GRAVITATIONAL LENSING

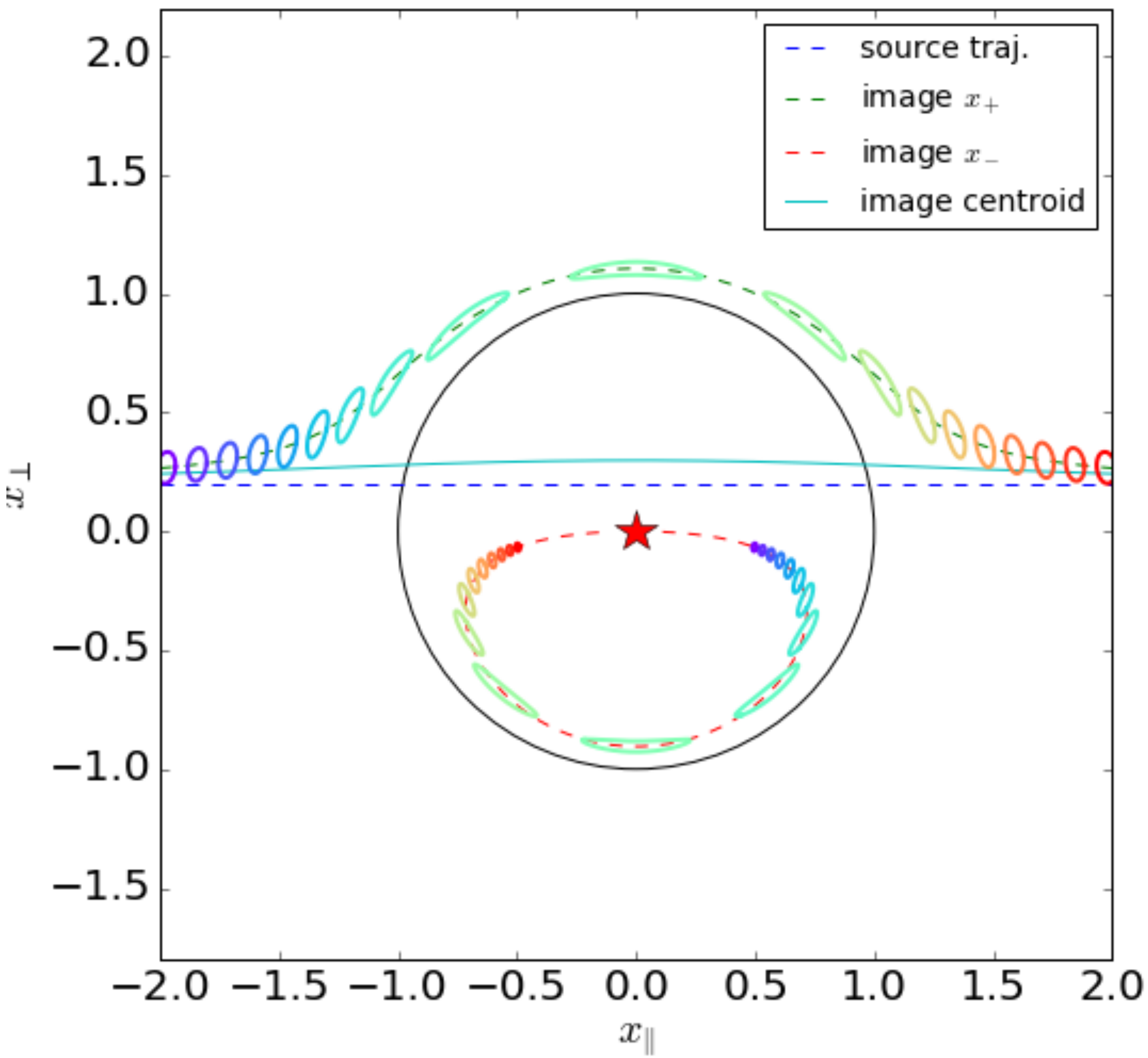
15 – PLANET MICROLENSING (III)

Massimo Meneghetti

AA 2019-2020

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

Lensing of an extended circular source



A point lens always produces two images, namely

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

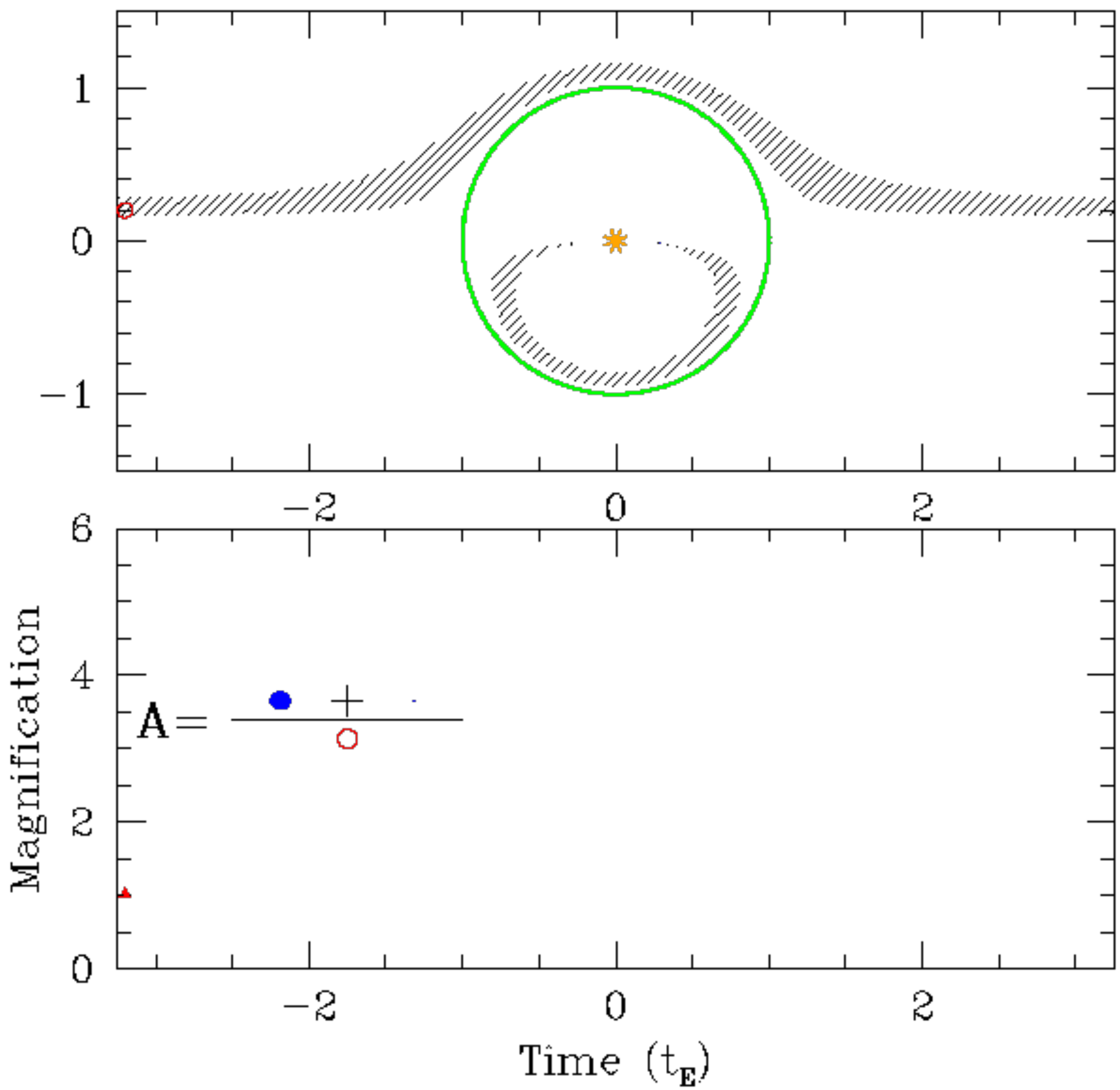
Imagine a source moving along the dashed line in the figure…

Remember: the two images are always aligned with the lens and the source!

As the source move, also the images move…

ANIMATION OF A MICROLENSING EVENT

The animation can be found here: http://www.astronomy.ohio-state.edu/~gaudi/movies.html



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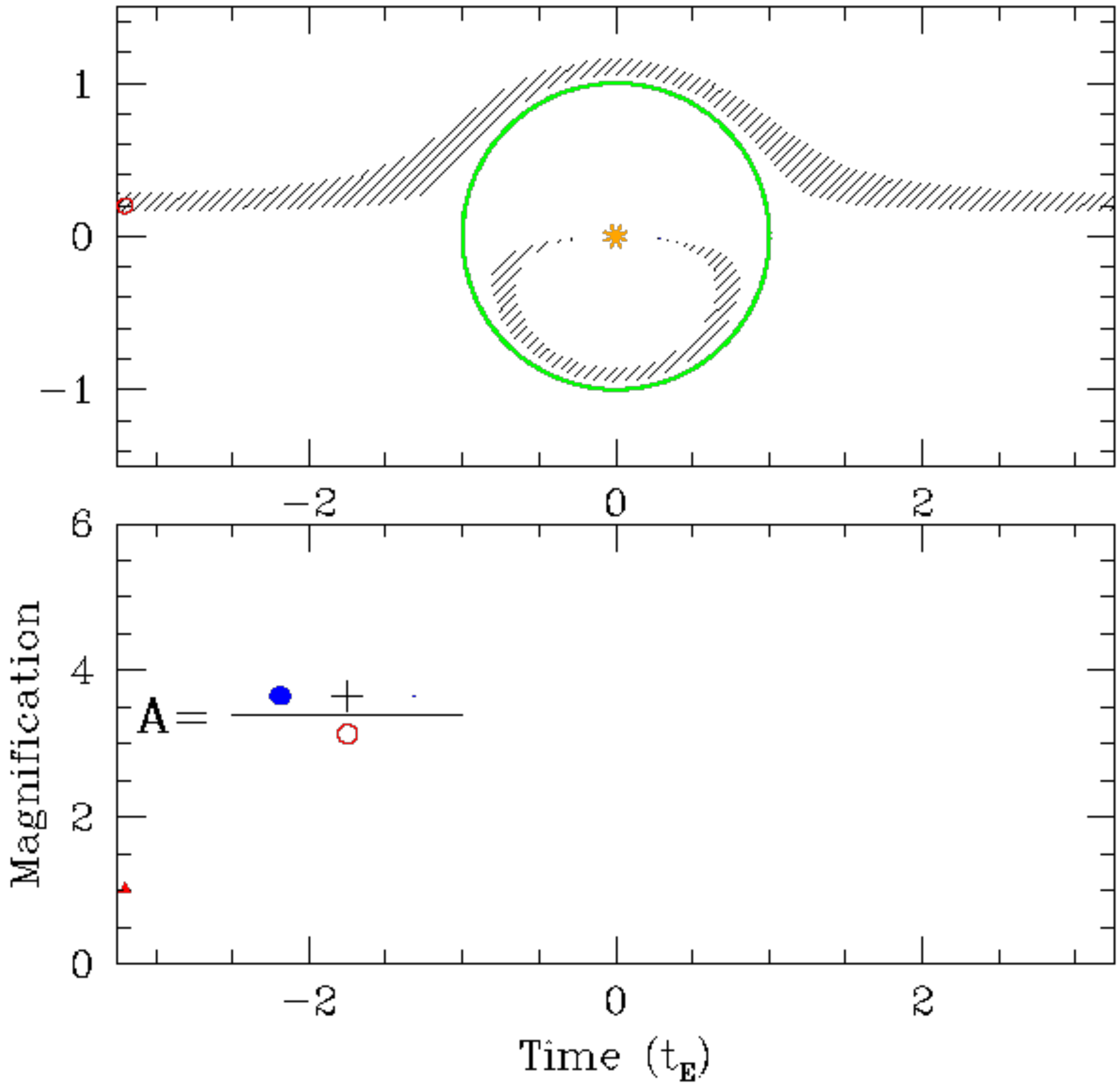
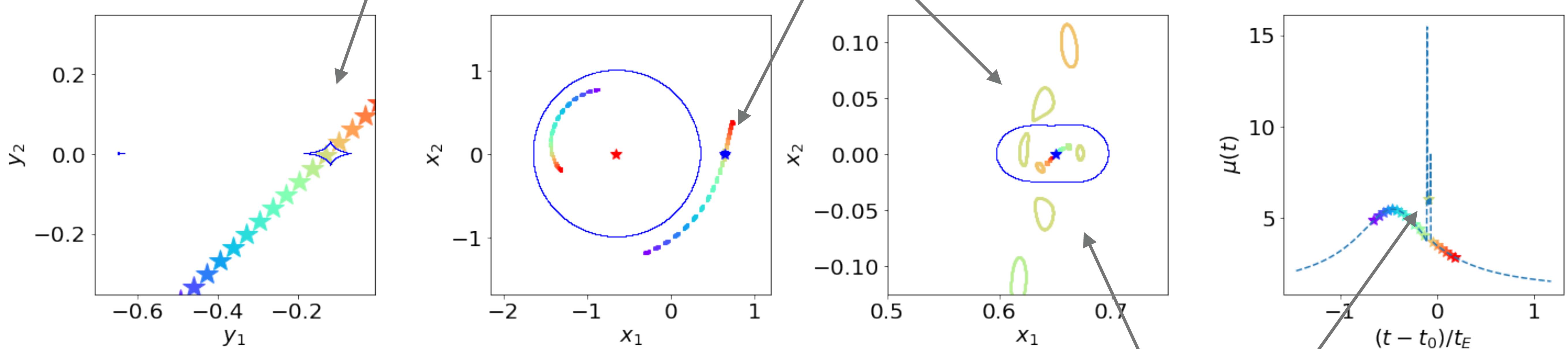


PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES

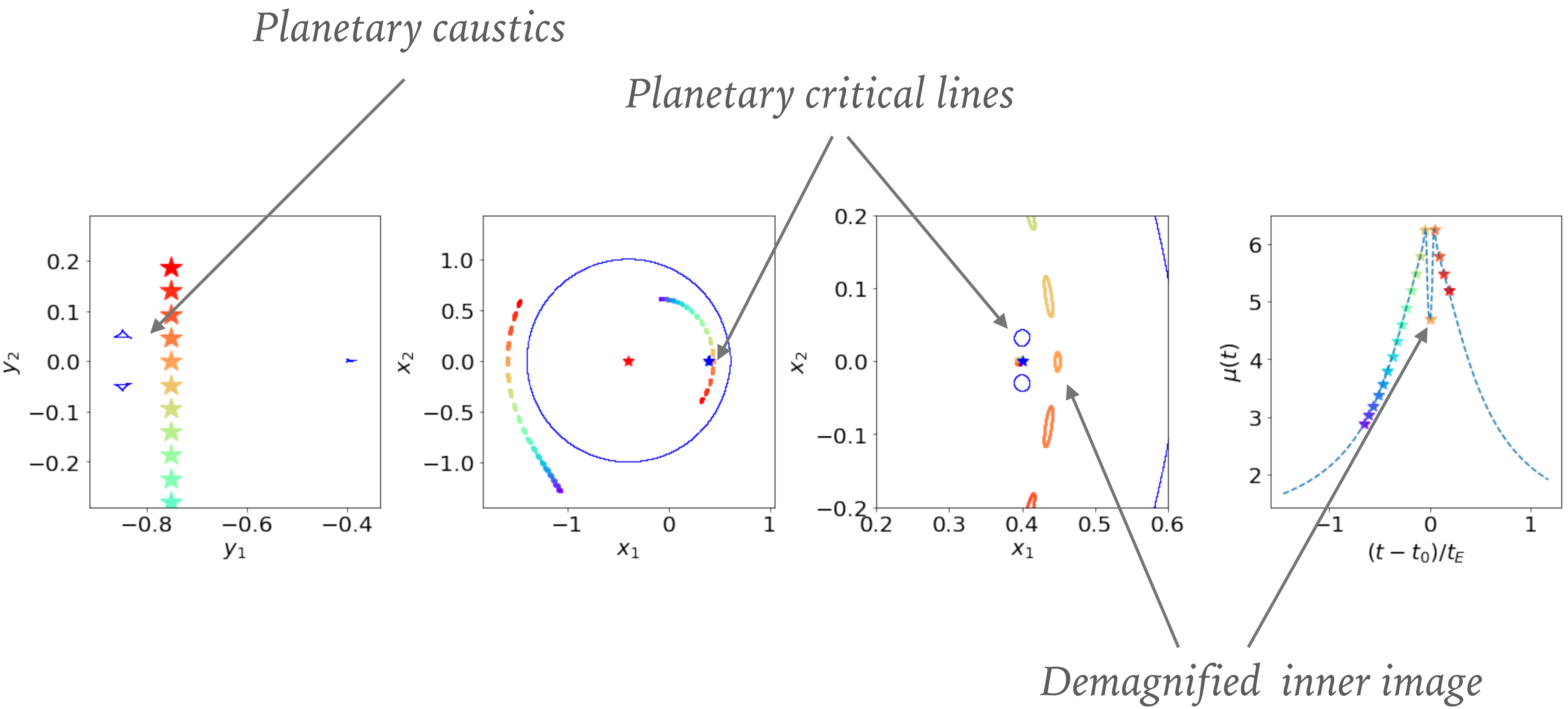
Planetary caustics

Planetary critical lines



magnified outer image

PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES



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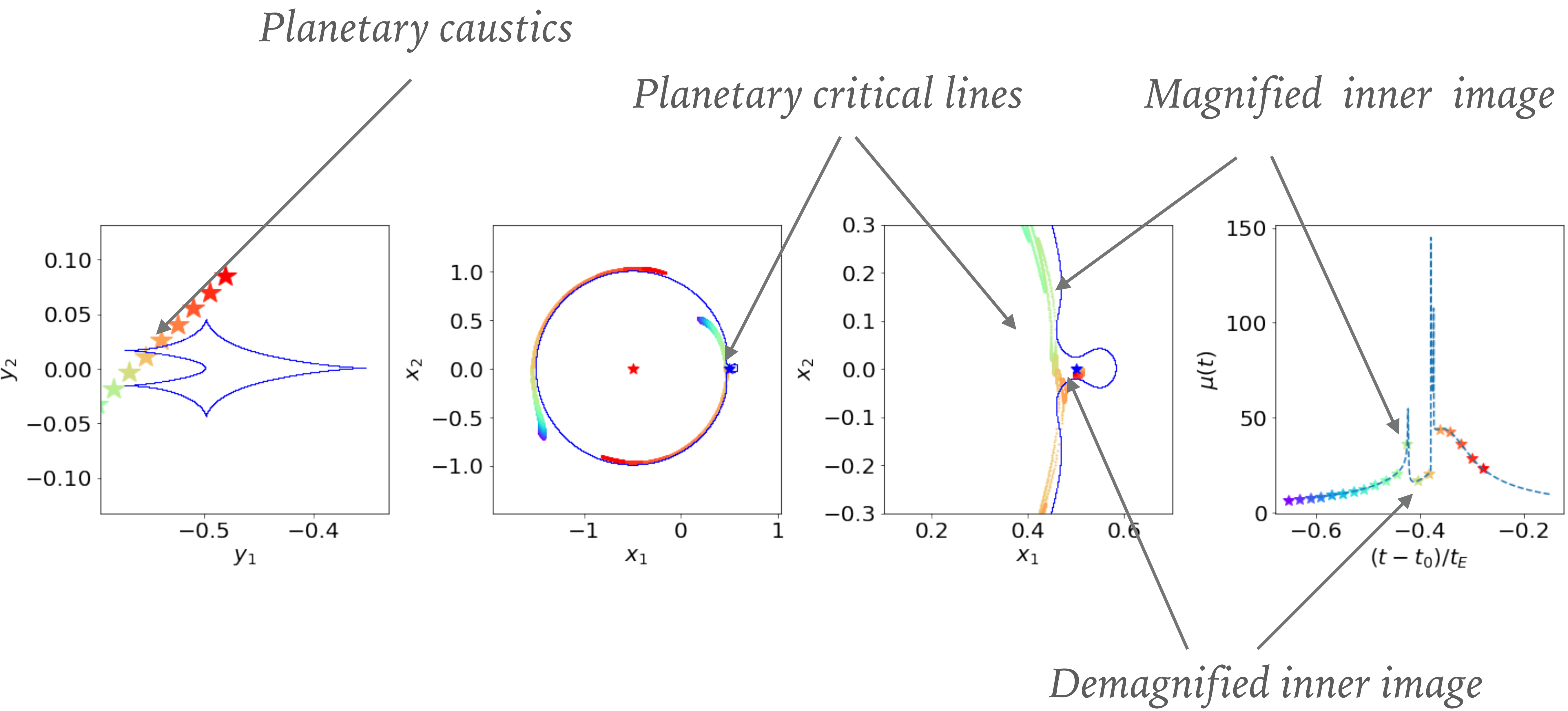

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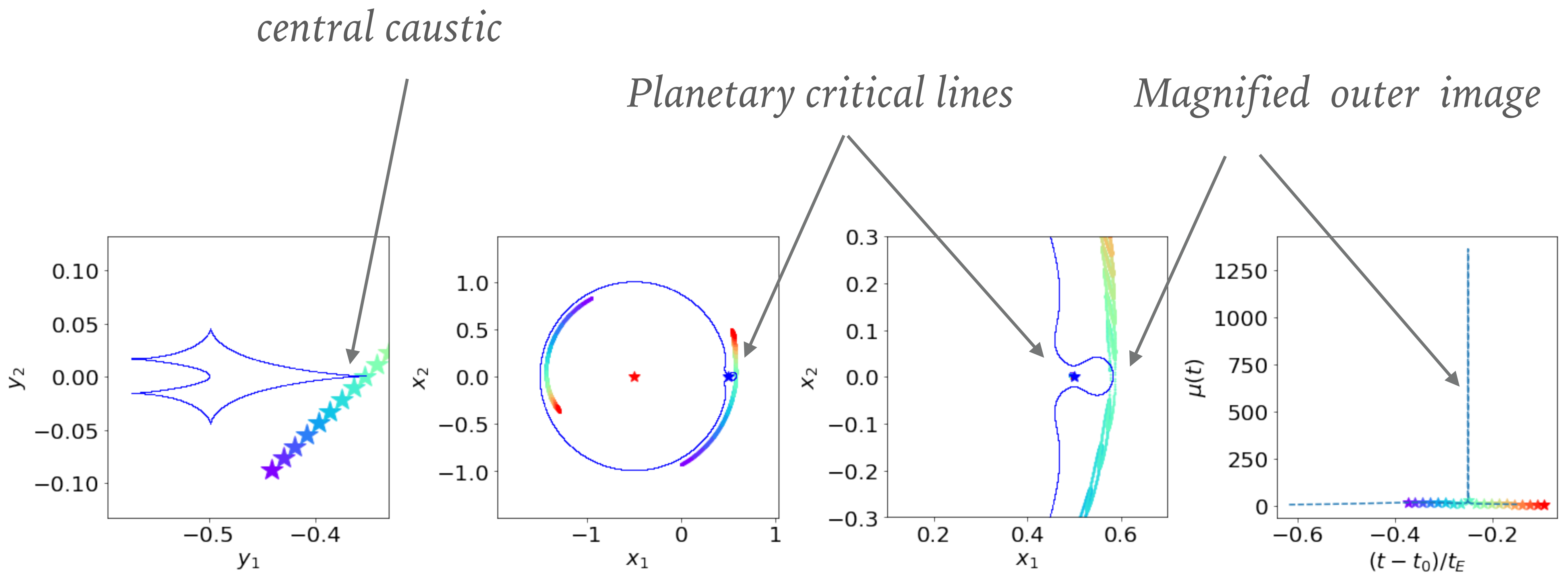


INTERPRETING THE LIGHT CURVES

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 position of the caustic which is being crossed 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:

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

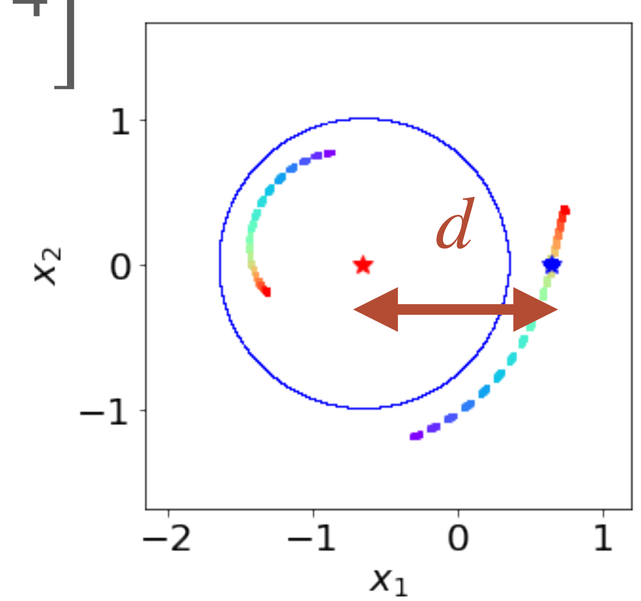
Case 1: perturbation of the outer image ($x_+ > 0$):

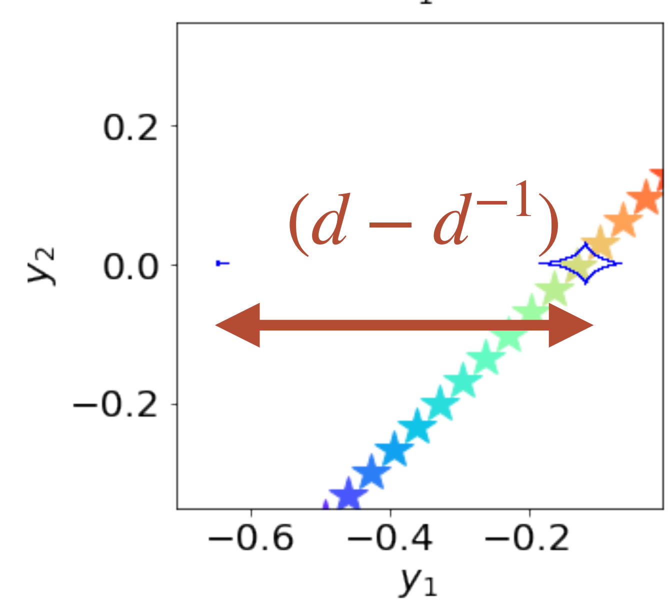
$$d = \frac{1}{2}y + \frac{1}{2}\sqrt{y^2+4}$$

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

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

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





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:

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

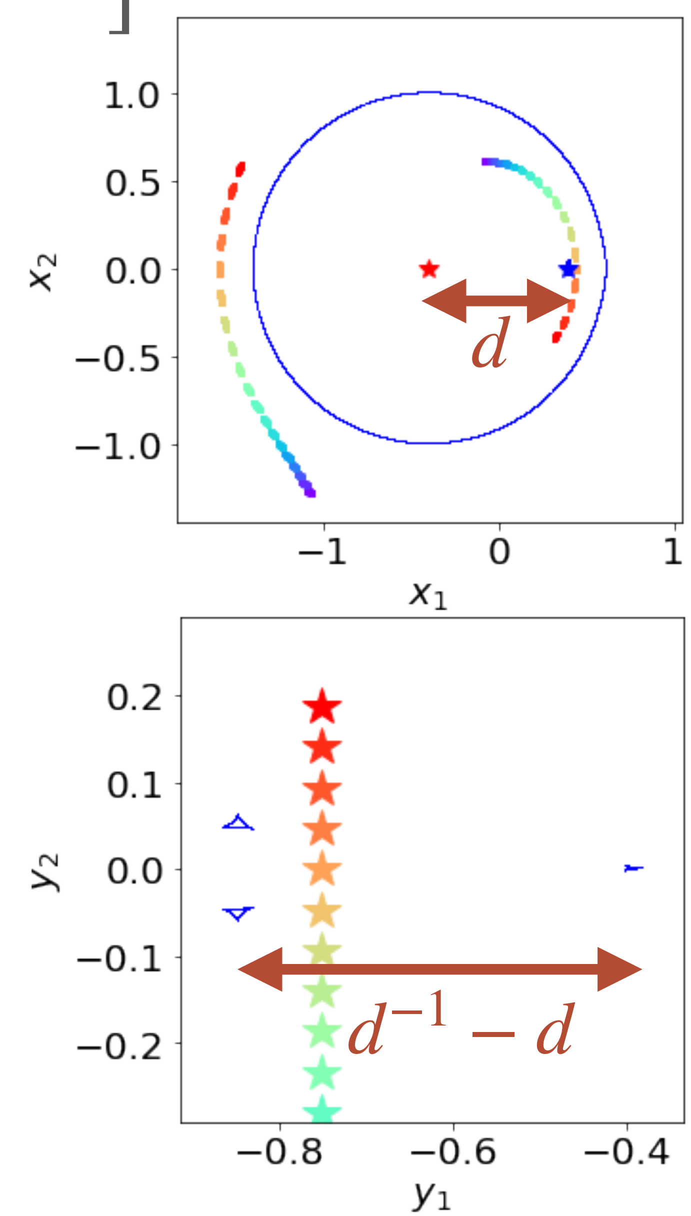
Case 2: perturbation of the inner image ($x_- < 0$):

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

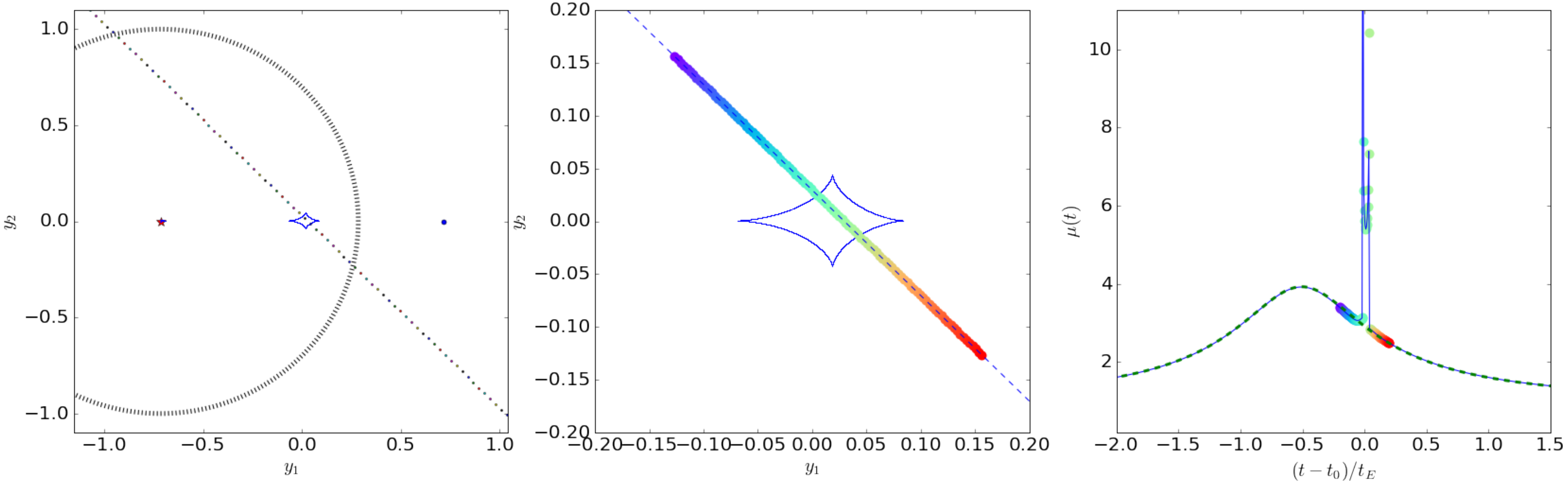
$$\frac{1}{2}\sqrt{y^2+4} = \left(\frac{1}{2}y + d\right)$$

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

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

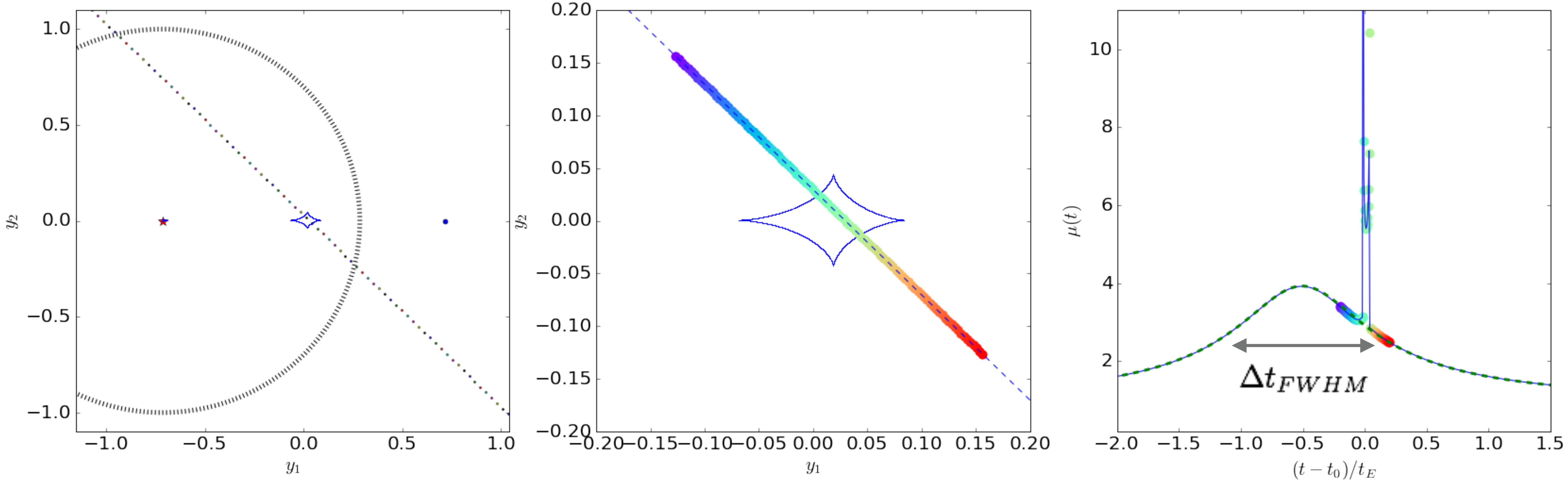


PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



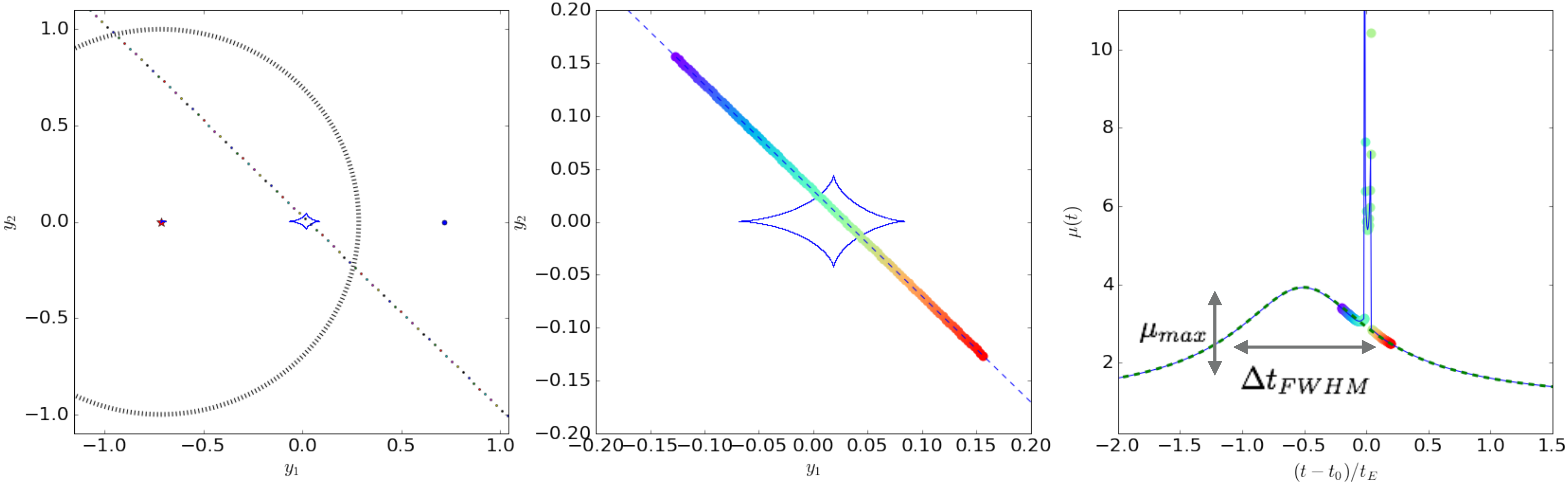
- primary event:
- planetary perturbation:

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



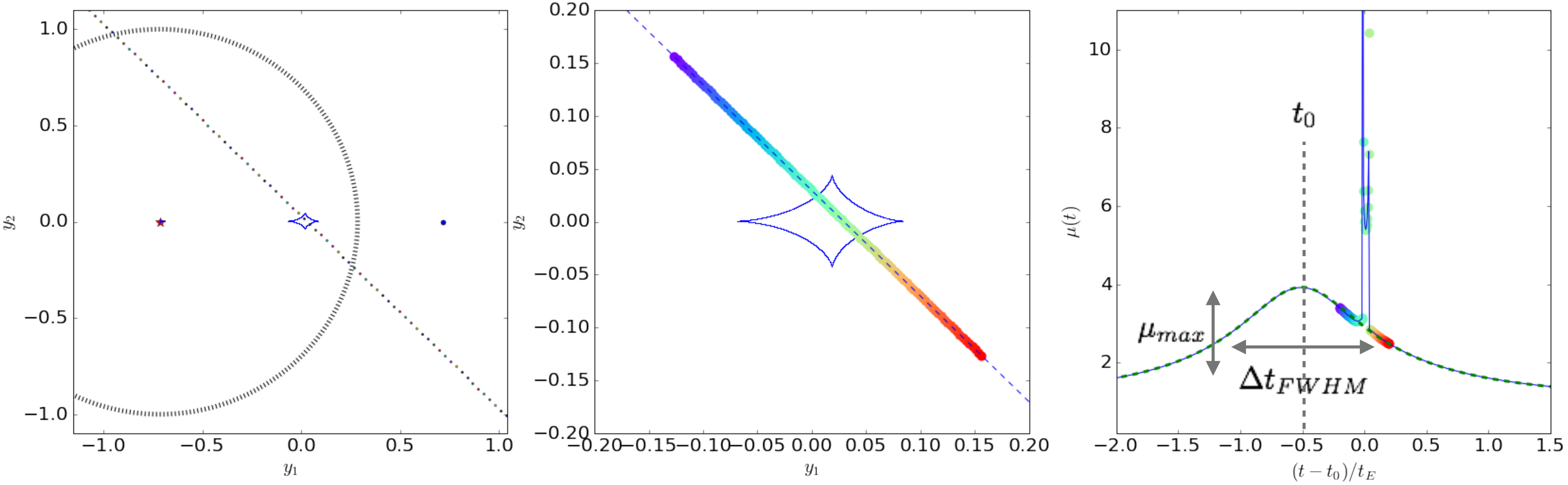
- primary event: Δt_{FWHM}
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



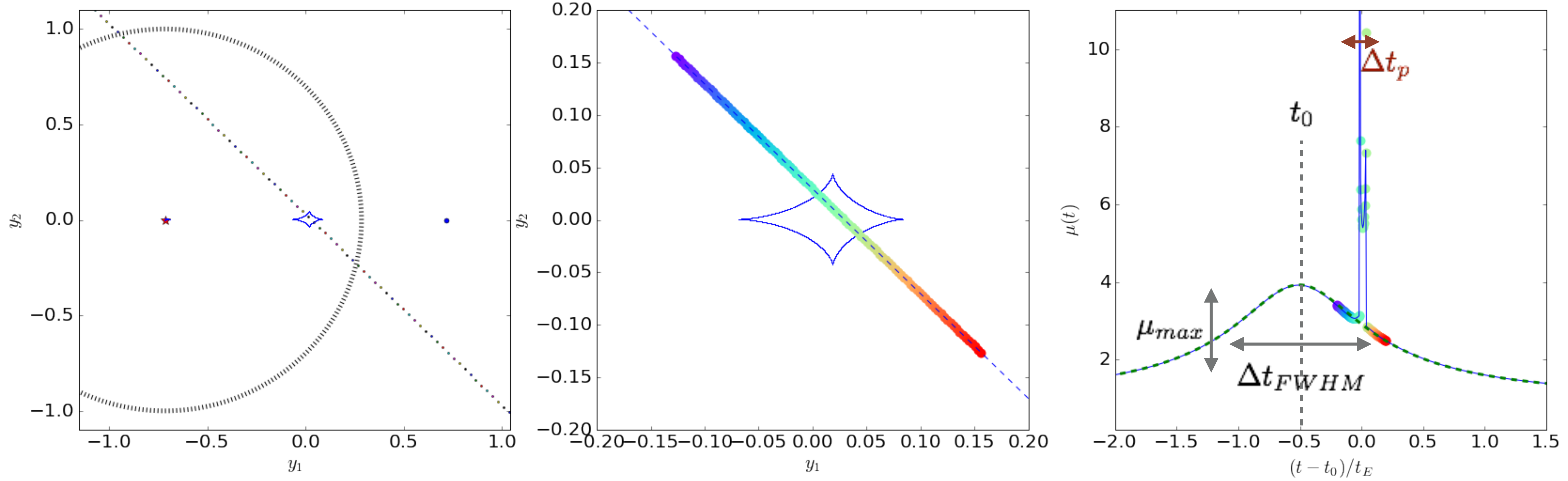
- primary event: Δt_{FWHM} μ_{max}
- planetary perturbation:

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



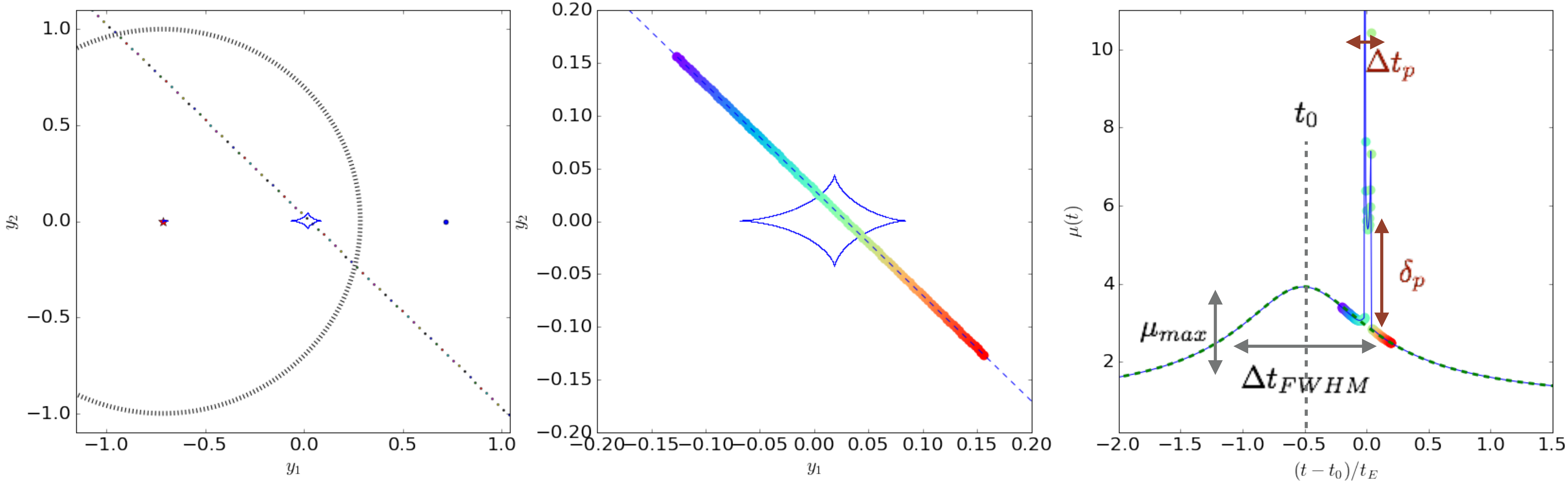
- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation:

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



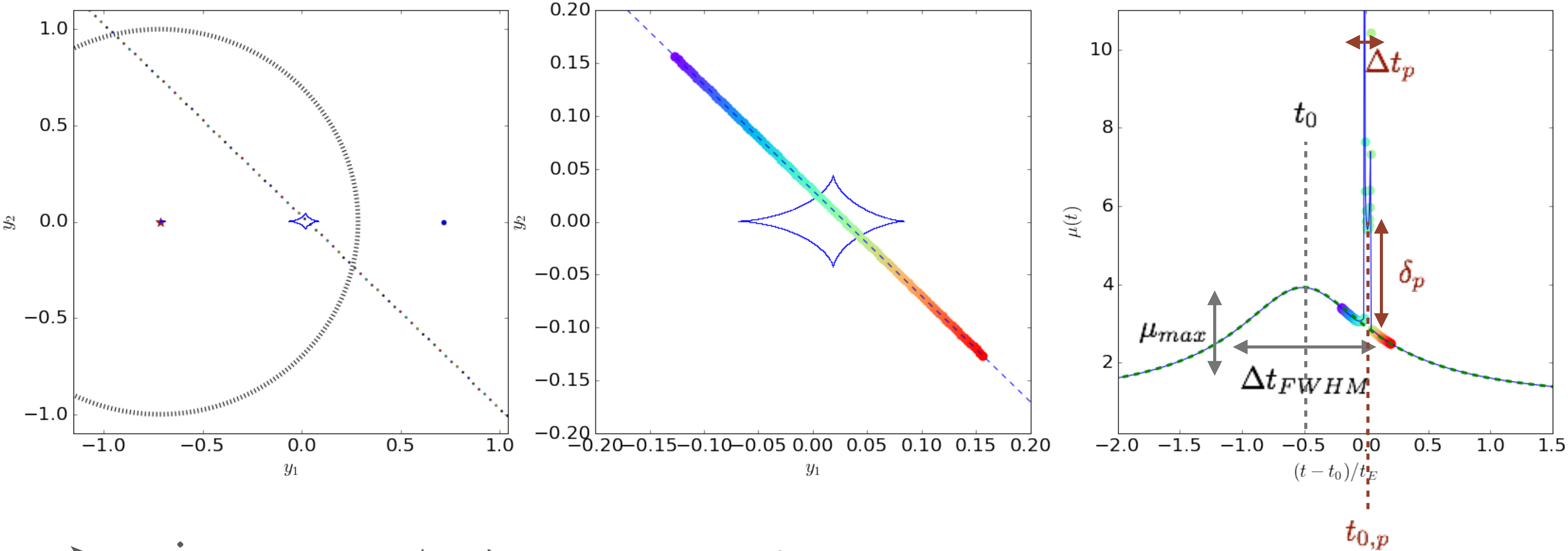
- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



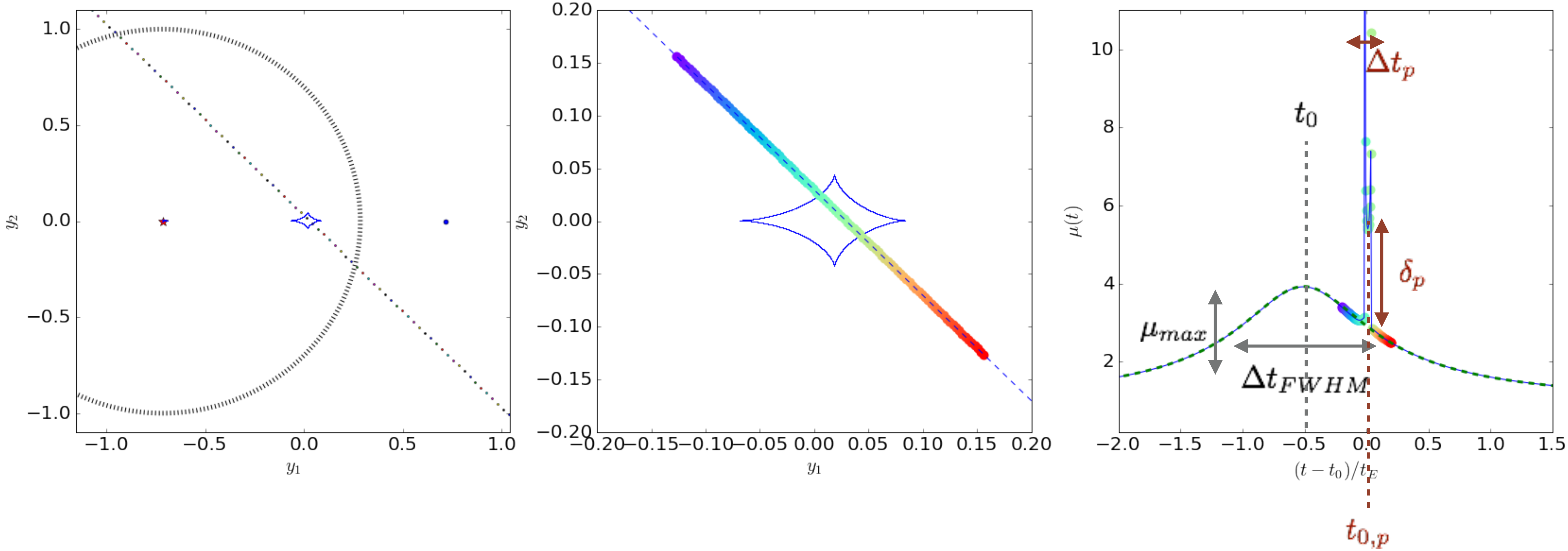
- primary event: Δt_{FWHM} μ_{max} t_0
- planetary perturbation: Δt_p δ_p

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



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

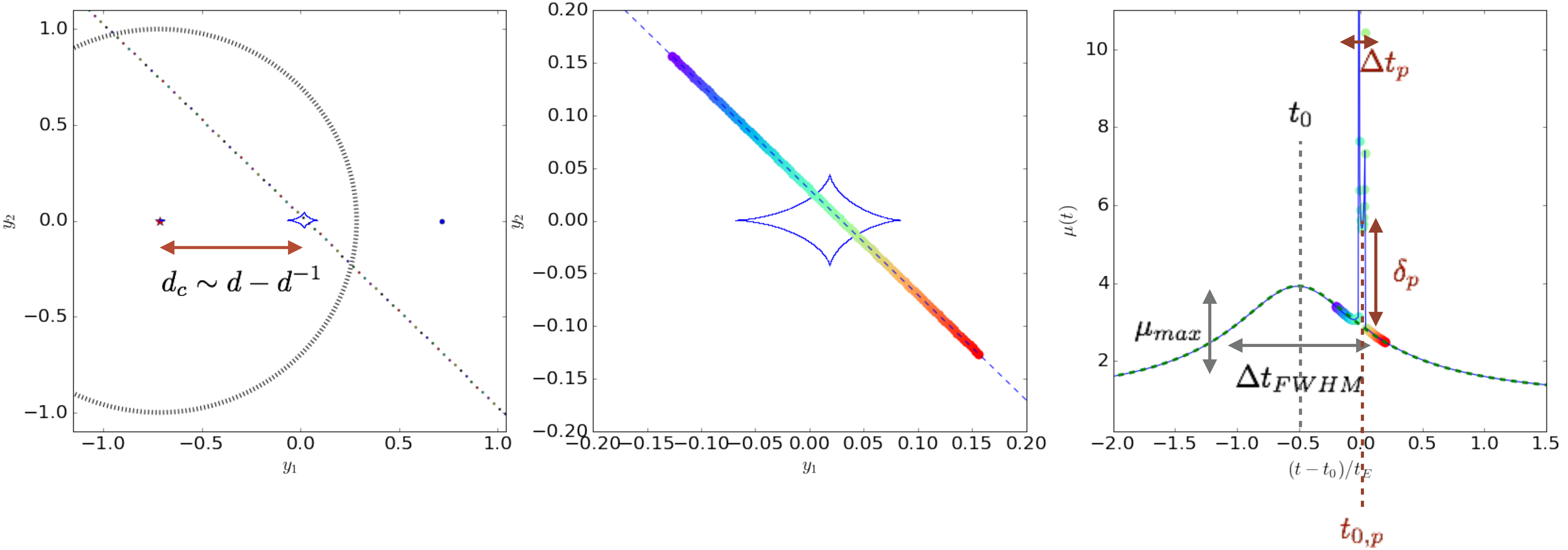
PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



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

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

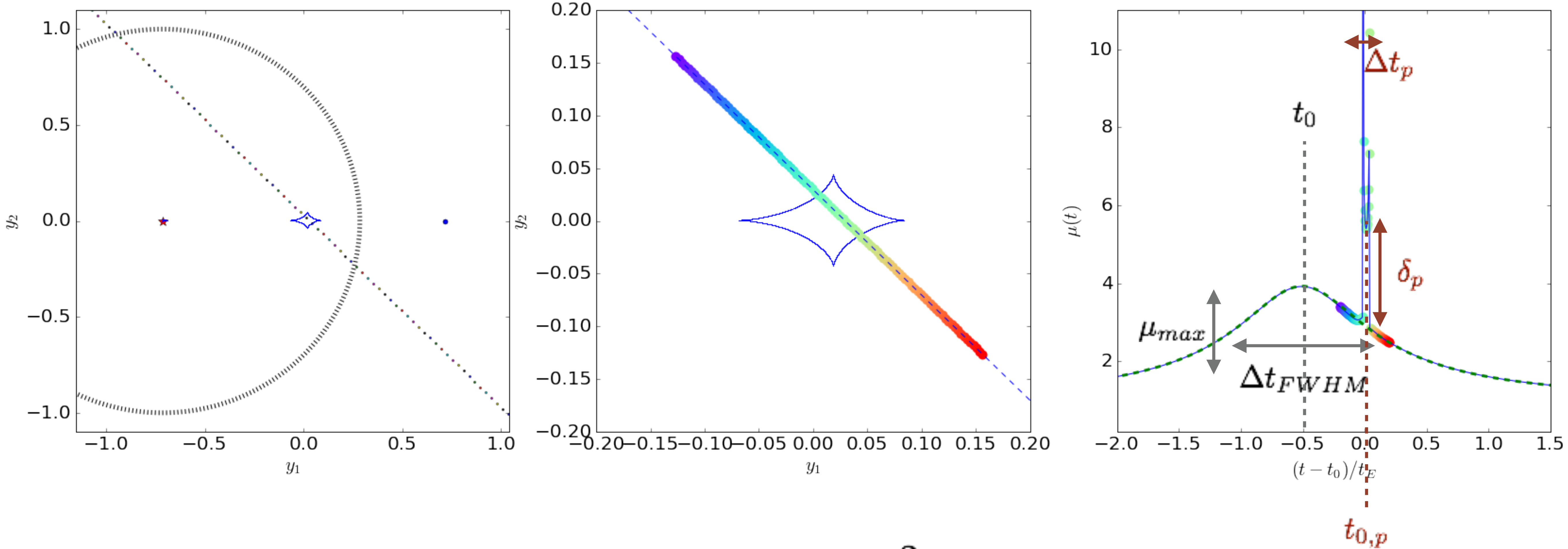
PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



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

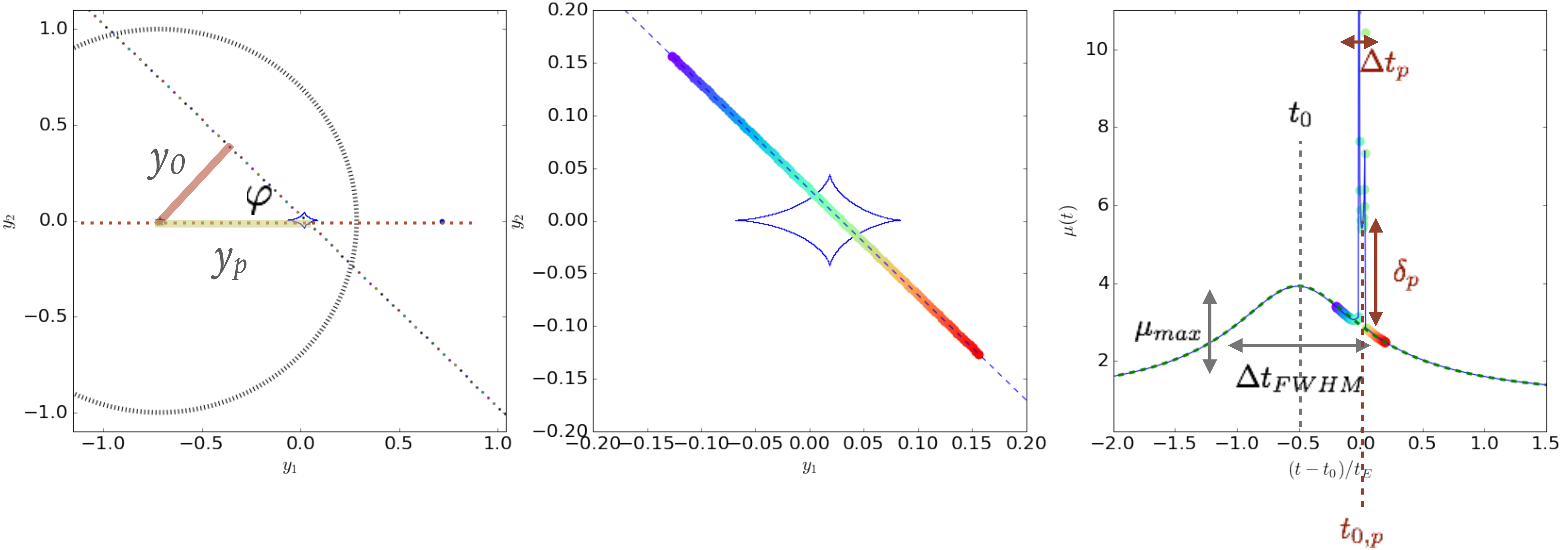
$$\Rightarrow d \sim \frac{1}{2}\left(y_p + \sqrt{y_p^2 + 4}\right)$$

PLANET PROPERTIES "READ OFF" OF THE LIGHT CURVES



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

PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES

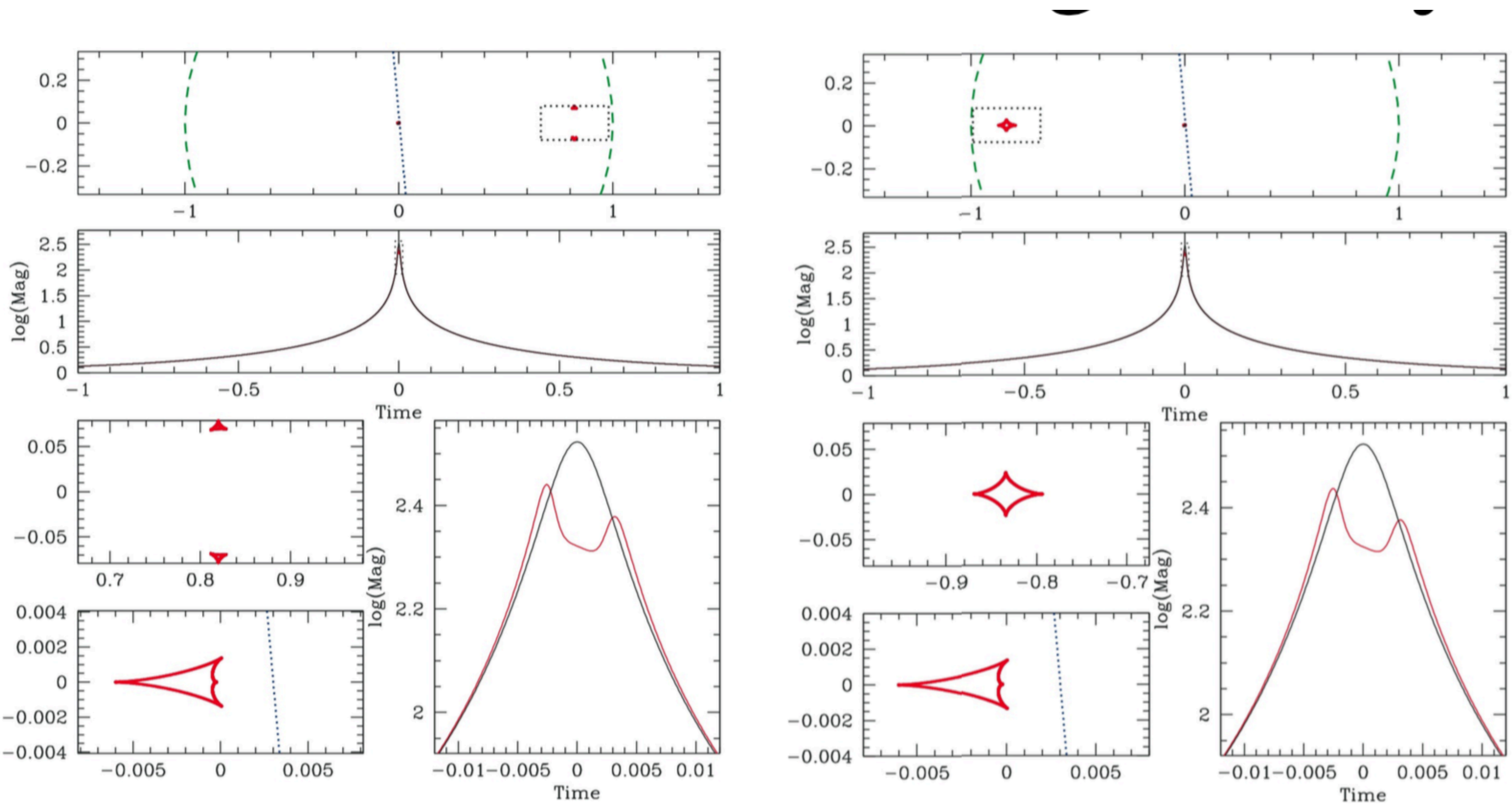


$$y_0, y_p \Rightarrow \varphi = \sin^{-1} \frac{y_0}{y_p}$$

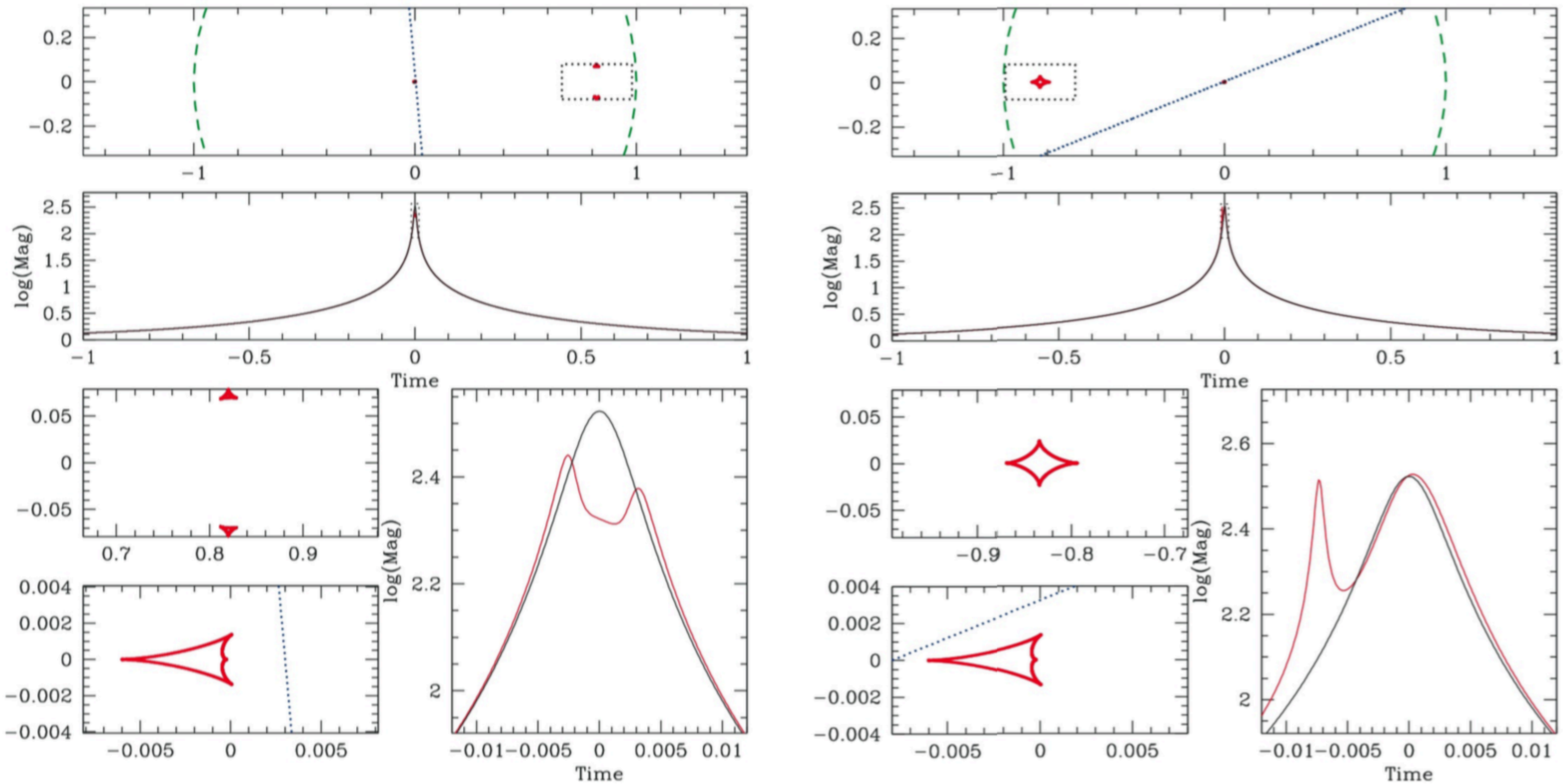
TO SUMMARIZE

- 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

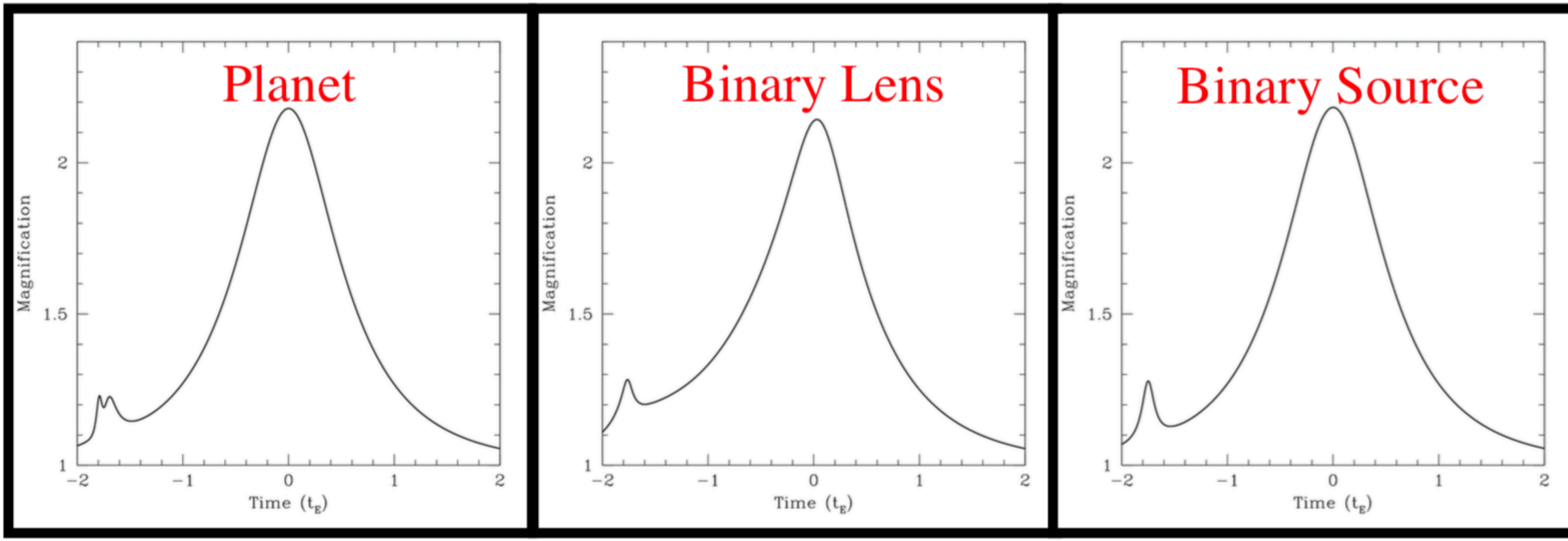


DOUBLE HORN OR BUMP



UNCERTAINTIES: SOME FEATURES CAN BE EXPLAINED IN DIFFERENT WAYS

Short duration deviations 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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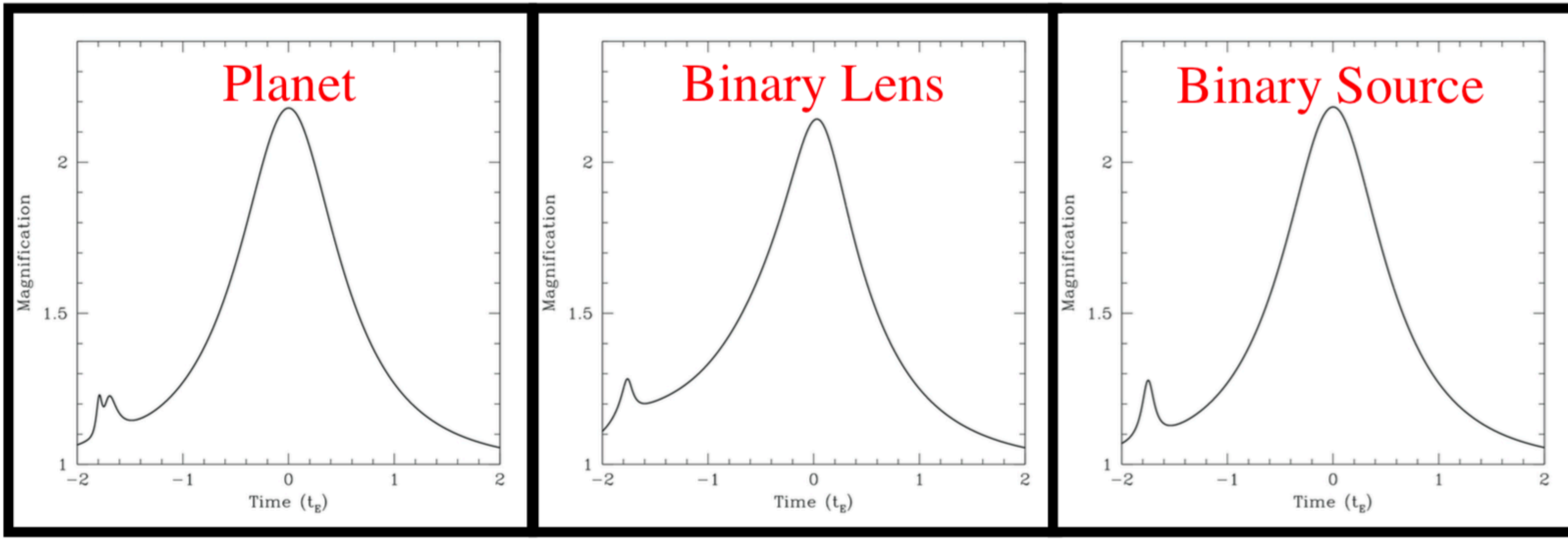

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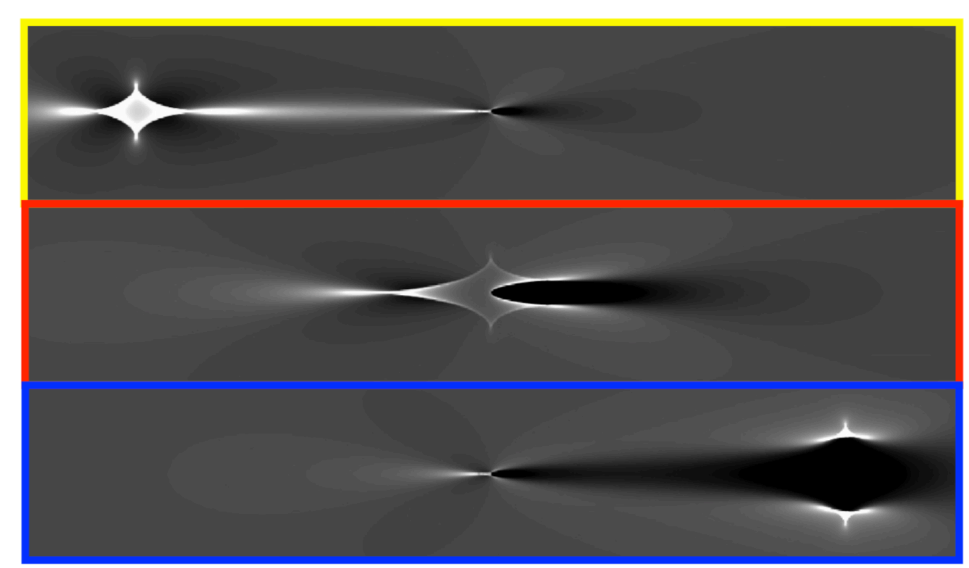
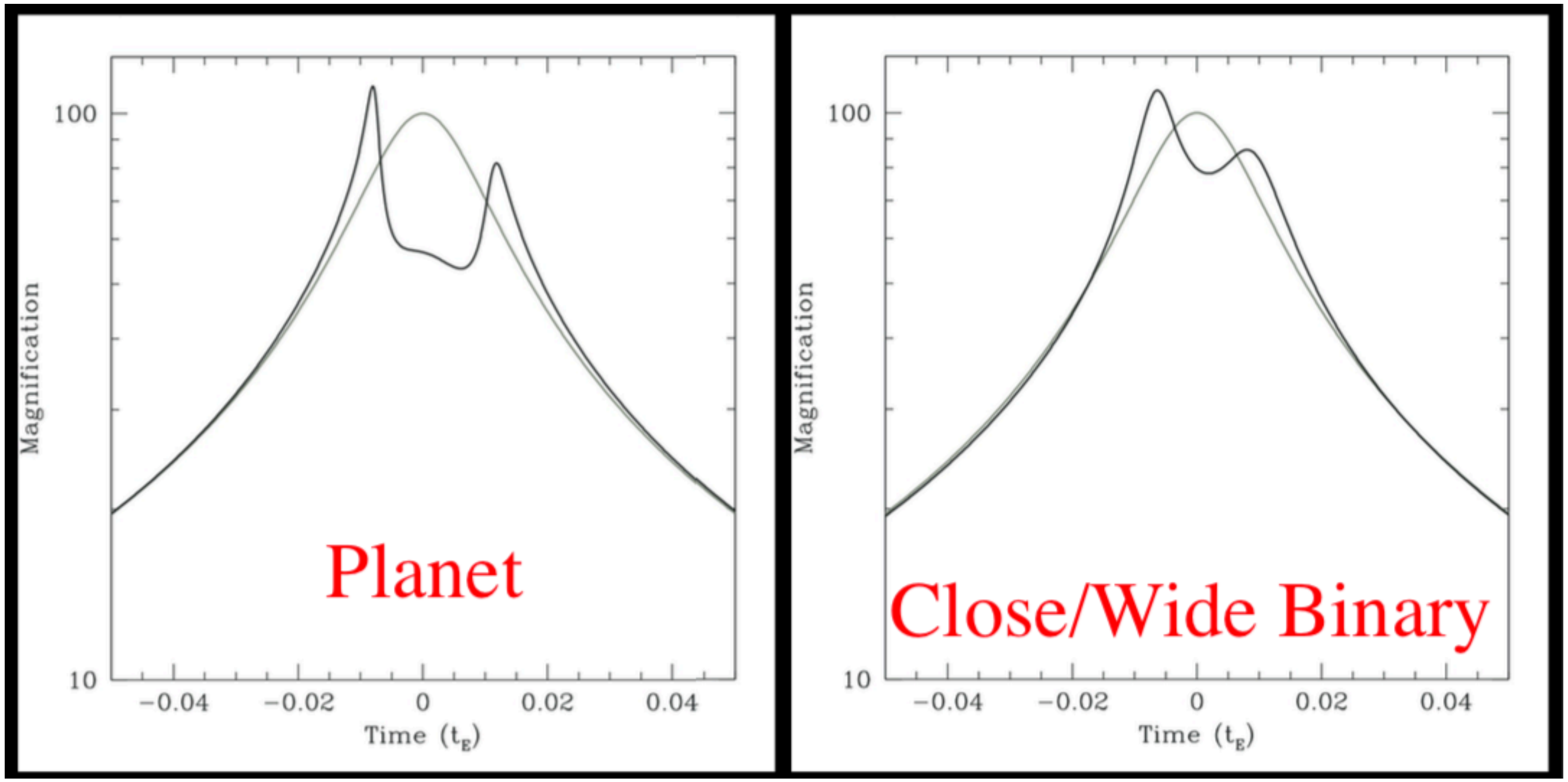


UNCERTAINTIES: SOME FEATURES CAN BE EXPLAINED IN DIFFERENT WAYS

Short duration deviations at the peak:

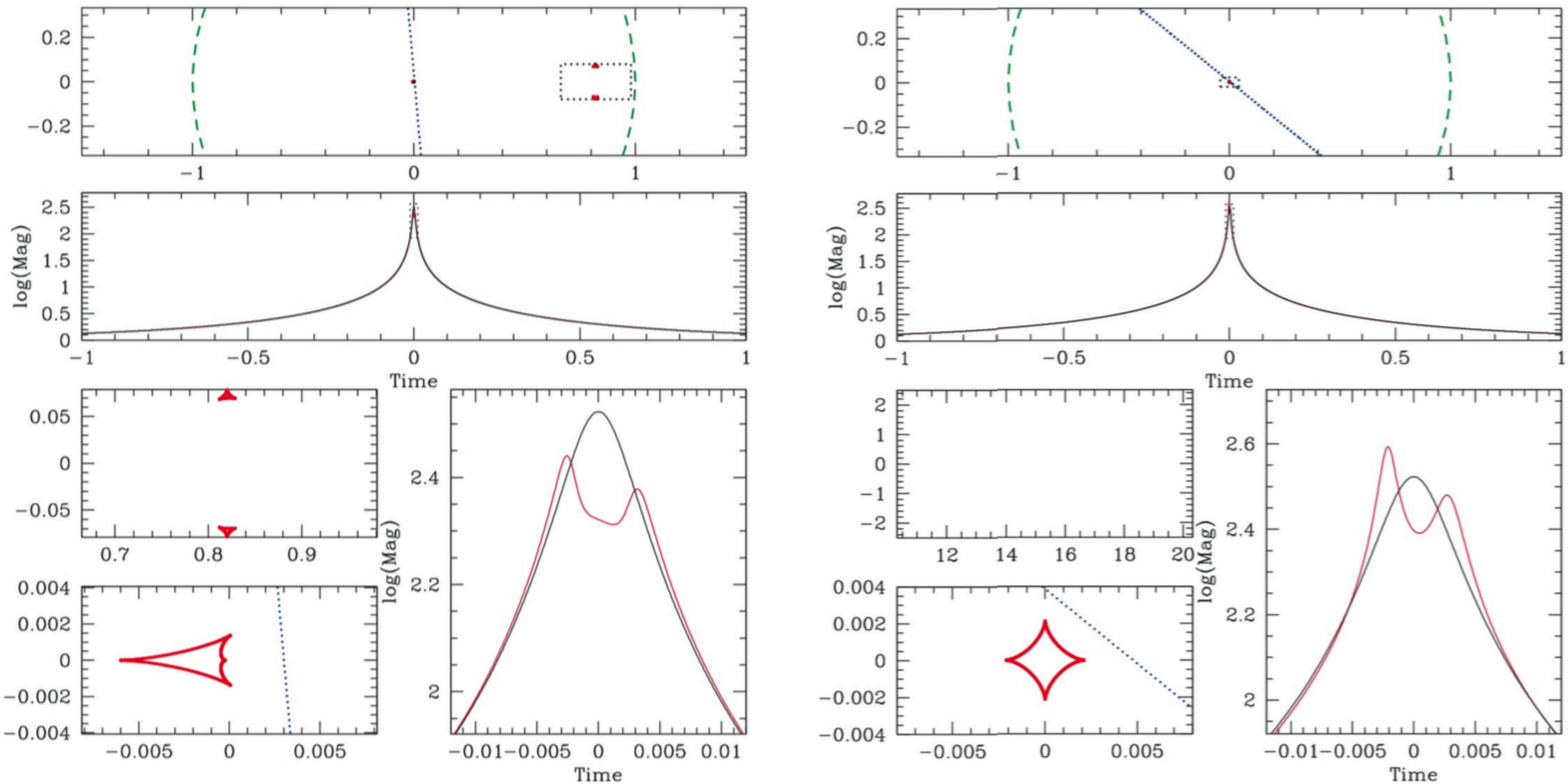


Can be caused by:

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

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

CLOSE BINARIES VS PLANETS



WHY SEARCHING PLANETS?

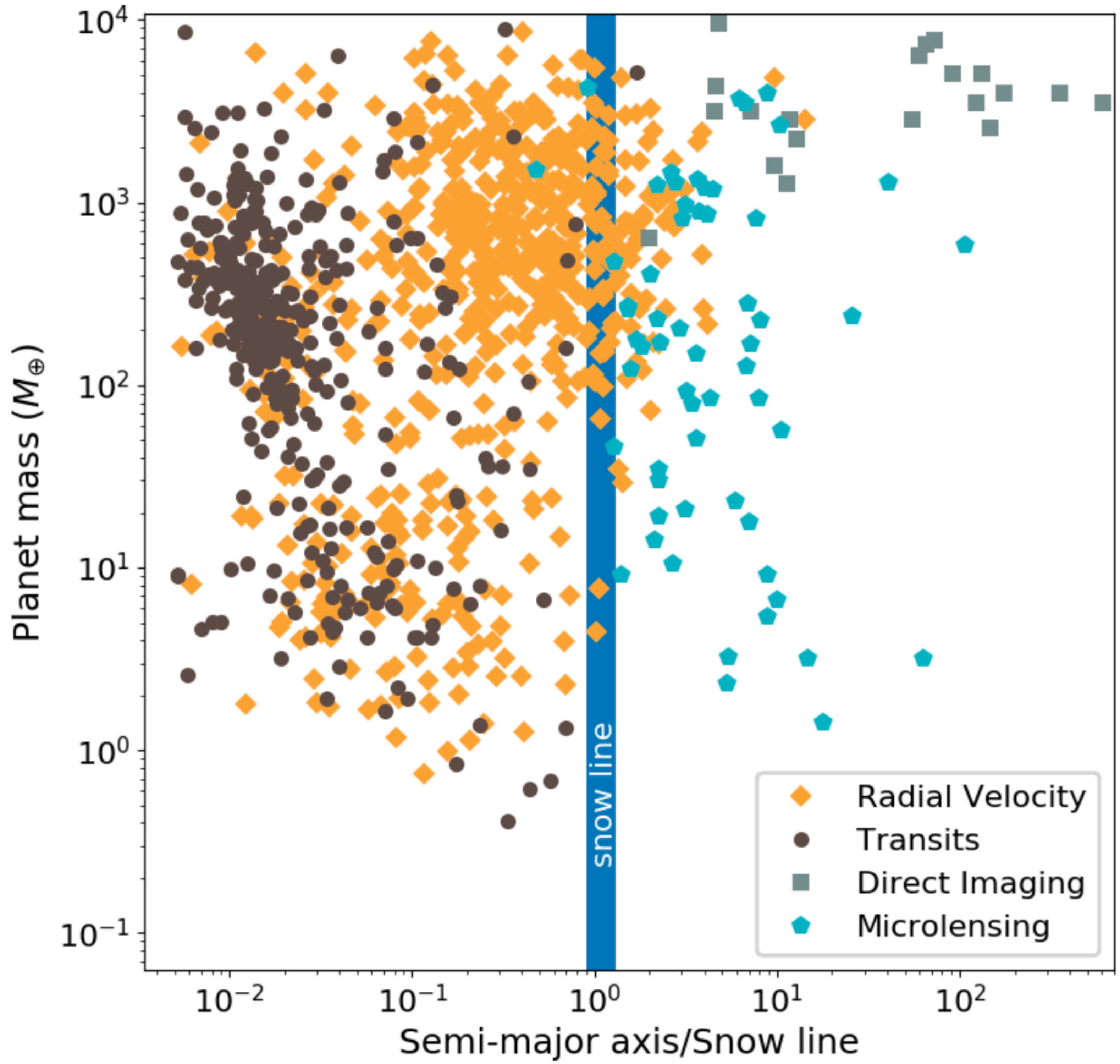
- Planet formation an d evolution is still not fully understood
- Different models predict different distributions of planet masses and distances from the host stars
- Sizes of planets may depend on the mass of the host star, on the position in the galaxy (e.g. on the local metallicity), etc
- Models are thus tested by counting planets of different masses and orbital parameters

METHODS TO SEARCH PLANETS OTHER THAN MICROLENSING

- **Radial velocity shift**: relies on the fact that a star does not remain completely stationary when it is orbited by a planet. The star moves, ever so slightly, in a small circle or ellipse, responding to the gravitational tug of its smaller companion. This produces periodic shifts of lines in the stellar spectra. This method was very successful in ***discovering giant planets near their hosts***.
- **Transit surveys:** identify exoplanets with near edge-on orbits that pass in front of their host stars. **Hundreds of planets within ~1 AU from their hosts** were found by e.g. the NASA's Kepler space mission.
- **Direct imaging:** Massive planets at large distances from their hosts can be visually identified in planetary systems that are not too far away.
- **Astrometry**: involves very precise measurements of a star's position in the sky. If the star is orbited by a planet, periodic shifts of its position occur (for the same reasons that cause the radial velocity shifts).
- **Pulsar timing:** pulsars are rapidly rotating neutron stars that emit periodic pulses of electromagnetic radiation. These pulses become irregular in case the pulsar is orbited by a planet.

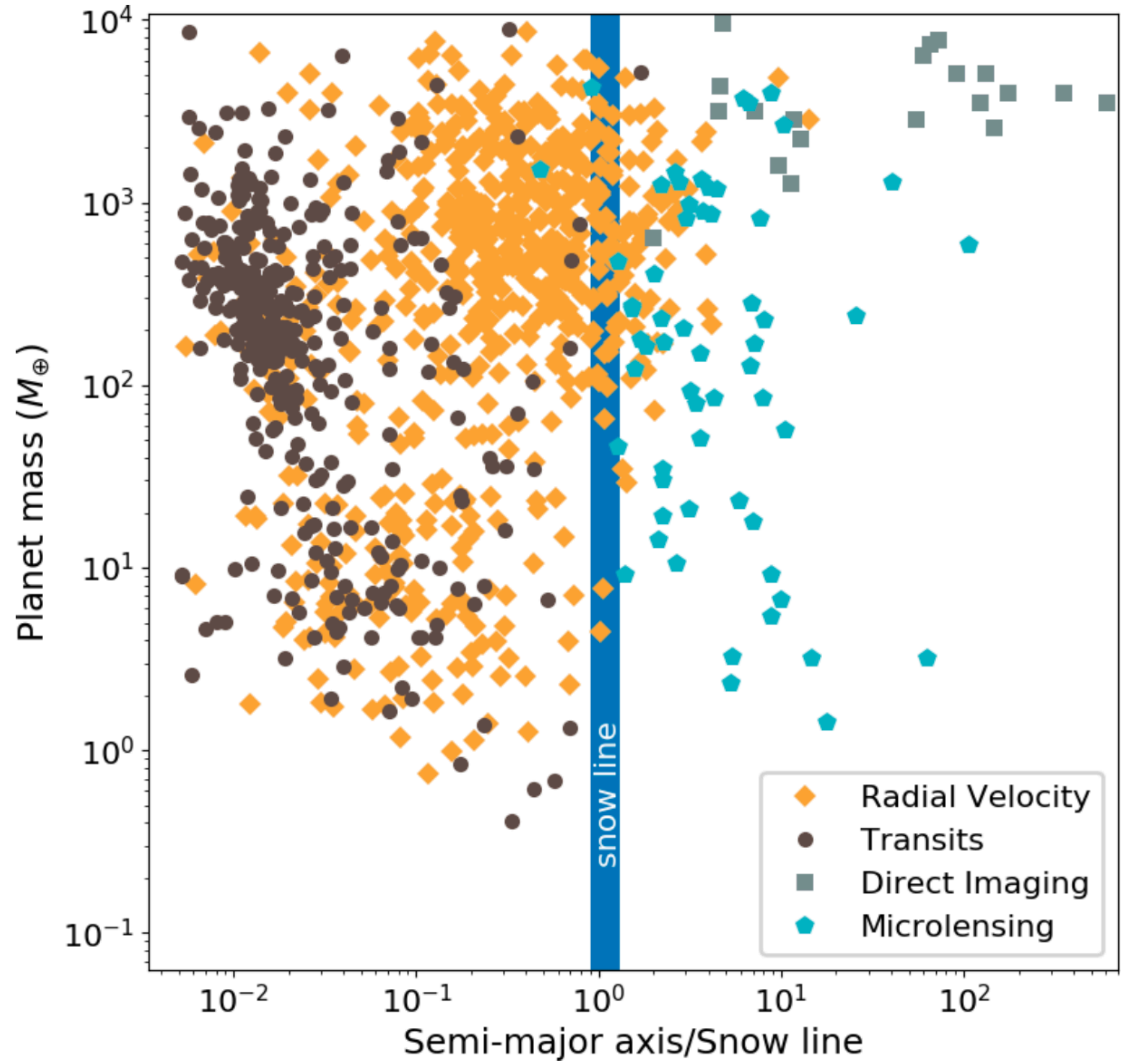
THE CURRENT PICTURE

- ~4400 confirmed exoplanets
- Transits and radial velocity shifts are by far the most successful techniques
- Astrometry: very precise measurements are necessary. Only one detection (not confirmed). Possibly GAIA will revolutionise the picture
- Vast majority of detections are massive planets close to their hosts (<1-2 AU)
- To explore the outer parts of planetary systems, only direct imaging works but it is limited to very massive planets



USING MICROLENSING FOR PLANET SEARCHES

- ~90 planets discovered via microlensing so far
- ~1% of all microlensing events contain planetary anomalies
- 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



USING MICROLENSING FOR PLANET SEARCHES

- planets are most easily identif when they are at a distance ~
- example: 1 mas at ~5kpc=5A
- peak sensitivity beyond the snow line
- the snow line marks a very important region for planet formation!
- Boundary distance from the star beyond which the ambient temperature drops below ~160K and water turns to ice

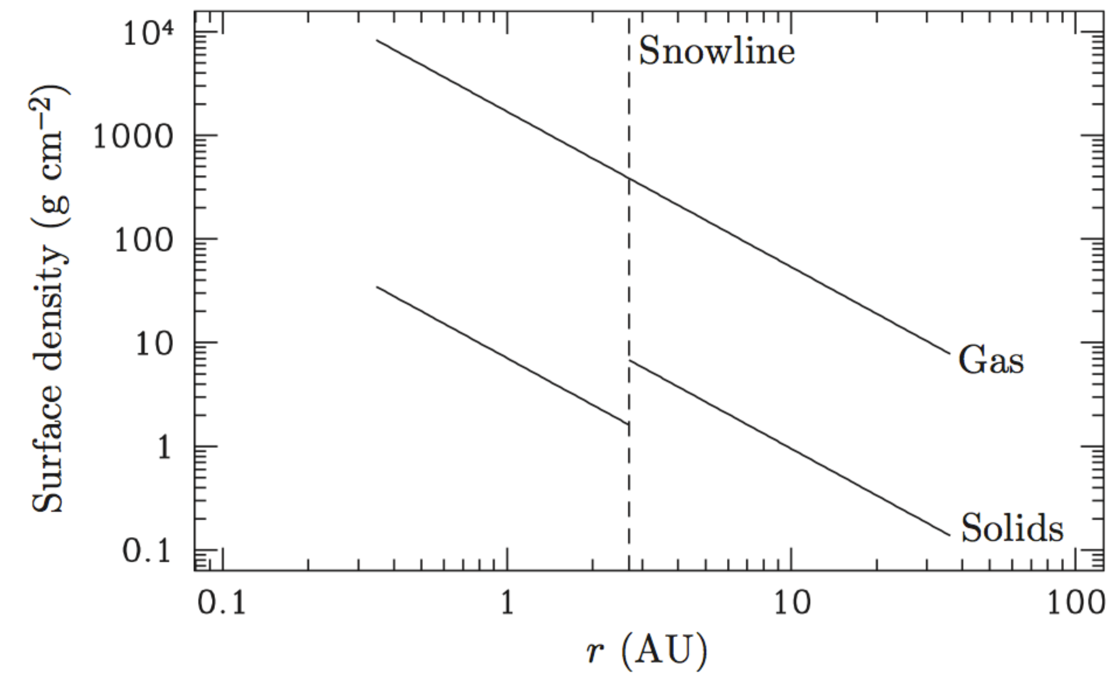
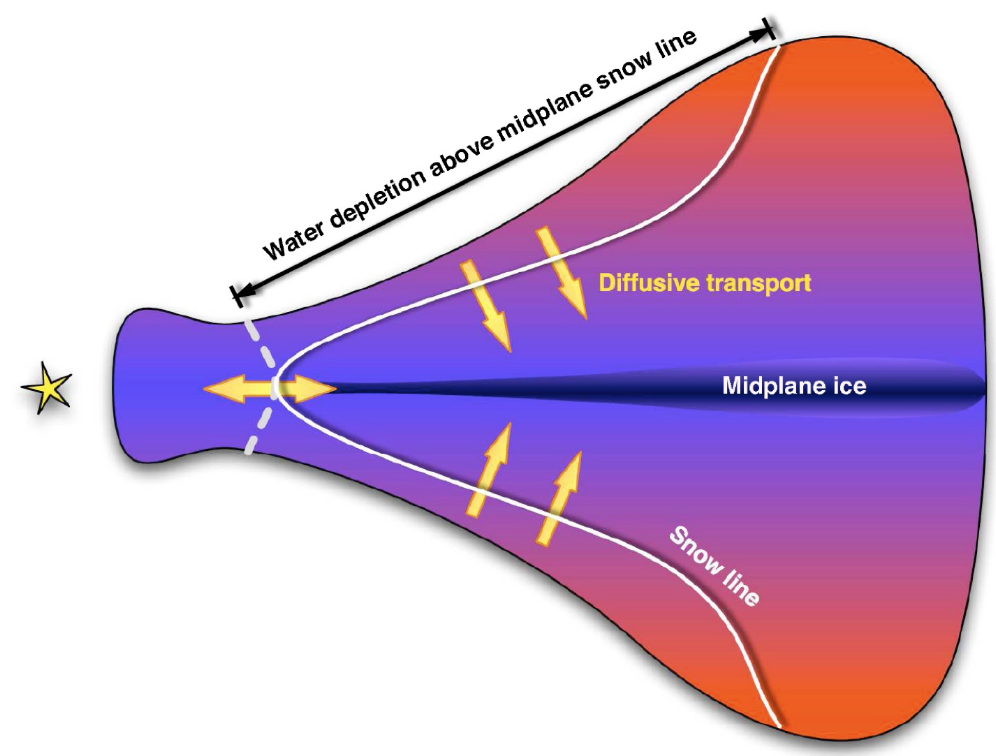
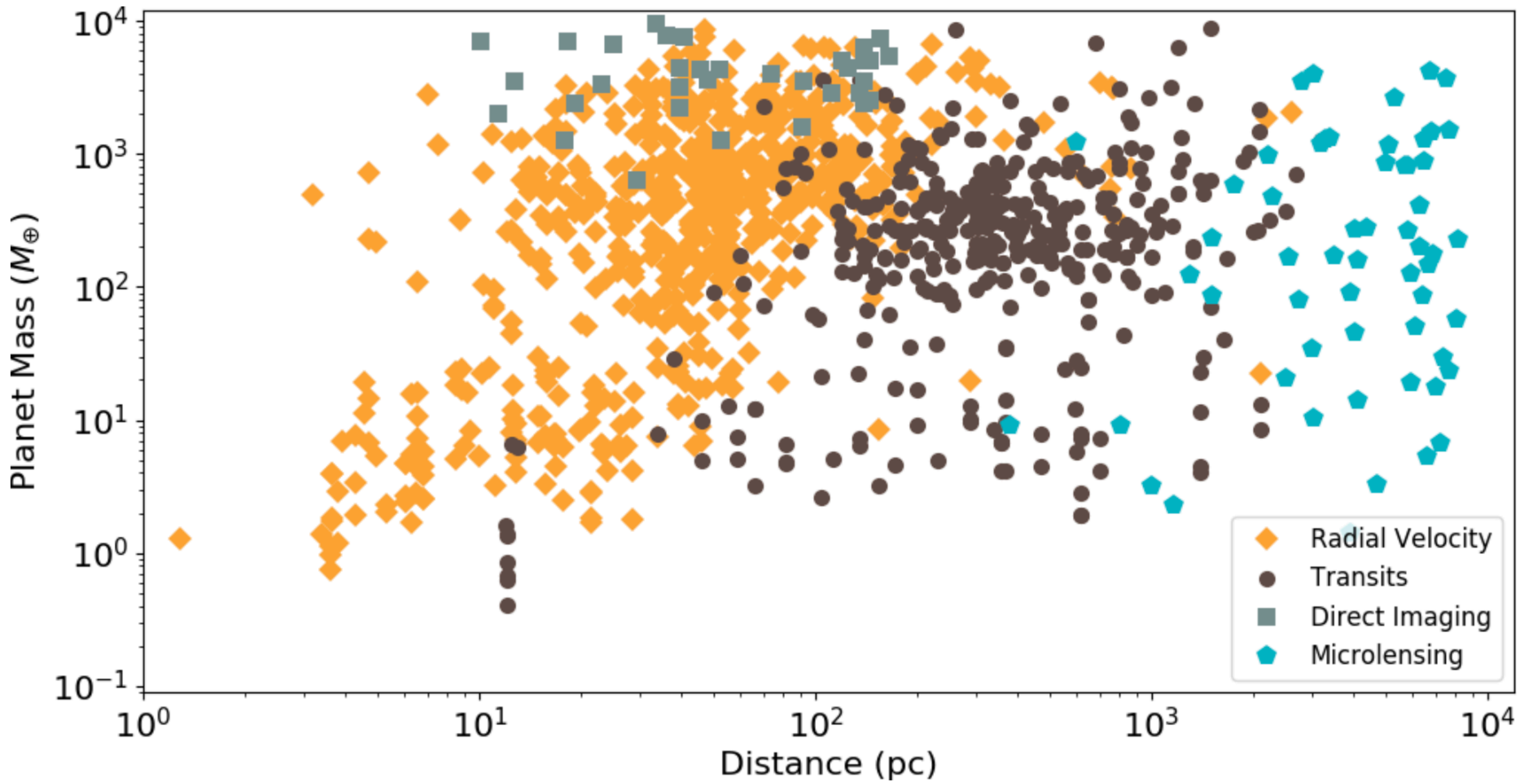


Fig. 1.1. The surface density in gas (upper line) and solids (lower broken line) as a function of radius in Hayashi's minimum mass Solar Nebula. The dashed vertical line denotes the location of the snowline.



IN ADDITION…



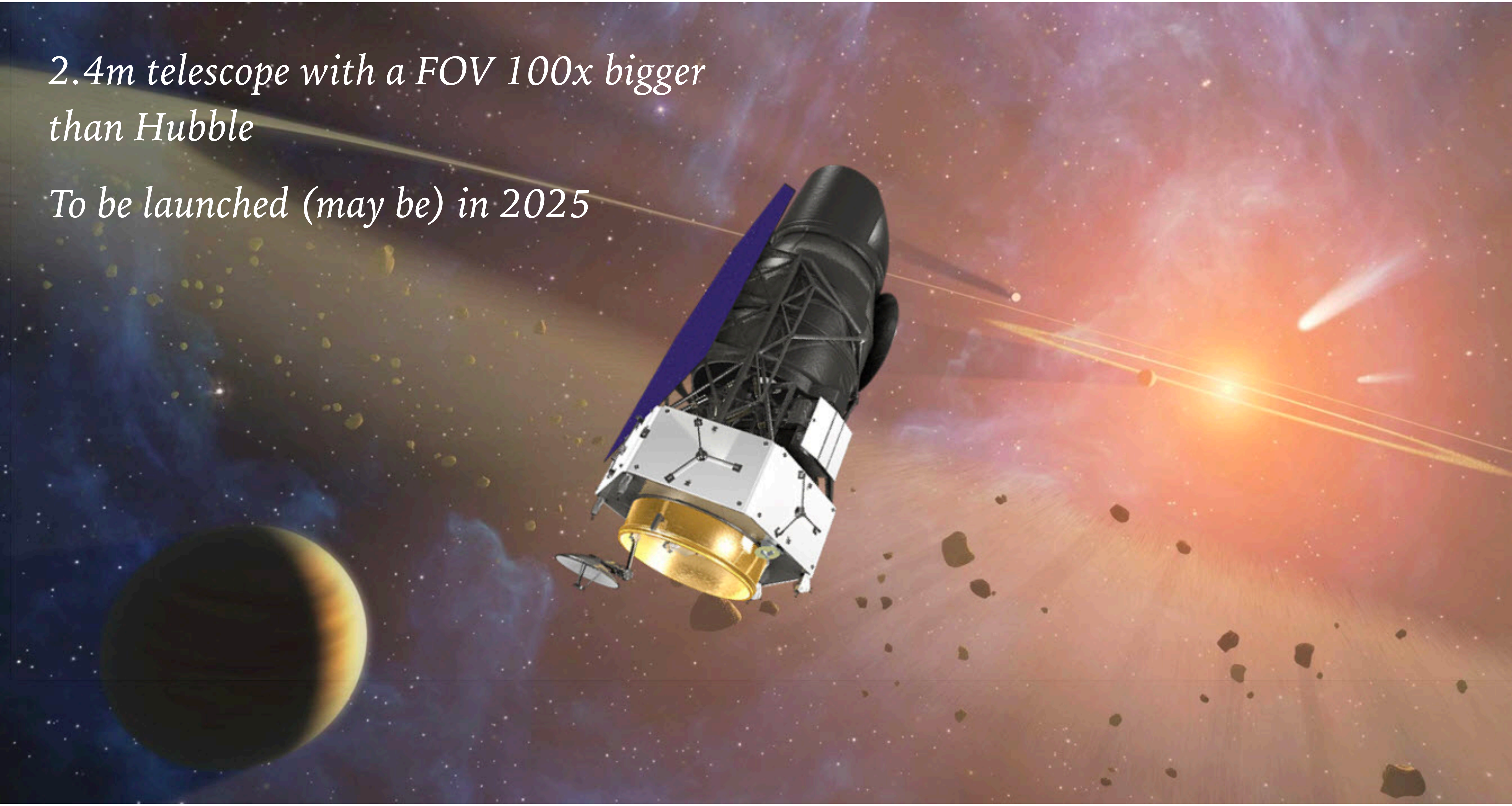
- sensitivity to low-mass planets
- sensitivity to long period and free-floating planets
- sensitivity to a wide range of host stars over a wide range of galacto-centric distances
- sensitivity to multiple planets and orbital parameters…

STRATEGIES TO FIND PLANETS WITH MICROLENSING

By-product of microlensing searches!

1. Find microlensing event: OGLE, MOA, now 10-30 min cadence; Korean Microlensing Telescope Network (KMTNet), 3 telescopes in Australia, South-Africa, and Chile, 1.6 m each monitoring 16 sq. degrees on the sky with a cadence of $\sim$10 mins
2. Planets found as anomalies in the standard light curves: automatic modelling
3. trigger follow-up from other telescopes (e.g. Spitzer)

THE FUTURE: WFIRST



2.4m telescope with a FOV 100x bigger than Hubble

To be launched (may be) in 2025

AND IN ADDITION…

- ➤ Astrometric microlensing (GAIA)
- ➤ VLBI observations to separate the images in a microlensing event