Introduction to Microlensing Theory and Observations

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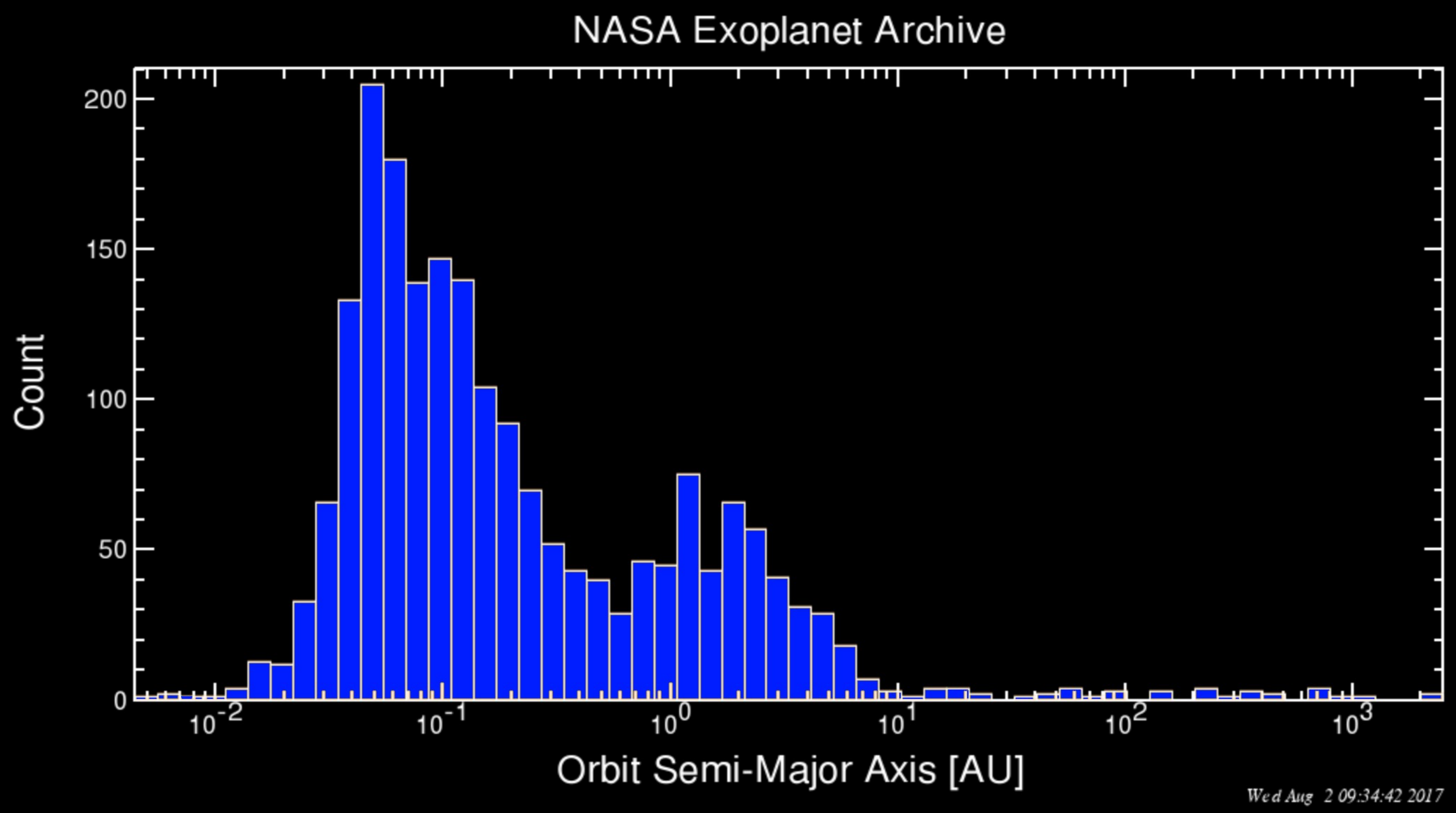
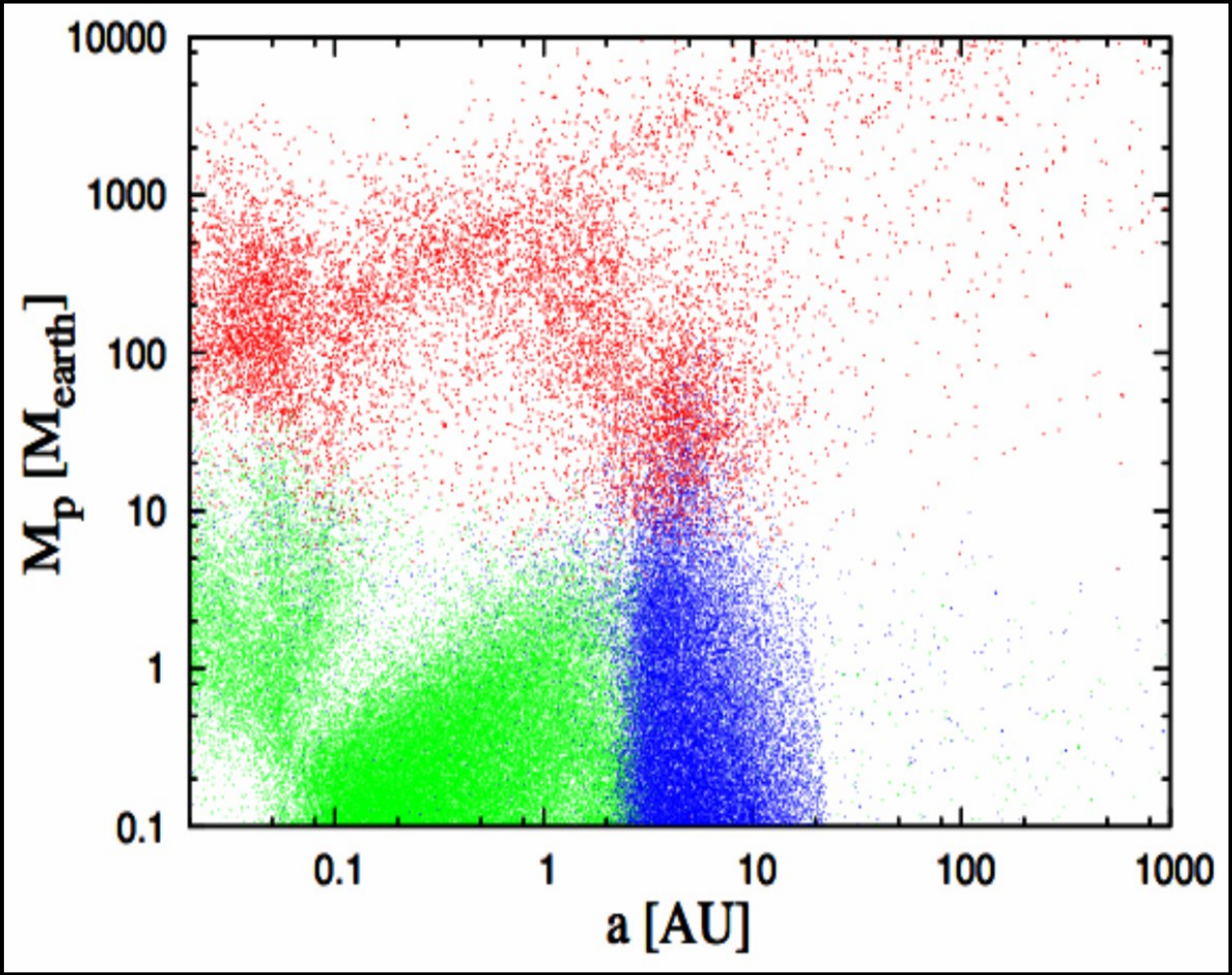
Exoplanet Discovery Space

In the last 25 years, we've found ~3,500 planets.

What's so important about microlensing?



Microlensing Discovery Space



Synthetic distribution of planets when protoplanetary nebula vanishes

From Ida et al. 2013

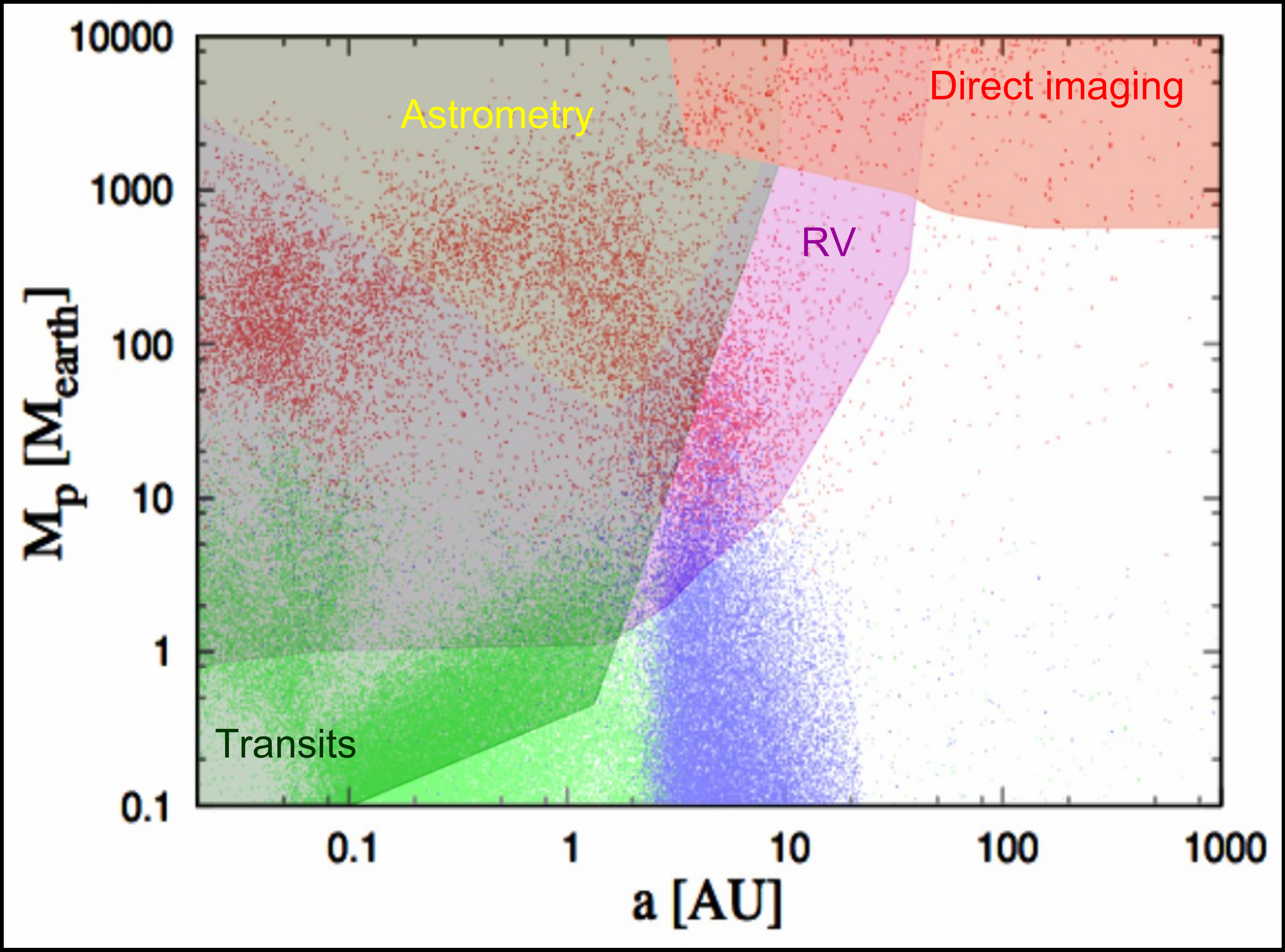
Rocky planets/low mass gas envelope

Icy planets/low mass gas envelope

Giant planets/massive gas envelope

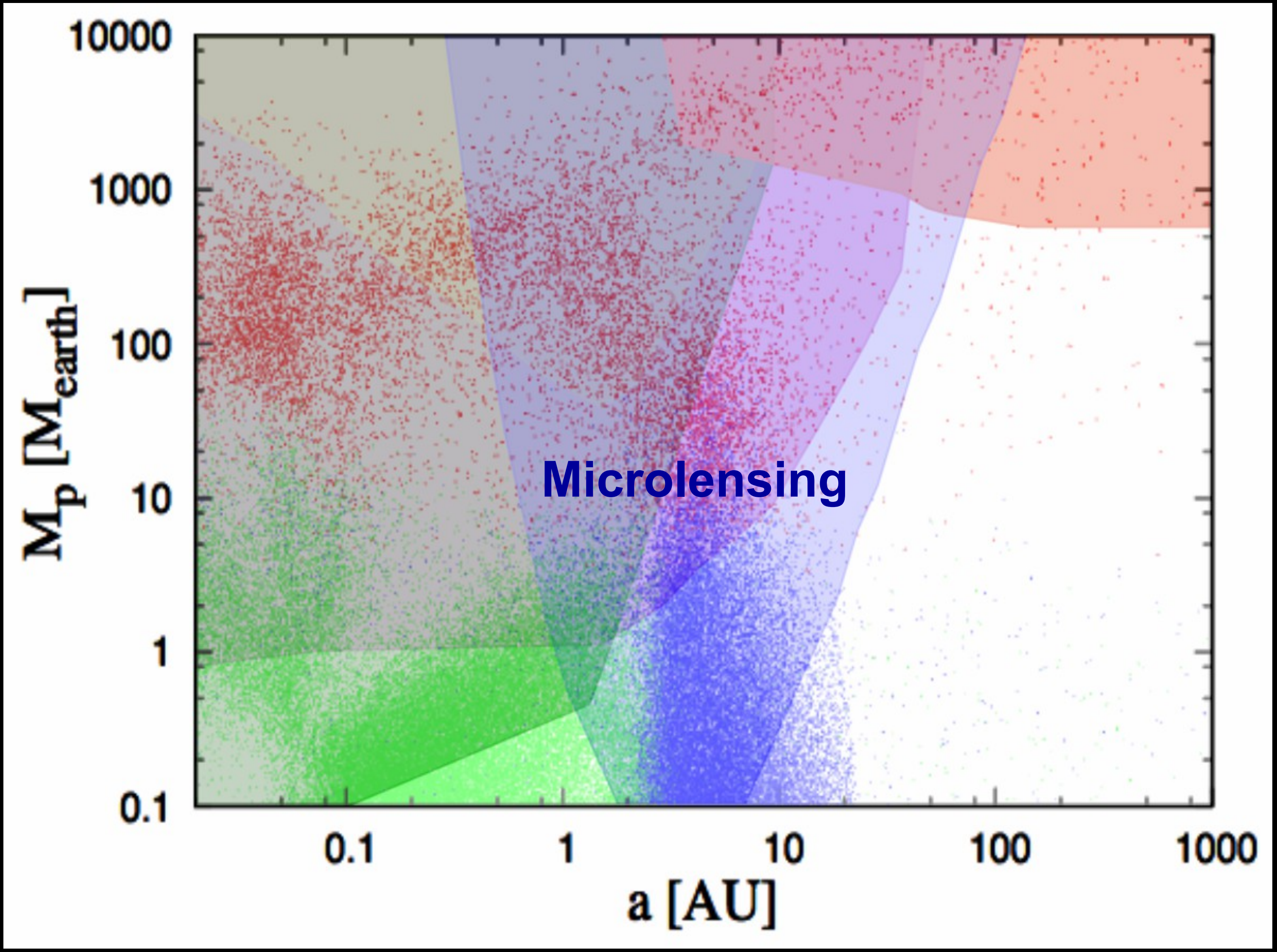
Microlensing Discovery Space

Approximate sensitivities of exoplanet detection techniques



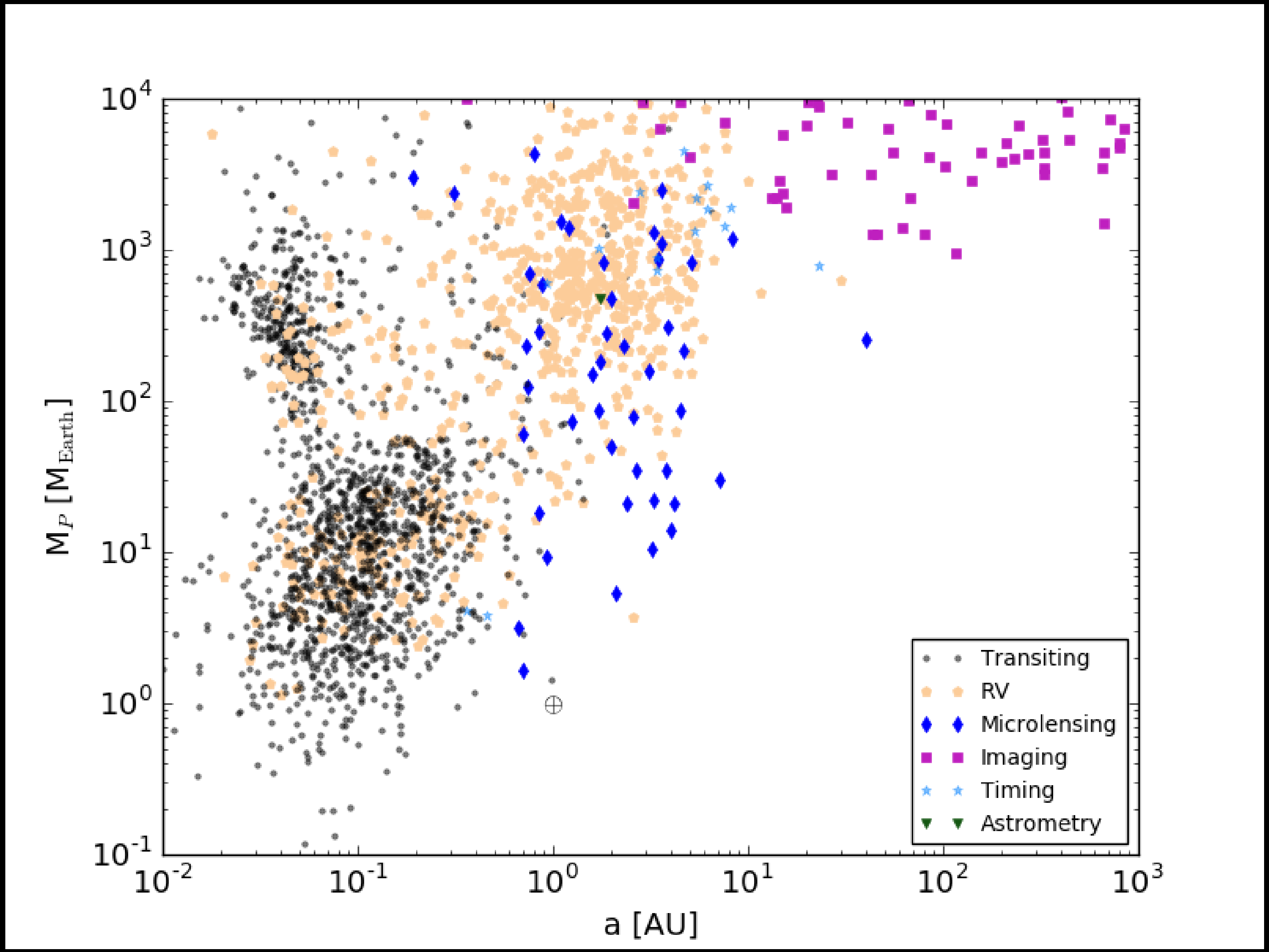
Microlensing Discovery Space

Approximate sensitivities of exoplanet detection techniques

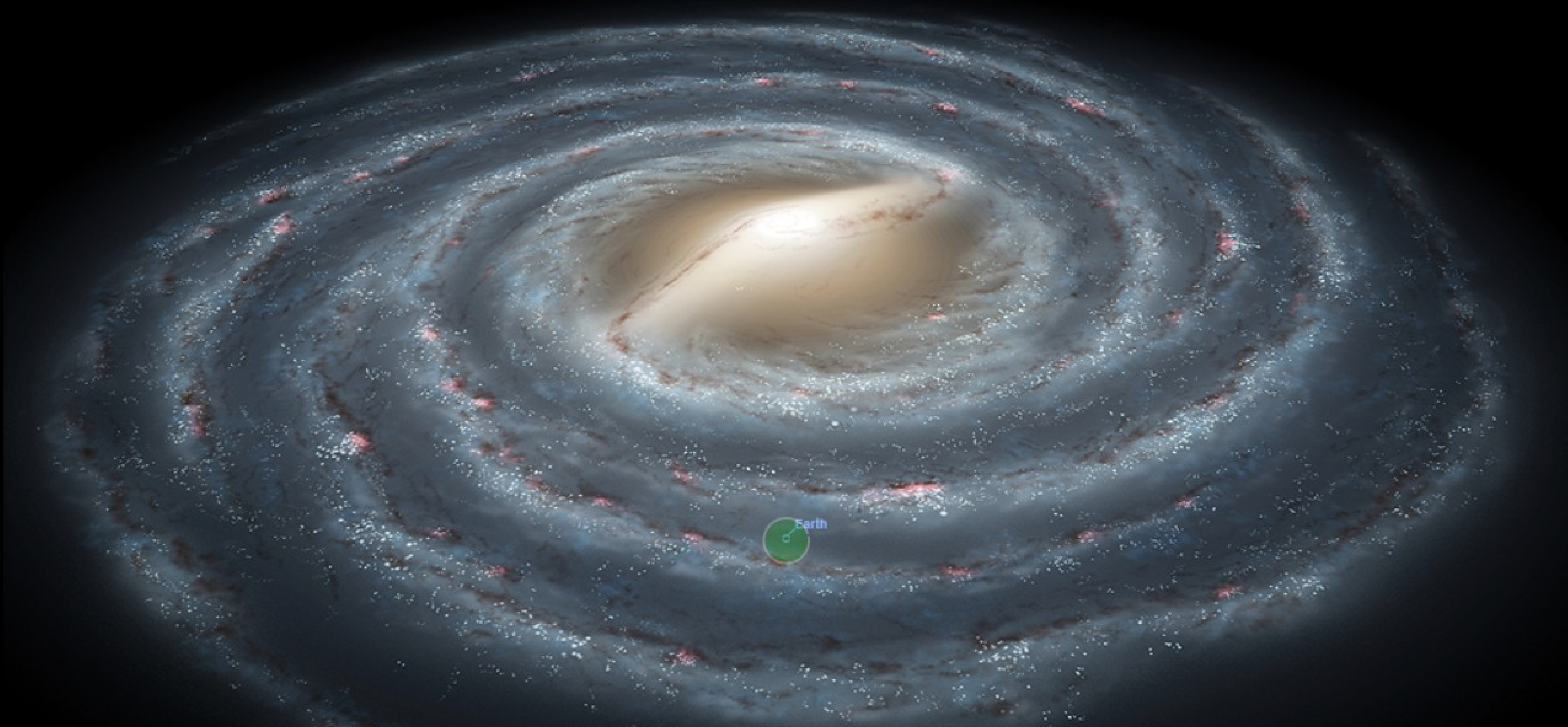


Microlensing Discovery Space

Actual exoplanet detections by various techniques



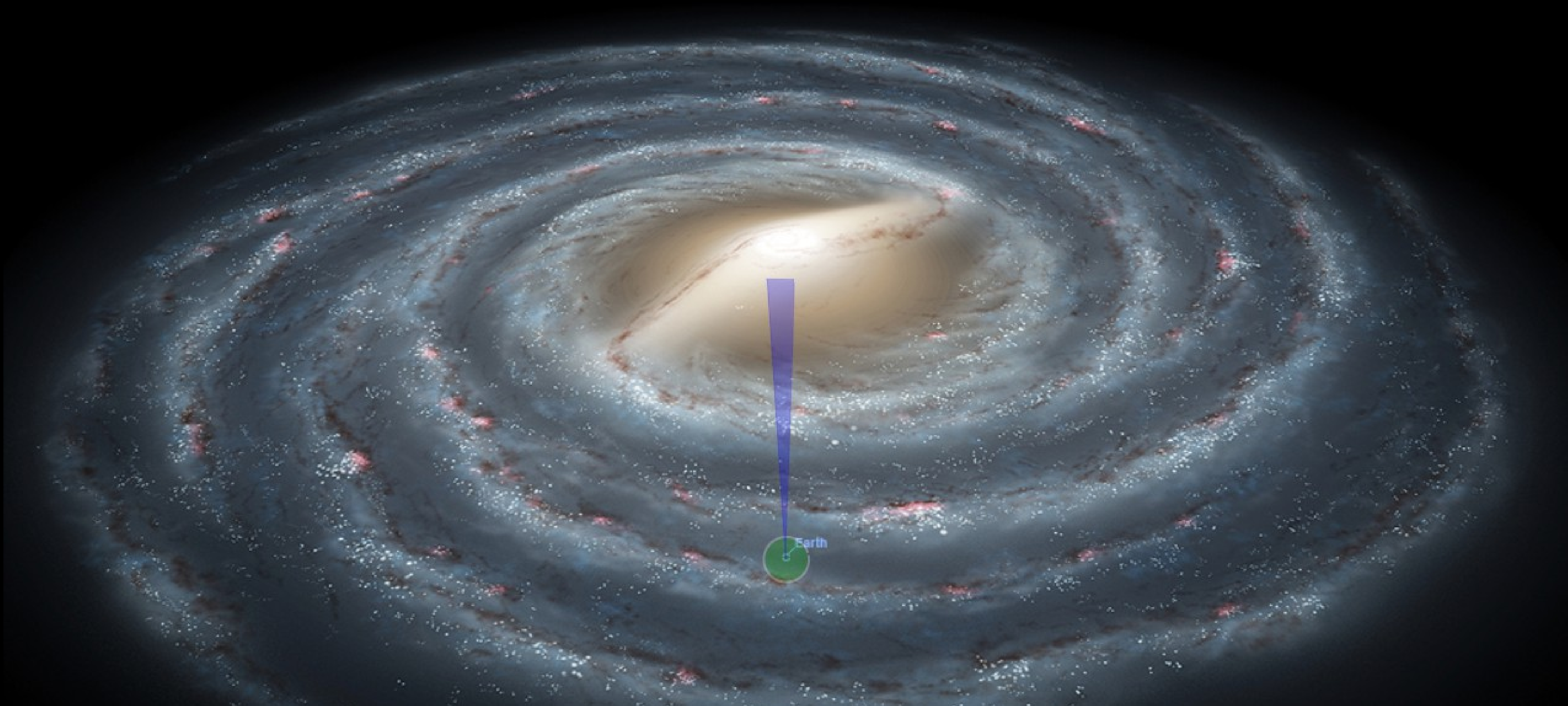
Microlensing Discovery Space



Direct imaging < 165pc
Astrometry <20pc (so far)
...radii smaller than the
“Earth” circle

Transits/RV detections out to ~1300pc

Microlensing Discovery Space



Direct imaging < 165pc
Astrometry <20pc (so far)
...radii smaller than the
"Earth" circle

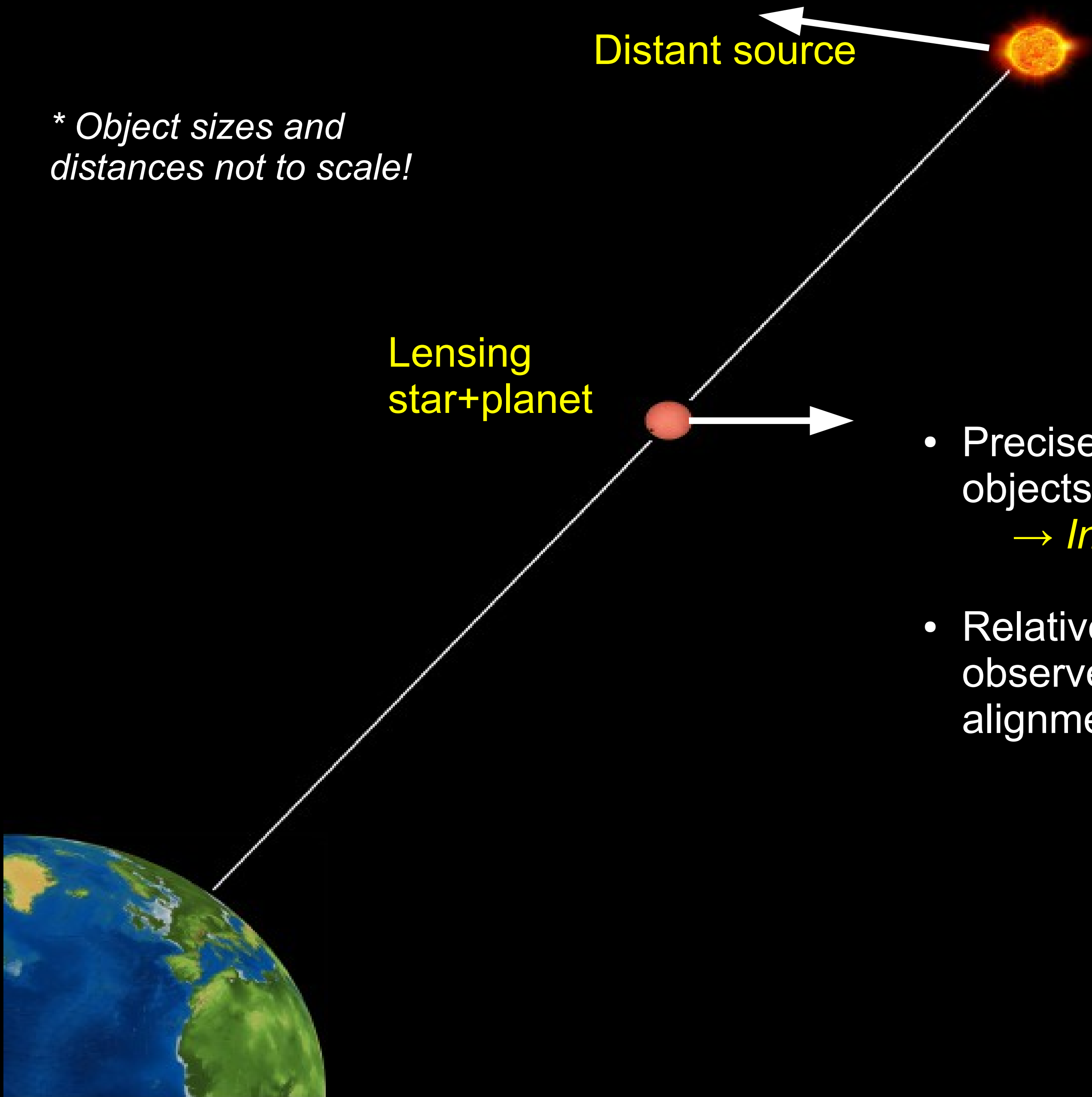
Transits/RV detections out to ~1300pc
Microlensing detections to ~8200pc

Microlensing Discovery Space

Microlensing is sensitive to planets of all masses at separations of ~1-10 AU, filling a critical gap between the sensitivities of other discovery techniques

It is capable of exploring planet formation in different stellar environments throughout the galaxy

Observing Microlensing Events

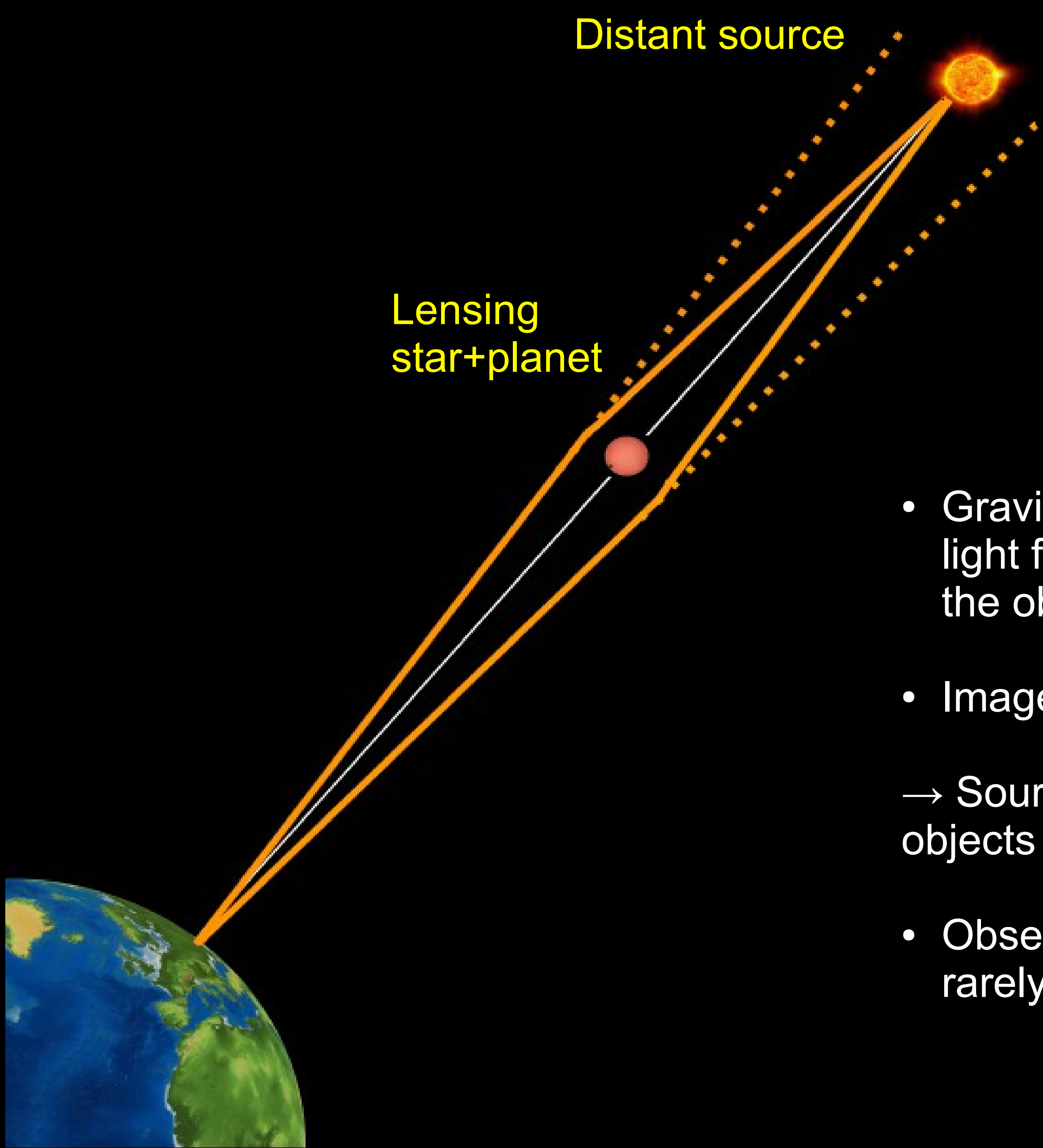


** Object sizes and distances not to scale!*

- Precise alignment between unrelated objects along the line-of-sight
  → *Intrinsically rare*

- Relative motion of source, lens and observer carry them into and out of alignment

Observing Microlensing Events



- Gravity of the lensing body deflects the light from the source. More of it reaches the observer

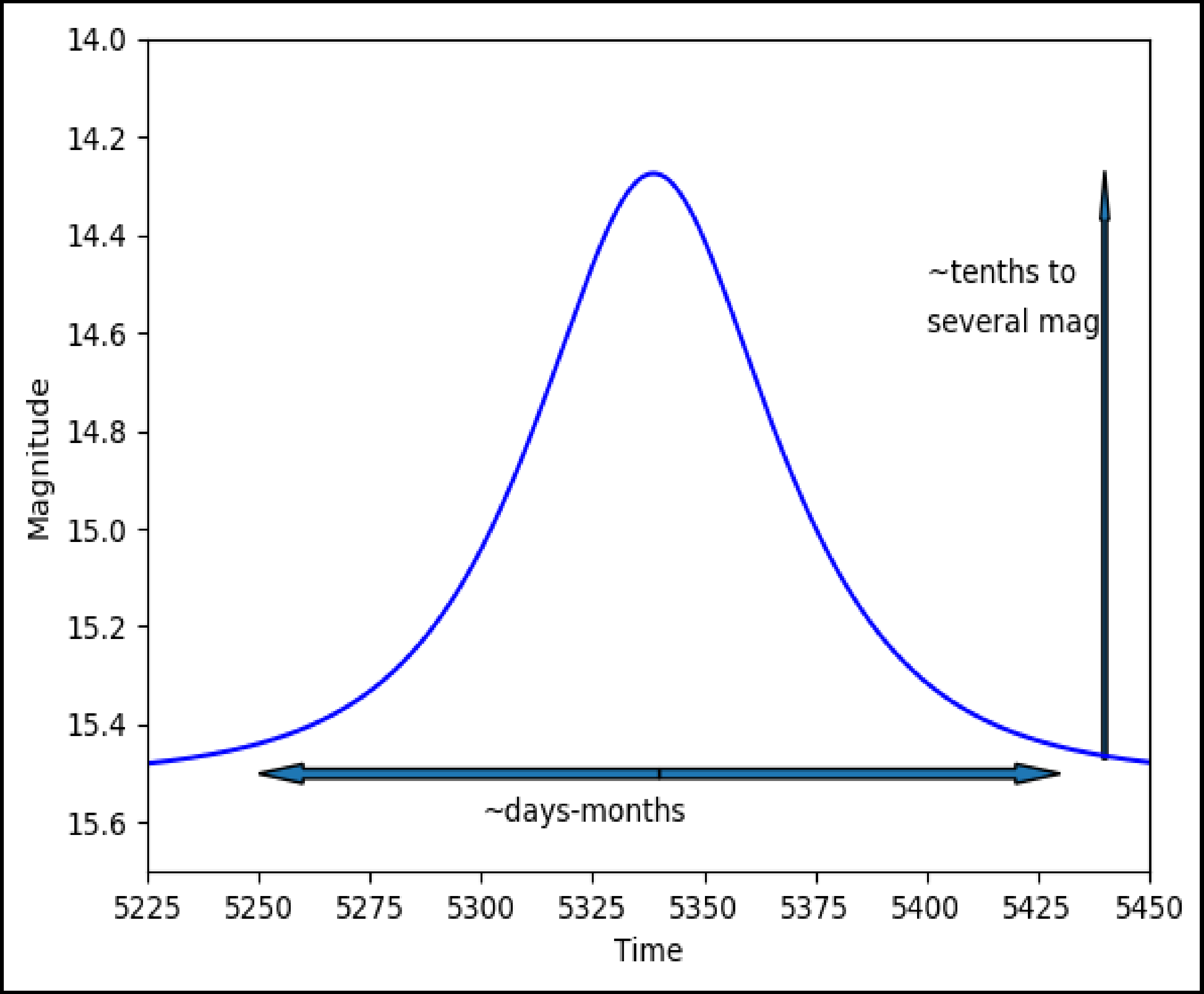
- Images of the source are created

→ Source appears to brighten and fade as objects move into/out of alignment

- Observe only light from the source – *<u>very</u>* rarely from the lens

Microlensing lightcurves

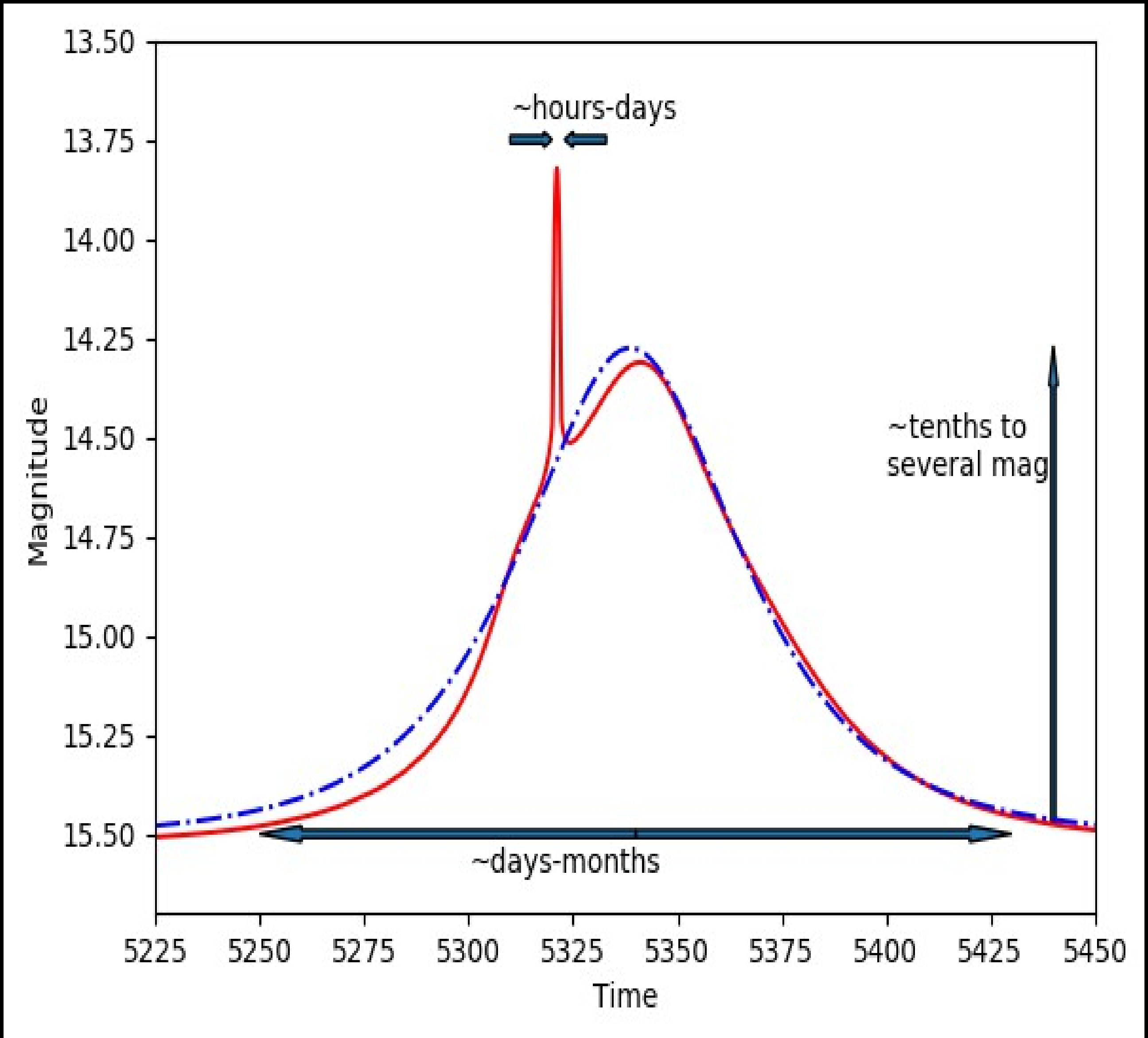
Single-object lens



- Magnification depends on angular separation *not* lens mass
- All wavelengths are magnified by the same amount

Microlensing lightcurves

Star + planet lens system



Presence of a 2nd mass causes additional lensing during the event

↓

Deviation from the smooth single-lens curve

= 'anomaly'

Microlensing Targets

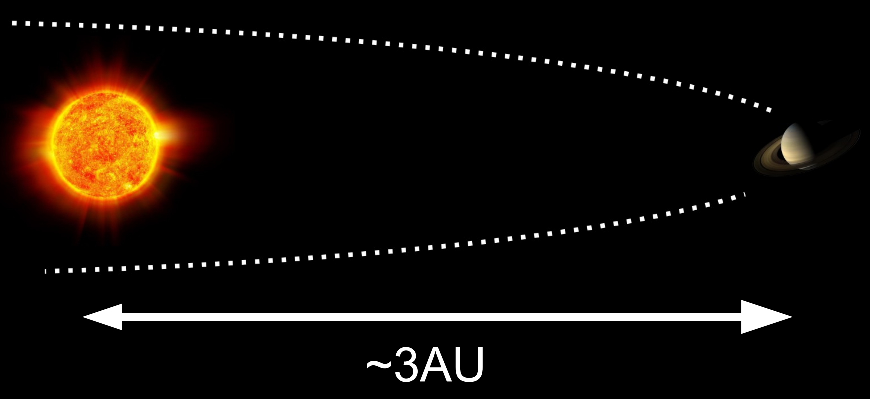
Intrinsically rare events, small probability of alignment
→ need to monitor many potential source stars

From OGLE

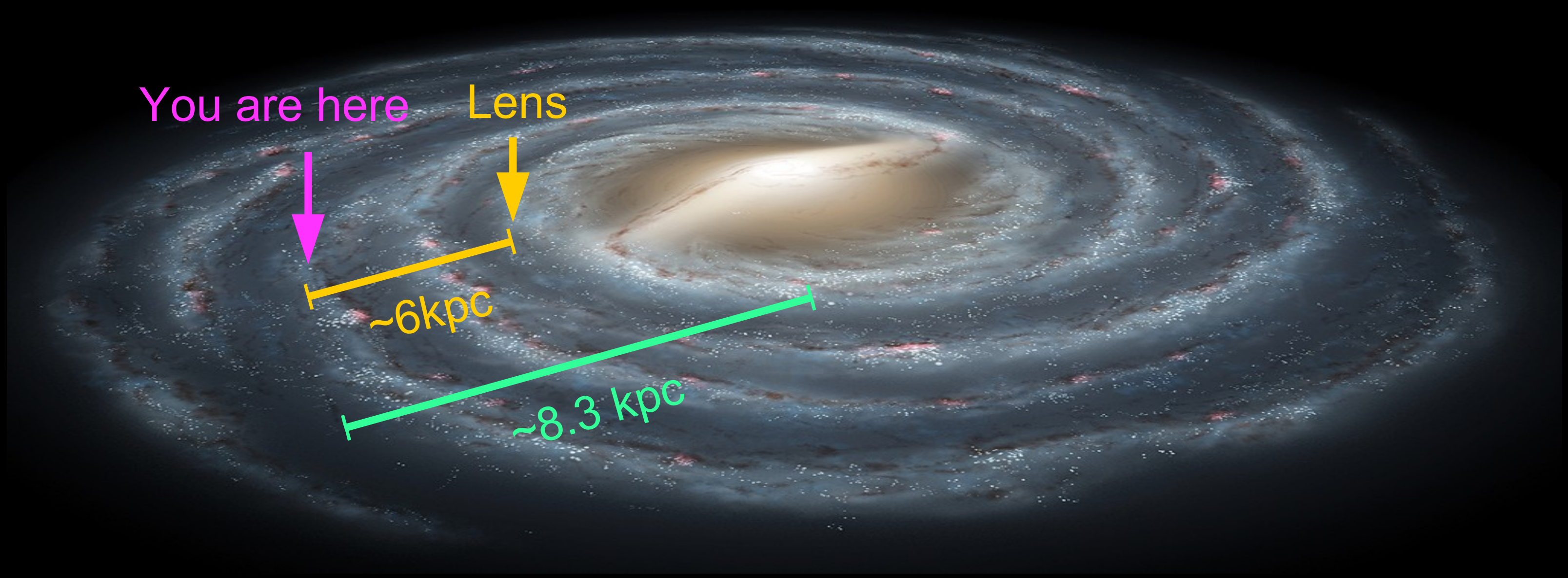
From LCO

Introduces observational limitations:
- Blending
- Extinction

“Typical” exoplanetary system discovered by microlensing



A Saturn-mass planet in a ~3AU orbit around an M dwarf, ~6 kpc from Earth toward the Galactic Bulge.



Microlensing Observations

Microlensing depends on the coincidental alignment of a foreground planet system with a background source

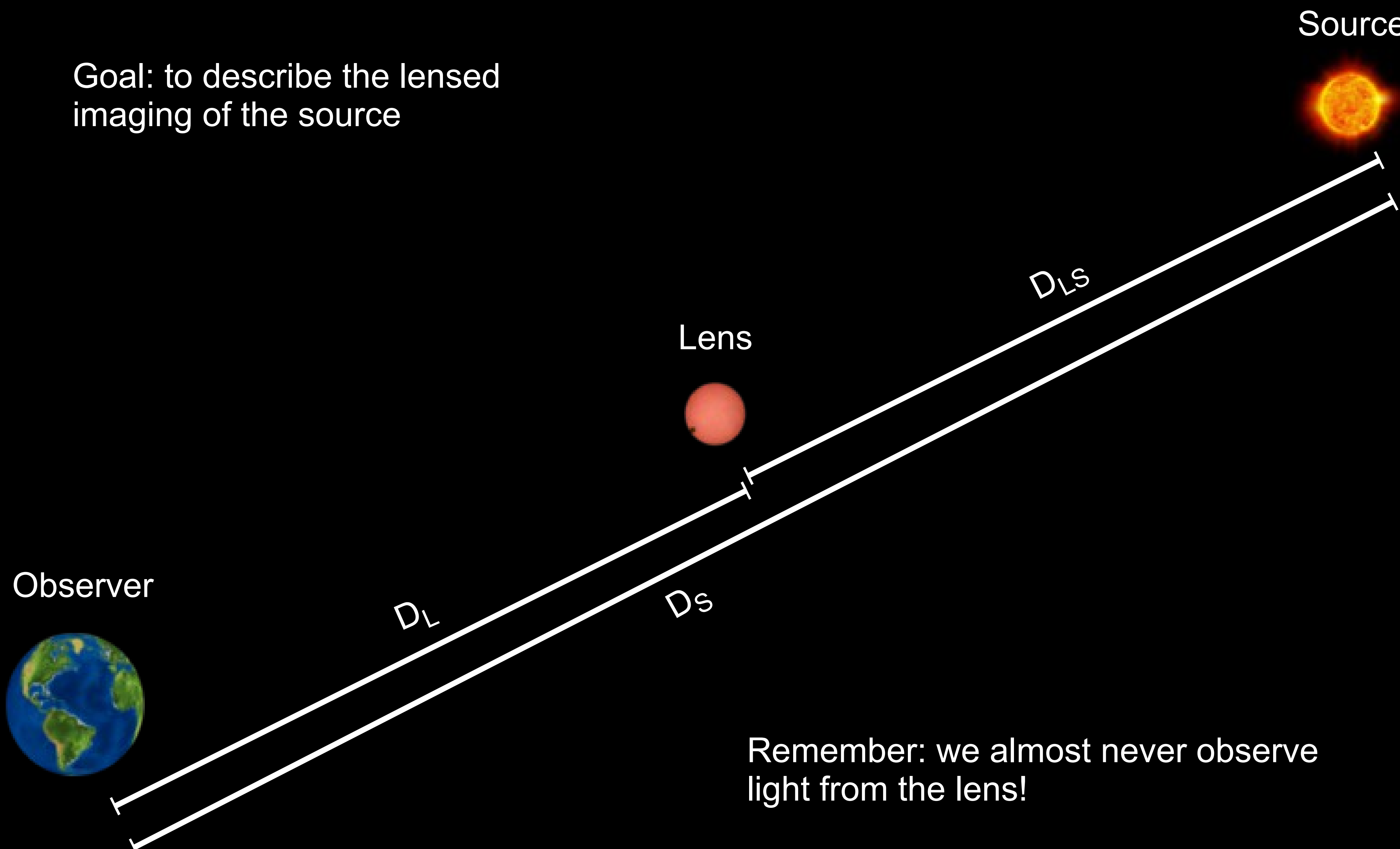
The gravity of the foreground system causes more light from the source to reach the observer, so it appears to brighten and fade over time

Gravity bends all wavelengths of light equally, so microlensing is independent of passband

Planets can be found around the foreground system by looking for rapid deviations ('anomalies') from a smooth lensing lightcurve

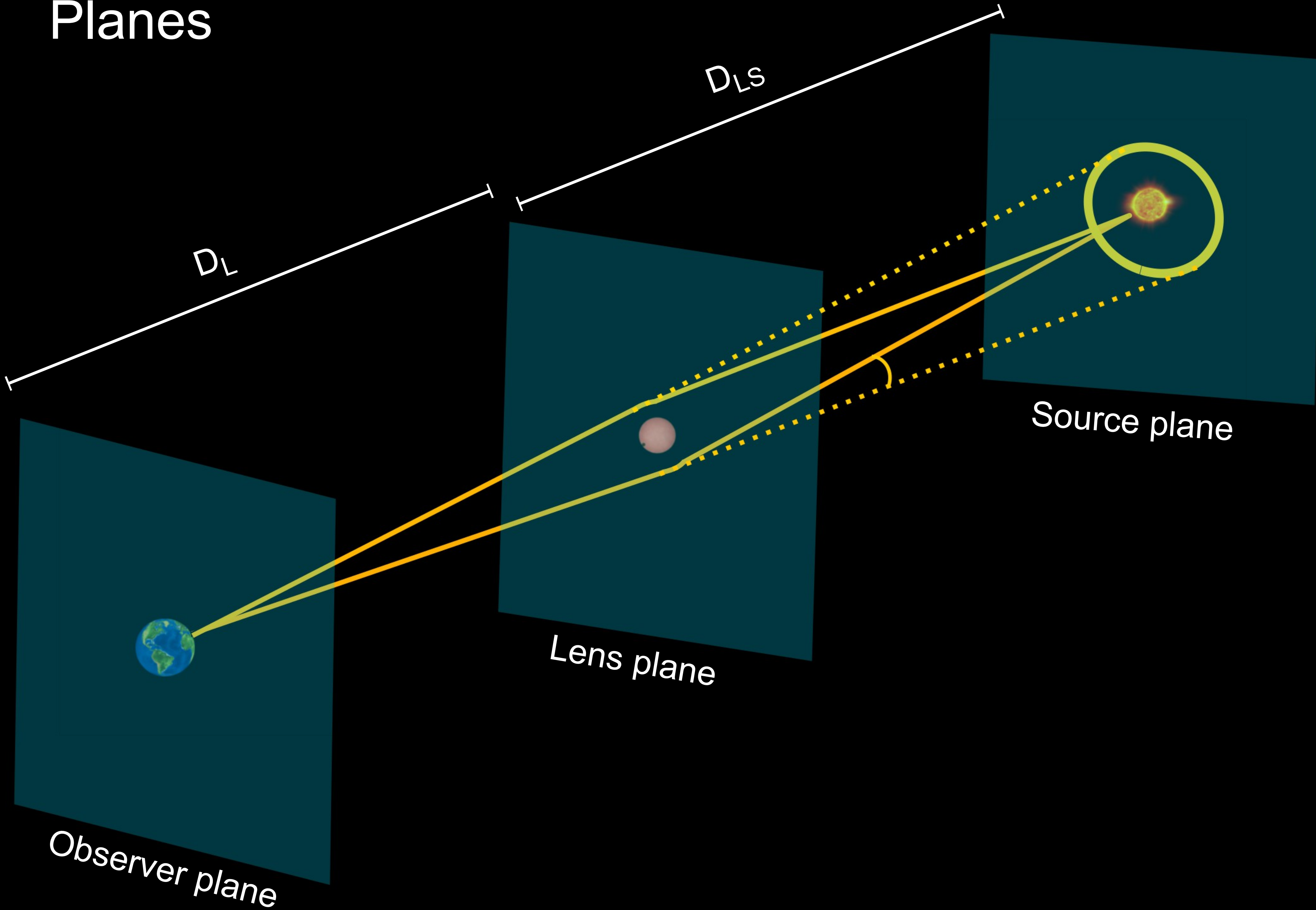
Distance Scales

Goal: to describe the lensed imaging of the source

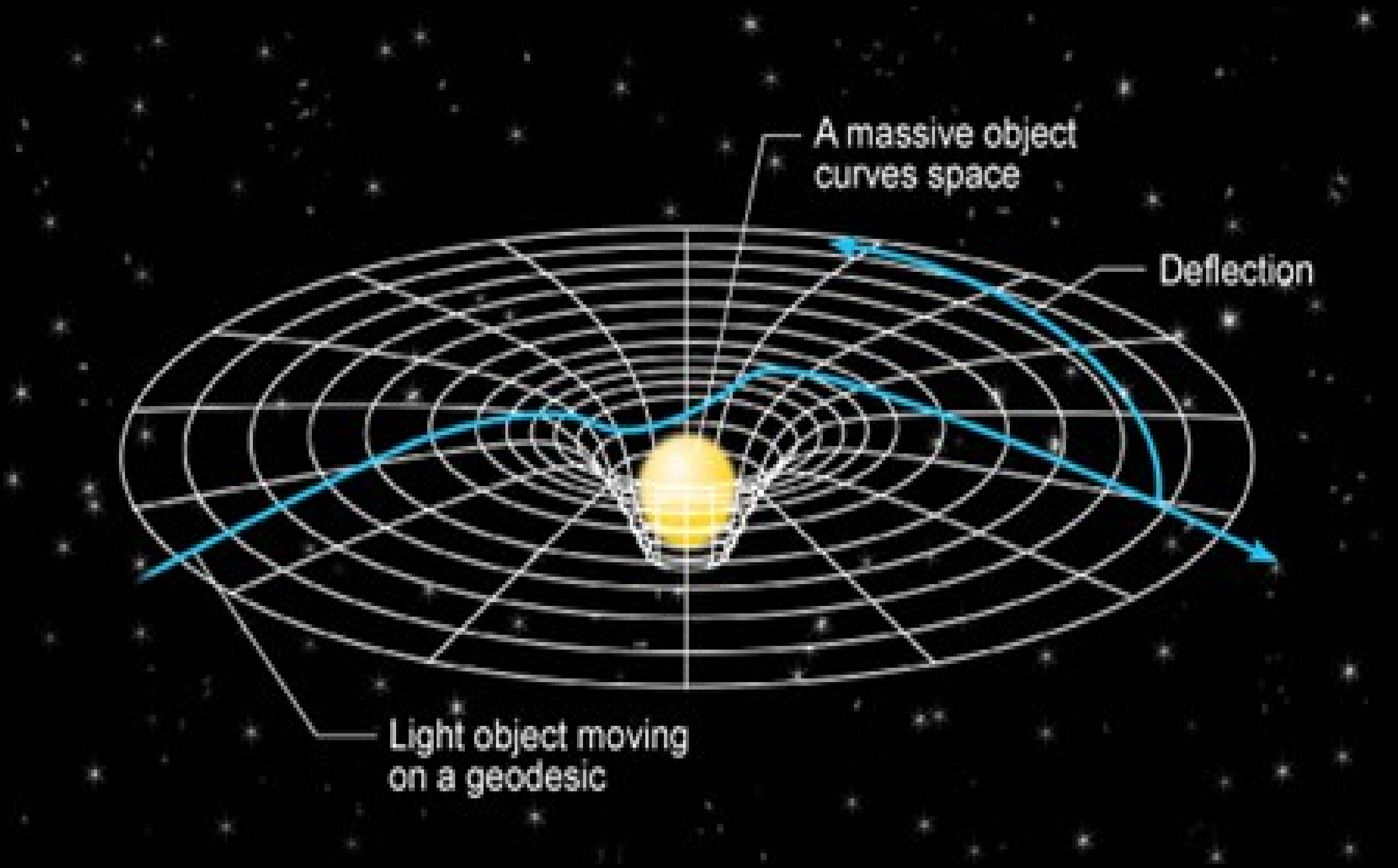


Remember: we almost never observe light from the lens!

Planes



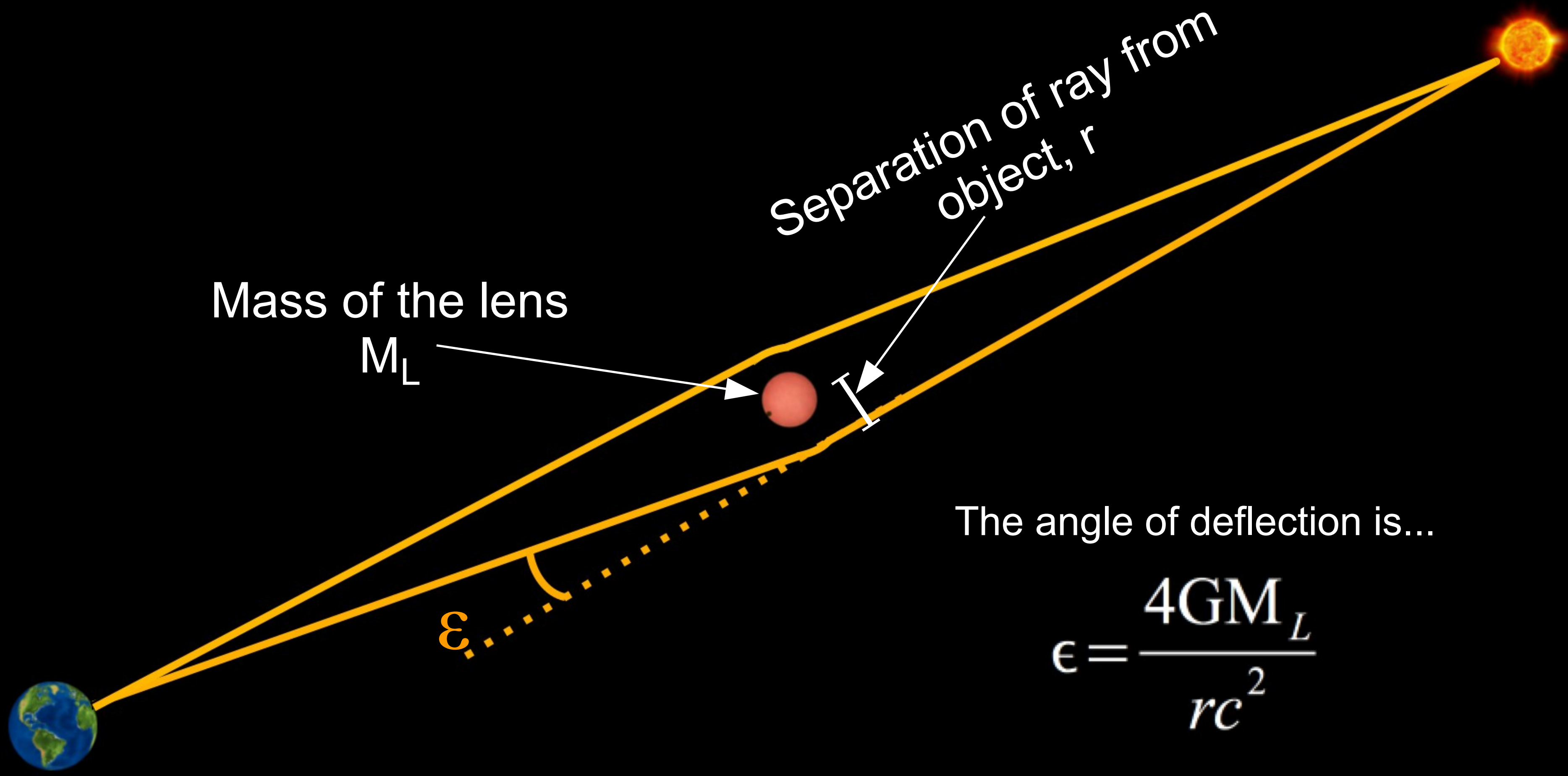
Bending light rays



General Relativity tells us that massive objects warp spacetime

Lightrays traveling through warped spacetime are deflected as they pass stars and planets

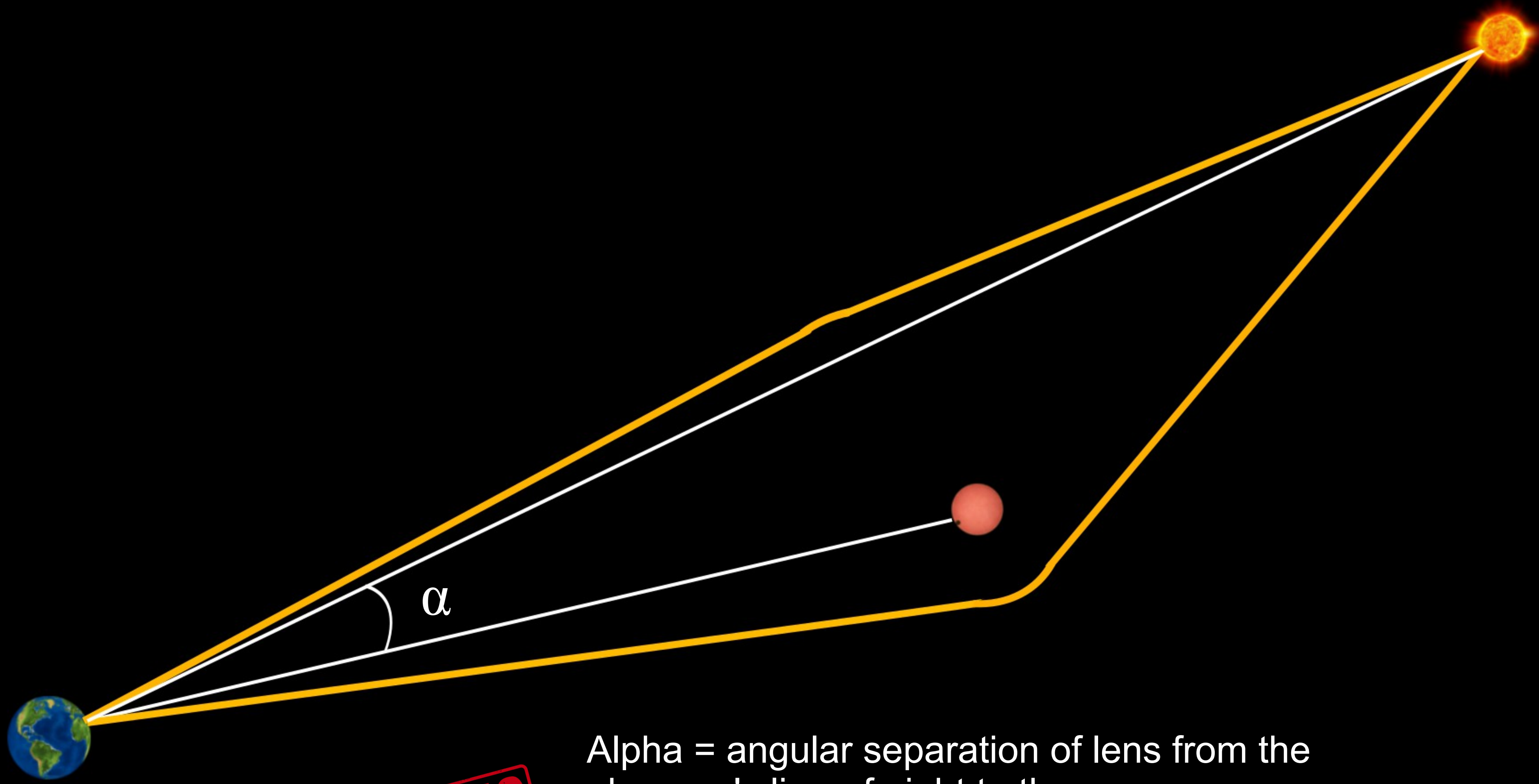
Deflection of light



The angle of deflection is...

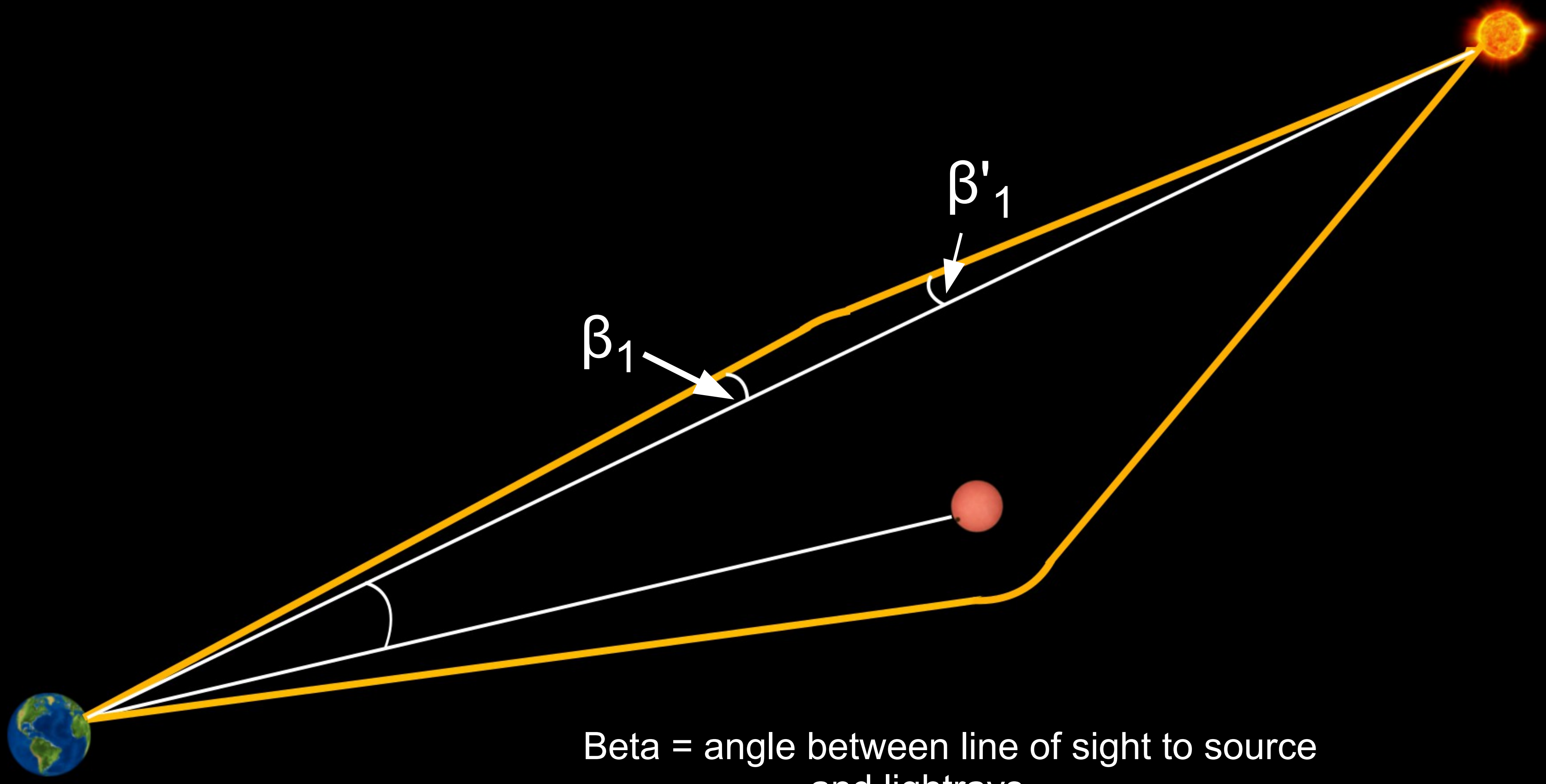
$$\epsilon = \frac{4GM_L}{rc^2}$$

Angles of microlensing



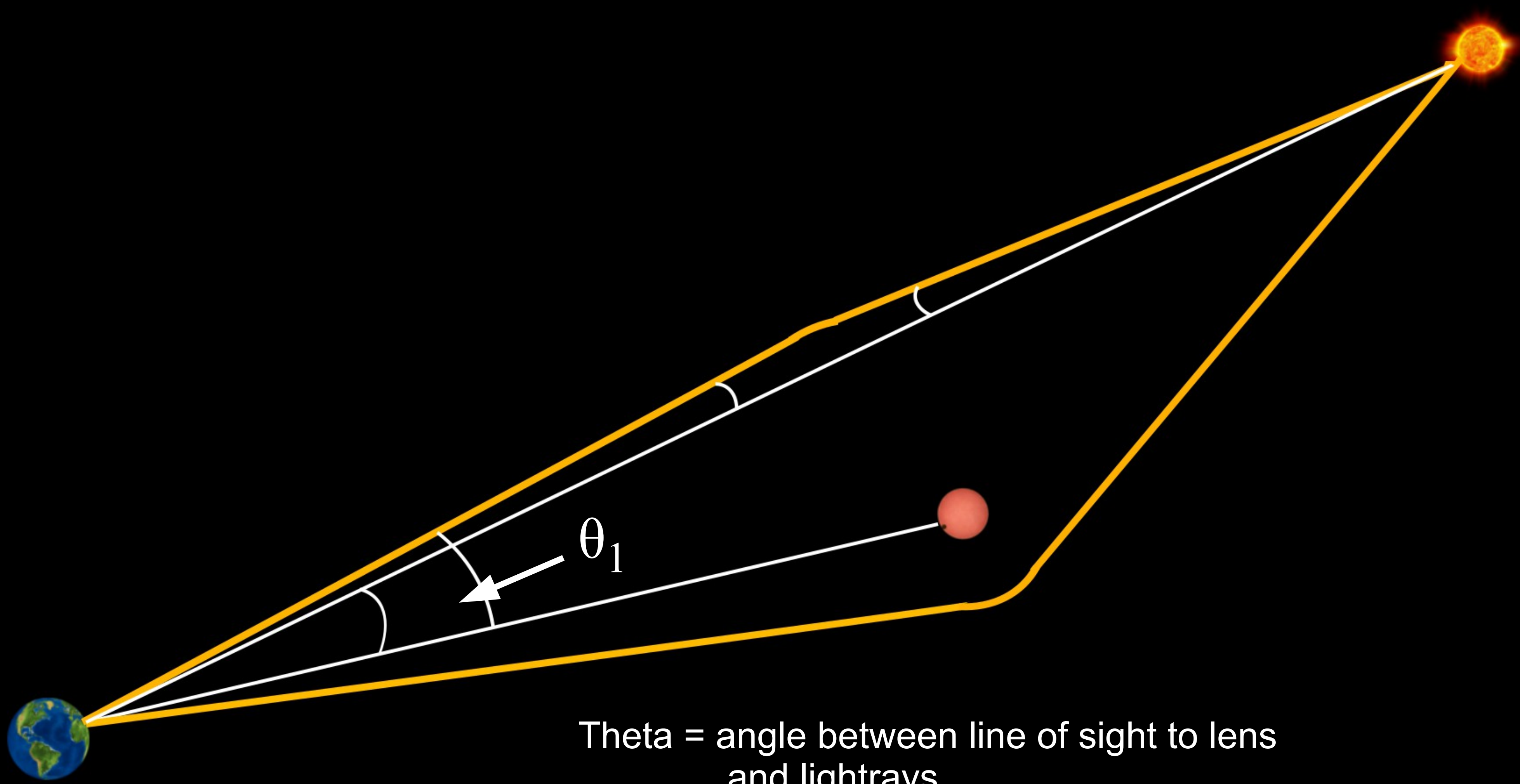
Alpha = angular separation of lens from the observer's line-of-sight to the source (Function of time)

Angles of microlensing



Beta = angle between line of sight to source and lightrays

Angles of microlensing

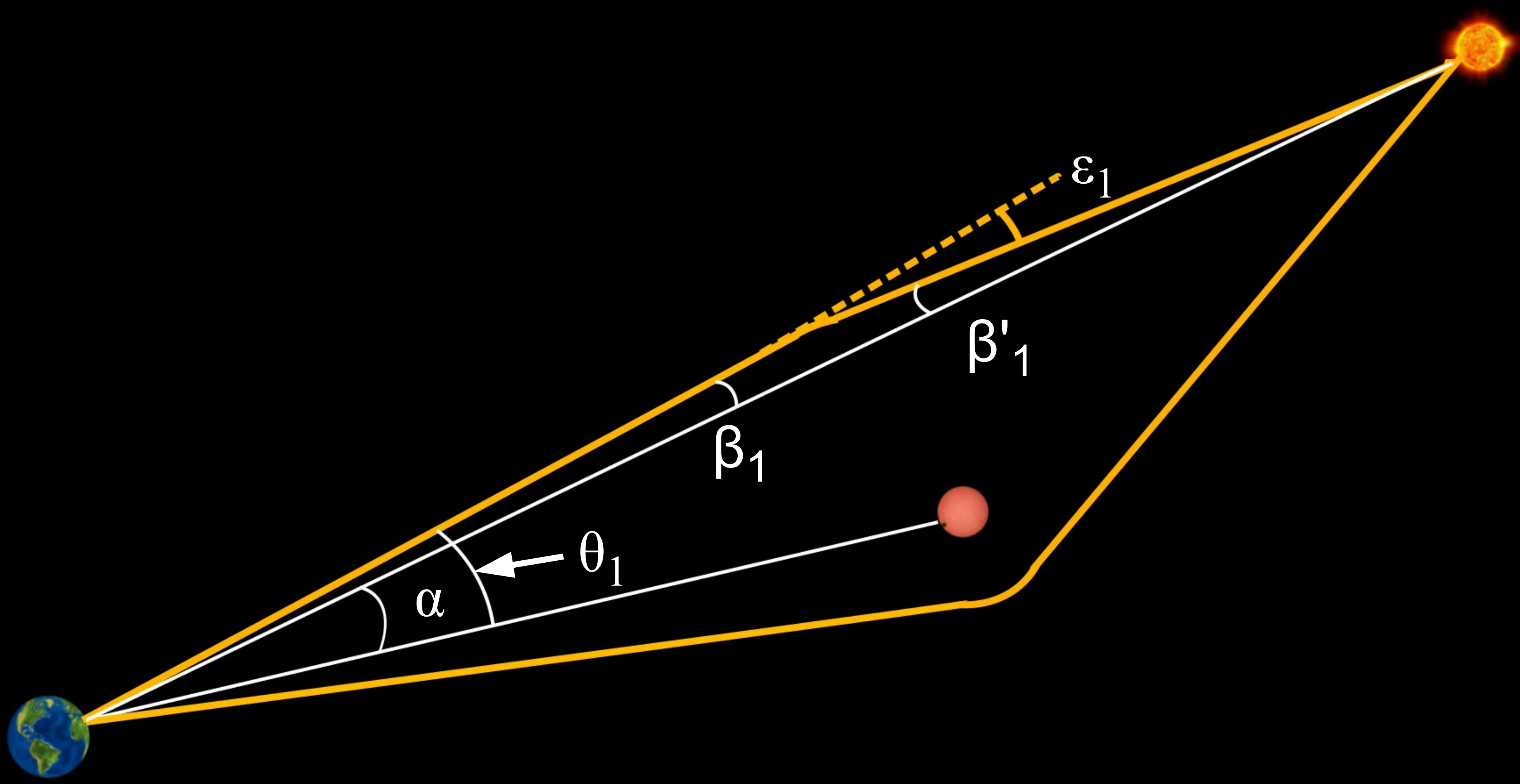


Theta = angle between line of sight to lens and lightrays

Deflection of light

$$\theta_1 = \alpha + \beta_1$$

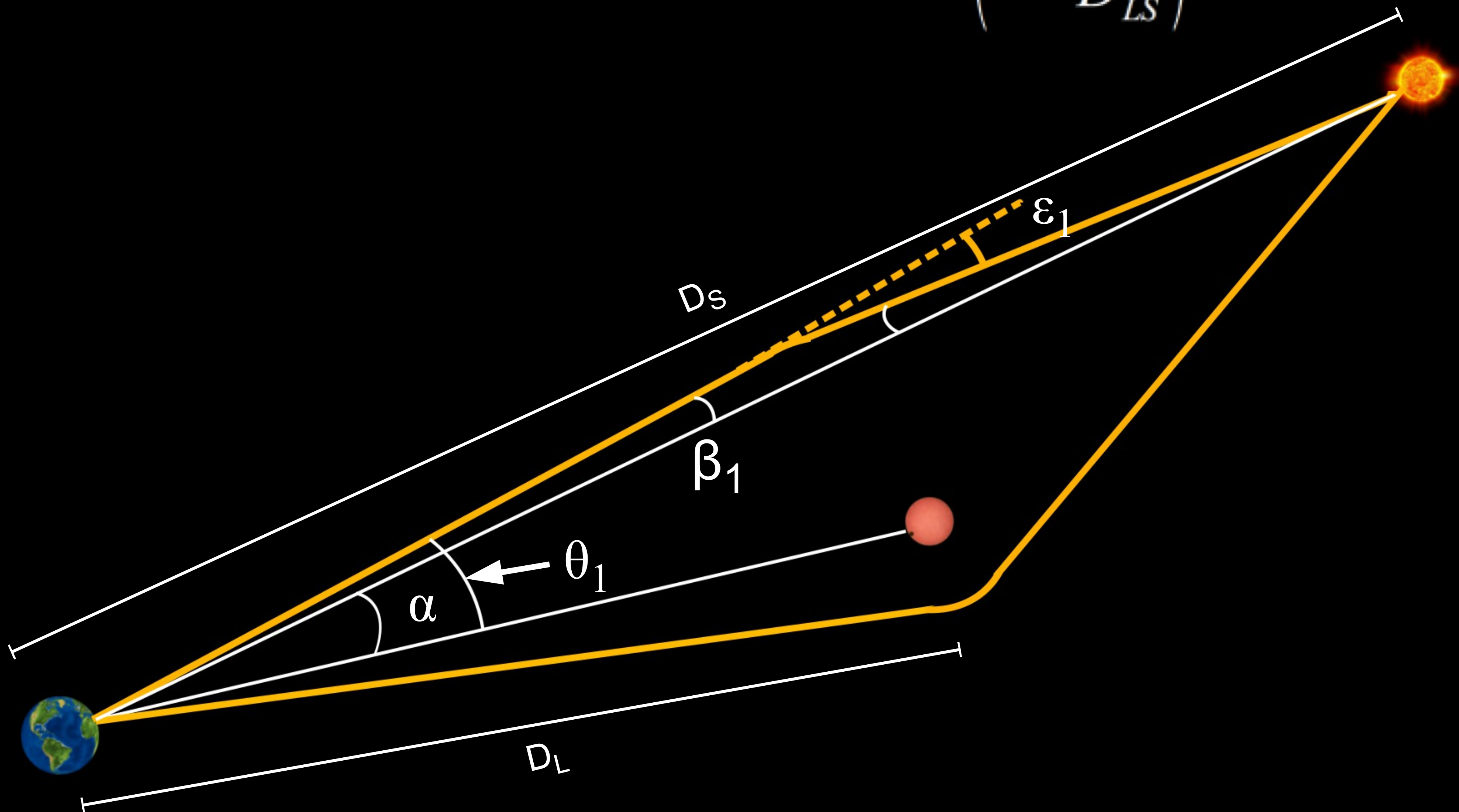
$$\epsilon_1 = \beta_1 + \beta_1'$$



Deflection of light

$$\theta_1 = \alpha + \beta_1$$

$$\epsilon_1 = \beta_1\left(1 + \frac{D_L}{D_{LS}}\right)$$

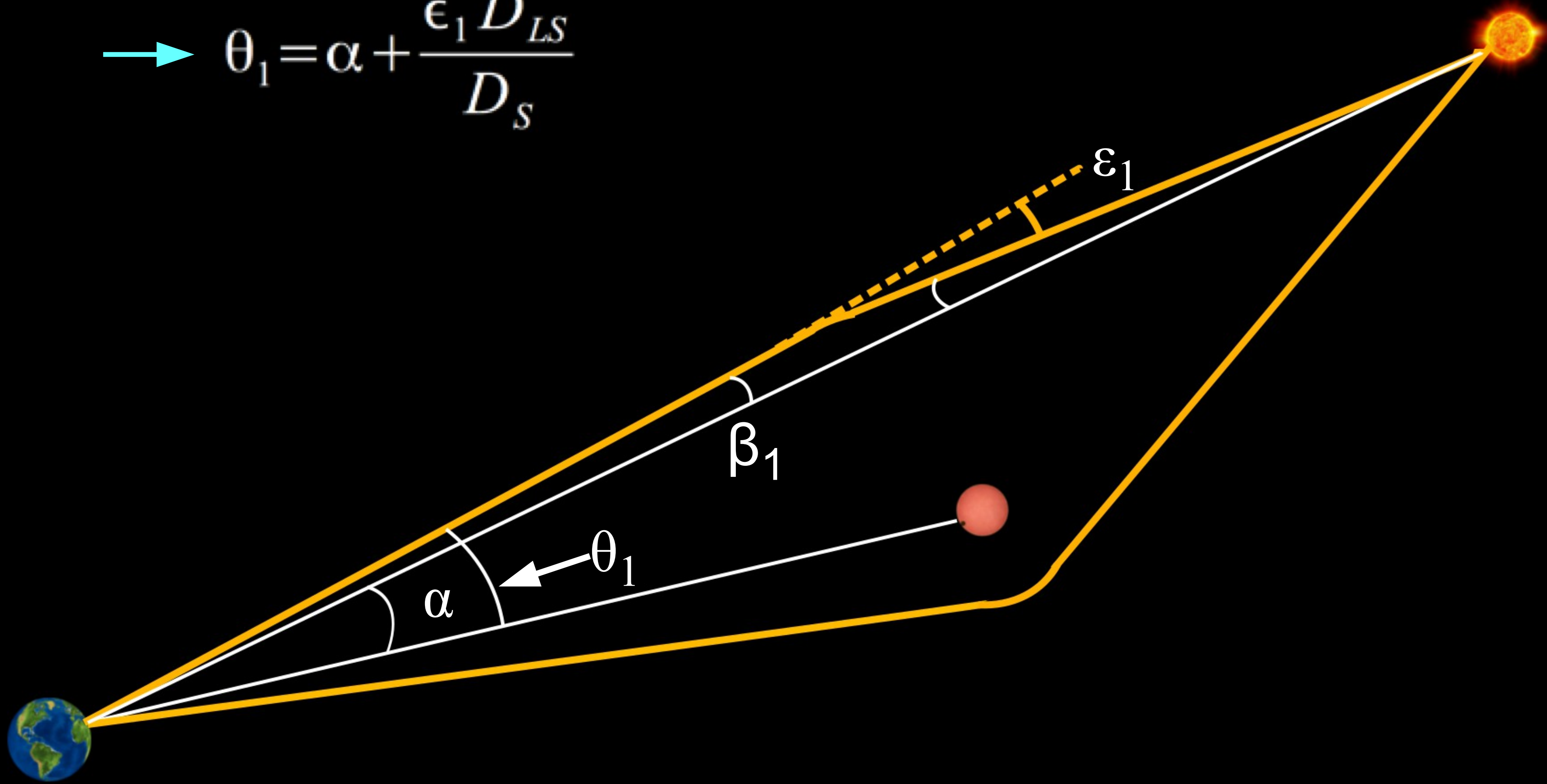


Deflection of light

$$\theta_1 = \alpha + \beta_1$$

$$\epsilon_1 = \beta_1 \left(1 + \frac{D_L}{D_{LS}}\right)$$

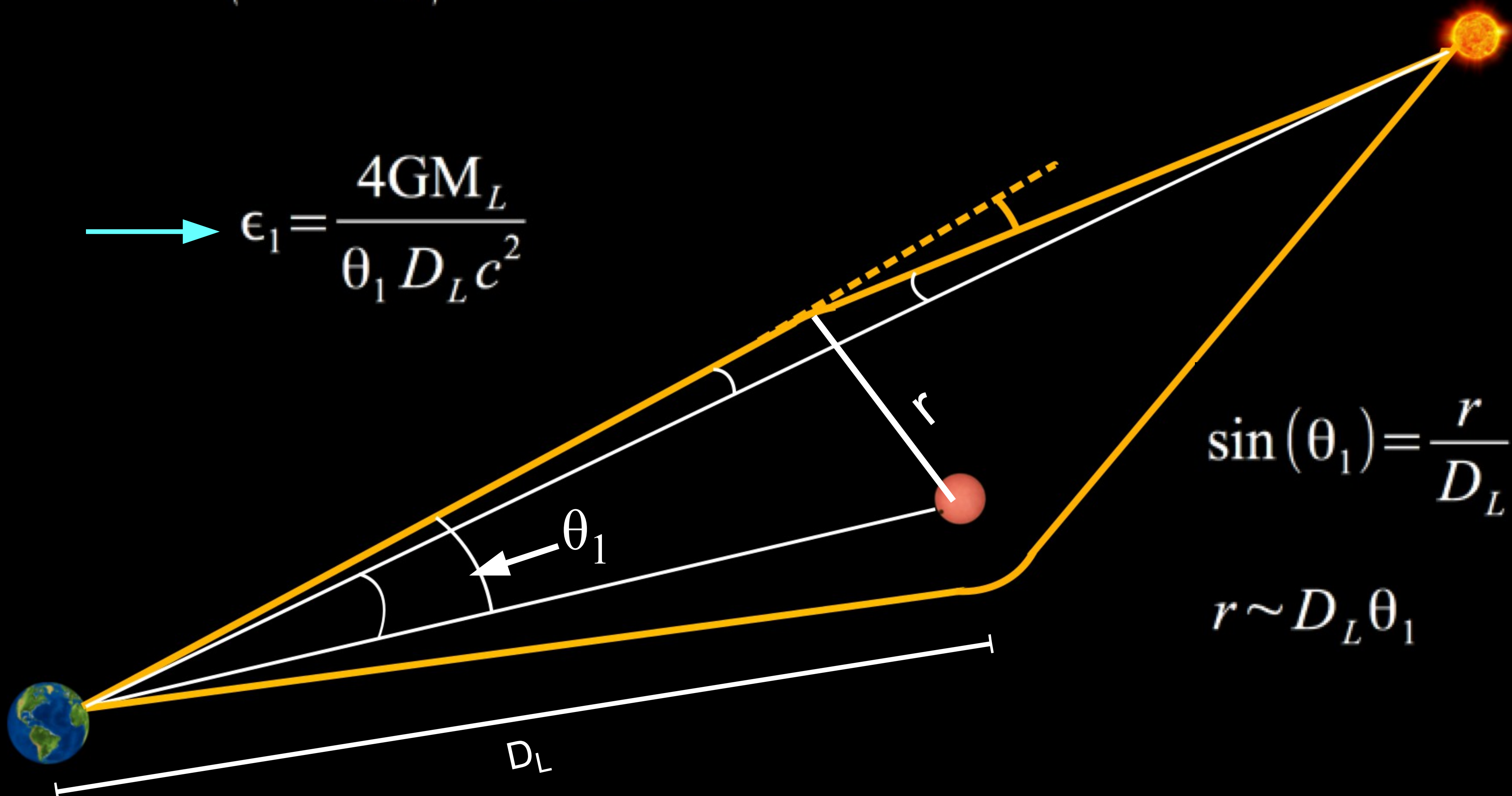
$$\rightarrow \quad \theta_1 = \alpha + \frac{\epsilon_1 D_{LS}}{D_S}$$



Deflection of light

$$\epsilon_1 = \beta_1 \left(1 + \frac{D_L}{D_{LS}} \right) = \frac{4GM_L}{rc^2}$$

$$\rightarrow \epsilon_1 = \frac{4GM_L}{\theta_1 D_L c^2}$$



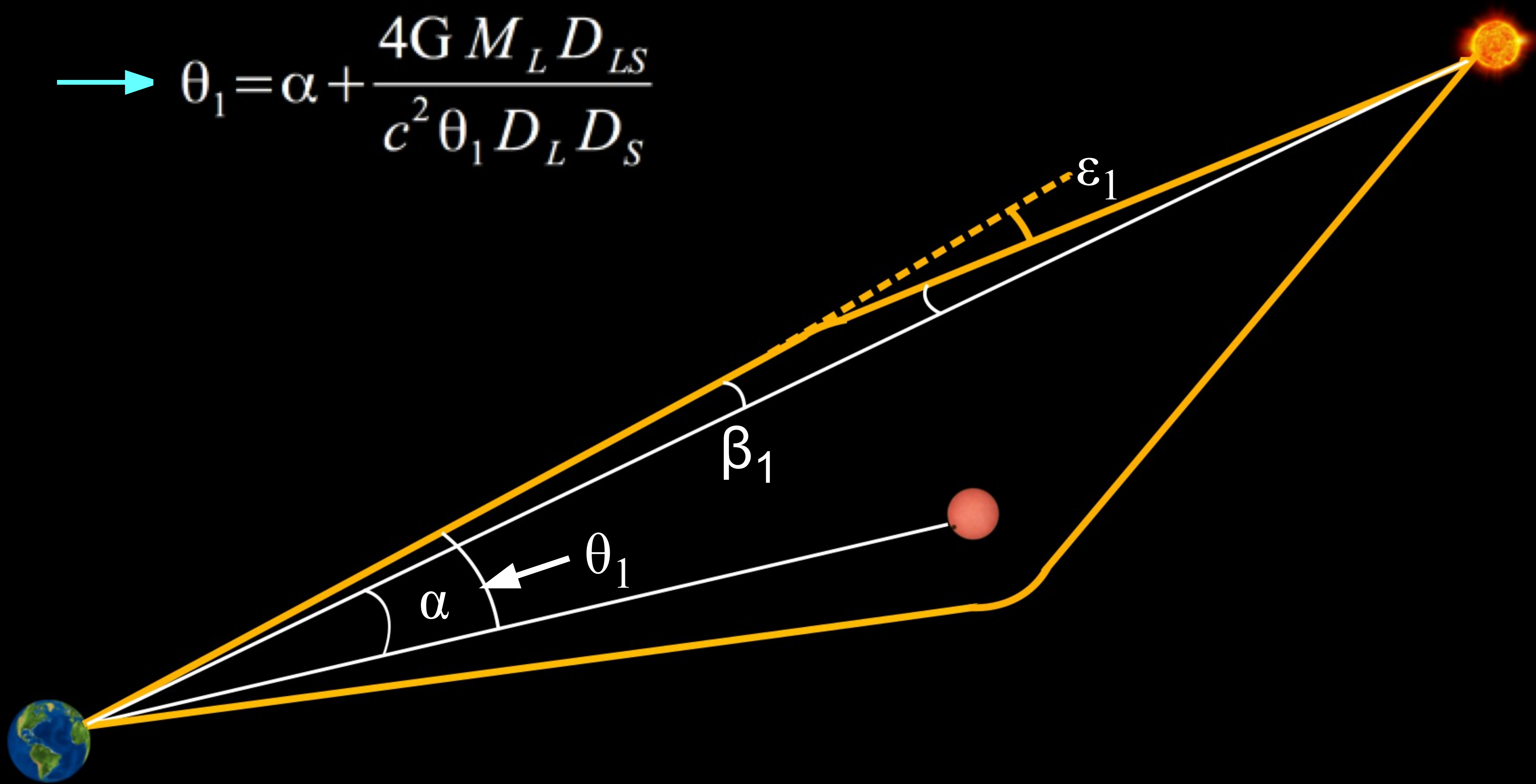
$$\sin(\theta_1) = \frac{r}{D_L}$$

$$r \sim D_L \theta_1$$

Deflection of light

$$\theta_1 = \alpha + \frac{\epsilon_1 D_{LS}}{D_S}$$

$$\rightarrow \quad \theta_1 = \alpha + \frac{4G M_L D_{LS}}{c^2 \theta_1 D_L D_S}$$



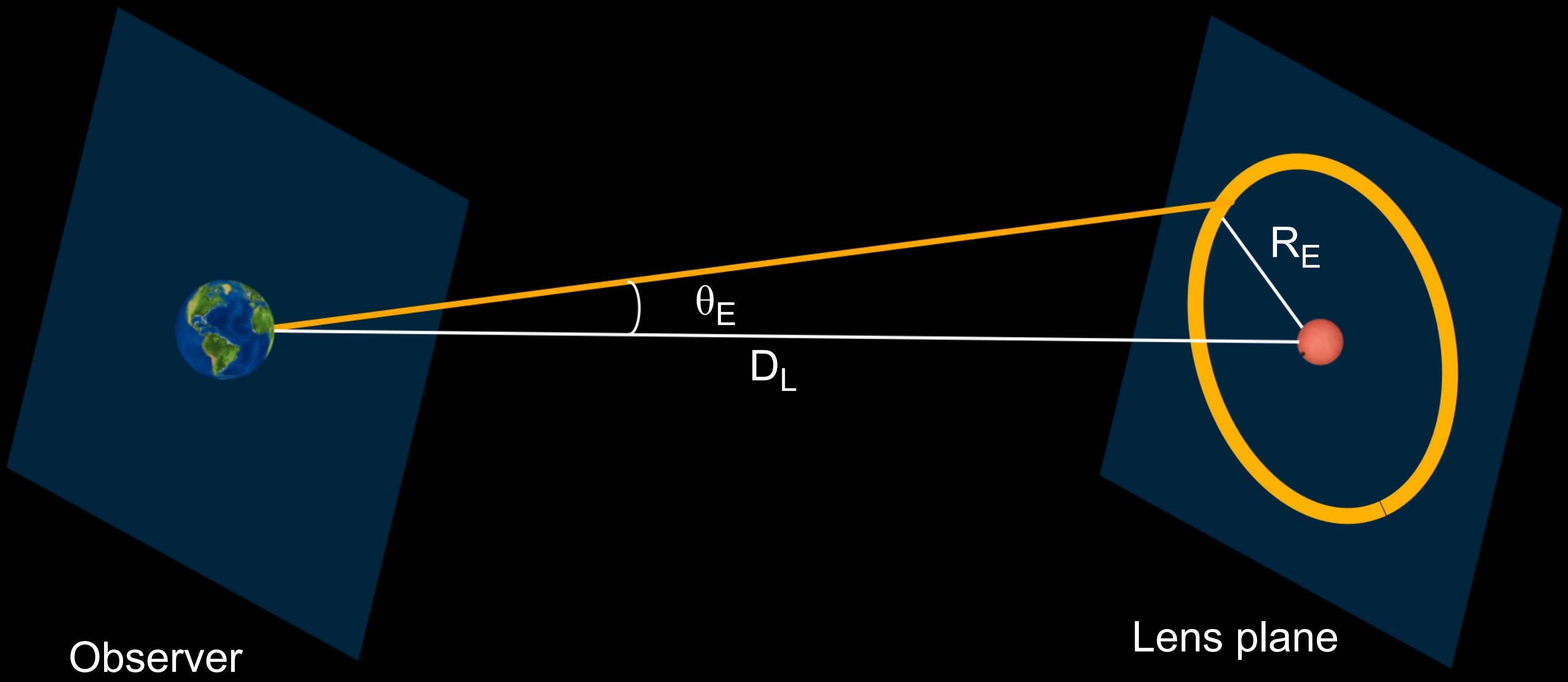
The Lens Equation...

$$\theta_1^2 - \alpha\,\theta_1 - \frac{4G\,M_L\,D_{LS}}{c^2\,D_L\,D_S} = 0$$

...and the Einstein radius

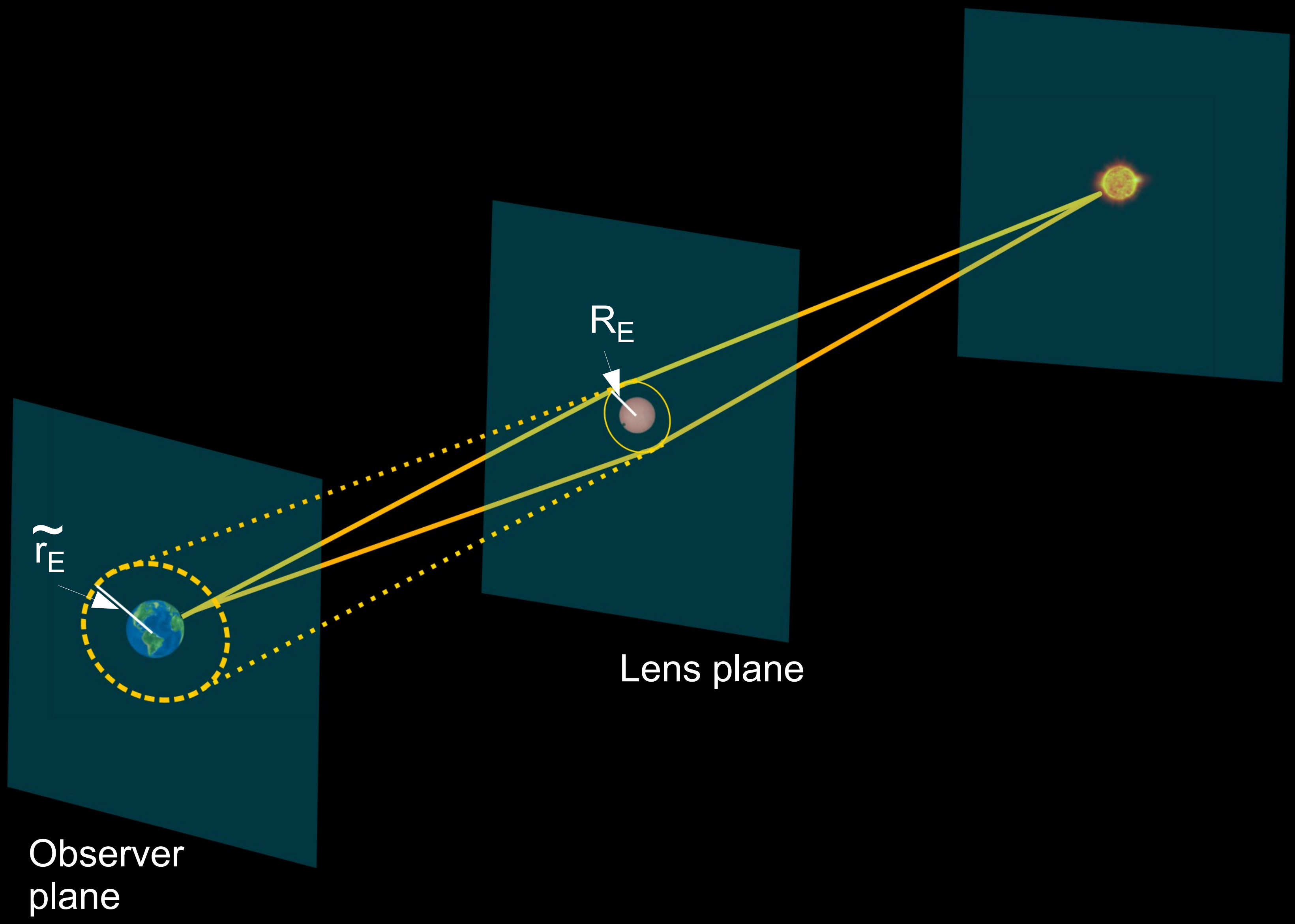
$$\theta_E = \sqrt{\frac{4G\,M_L\,D_{LS}}{c^2\,D_L\,D_S}}$$

(Sometimes written θ_0)



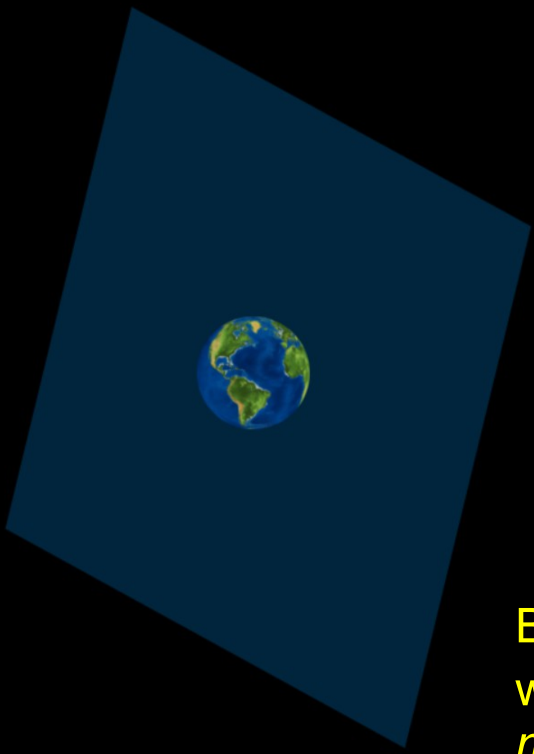
Projected Einstein Radius

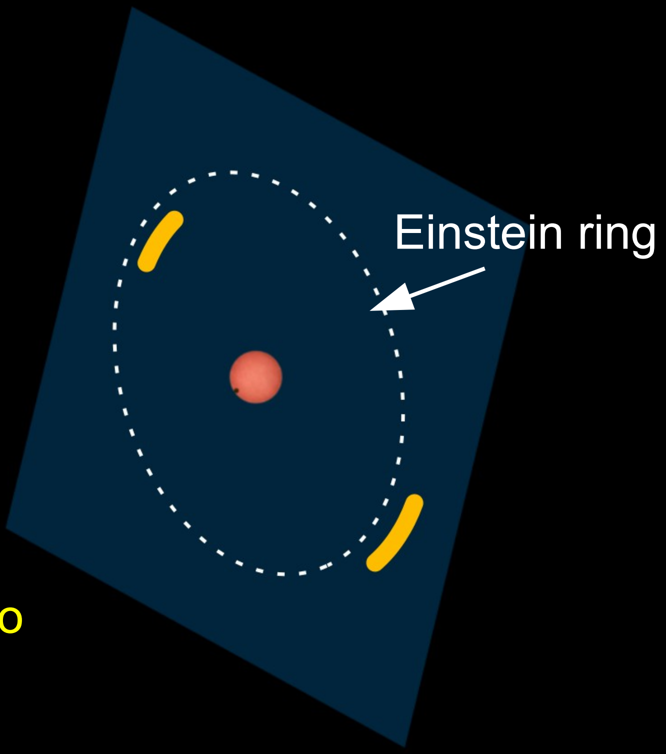
The radius of the Einstein ring projected back to the observer's plane



Two solutions → Two images (for single lenses)

$$\theta_{1,2} = \frac{\pm\alpha + \sqrt{\left(\frac{1}{2}\alpha\right)^2 + \theta_E^2}}{2}$$

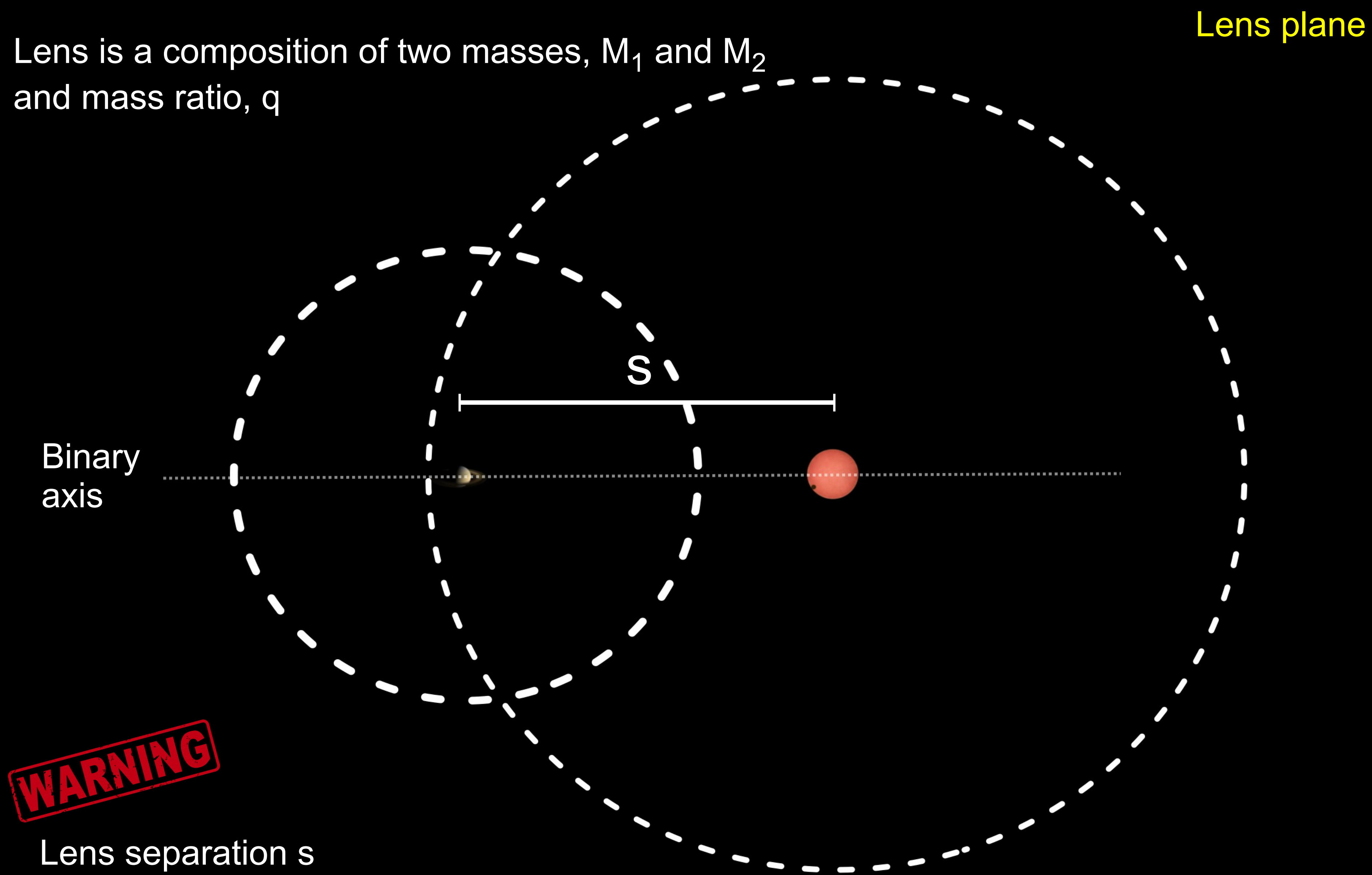




But $\theta_{1,2}$ are too small to resolve, so we actually observe just the *magnification* of the source

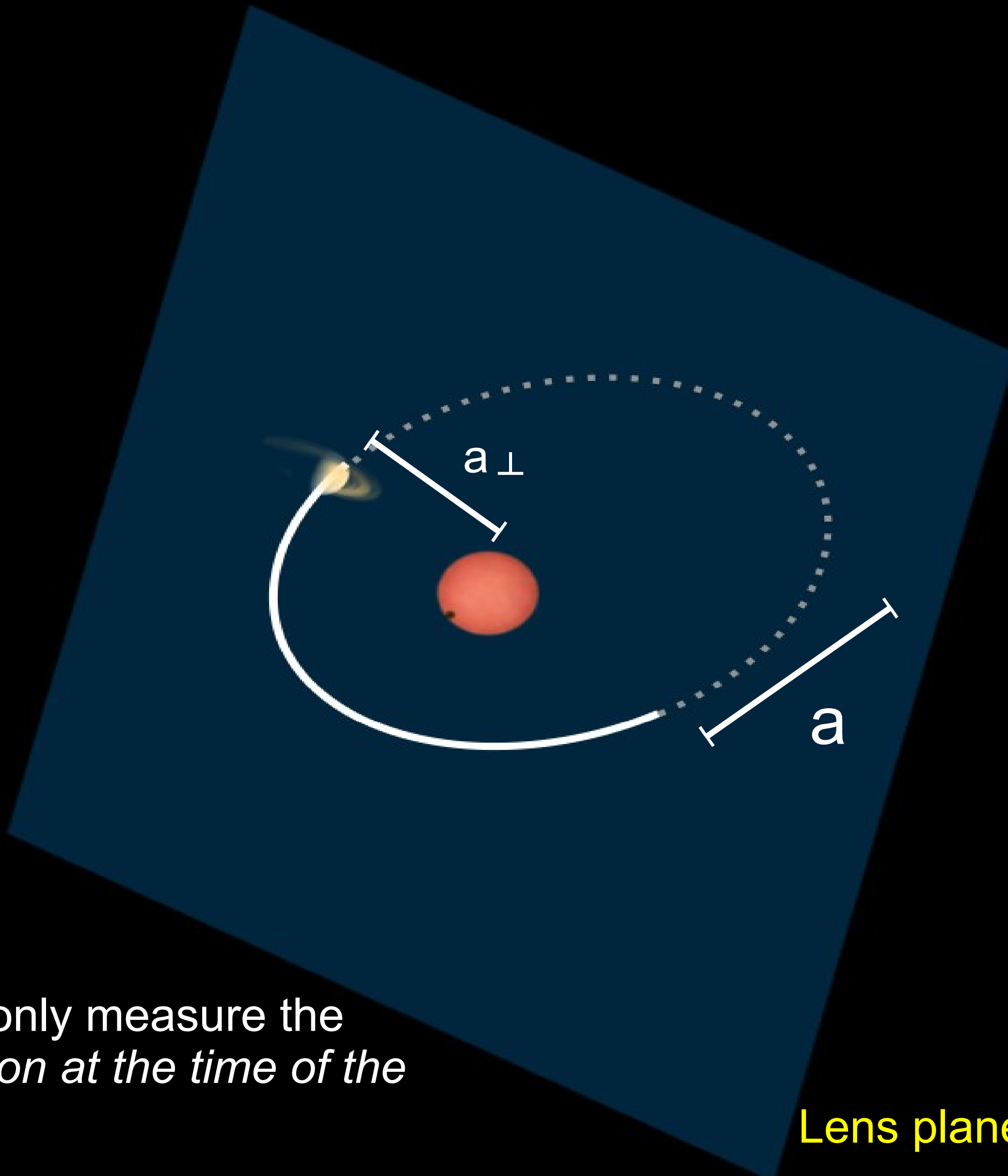
Two-body microlensing

Lens is a composition of two masses, M_1 and M_2 and mass ratio, q



Lens separation s is sometimes also called s_0, d, or b

Two-body microlensing

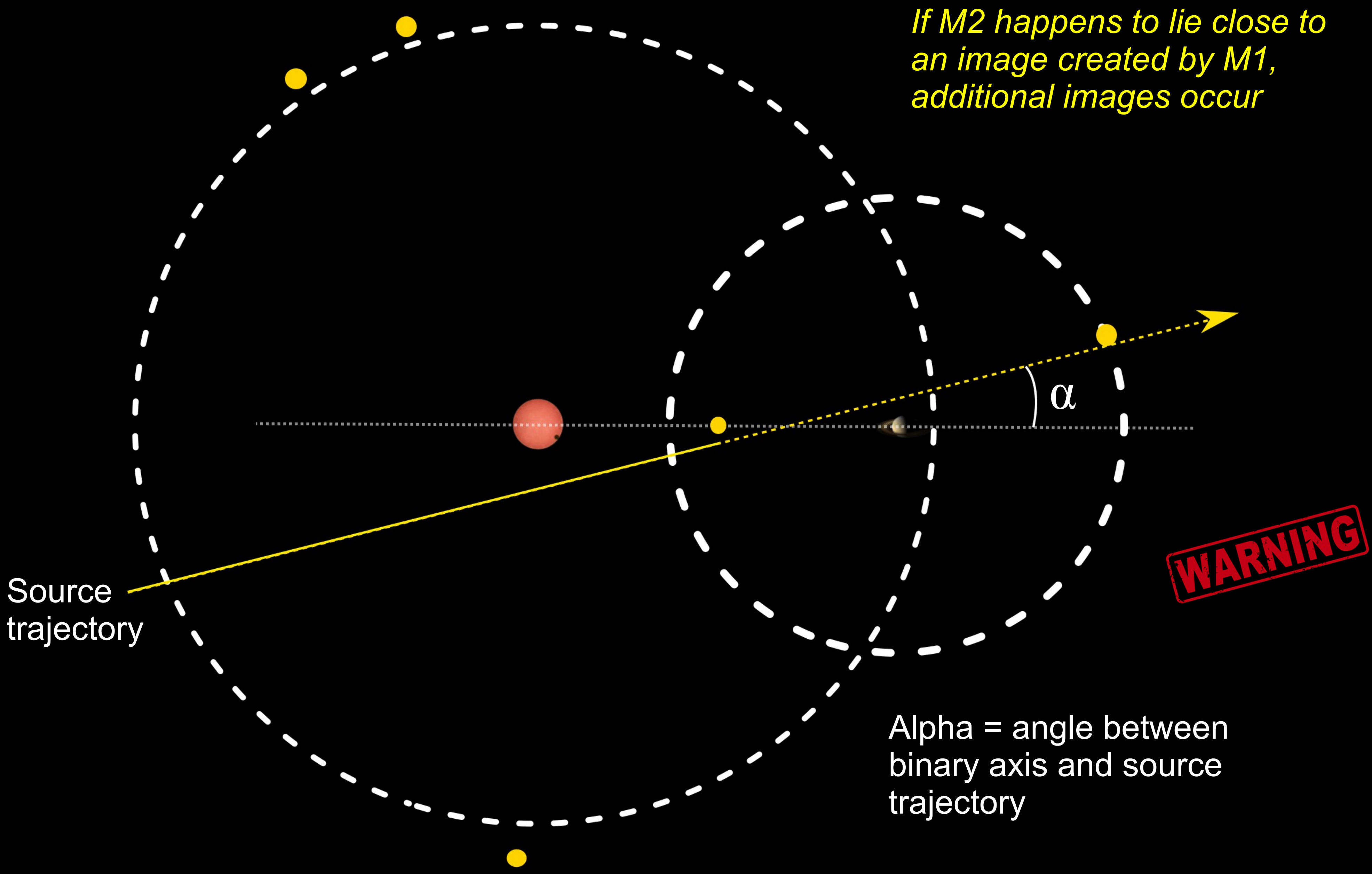


Lens plane

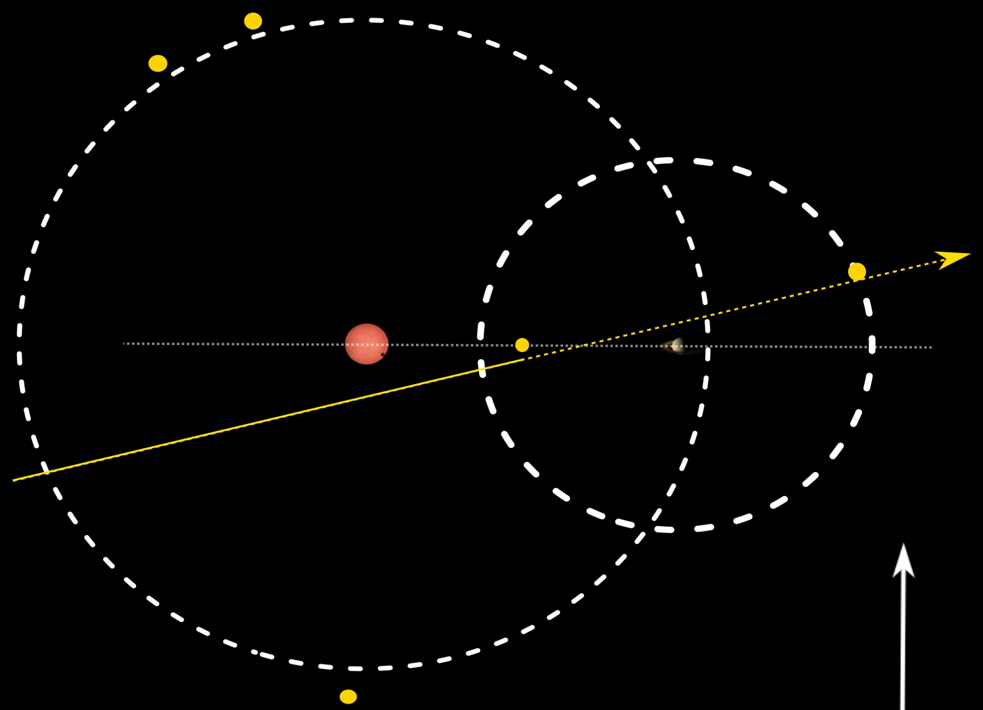
WARNING

Microlensing can only measure the *projected separation at the time of the event*

Binary lenses may create more images

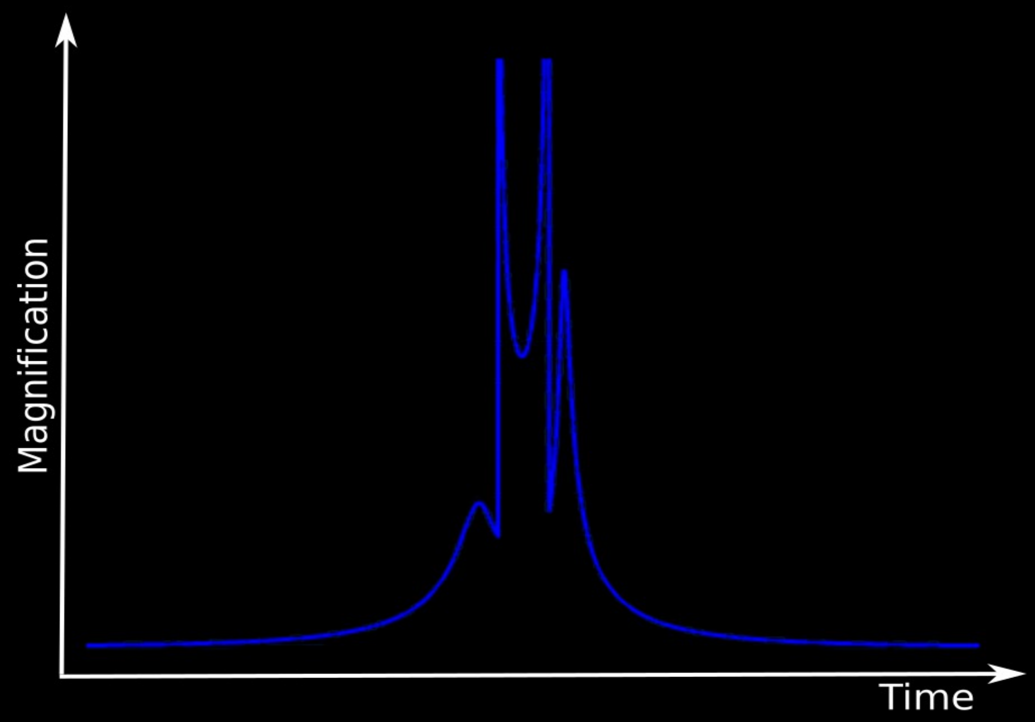


Binary lenses create more images



Can have 3 or 5, depending on event parameters

This results in an amazing variety of lightcurves



Microlensing Theory 101

Single lenses produce two images of the source.
Binary lenses produce 3 or 5

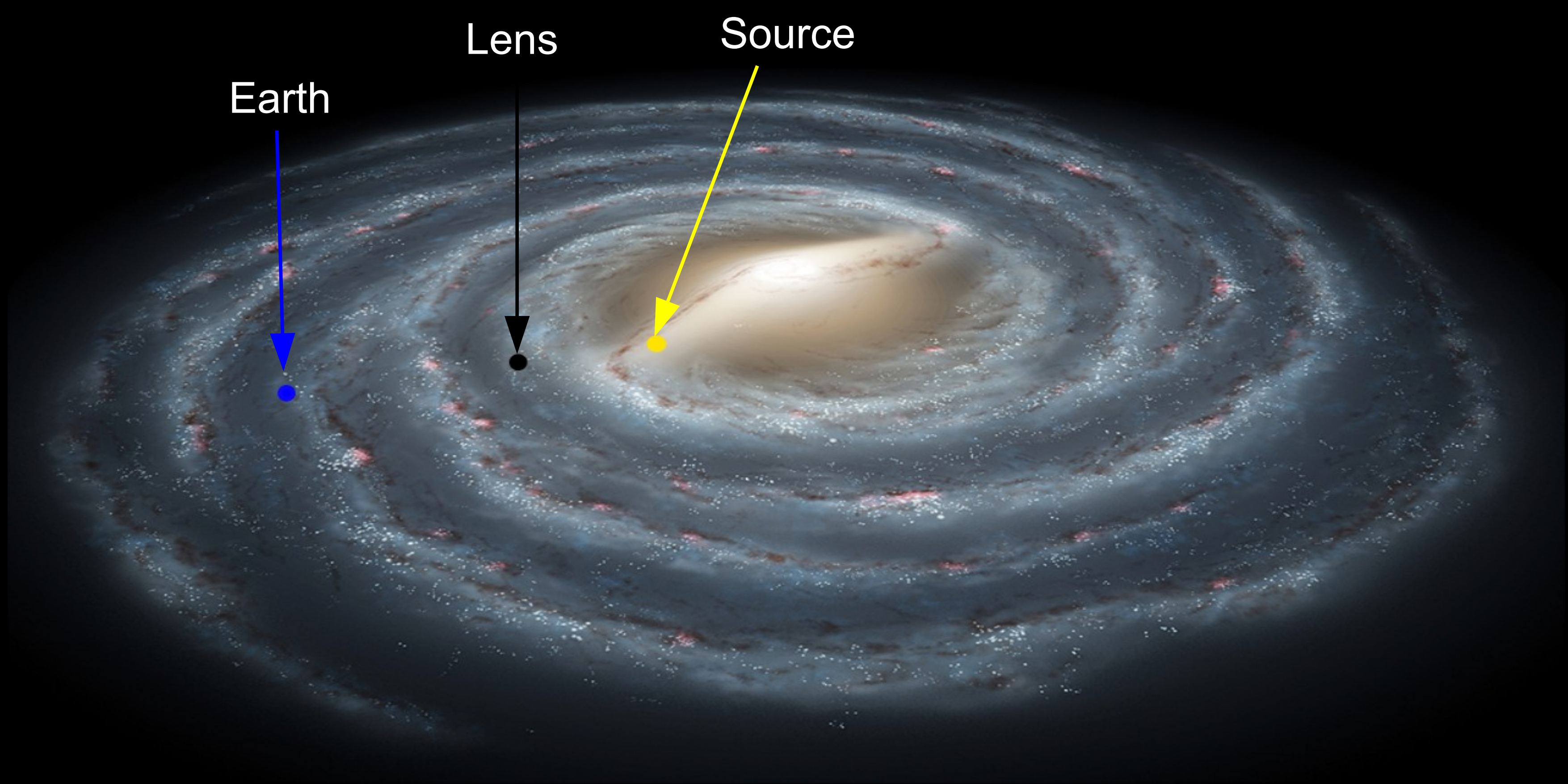
If a planet orbiting the lens happens to approach one of the images during the event, the image is peturbed and additional light is received from the source

The resulting anomaly is visible in the lightcurve of the event.

For more information, see
http://microlensing-source.org/tutorial/pspl/

Example Microlensing Event

M dwarfs are the most common type of star:	M_L = 0.5 M_{Sun}
Source star typically in the Galactic Bulge:	D_S = 7.5 Kpc from Earth
Lens distance:	D_L = 6 Kpc from Earth



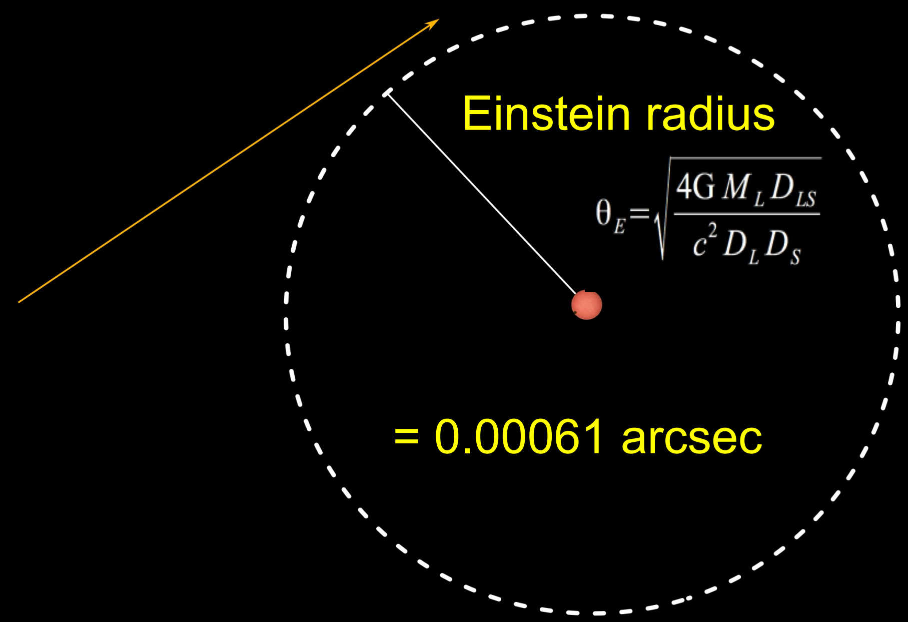
Example Microlensing Event

M dwarfs are the most common type of star:	M_L = 0.5 M_{Sun}
Source star typically in the Galactic Bulge:	D_S = 7.5 Kpc from Earth
Lens distance:	D_L = 6 Kpc from Earth

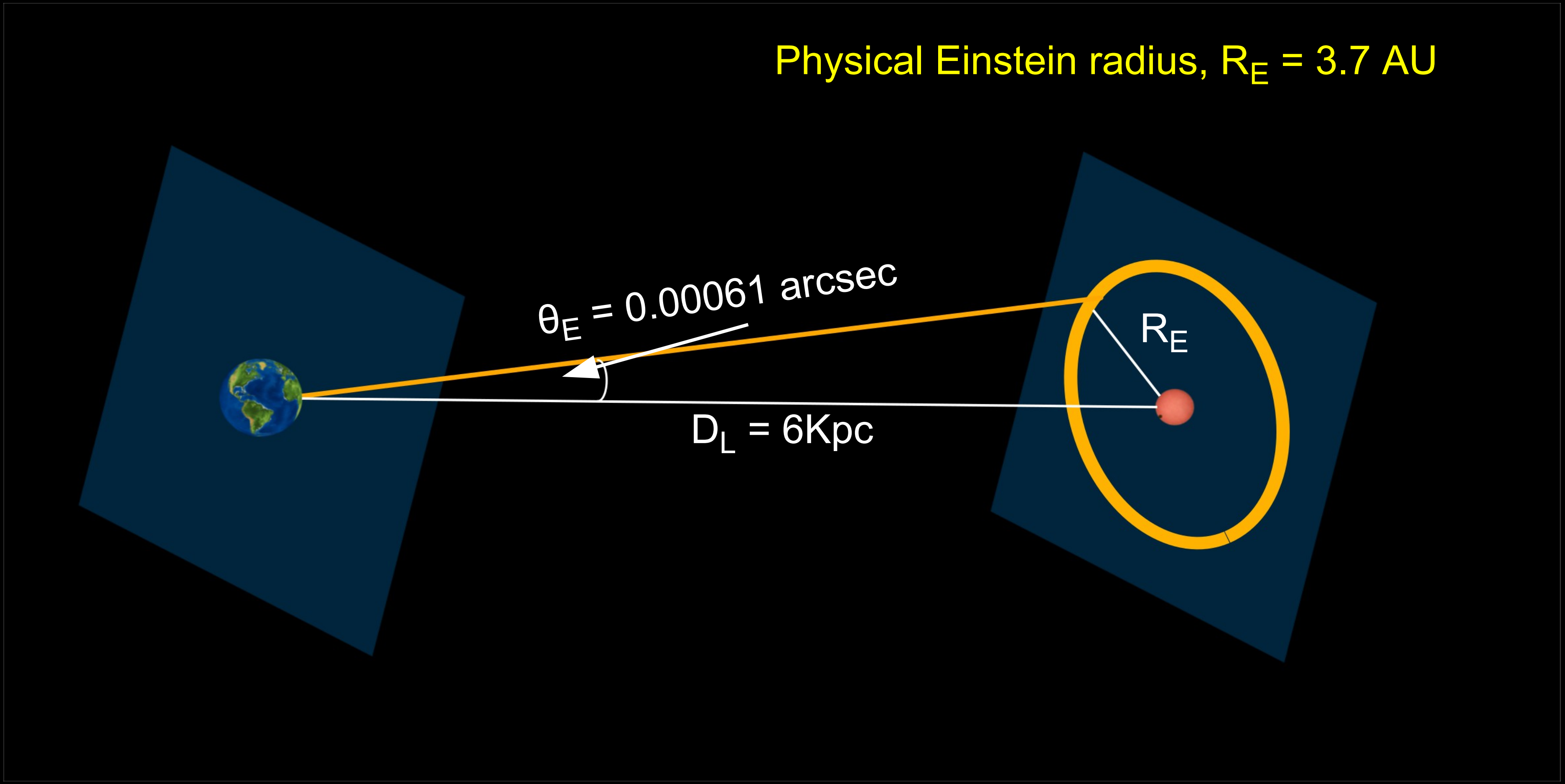
Separation of lensed images too small to resolve

Very small cross-section of interaction!

→ Intrinsically rare
→ Need to look towards dense starfields for potential sources



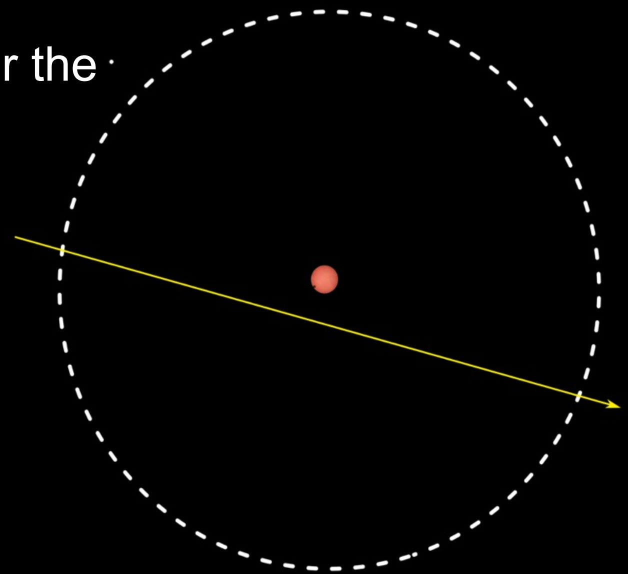
Example Microlensing Event



This is why microlensing is a great way to look for exoplanets at 1-10 AU -
They're most easily detectable when they're located close to images forming around R_E

Example Microlensing Event

Einstein crossing timescale, tE, is the time taken for the source to pass behind the Einstein ring of the lens



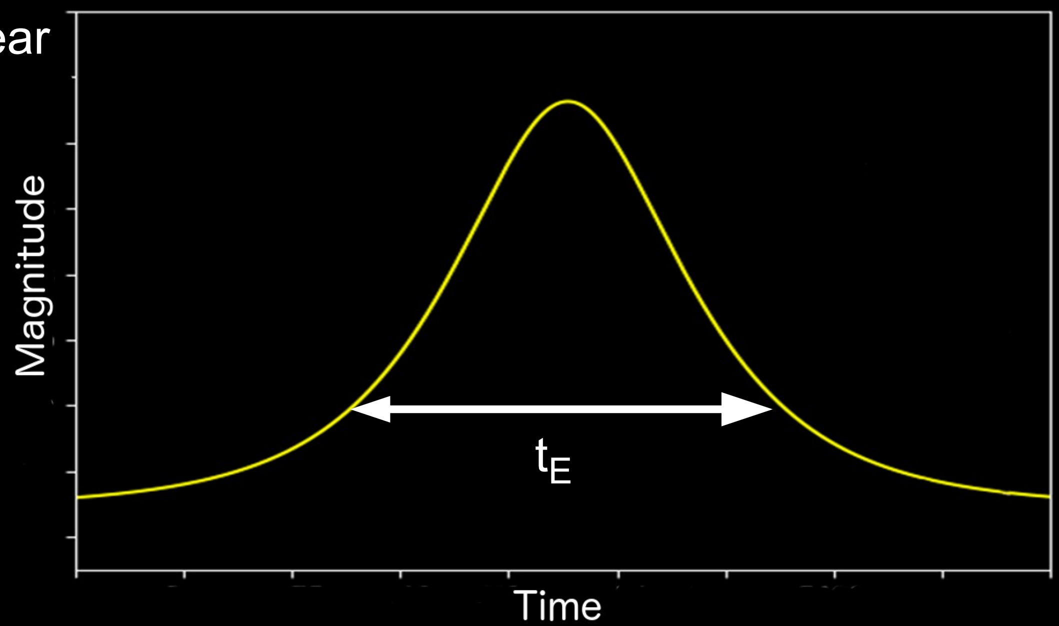
$$t_E = \frac{\theta_E}{\mu_{rel}}$$

μ_{rel} is lens-source relative proper motion

Typical proper motion ~0.1 arcsec/year
Relative proper motion ~0.005 arcsec/year

→ t_E ~ 45 days

→ To detect microlensing events we need to observe ~once / day



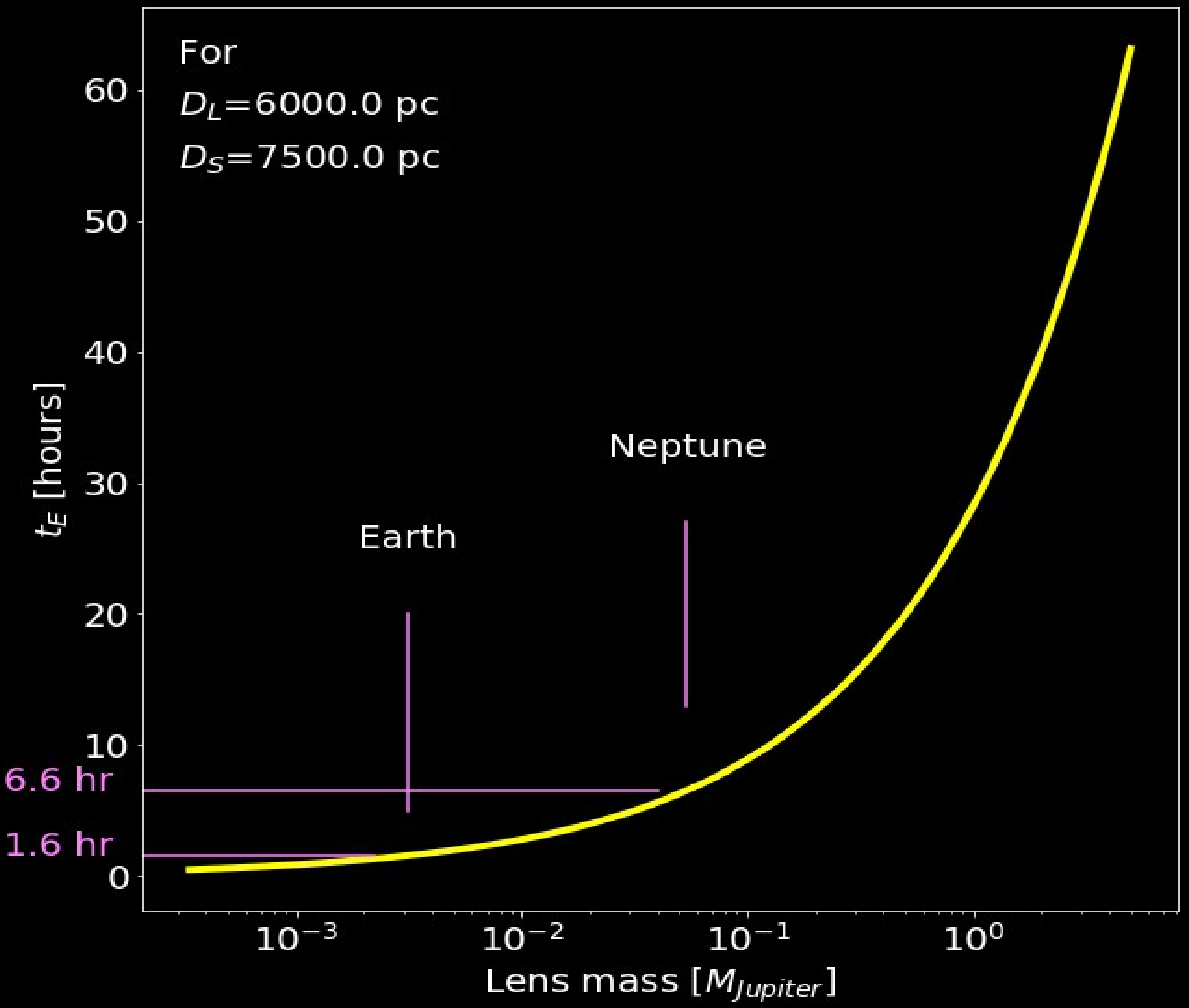
Example Microlensing Event

Einstein crossing timescale, t_E, for a typical stellar event is ~months

But for planet-mass lenses t_E is <1 day

$$t_E = \frac{\theta_E}{\mu_{rel}}$$

→ To detect planetary anomalies, we need to observe ~every 15min



References and Resources

Liebes, S. (1964), Physical Review, 133, B835

Paczyński, B. (1986), ApJ, 301, 503

Wambsganss, J. (1998), Living Reviews in Relativity, 1, 12

Gould, A. (2000), ApJ, 542, 785

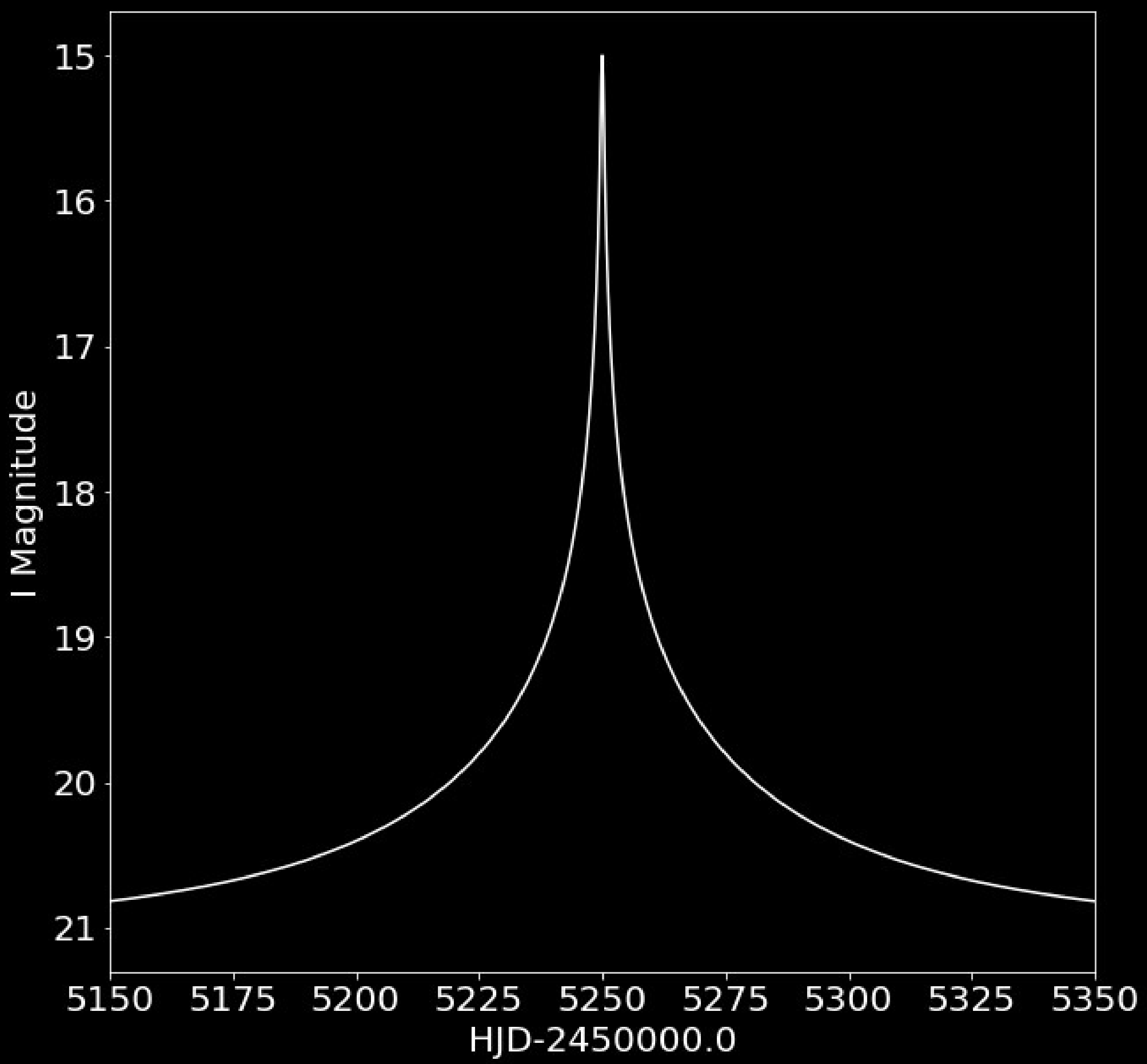
See also microlensing-source.org

Planet-Hunting Lightcurve Challenge

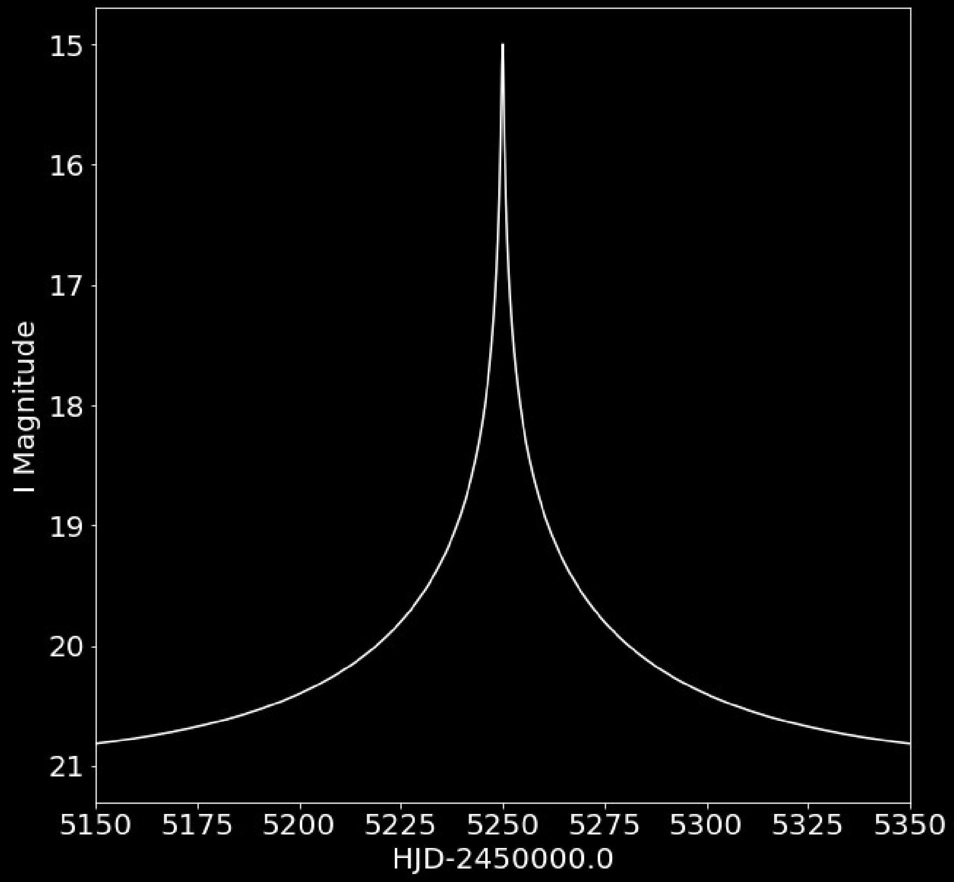
Goal:

Develop experience in identifying planetary microlensing signatures

Lightcurve Challenge



Lightcurve Challenge



Classification:

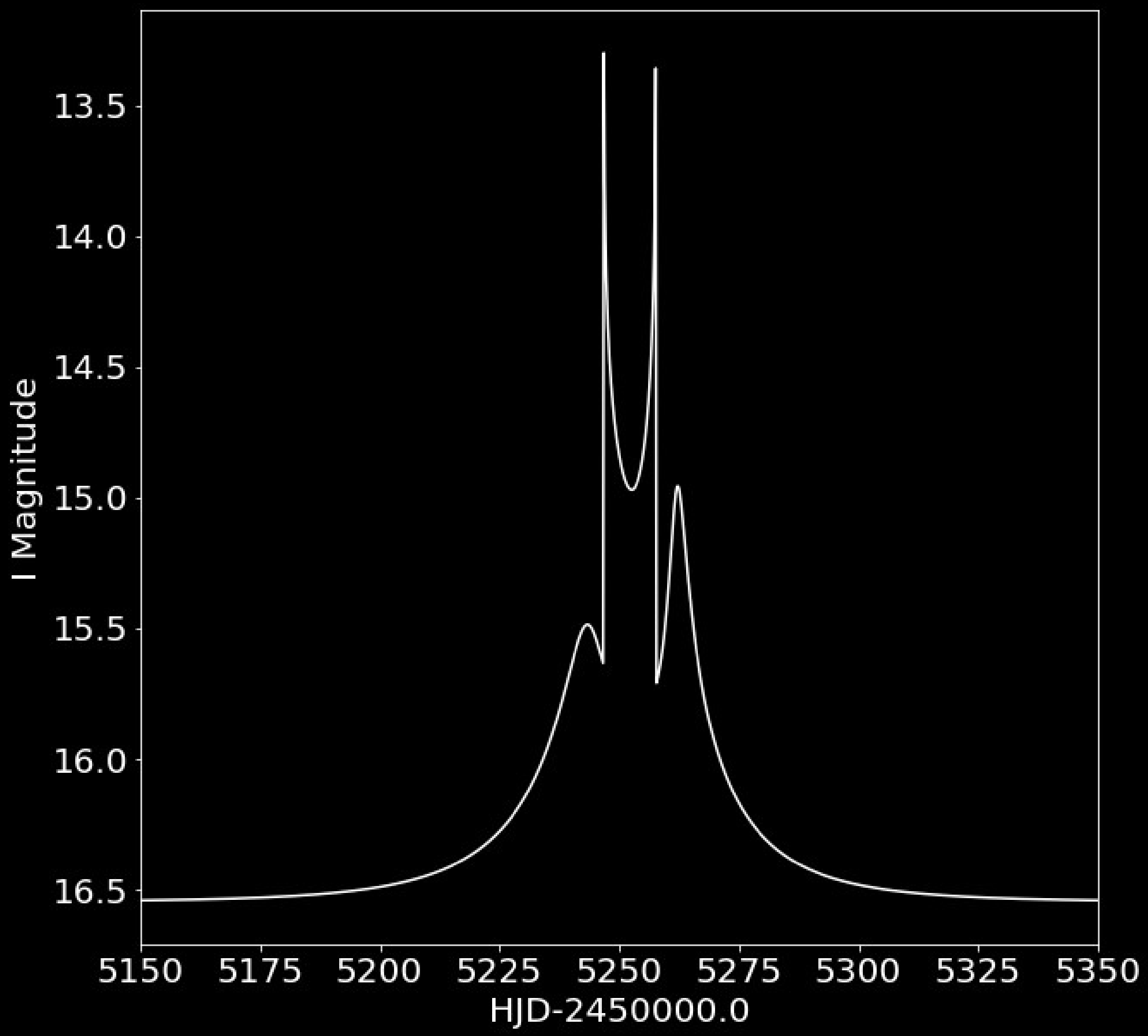
Single star event

Reason:

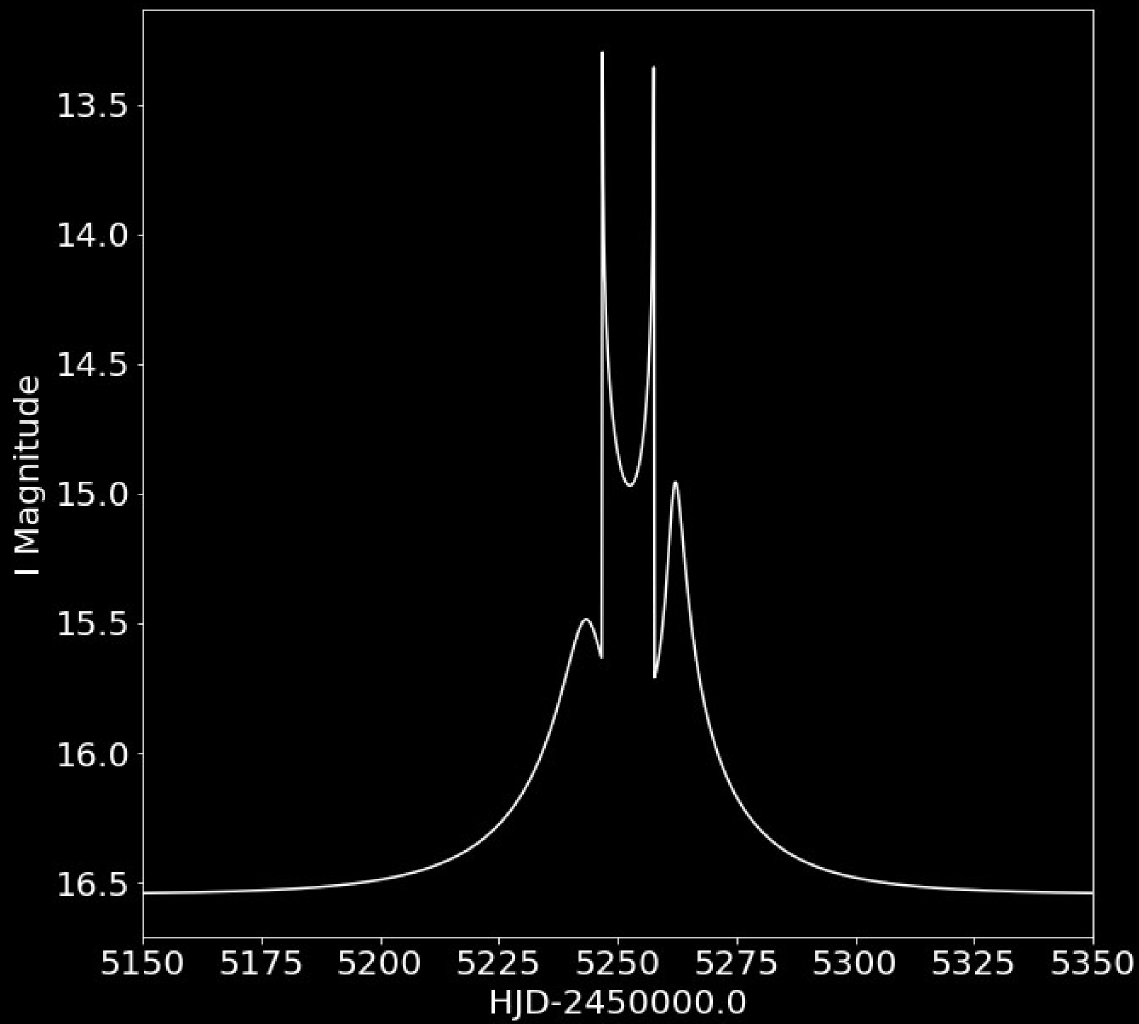
t_E *~ 90days*

Symmetrical, no anomalies

Lightcurve Challenge



Lightcurve Challenge



Classification:

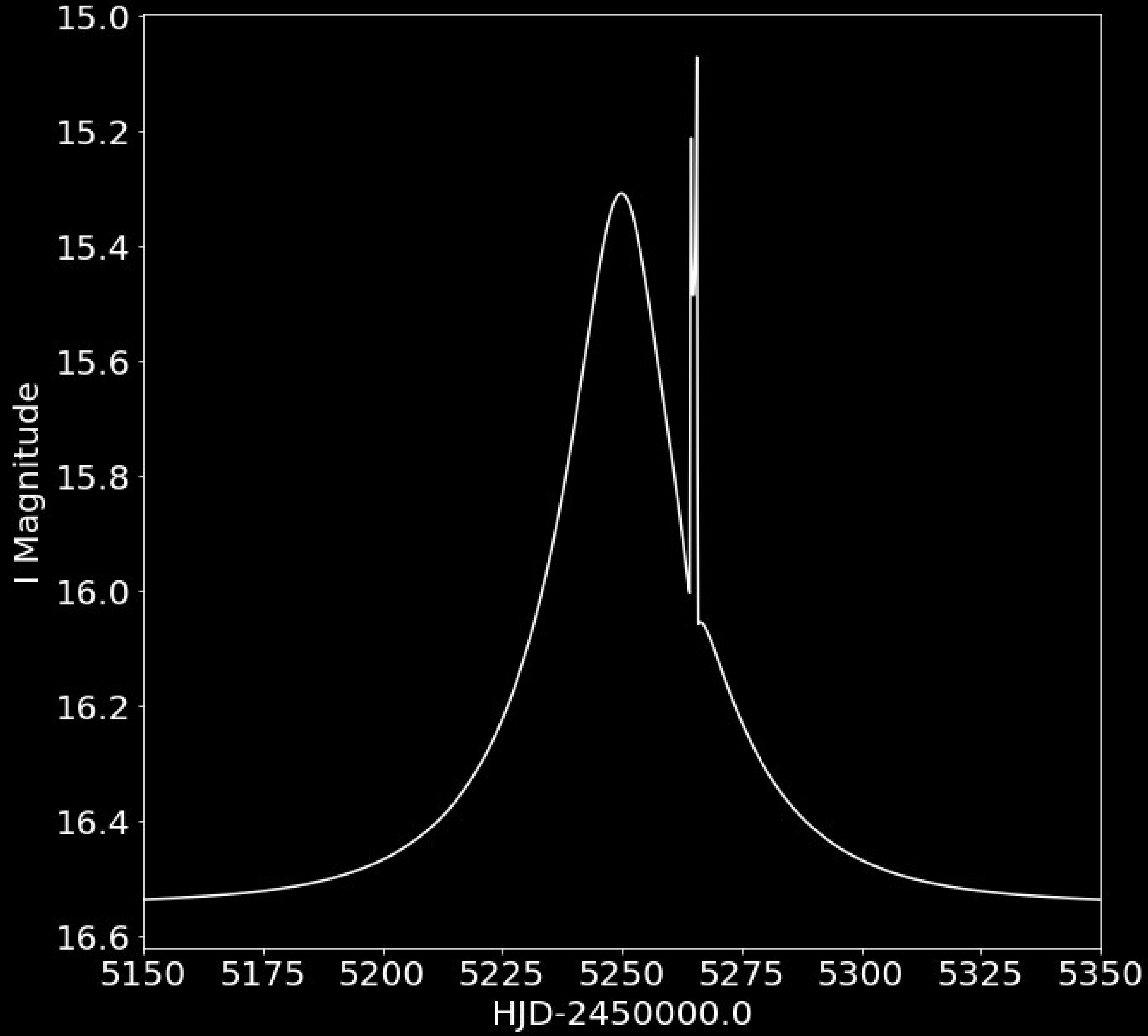
Binary star event

Reason:

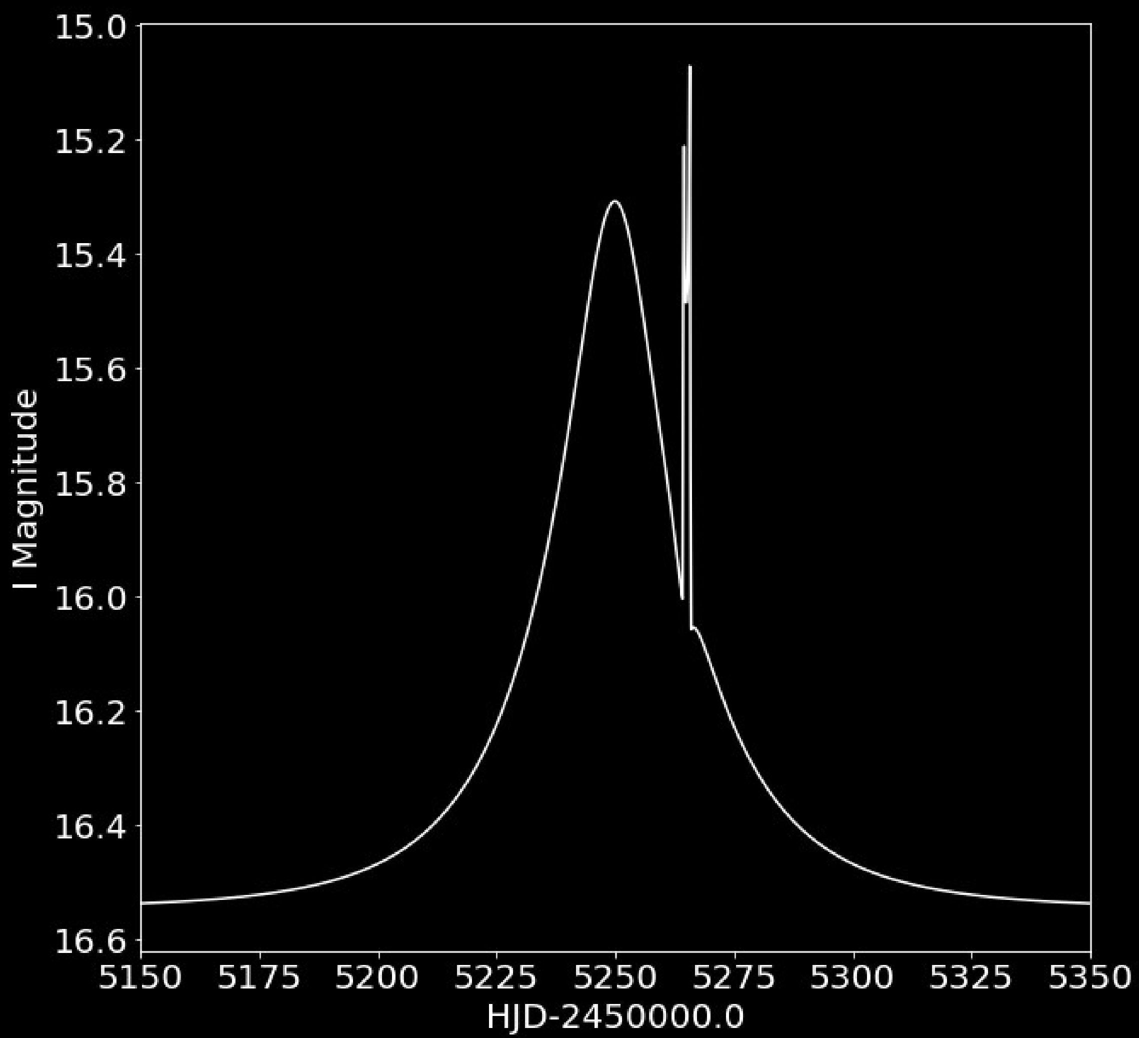
Clear anomaly

$t_{anomaly} \sim 20 days$

Lightcurve Challenge



Lightcurve Challenge



Classification:
Star + planet candidate

Reason:
Mostly symmetrical
$t_{anomaly}$ *~ 1 day*