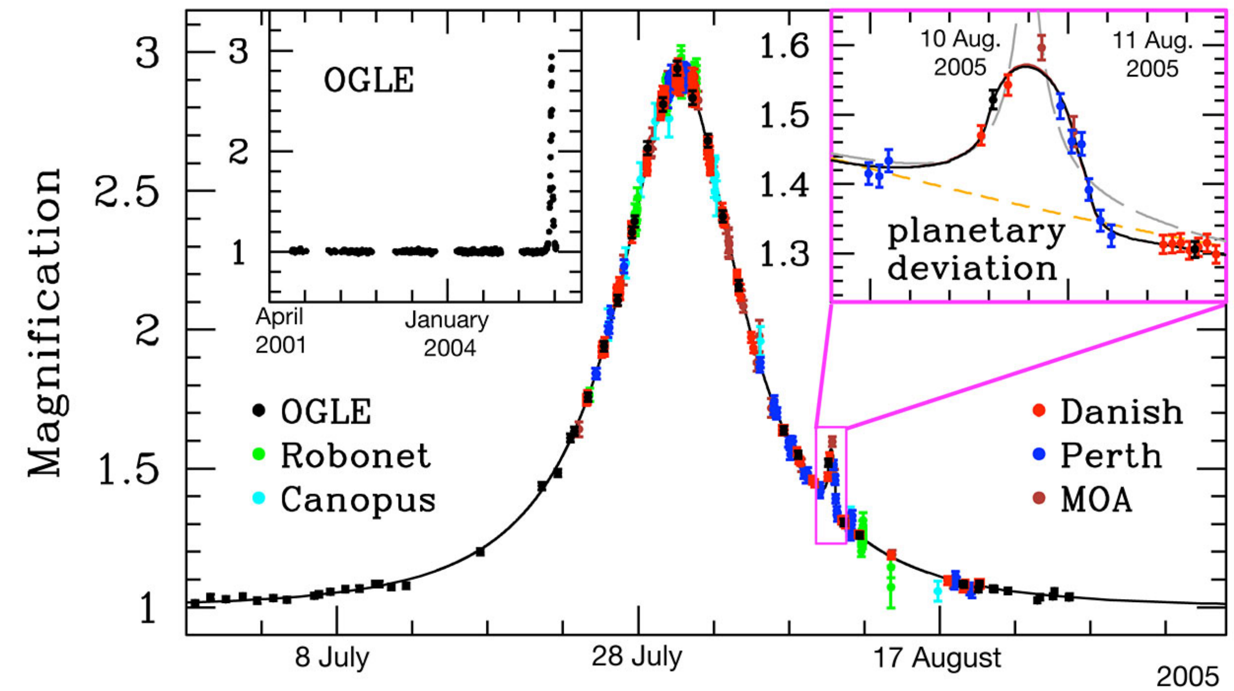
CURRENT PLANET SEARCHES

- 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

INTERESTING CASES: COLD SUPER-EARTHS

Beaulieu et al. 2005

- OGLE-2005-BLG-390Lb: the first icy super-earth just beyond the snow line discovered via microlensing



$$M_\star = 0.22^{+0.21}_{-0.11} M_\odot$$

$$q \sim 8 \times 10^{-5} \quad M_p = 5.5^{+5.5}_{-2.7} M_\oplus$$

$$a = 2.6^{+1.5}_{-0.6} AU$$

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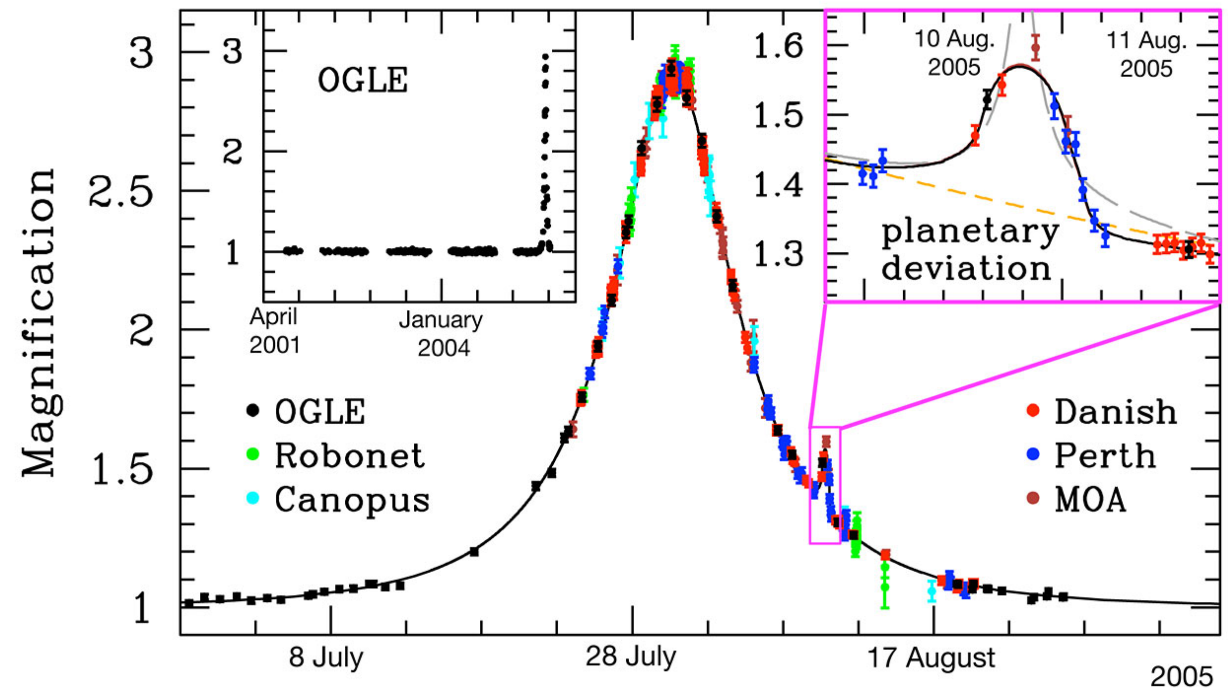
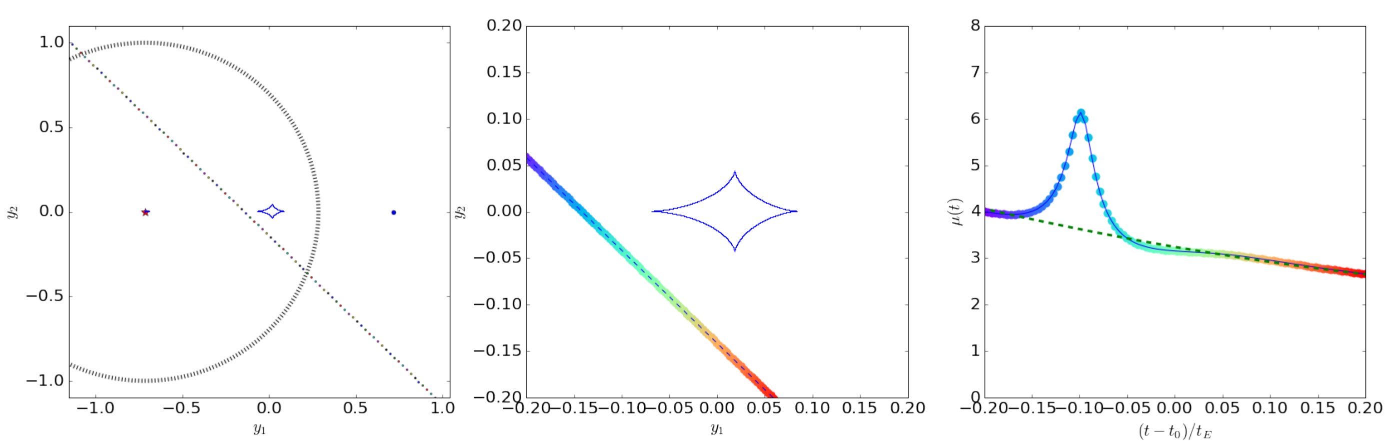




$$M_\star = 0.22^{+0.21}_{-0.11} M_\odot$$

$$q \sim 8 \times 10^{-5} \quad M_p = 5.5^{+5.5}_{-2.7} M_\oplus$$

$$a = 2.6^{+1.5}_{-0.6} AU$$

INTERESTING CASES: COLD SUPER-EARTHS

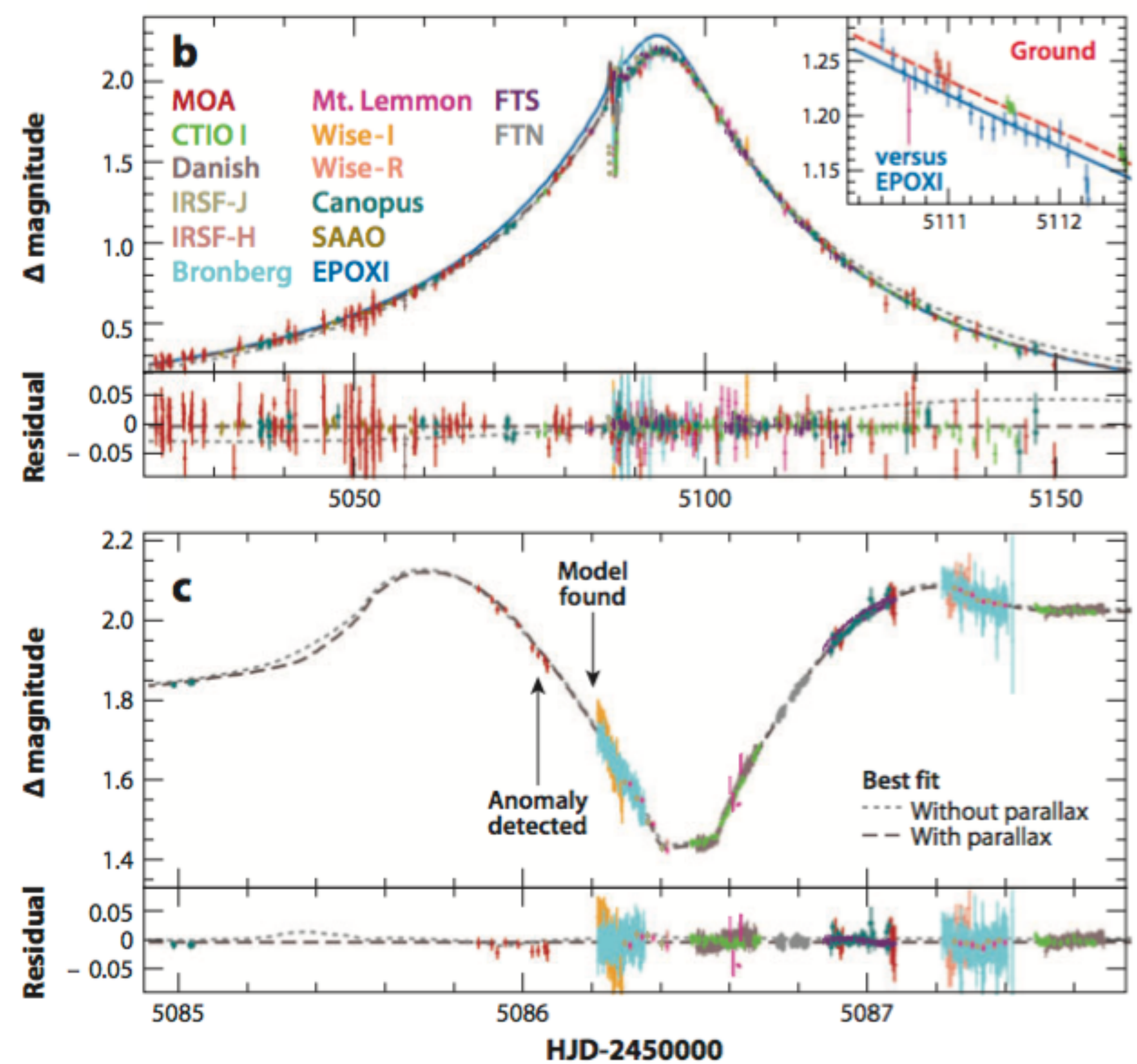
- OGLE-2005-BLG-390Lb: the first icy super-earth just beyond the snow line discovered via microlensing

- other cases: MOA-2007-BLG-192Lb and, in particular, MOA-2009-BLG-266Lb

$$M_\star = 0.56^{+0.09}_{-0.09} M_\odot$$

$$M_p = 10.4^{+1.7}_{-1.7} M_\oplus$$

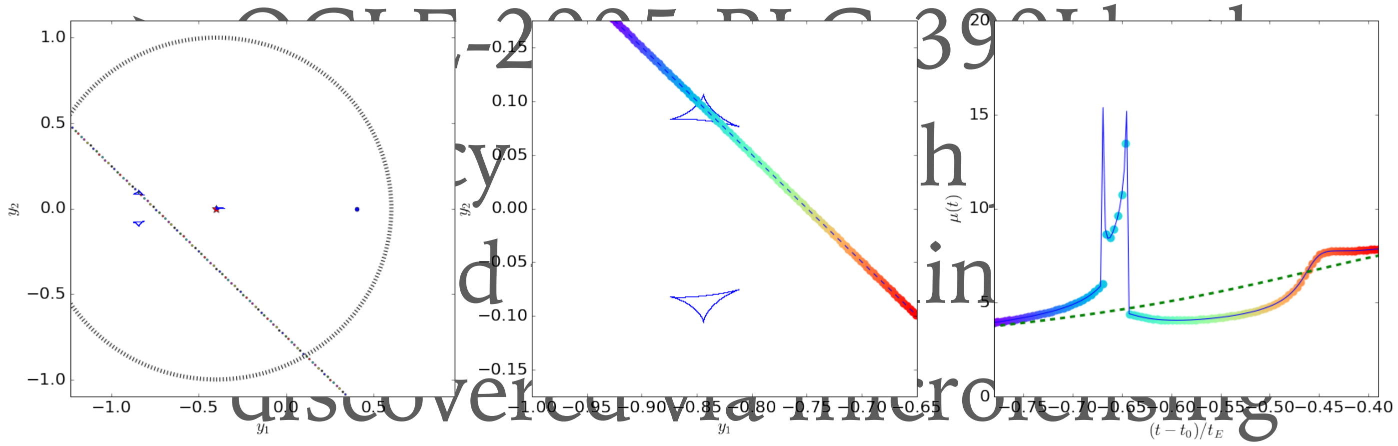
$$q = 5.63 \pm 0.25 \times 10^{-4}$$



Mouraki et al. 2011

$$a = 3.2^{+1.9}_{-0.6} AU$$

INTERESTING CASES: COLD SUPER-EARTHS

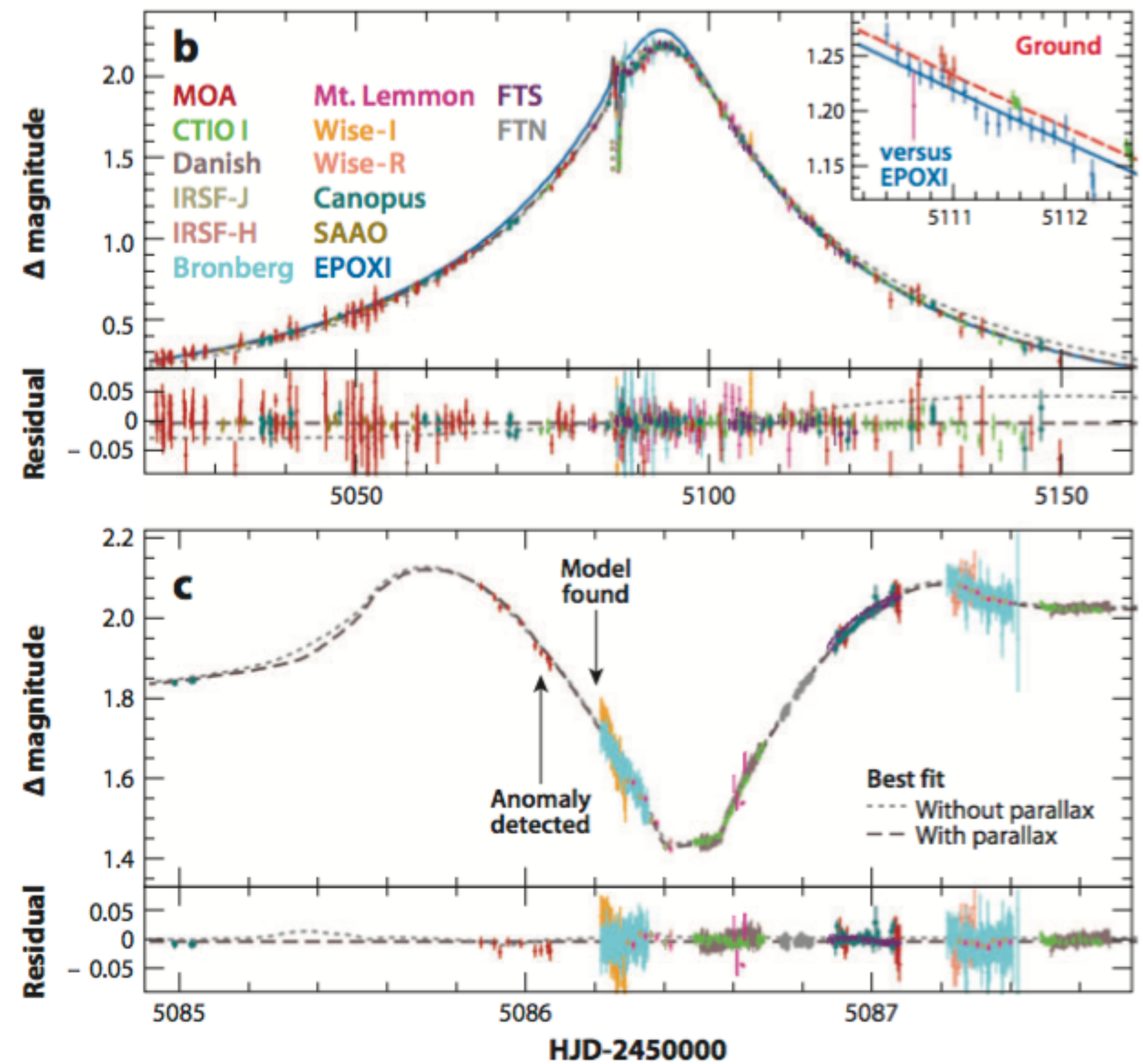


- other cases: MOA-2007-BLG-192Lb and, in particular, MOA-2009-BLG-266Lb

$$M_\star = 0.56^{+0.09}_{-0.09} M_\odot$$

$$M_p = 10.4^{+1.7}_{-1.7} M_\oplus$$

$$q = 5.63 \pm 0.25 \times 10^{-4}$$

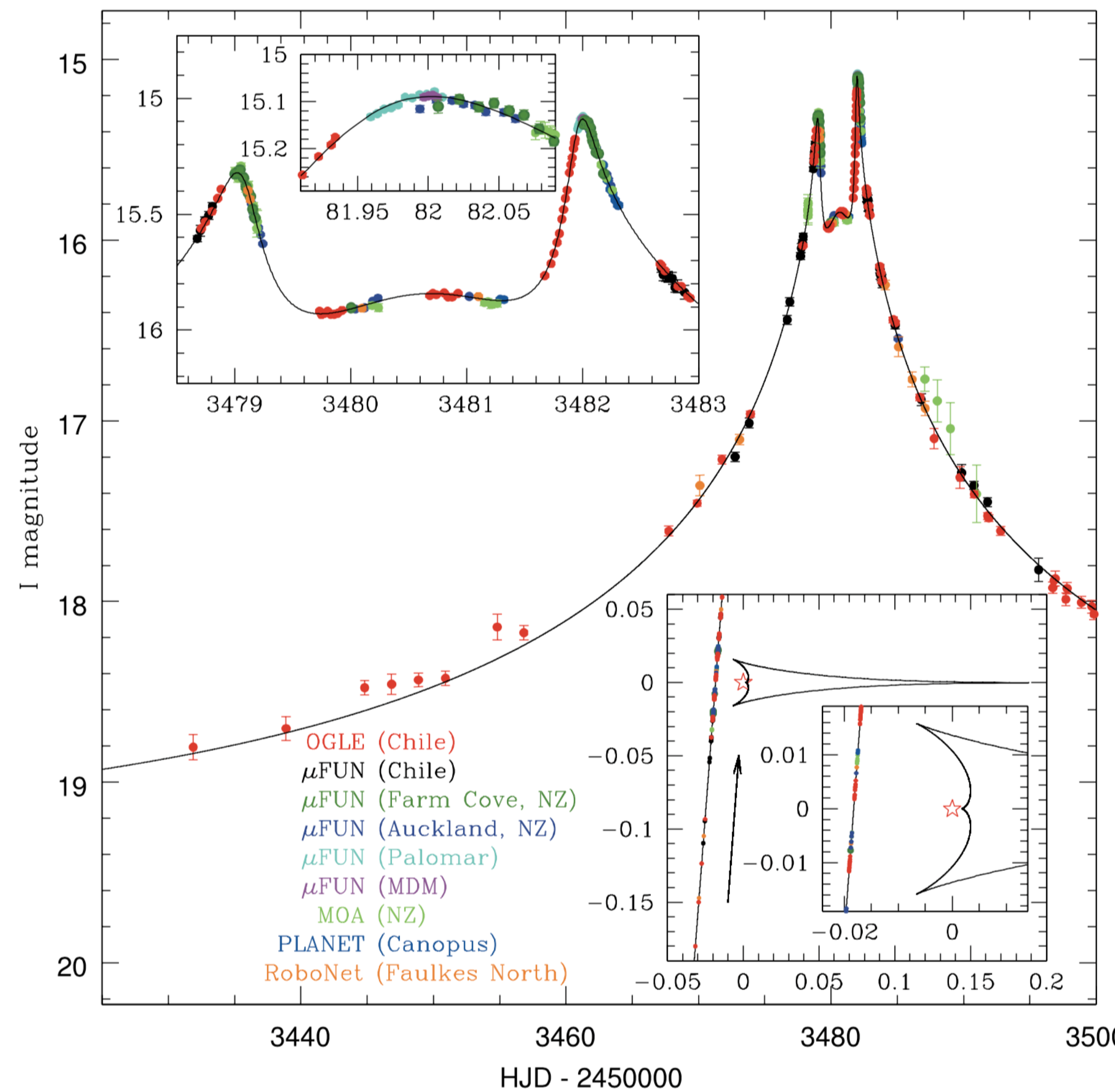


Mouraki et al. 2011

$$a = 3.2^{+1.9}_{-0.6} AU$$

INTERESTING CASES: MASSIVE COMPANIONS TO M-DWARFS

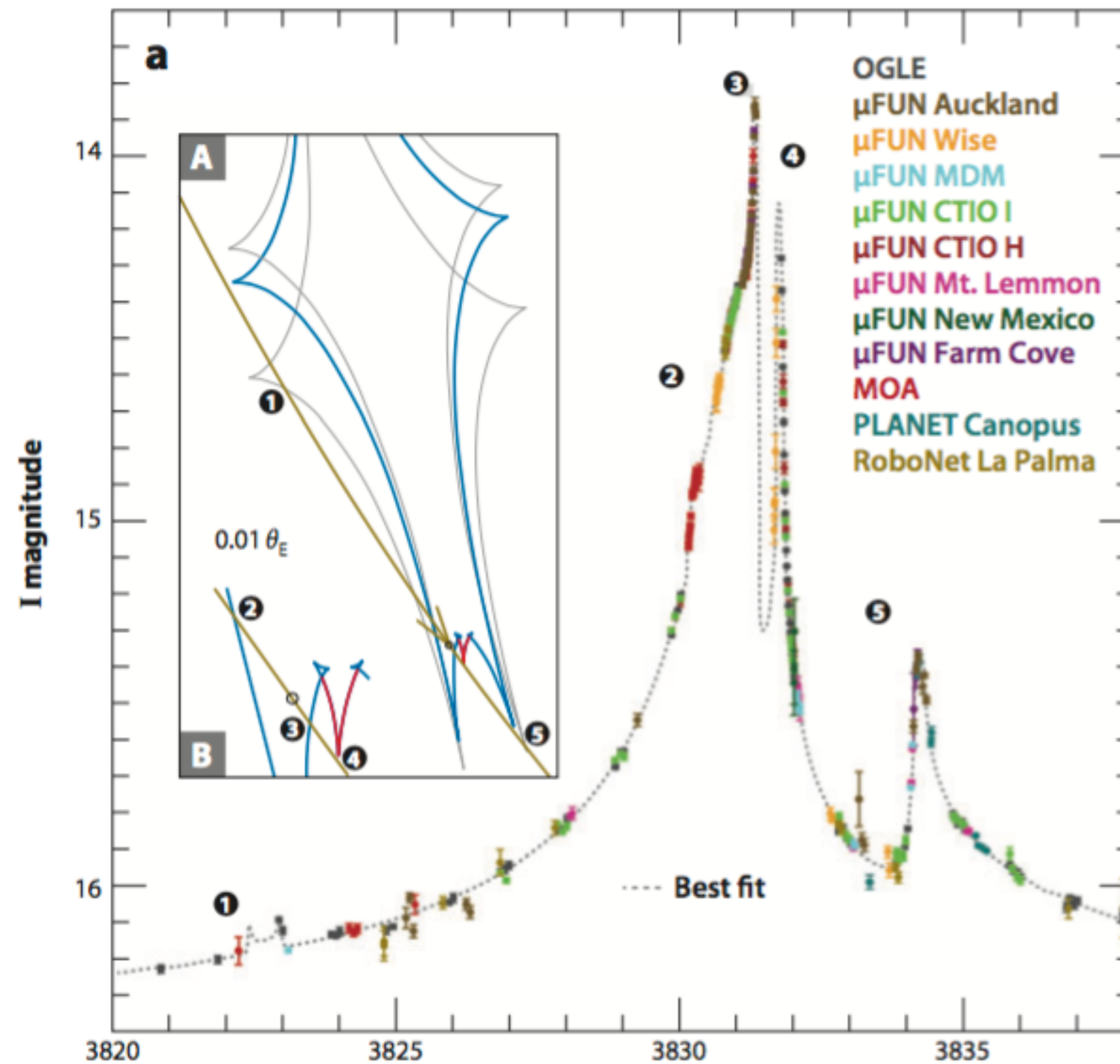
- OGLE-2005-BLG-071Lb: a Jovian-mass planet around a relatively small star
- Other cases: MOA-2009-BLG-387Lb, MOA-2011-BLG-293Lb
- At 2013: 3 out of 14 planets are Jovian companions of M-dwarf stars.
- they seem common, contrary to expectations



Udalski et al. (2005)

INTERESTING CASES: MULTIPLE PLANETS AND EVOLVING CAUSTIC

- OGLE-2006-BLG-109Lb,c: the first detection of a multiple planet system via microlensing
- M-dwarf star host star
- A Saturn-like planet generating a resonant caustic
- A Jupiter-like planet generating a small perturbation (central caustic)
- **There are indications for an evolution of the caustic of the Saturn-like planet due to its orbital motion**



Gaudi et al. (2008), Bennet et al. (2010)

SOME MORE RESULTS

- relatively uniform distribution of masses, although detection efficiency decreases with q. This suggests that there are many small planets!
- 40% of stars are likely to host cold super-earths
- high frequency of saturn-like planets
- but not all planetary systems host giant planets, otherwise we would have detected more multi planet systems
- Cassan et al. (2012) derived a power-law mass function of planets

$$\frac{d^2 N_{\mathrm{pl}}}{d \log a \; d \log m_{\mathrm{p}}} = 10^{-0.62\pm0.22} \left(\frac{m_{\mathrm{p}}}{M_{\mathrm{Saturn}}} \right)^{-0.73\pm0.17}$$

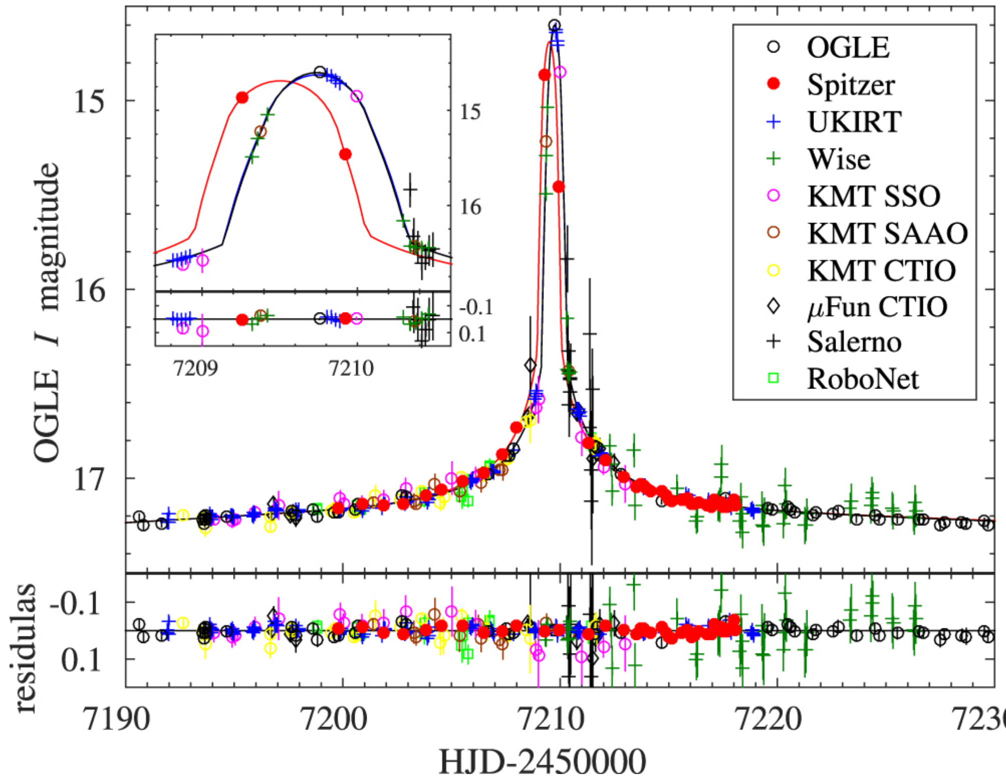
$$\langle N_{\mathrm{pl}} \rangle = 1.6^{+0.7}_{-0.9}$$

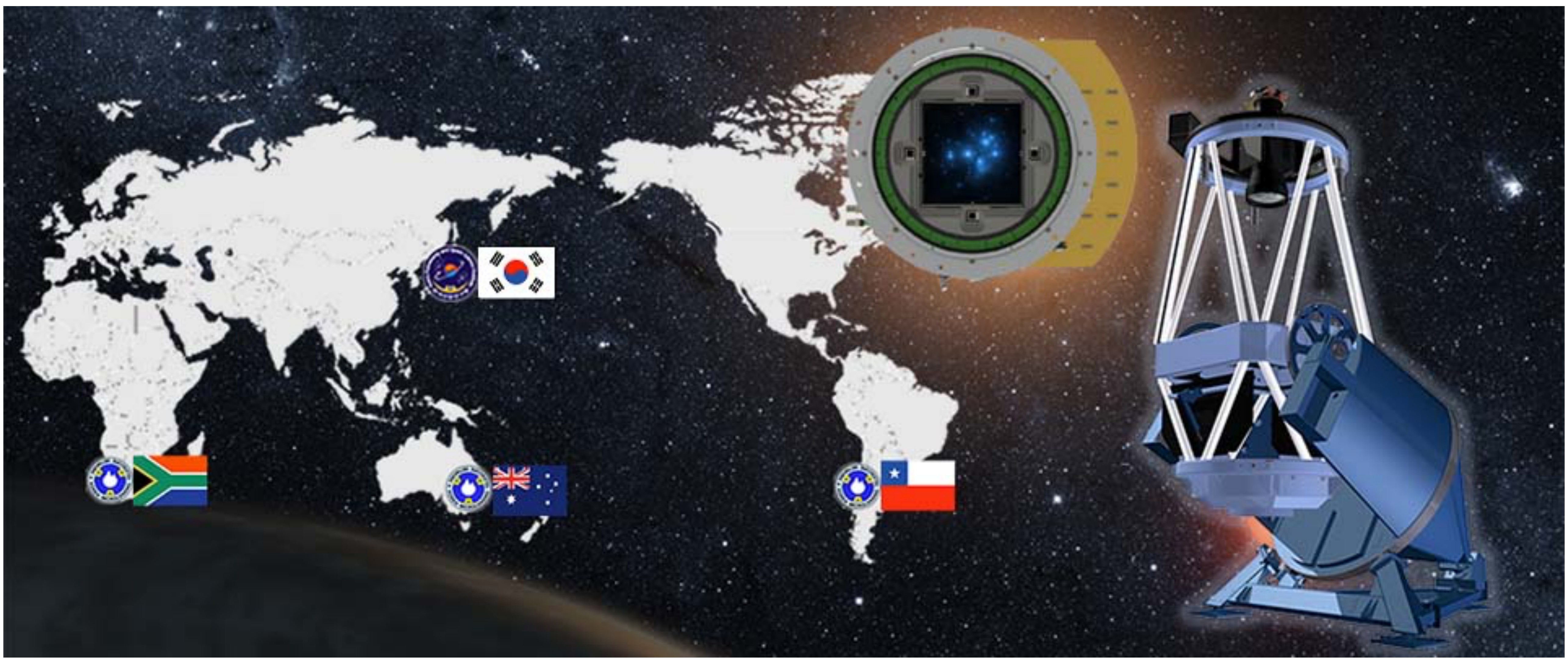
in the range 0.5-10 AU

THE FUTURE OF MICROLENSING

- Korean Microlensing Telescope Network (KMTNet, South Africa, South America, Australia, 3x1.6m, 4 sq. deg.)

Shvartzvald et al. 2015

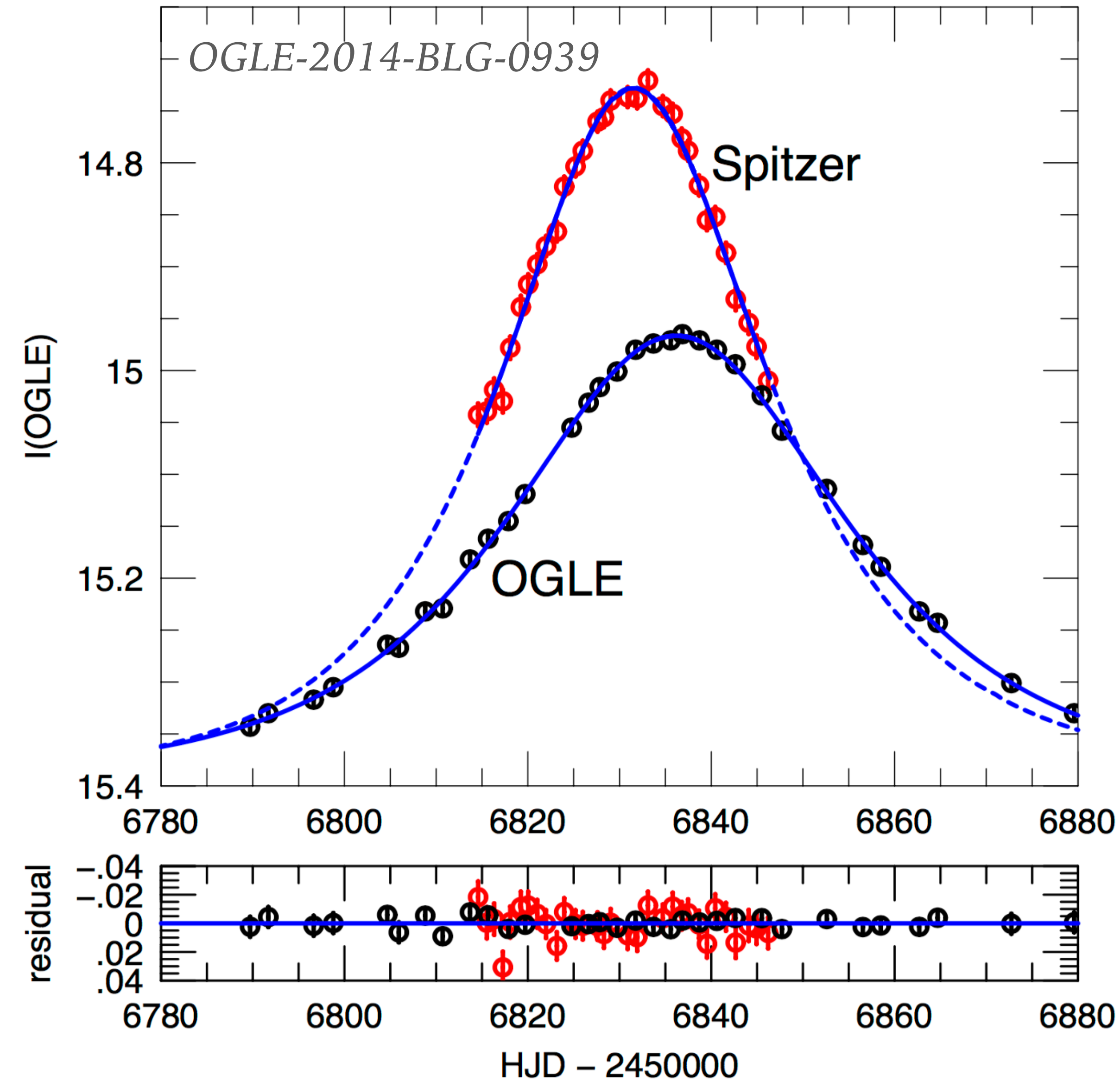




THE FUTURE OF MICROLENSING

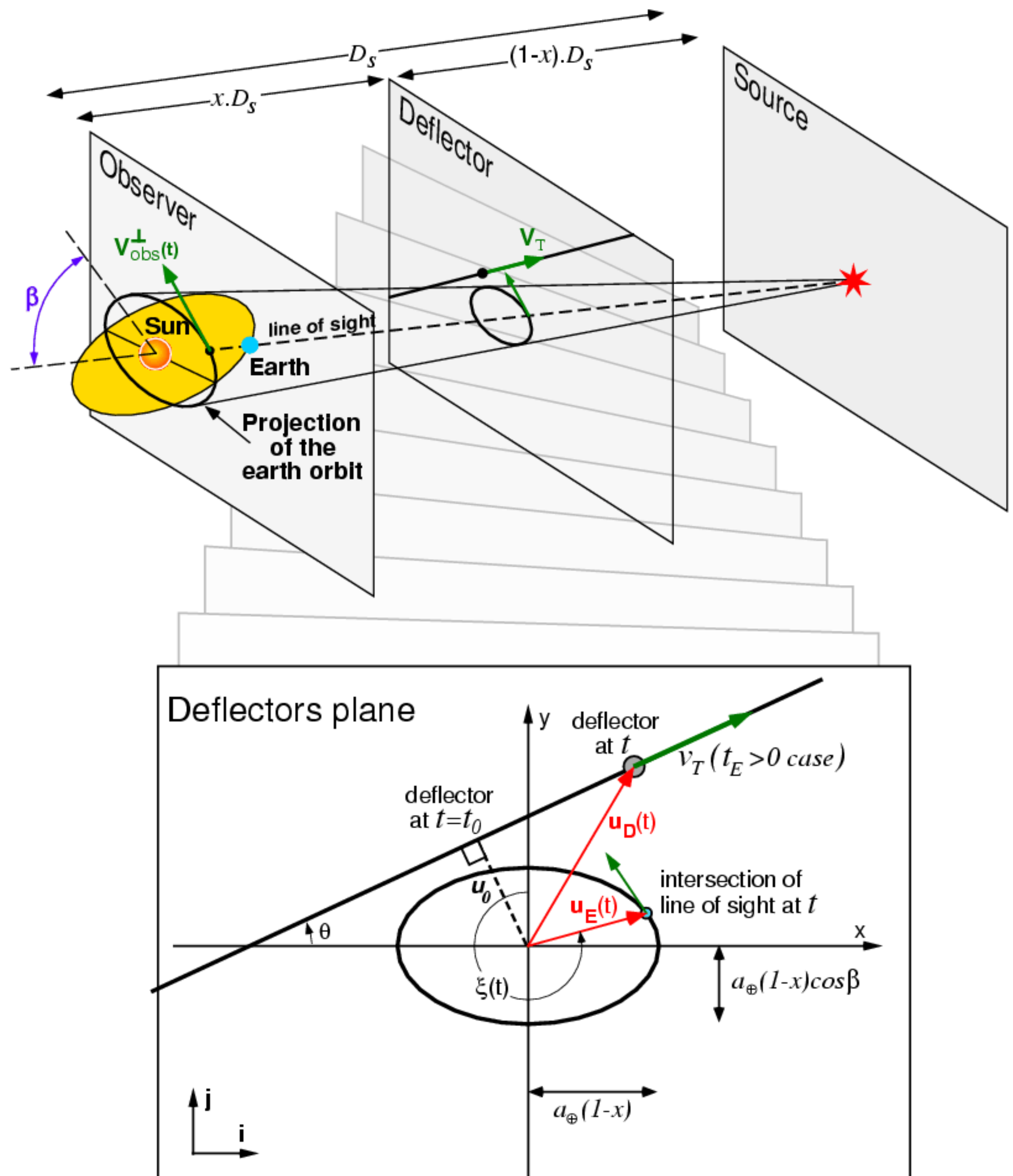
- microlensing searches from space
- possibility to resolve main sequence star lenses
- continuity of observations
- possibility to observe in the NIR-IR where several lenses are brighter
- satellite microlensing parallax
- currently: Spitzer (parallax measurements of 21 single-lens events)
- in 5-10 years: WFIRST, Euclid

Yee et al. 2014



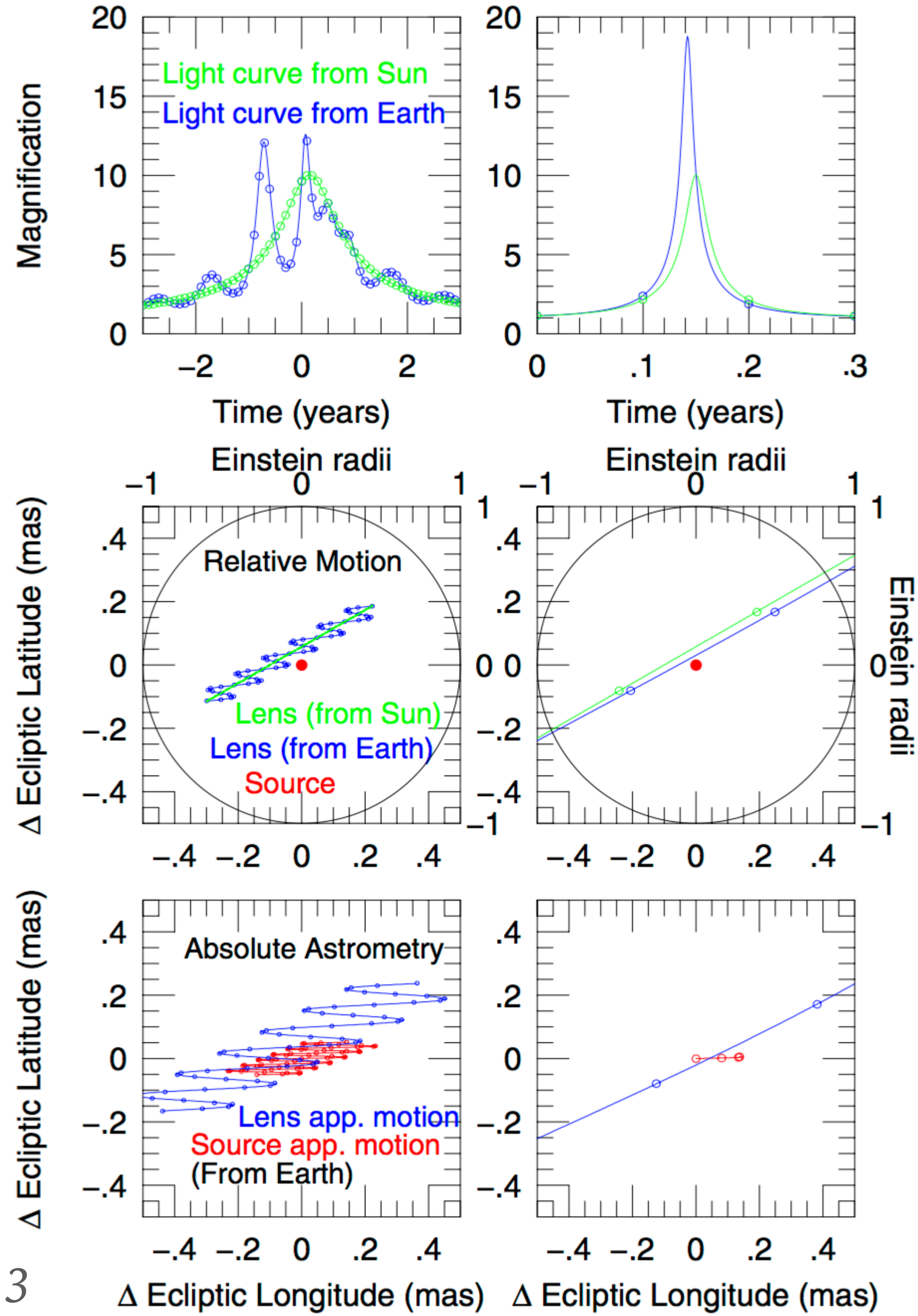
MICROLENS PARALLAX

- Microlens parallax induces variations of the shape of the (classical) microlensing light curve, because the source trajectory is no longer rectilinear
- it can be due e.g. to the orbital motion of the earth around the sun…



MICROLENS PARALLAX

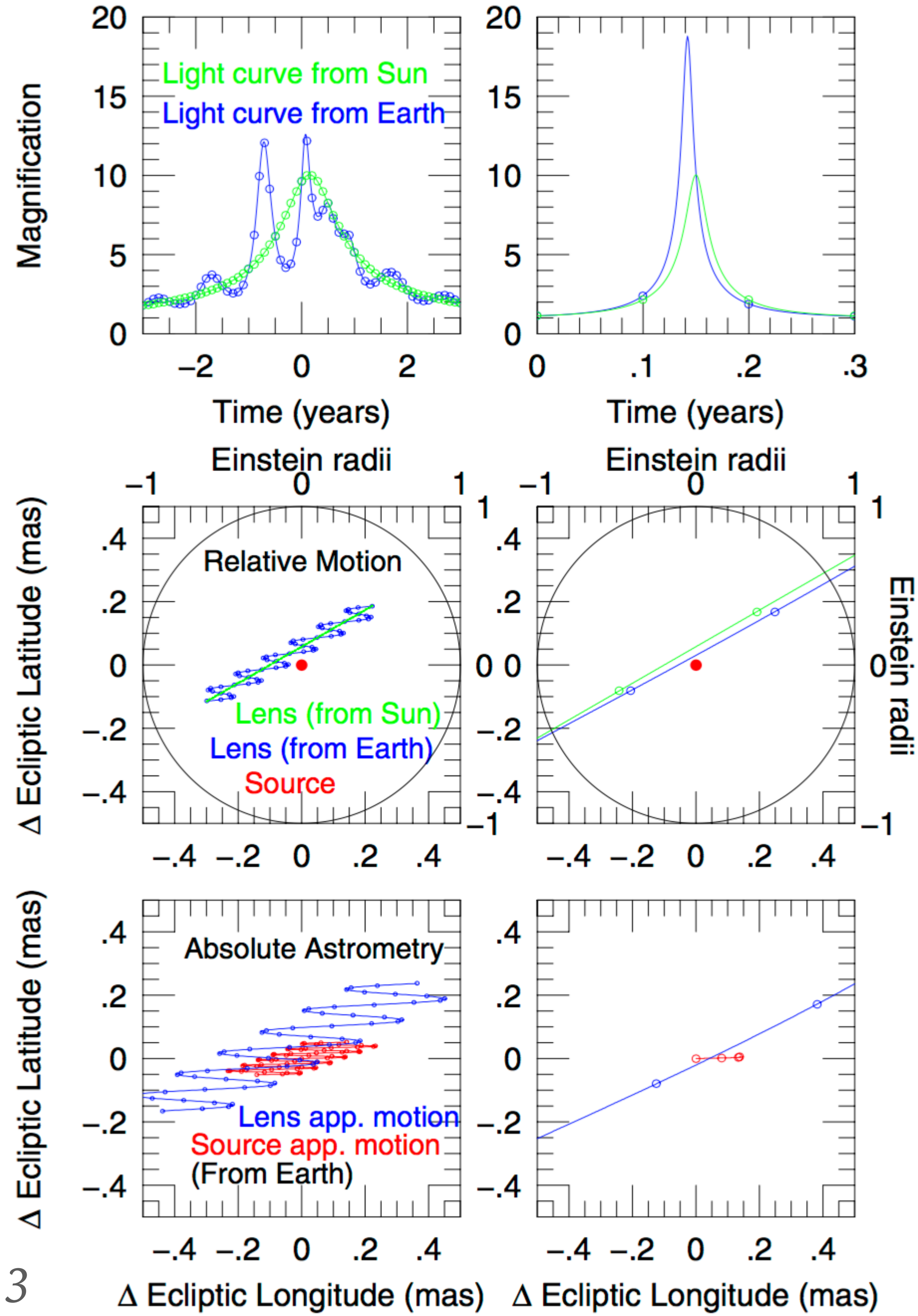
- on the left: what we would see if the $\mu_{hel}=0.1$ mas/year
- on the right: the typical $\mu_{hel}=5$ mas/year
- the effect is relevant if the change in baseline is a significant fraction of the projected Einstein radius



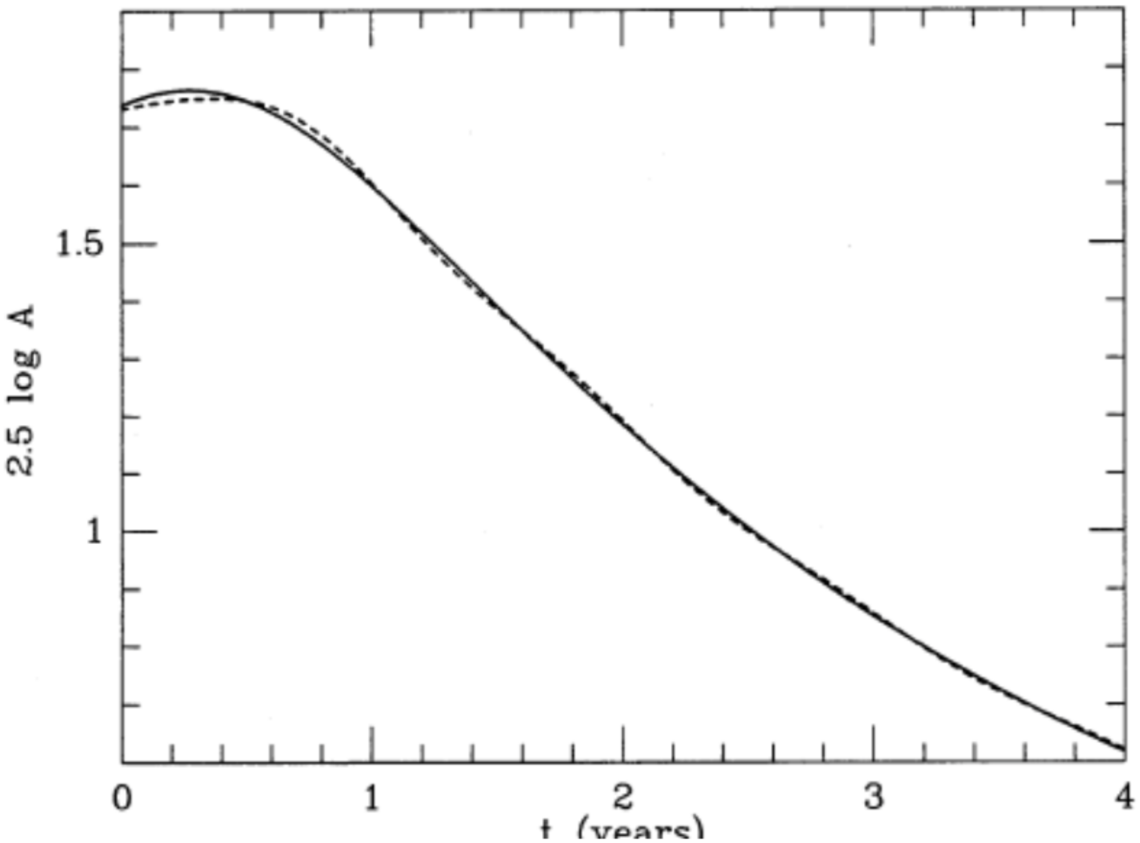
Gould & Horne, 2013

MICROLENS PARALLAX

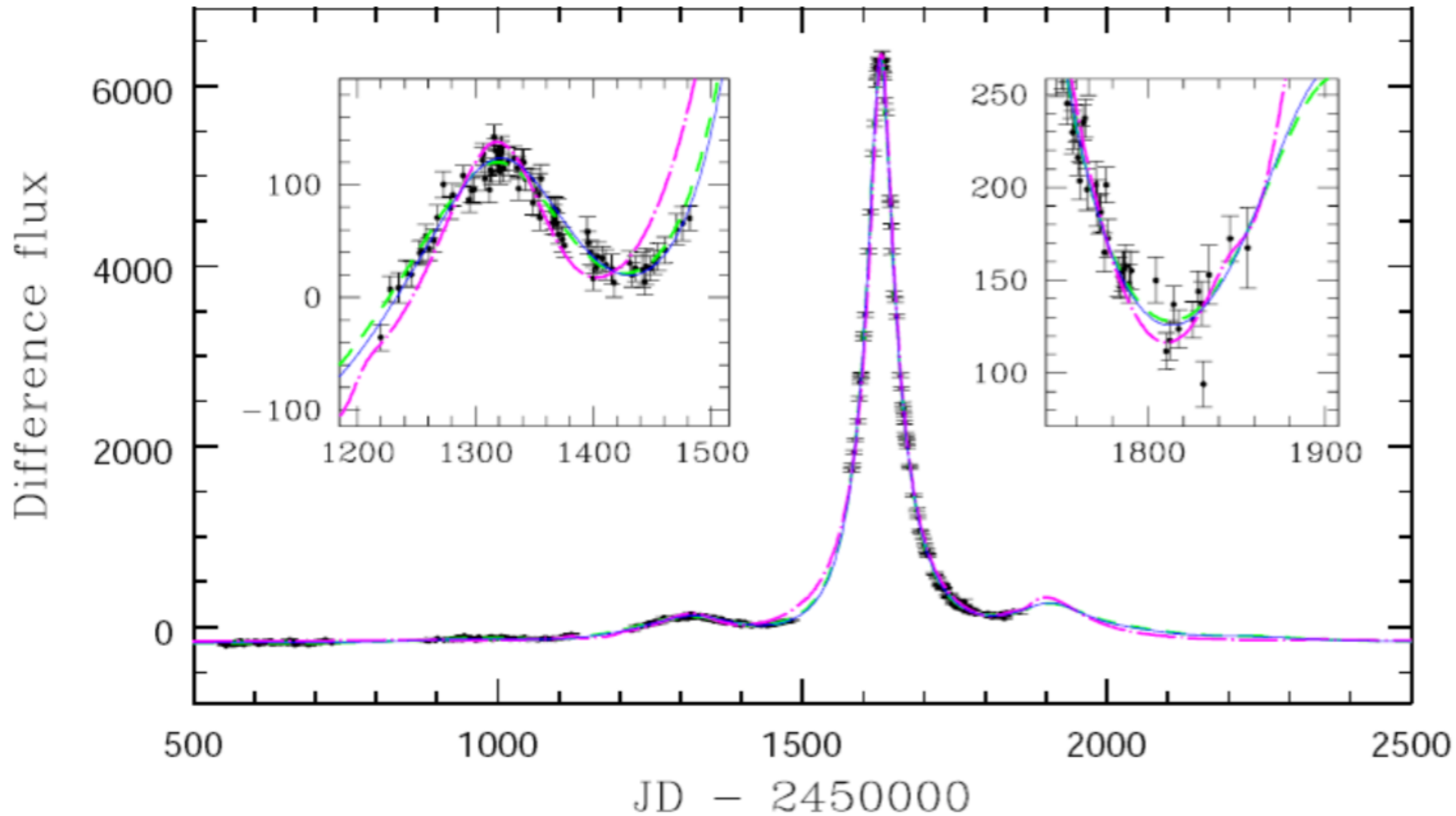
- on the left: what we would see if the $\mu_{hel}=0.1$ mas/year
- on the right: the typical $\mu_{hel}=5$ mas/year
- the effect is relevant if the change in baseline is a significant fraction of the projected Einstein radius
- can be used to measure the ER!



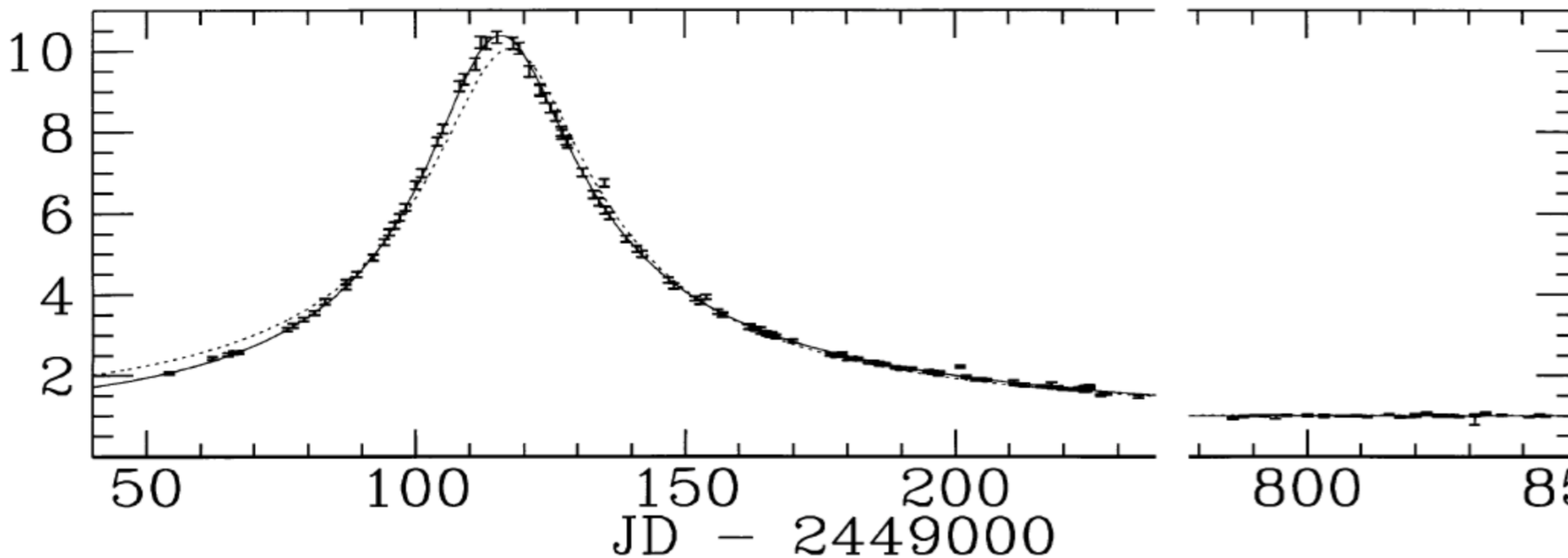
Gould & Horne, 2013



2.5 log A
1.5
1
0
1
2
3
4
t (years)



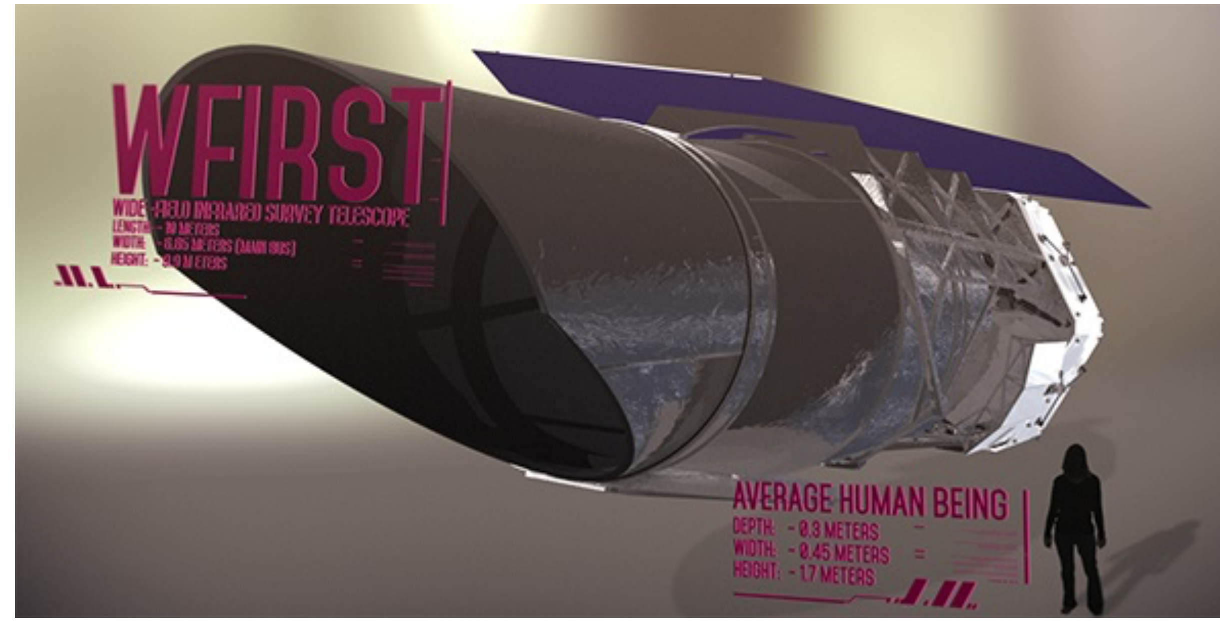
Difference flux
6000
4000
2000
0
500
1000
1500
2000
2500
JD − 2450000
100
0
−100
1200
1300
1400
1500
250
200
150
100
1800
1900



10
8
6
4
2
50
100
150
200
800
85
JD − 2449000

THE FUTURE OF MICROLENSING: WFIRST

- WFIRST expected in 2025: 2.4m telescope with 0.28 sq. deg FOV; NIR, 0.76-2.0 mum, ~0.2” res.
- primary science: cosmology and planets
- NIR imaging for microlensing
- Chronograph for characterizing the planets and their atmospheres (via direct imaging)
- more flexible telescope: will perform several surveys and will host a GO program



- expected performance (5 years survey)
  - 3250 bound exoplanets in the range 0.1-1000 Earth mass, 0.1-40 AU
  - 2080 free-floating planets