

# GRAVITATIONAL LENSING

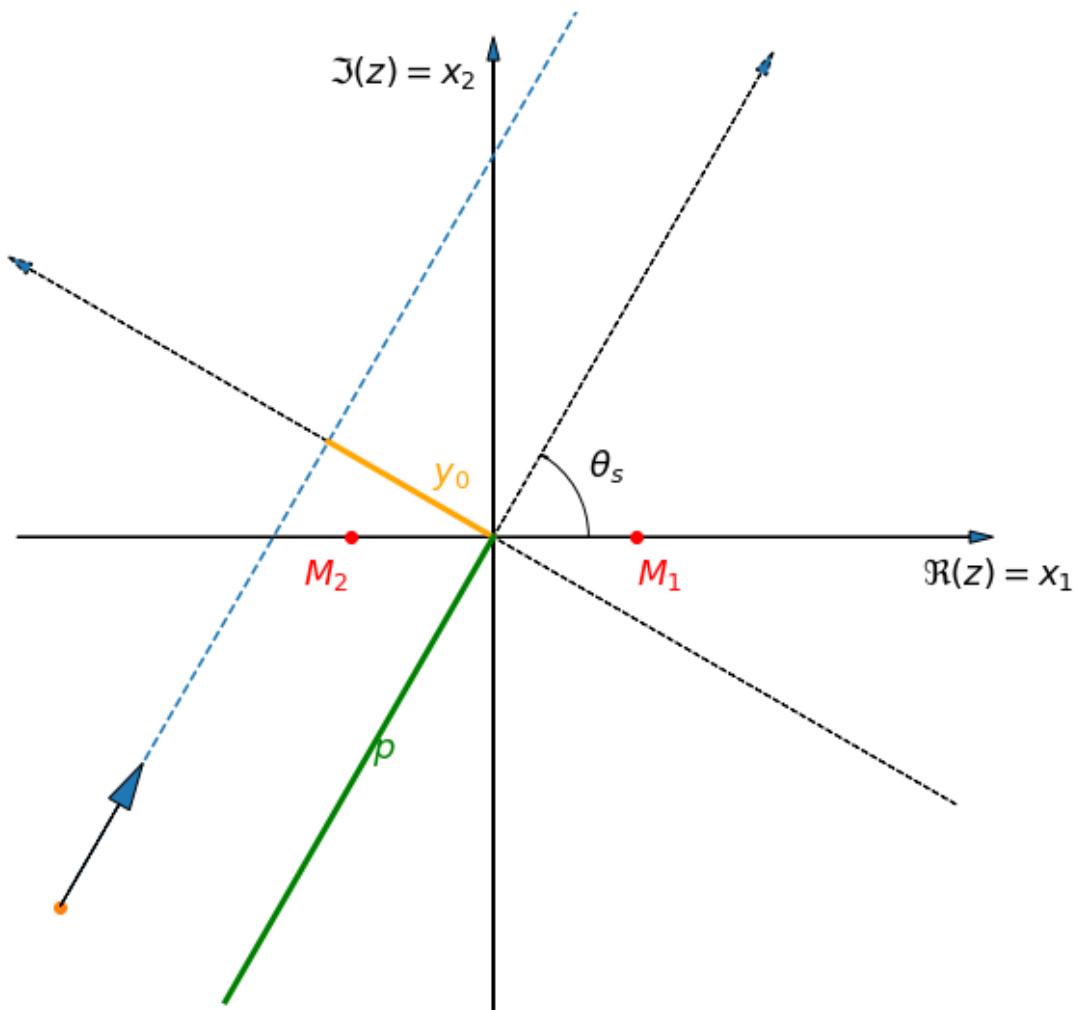
## 10- GRAVITATIONAL MICROLENSING III : BINARY LENSES

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*R. Benton Metcalf*  
2022-2023

# GEOMETRY OF A BINARY LENS

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- Two point masses  $M_1$  and  $M_2$
- Origin is chosen to coincide with the midpoint between the two masses Real axis passes through the two lenses.
- $\theta_S$  inclination of the source trajectory relative to the real axis
- $y_0$ : impact parameter with respect to the origin
- $t_0$ : time of minimum distance from the origin
- $p = \frac{t - t_0}{t_E}$ : time from  $t_0$  in units of  $t_E$
- Position of the source in the complex plane:

$$\Re(z) = p \cos \theta_S - y_0 \sin \theta_S$$

$$\Im(z) = p \sin \theta_S + y_0 \cos \theta_S$$

# LENS EQUATION FOR THE BINARY LENS

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$$z_s = z - \sum_{i=1}^2 \frac{m_i}{z^* - z_i^*} = z - \frac{m_1}{z^* - z_1^*} - \frac{m_2}{z^* - z_2^*}$$

Take the complex conjugate to compute  $z^*$  and insert it back... we obtain a polynomial equation of degree  $(N^2 + 1) = 5$ :

$$p_5(z) = \sum_{i=0}^5 c_i z^i = 0 \quad \Delta m = \frac{m_1 - m_2}{2} \quad m = \frac{m_1 + m_2}{2} \quad z_2 = -z_1 \quad z_1 = z_1^*$$

$$c_0 = z_1^2 [4(\Delta m)^2 z_s + 4m\Delta m z_1 + 4\Delta m z_s z_s^* z_1 + 2m z_s^* z_1^2 + z_s z_s^{*2} z_1^2 - 2\Delta m z_1^3 - z_s z_1^4]$$

$$c_1 = -8m\Delta m z_s z_1 - 4(\Delta m)^2 z_1^2 - 4m^2 z_1^2 - 4m z_s z_s^* z_1^2 - 4\Delta m z_s^* z_1^3 - z_s^{*2} z_1^4 + z_1^6$$

$$c_2 = 4m^2 z_s + 4m\Delta m z_1 - 4\Delta m z_s z_s^* z_1 - 2z_s z_s^{*2} z_1^2 + 4\Delta m z_1^3 + 2z_s z_1^4$$

$$c_3 = 4m z_s z_s^* + 4\Delta m z_s^* z_1 + 2z_s^{*2} z_1^2 - 2z_1^4$$

$$c_4 = -2m z_s^* + z_s z_s^{*2} - 2\Delta m z_1 - z_s z_1^2$$

$$c_5 = z_1^2 - z_s^{*2}$$

Up to 5 images

# CRITICAL LINES AND CAUSTICS

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$$\det A = 1 - \left| \sum_{i=1}^2 \frac{m_i}{(z^* - z_i^*)^2} \right|^2 = 1 - \left| \frac{m_1}{(z^* - z_1^*)^2} + \frac{m_2}{(z^* - z_2^*)^2} \right|^2 = 0$$

Or

$$\left| \frac{m_1}{(z^* - z_1^*)^2} + \frac{m_2}{(z^* - z_2^*)^2} \right|^2 = 1 \Rightarrow \frac{m_1}{(z^* - z_1^*)^2} + \frac{m_2}{(z^* - z_2^*)^2} = e^{i\phi} \quad \forall \phi \in [0, 2\pi)$$

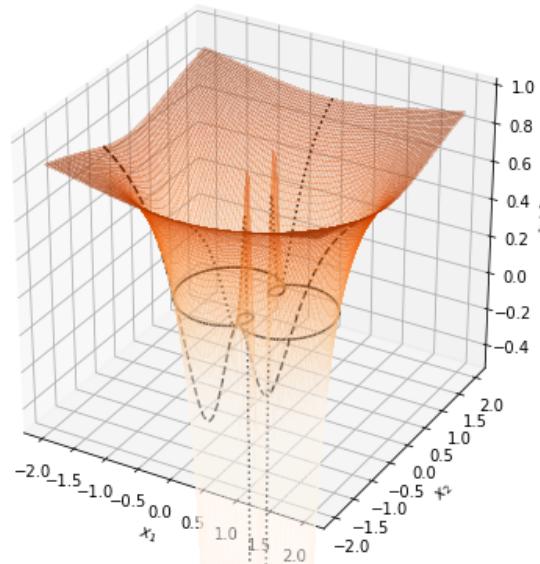
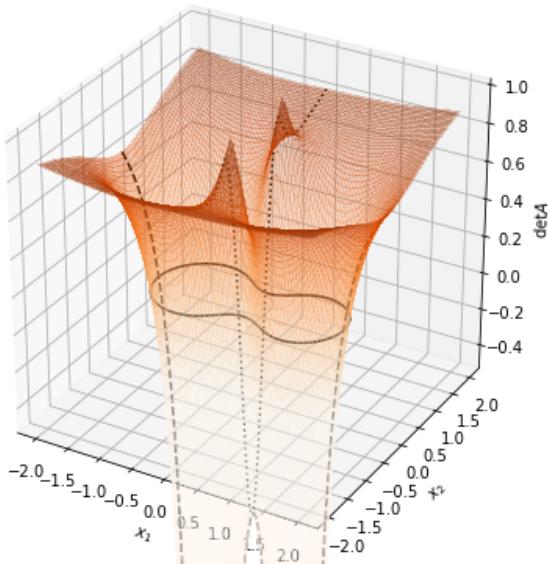
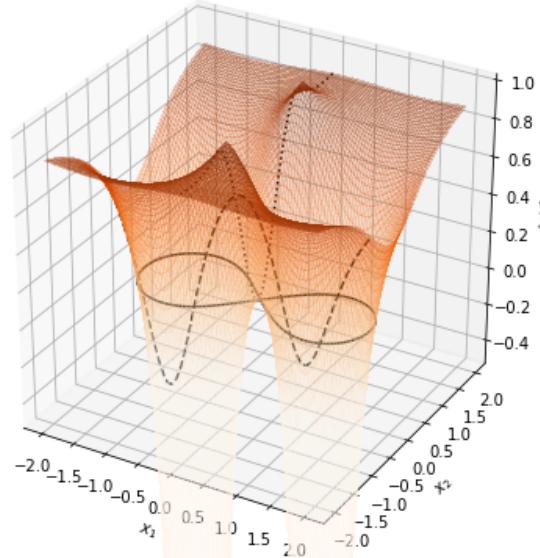
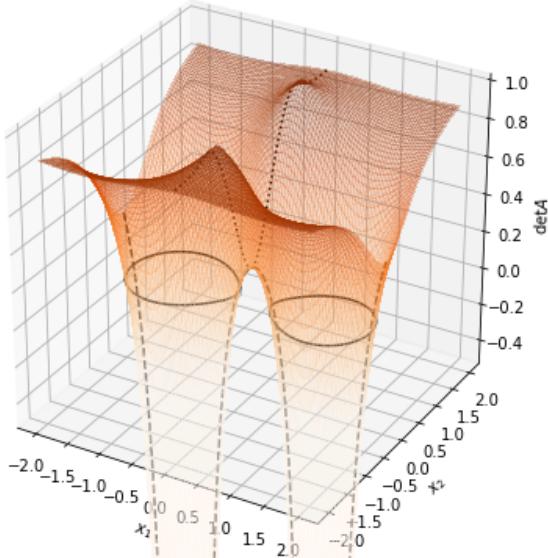
Which can be reduced to

$$p_4(z) = z^4 - z^2(2z_1^{*2} + e^{i\phi}) - zz_1^*2(m_1 - m_2)e^{i\phi} + z_1^{*2}(z_1^{*2} - e^{i\phi}) = 0$$

Once the roots are found (critical points), the caustics can be obtained using the lens equation:

$$z_{cau} = z_{crit} - \frac{m_1}{z_{crit}^* - z_1^*} - \frac{m_2}{z_{crit}^* - z_2^*}$$

# $\det A$ SURFACES



Depending on the distance between the two lenses

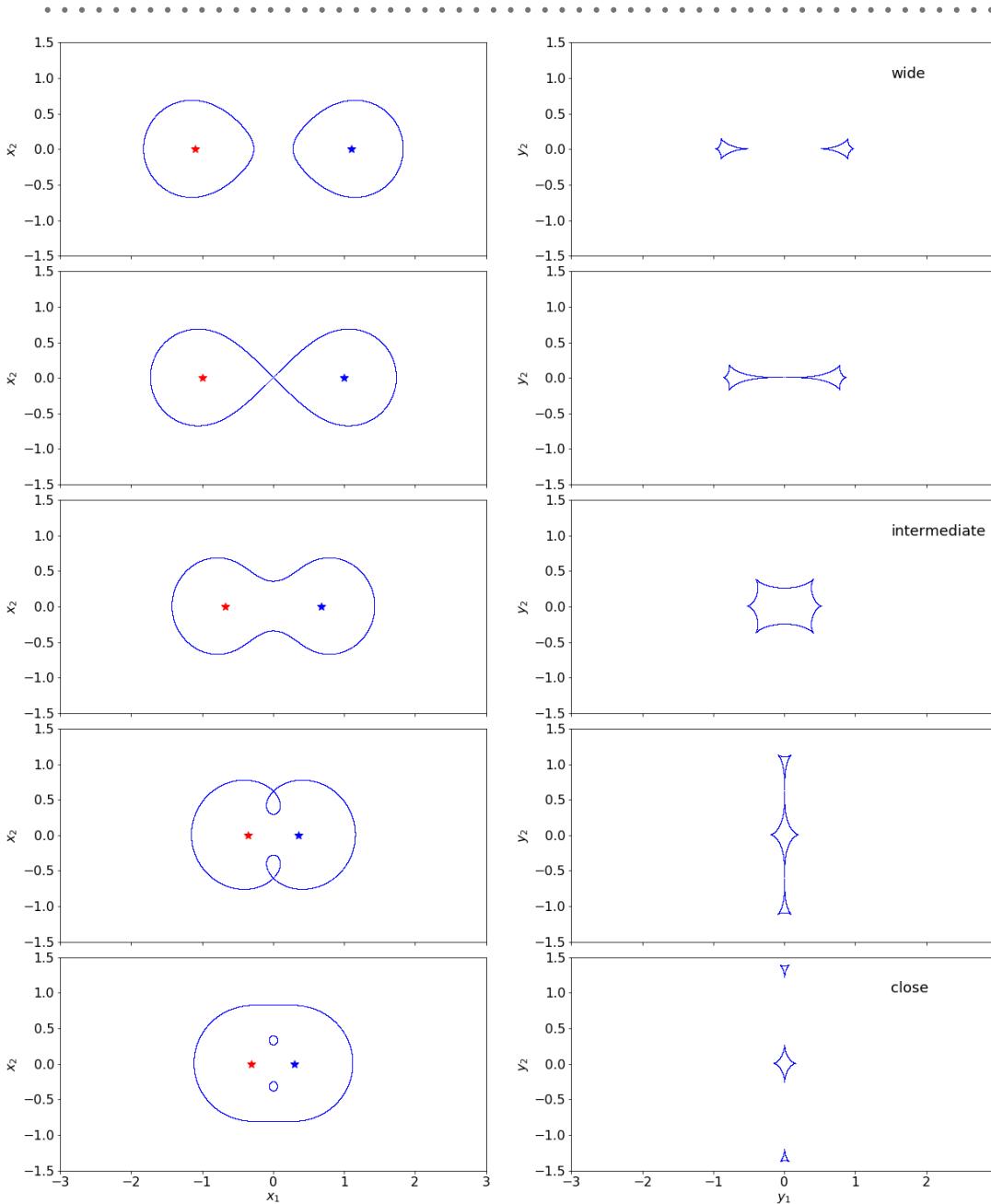
$$d = z_1 - z_2 = 2z_1$$

we can have one, two, or three critical lines. Note that the transitions between these three regimes happen when critical lines touch.

This happens at saddle points of the  $\det A$  surface!

$$\frac{\partial \det A}{\partial z^*} = 0$$

# CAUSTIC (AND CRITICAL LINE) TOPOLOGIES



$$d > d_{WI}$$

$$d = d_{WI} = (m_1^{1/3} + m_2^{1/3})^{3/2}$$

$$d_{IC} < d < d_{WI}$$

$$d = d_{IC} = (m_1^{1/3} + m_2^{1/3})^{-3/4}$$

$$d < d_{IC}$$

# MAGNIFICATION

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*On the lens plane, the magnification is*

$$\det A(z) = 1 - \left| \sum_{i=1}^2 \frac{m_i}{(z^* - z_i^*)^2} \right| \quad \mu(z) = \det A(z)^{-1}$$

*Remember that even microlensing by binary lenses will be revealed through magnification effects.*

*No single images will be observed! Thus, what matters is the total magnification of all images of a given source:*

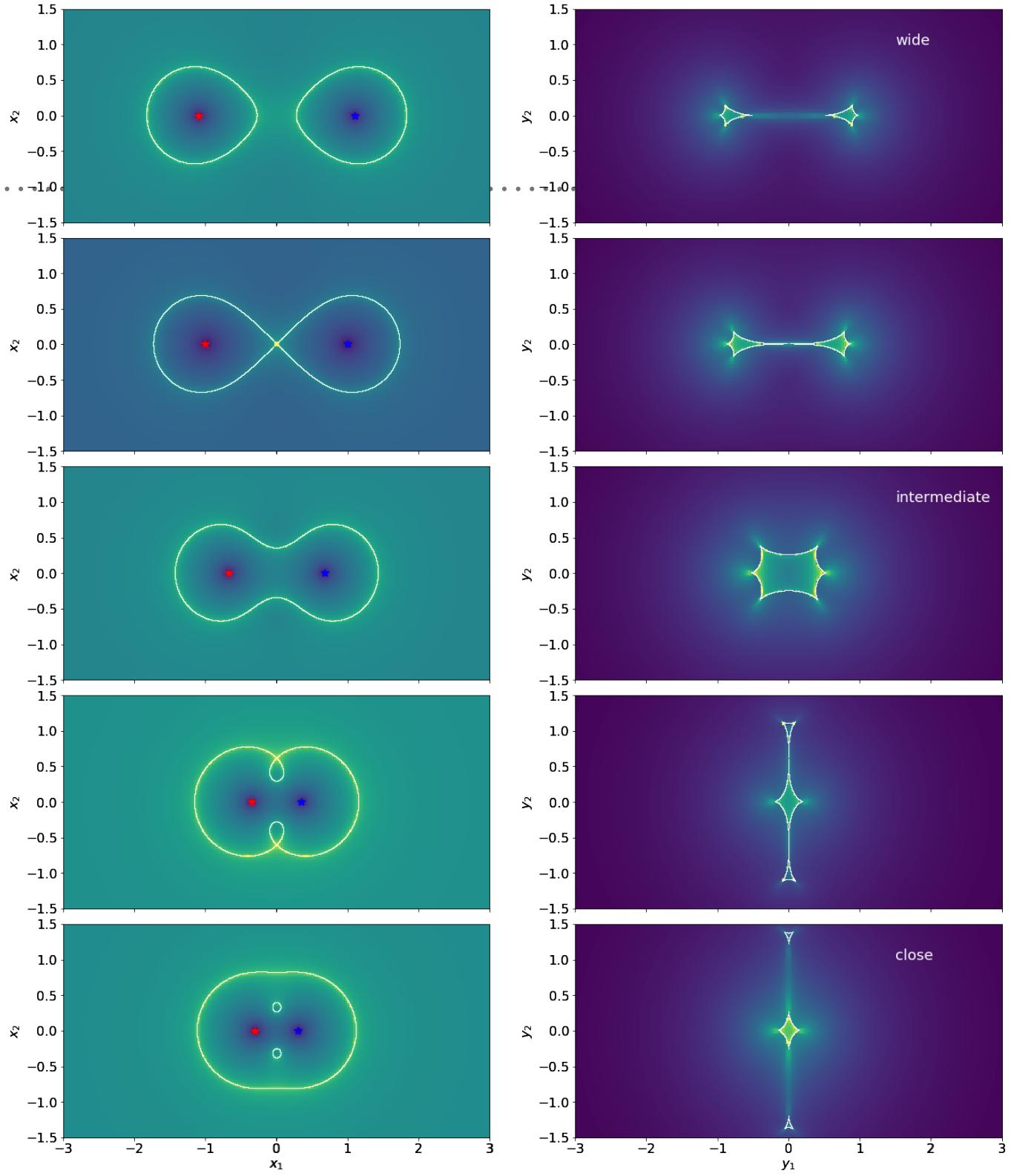
$$\mu(z_s) = \sum_{\text{images}} |\mu_{ima}(z_{ima})| \quad \text{where } z_{ima} \text{ are now the positions of the images of the source at } z_s$$

# EXAMPLES

Shown are maps of the magnification on the lens (left) and on the source plane (right)

We can recognise the critical lines and the caustics (where magnification diverges)

These maps are very important: depending on the trajectory on the source relative to the lens, several of these features will be impressed in the light-curves!



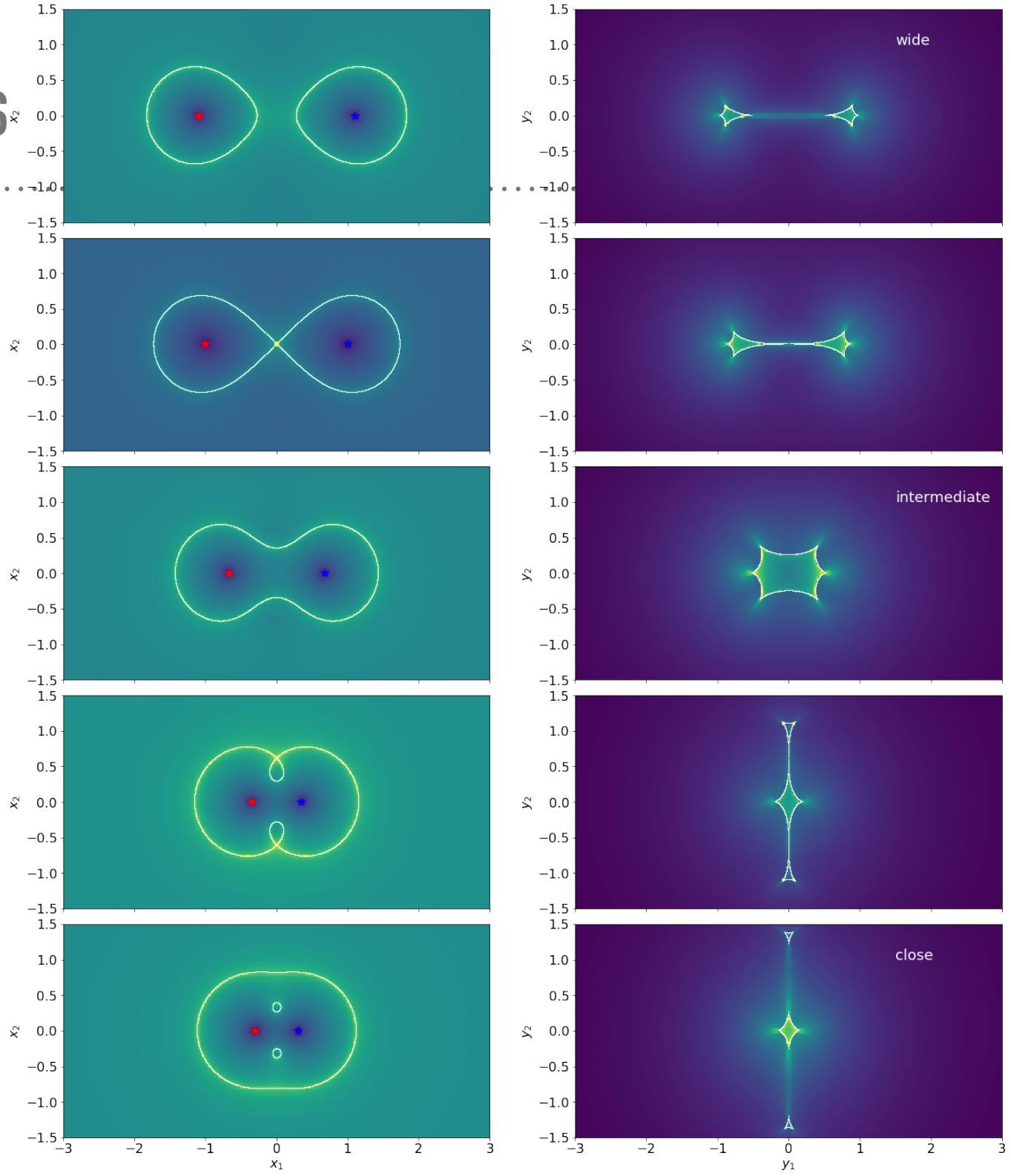
# INTERESTING PROPERTIES

*Lobes of high magnification near the cusps*

*Sharp magnification changes on the folds*

*Inside the caustics: moderately high magnification  $\mu > 3$  (Witt & Mao 1995)*

*Extended regions of high magnification in between the caustics in wide and close systems*



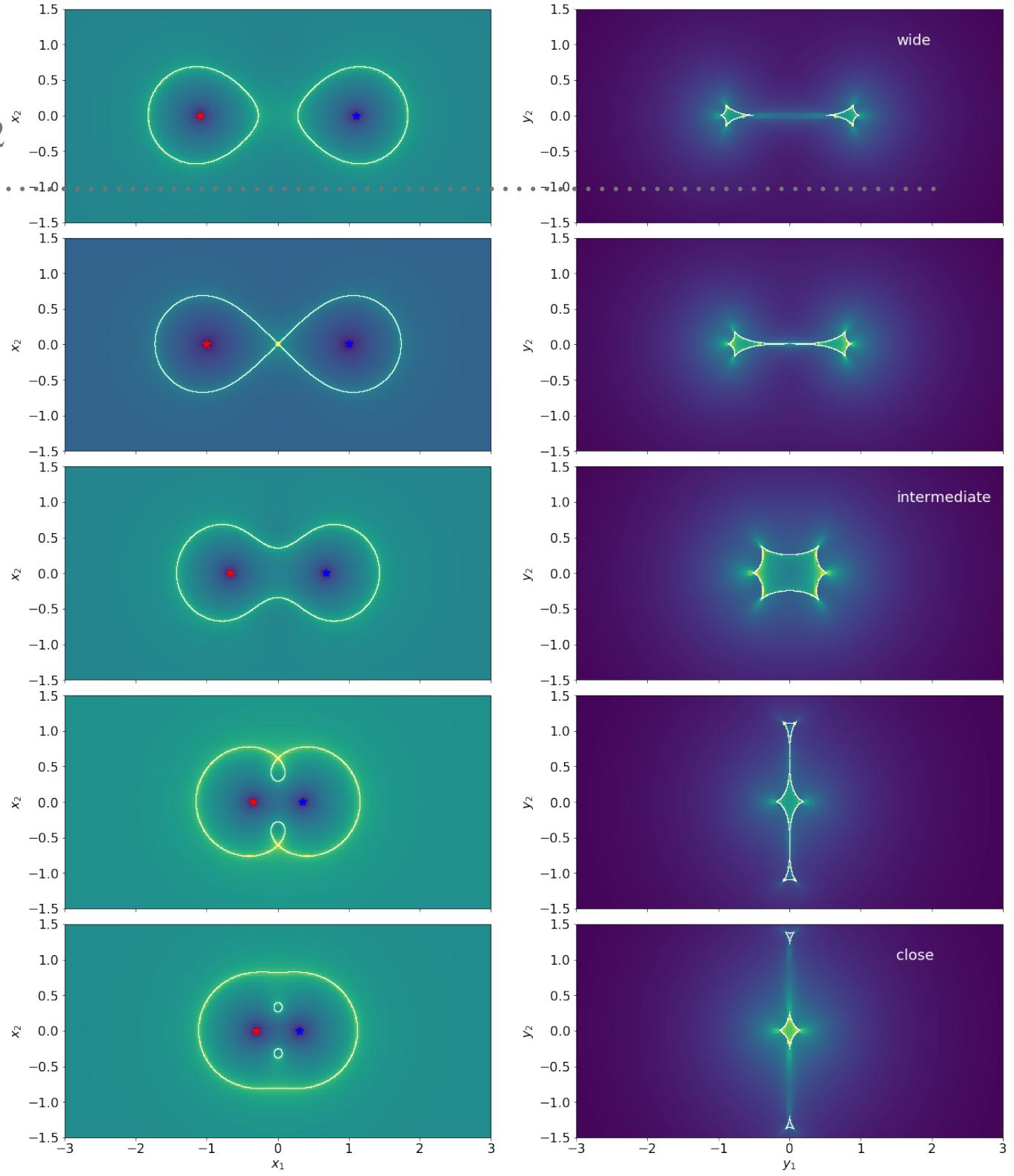
## DEPENDENCE ON $q = M_1/M_2$

As  $q$  changes, the morphologies of the magnification maps, critical lines and caustics change

Critical lines: larger around the primary lens, smaller around the secondary

Wide systems: smaller caustic for the primary, larger for the secondary

Close systems: secondary caustics move to the back of the primary



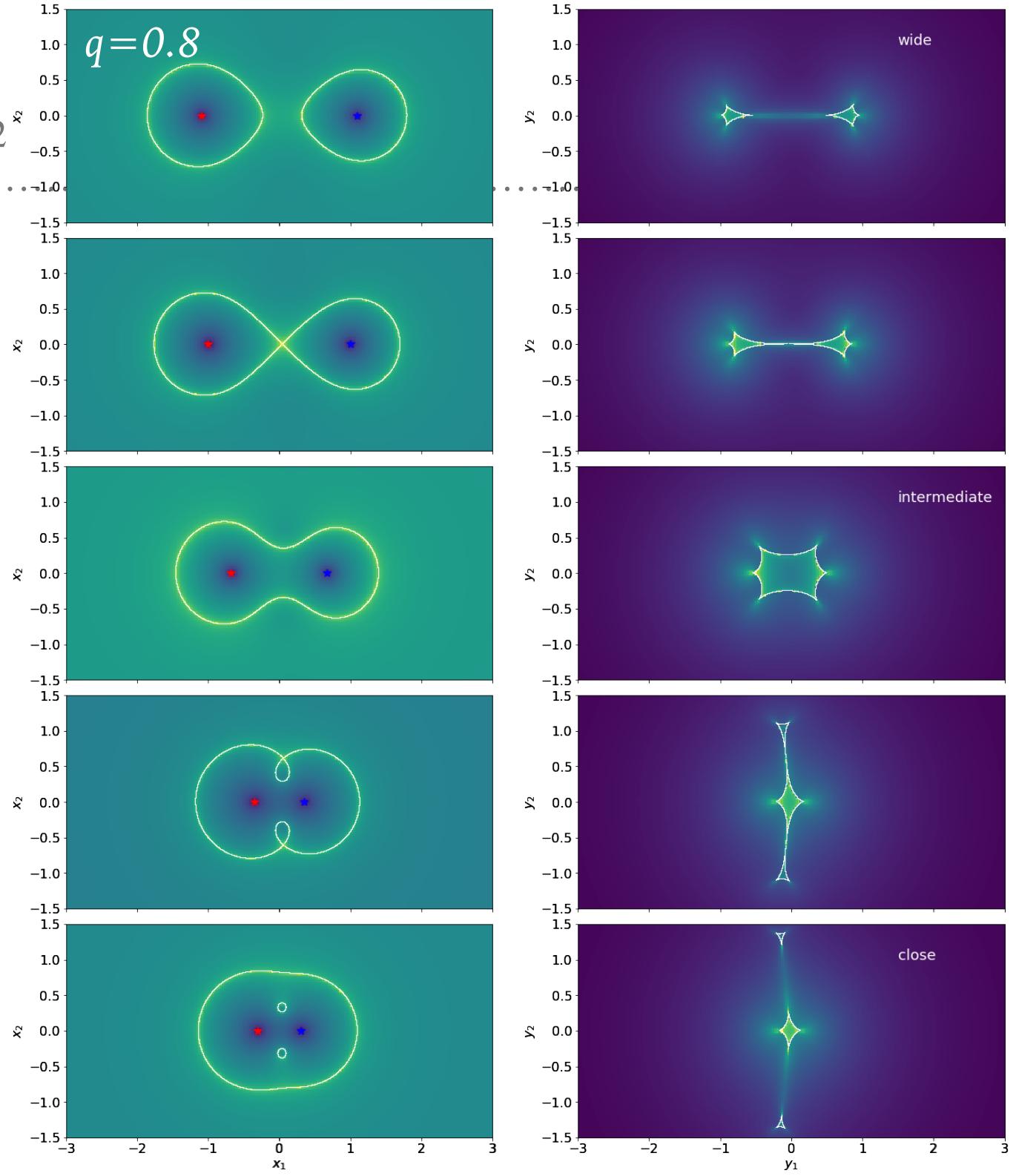
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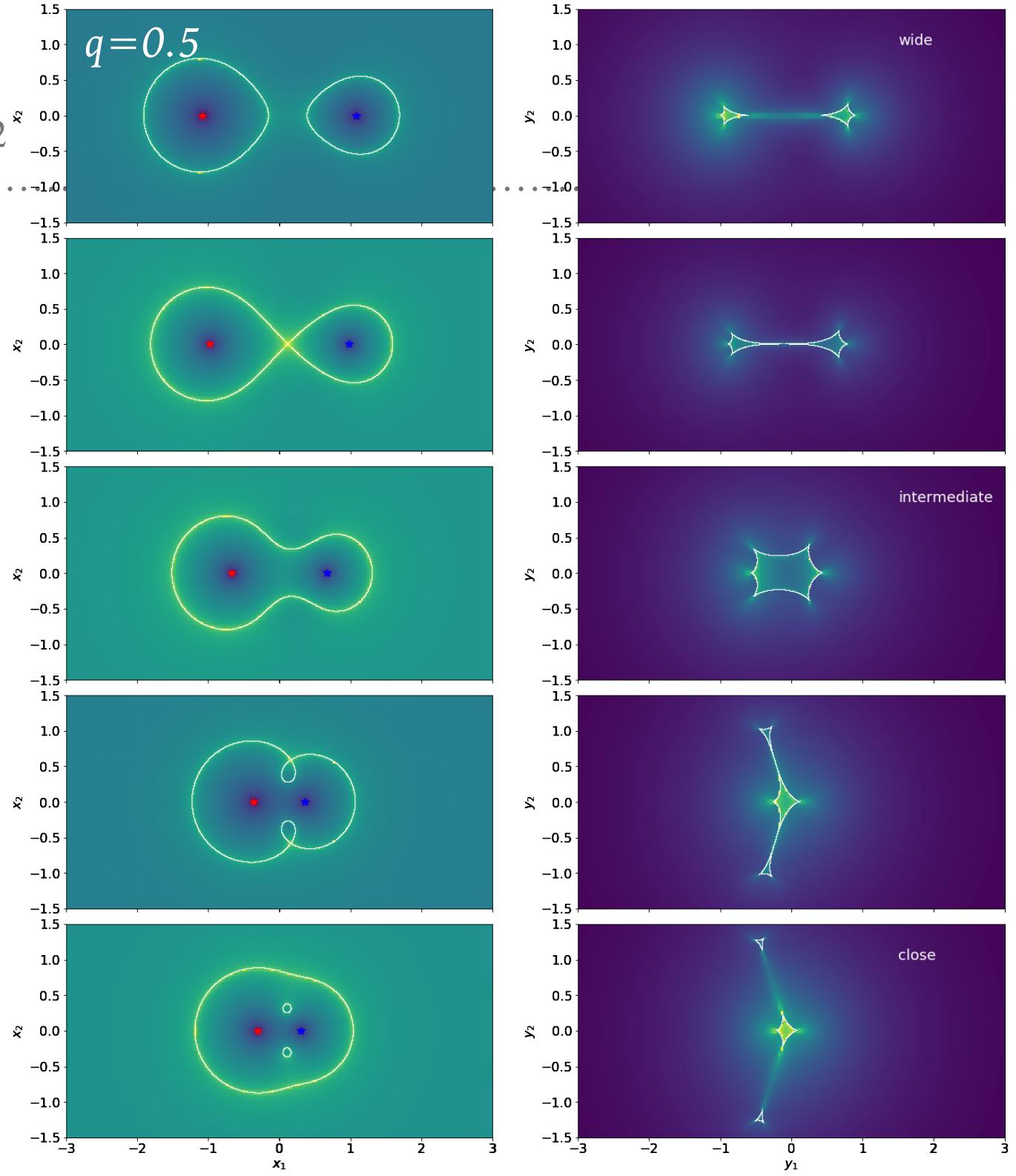
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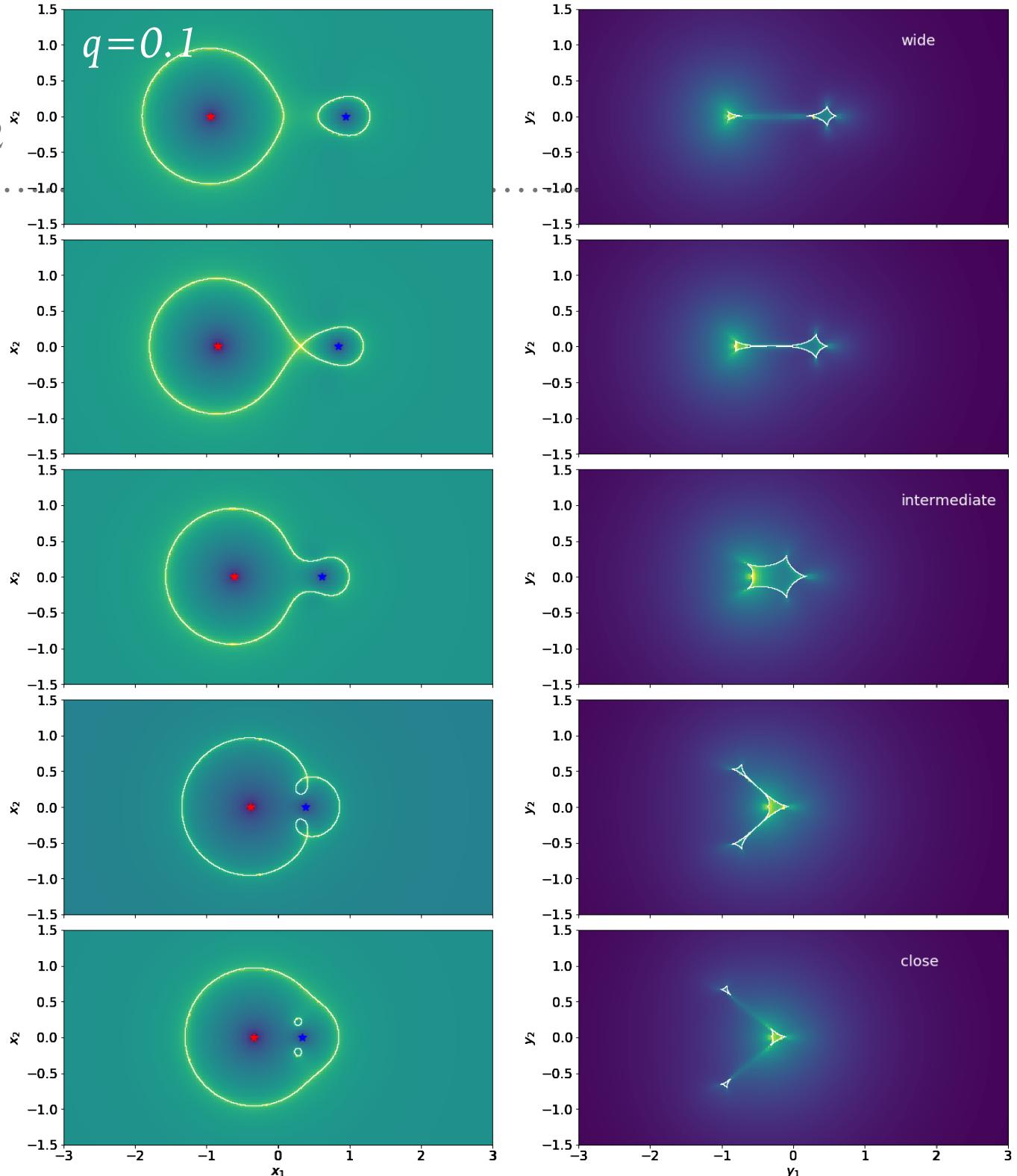
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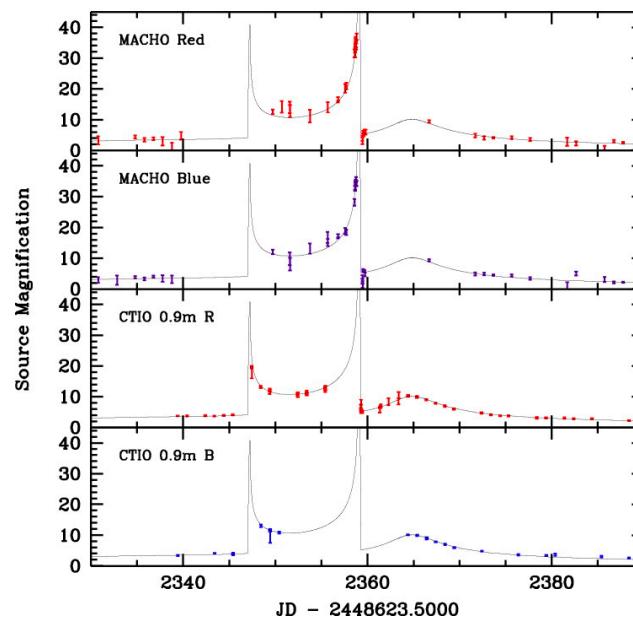
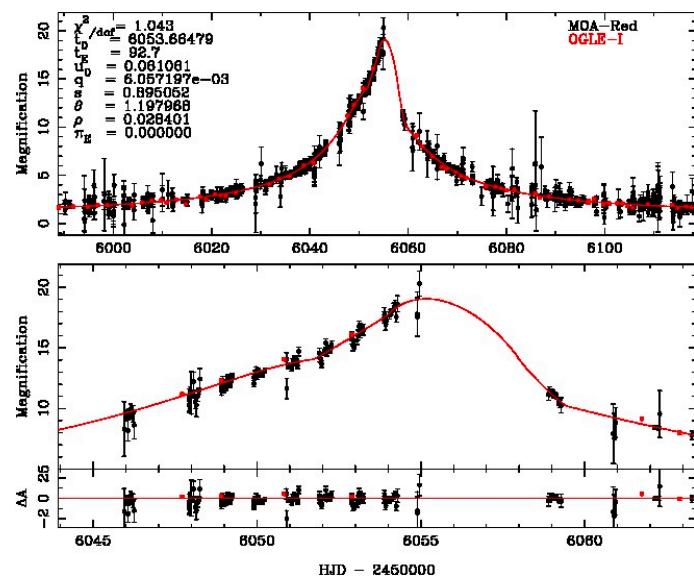
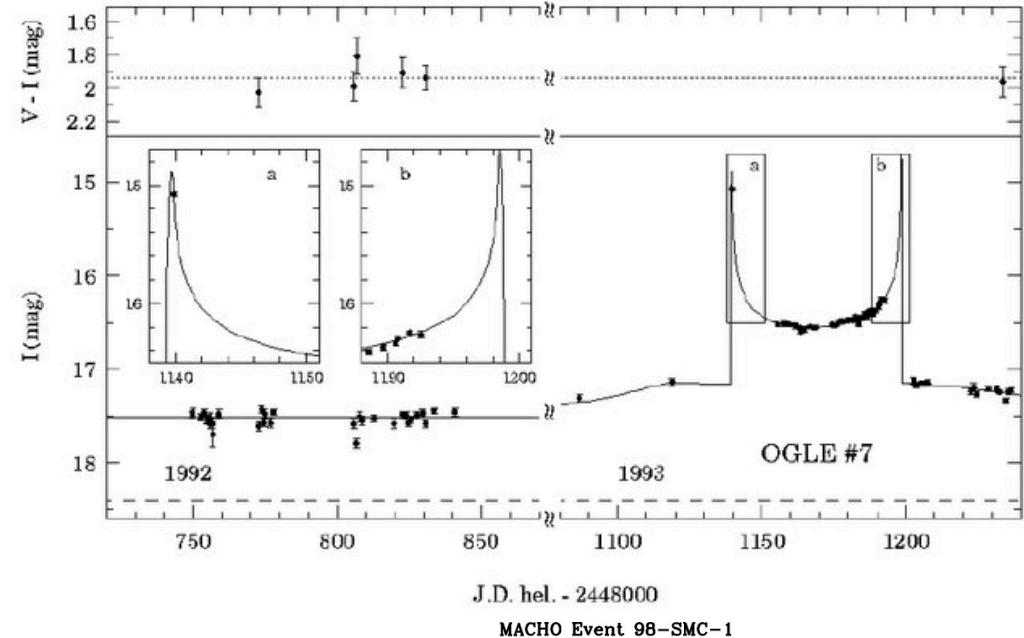
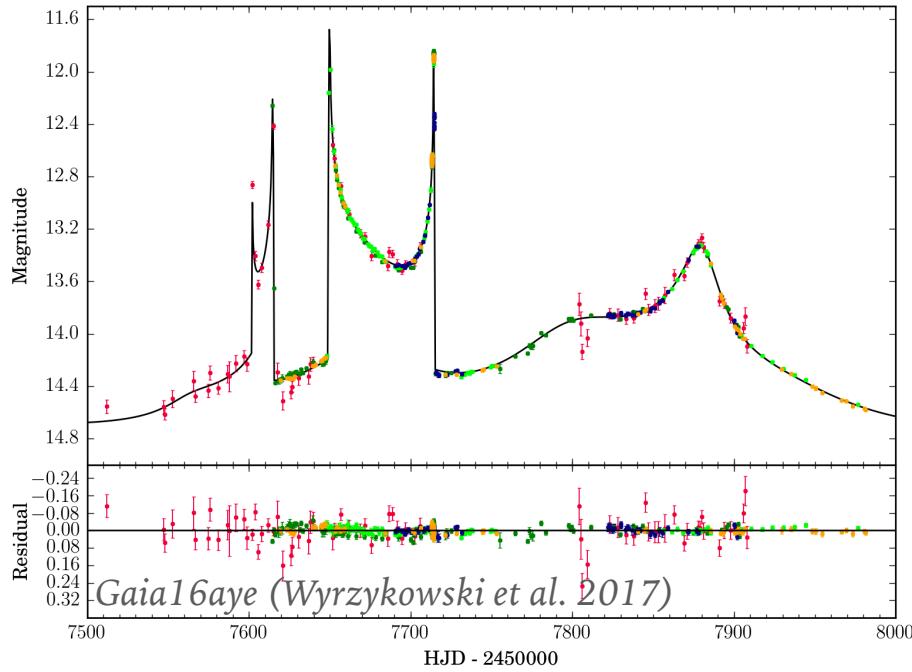
*Wide systems: smaller caustic for the primary, larger for the secondary*

*Close systems: secondary caustics move to the back of the primary*



# SOME OBSERVED LIGHT CURVES

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# PLANETARY MICROLENSING

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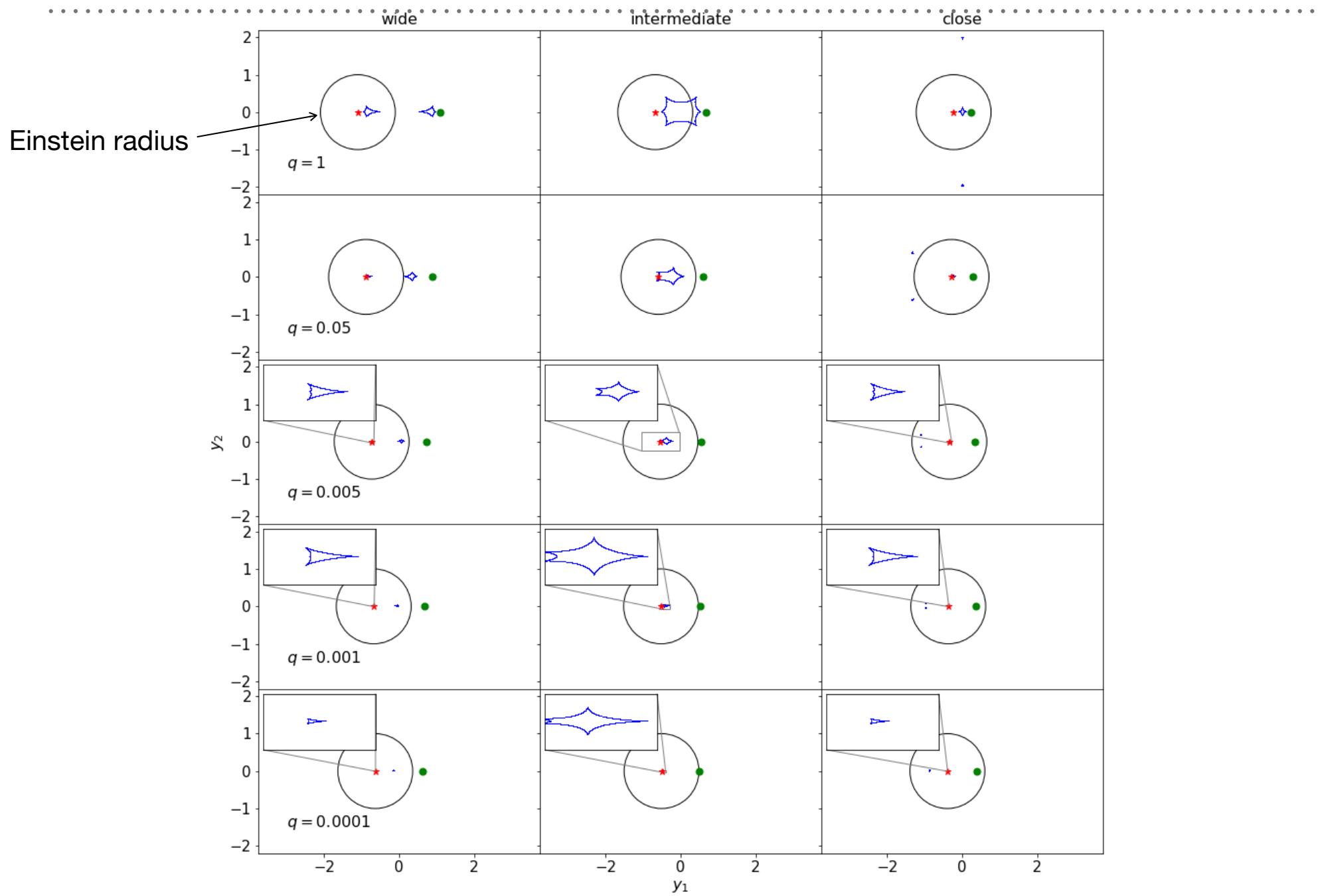
Consider a system of a host star and a planet orbiting it.

This is a binary system where the mass ratio  $q$  is very small.

example : For the Jupiter- Sun system  $q = 0.001$ .

example : For the Earth- Sun system  $q = 3 \times 10^{-6}$ .

# CAUSTICS AS A FUNCTION OF $q = m_2/m_1$



# PLANETARY MICROLENSING

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Light curve is mostly that of an isolated star, but ...

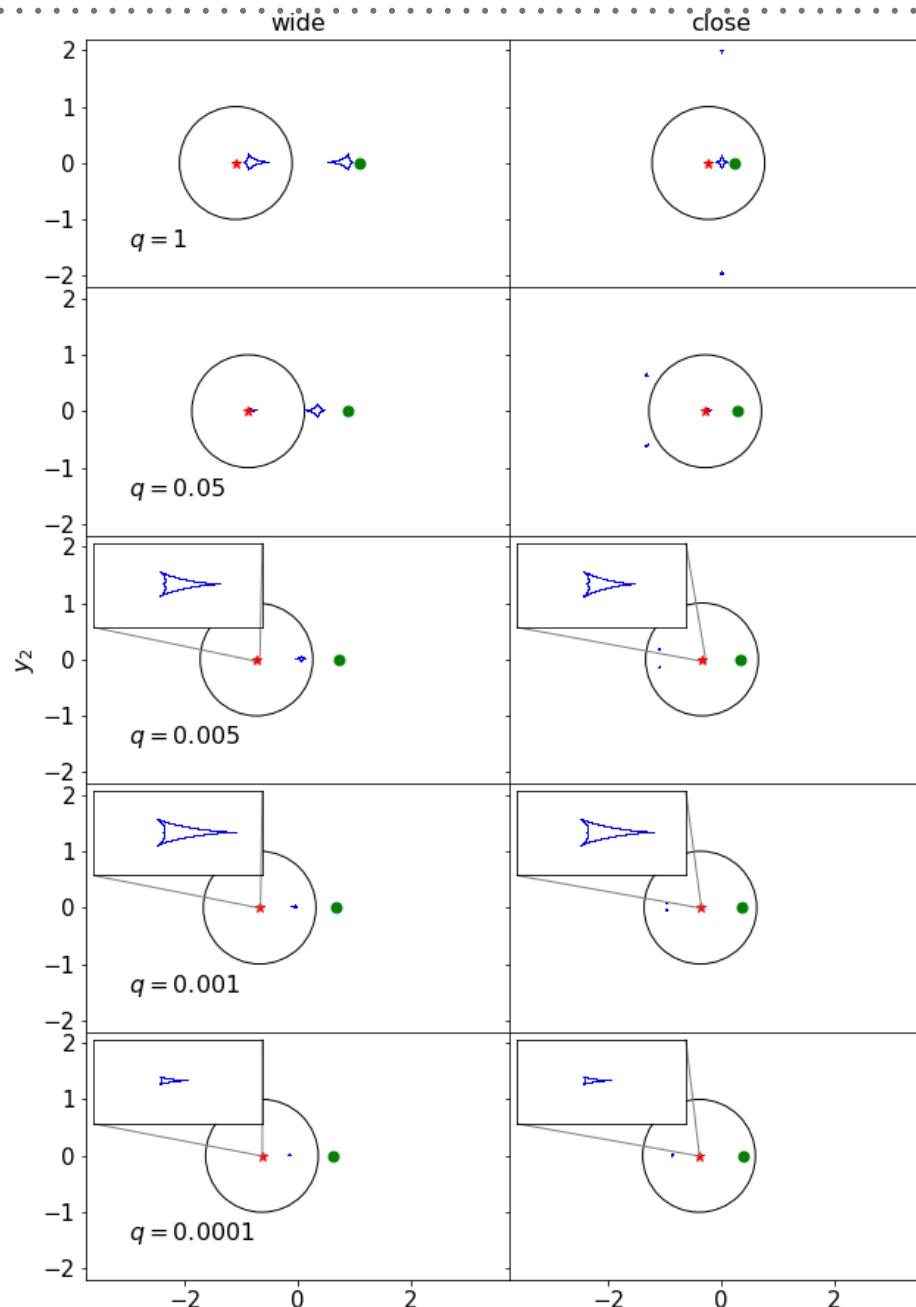
The planets produce small perturbations to the magnification pattern, localized to a small region of near the caustics.

The source must cross one of these perturbed regions to produce a detectable effect.

The shape of the perturbation to the light curve is determined by the caustic configuration.

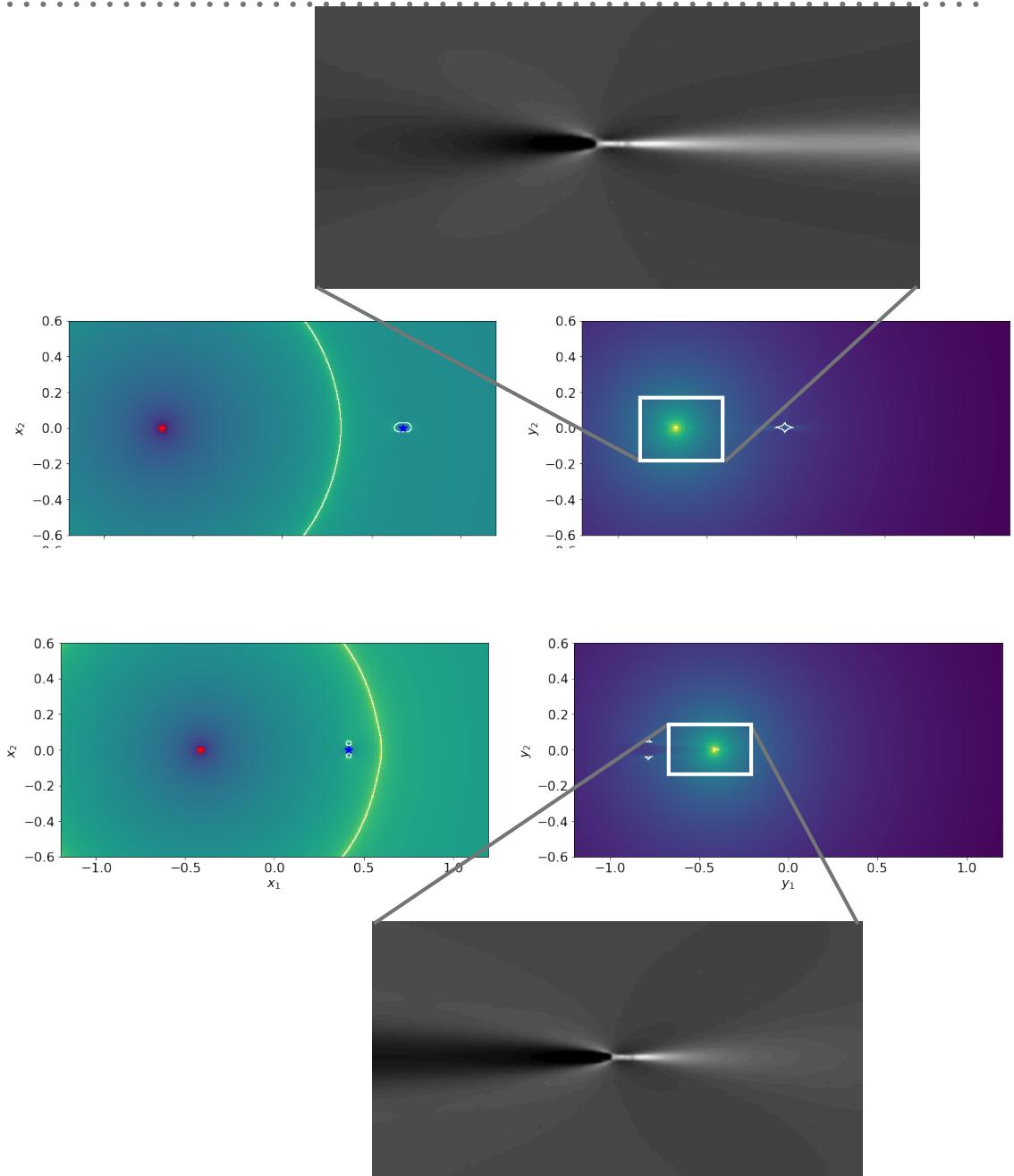
# PERTURBATIONS OF THE CENTRAL CAUSTIC (WIDE/CLOSE SYSTEMS)

- As  $q$  decreases, we see that one caustic shrinks and approaches the primary lens (i.e. the star)
- This is what we call the “*central caustic*” in wide and close systems
- Four cusps and four folds
- One cusp is elongated towards the planet
- Three cusps on the back
- Different from point-like caustic of a point lens!

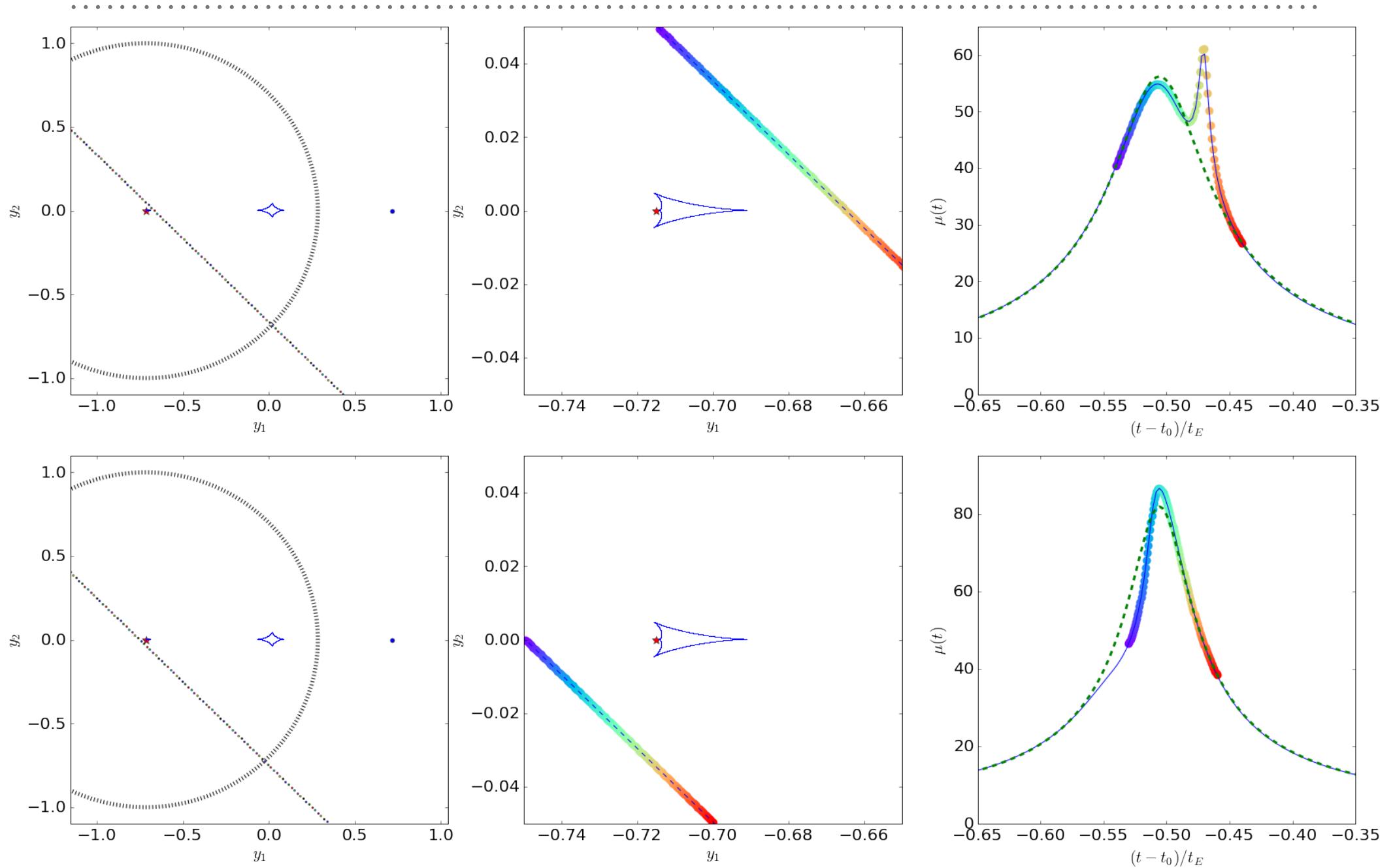


# WHAT KIND OF SIGNATURES?

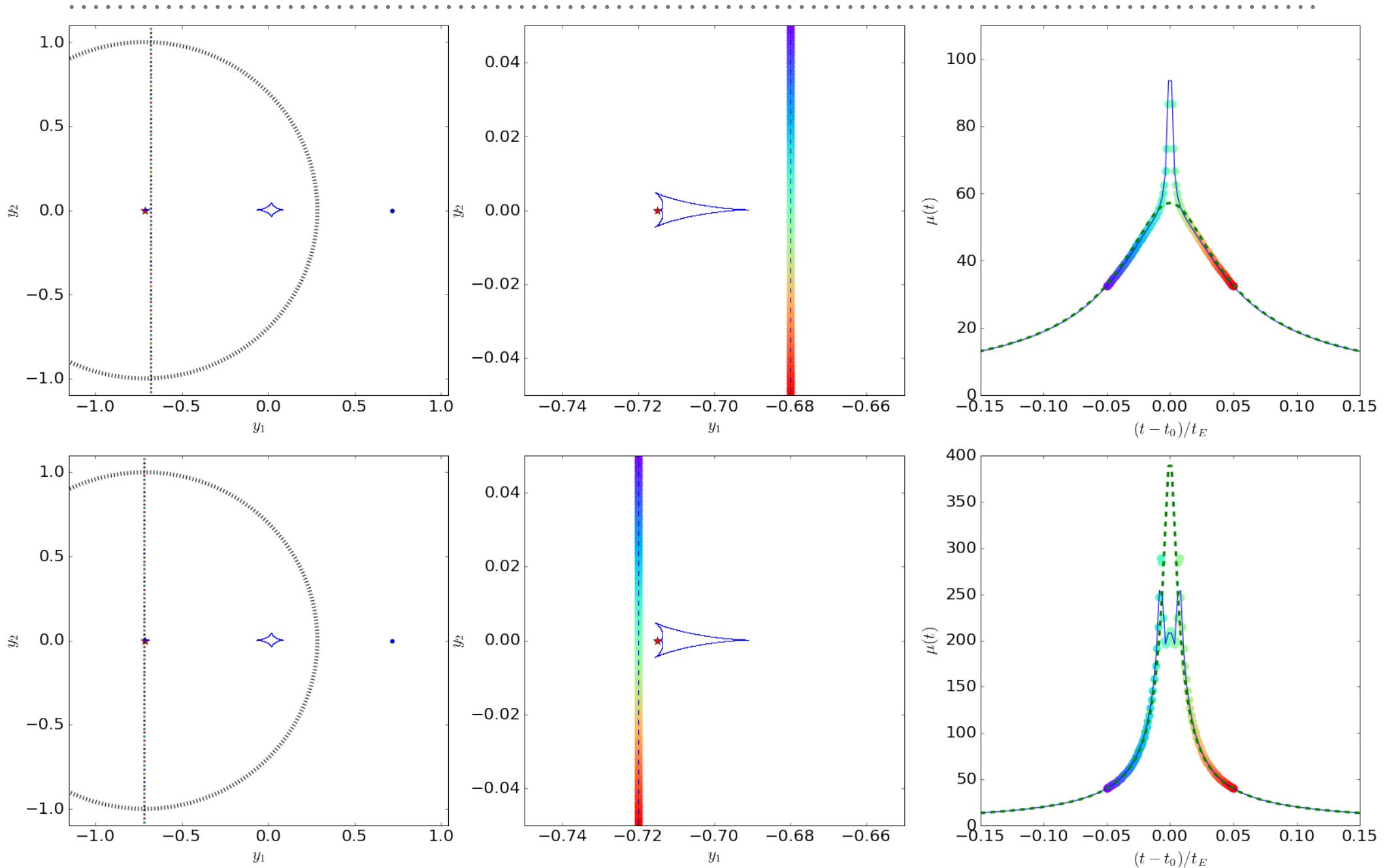
- Magnification if the source passes in between the planet and the star
- De-magnification if the source passes on the back of the caustic!
- Some examples...



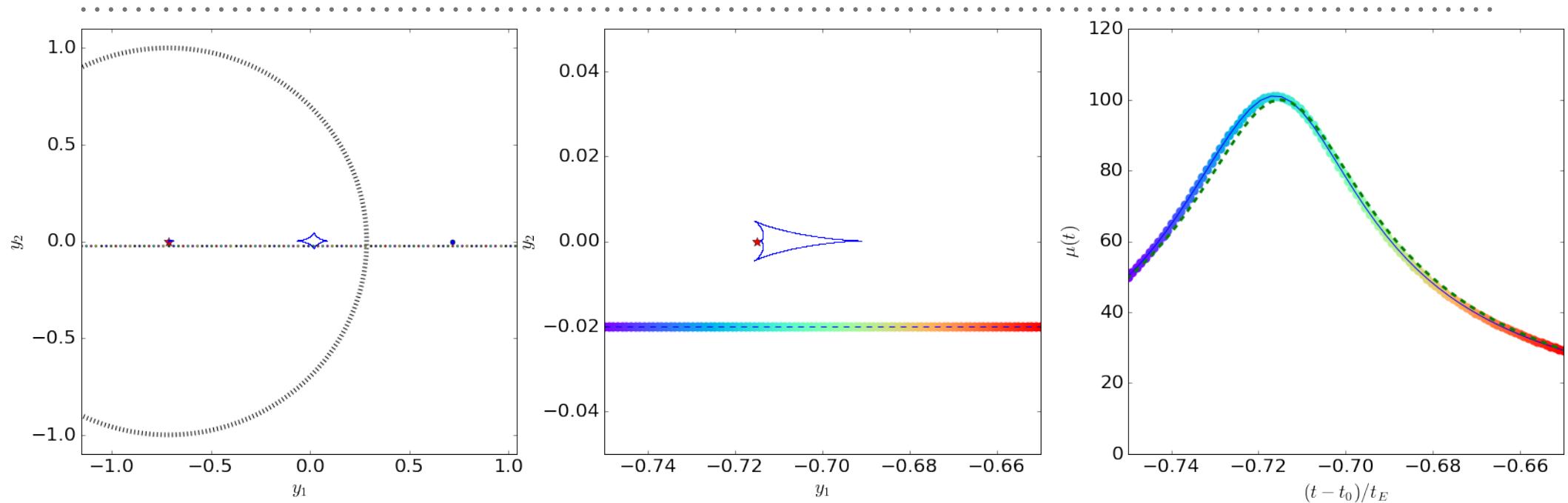
# CENTRAL CAUSTIC PERTURBATIONS



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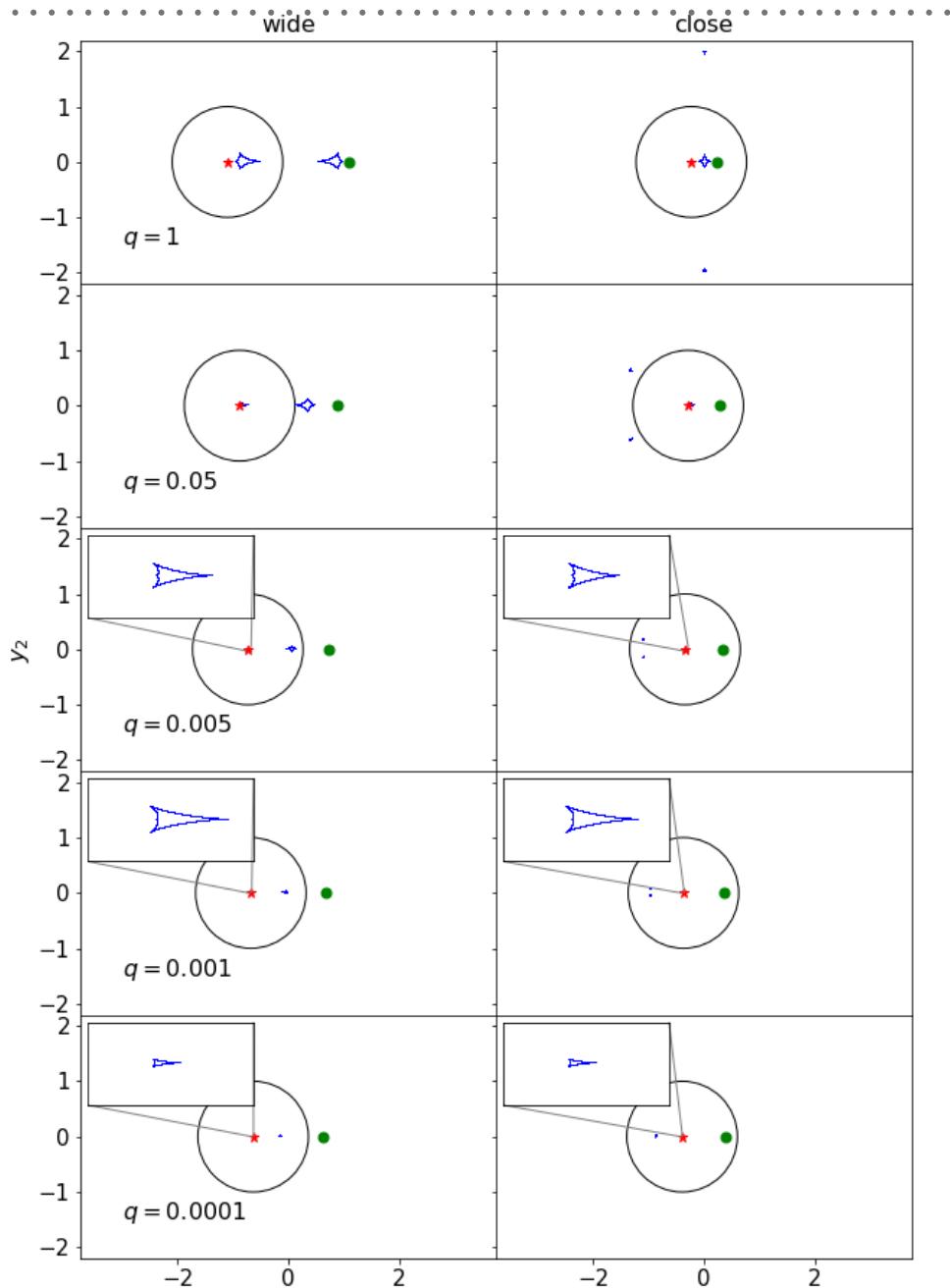
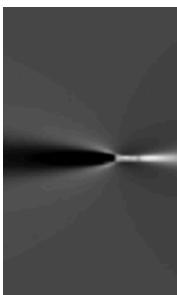
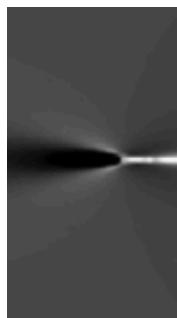
# CENTRAL CAUSTIC PERTURBATIONS



# WIDE-CLOSE DEGENERACY!

- Caustics and magnification patterns are identical in wide and close systems with

$$d_w = d_c^{-1}$$



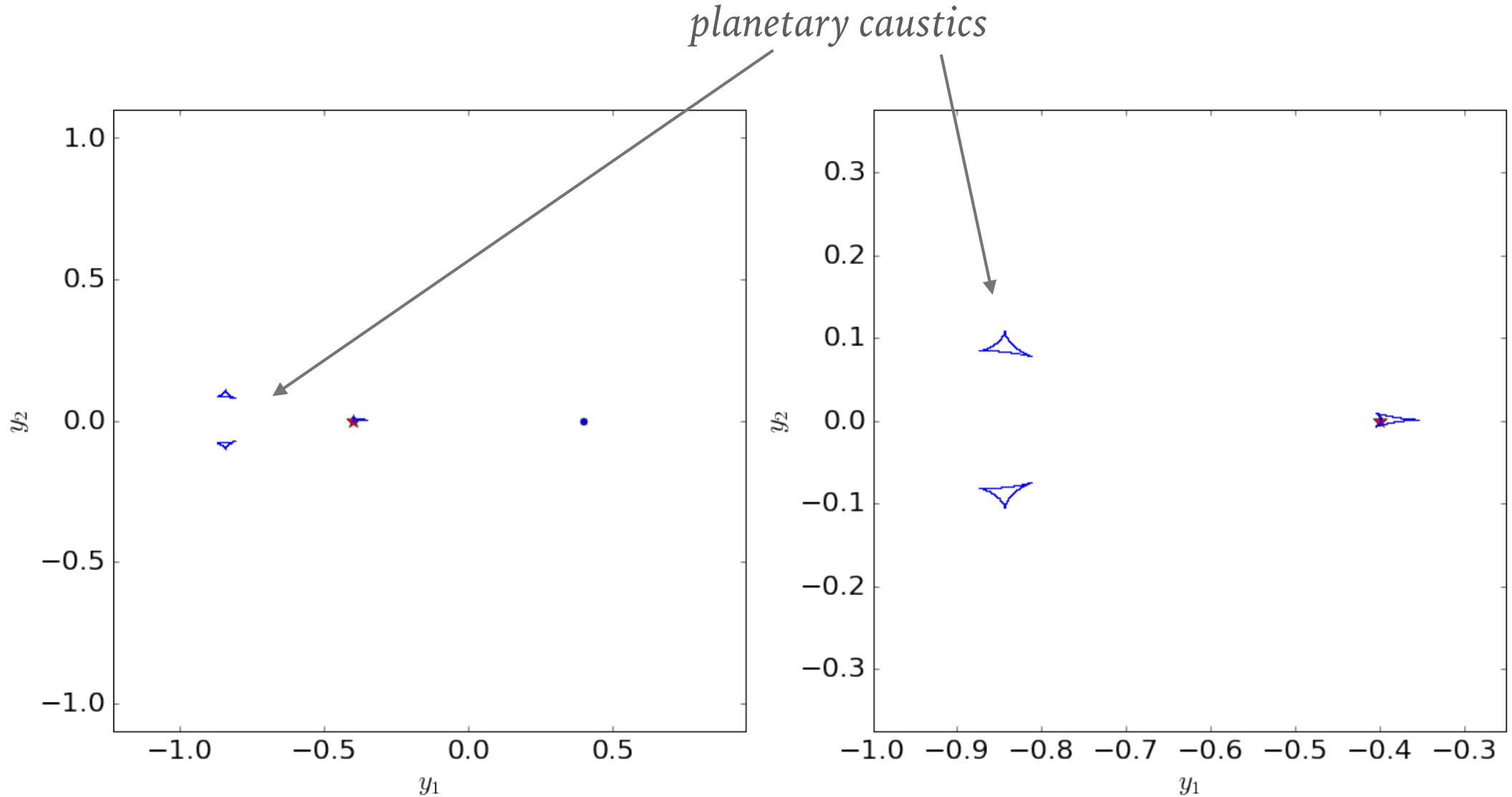
# PLANET DETECTION THROUGH CENTRAL CAUSTICS PERTURBATIONS

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- Only possible in the case of high magnification events (sources passing very close to the host stars)
- For this reason, they are rare events
- Advantages:
  - near the peak of the event
  - can sometimes be predicted in advance
  - high magnification makes possible to follow-up the events using small telescopes
  - more accurate photometry
- Disadvantages:
  - degeneracy wide-close topologies

# PLANETARY CAUSTICS IN CLOSE TOPOLOGIES

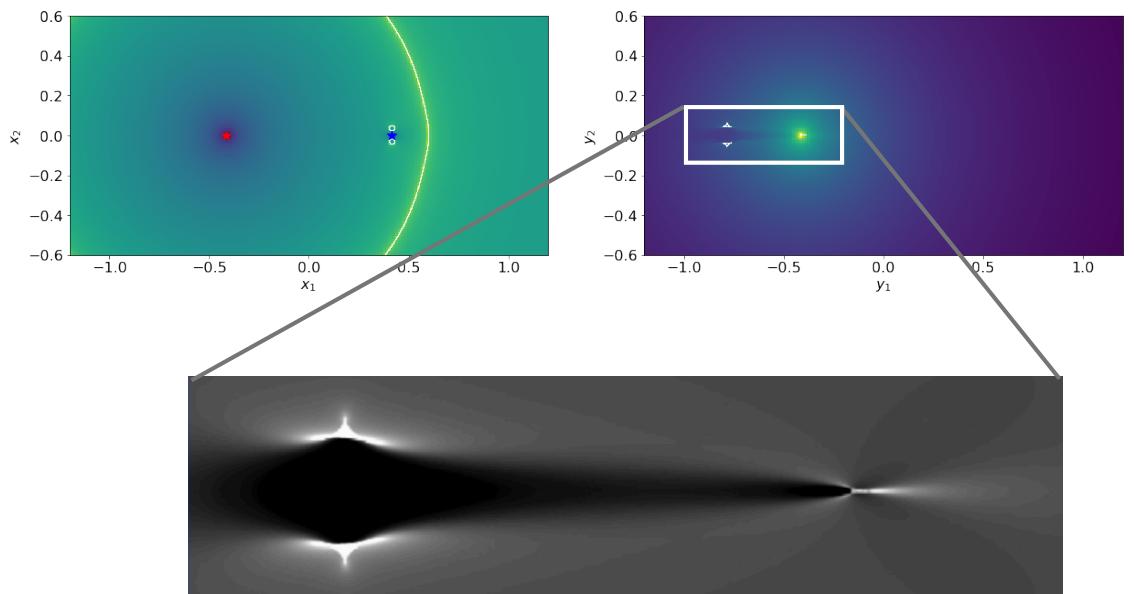
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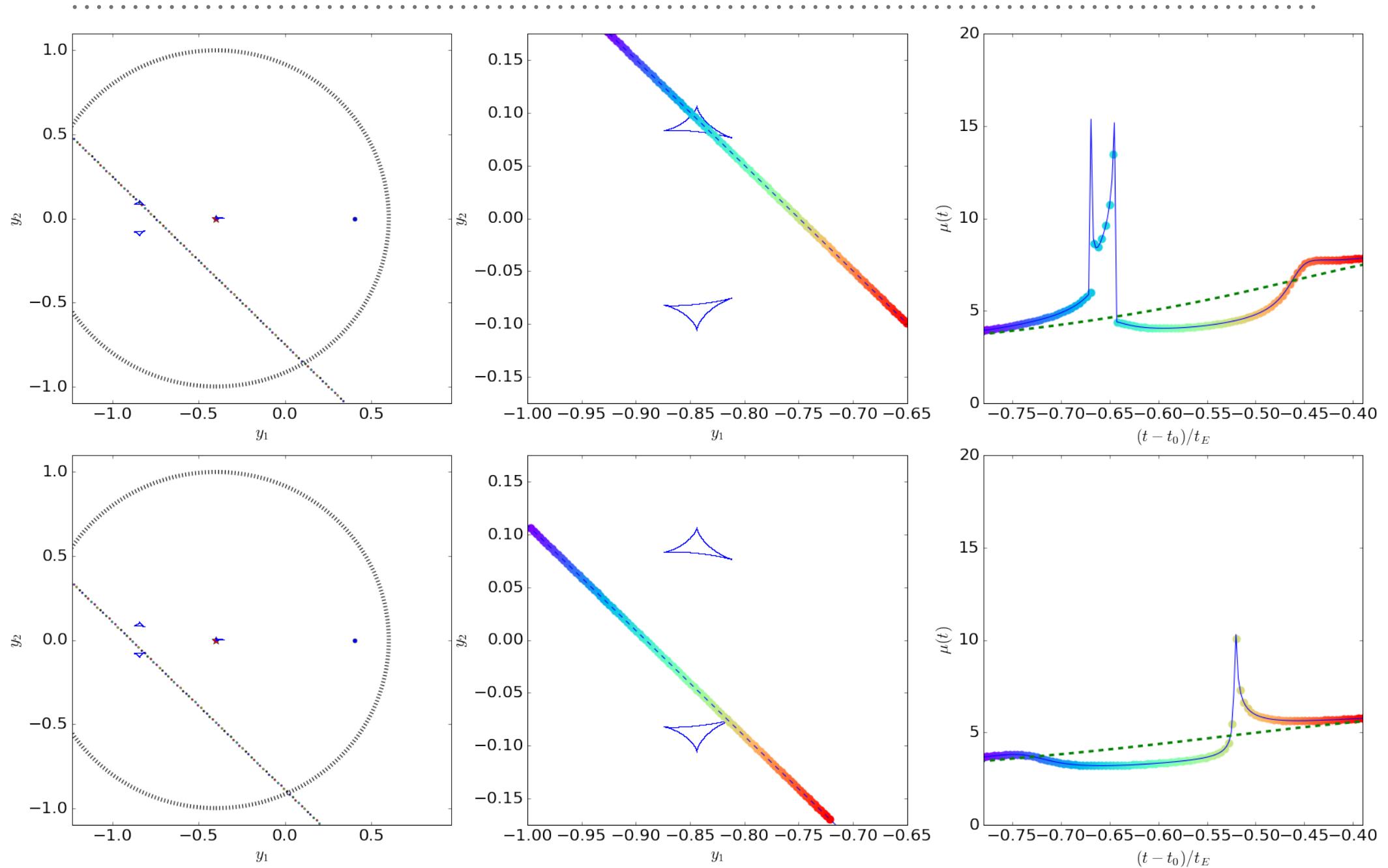
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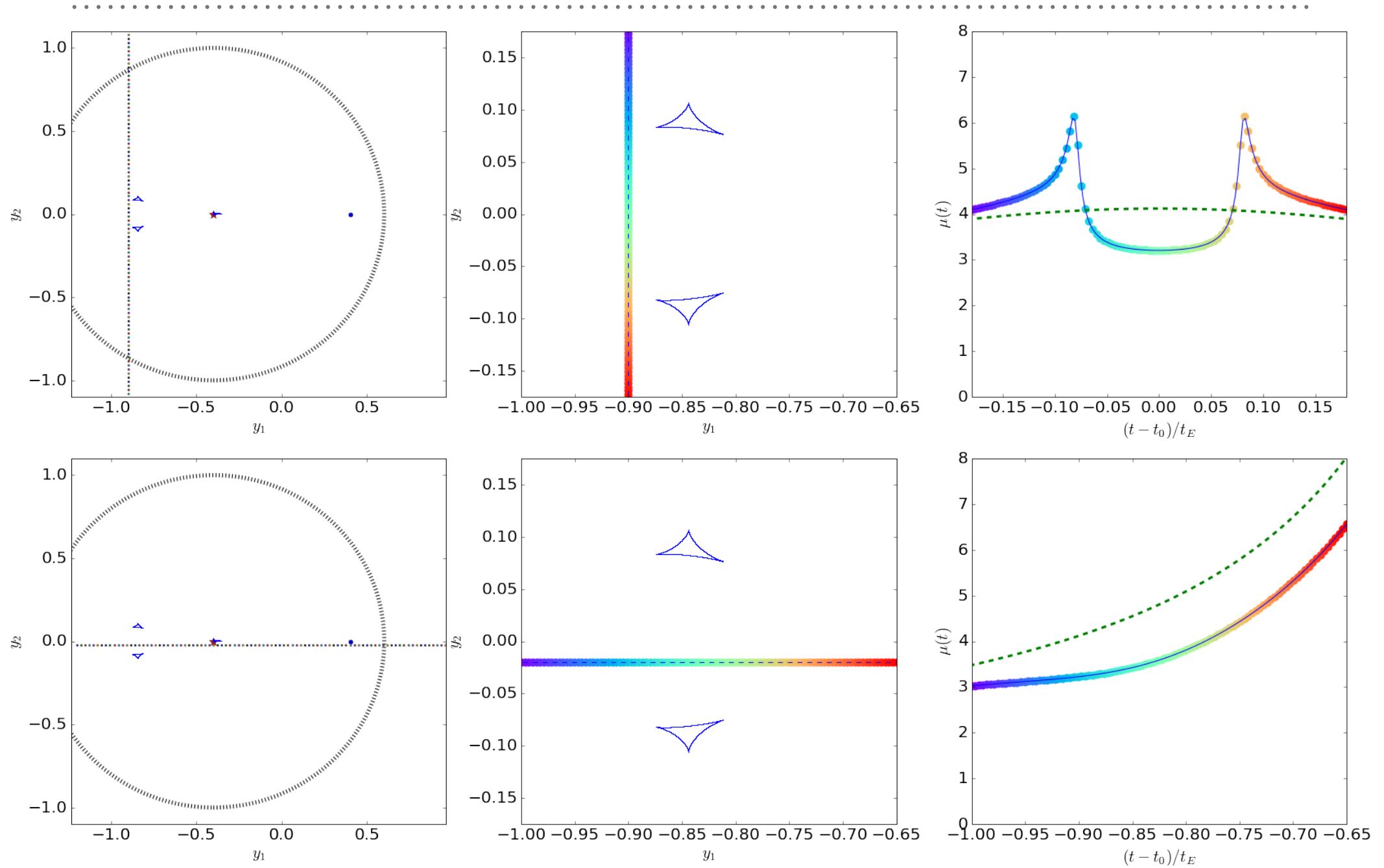
- Caustics have three cusps: magnification near the cusps
- They also have three folds: sudden magnification jumps
- Strong demagnification in between the planetary caustics



# PLANETARY CAUSTICS PERTURBATIONS IN CLOSE TOPOLOGIES

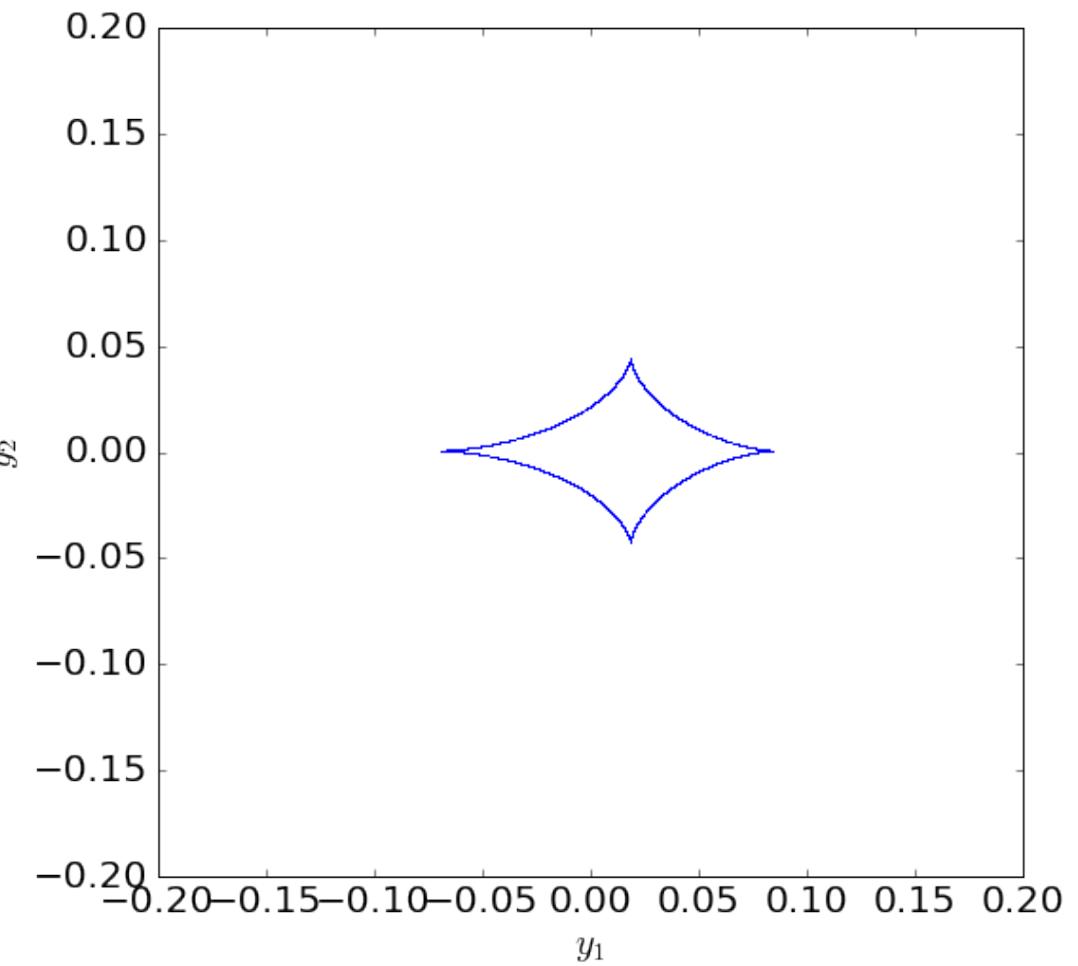
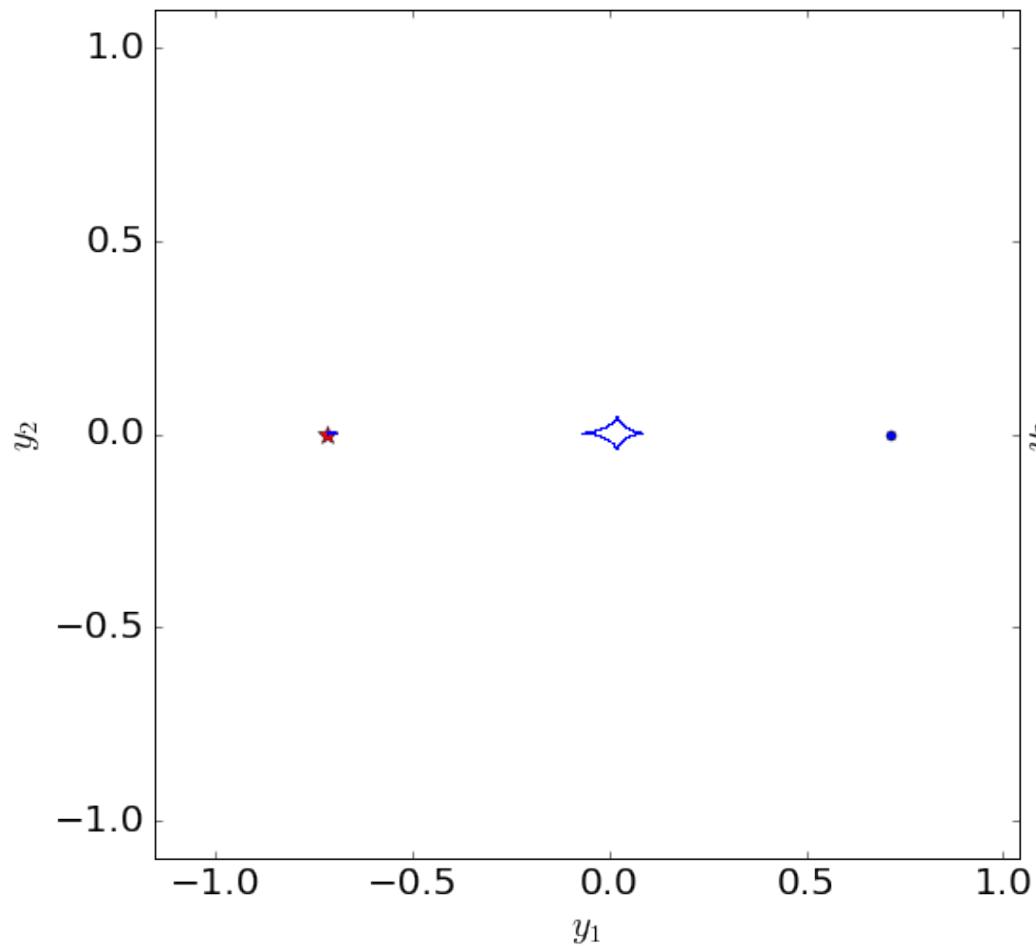


# PLANETARY CAUSTICS PERTURBATIONS IN CLOSE TOPOLOGIES



# PLANETARY CAUSTICS IN WIDE TOPOLOGIES

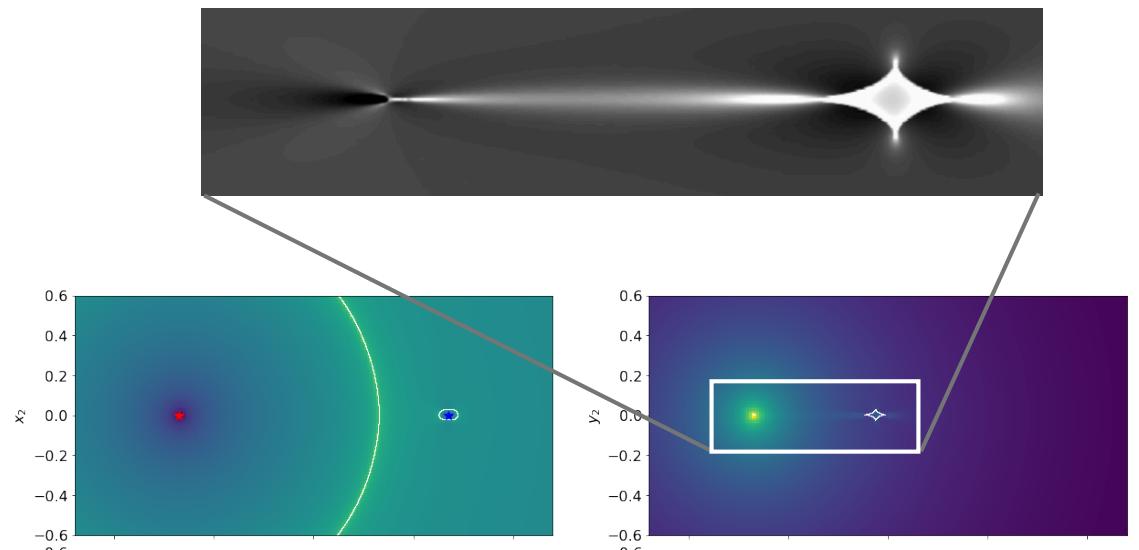
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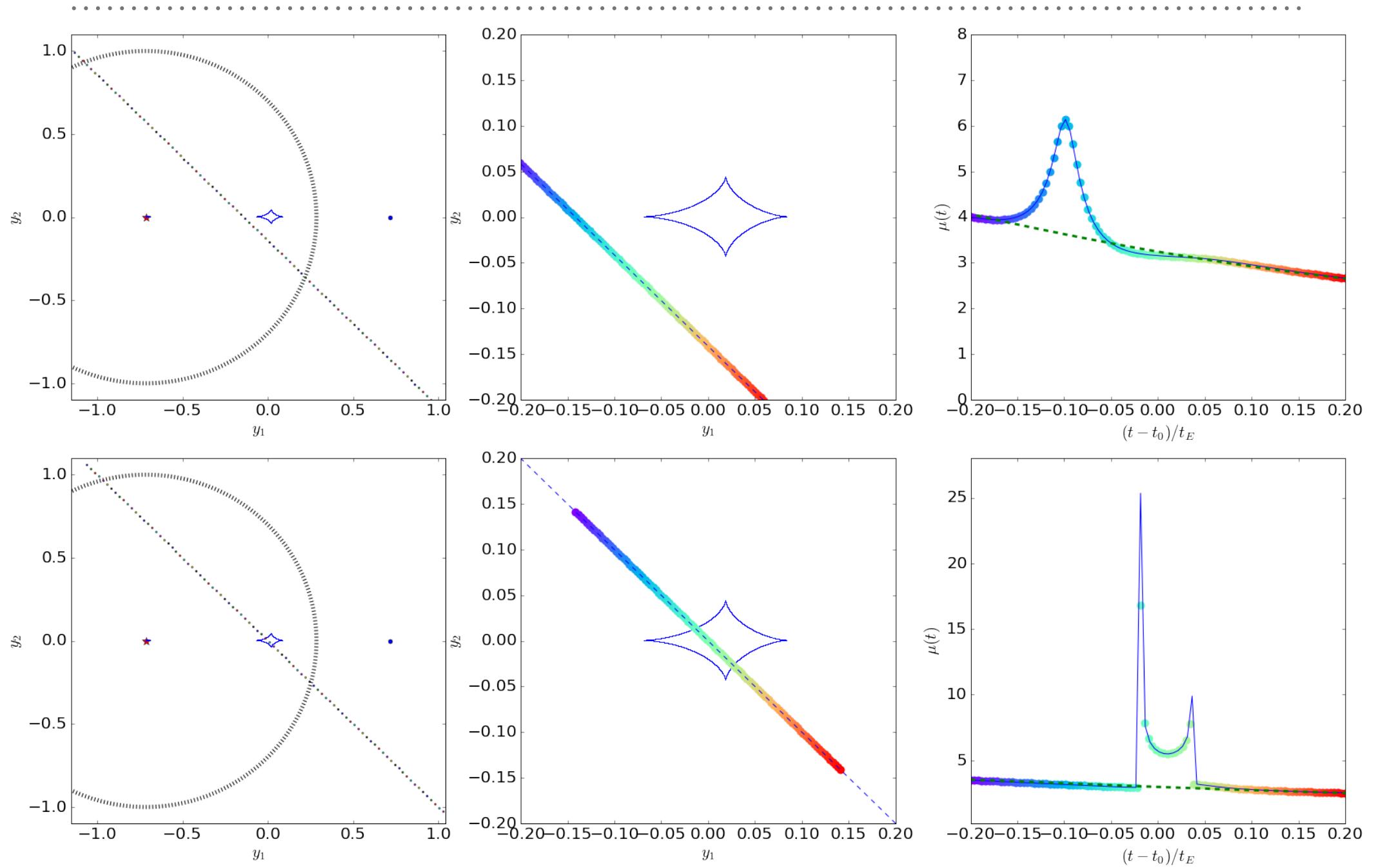
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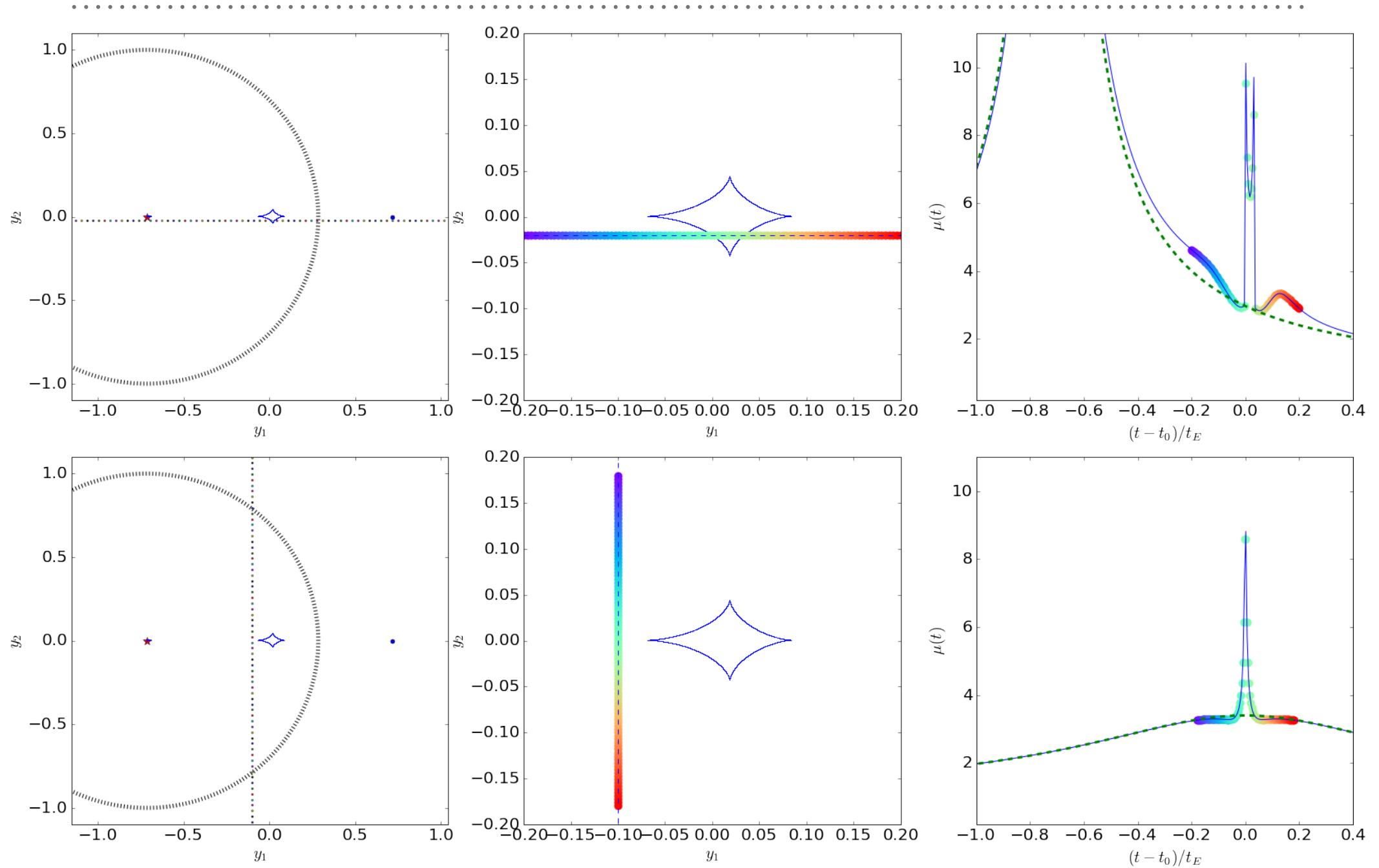
- Four cusps, four folds
- Strong magnification near the cusps
- Sudden magnification jumps when crossing the folds
- De-magnification on the outer parts of the folds
- Mild magnification inside the caustic



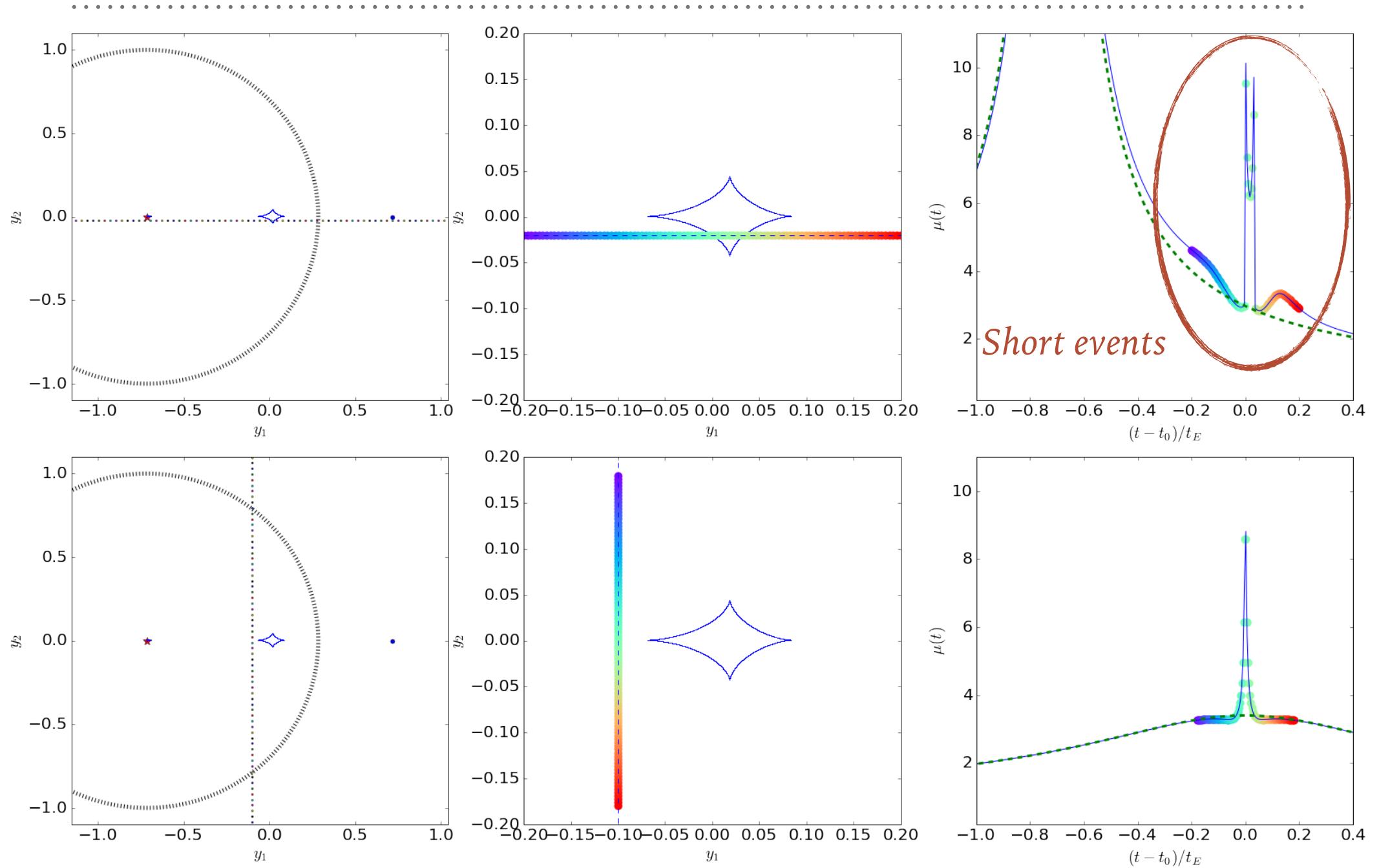
# PLANETARY CAUSTICS PERTURBATIONS IN WIDE TOPOLOGIES



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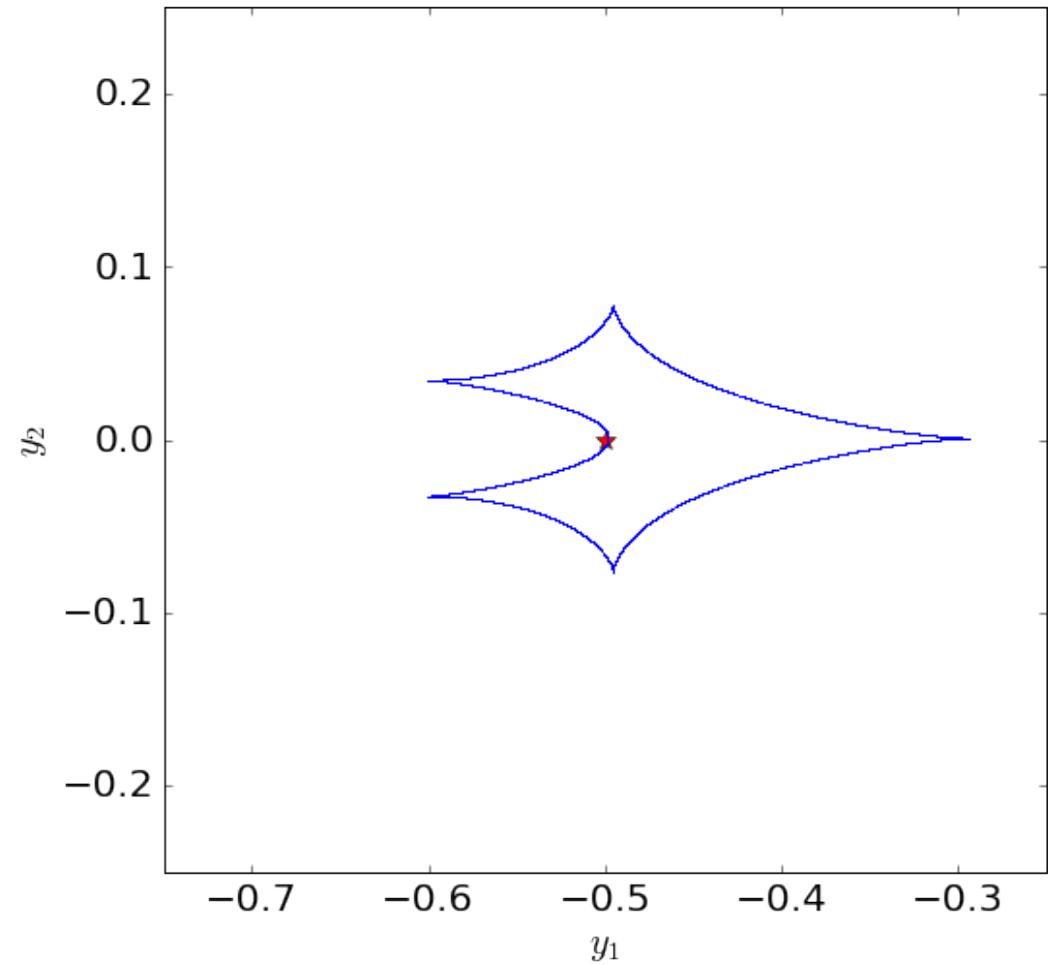
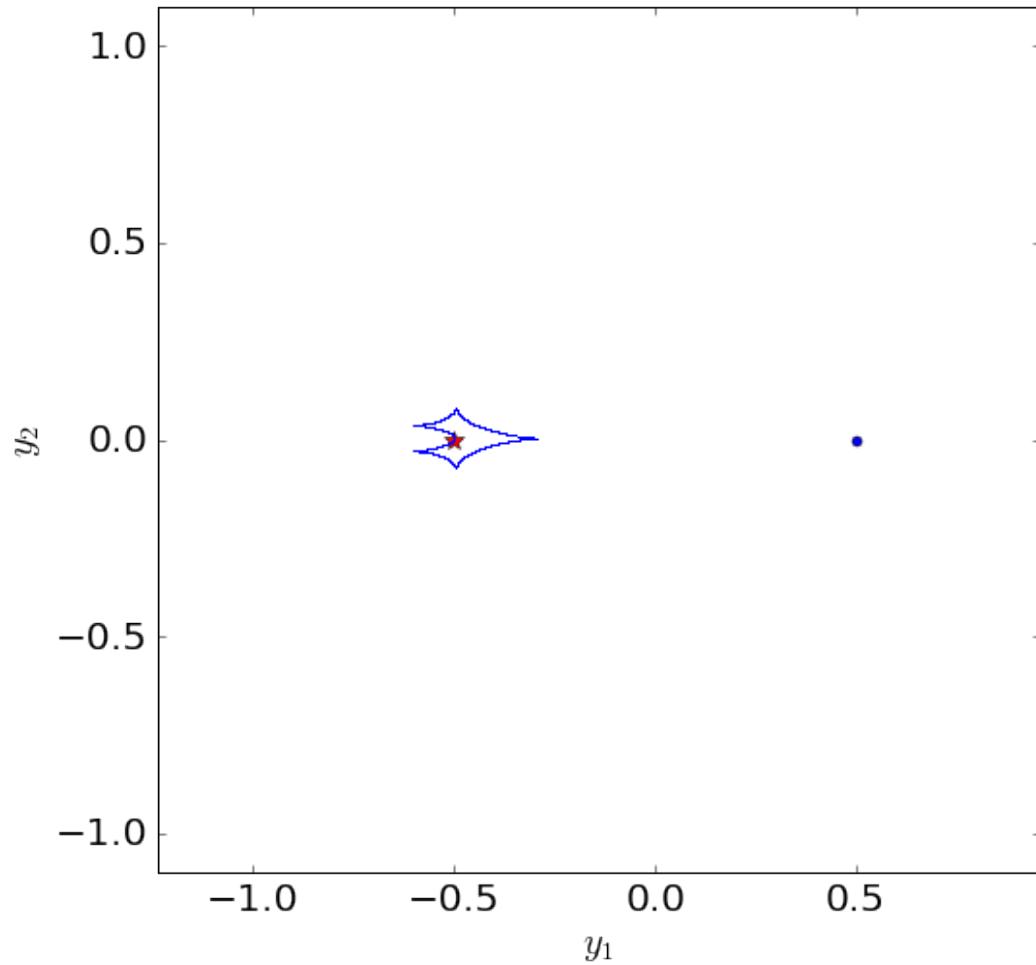
# PLANET DETECTION THROUGH PLANETARY CAUSTICS PERTURBATIONS

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- Typically in low-to-mid magnification regimes, as the source passes at relatively large distance from the primary lens
- Short!
- More frequent
- Less predictable

# PLANETARY CAUSTICS IN INTERMEDIATE TOPOLOGIES

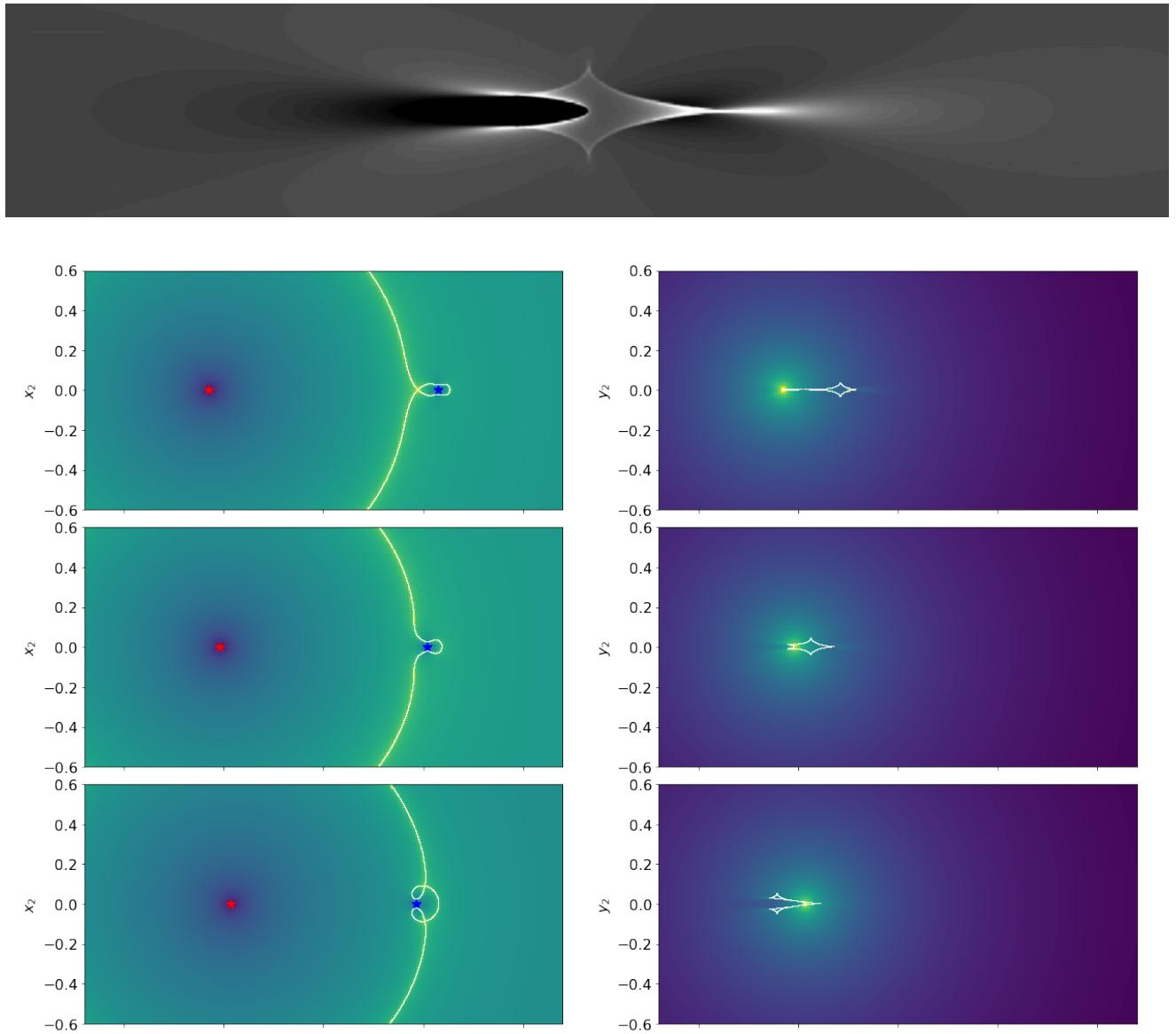
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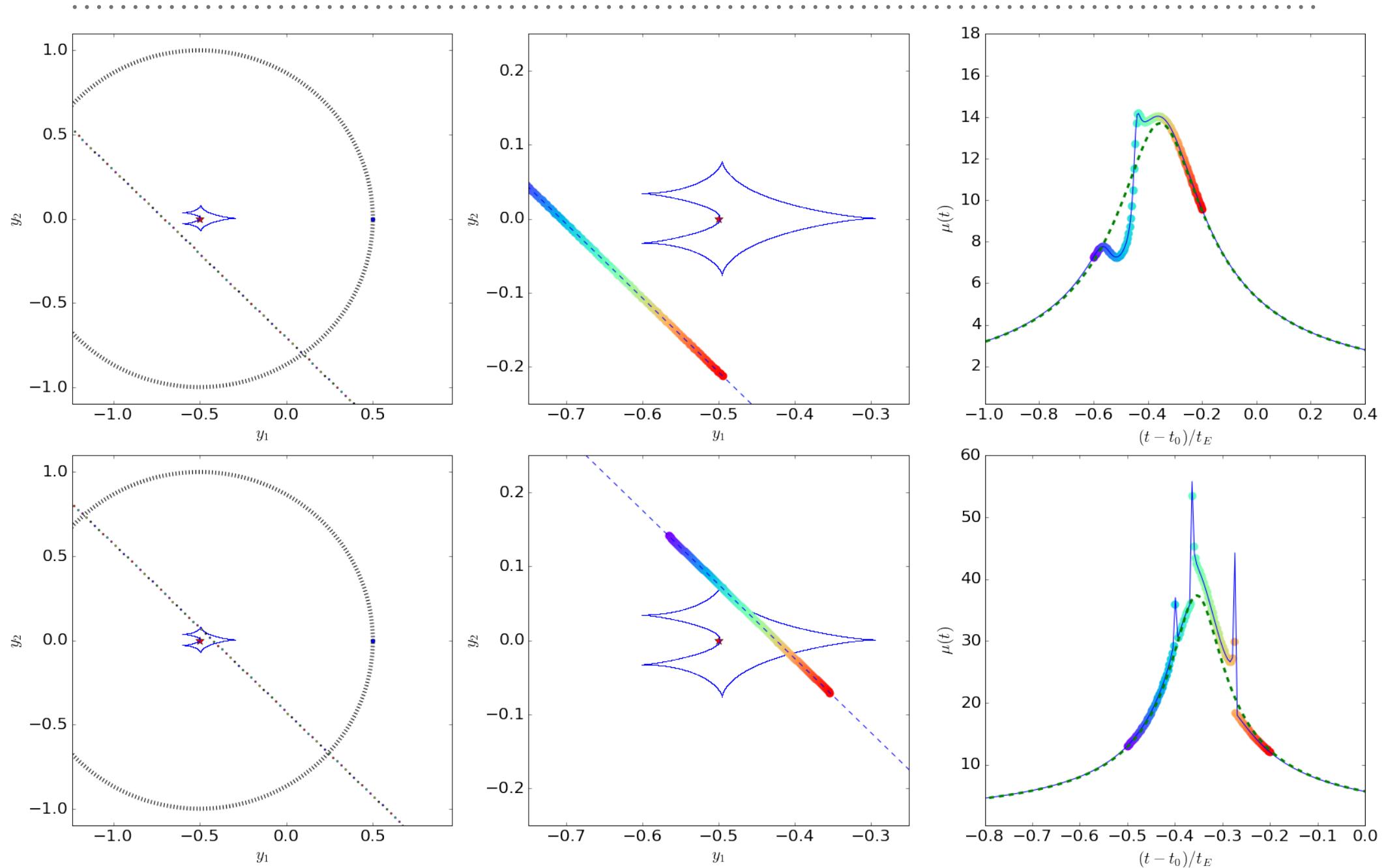
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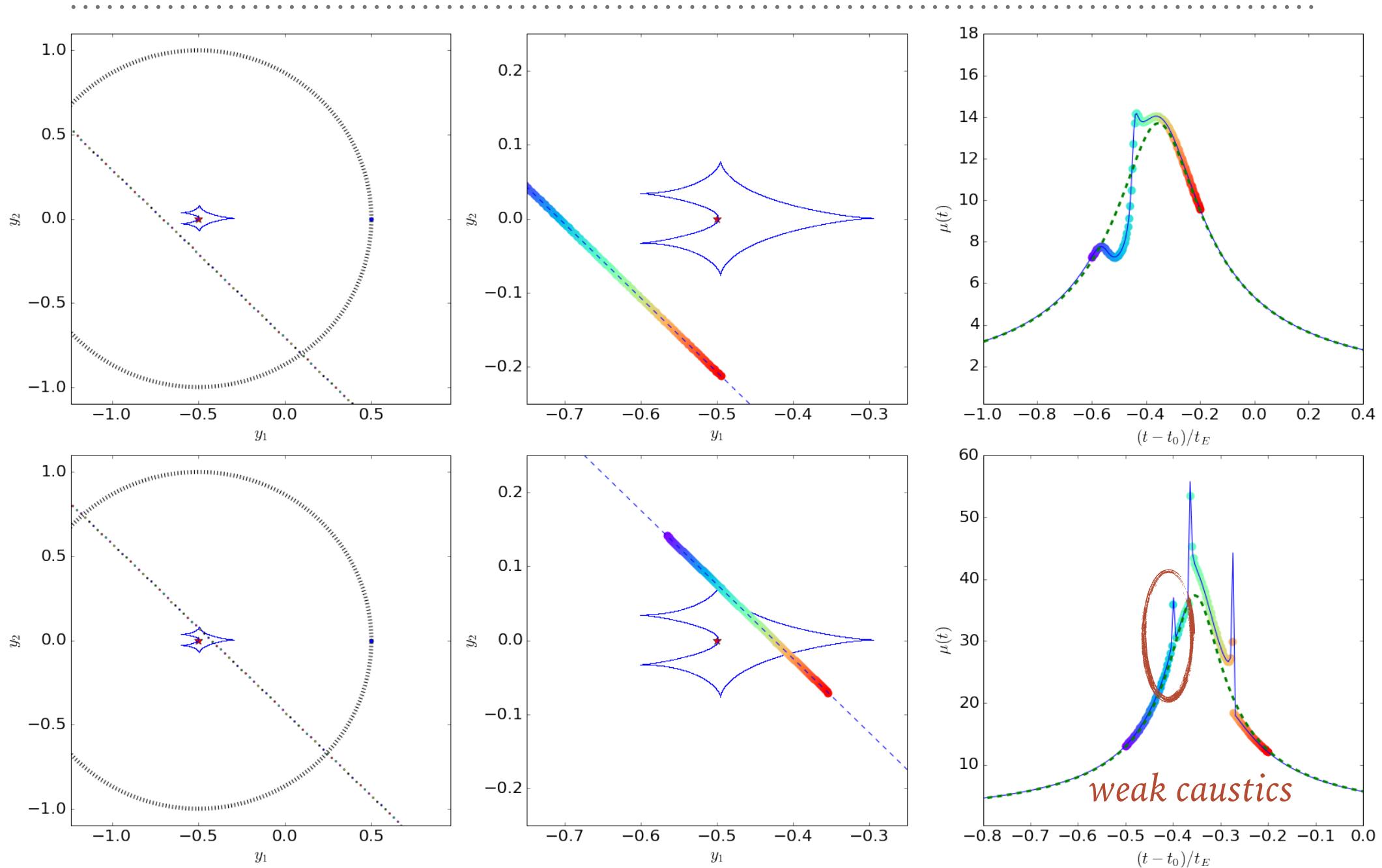
- 6 cusps, 6 folds
- Weak and strong cusps
- Extended
- De-magnification on the back of the caustic
- Examples:



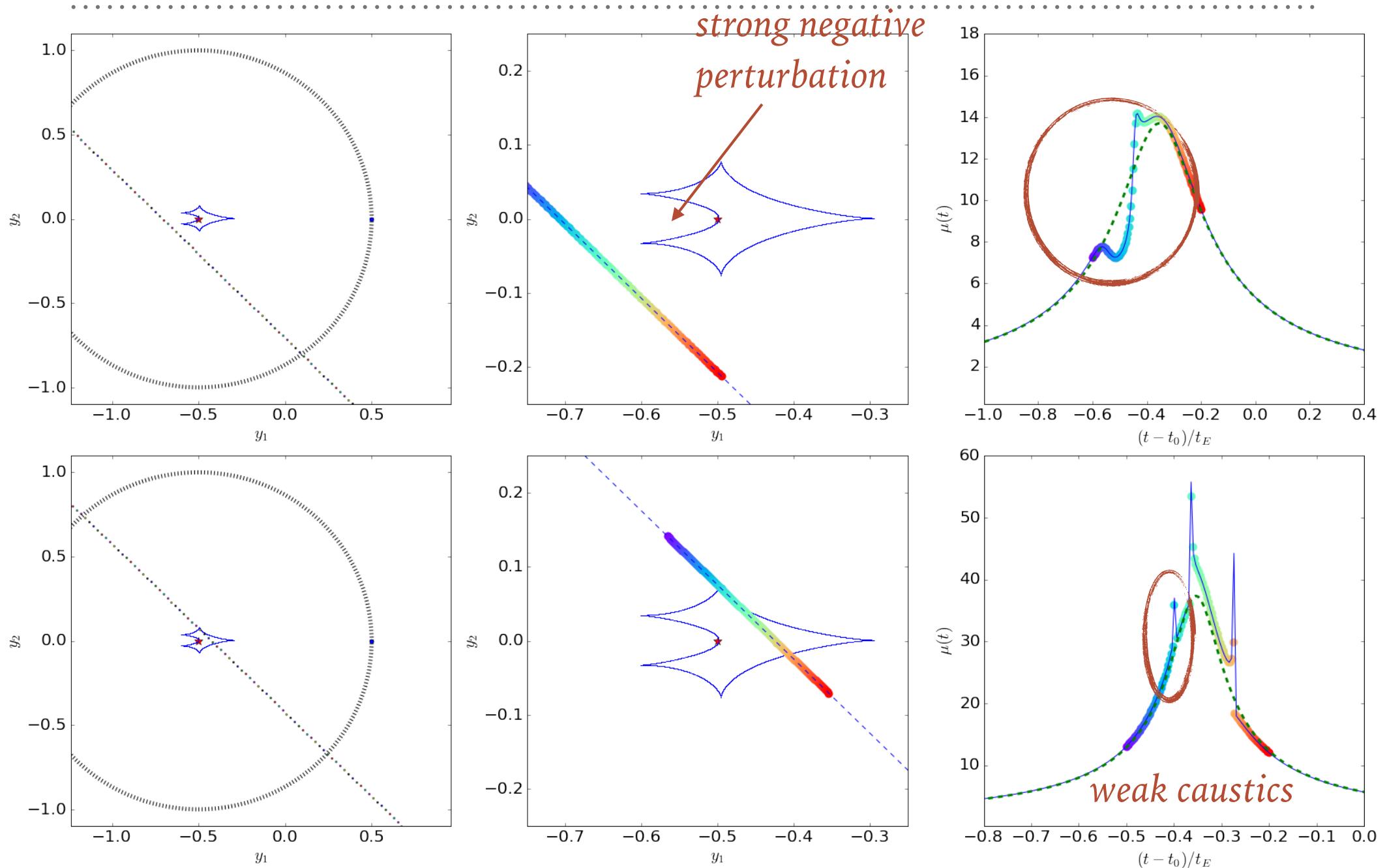
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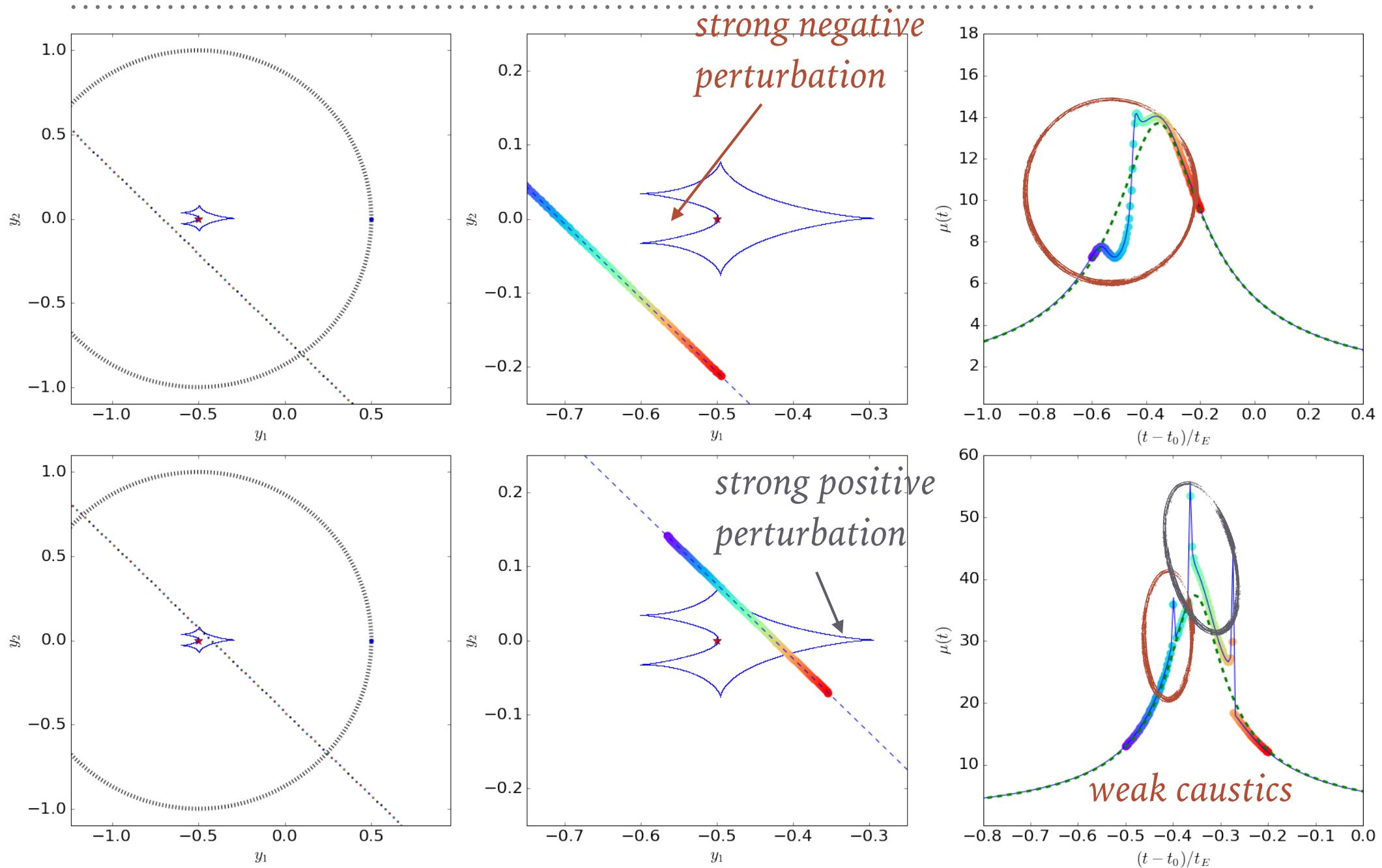
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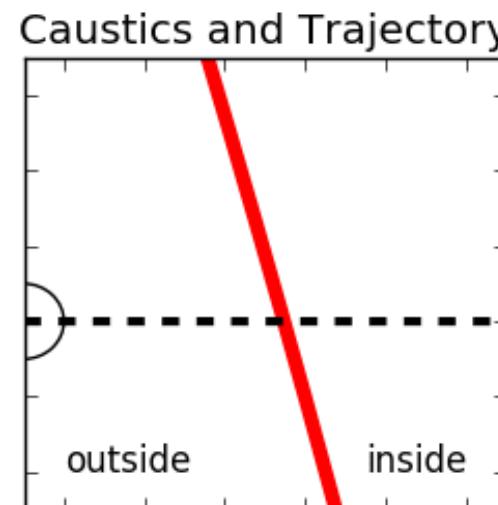
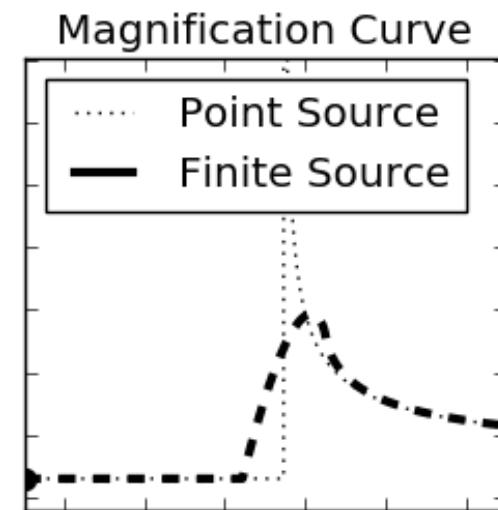
# PLANETARY CAUSTICS PERTURBATIONS IN INTERMEDIATE TOPOLOGIES



# PLANET DETECTION THROUGH RESONANT CAUSTIC PERTURBATIONS

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- Typically in intermediate-to-high magnification regimes, as the source passes close the primary lens
- Weak caustics: sharp peaks that can be washed out by finite source effects
- Long events
- Sensitive to orbital motions



*Credit: J. Yee*

# INTERMEDIATE OR RESONANT CAUSTICS

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*In order to have a resonant caustic the distance between the binary components must be*

$$d_{IC} < d < d_{WI}$$

*where*  $d_{WI} = (m_1^{1/3} + m_2^{1/3})^{3/2}$   $d_{IC} = (m_1^{1/3} + m_2^{1/3})^{-3/4}$

*These two relations can be written in a different form:*

$$d_{WI} = m_2^{1/2}(1 + q^{1/3})^{3/2} \quad d_{IC} = m_2^{-1/4}(1 + q^{1/3})^{-3/4}$$

*Considering that  $q \ll 1$ , we have that  $m_2 \sim 1$  and that both  $d_{WI}$  and  $d_{IC}$  differ very little from unity:*

$$d_{WI} \sim \left(1 + \frac{3}{2}q^{1/3}\right) \quad d_{IC} \sim \left(1 - \frac{3}{4}q^{1/3}\right)$$

# INTERMEDIATE OR RESONANT CAUSTICS

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*Therefore, in the case of star-planet pairs, resonant caustics exist within a very narrow range of distances around the Einstein radius of the star:*

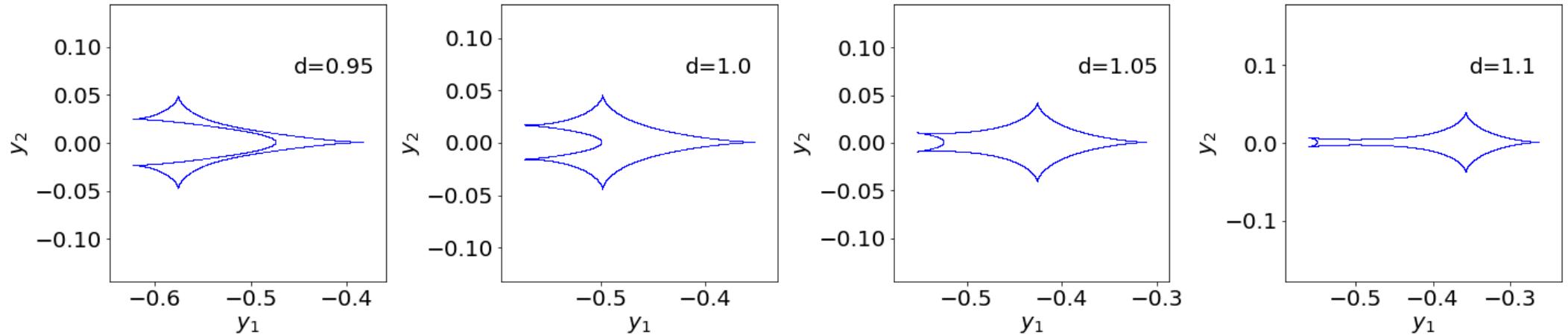
$$d_{WI} \sim \left(1 + \frac{3}{2}q^{1/3}\right) \quad d_{IC} \sim \left(1 - \frac{3}{4}q^{1/3}\right)$$

$$\frac{d_{WI} + d_{IC}}{2} \sim 1$$

$$d_{WI} - d_{IC} \sim \frac{9}{4}q^{1/3}$$

# RESONANT CAUSTIC DEPENDENCE ON $d$

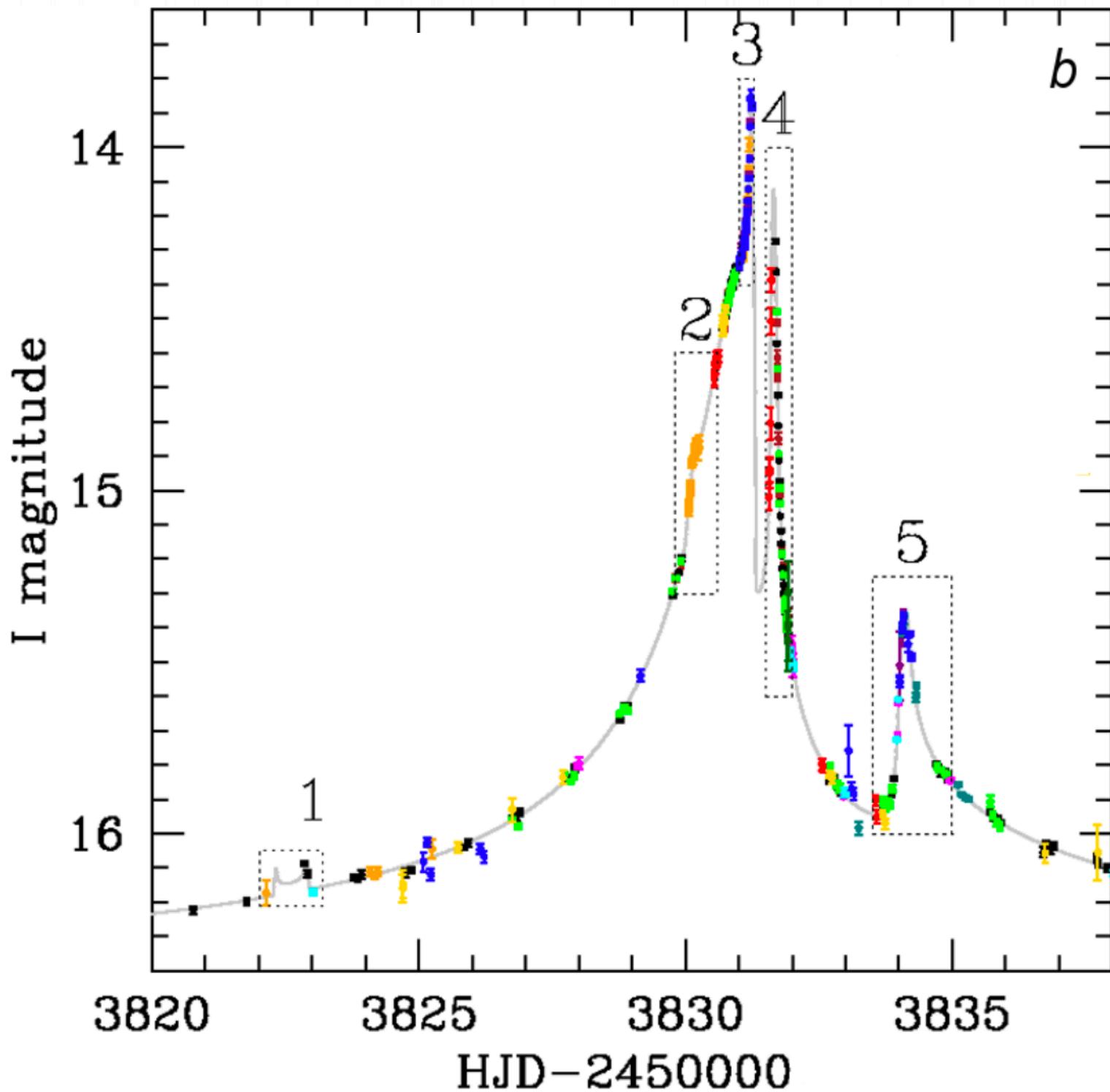
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*The shape of the resonant caustic changes dramatically if  $d$  varies.*

*Since events are long, it happens that, on the timescale of the event the distance between the star and the planet changes due to the planet orbital motion.*

*Consequently, the structure of the caustic changes. This effect can be modelled.*



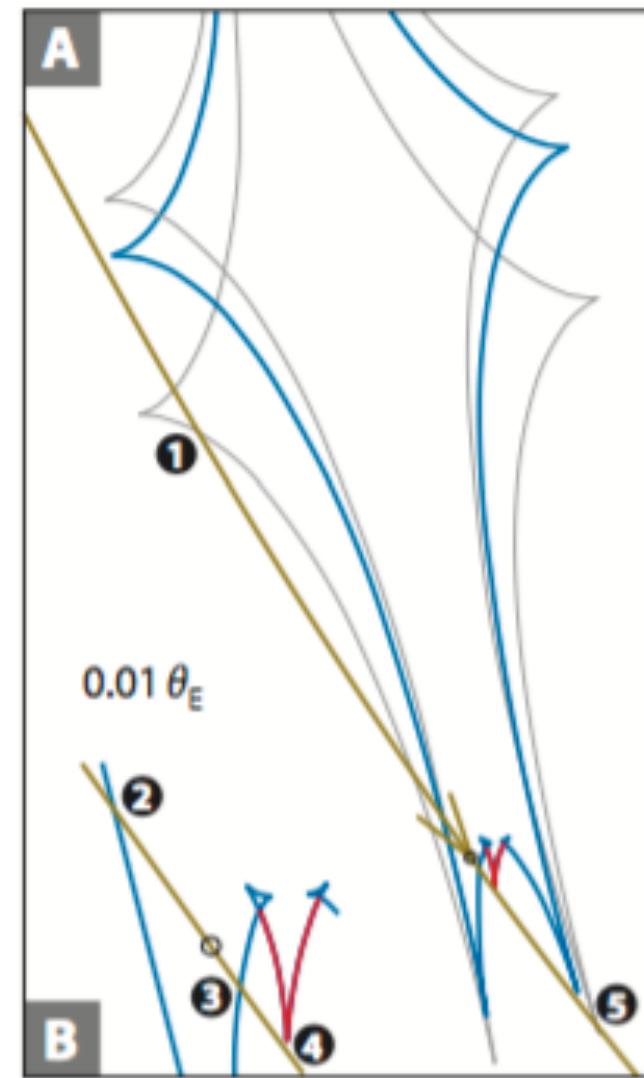
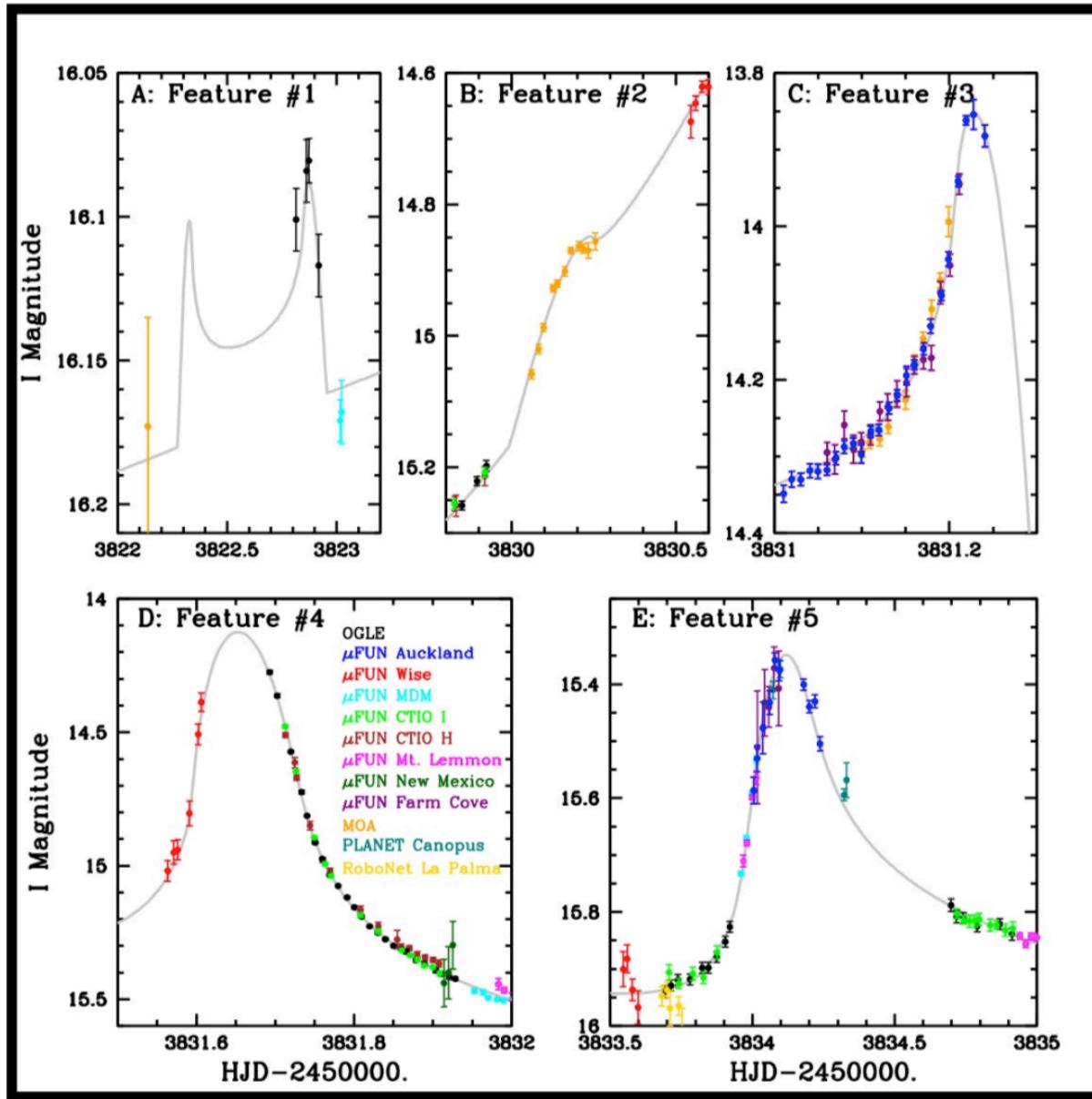
*OGLE-2006-*  
*BLG-109*

*Several deviations  
from standard  
microlensing LC.*

*Features are  
typical of a  
resonant caustic  
perturbation.*

# MULTIPLE PLANETS AND EVOLVING CAUSTIC

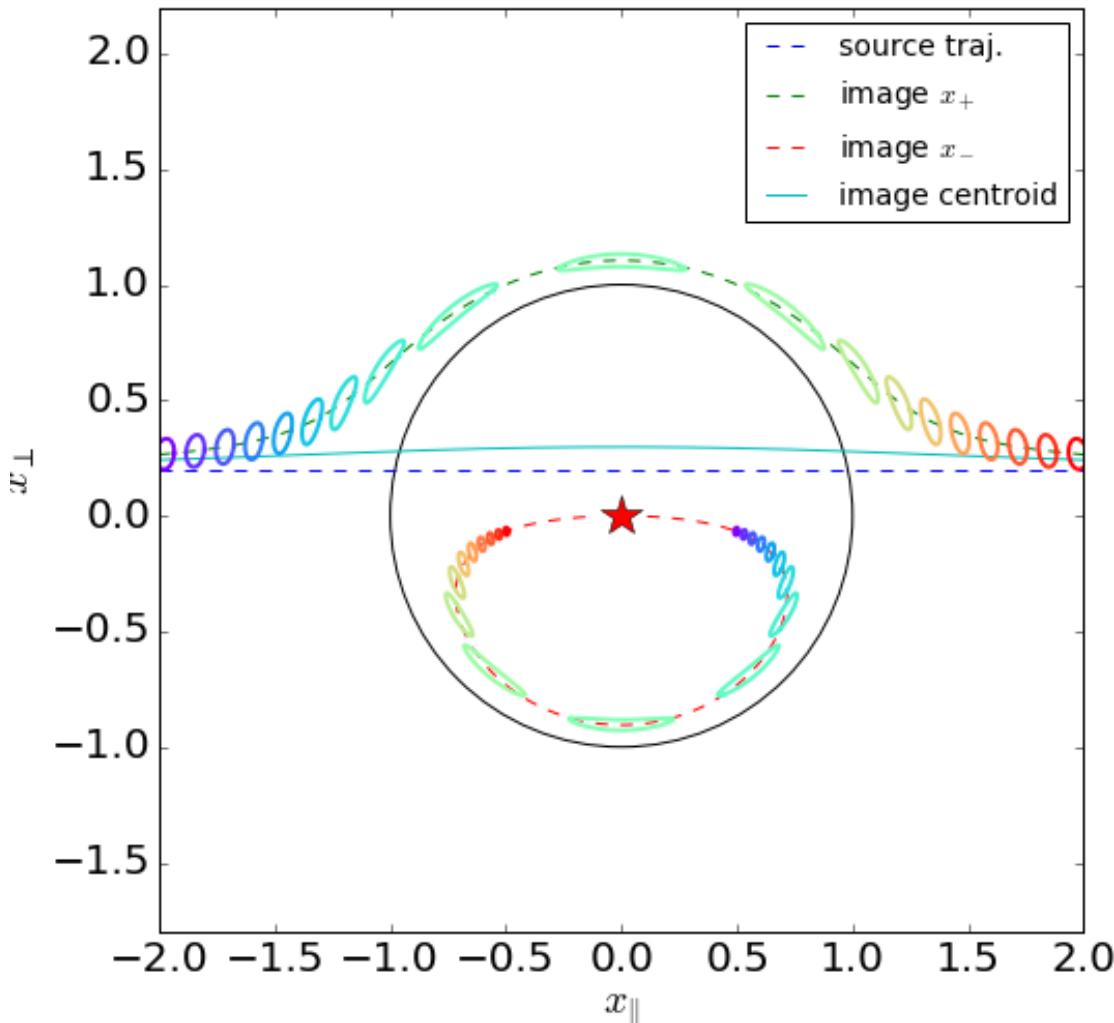
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# ANOTHER WAY TO LOOK AT THE LIGHT CURVES: POINT MASS LENS

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*Lensing of an extended circular source*



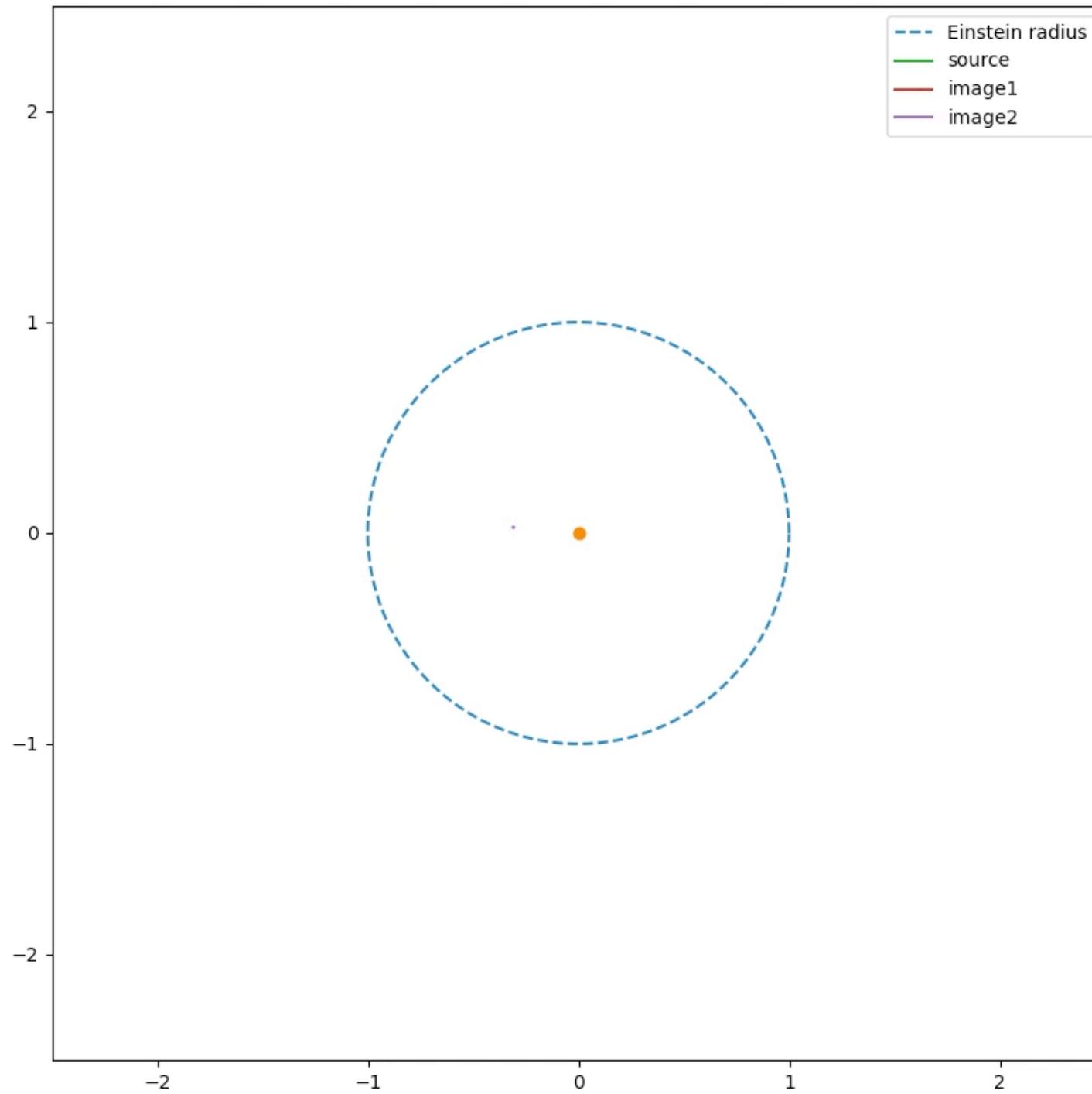
*A point lens always produces two images, namely*

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

*Imagine a source moving along the dashed line in the figure...*

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

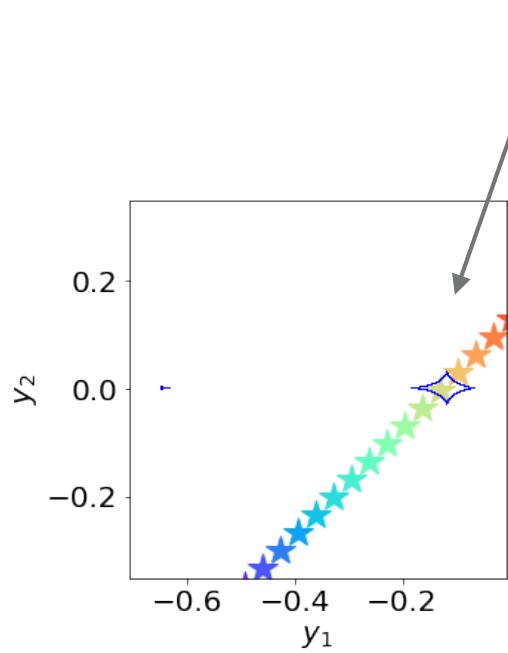
*As the source move, also the images move...*



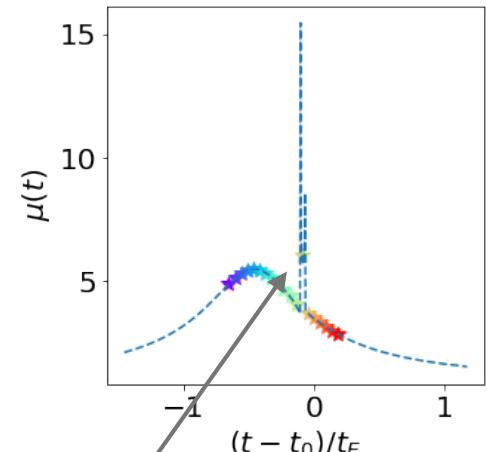
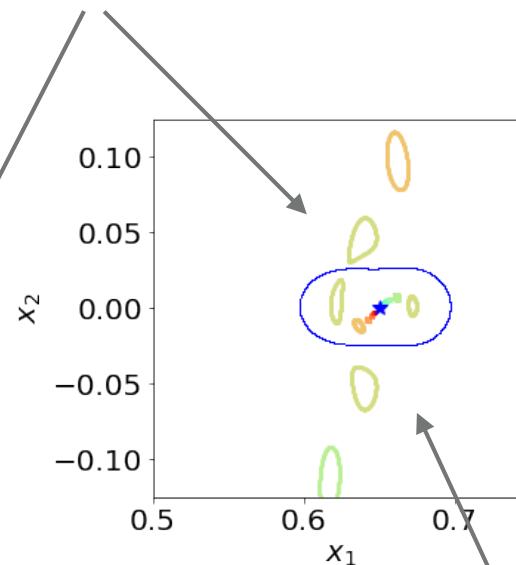
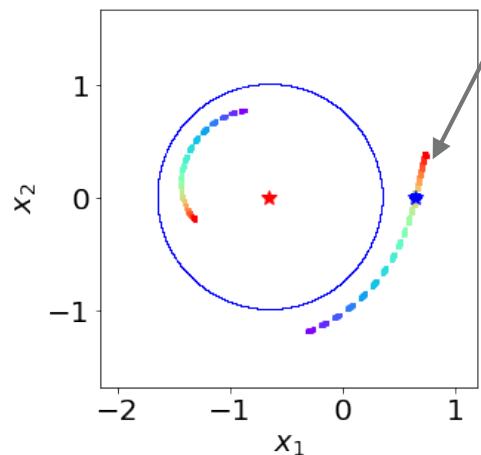
# PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES

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*Planetary caustics*



*Planetary critical lines*

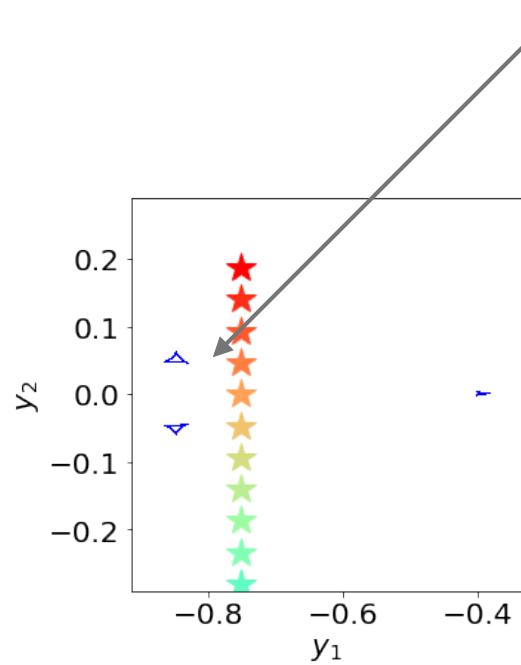


*magnified outer image*

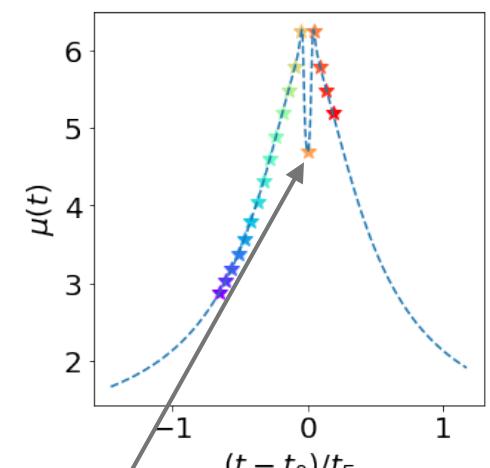
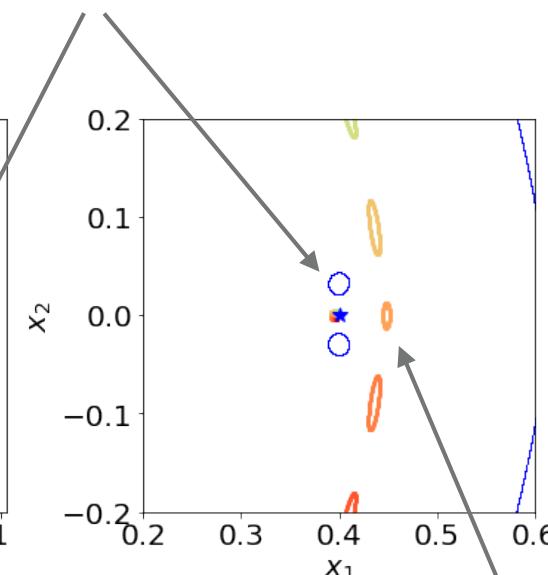
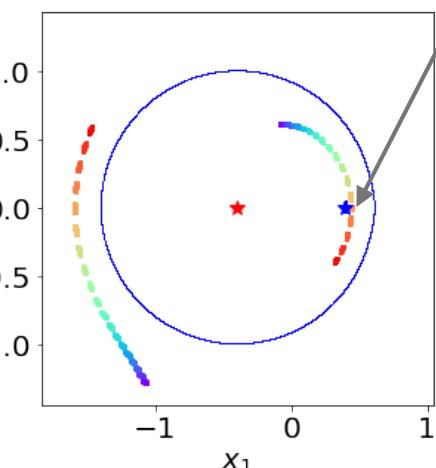
# PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES

---

*Planetary caustics*



*Planetary critical lines*

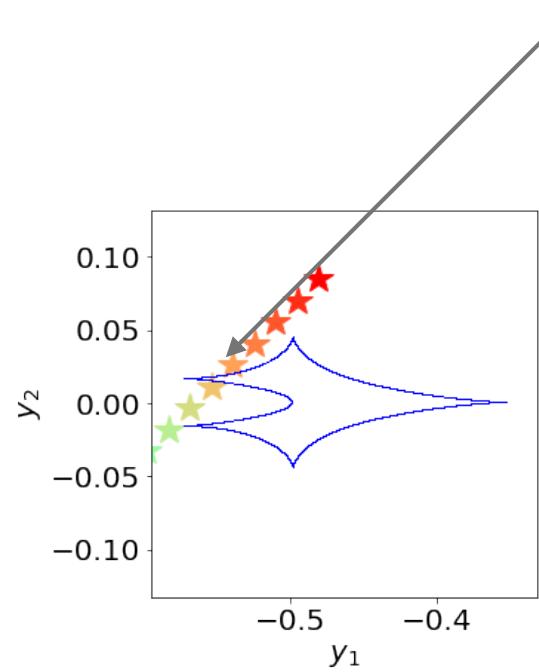


*Demagnified inner image*

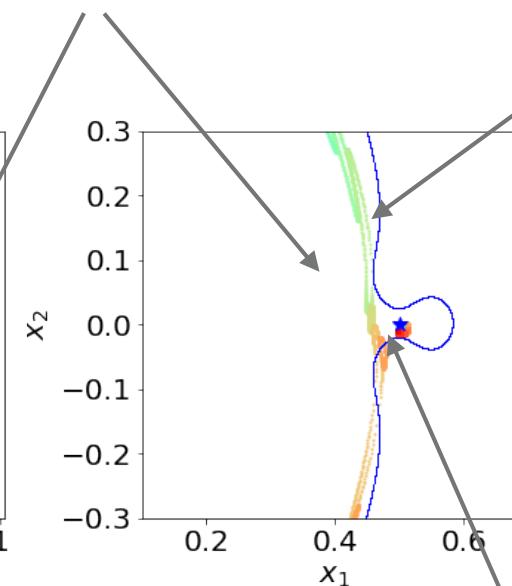
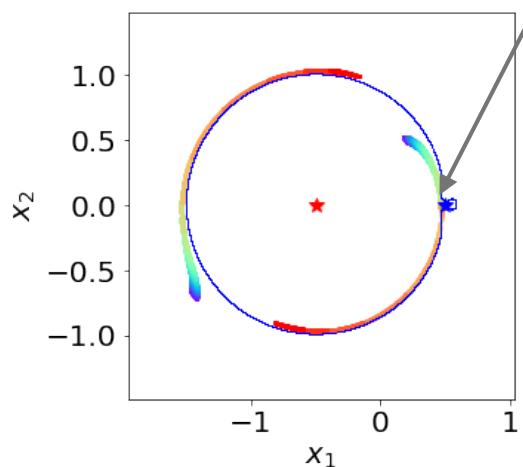
# PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES

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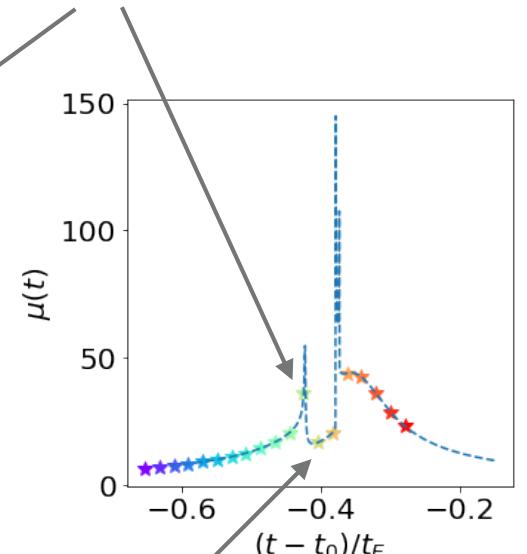
*Planetary caustics*



*Planetary critical lines*



*Magnified inner image*

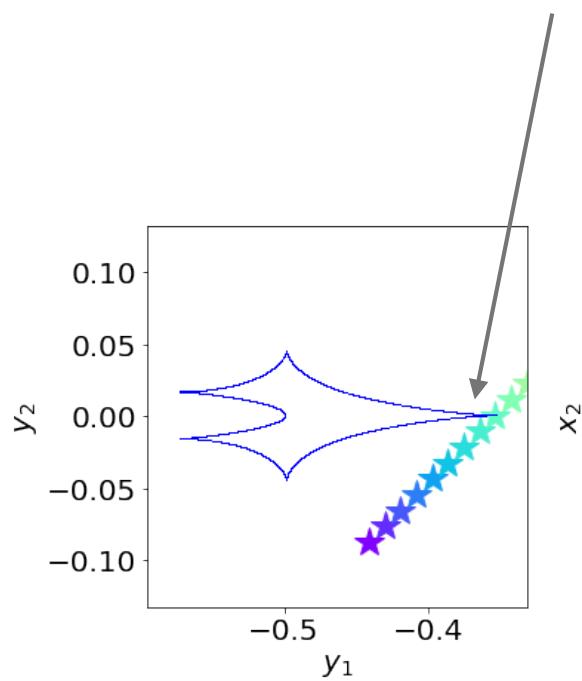


*Demagnified inner image*

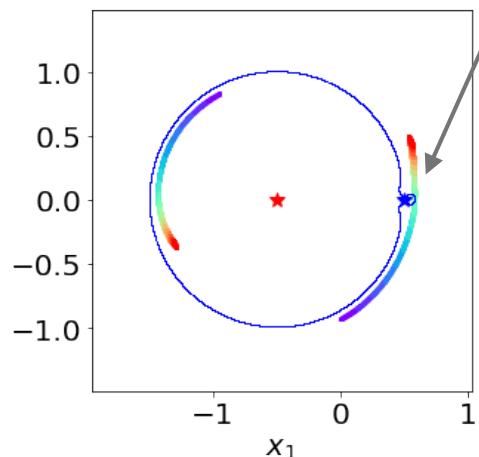
# PLANETARY PERTURBATIONS AS PERTURBATIONS OF SINGLE IMAGES

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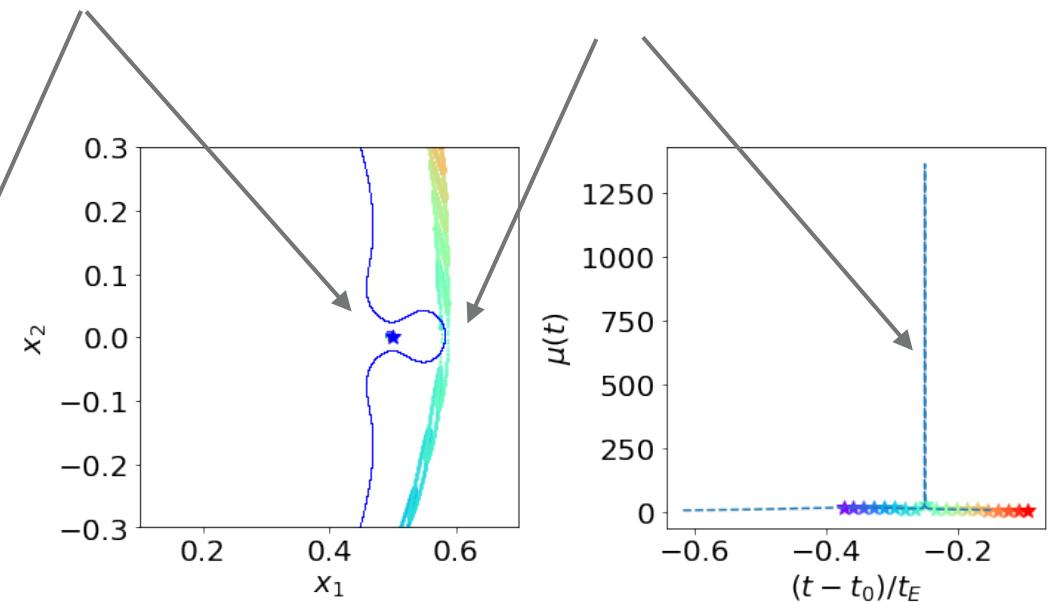
*central caustic*



*Planetary critical lines*



*Magnified outer image*



**Some interesting movies of this are available at:**

<https://www.astronomy.ohio-state.edu/gaudi.1/movies.html>

# INTERPRETING THE LIGHT CURVES

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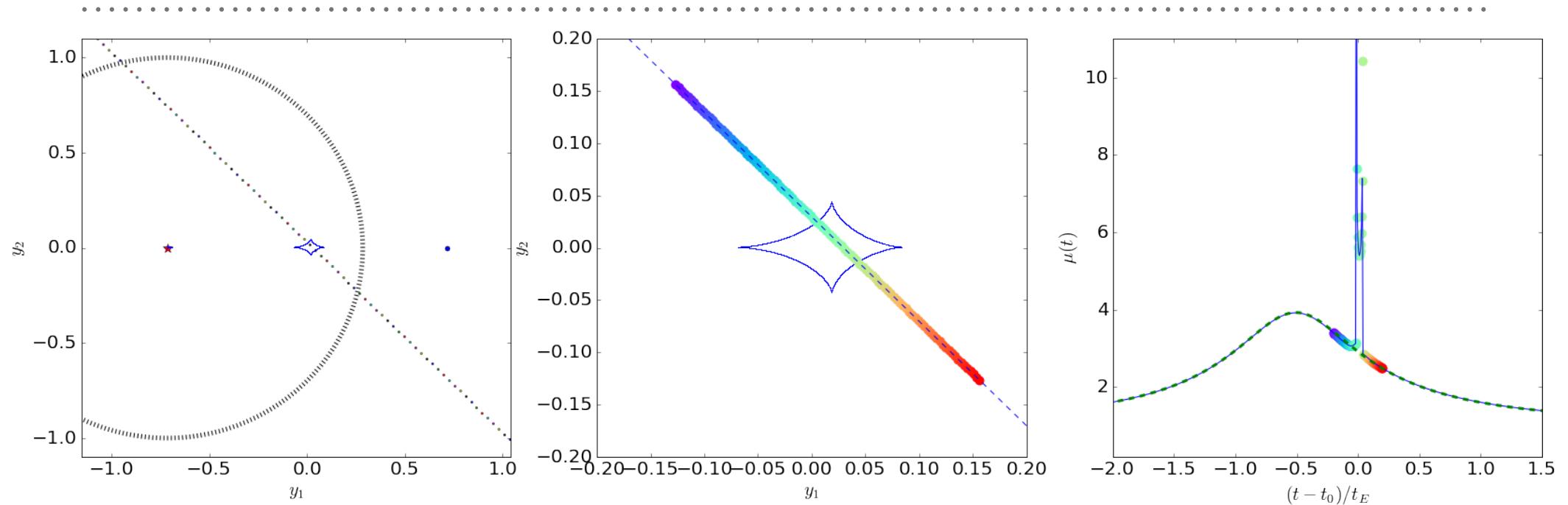
*If we notice a planetary caustic perturbation, it means that the planet is located at the position of one of the images:*

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

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

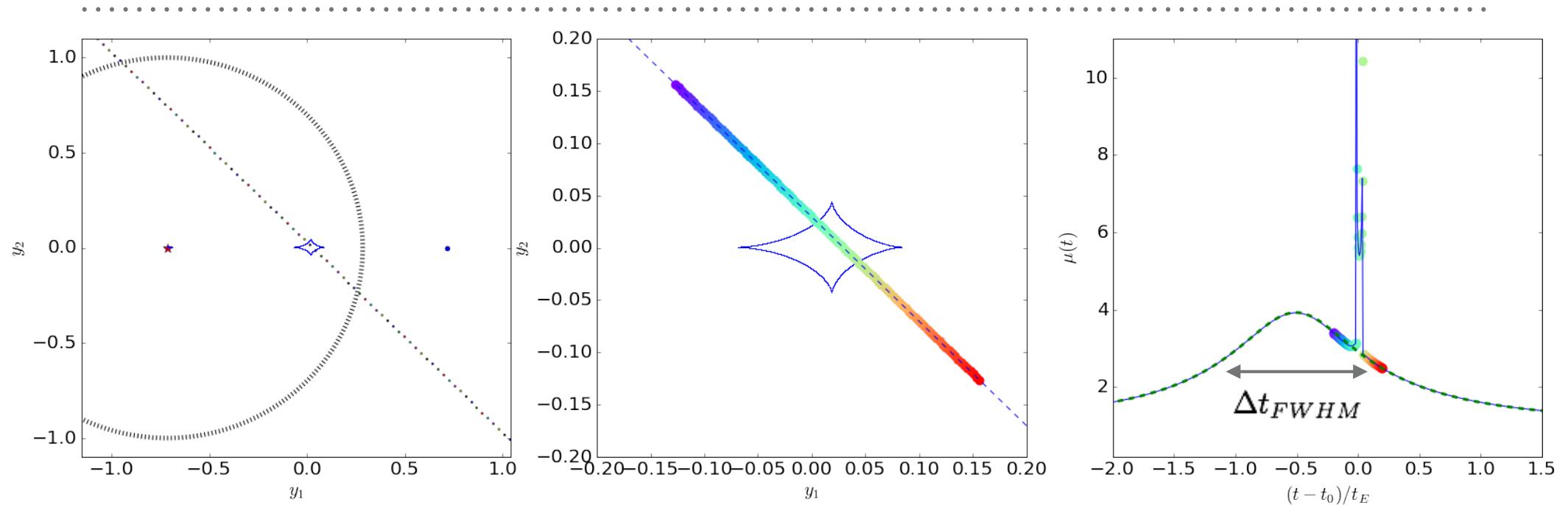
$$x_{\pm} = \frac{1}{2} \left[ y \pm \sqrt{y^2 + 4} \right]$$

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



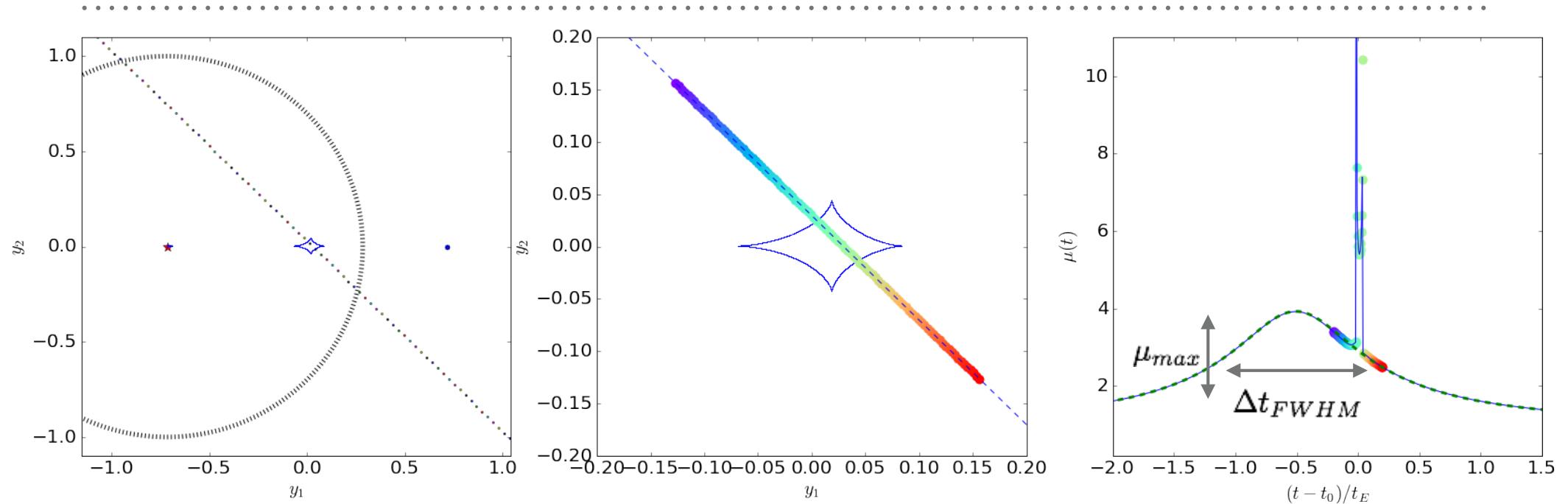
- primary event:
- planetary perturbation:

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



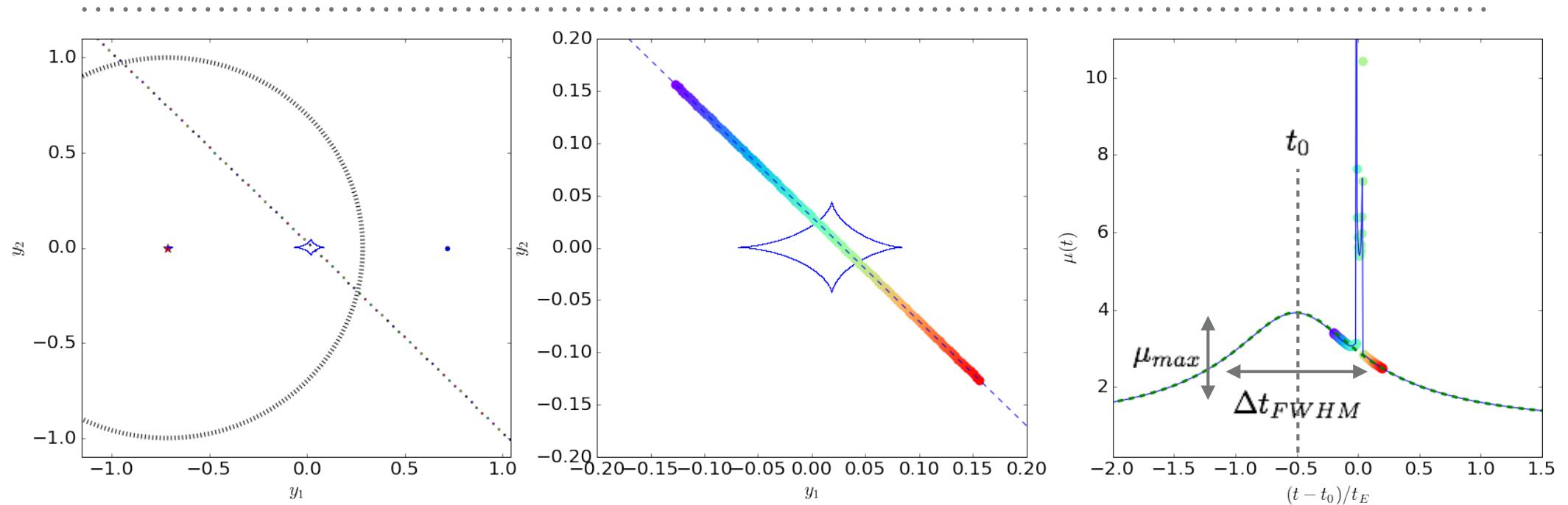
- primary event:  $\Delta t_{FWHM}$
- planetary perturbation:

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



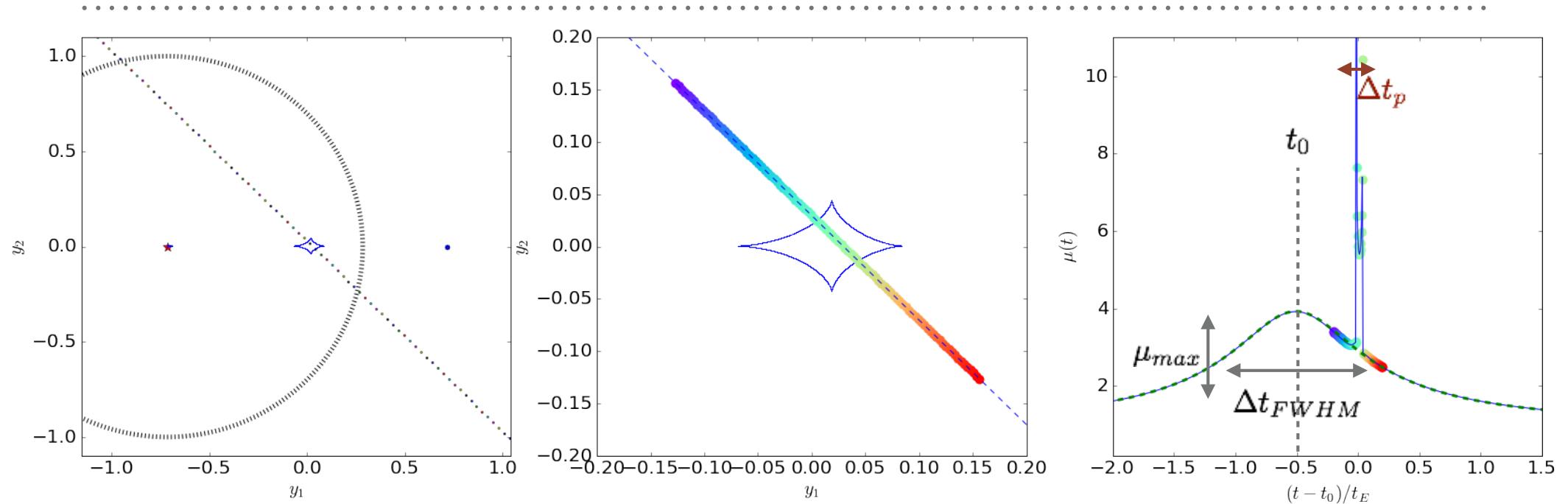
- primary event:  $\Delta t_{FWHM}$      $\mu_{max}$
- planetary perturbation:

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



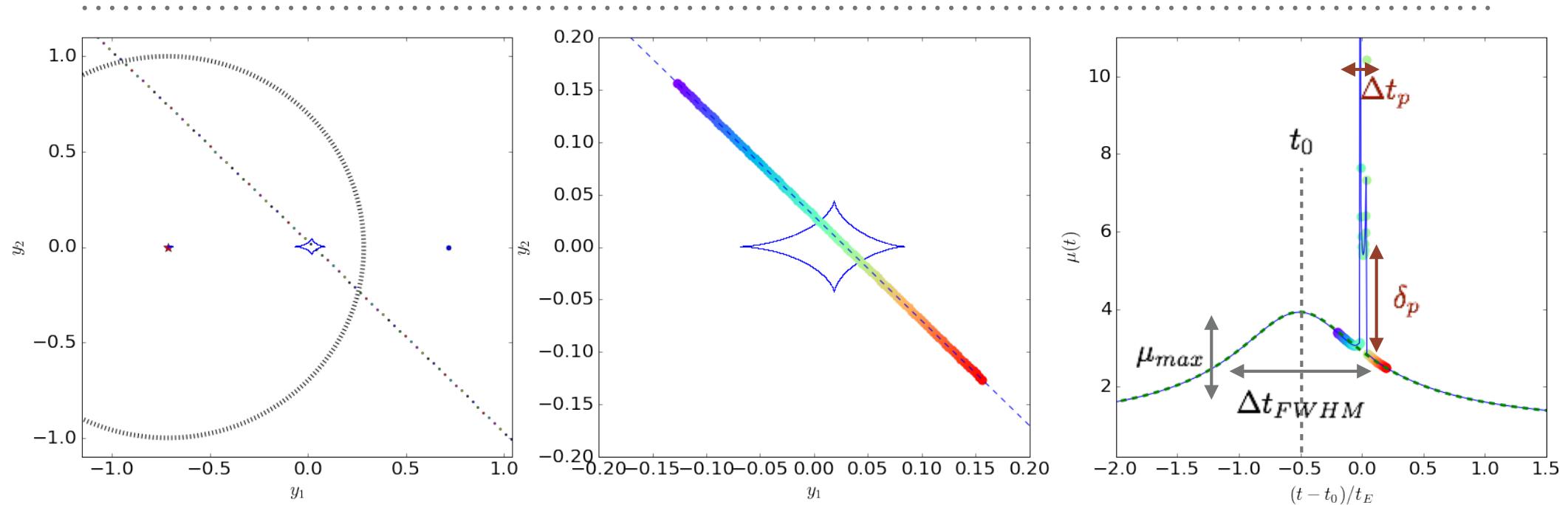
- primary event:  $\Delta t_{FWHM}$     $\mu_{max}$     $t_0$
- planetary perturbation:

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



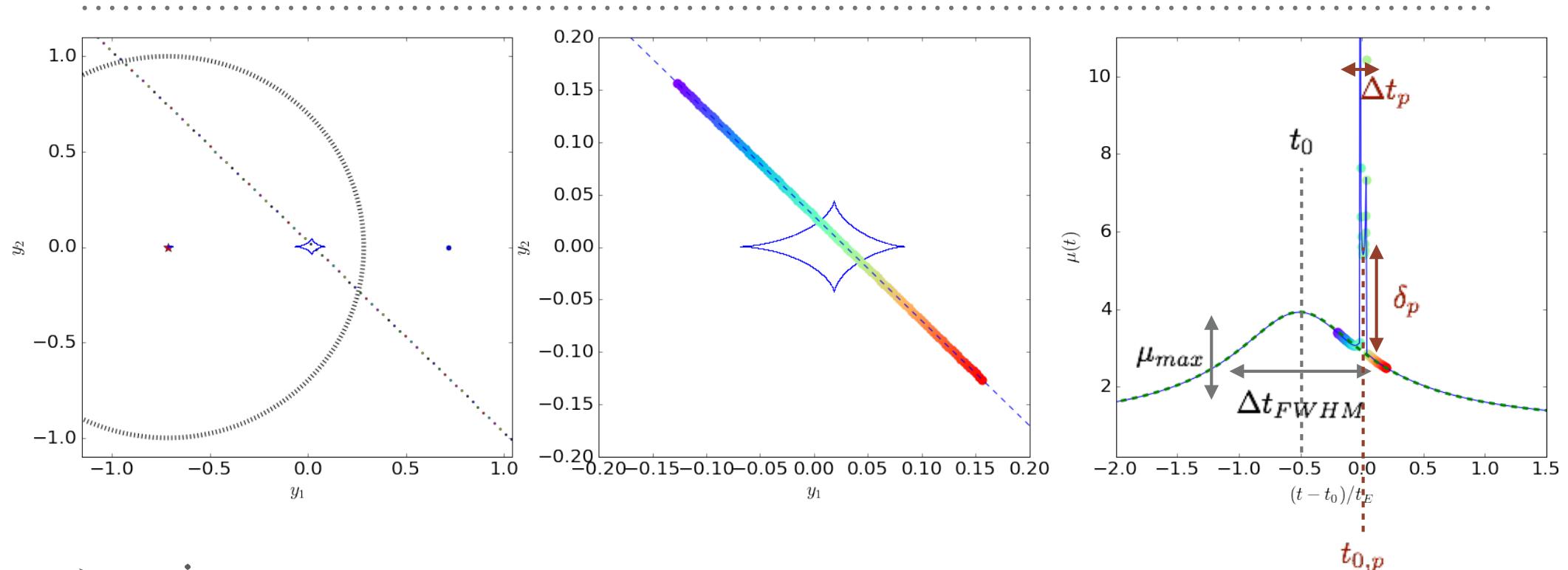
- primary event:  $\Delta t_{FWHM}$     $\mu_{max}$     $t_0$
- planetary perturbation:       $\Delta t_p$

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



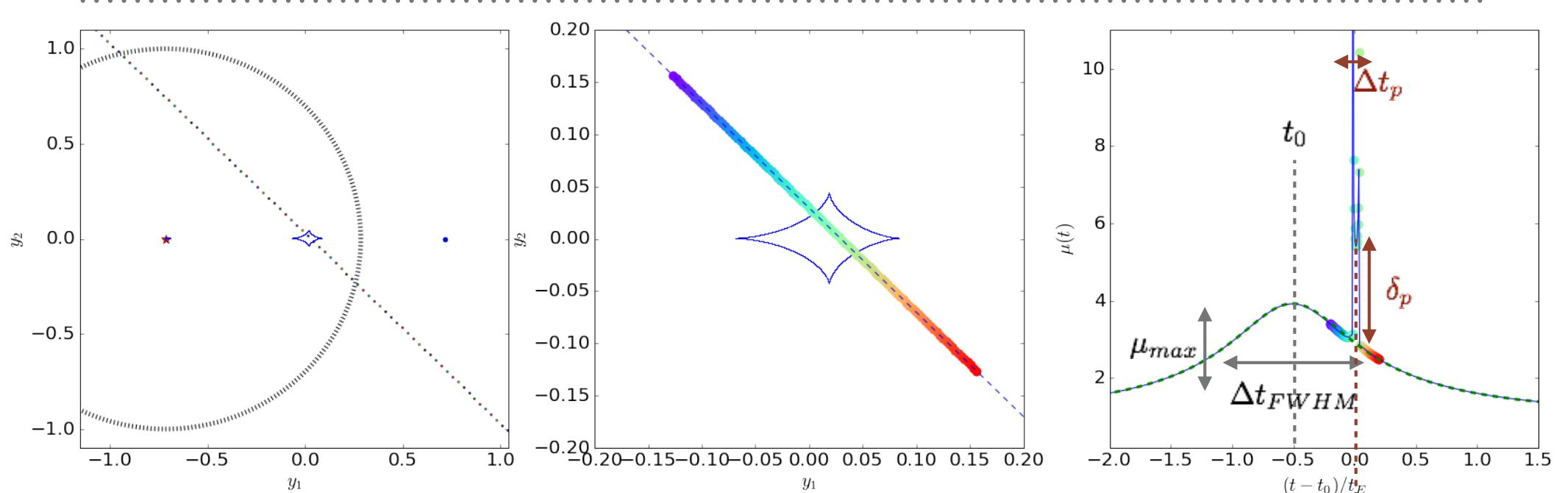
- primary event:  $\Delta t_{FWHM}$     $\mu_{max}$     $t_0$
- planetary perturbation:       $\Delta t_p$     $\delta_p$

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



- primary event:  $\Delta t_{FWHM}$     $\mu_{max}$     $t_0$
- planetary perturbation:       $\Delta t_p$     $\delta_p$     $t_{0,p}$

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES

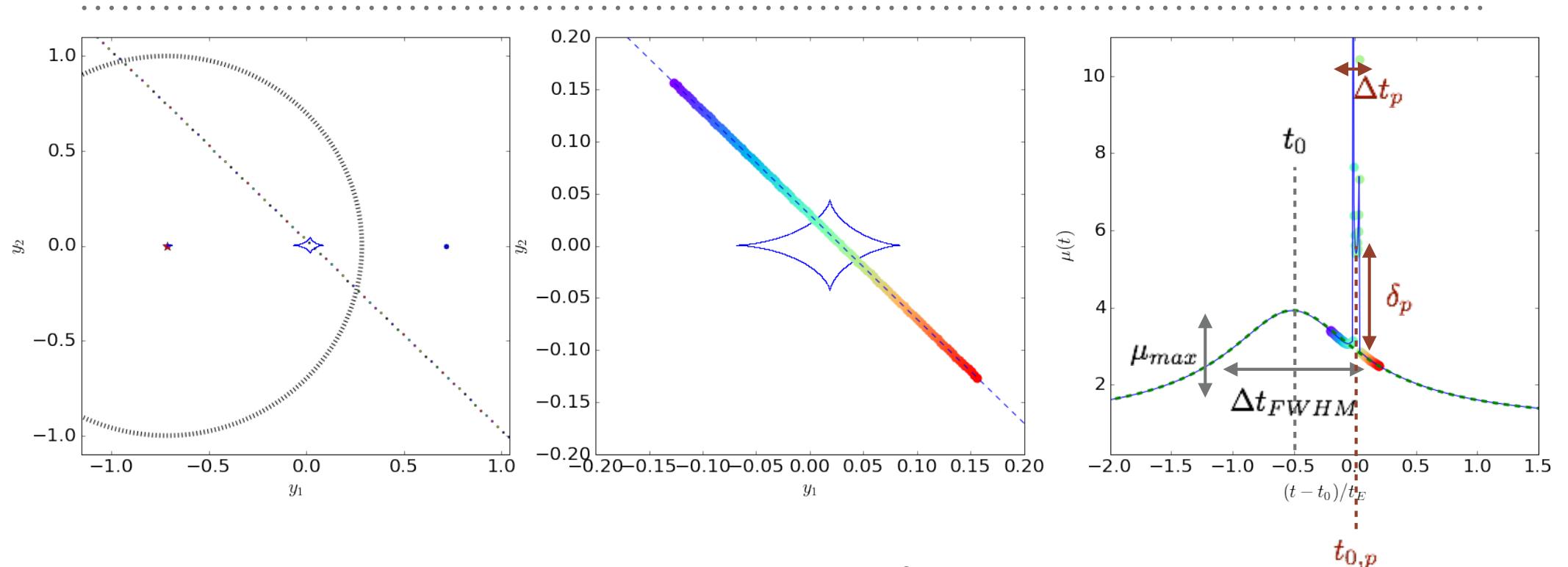


$$y_o = \sqrt{2 \left( \frac{\mu_{\max}}{\sqrt{\mu_{\max}^2 - 1}} - 1 \right)}$$

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

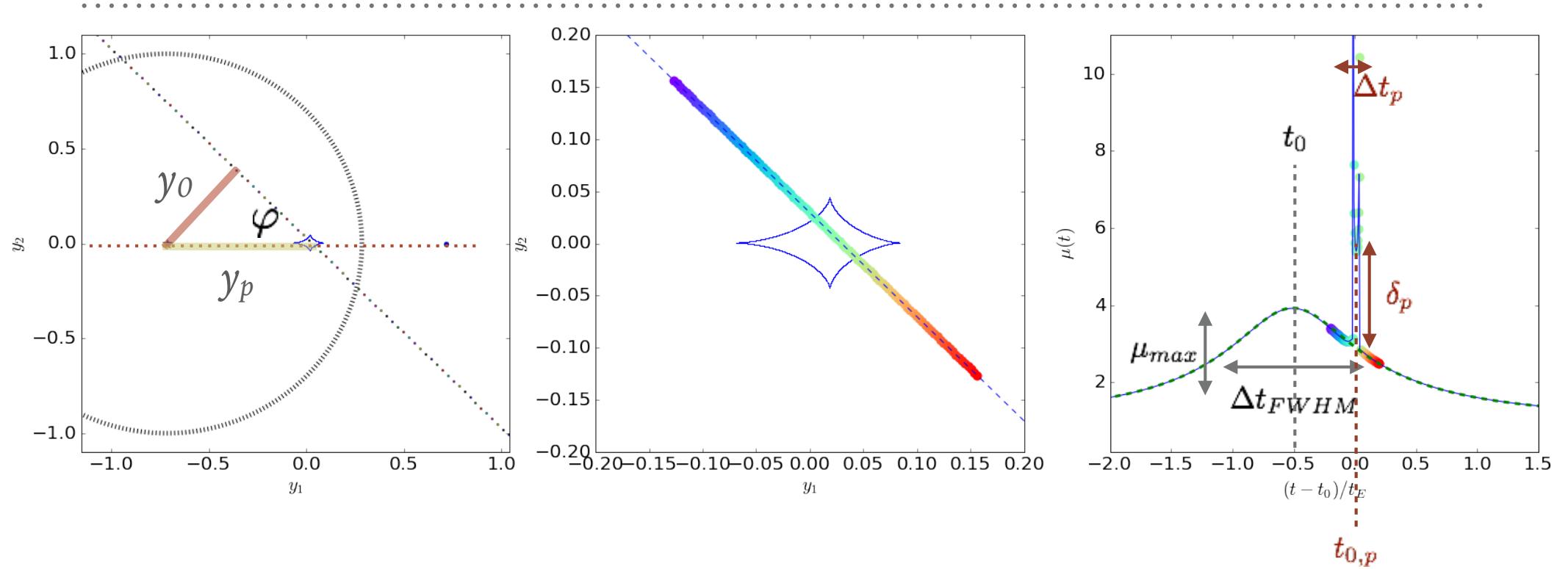
$$\Rightarrow \quad y_0 \quad t_E$$

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



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

# PLANET PROPERTIES “READ OFF” OF THE LIGHT CURVES



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

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

# TO SUMMARIZE

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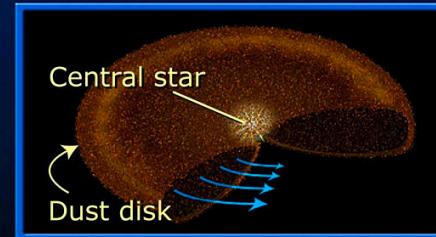
- different caustic topologies give rise to different kind of perturbations on the light curves
- planets can be detected in only a few qualitatively different ways:
  - at relatively low magnification of the primary, if the source crosses the planetary caustics from close or wide planets
  - near the 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...

# WHY SEARCHING PLANETS?

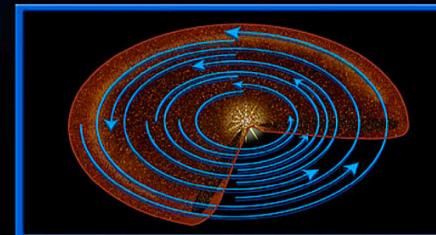
- Planet formation and evolution is still not fully understood
- Different models predict different distributions of planet masses and distances from the host stars
- Sizes of planets may depend on the mass of the host star, on the position in the galaxy (e.g. on the local metallicity), etc
- Models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

## TWO PLANET FORMATION SCENARIOS

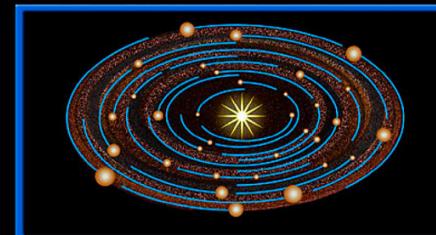
Accretion model



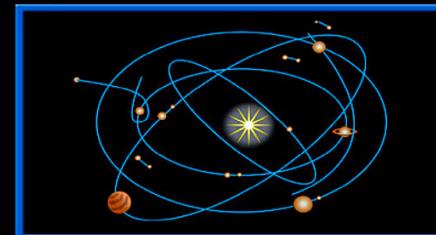
Orbiting dust grains accrete into "planetesimals" through nongravitational forces.



Planetesimals grow, moving in near-coplanar orbits, to form "planetary embryos."

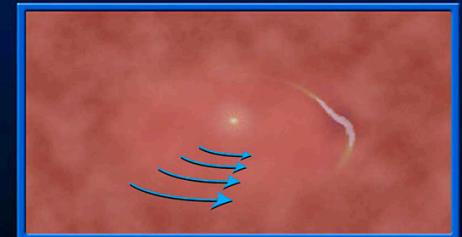


Gas-giant planets accrete gas envelopes before disk gas disappears.



Gas-giant planets scatter or accrete remaining planetesimals and embryos.

Gas-collapse model



A protoplanetary disk of gas and dust forms around a young star.



Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.



Dust grains coagulate and sediment to the center of the protoplanet, forming a core.



The planet sweeps out a wide gap as it continues to feed on gas in the disk.

# METHODS TO SEARCH PLANETS OTHER THAN MICROLENSING

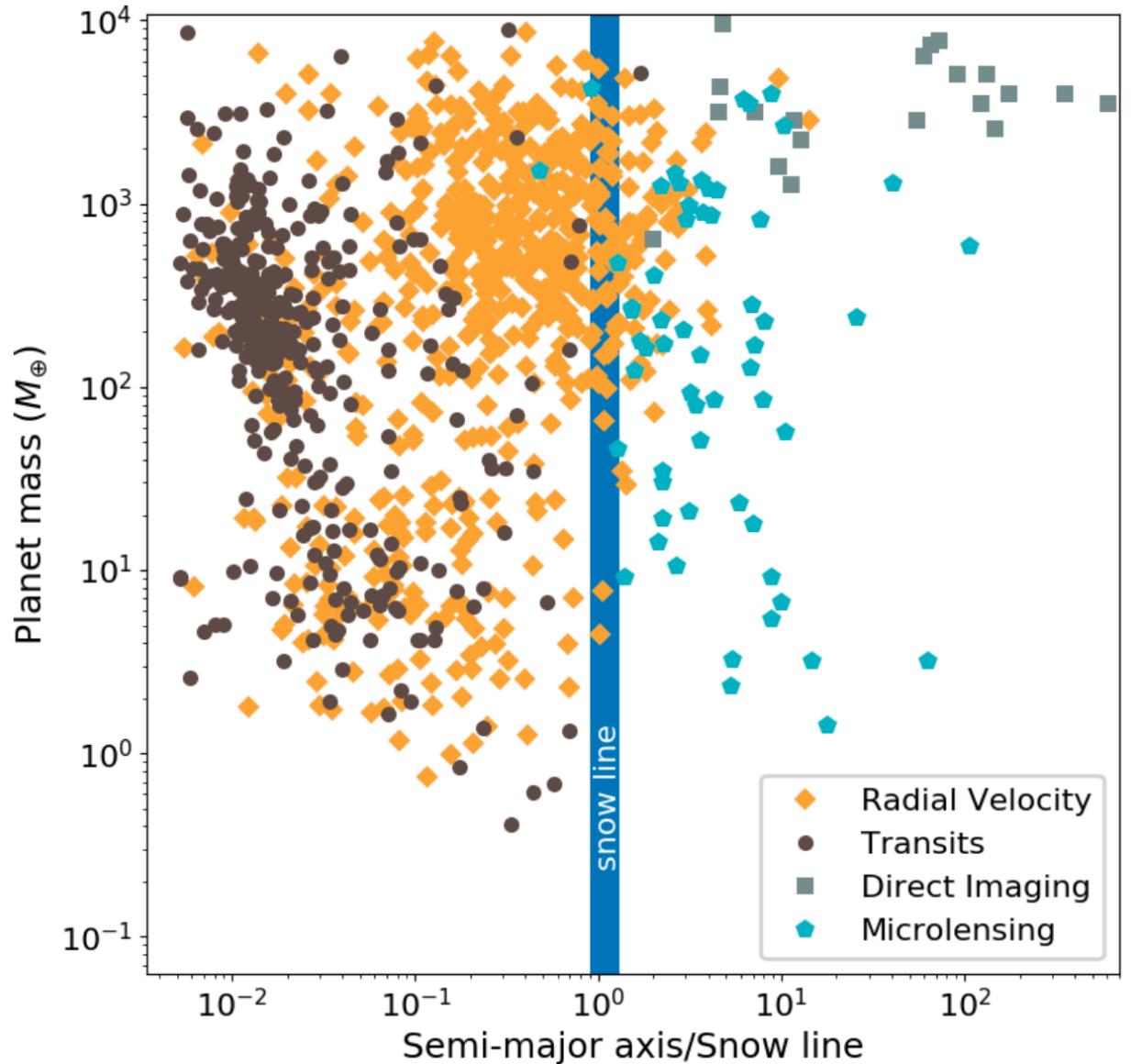
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- **Radial velocity shift:** relies on the fact that a star does not remain completely stationary when it is orbited by a planet. The star moves, ever so slightly, in a small circle or ellipse, responding to the gravitational tug of its smaller companion. 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  $\sim 1$  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

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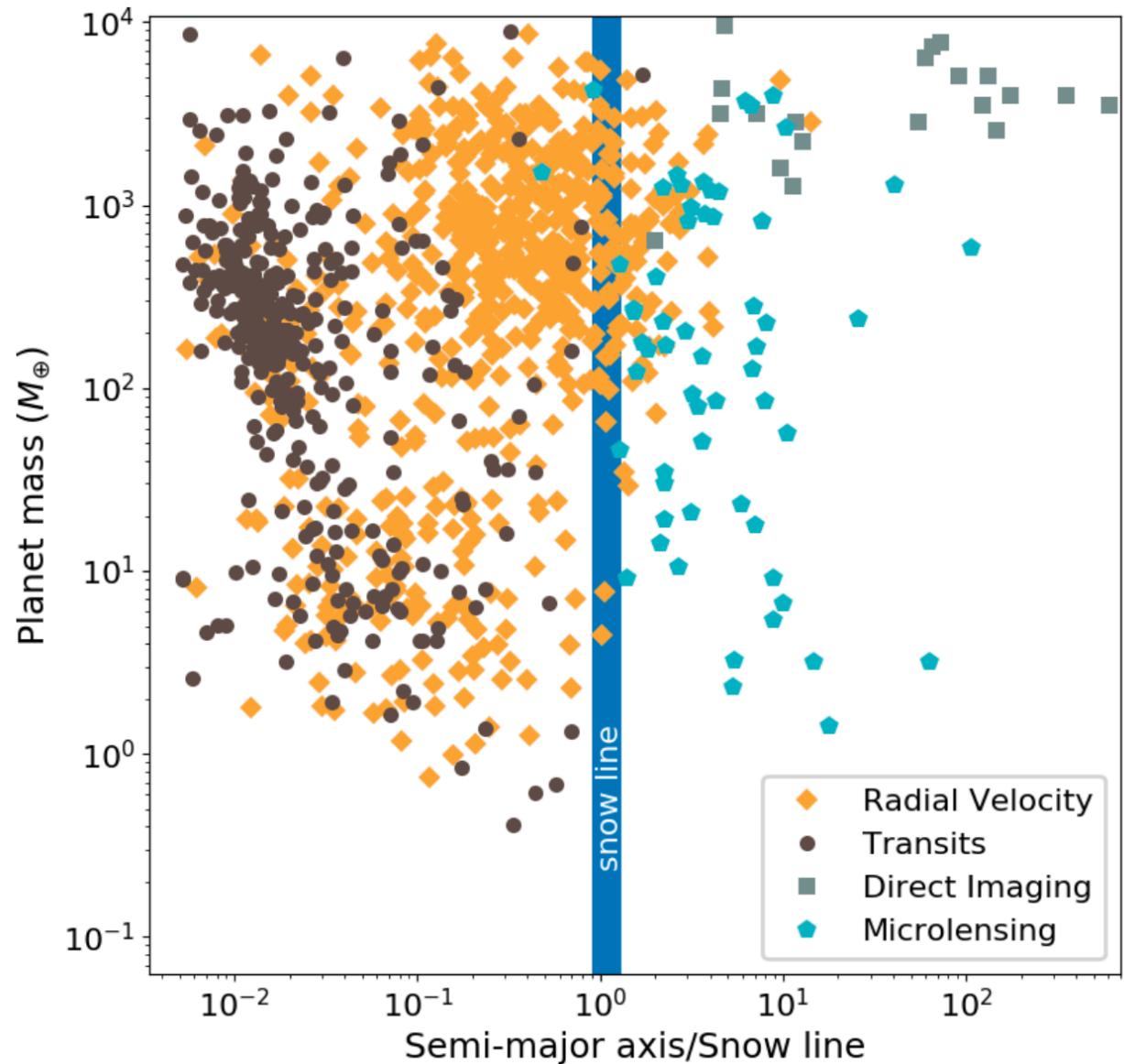
- ~4400 confirmed exoplanets
- Transits and radial velocity shifts are by far the most successful techniques
- Astrometry: very precise measurements are necessary.  
Only one detection (not confirmed). Possibly GAIA will revolutionise the picture
- Vast majority of detections are massive planets close 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
- $d_{\min} = 0.66 \text{ AU}$
- bulk of planets at  $d \sim 3 \text{ AU}$
- 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 identified when they are at a distance  $\sim$ ER
- example: 1 mas at  $\sim$ 5kpc=5AU
- 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  $\sim$ 160K and water turns to ice

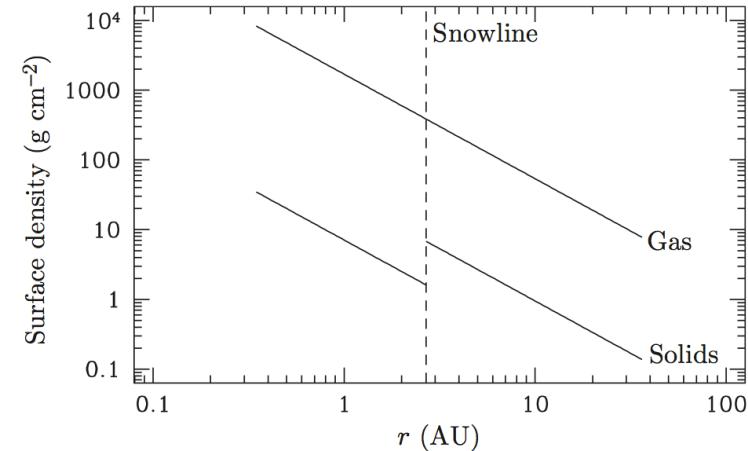
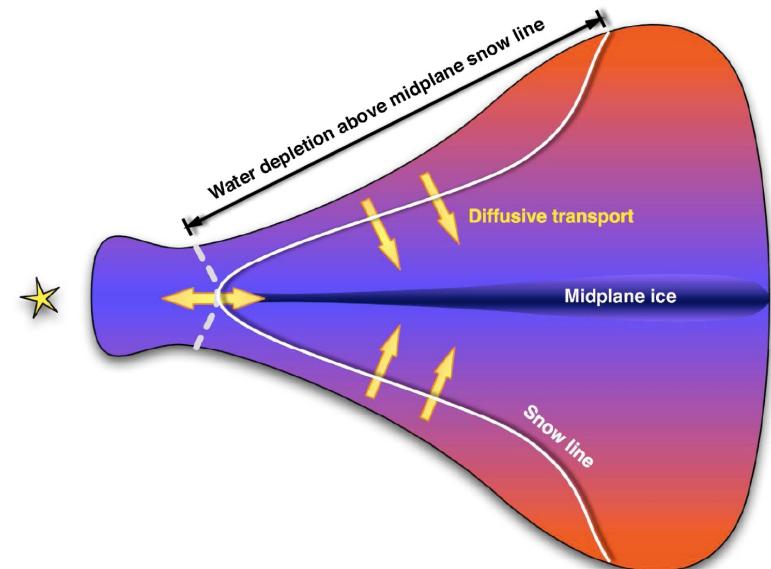
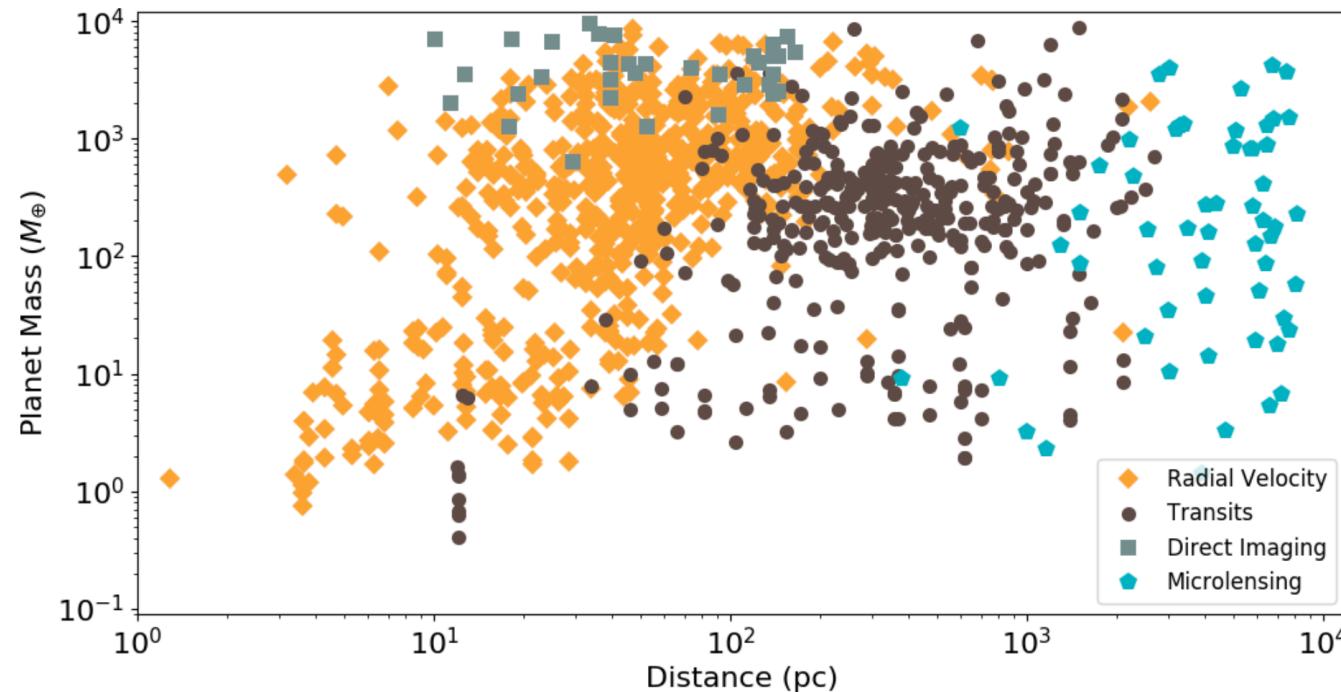


Fig. 1.1. The surface density in gas (upper line) and solids (lower broken line) as a function of radius in Hayashi's minimum mass Solar Nebula. The dashed vertical line denotes the location of the snowline.



# IN ADDITION...

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- 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

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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

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*2.4m telescope with a FOV 100x bigger  
than Hubble*

*To be launched (may be) in 2025*

