Parallaxes: Orbital, Terrestrial, Satellite

Jennifer Yee

SAO

What is parallax?

3 Types of Parallax due to 2 Effects

- Motion of the observer

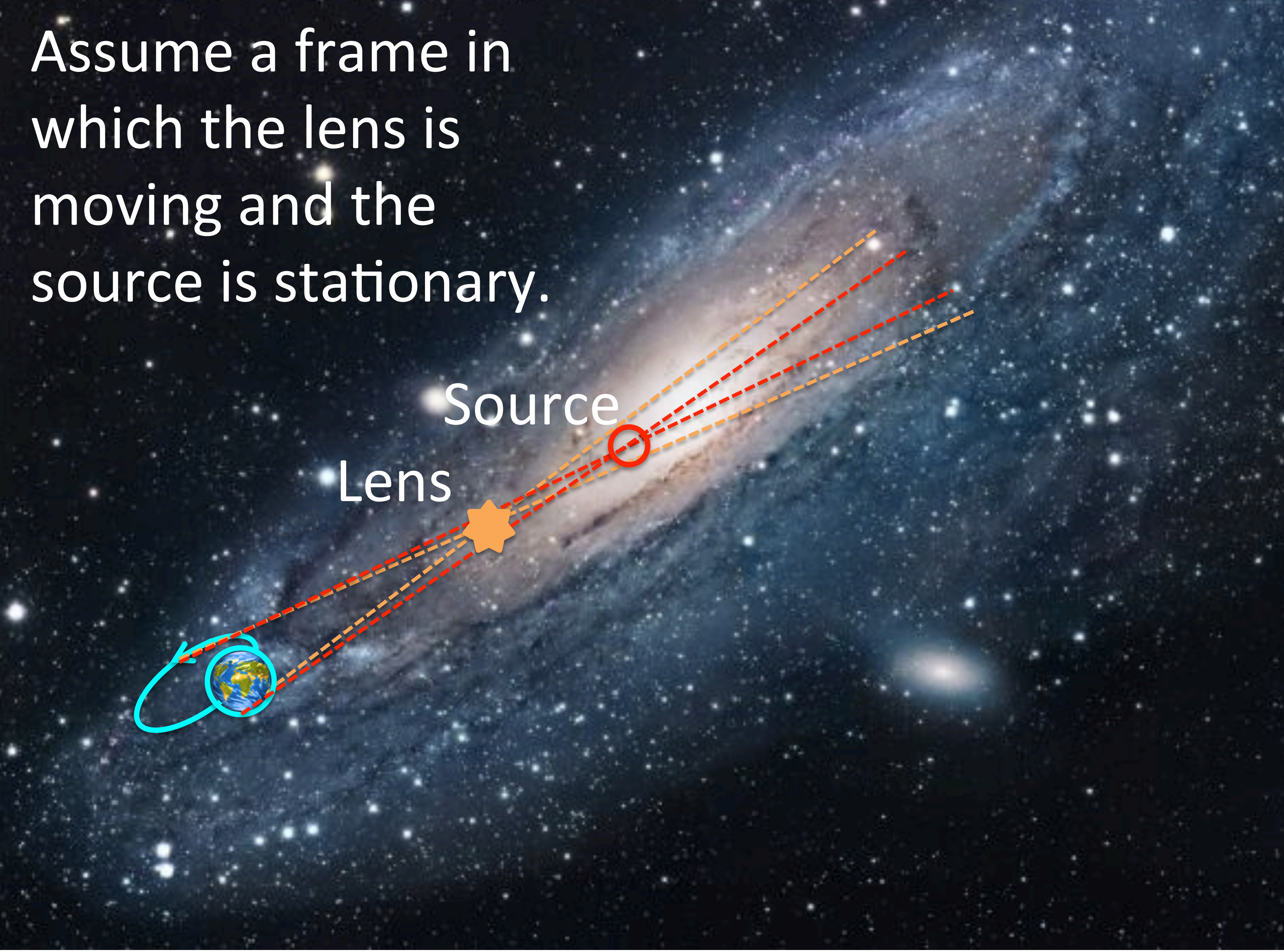
  → **Orbital/Annual** Parallax

- Separation between 2 observers

  → **Satellite** parallax

  → **Terrestrial** parallax

Assume a frame in which the lens is moving and the source is stationary.



What matters is the source-lens *relative* parallax.

$$\pi_{\mathrm{rel}} = \frac{\mathrm{AU}}{D_{Lens}} - \frac{\mathrm{AU}}{D_{Source}}$$

…but this is not what we measure.

The observed magnification depends only on the *relative* (projected) separation between the source and lens.

$$A(t) = \frac{u(t)^2 + 2}{u(t)\sqrt{u(t)^2 + 4}}$$

The basic PSPL curve assumes uniform, rectilinear motion (i.e. a constant *relative* velocity).

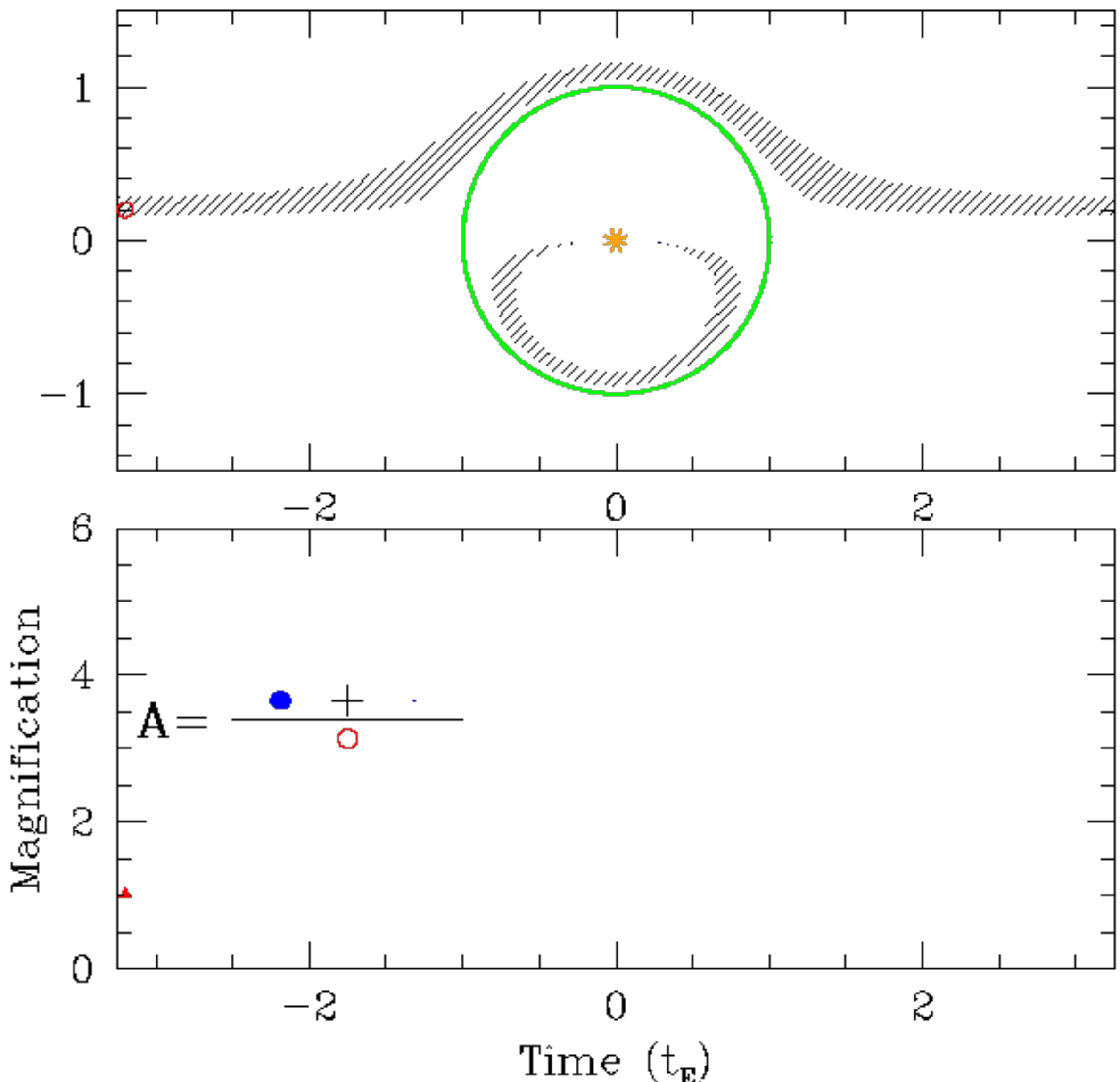
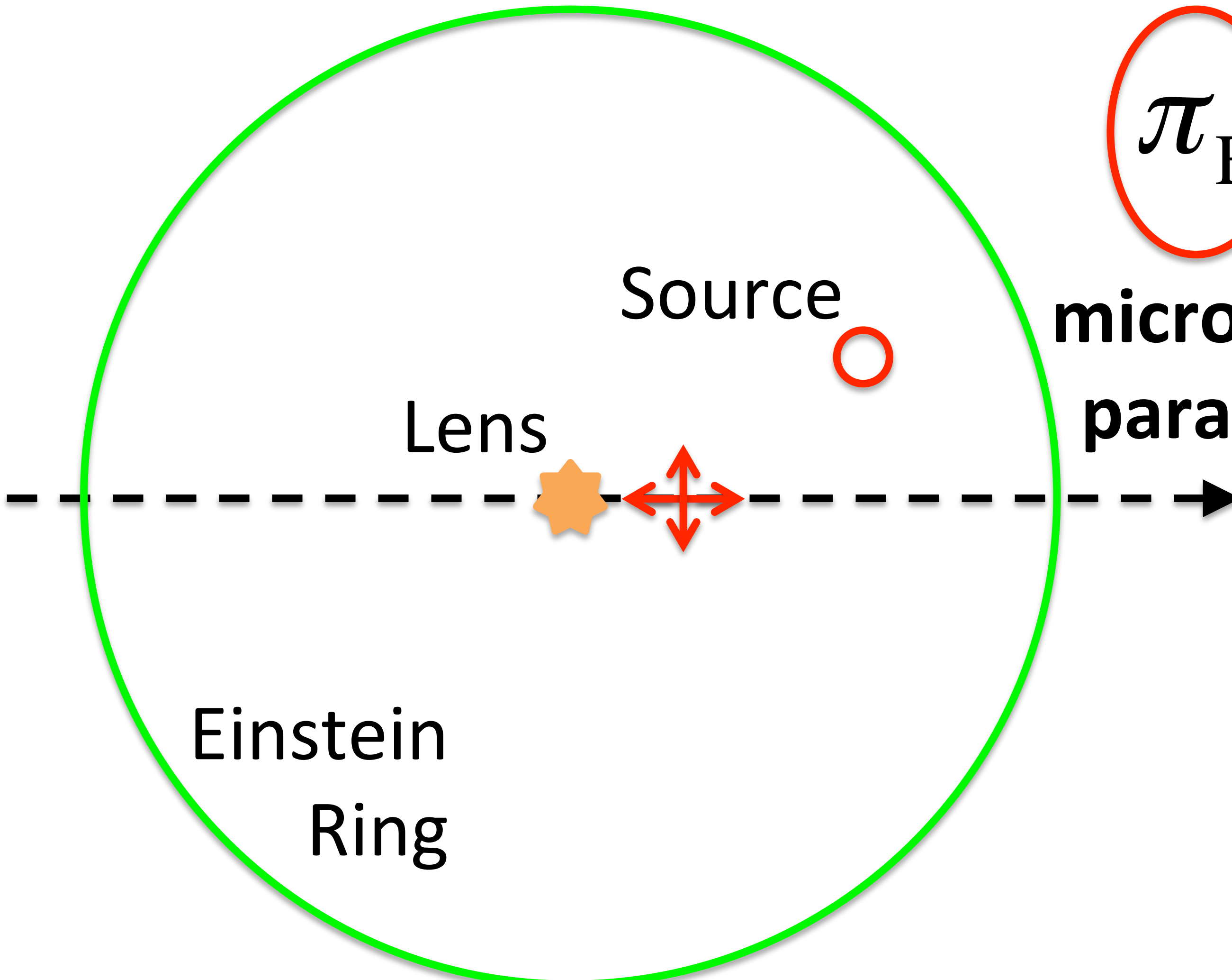


Image courtesy of B. Scott Gaudi
http://www.astronomy.ohio-state.edu/~gaudi/movies.html

We only care about the *relative speed* and the *displacement Δu* (i.e. *relative* to the Einstein ring).



$$\pi_E = \frac{\pi_{rel}}{\theta_E}$$

microlens parallax

Why care about microlens parallax?

1. It's physics.
2. It lets us measure physical scales (if we have θ_E):
    a. ***absolute masses*** for the lenses, and therefore the planets.
    b. ***distances*** *to* the lens (planetary) systems
    c. (projected) ***separations*** between the planet and star

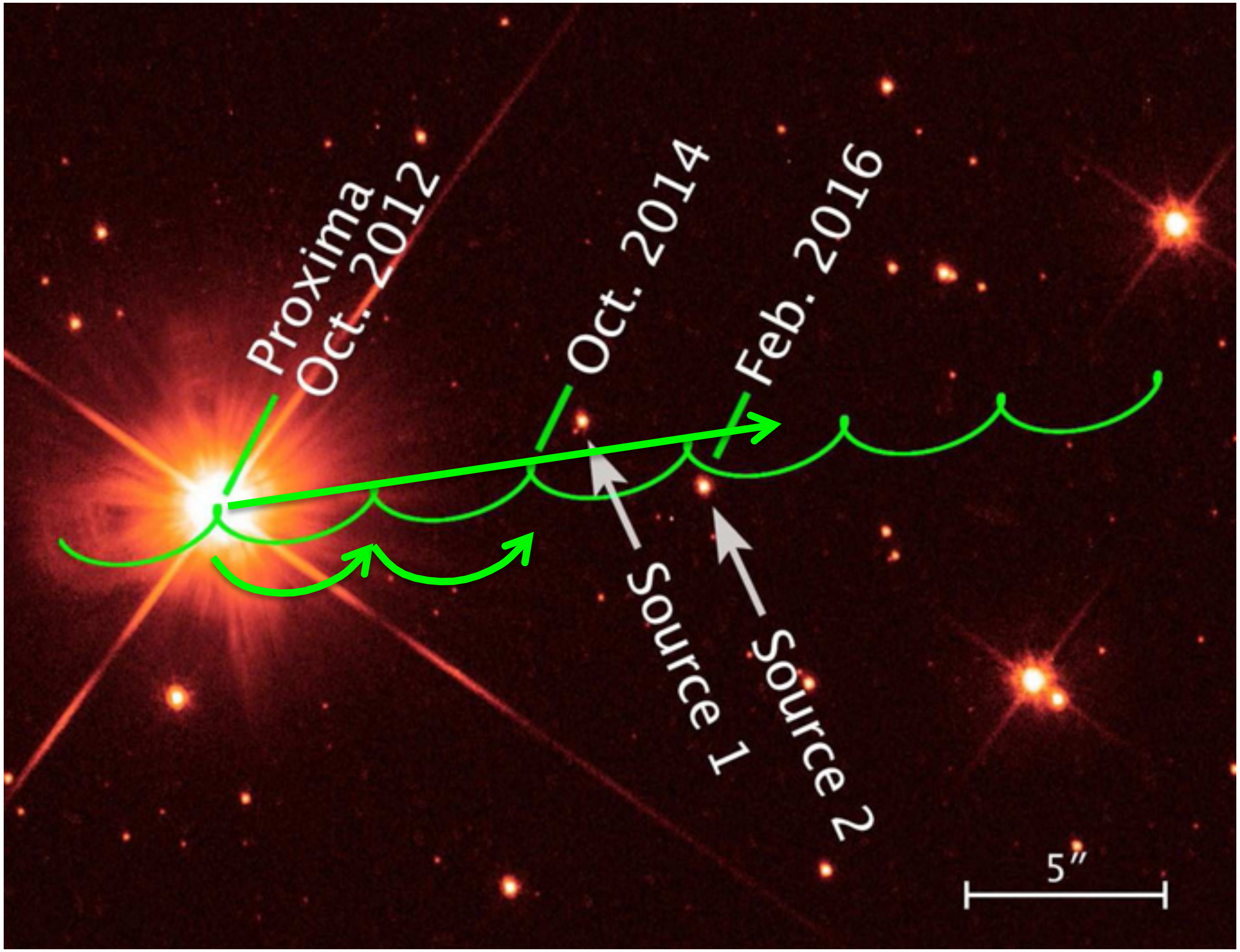
The lens mass is measured from *lightcurve features* without measuring *light* from the lens.

$$M_{star} = \theta_E/(\kappa\pi_E)$$

$\kappa = 8.41$ mas $(M_{sun})^{-1}$

Fun fact:
Microlens Parallax Is a Vector!?

2 Components to the motion of Proxima Centauri (or any star)



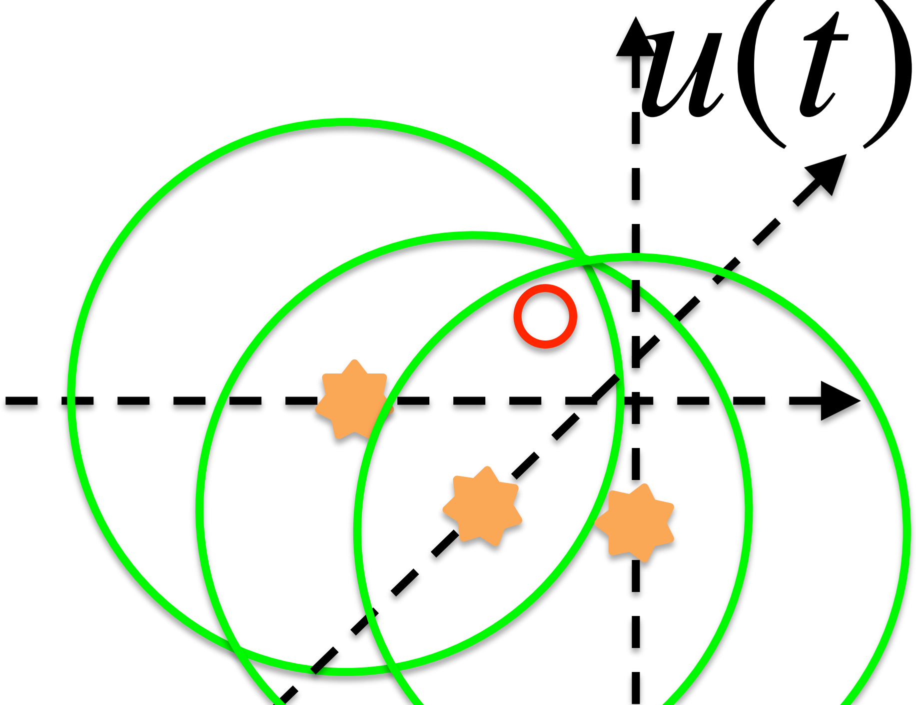
Sahu et al. 2014 ApJ 792, 89

In microlensing, direction matters only if there is parallax.

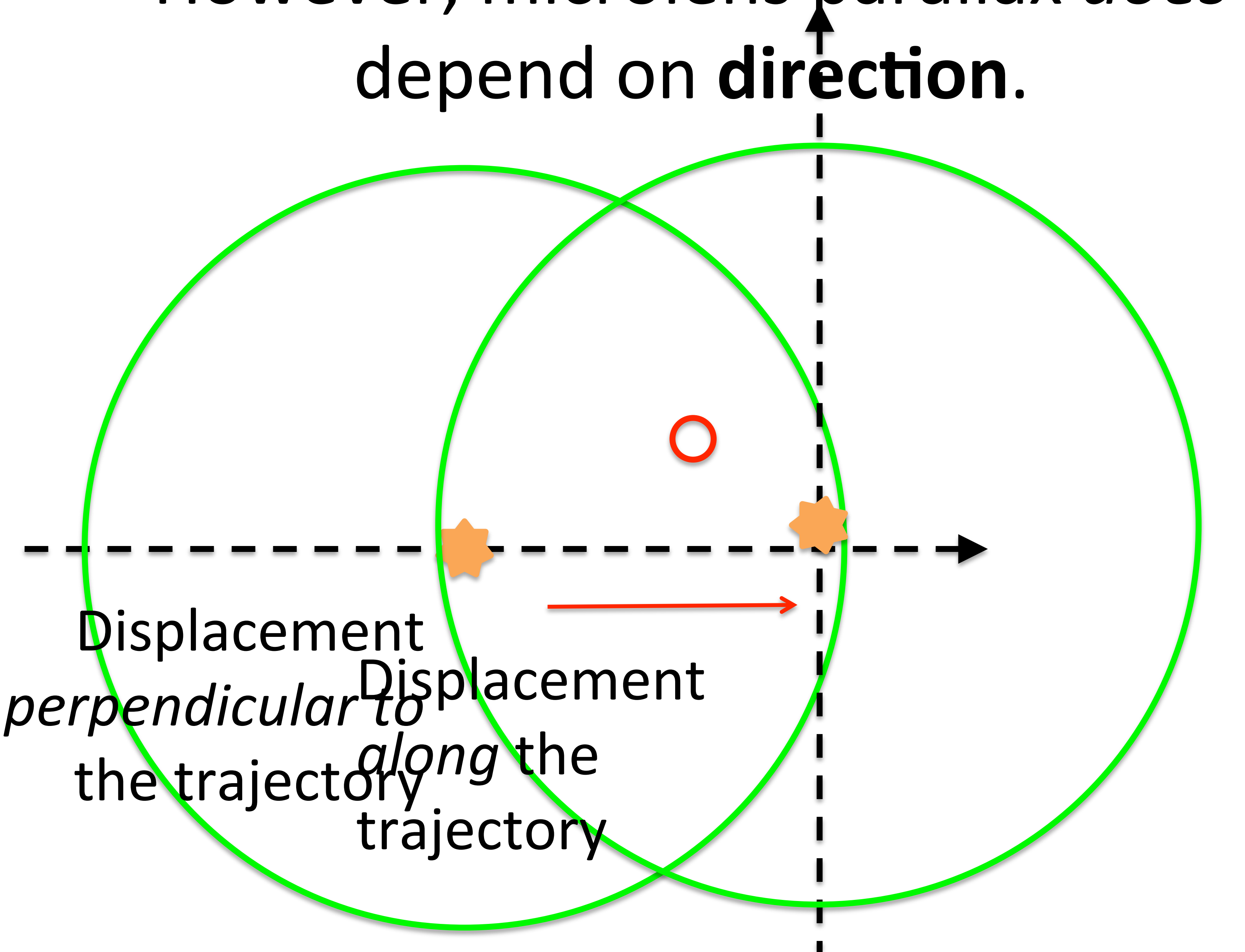
	Normal Astronomy	**Microlensing**
Proper Motion	Vector	Scalar
Parallax	Scalar	Vector

The magnification equation depends only on the **scalar** *u*(*t*).

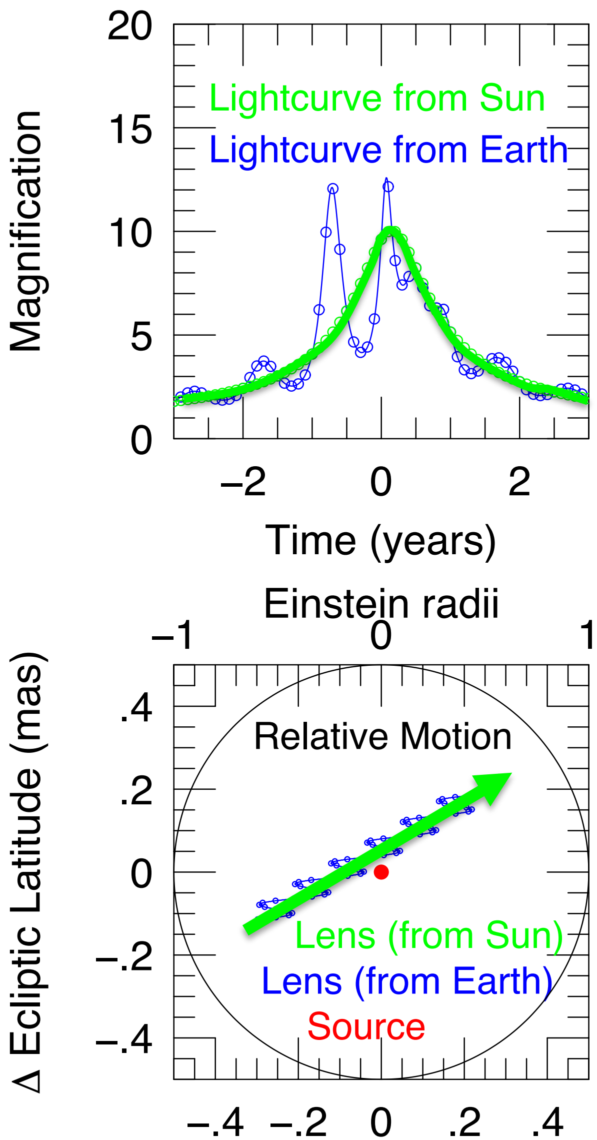
$$A(t) = \frac{u(t)^2 + 2}{u(t)\sqrt{u(t)^2 + 4}}$$



However, microlens parallax *does* depend on **direction**.

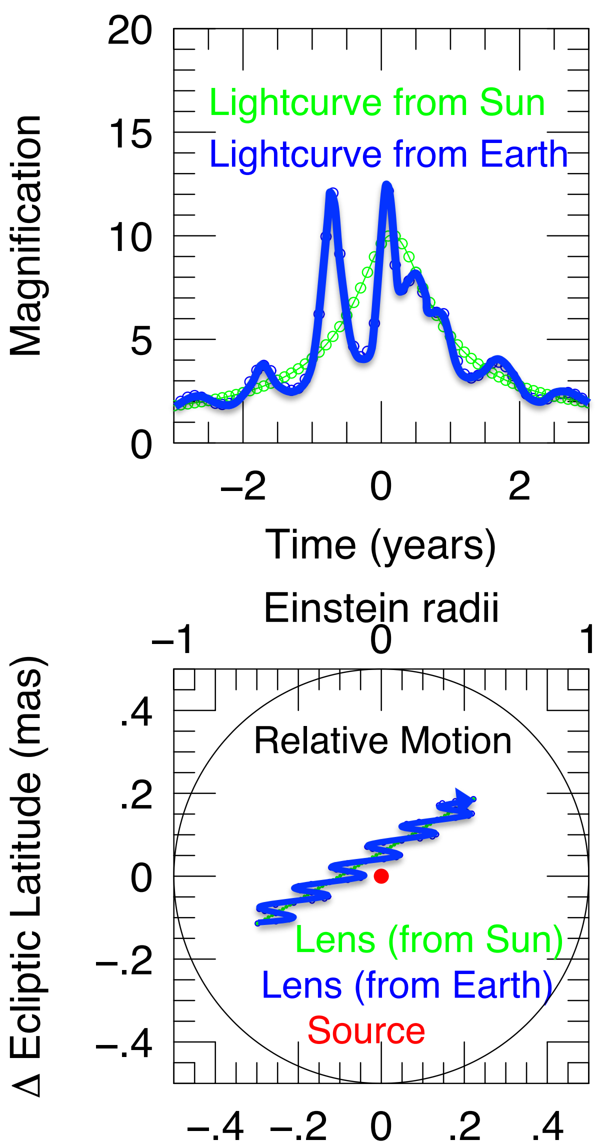


Orbital Parallax



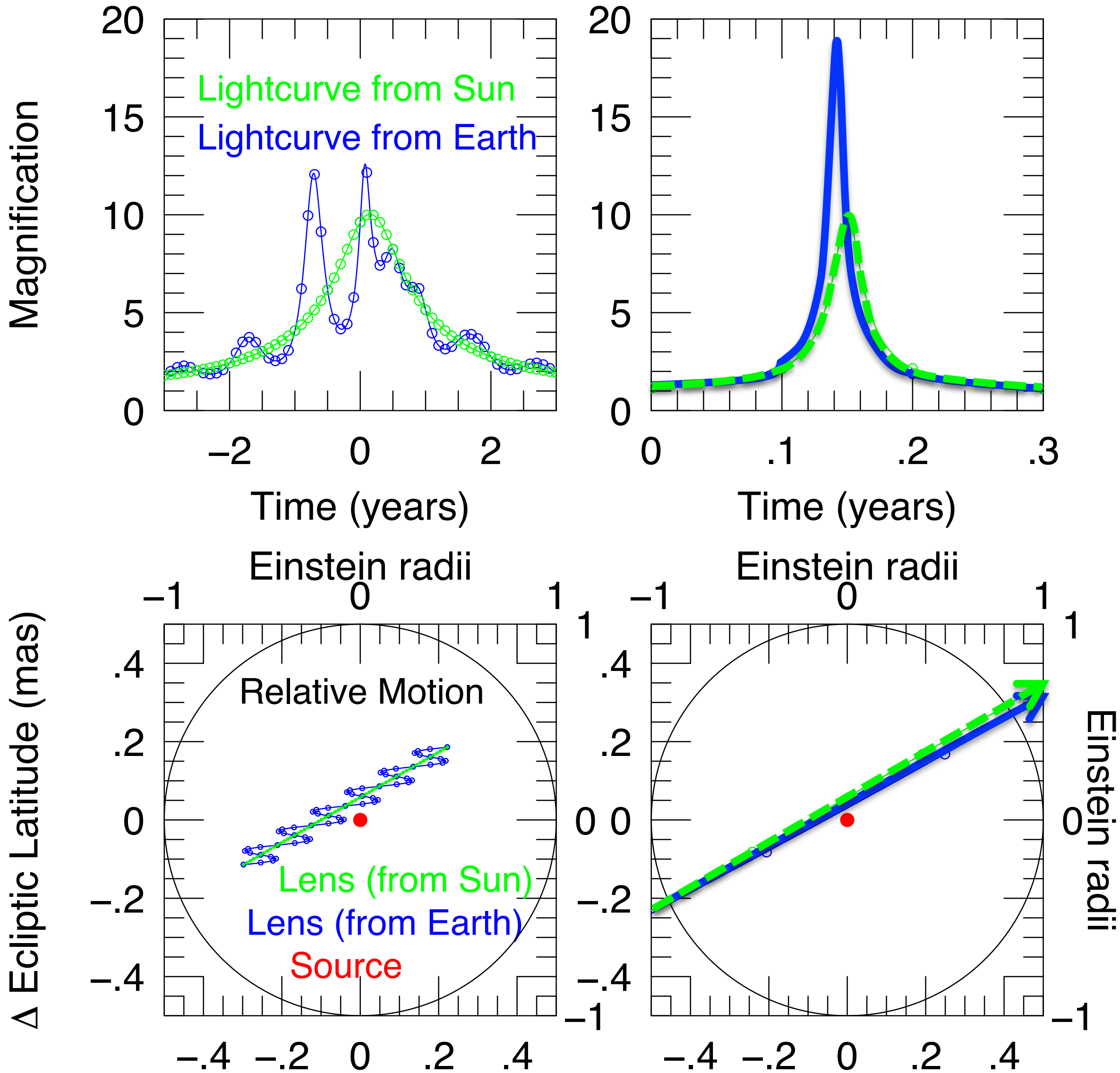
Gould & Horne 2013, ApJ, 779, 28

Orbital Parallax



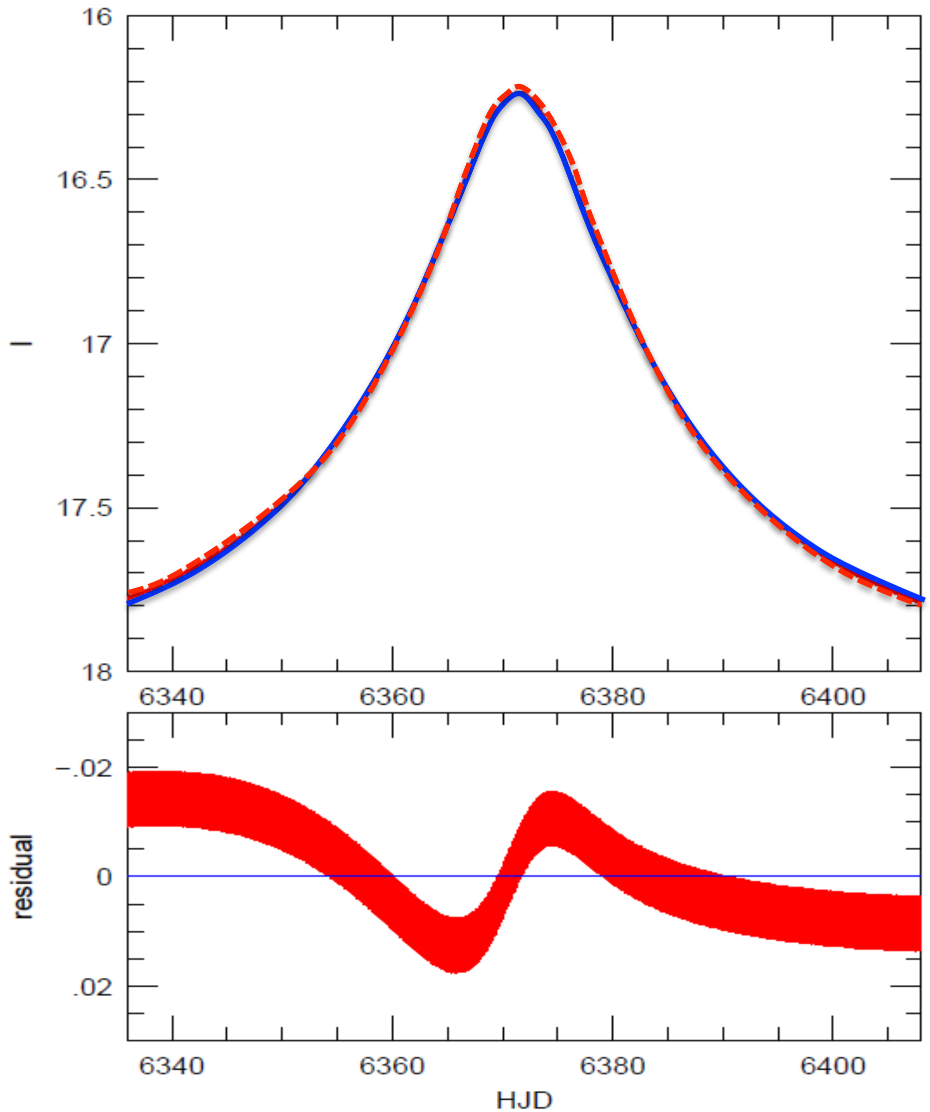
Gould & Horne 2013, ApJ, 779, 28

Orbital Parallax

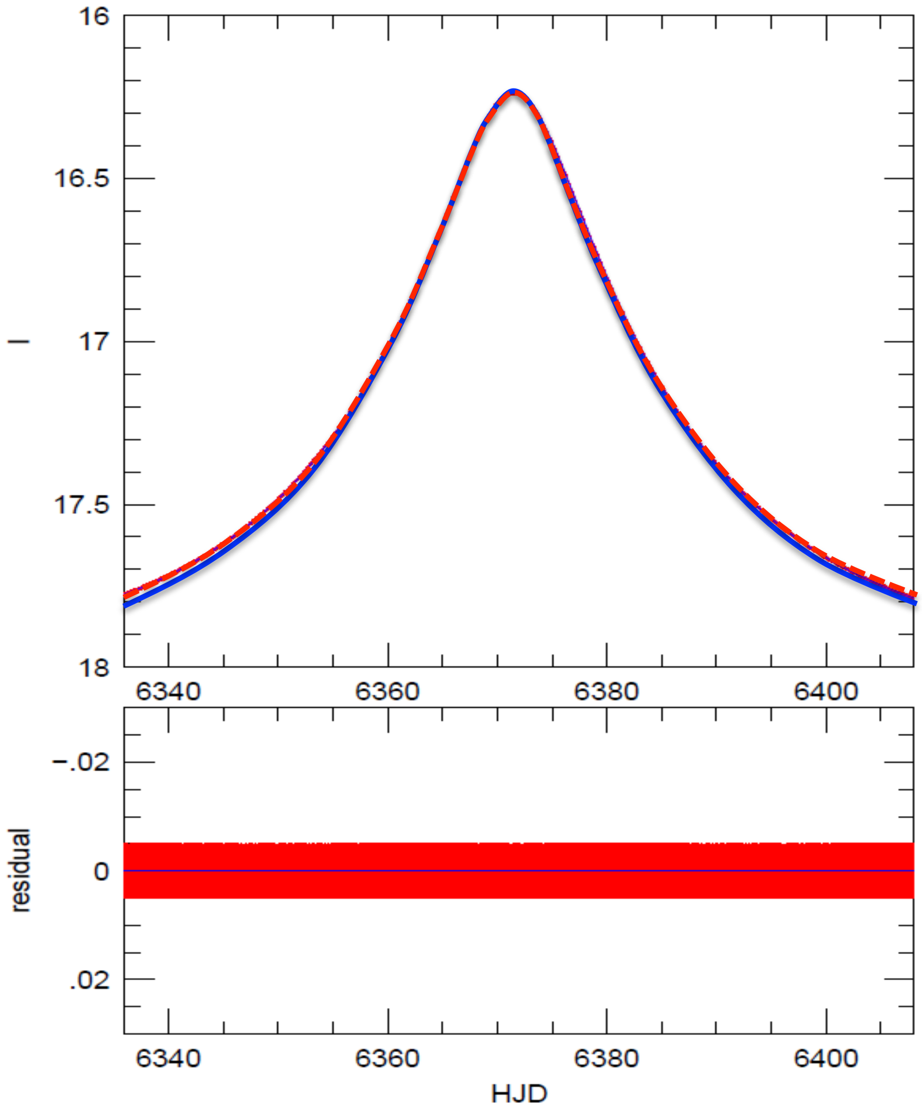


Gould & Horne 2013, ApJ, 779, 28

Component PARALLEL to lens trajectory
➔ASYMMETRIC Distortion



Component PERPENDICULAR to lens trajectory ➔ SYMMETRIC Distortion



Are we more likely to see annual parallax for an event with

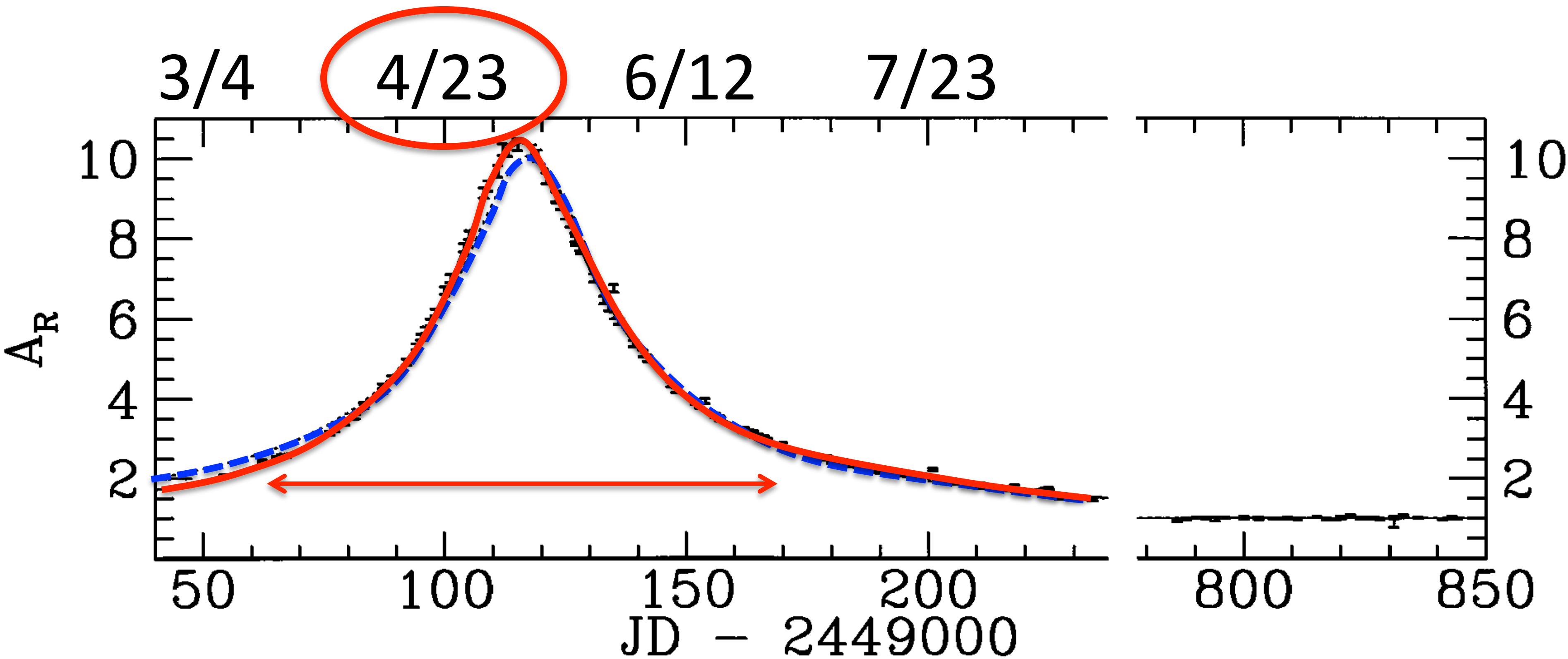
t_E = 10 days

or

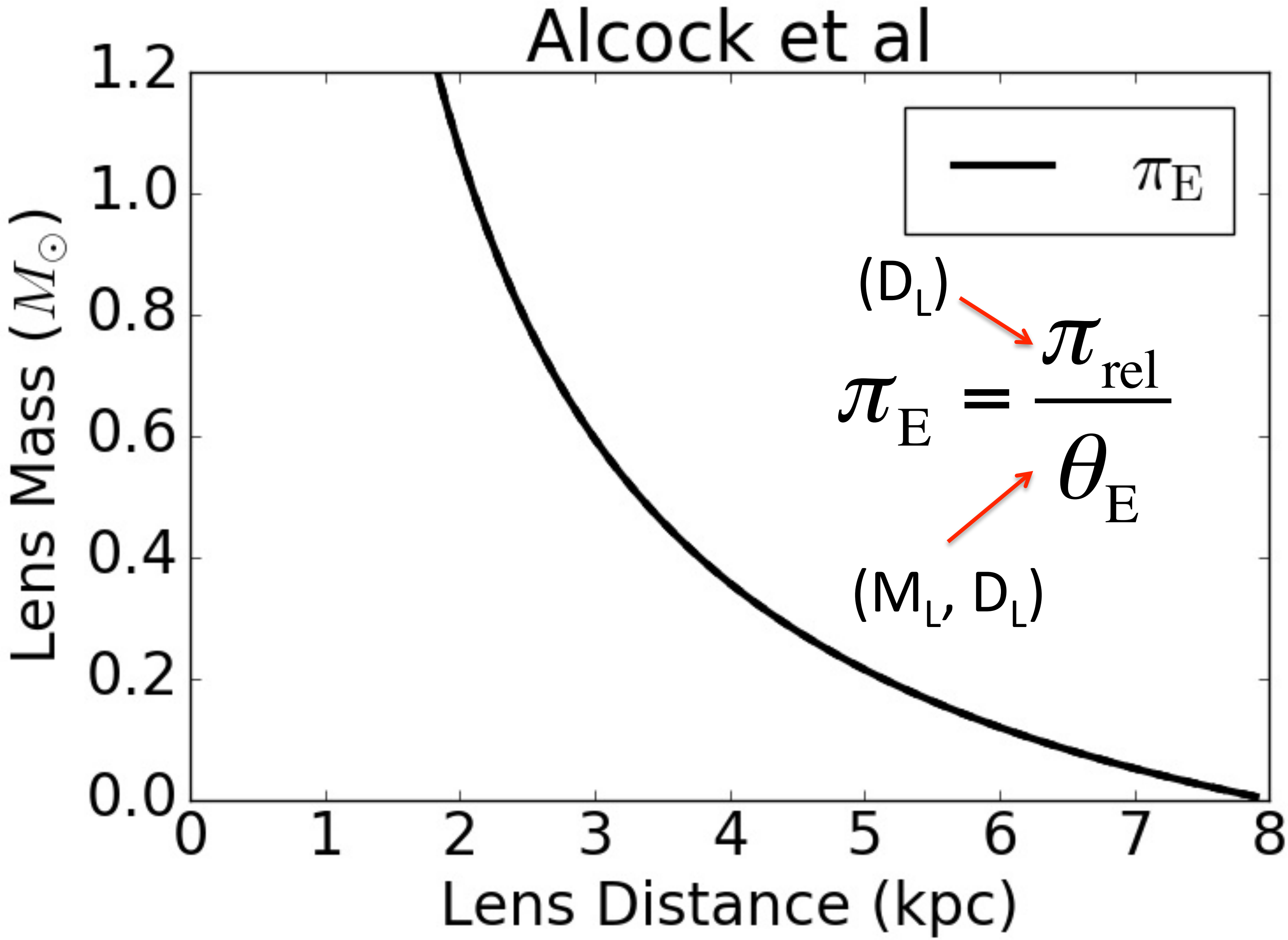
t_E = 100 days?

Microlens parallax is easier to measure in Spring and Fall.

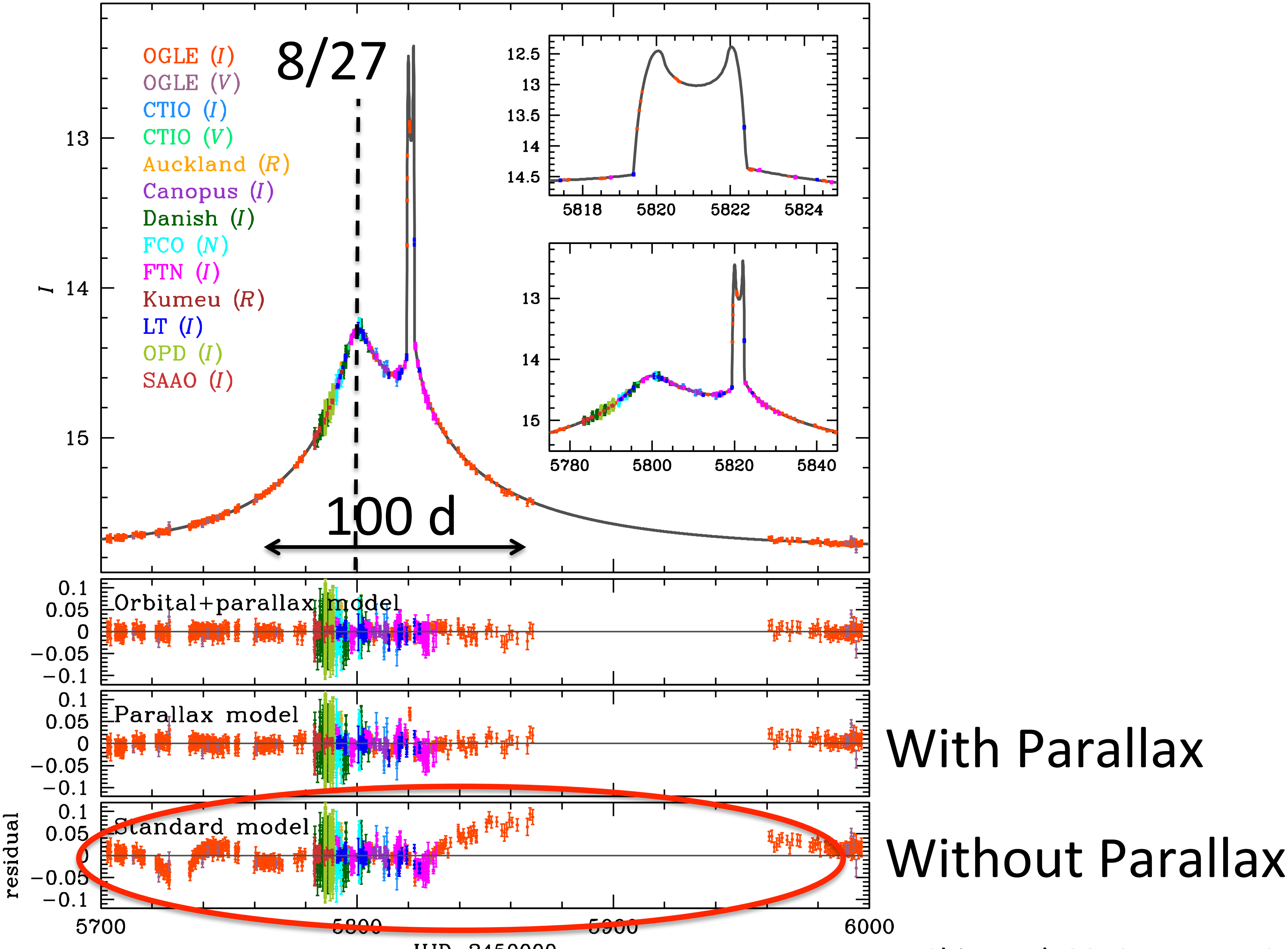
Alcock et al. 1995: First detection of microlens parallax.



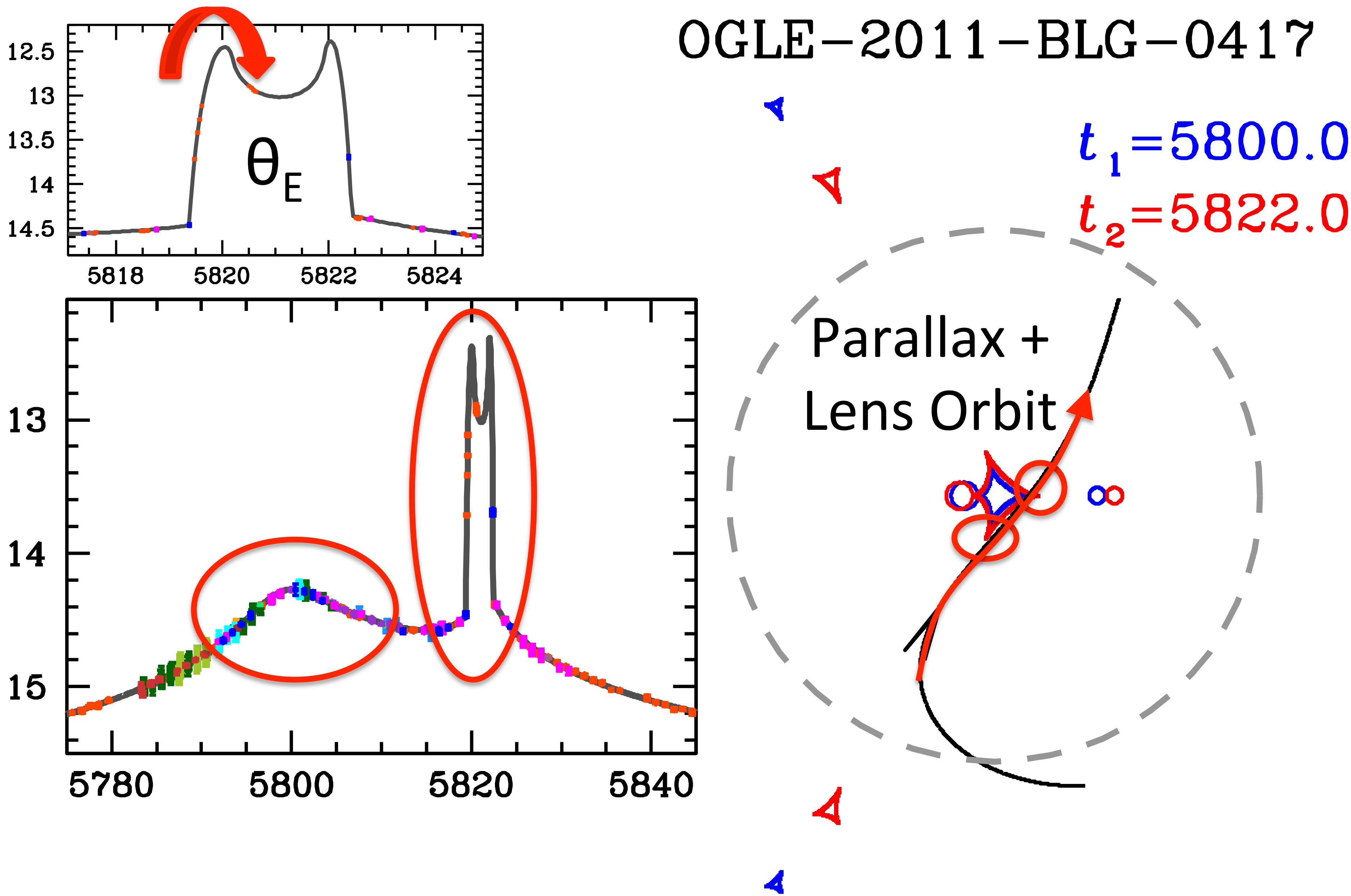
Without parallax, the point lens fit cannot match the asymmetry in the light curve.



Alcock et al
Lens Mass ($M_\odot$)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
Lens Distance (kpc)
π_E
(D_L)
$\pi_E = \frac{\pi_{rel}}{\theta_E}$
(M_L, D_L)

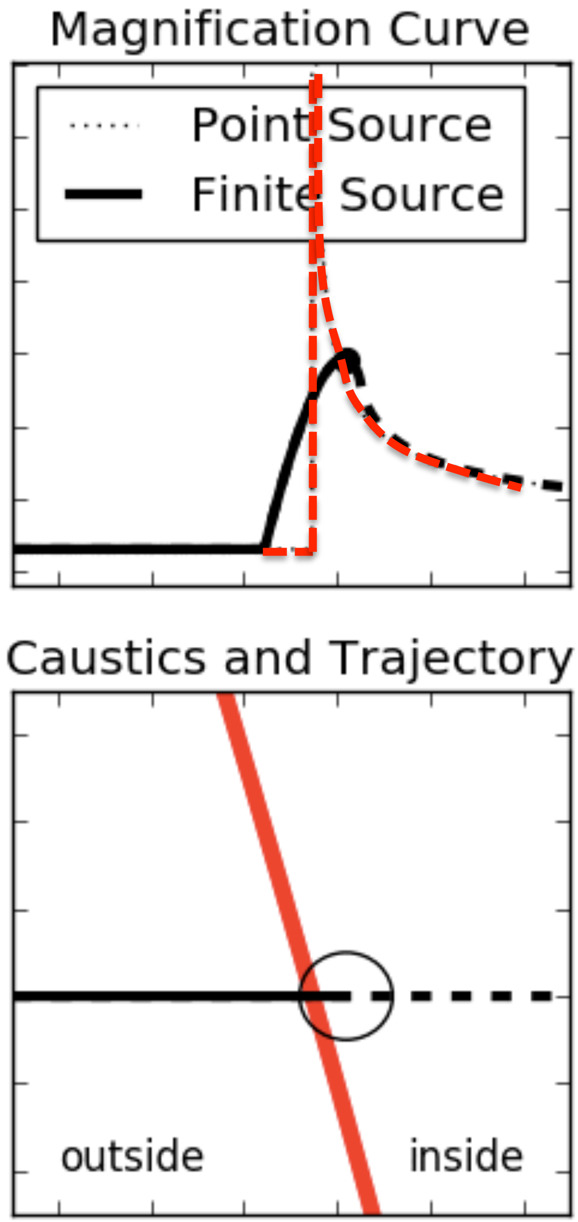


Shin et al. 2012 ApJ 755, 91



OGLE−2011−BLG−0417
t_1=5800.0
t_2=5822.0
Parallax +
Lens Orbit
θ_E
12.5
13
13.5
14
14.5
5818
5820
5822
5824
13
14
15
5780
5800
5820
5840

The Finite Source Effect

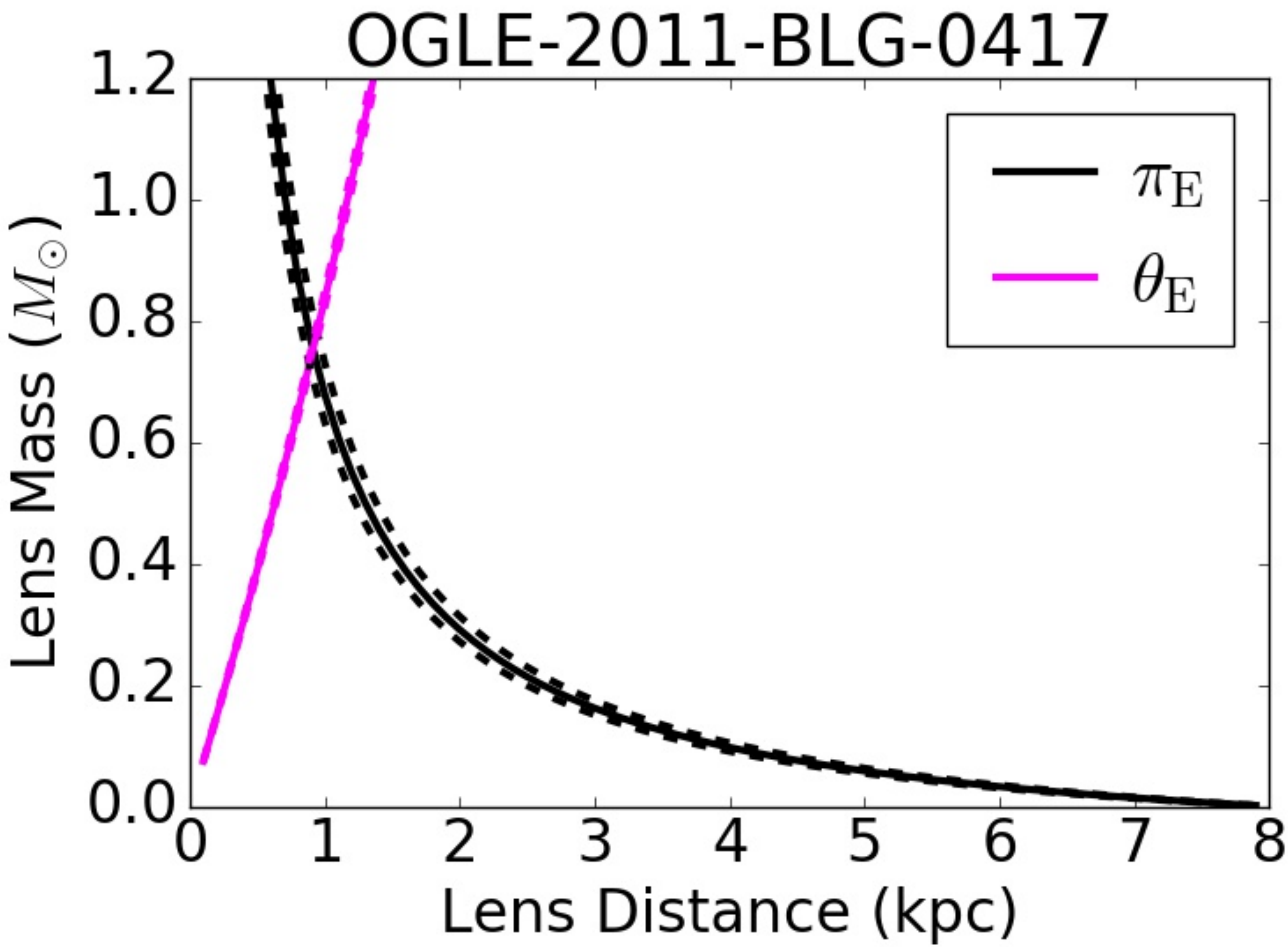


Angular size of the Source Star (known)

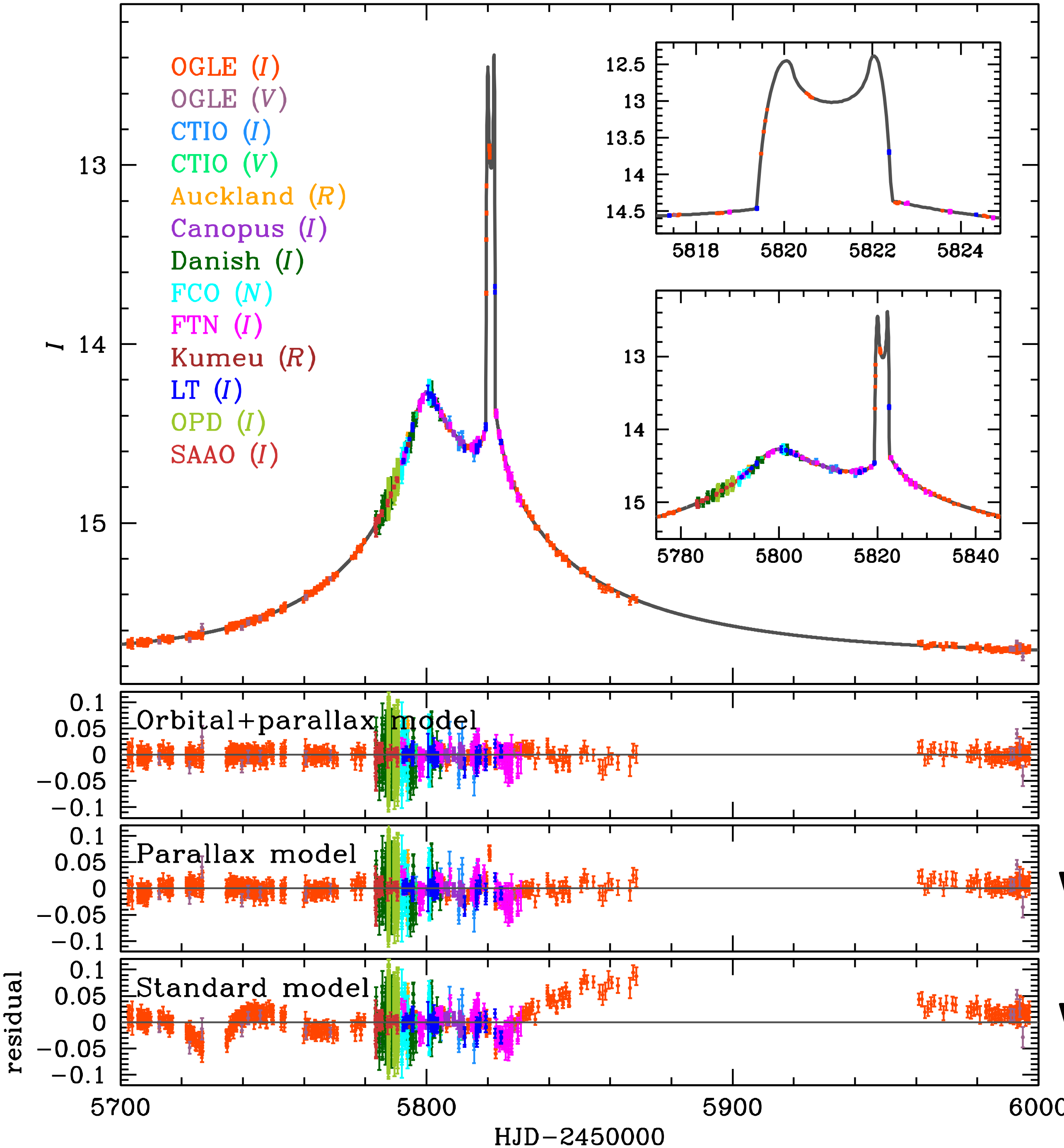
measured

$$\rho = \frac{\theta_*}{\theta_E}$$

Angular size of the Einstein ring.



OGLE-2011-BLG-0417
$\pi_{\rm E}$
$\theta_{\rm E}$
Lens Mass ($M_\odot$)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
Lens Distance (kpc)

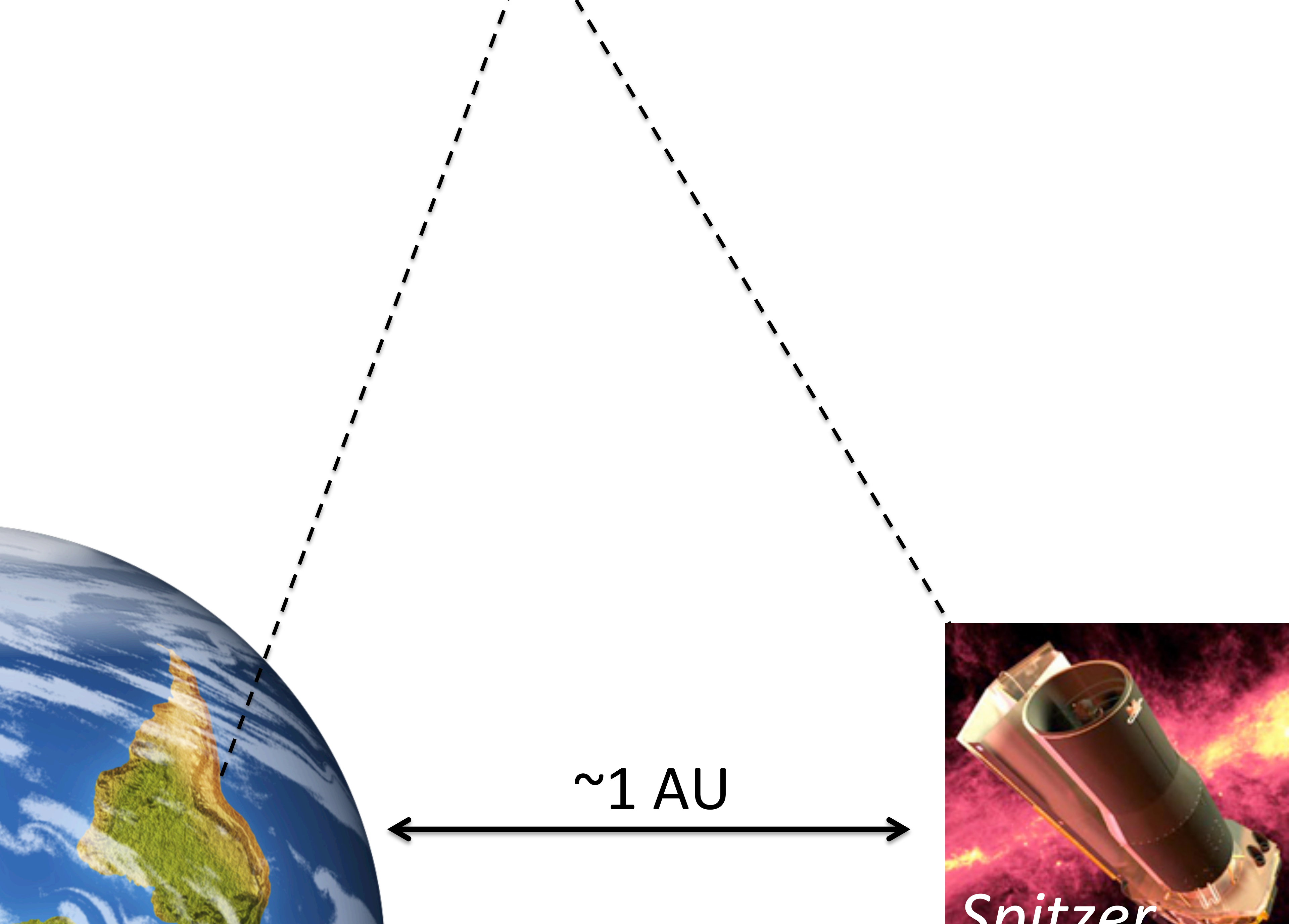


$M_1 = 0.57\ M_{Sun}$
$M_2 = 0.17\ M_{Sun}$
$D_L = 0.89$ kpc
a = 1.15 AU

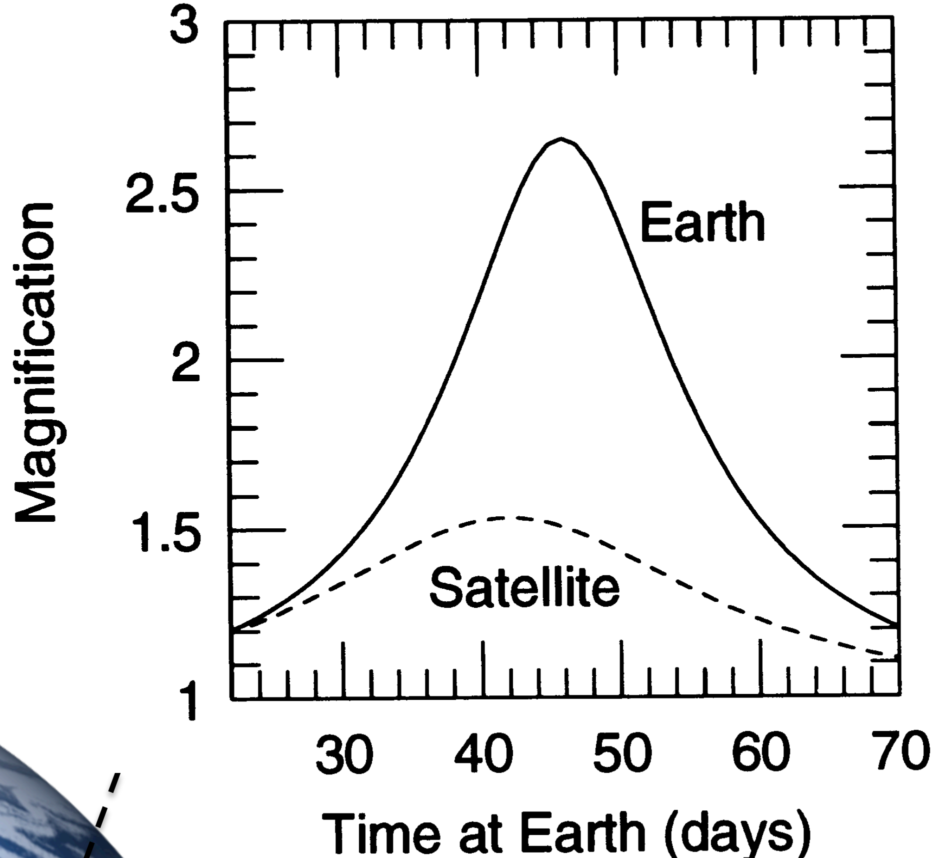
With Parallax

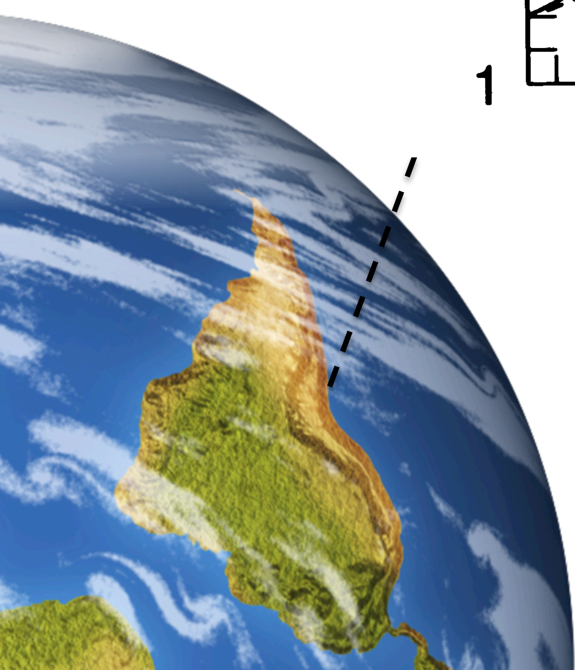
Without Parallax

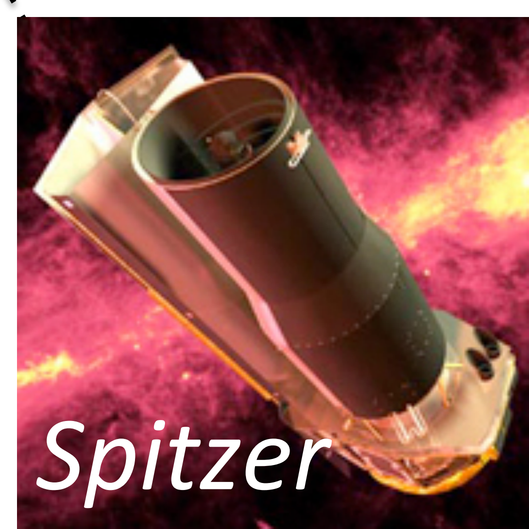
Shin et al. 2012 ApJ 755, 91



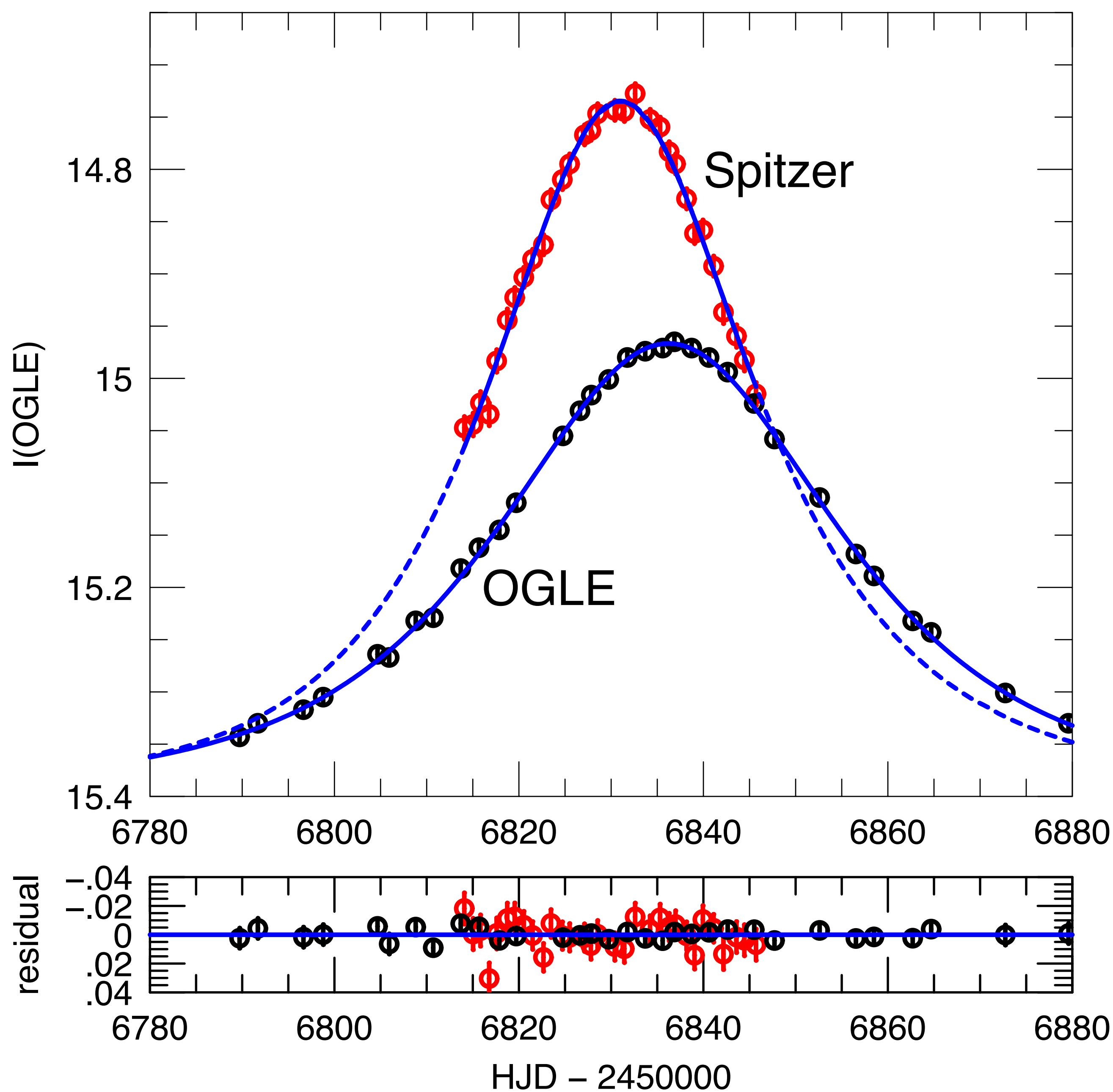
Gould 1994 ApJL, 421, 75



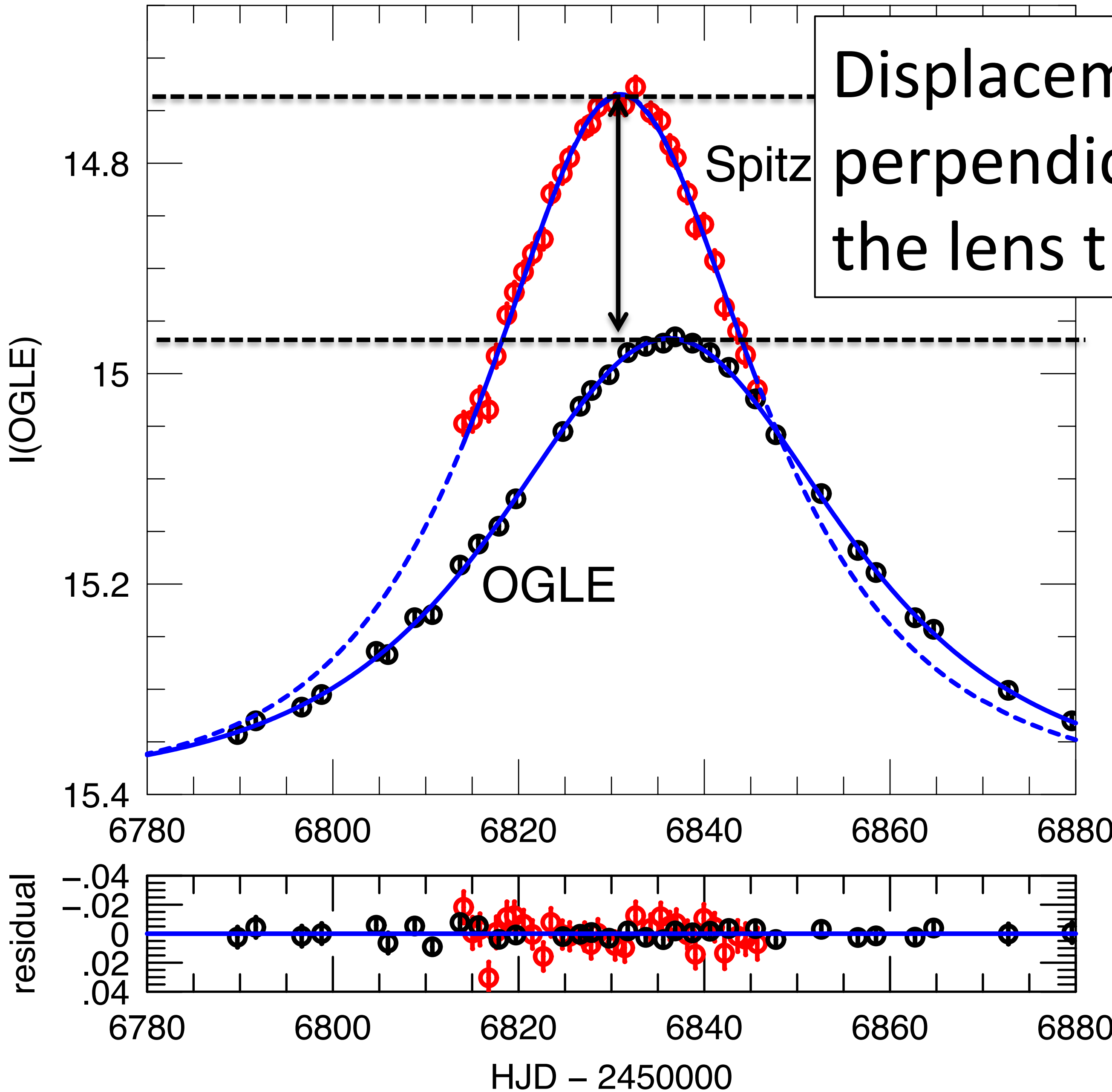




Gould 1994 ApJL, 421, 75



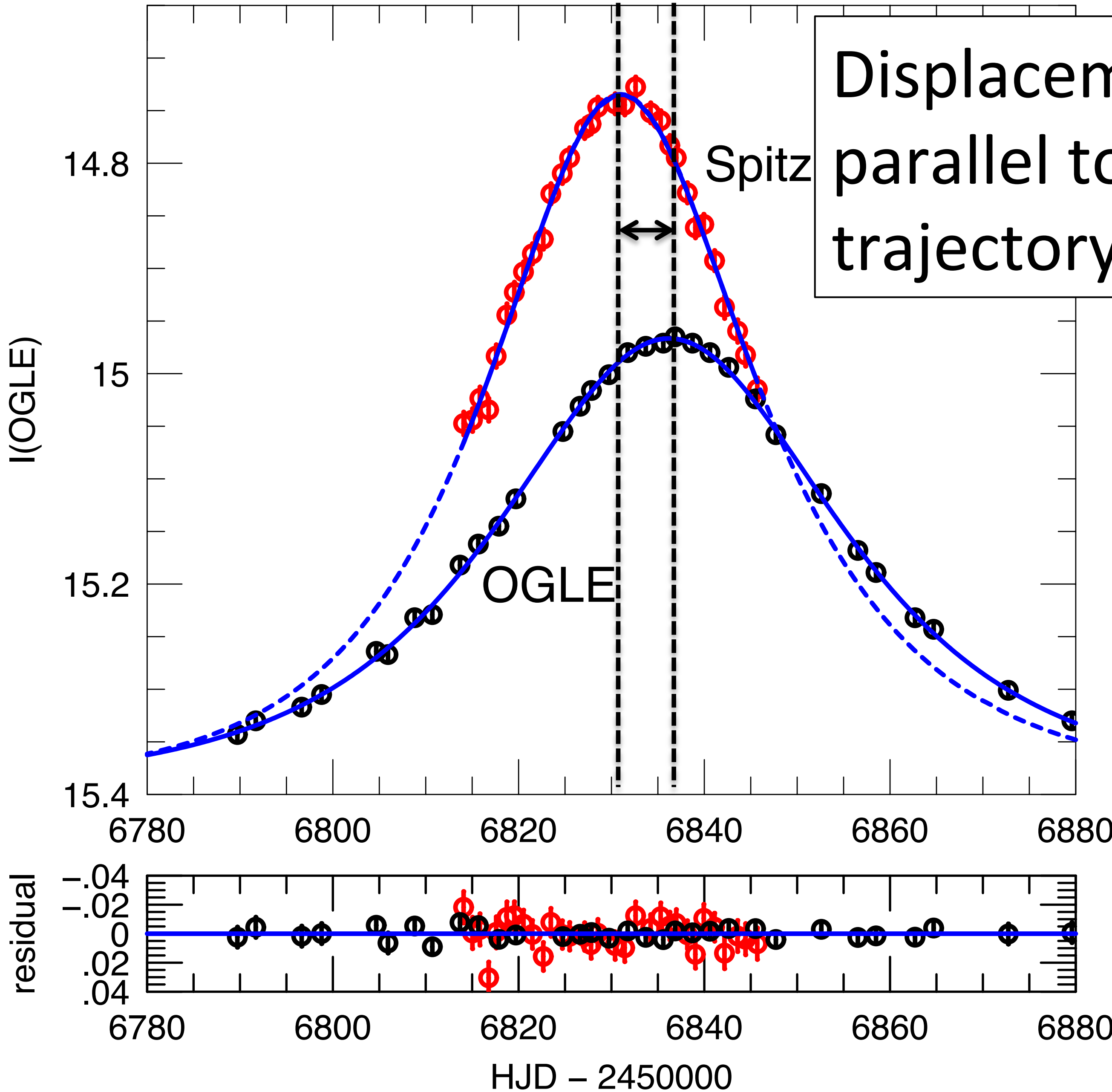
Yee et al. 2015, ApJ, 802, 76



Displacement perpendicular to the lens trajectory

Yee et al. 2015, ApJ, 802, 76

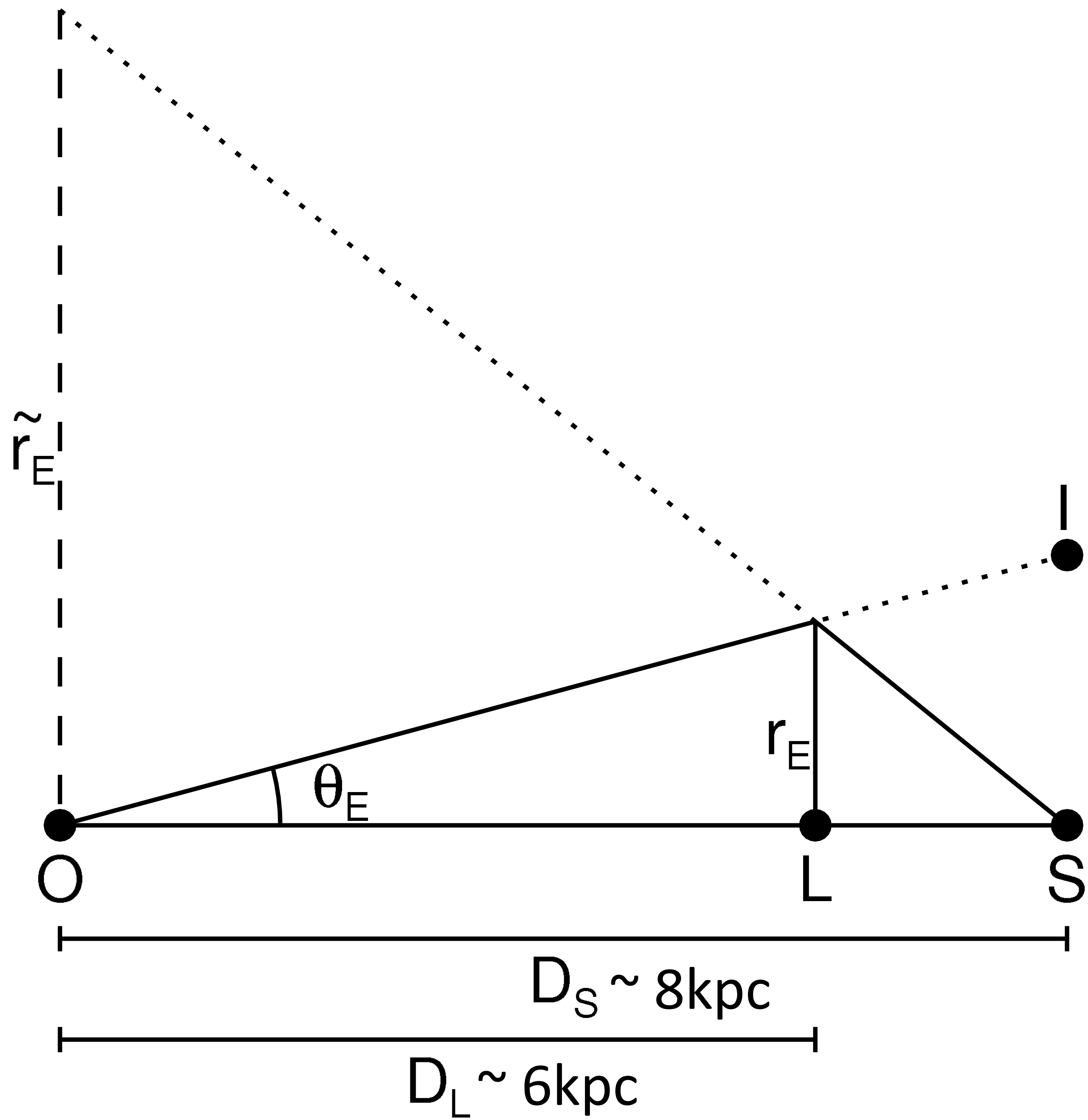
Displacement parallel to the lens trajectory



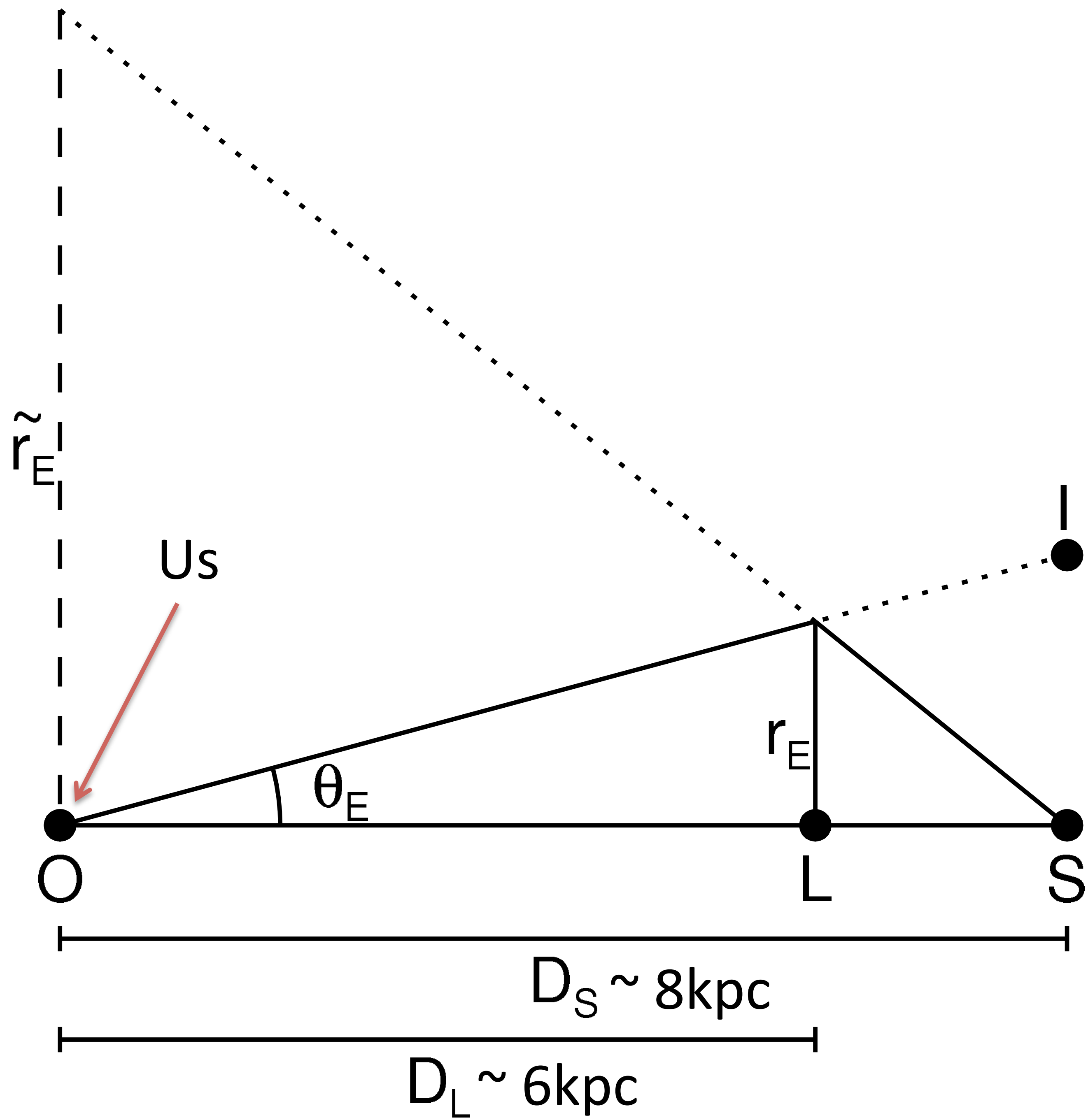
Yee et al. 2015, ApJ, 802, 76

Because the parallax effect depends on the OBSERVER, the critical scale is the size of the Einstein ring in the OBSERVER PLANE:

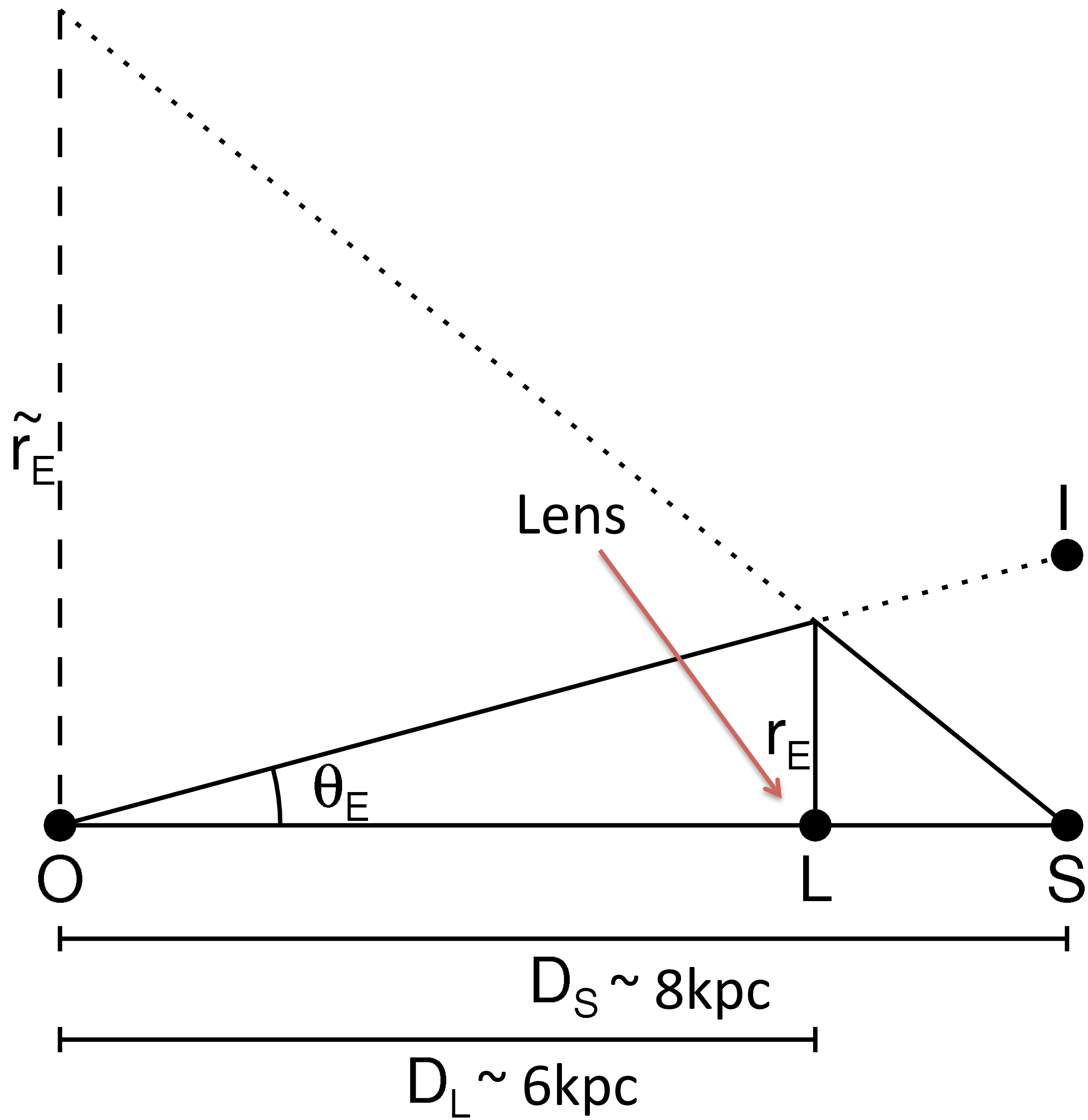
$$\tilde{r}_E$$



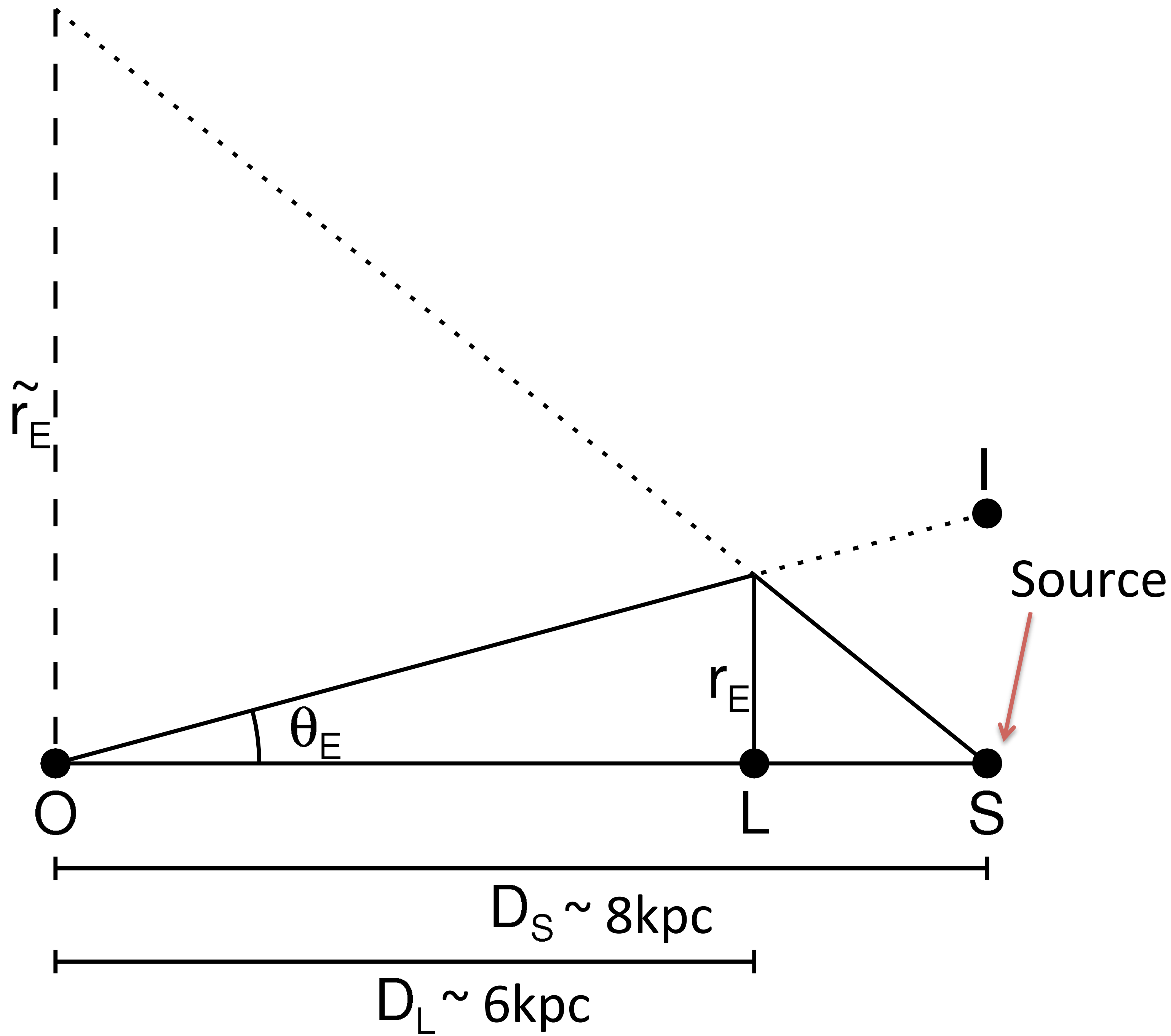
$\tilde{r}_E$
I
r_E
θ_E
O
L
S
$D_S \sim 8kpc$
$D_L \sim 6kpc$



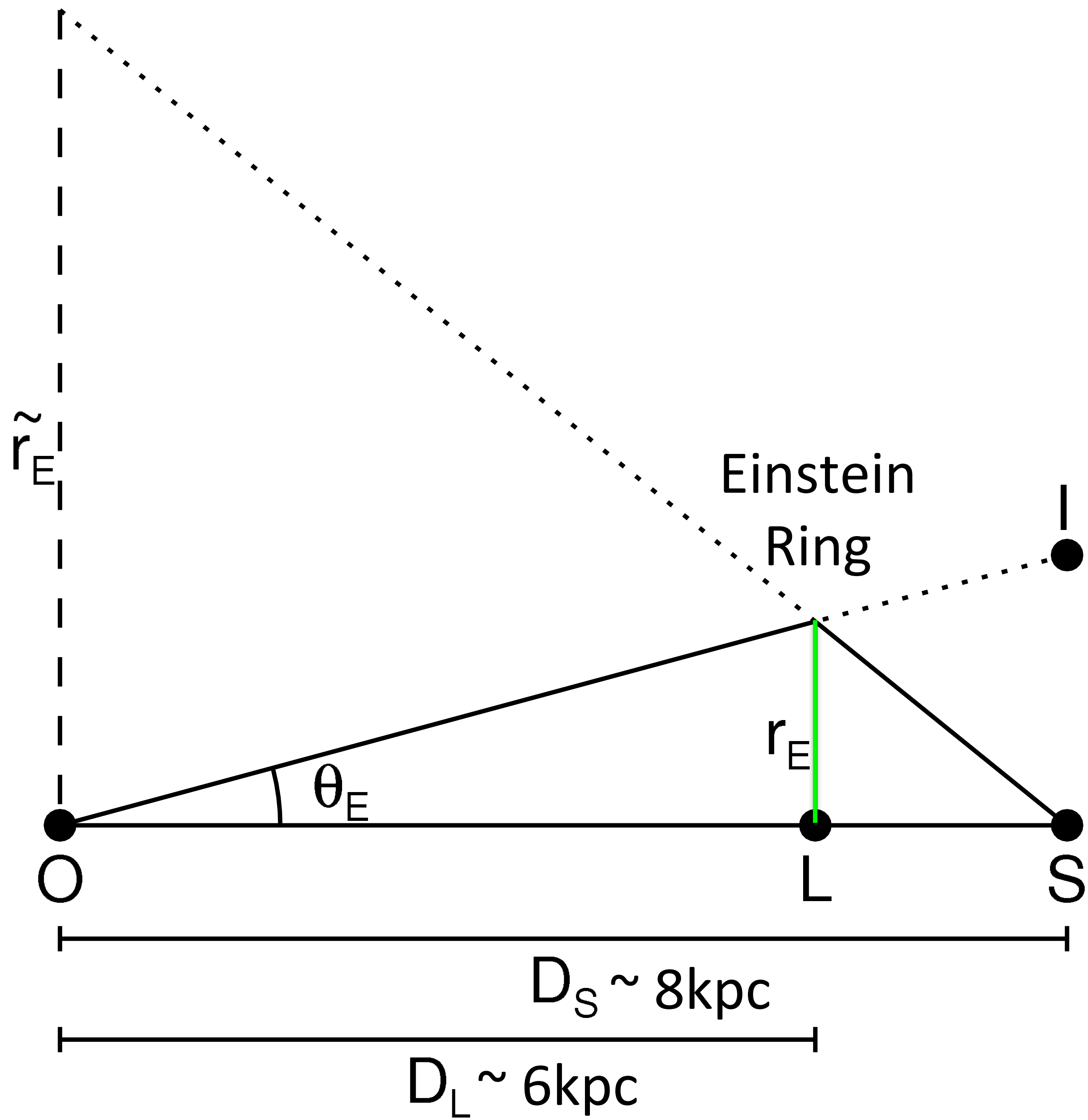
$\tilde{r}_E$
Us
I
r_E
θ_E
O
L
S
$D_S \sim 8$kpc
$D_L \sim 6$kpc



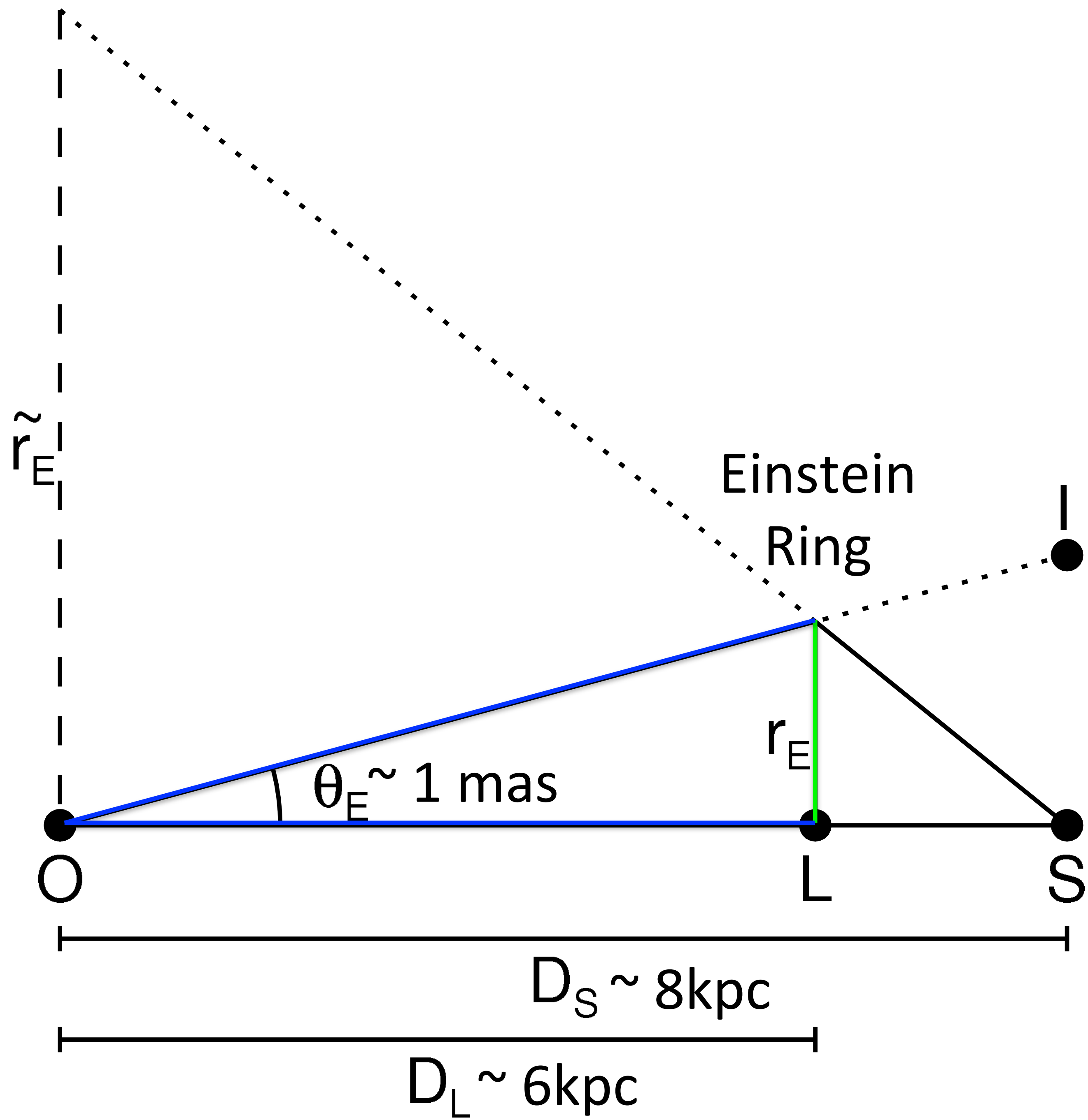
$\tilde{r}_E$
Lens
I
r_E
θ_E
O
L
S
D_S ~ 8kpc
D_L ~ 6kpc



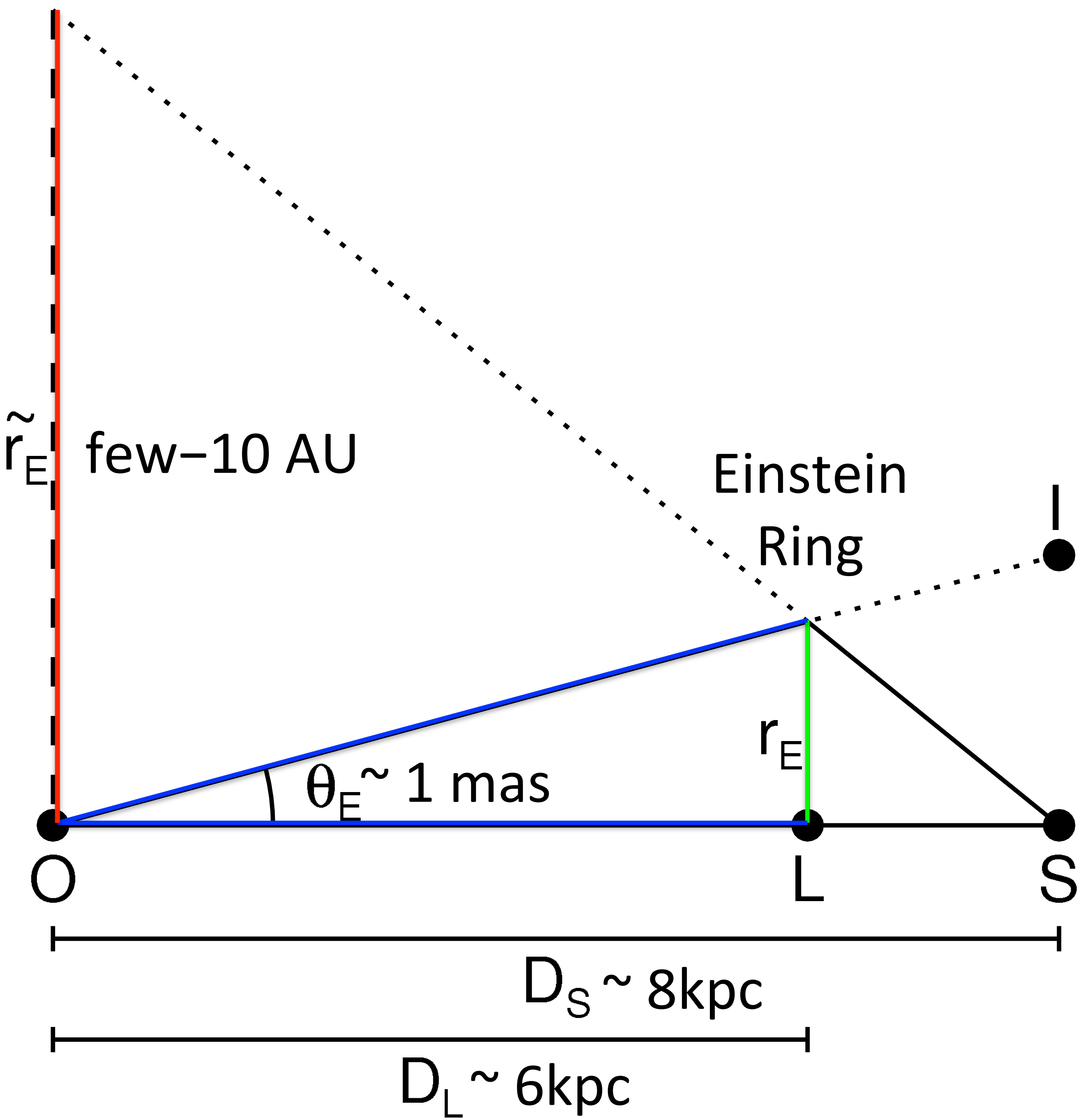
$\tilde{r}_E$
I
Source
r_E
θ_E
O
L
S
D_S ~ 8kpc
D_L ~ 6kpc



$\tilde{r}_E$
Einstein Ring
I
r_E
θ_E
O
L
S
$D_S \sim 8kpc$
$D_L \sim 6kpc$

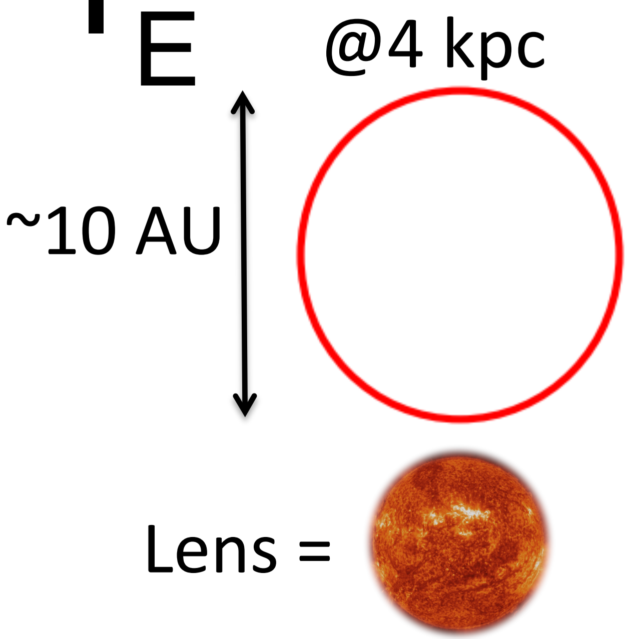


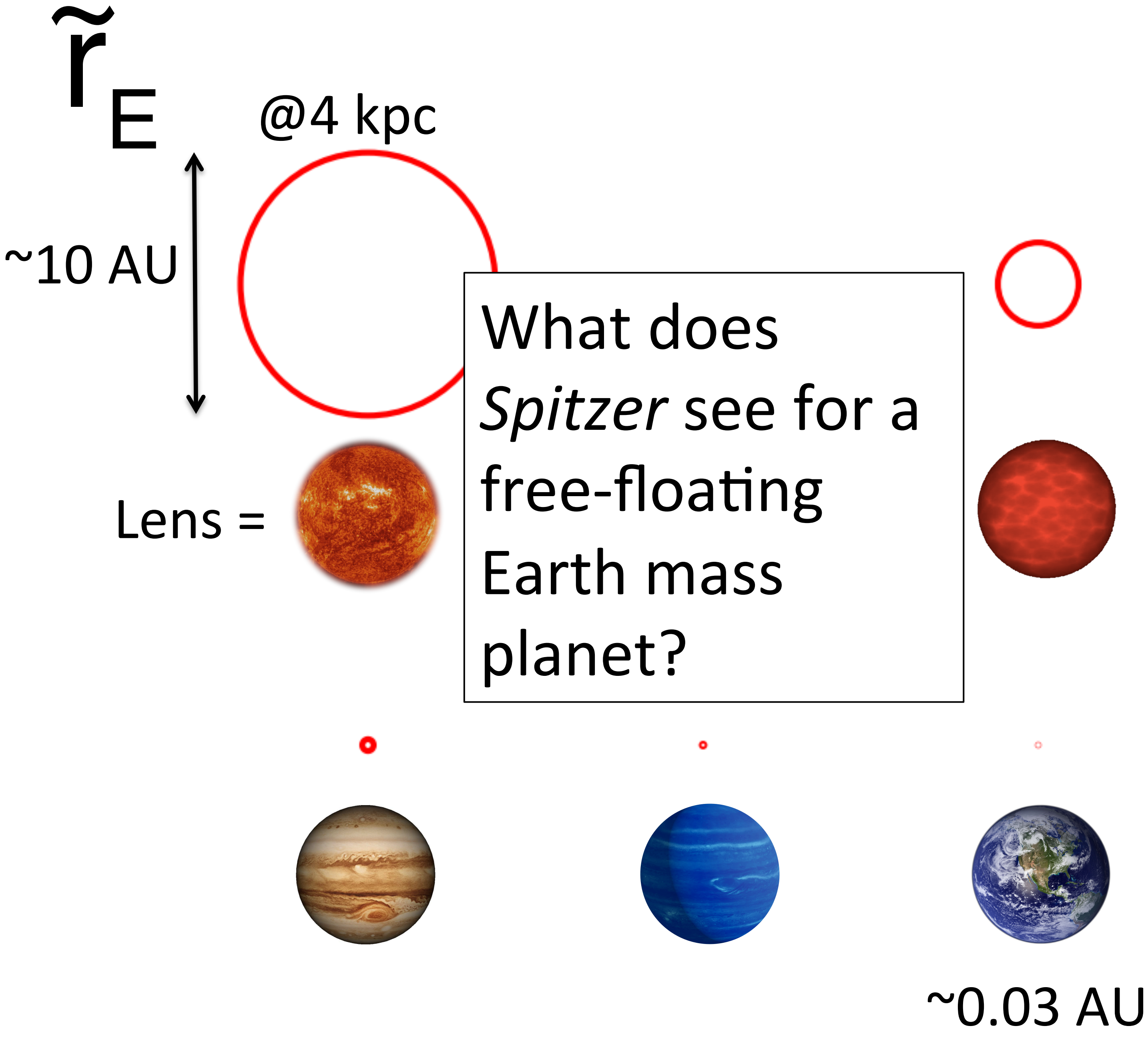
$\tilde{r}_E$
Einstein
Ring
I
r_E
θ_E~ 1 mas
O
L
S
D_S ~ 8kpc
D_L ~ 6kpc

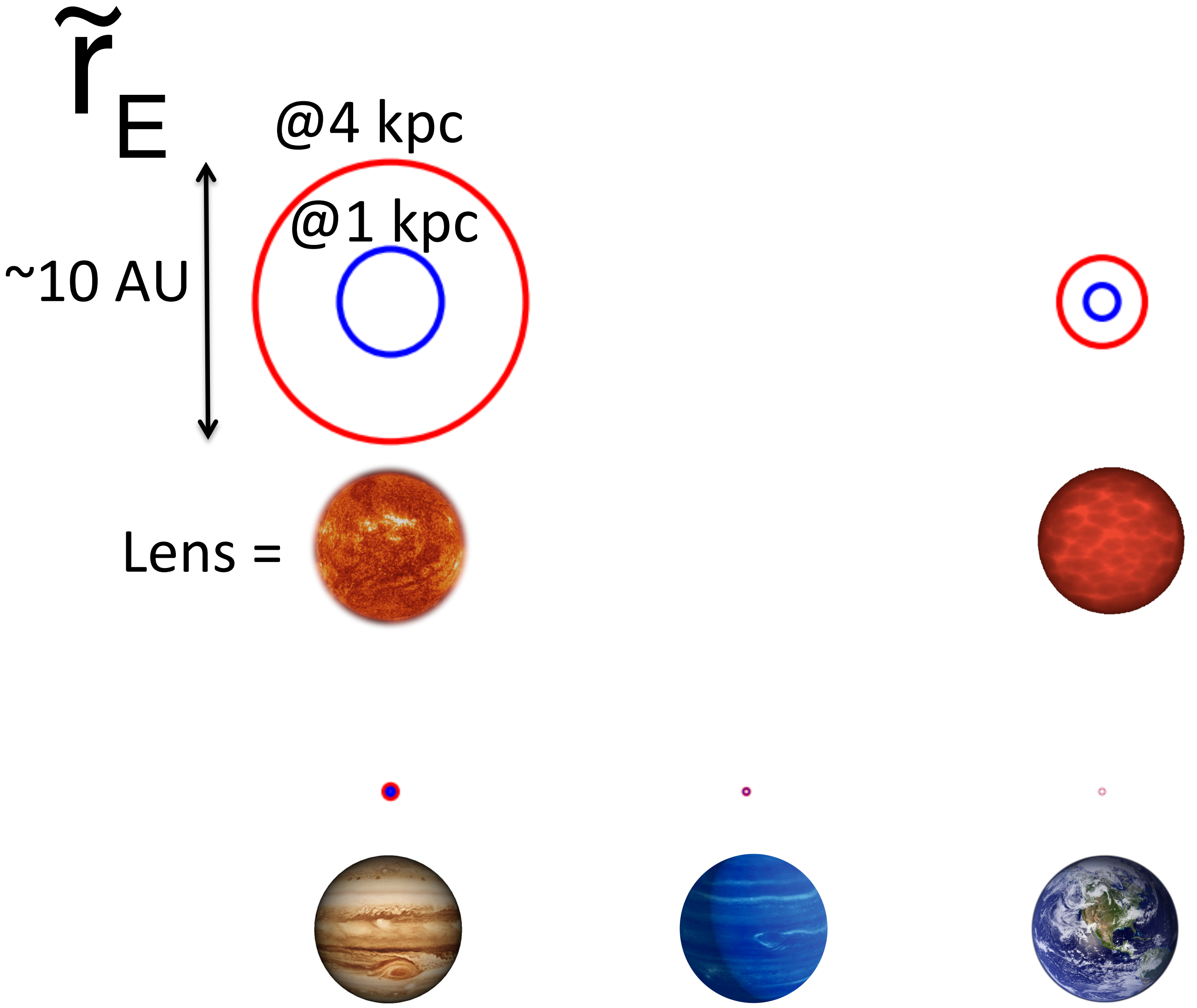


$\tilde{r}_E$ few–10 AU
Einstein Ring
I
r_E
θ_E ~ 1 mas
O
L
S
D_S ~ 8kpc
D_L ~ 6kpc

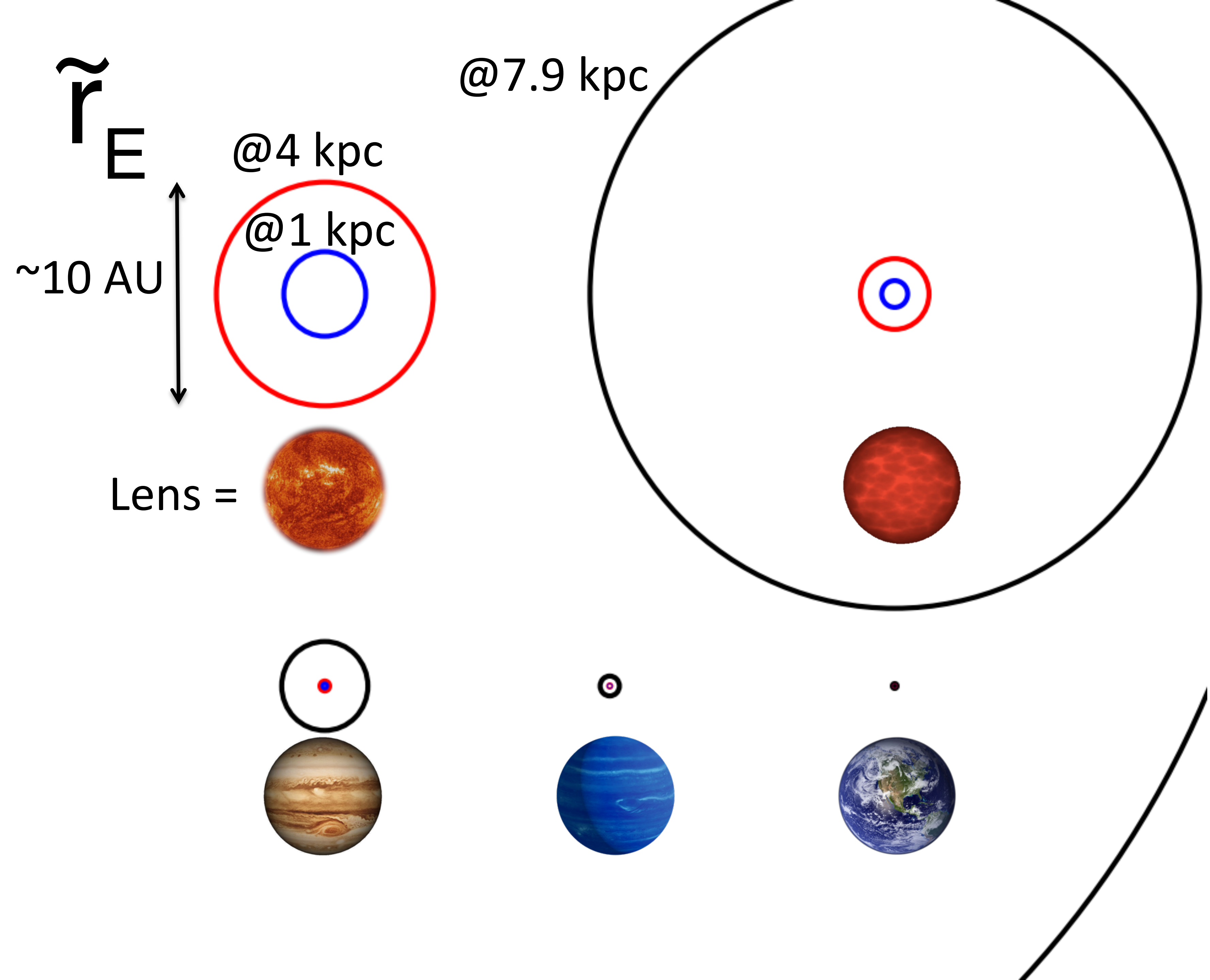
$\tilde{r}_E$



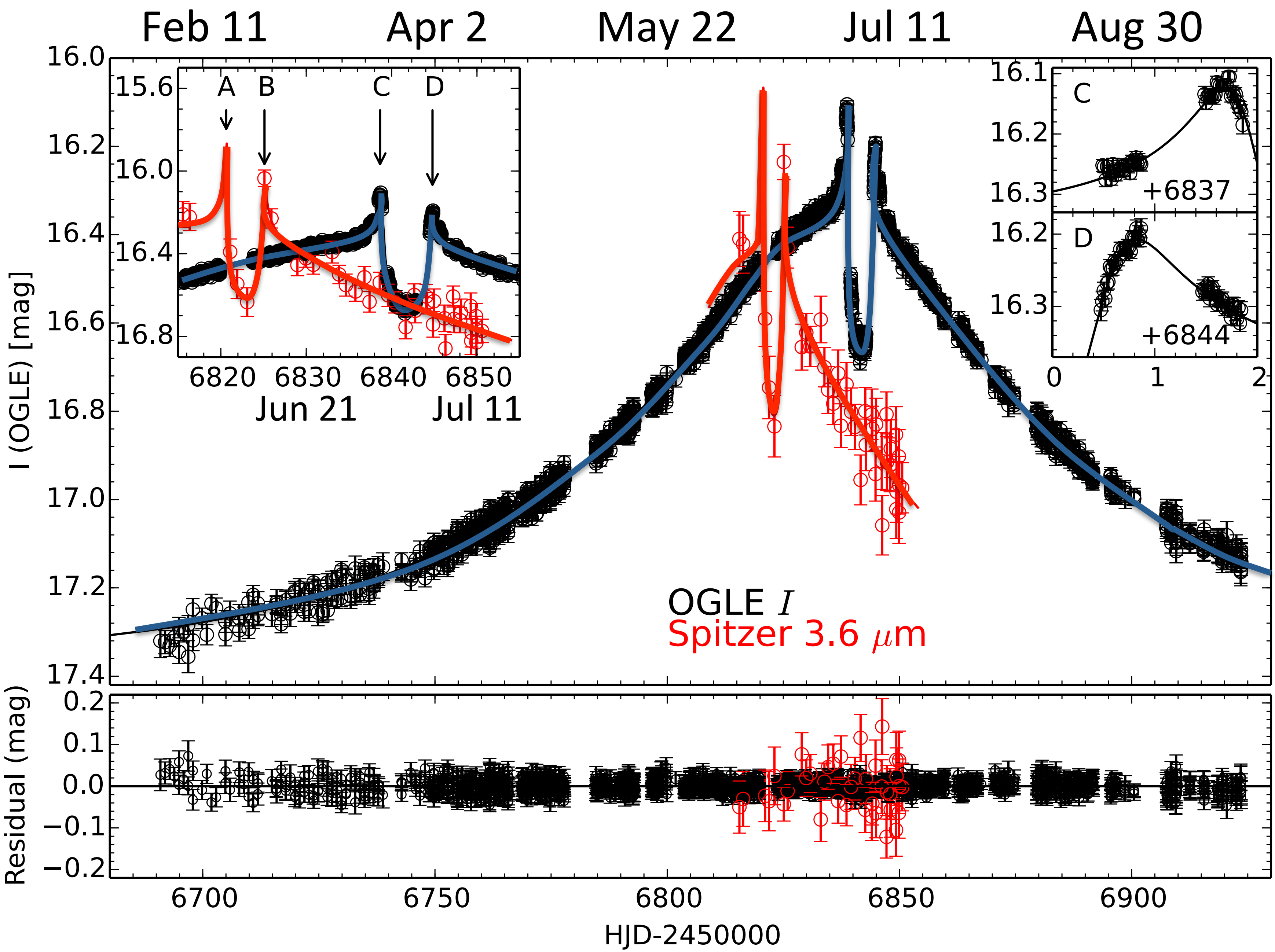

$\tilde{r}_E$
@4 kpc
~10 AU
Lens =
What does *Spitzer* see for a free-floating Earth mass planet?
~0.03 AU



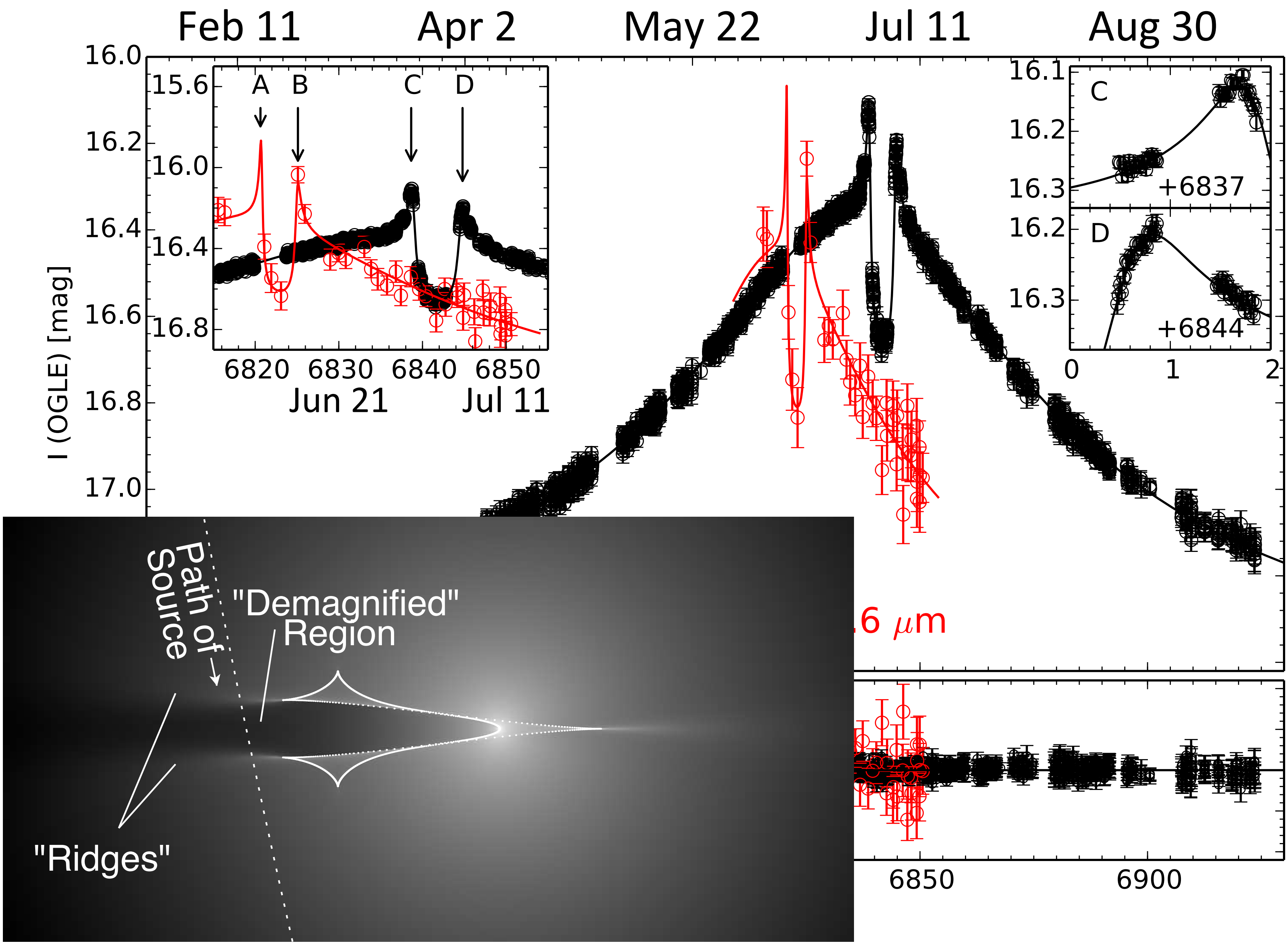
$\tilde{r}_E$
@4 kpc
@1 kpc
~10 AU
Lens =



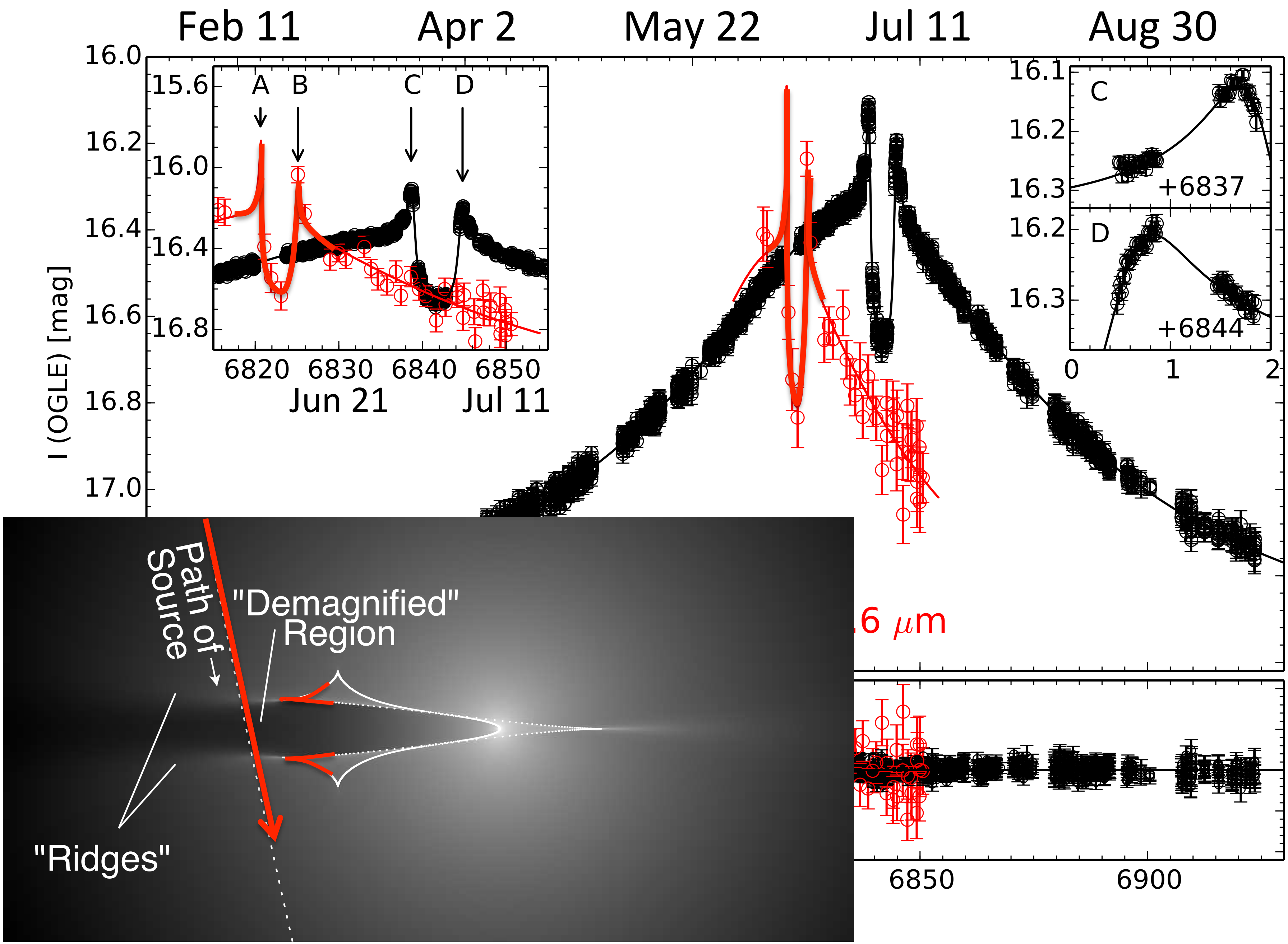
$\tilde{r}_E$
@7.9 kpc
@4 kpc
@1 kpc
~10 AU
Lens =



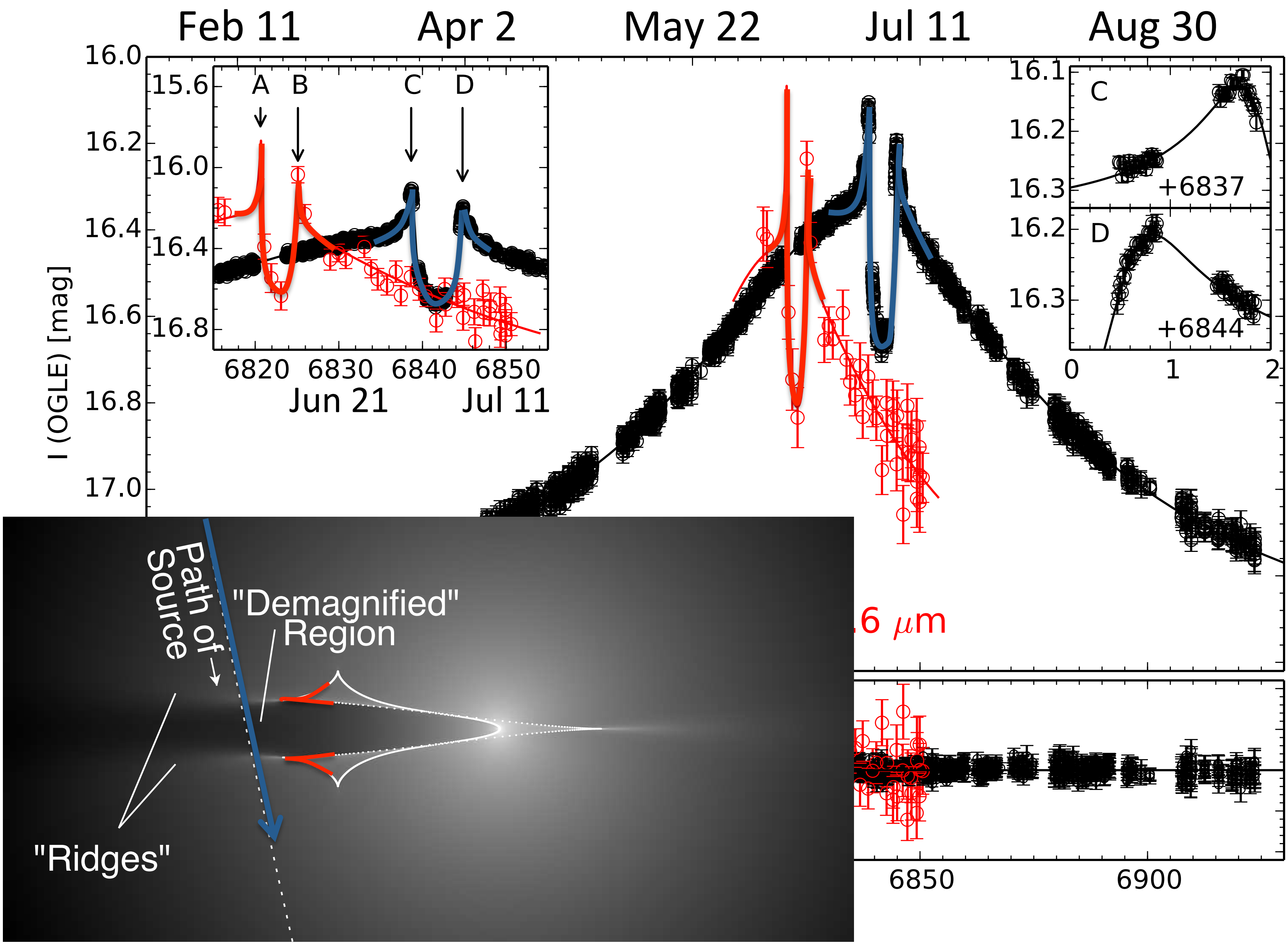
Udalski, Yee et al. 2015, ApJ, 799, 237



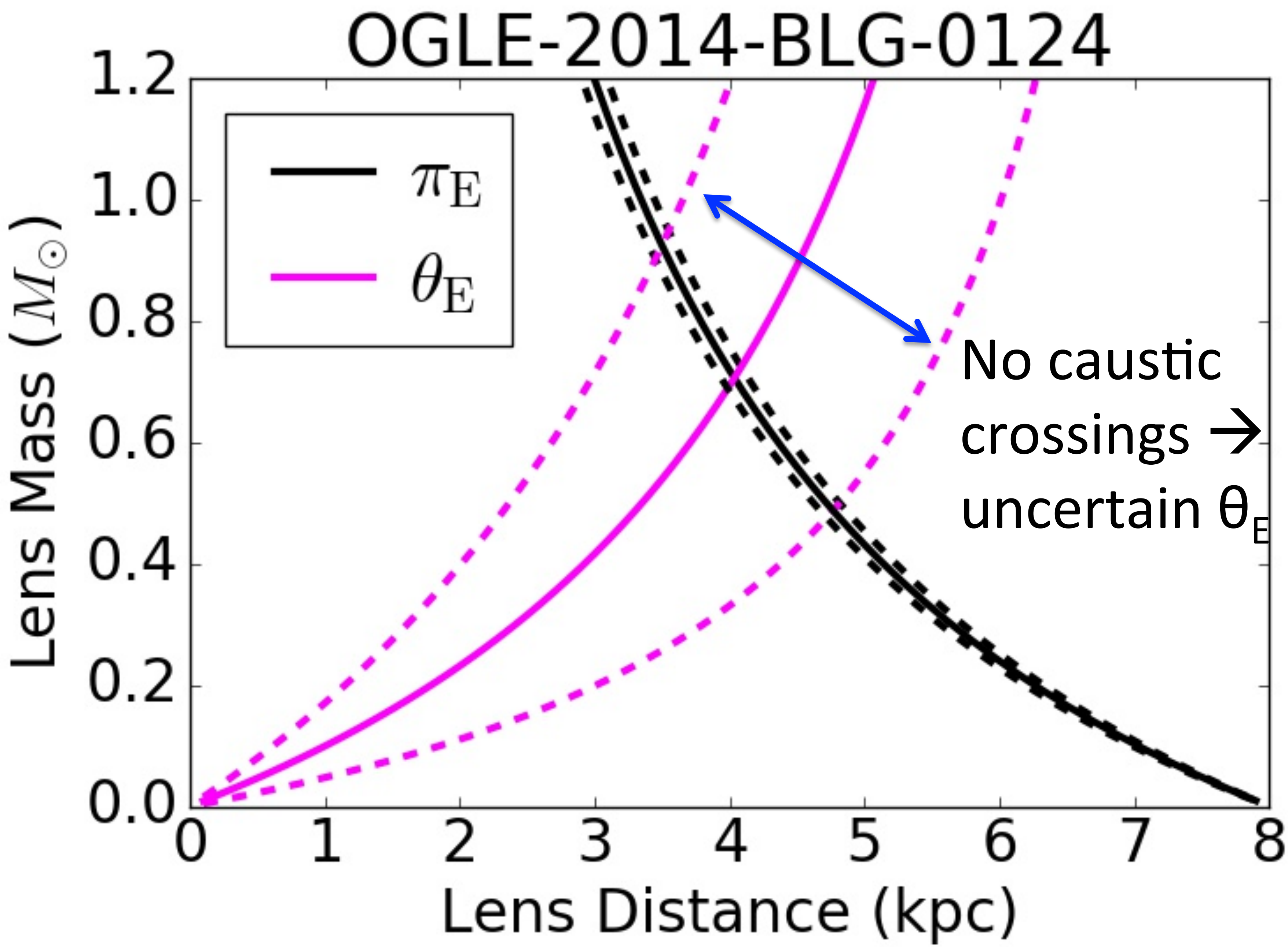
Udalski, Yee et al. 2015, ApJ, 799, 237

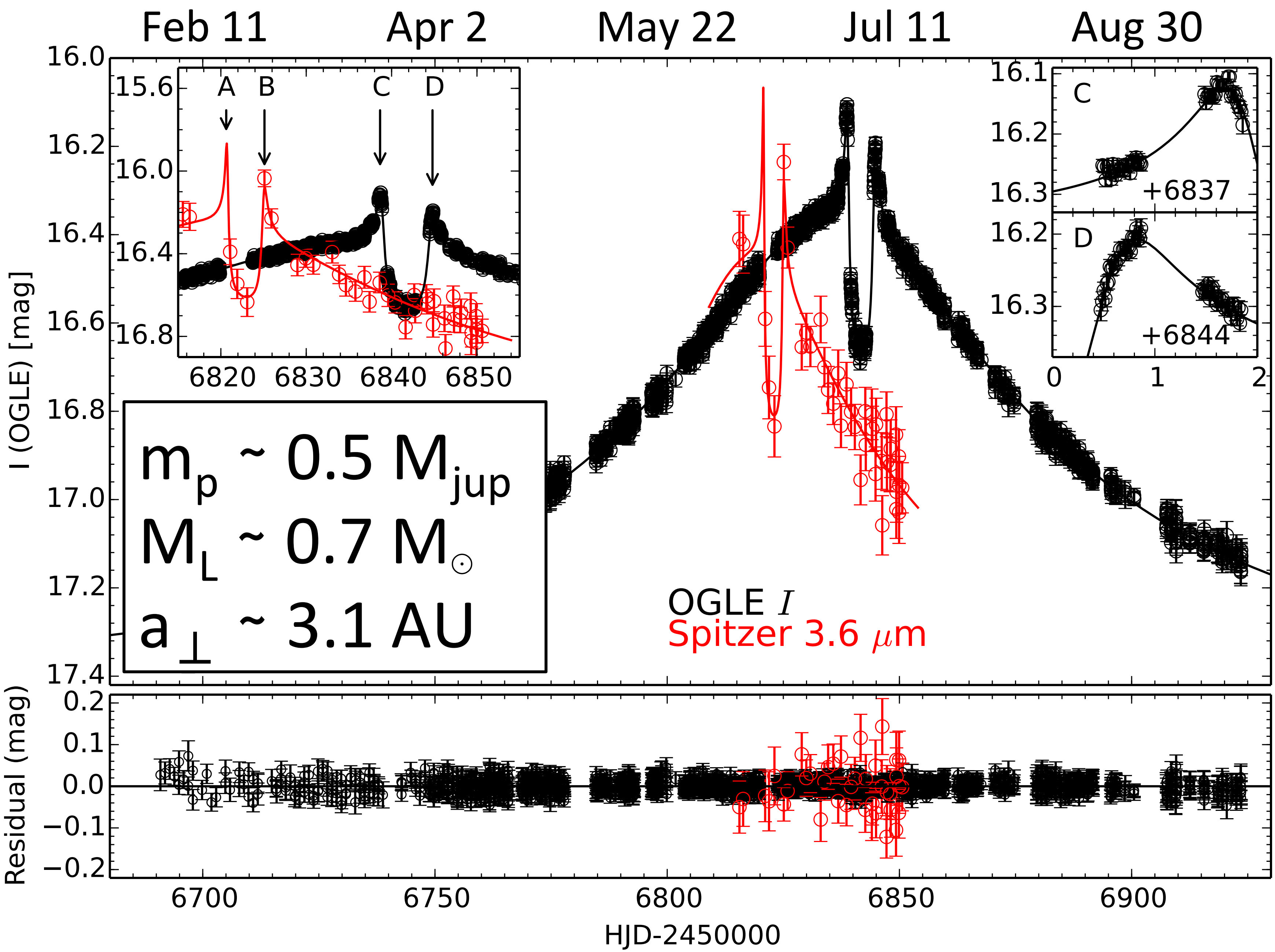


Udalski, Yee et al. 2015, ApJ, 799, 237



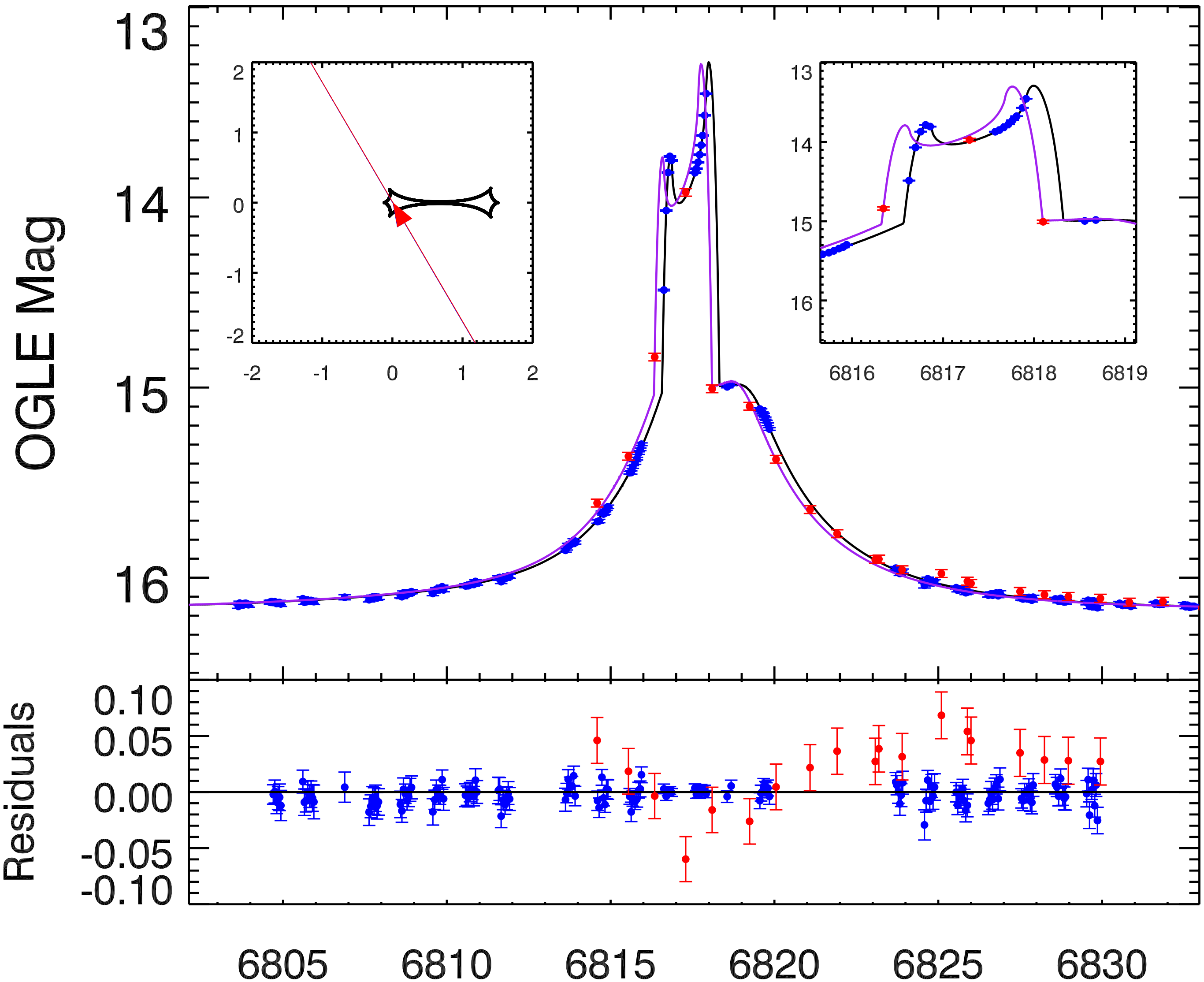
Udalski, Yee et al. 2015, ApJ, 799, 237


OGLE-2014-BLG-0124
Lens Mass ($M_\odot$)
Lens Distance (kpc)
π_E
θ_E
No caustic crossings → uncertain θ_E
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8



Udalski, Yee et al. 2015, ApJ, 799, 237

Yutong Shan's Poster: binary w/*Spitzer* parallax



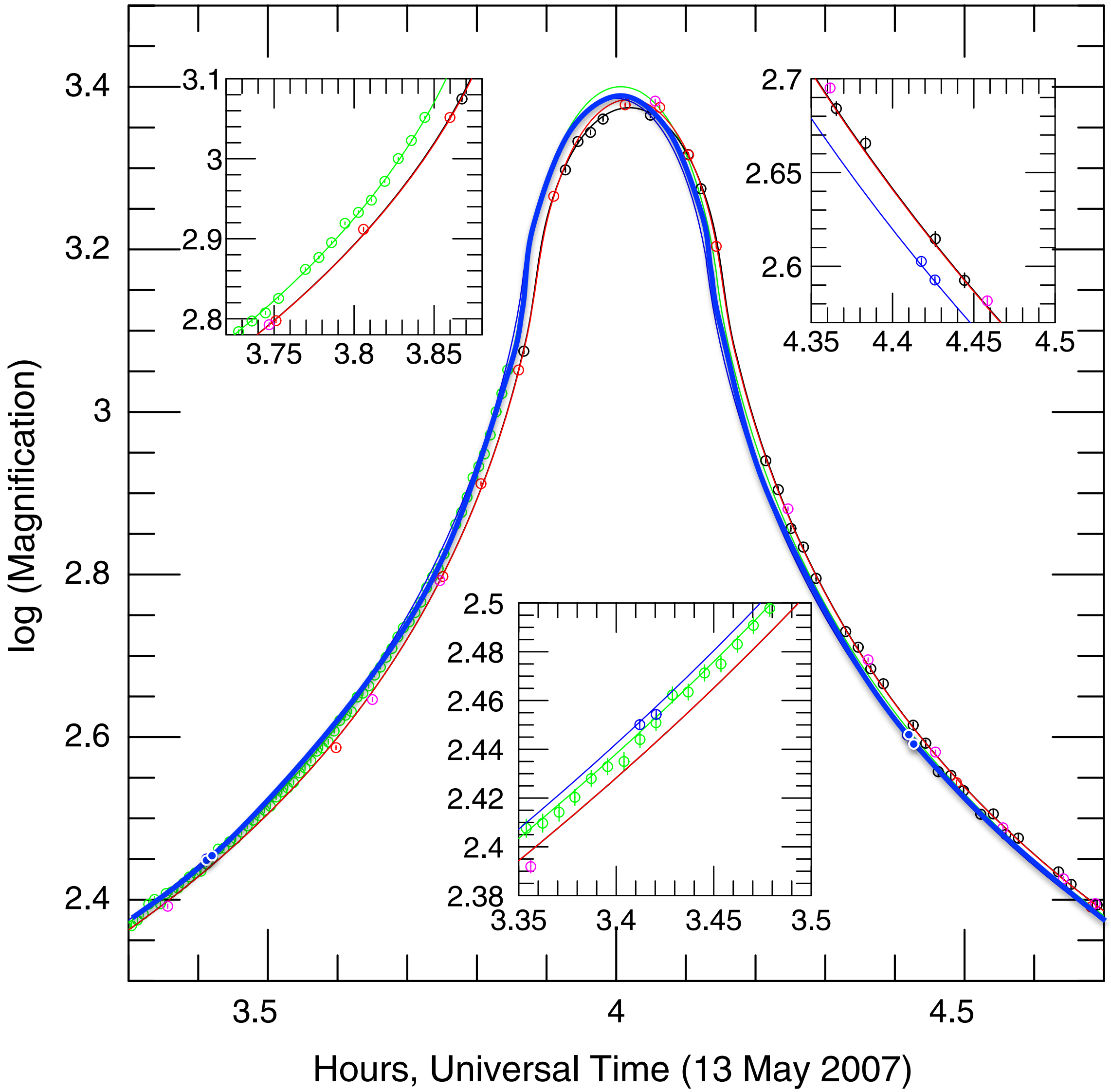
Satellite parallax programs have 2 goals

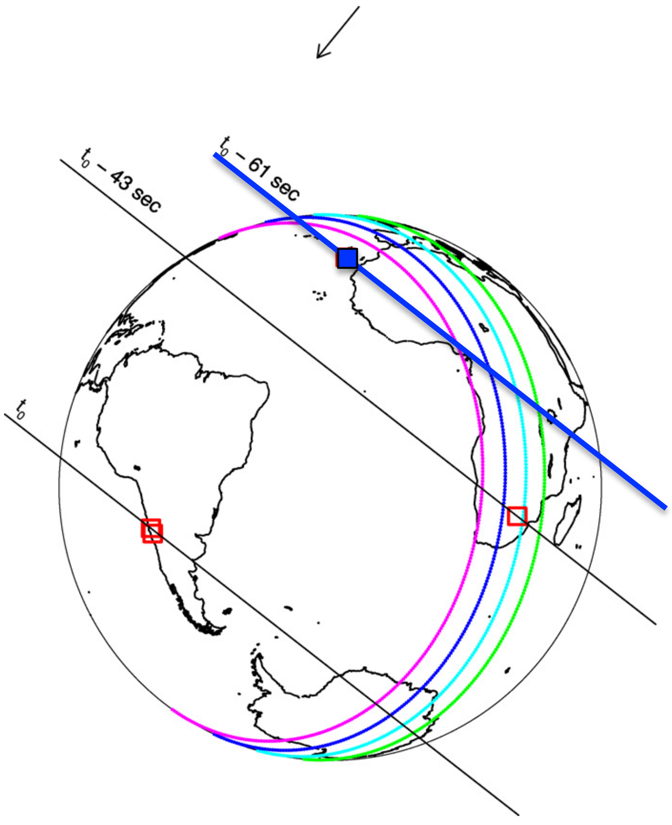
1. Measure the masses of planets (and other interesting objects)
2. Measure the distribution of planets throughout the galaxy.

Satellite parallax is easier to measure than annual parallax because the scales are better matched.

	Observational Scale	**Relevant Einstein Scale**
Satellite Parallax	1 AU	10 AU
Annual Parallax	365 days	30 days

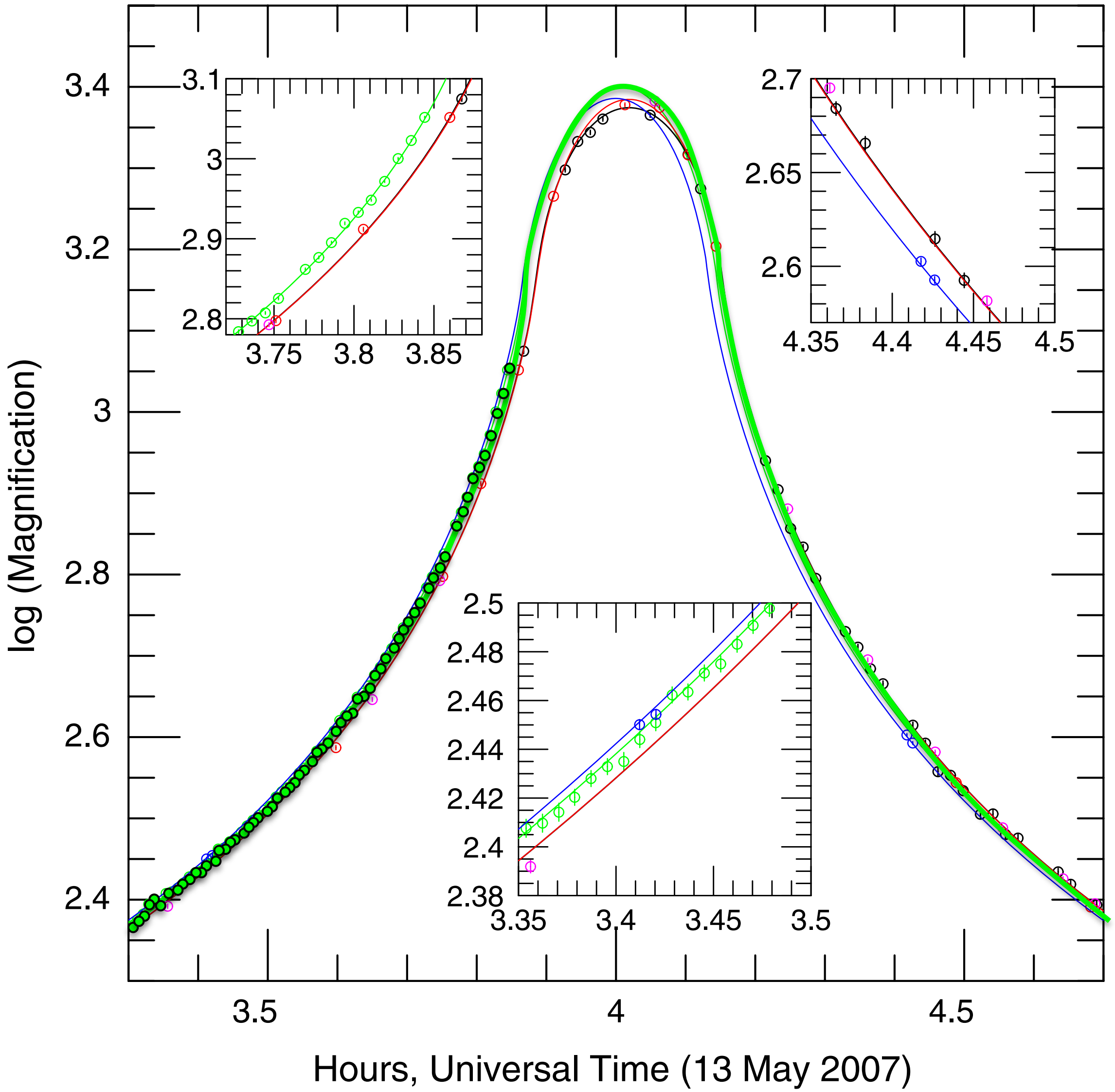
Terrestrial Parallax

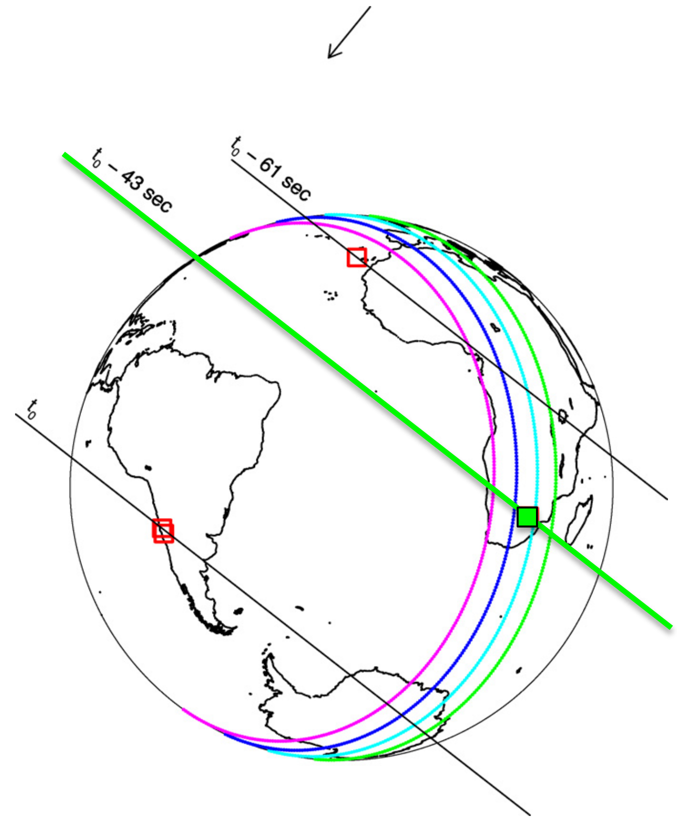




Gould et al 2009, ApJL, 698, 147

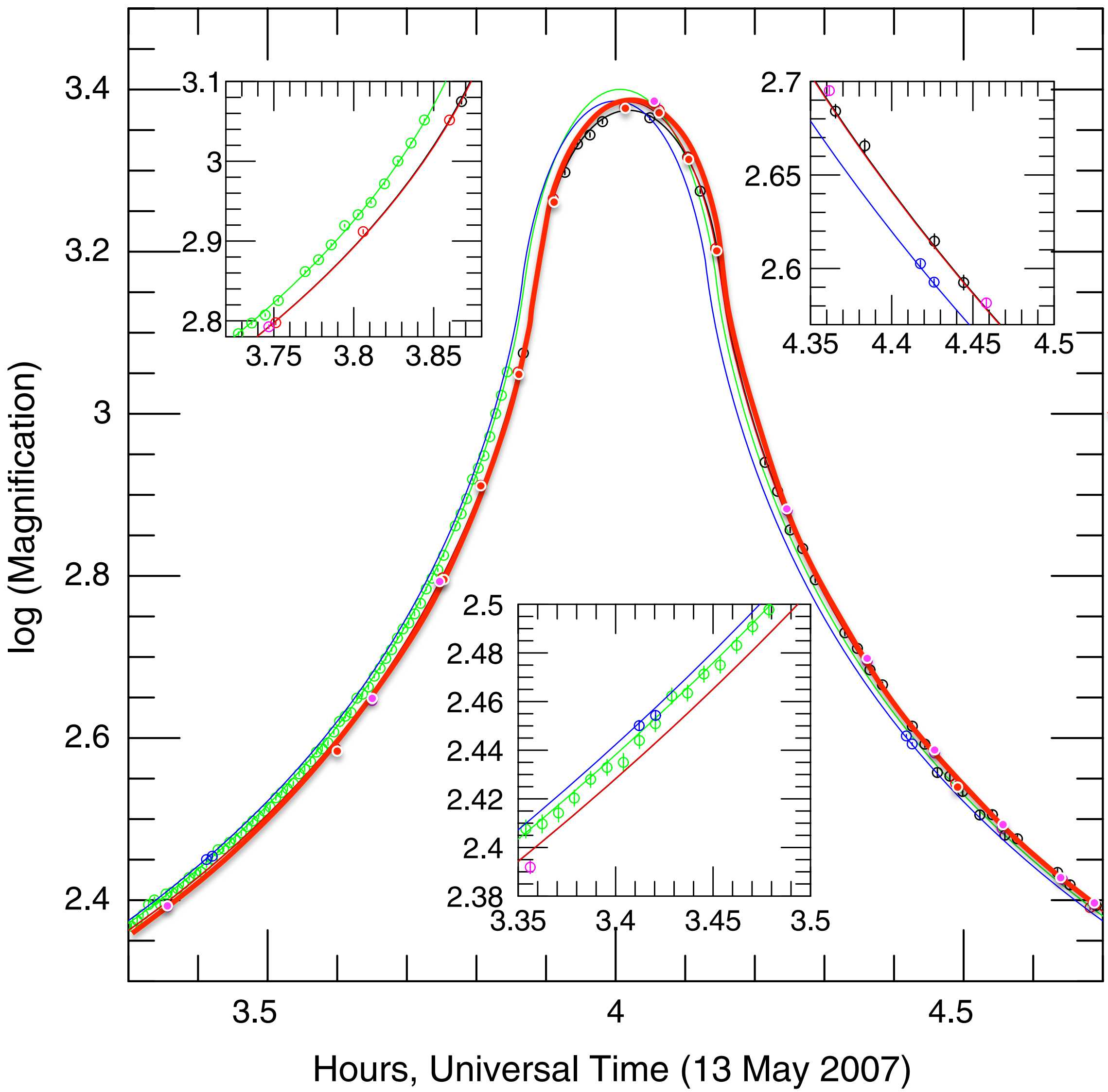
Terrestrial Parallax

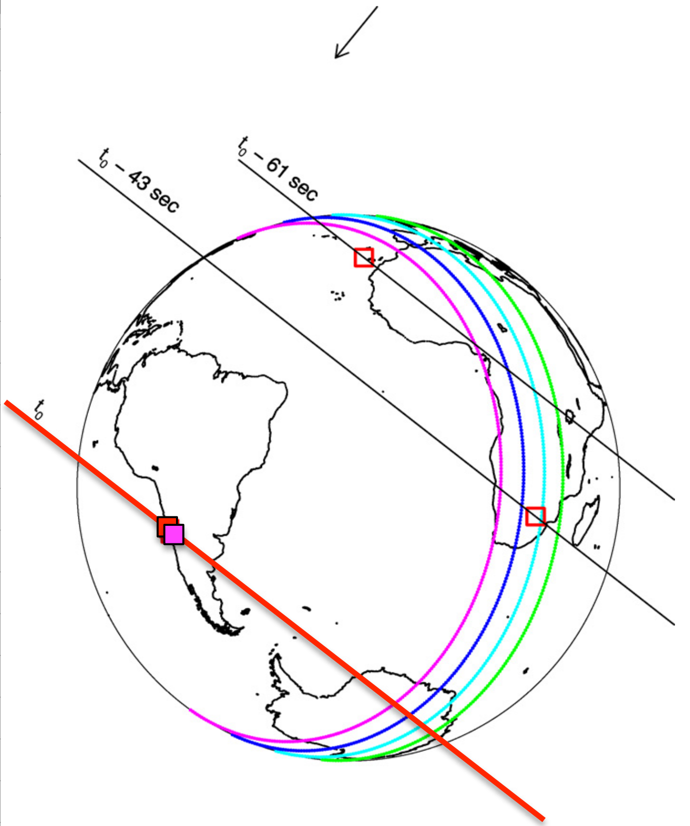




Gould et al 2009, ApJL, 698, 147

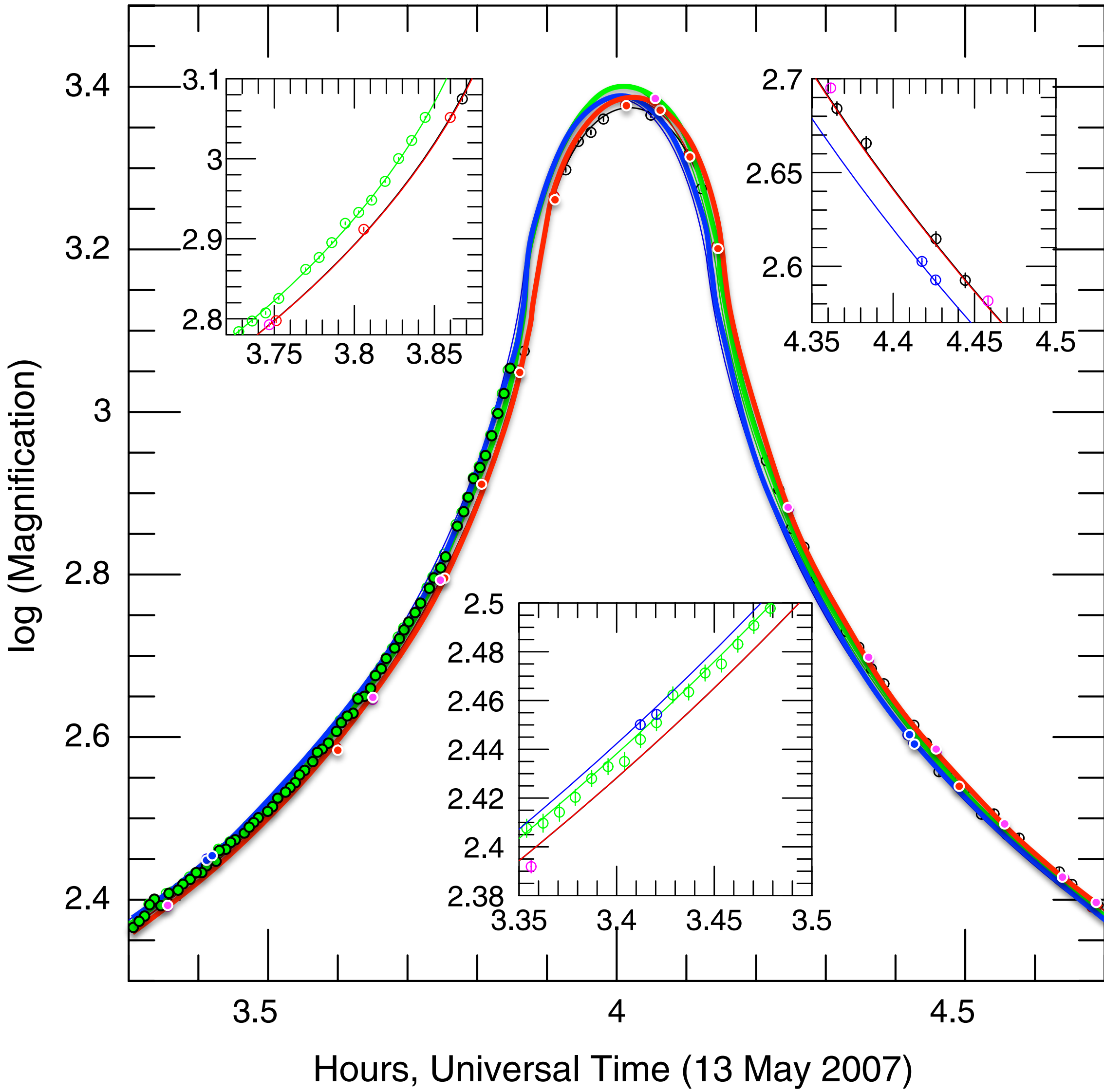
Terrestrial Parallax

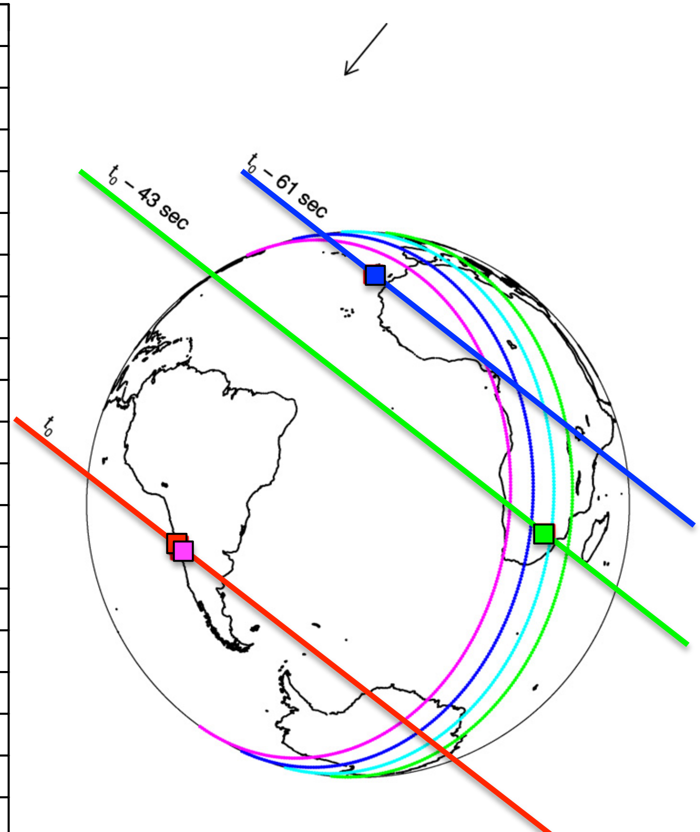




Gould et al 2009, ApJL, 698, 147

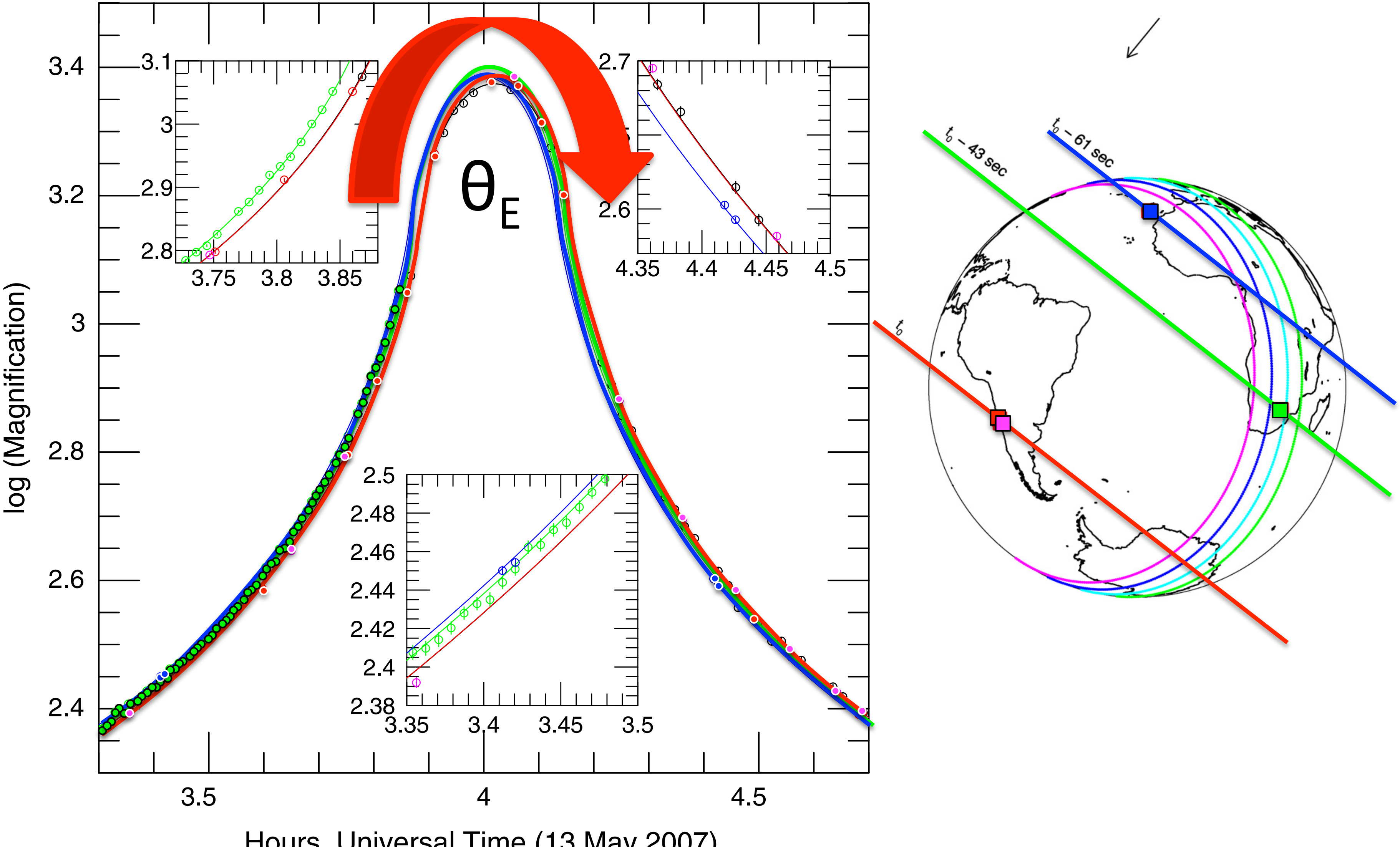
Terrestrial Parallax



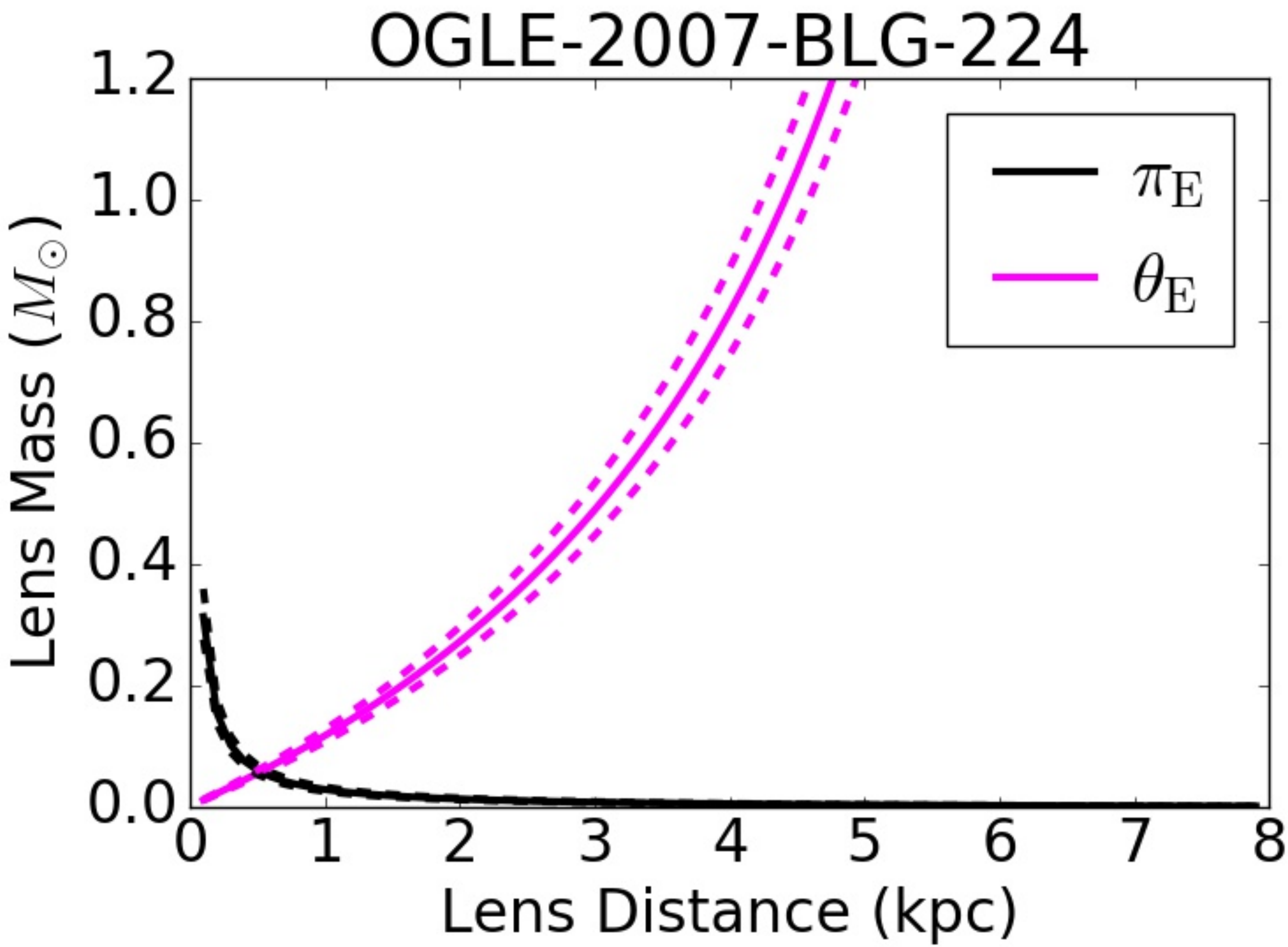


Gould et al 2009, ApJL, 698, 147

Terrestrial Parallax



Gould et al 2009, ApJL, 698, 147



OGLE-2007-BLG-224
Lens Mass ($M_\odot$)
Lens Distance (kpc)
$\pi_{\rm E}$
$\theta_{\rm E}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
1
2
3
4
5
6
7
8

Parallax & WFIRST

WFIRST will be at L2

→ Annual Parallax Effect (but with better photometric precision)

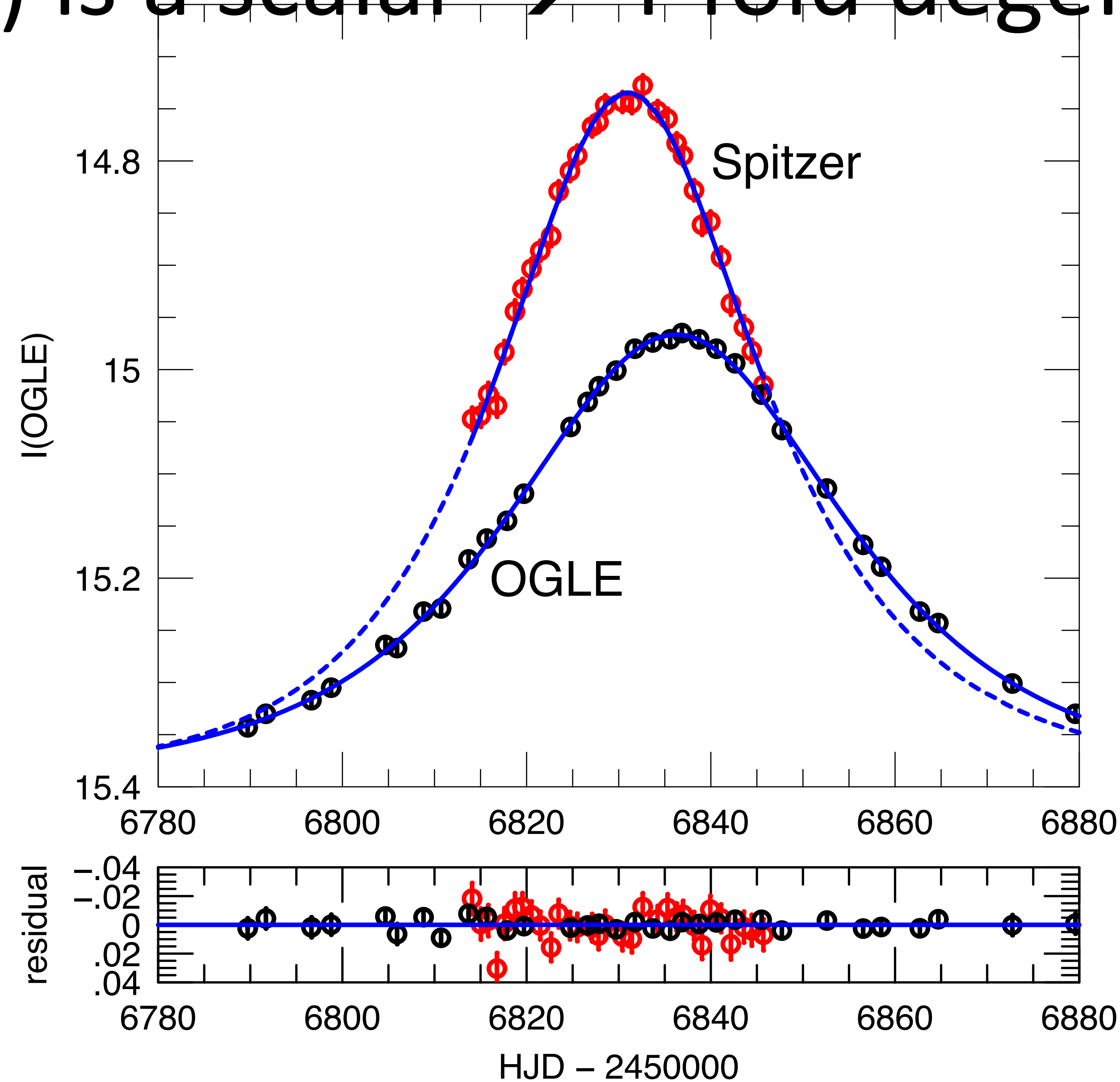
→ Possibility to measure Earth-L2 parallax (separation 0.01AU)

WFIRST will observe in Spring and Fall

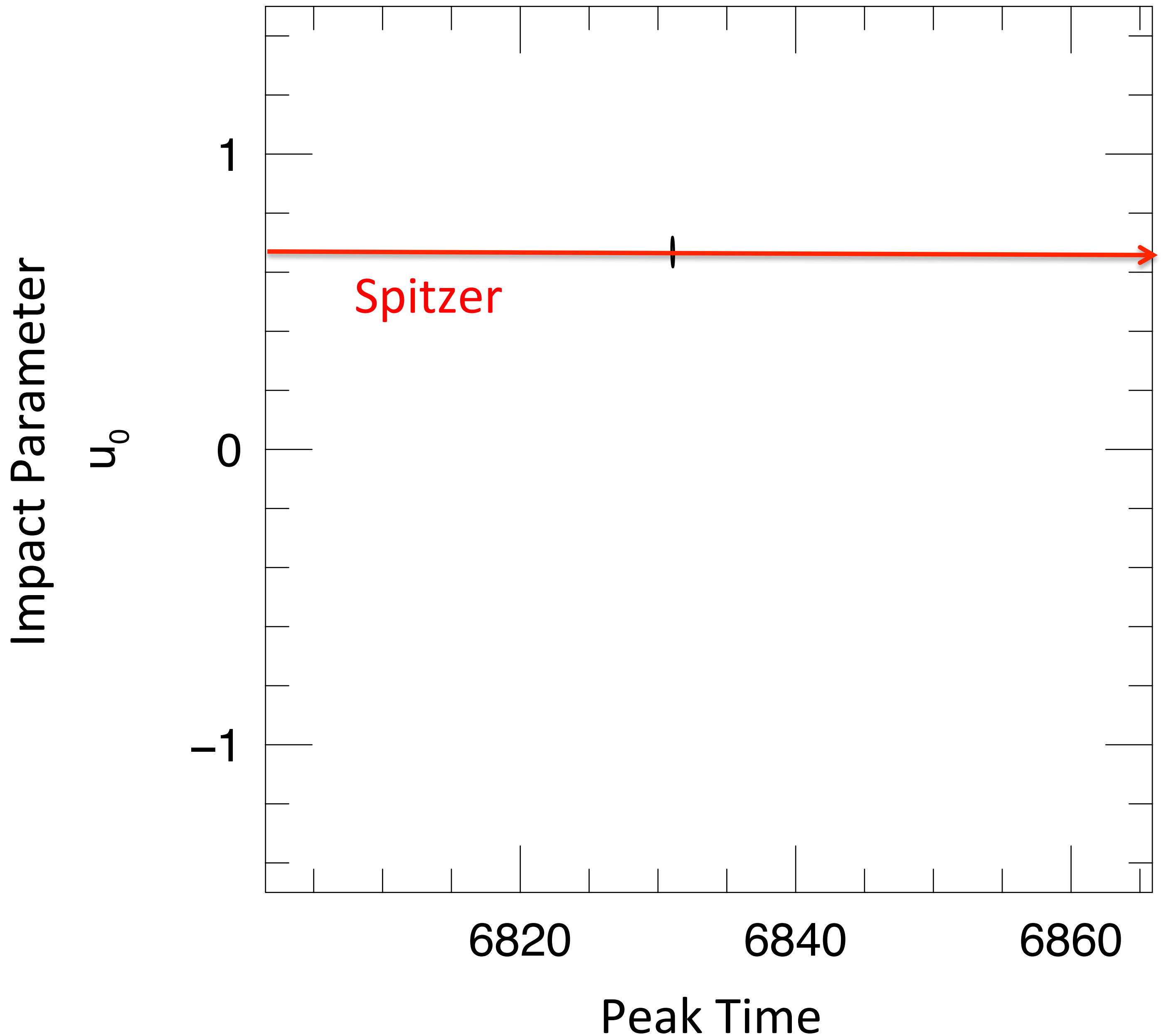
→ Better for annual parallax

4-fold degeneracy

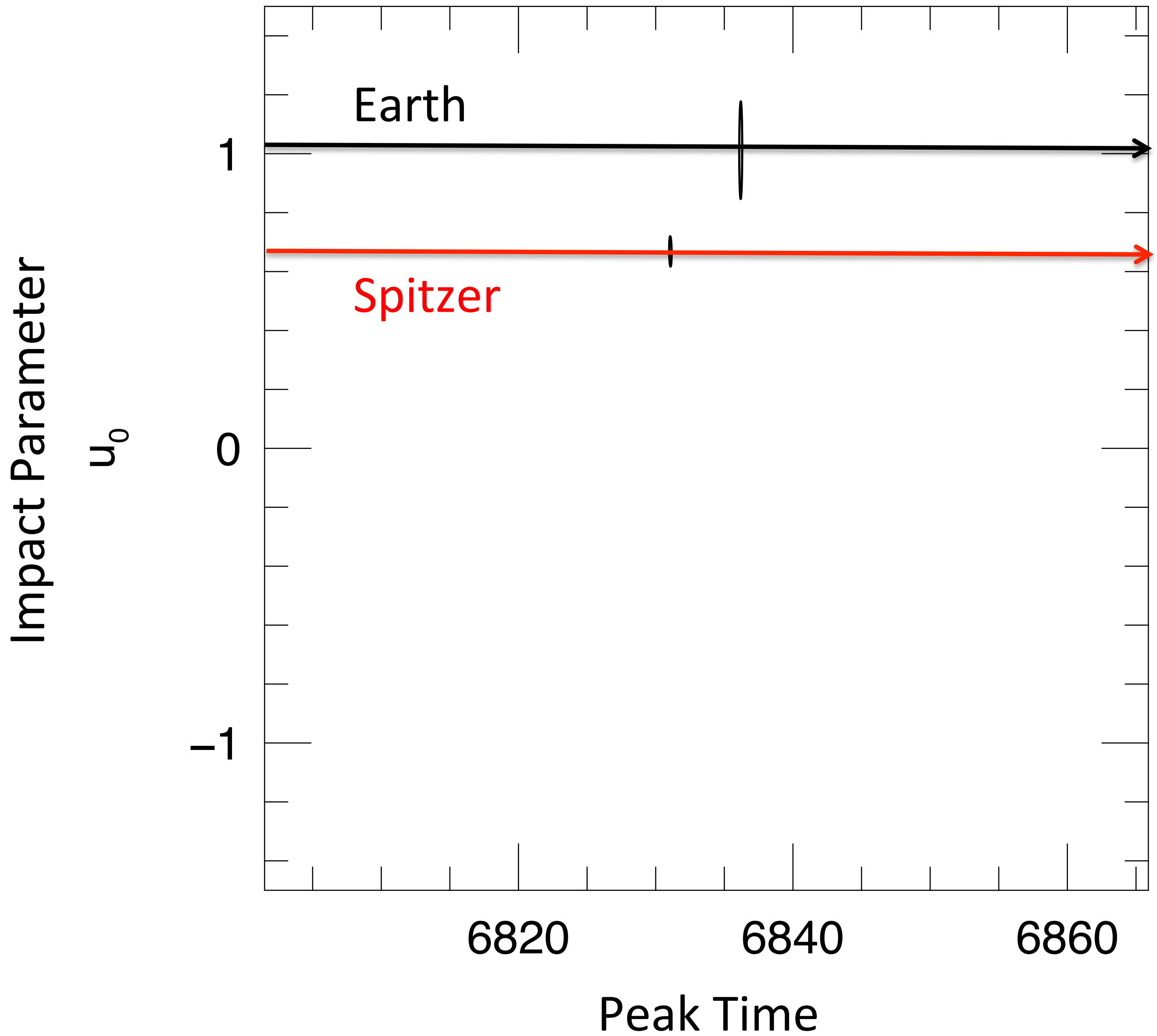
u(t) is a scalar → 4-fold degeneracy



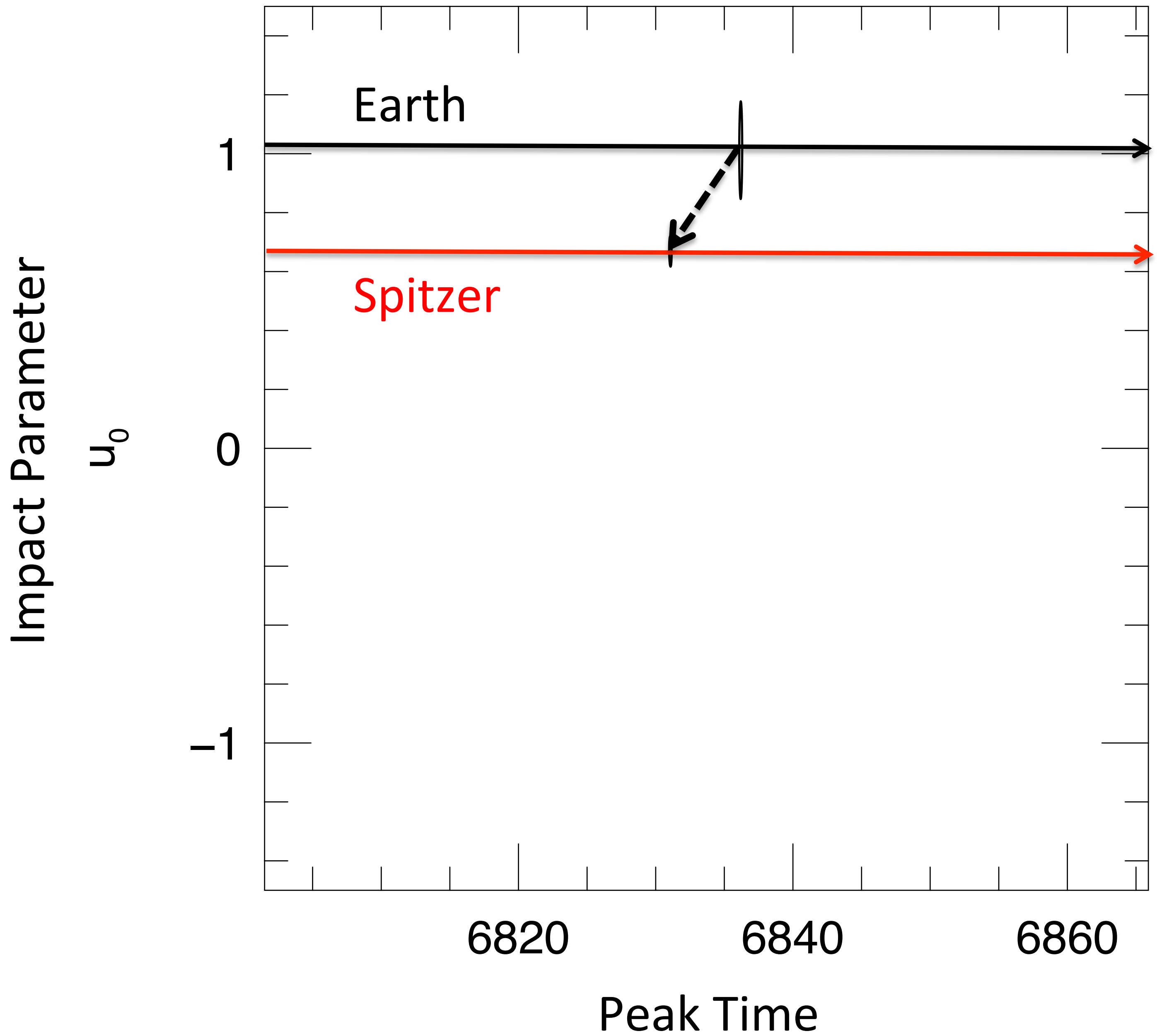
Yee et al. 2015, ApJ, 802, 76



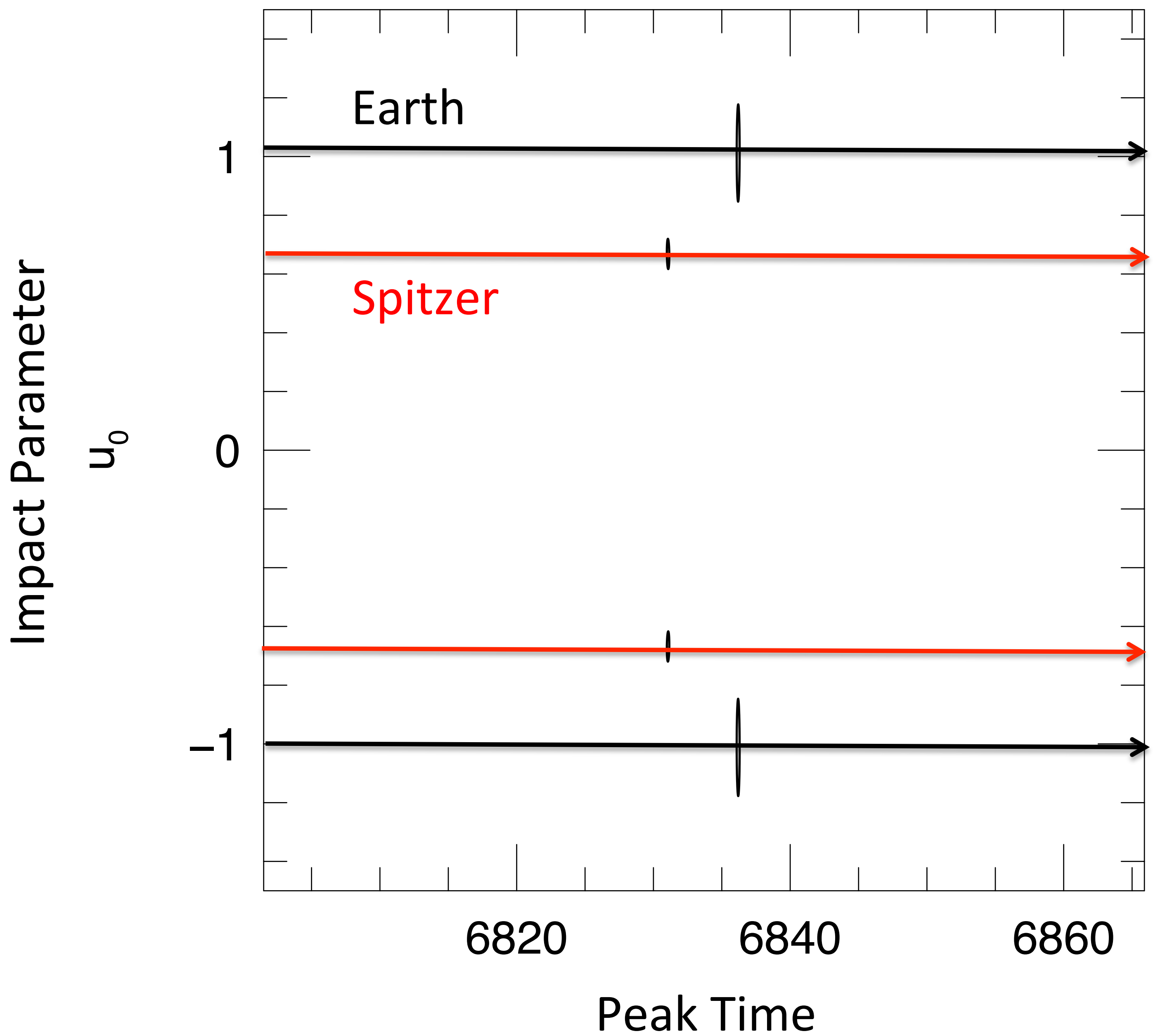
Yee et al. 2015, ApJ, 802, 76



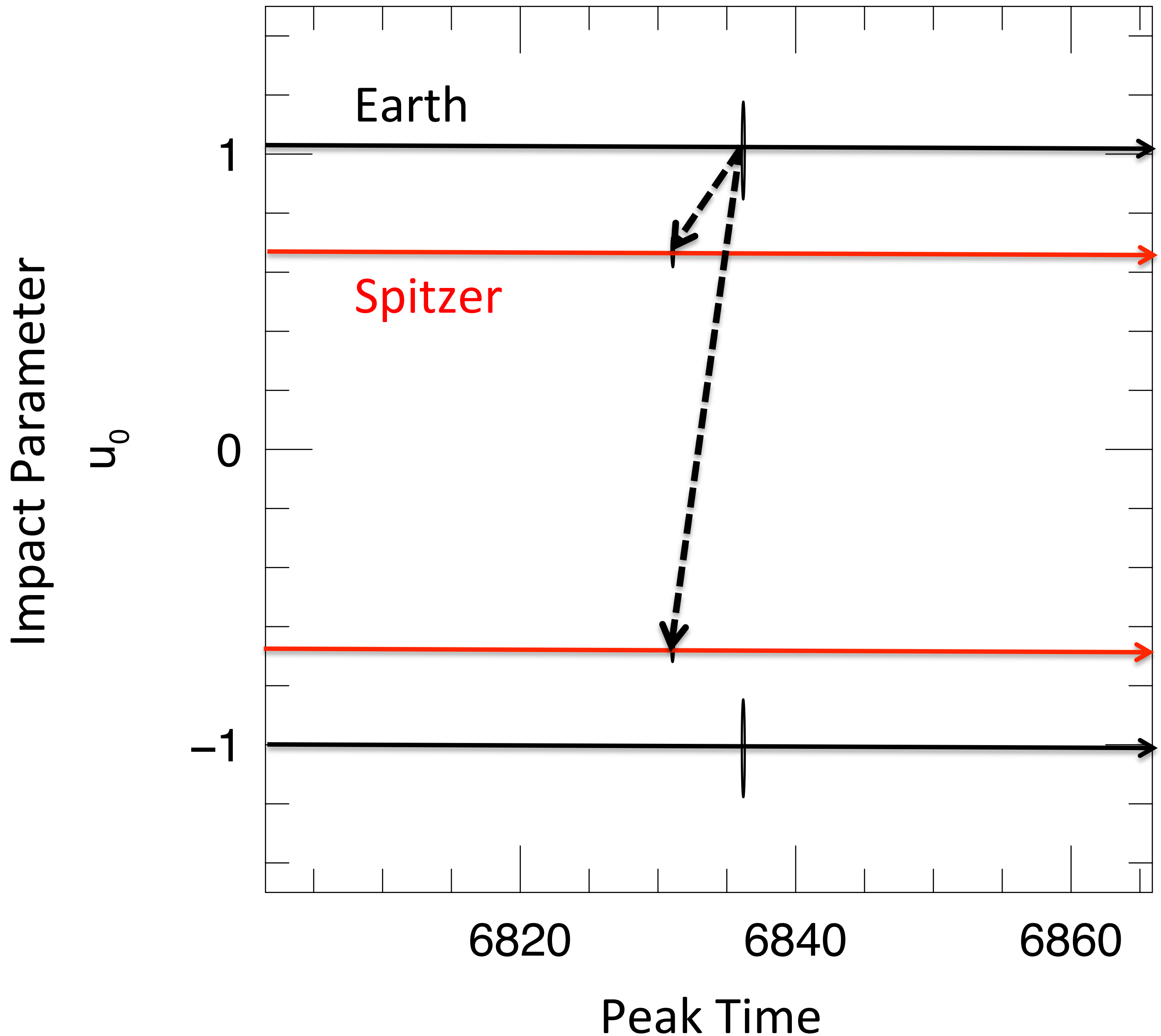
Yee et al. 2015, ApJ, 802, 76



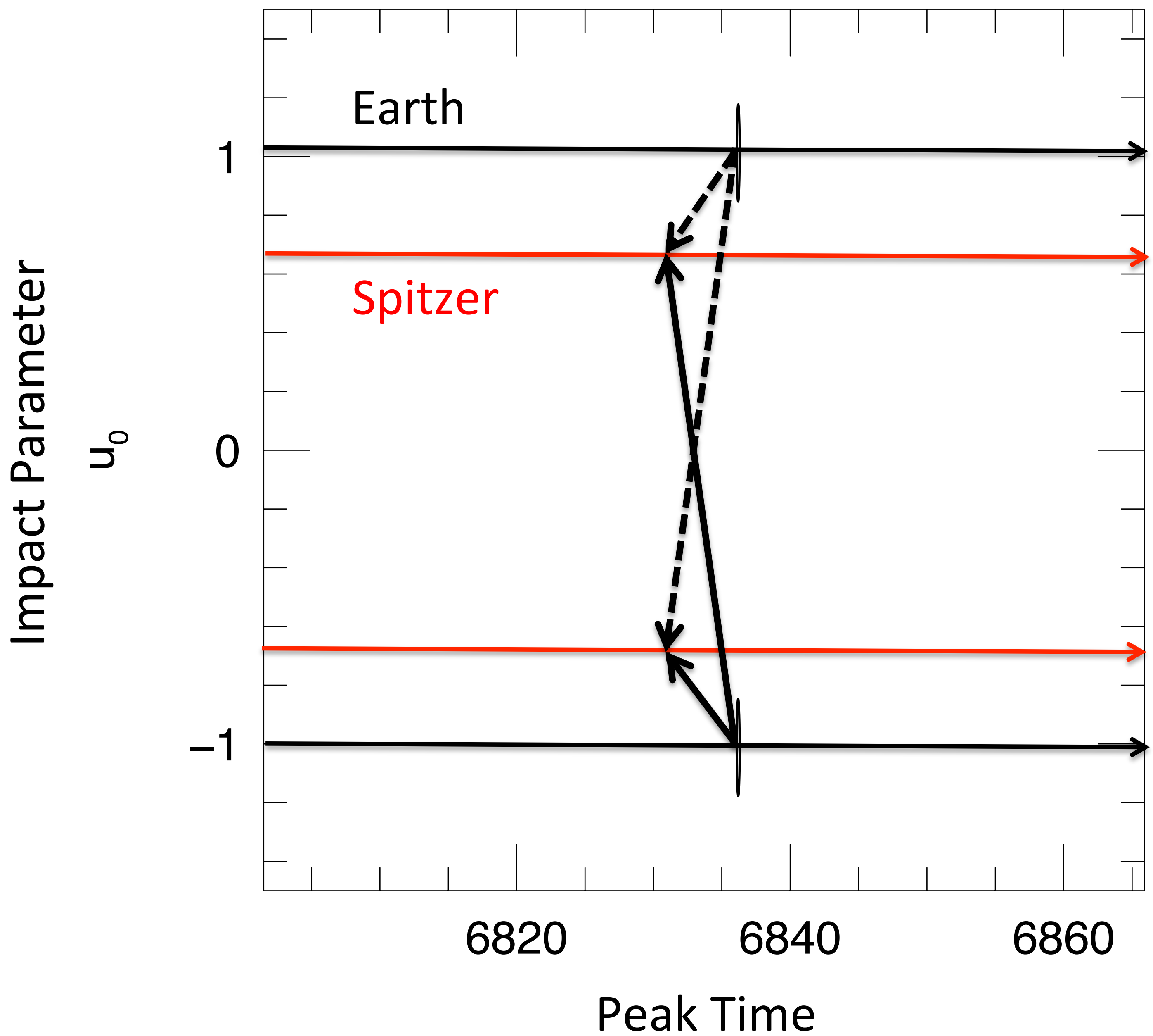
Yee et al. 2015, ApJ, 802, 76



Yee et al. 2015, ApJ, 802, 76



Yee et al. 2015, ApJ, 802, 76



Yee et al. 2015, ApJ, 802, 76

3 Types of Parallax due to 2 Effects

- Motion of the observer

  → **Orbital/Annual** Parallax
- Separation between 2 observers

  → **Satellite** parallax

  → **Terrestrial** parallax