Exoplanetary Microlensing science with WFIRST

Part II

Yossi Shvartzvald & Calen Henderson
NPP Fellows @ JPL
Sebastiano Calchi Novati

photo by Cyril Cavadore

WFIRST Microlensing Primer Series

I. Basic Introduction to the Methodology and Theory of Gravitational Microlensing Searches for Exoplanets

W, 21/Sept , Yossi Shvartzvald

II. Lens Companion Detection and Characterization

W, 28/Sept , Yossi Shvartzvald

III. Results from and Future Directions for **Ground**-based Microlensing Surveys

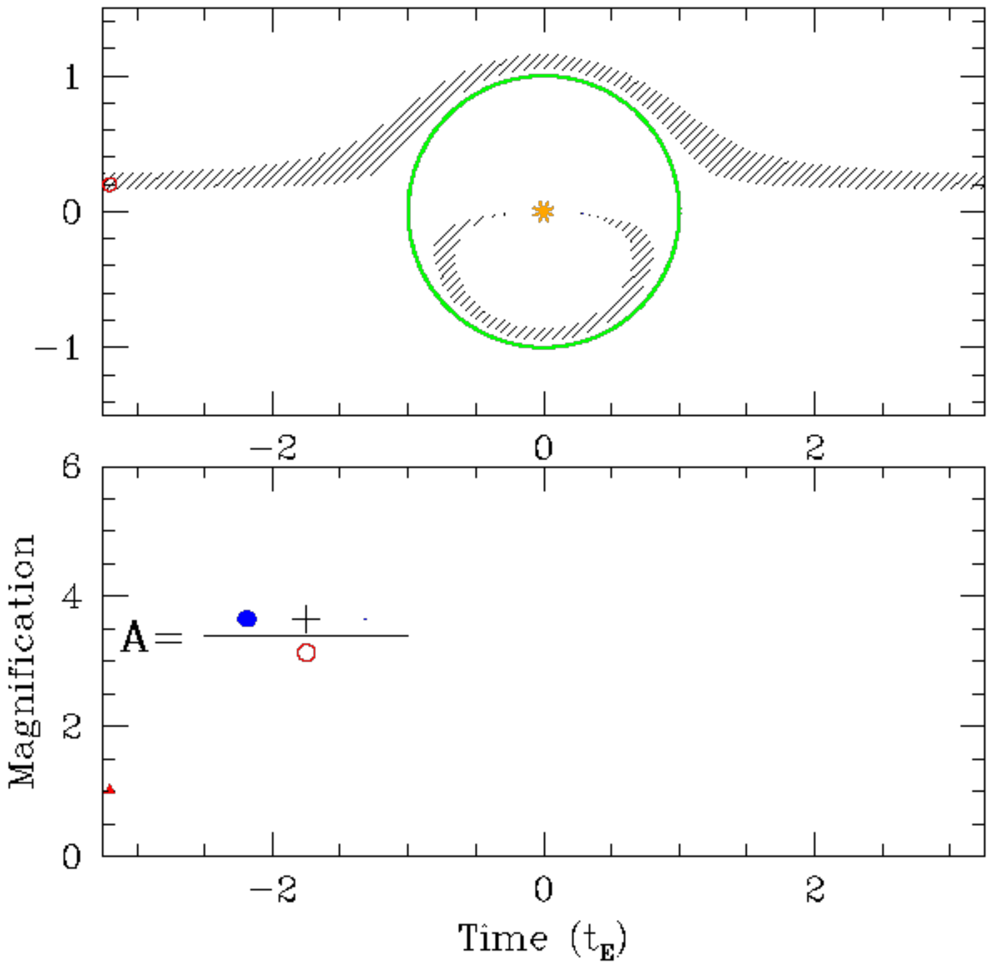
W, 12/Oct , Calen Henderson

IV. Results from and Future Directions for **Space**-based Microlensing Surveys (including *WFIRST*)

W, 02/Nov , Calen Henderson

Microlensing basics summary

Microlensing basics

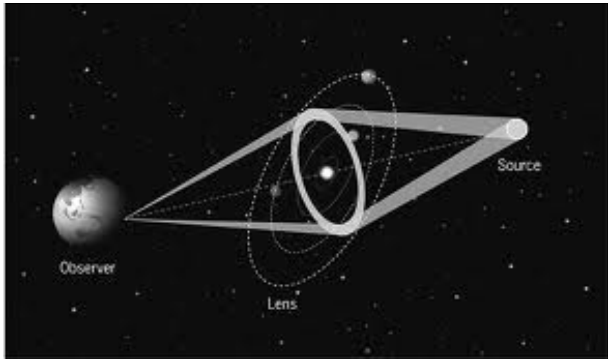


Event timescale

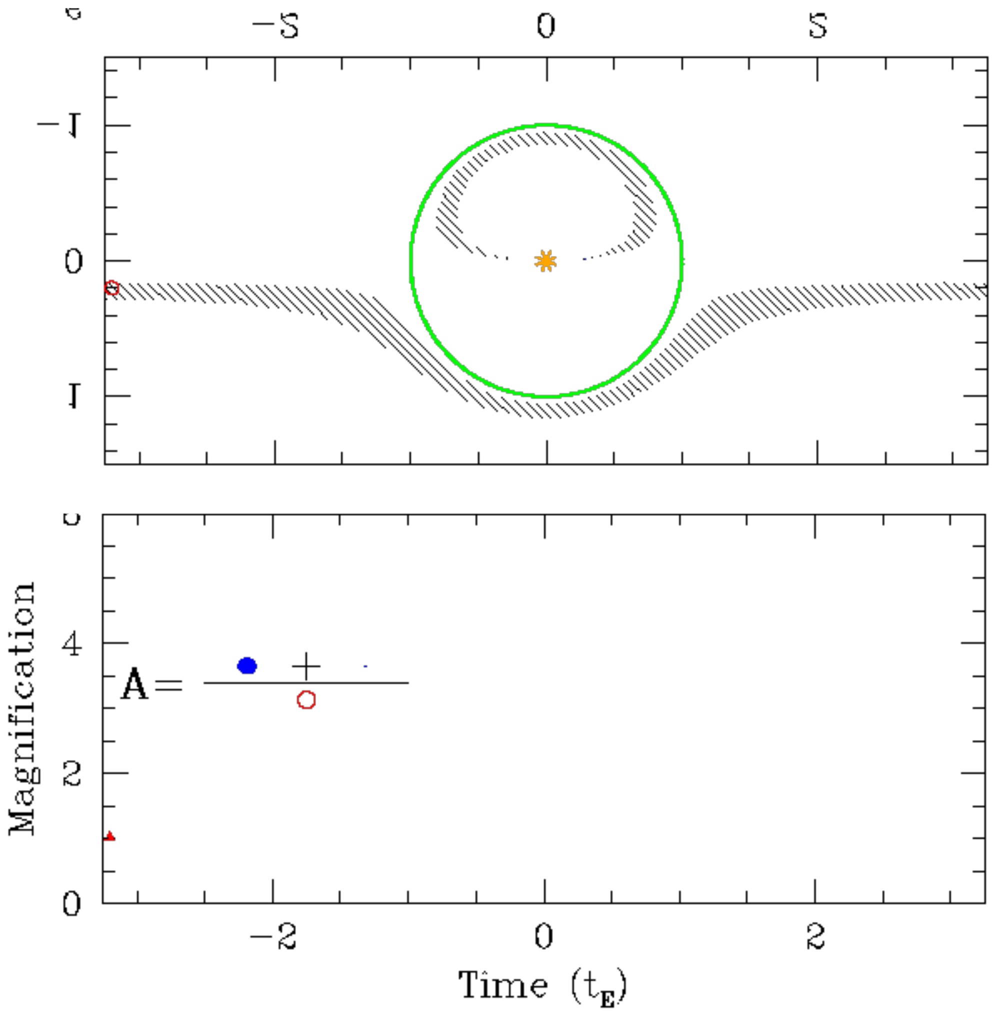
$$t_E\left(M_L, D_L, D_S, \mu_{rel}\right) = \frac{\theta_E}{\mu_{rel}}$$

≈20 d for $0.3 M_{\odot}$

≈1 d for M_J



Microlensing basics

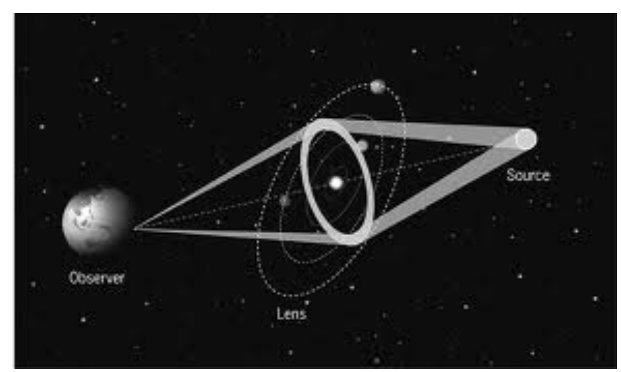


Event timescale

$$t_E\left(M_L, D_L, D_S, \mu_{rel}\right) = \frac{\theta_E}{\mu_{rel}}$$

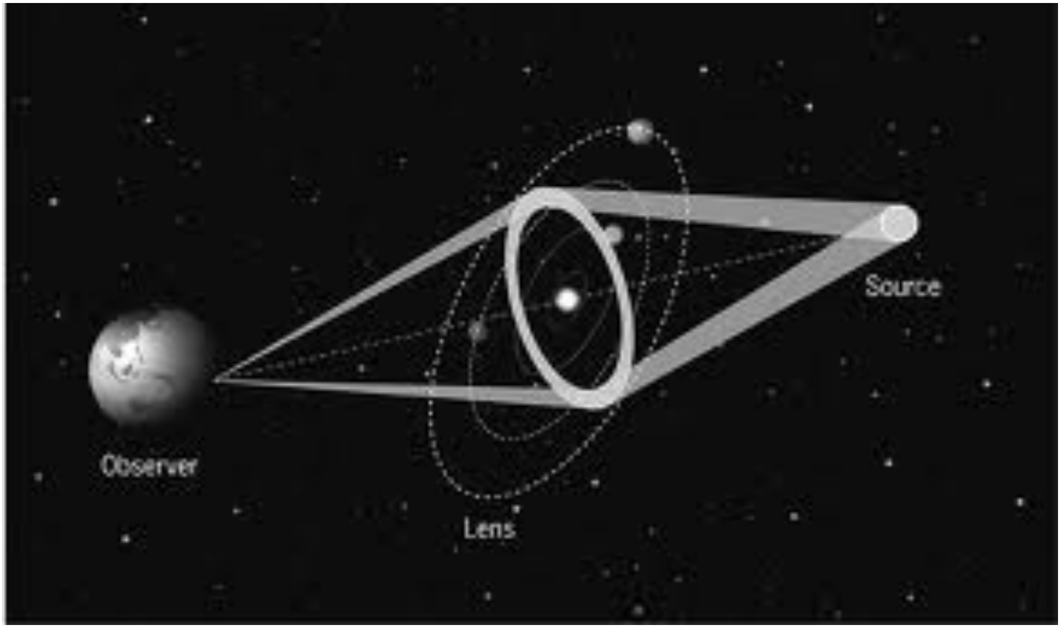
$\approx$20 d for $0.3 M_\odot$

$\approx$1 d for M_J

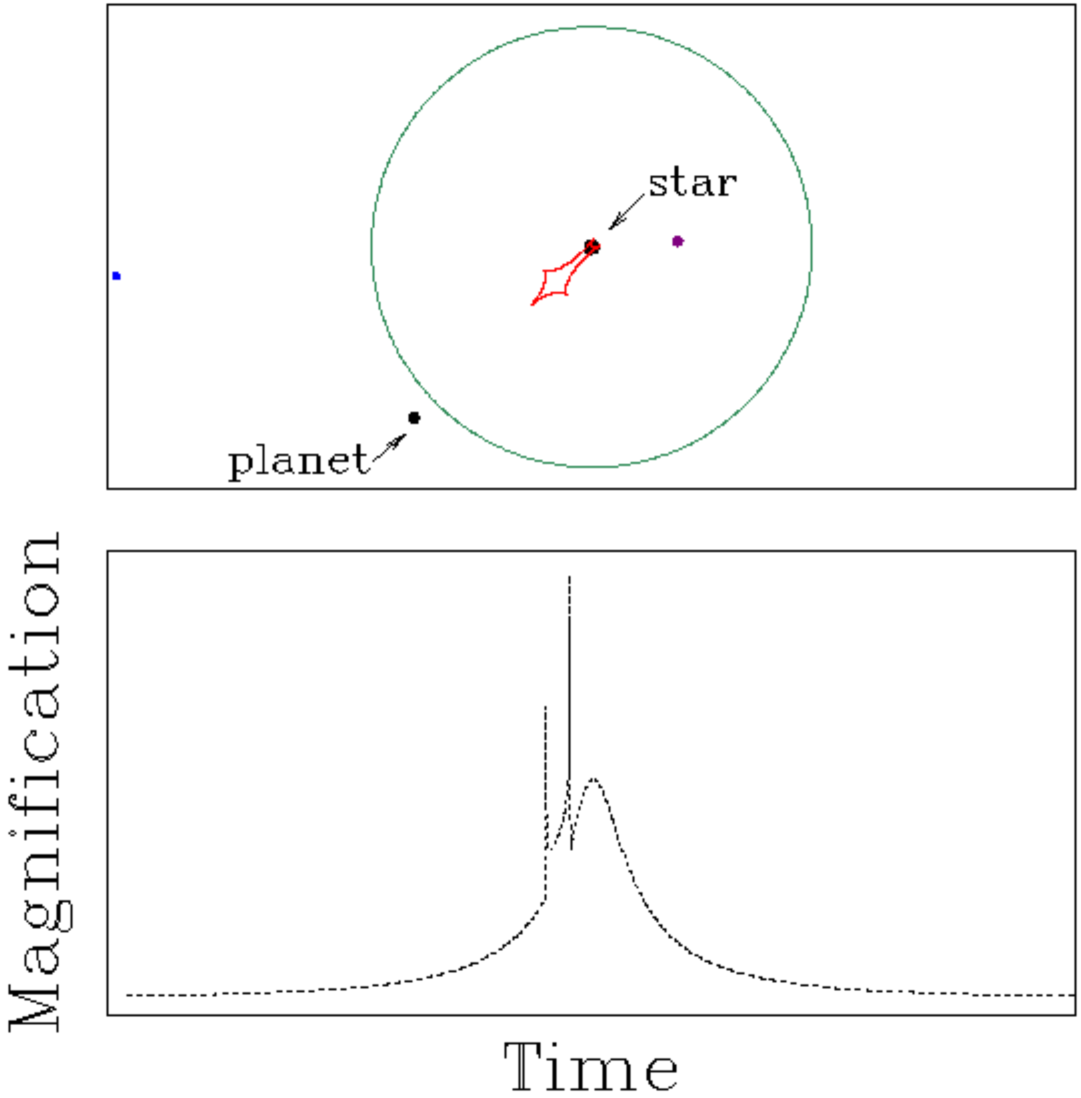


Companion detection

Detecting bound exoplanets

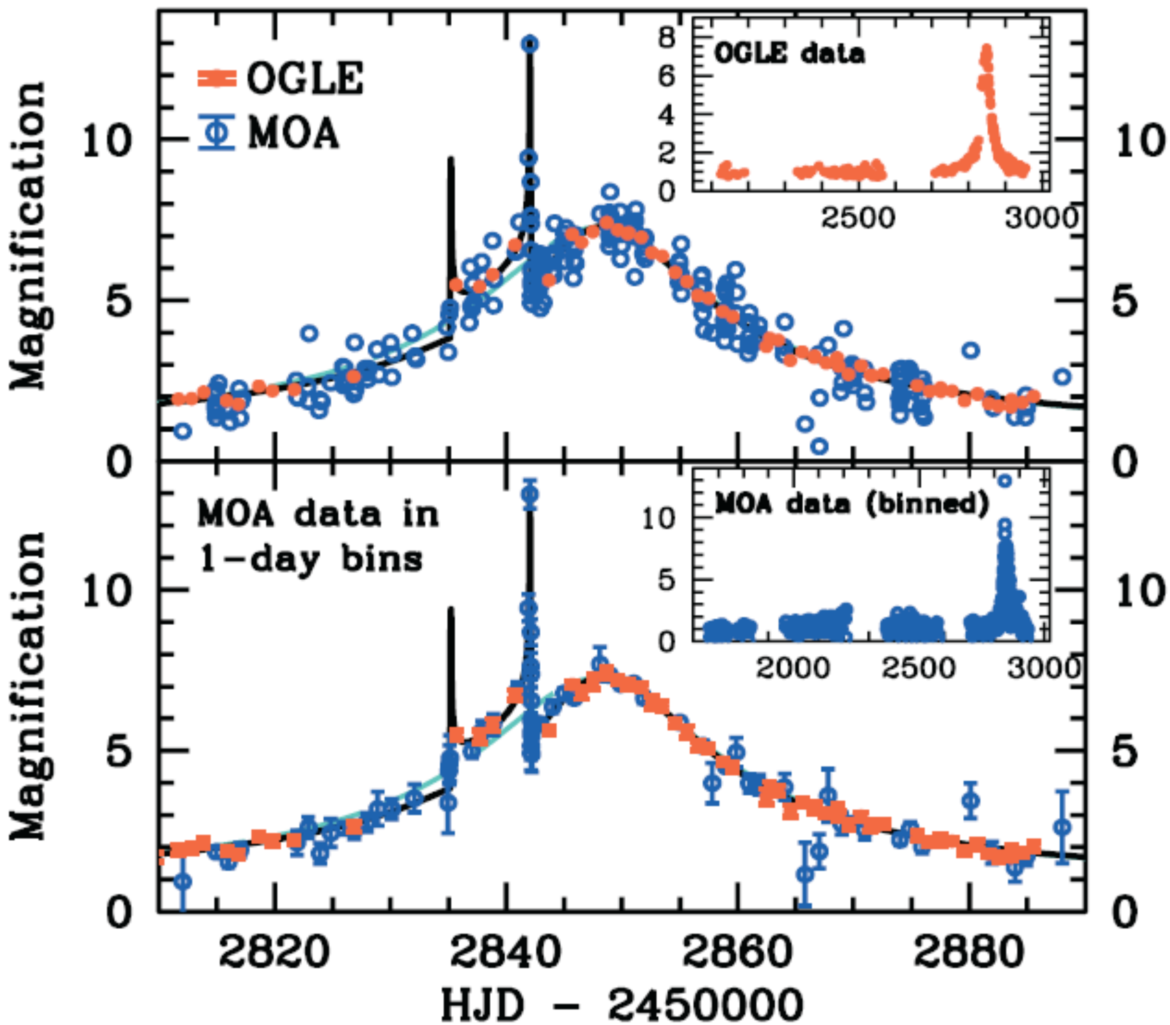


Detecting bound exoplanets



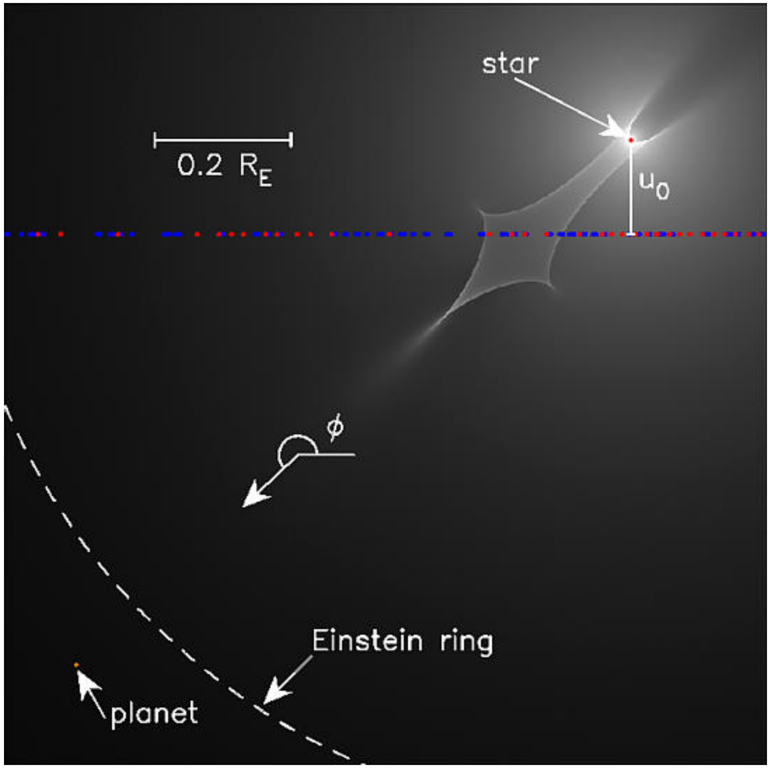
S. Gaudi

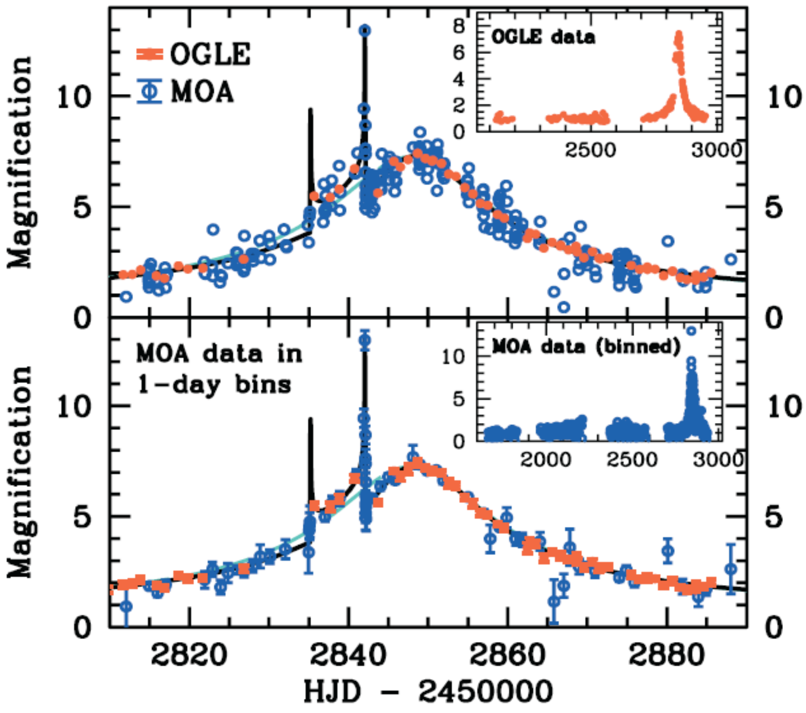
Detecting bound exoplanets



Bond et al. 2004

Detecting bound exoplanets





Bond et al. 2004

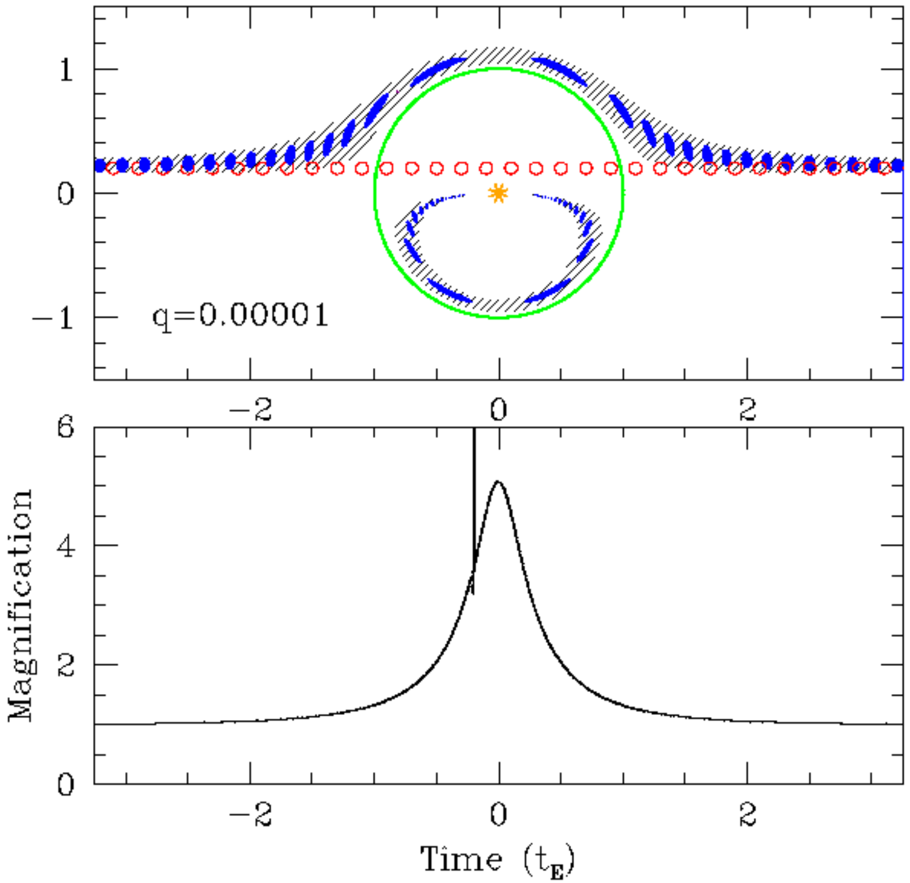
Detecting bound exoplanets

Planet-Star mass ratio

$$q = \frac{M_P}{M_L}$$

Planet-Star separation

Angle with respect to proper motion



S. Gaudi

Detecting bound exoplanets

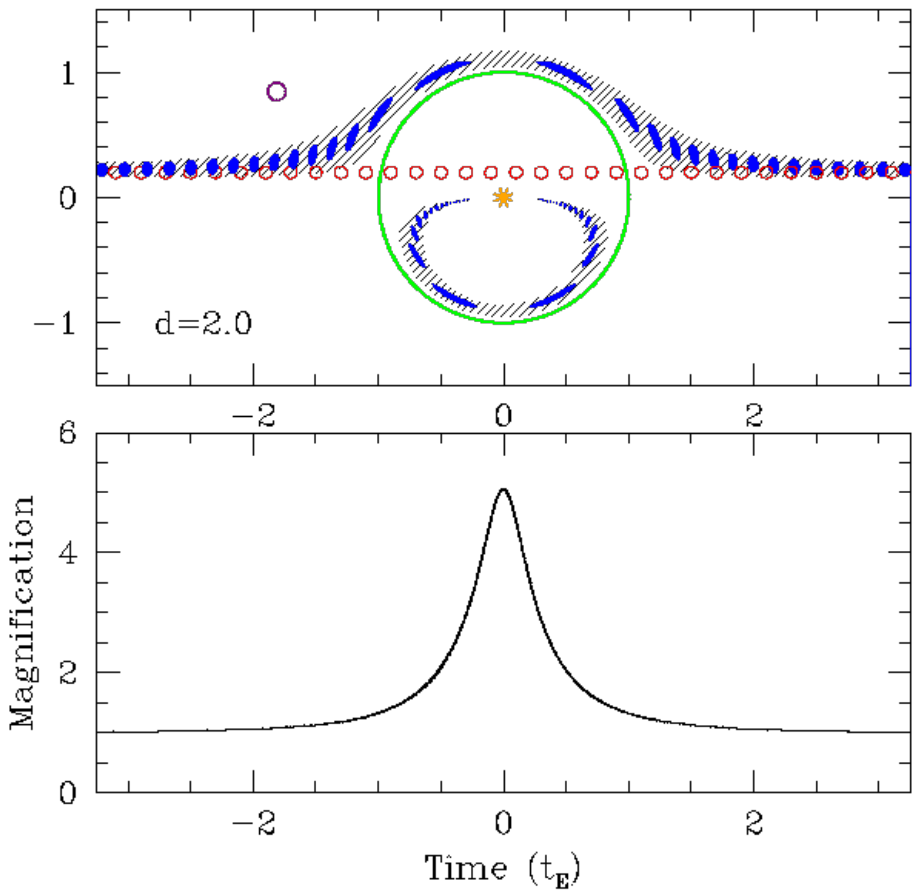
Planet-Star mass ratio

$$q = \frac{M_P}{M_L}$$

Planet-Star separation

$$s = \frac{a_\perp}{r_E}$$

Angle with respect to proper motion



S. Gaudi

Detecting bound exoplanets

Planet-Star mass ratio

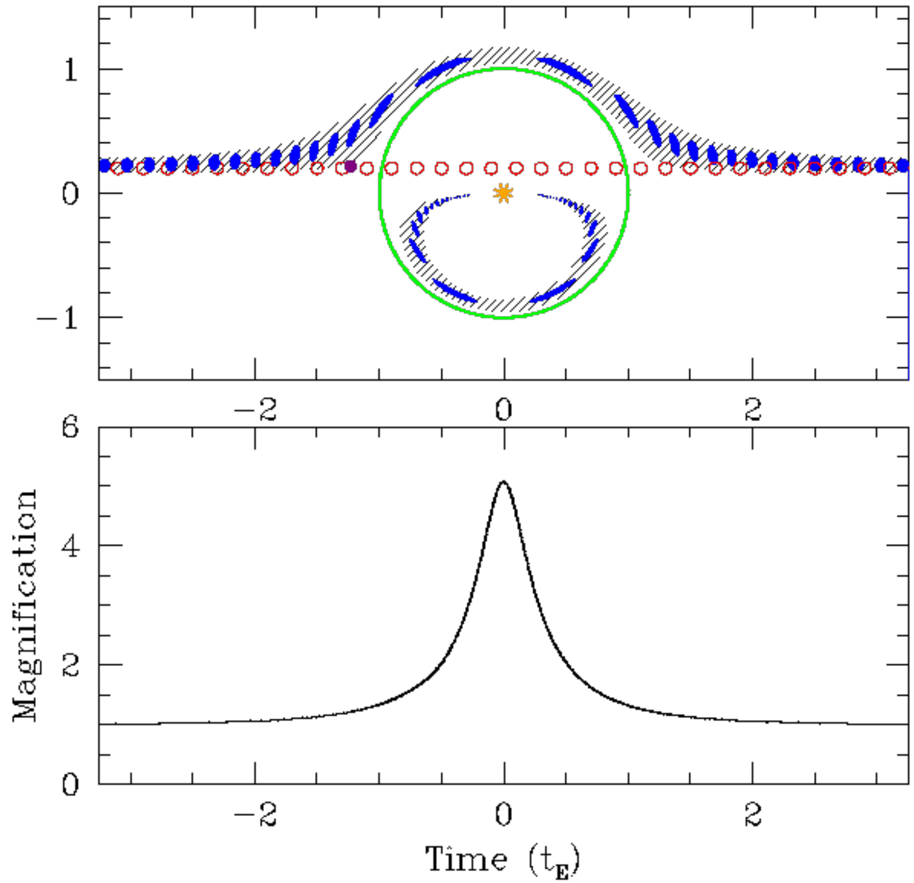
$$q = \frac{M_P}{M_L}$$

Planet-Star separation

$$s = \frac{a_\perp}{r_E}$$

Angle with respect to proper motion

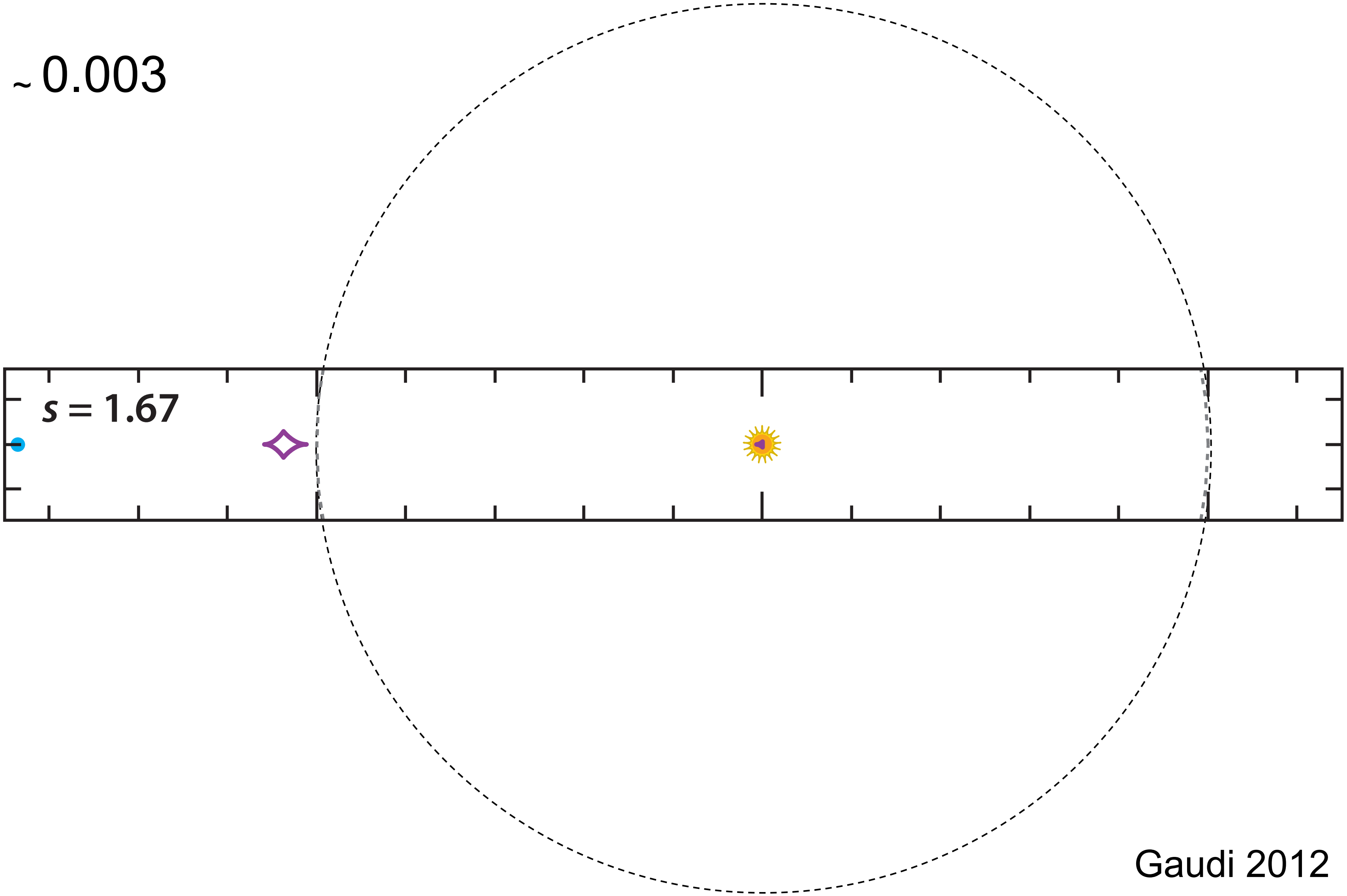
$$\alpha$$



S. Gaudi

Caustics

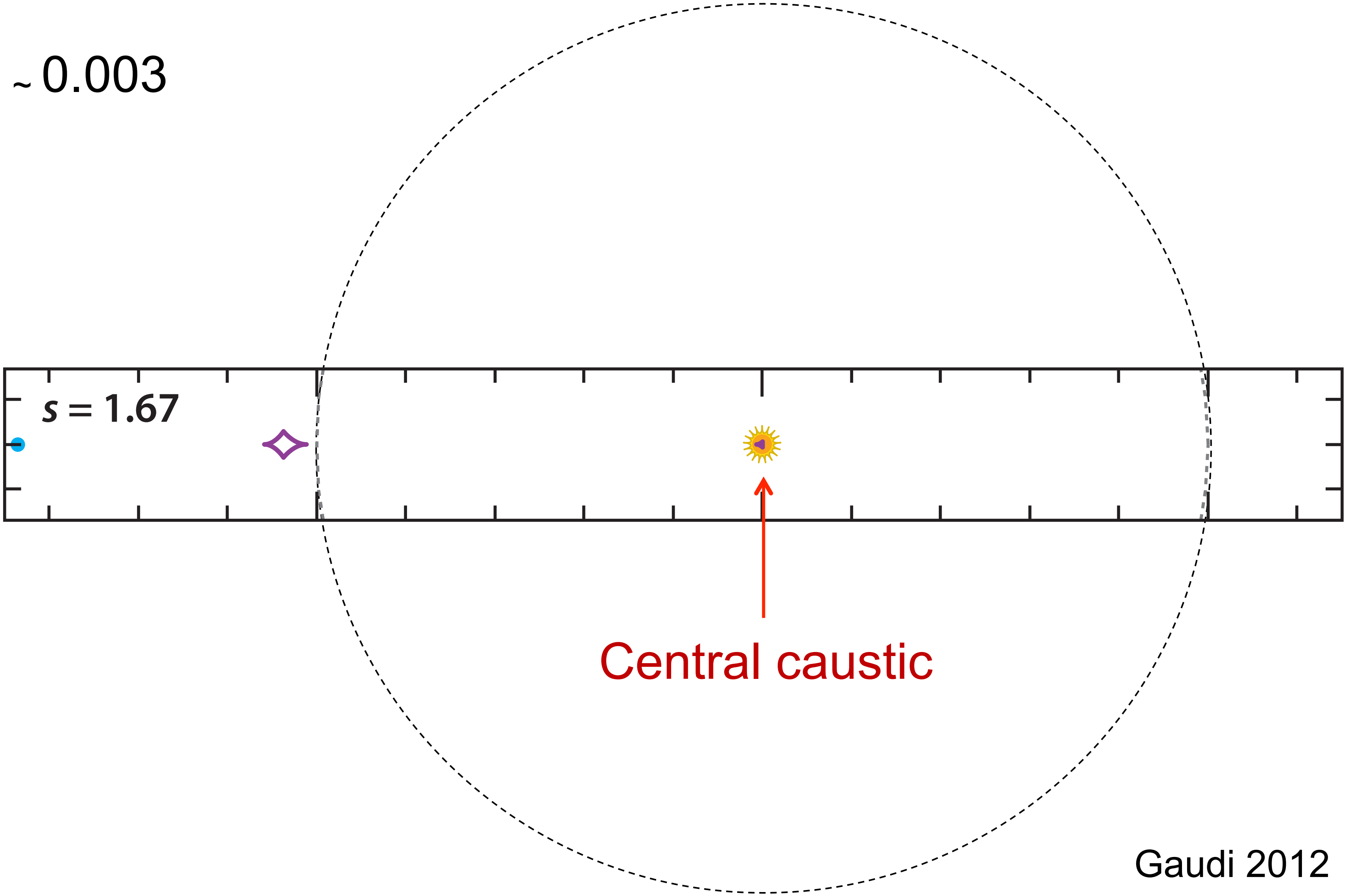
q ~ 0.003



Gaudi 2012

Caustics

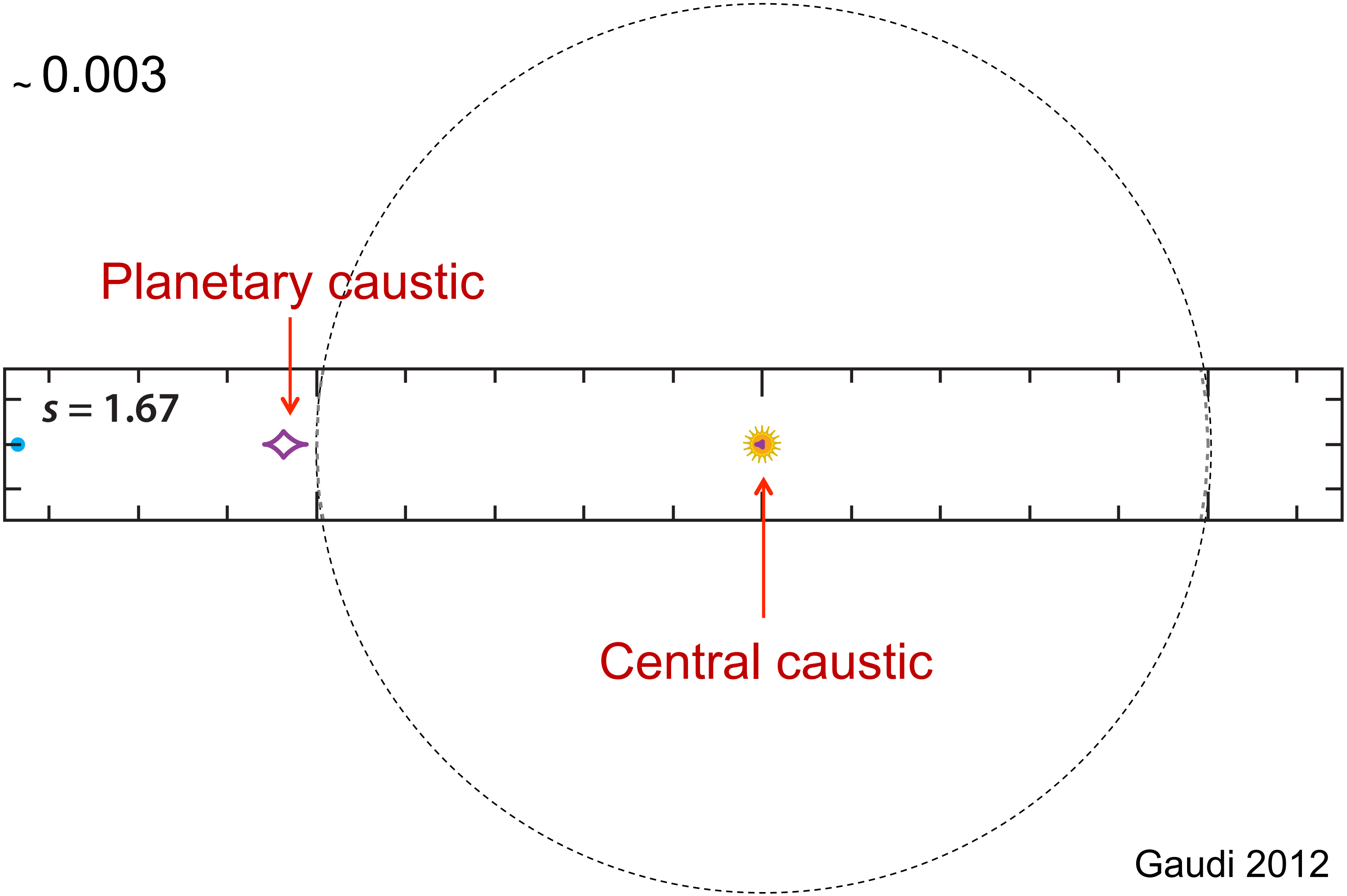
q ~ 0.003



Gaudi 2012

Caustics

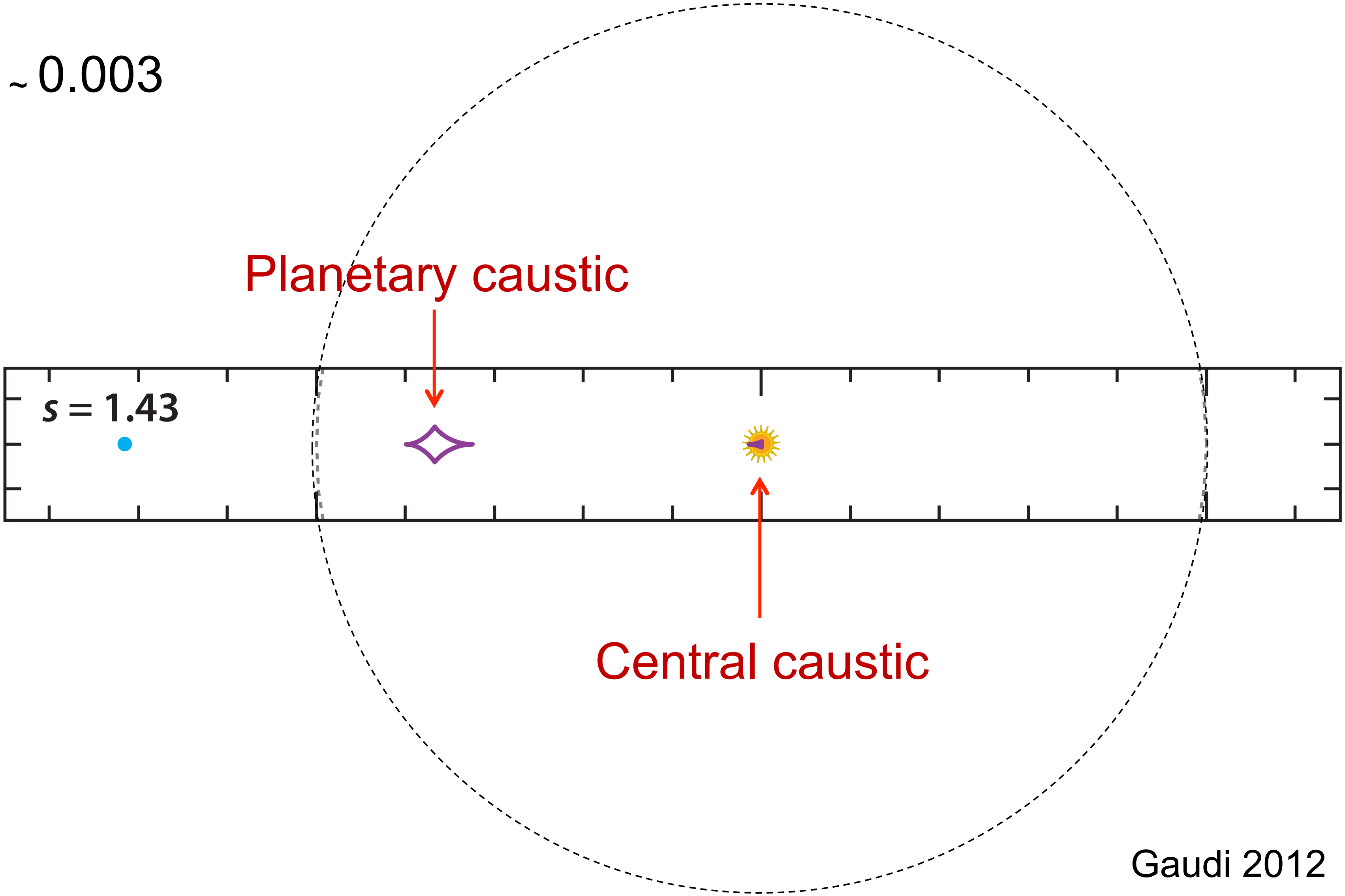
q ~ 0.003



Gaudi 2012

Caustics

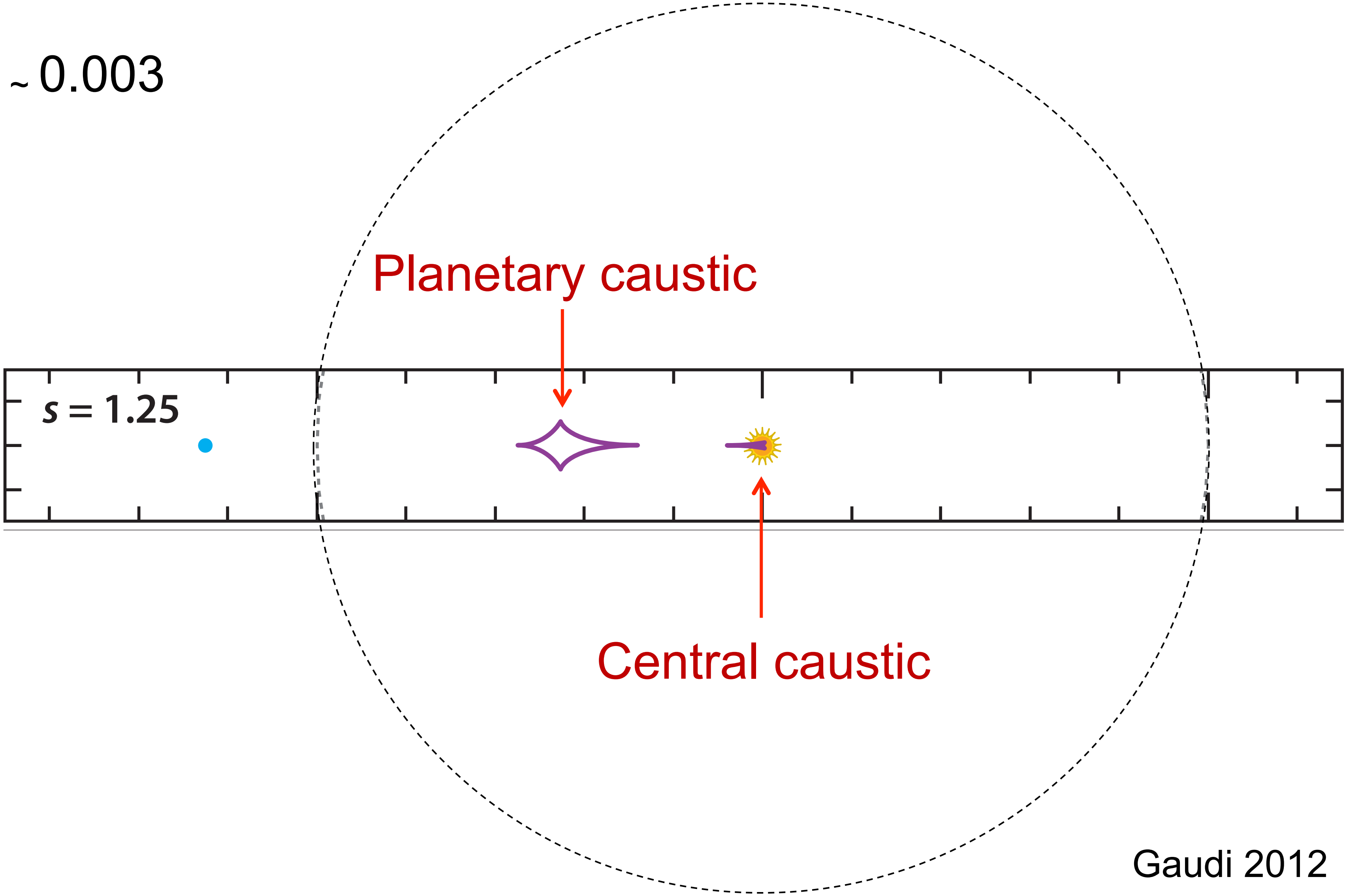
q ~ 0.003



Gaudi 2012

Caustics

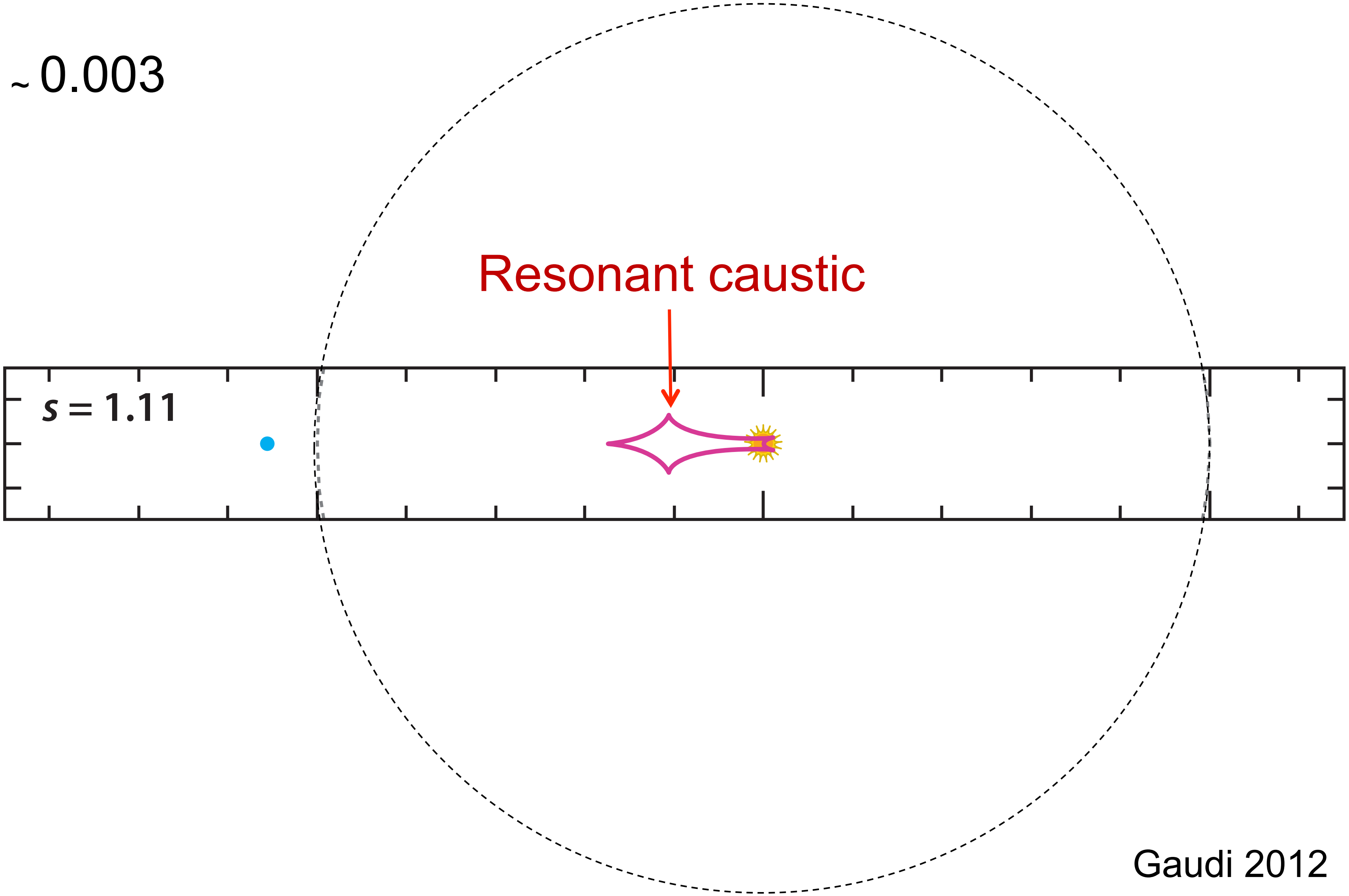
q ~ 0.003



Gaudi 2012

Caustics

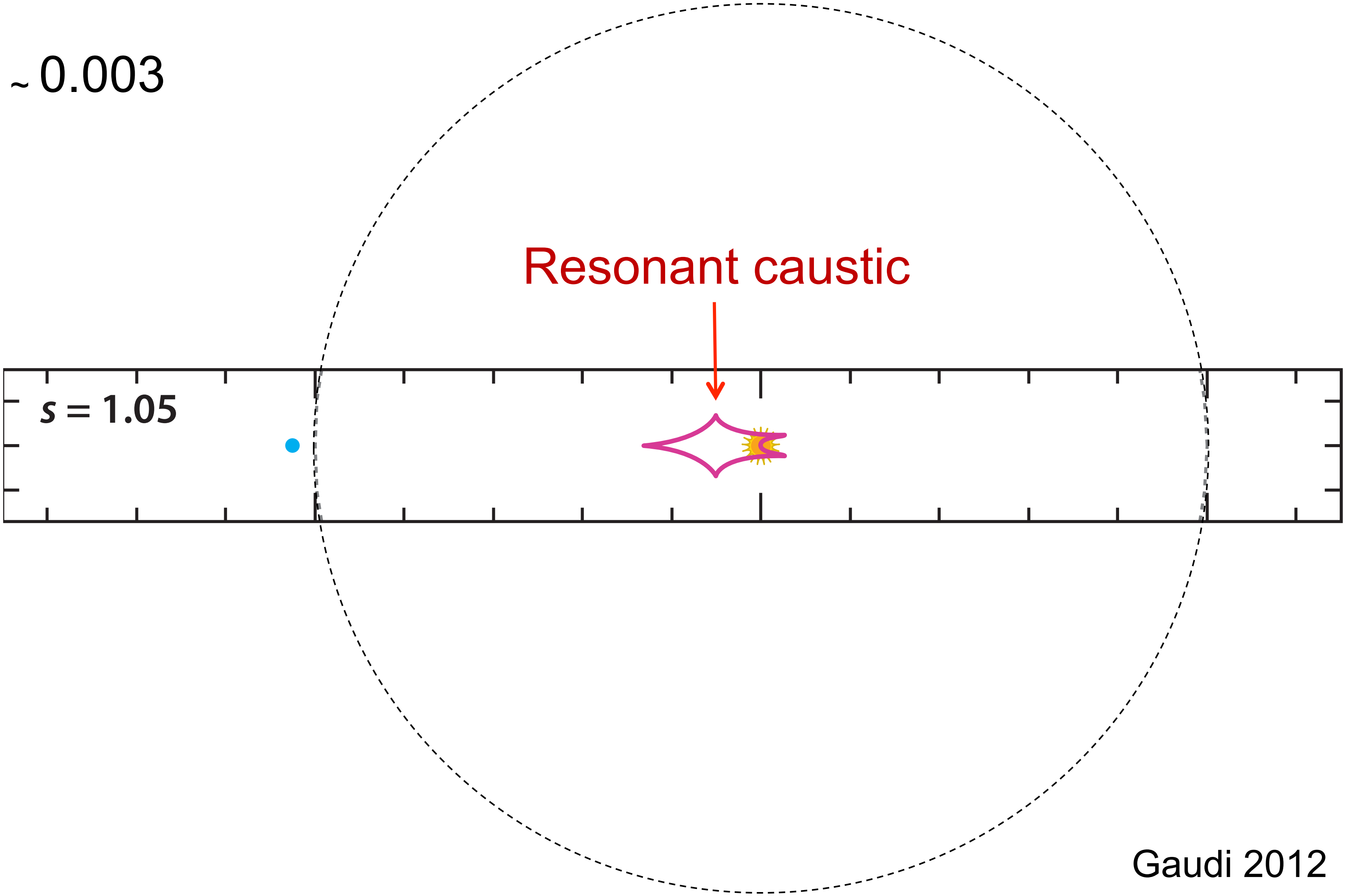
q ~ 0.003



Gaudi 2012

Caustics

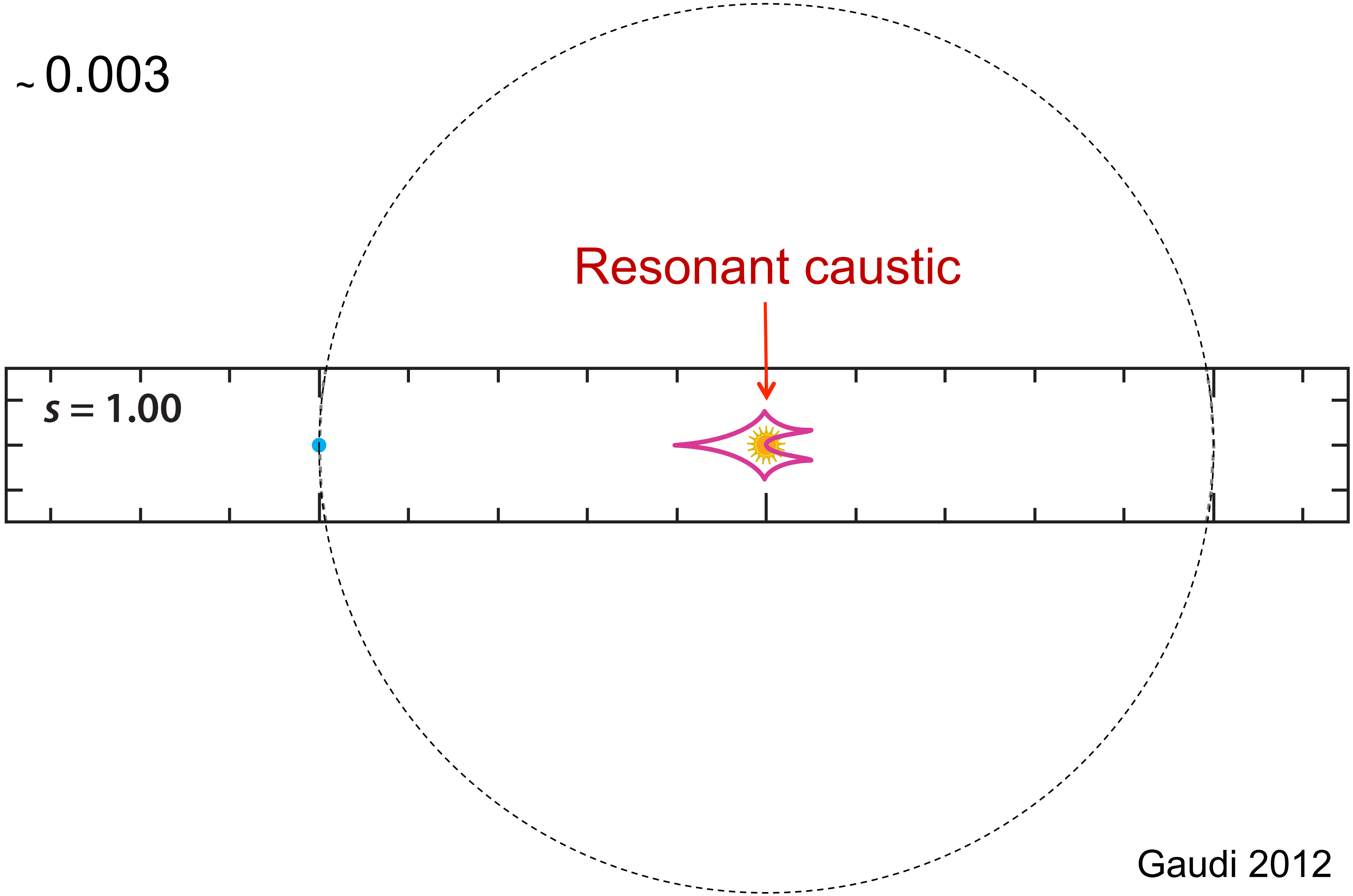
q ~ 0.003



Gaudi 2012

Caustics

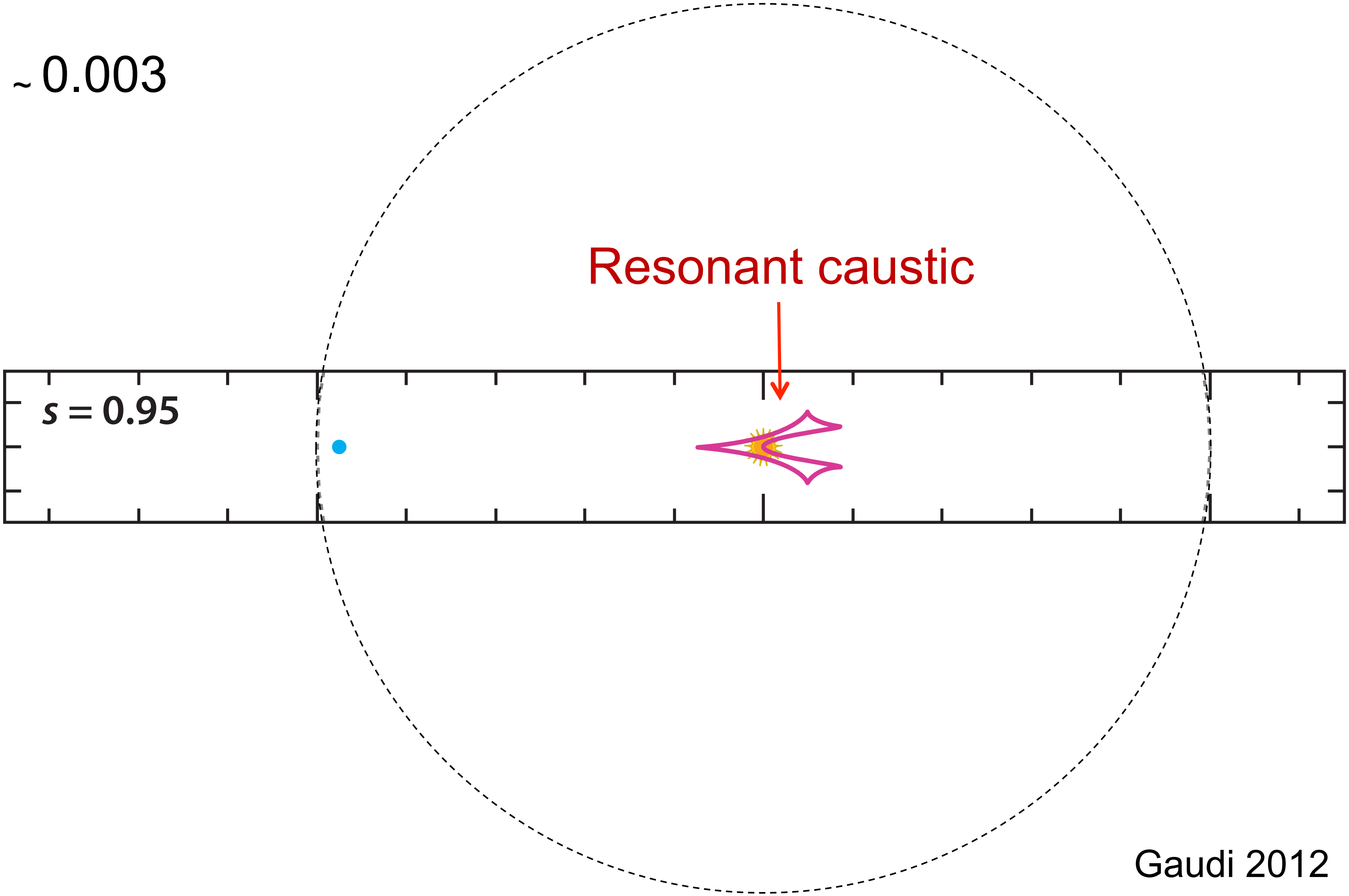
q ~ 0.003



Gaudi 2012

Caustics

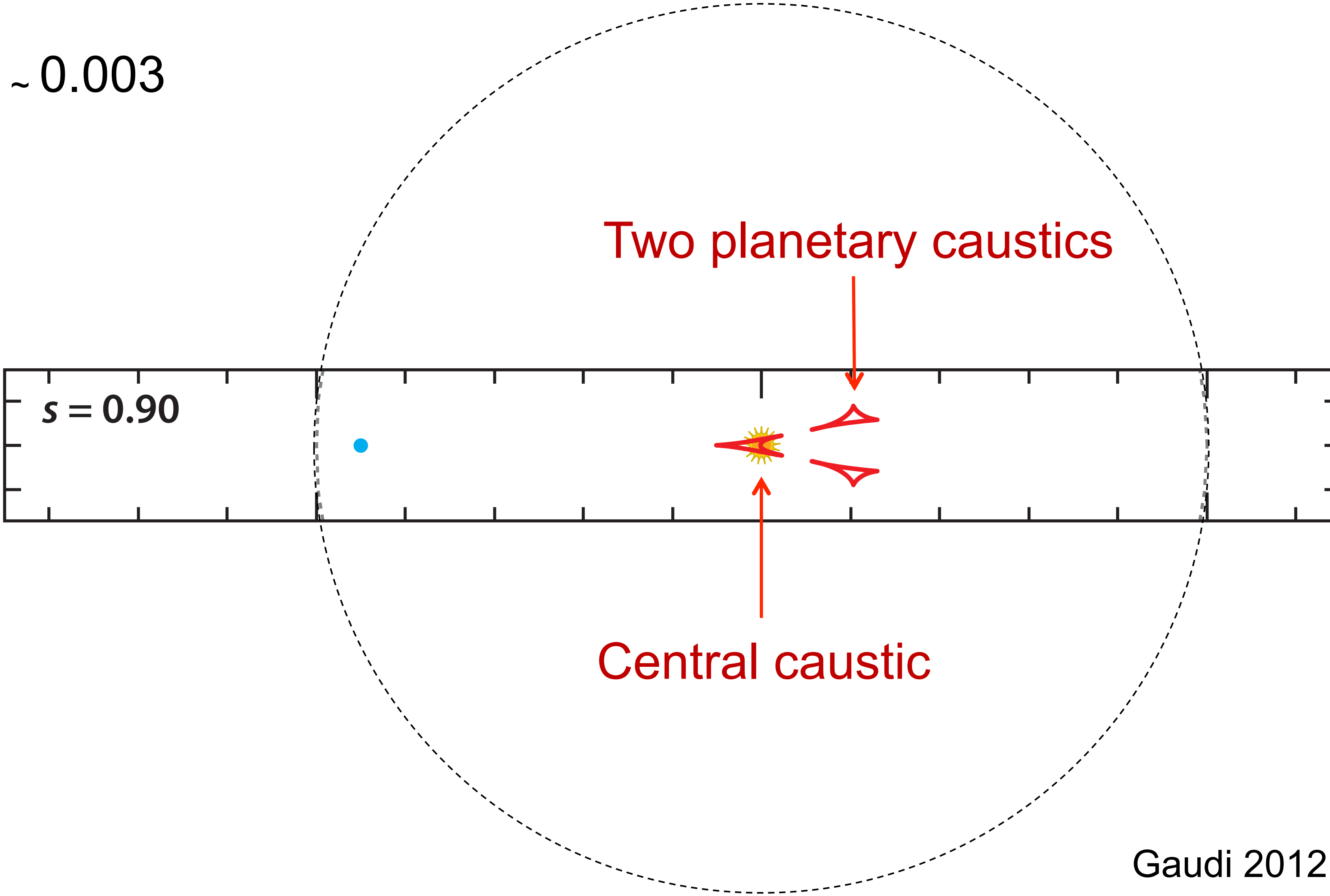
q ~ 0.003



Gaudi 2012

Caustics

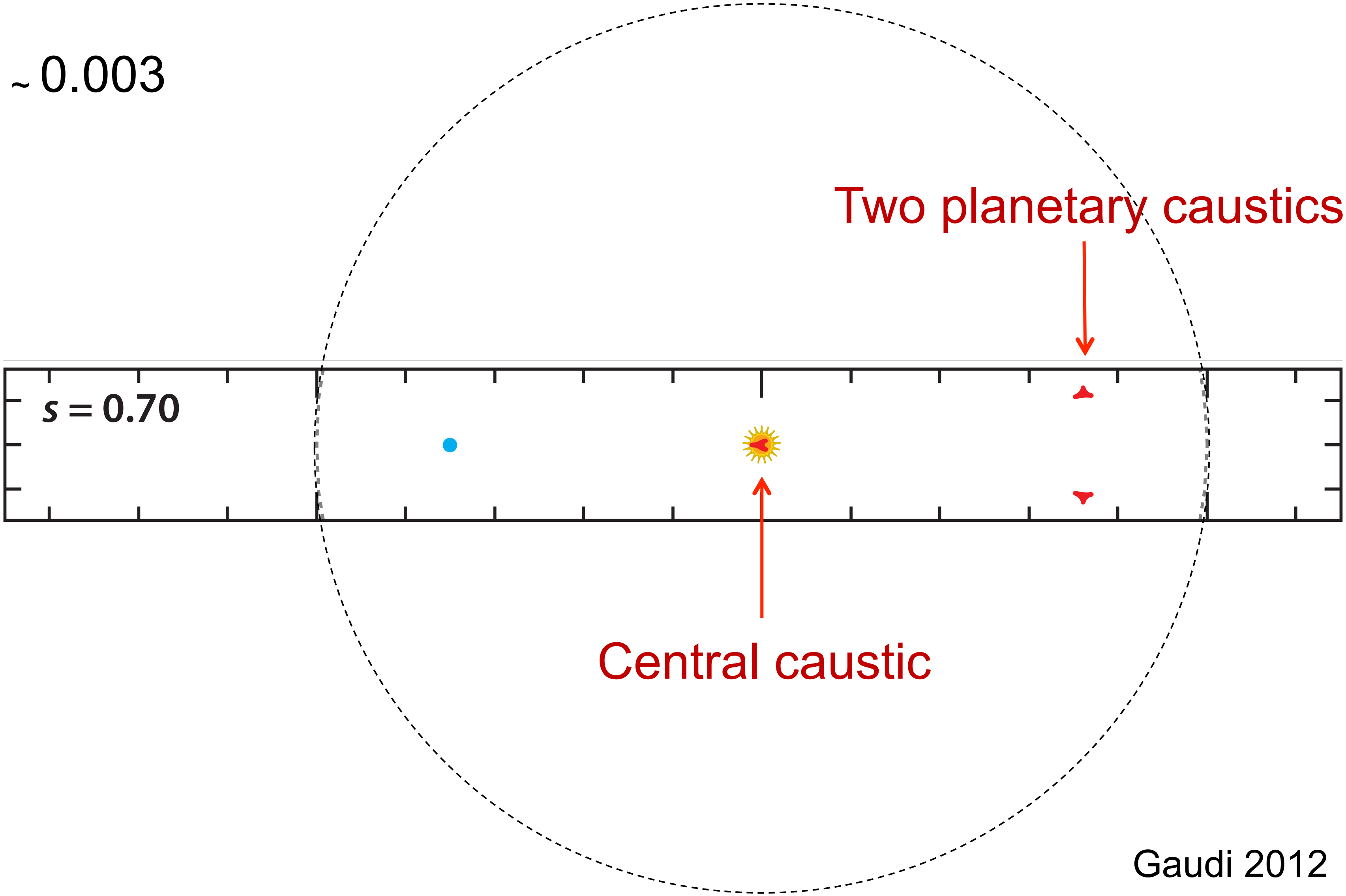
q ~ 0.003



Gaudi 2012

Caustics

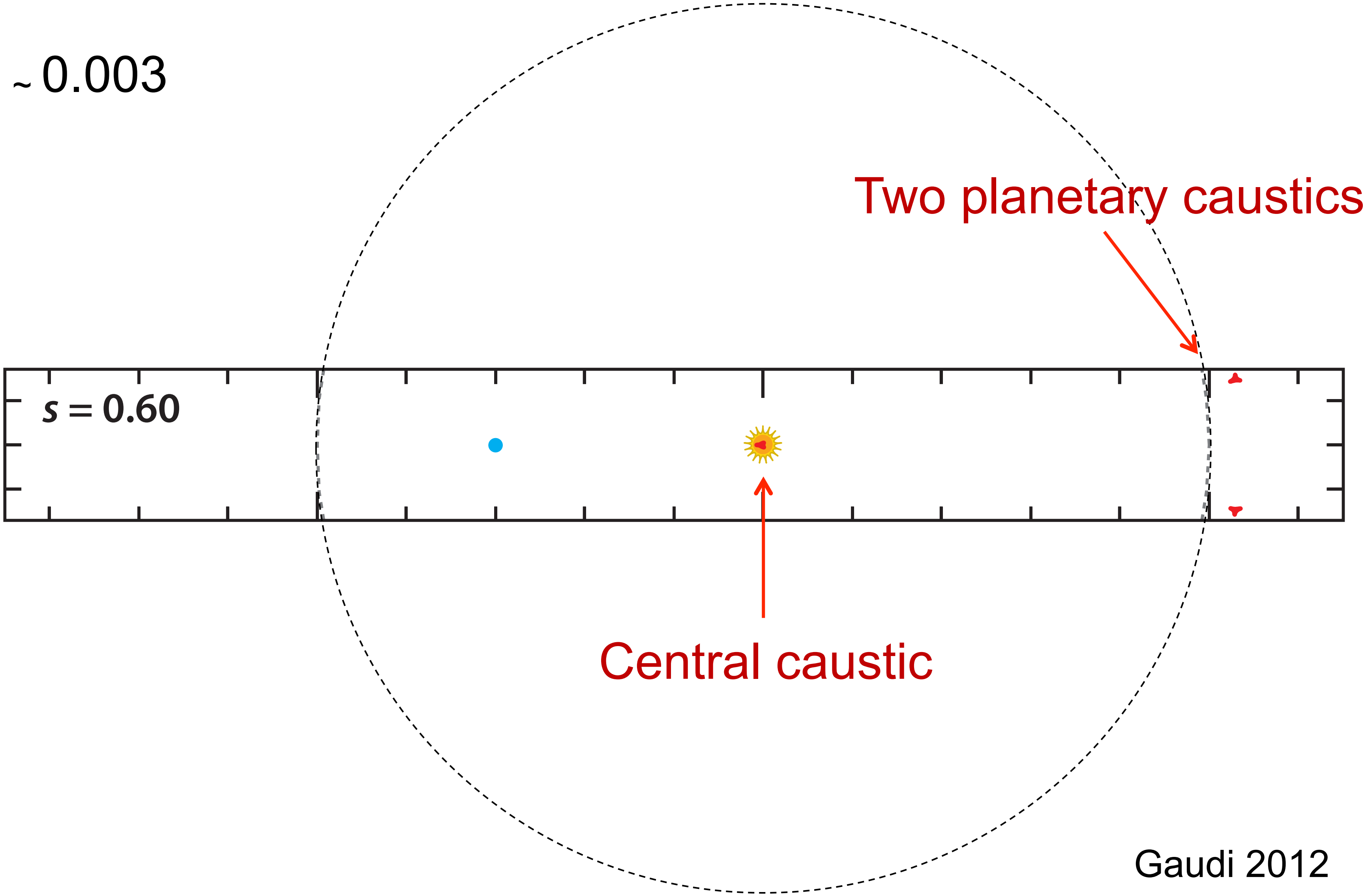
q ~ 0.003



Gaudi 2012

Caustics

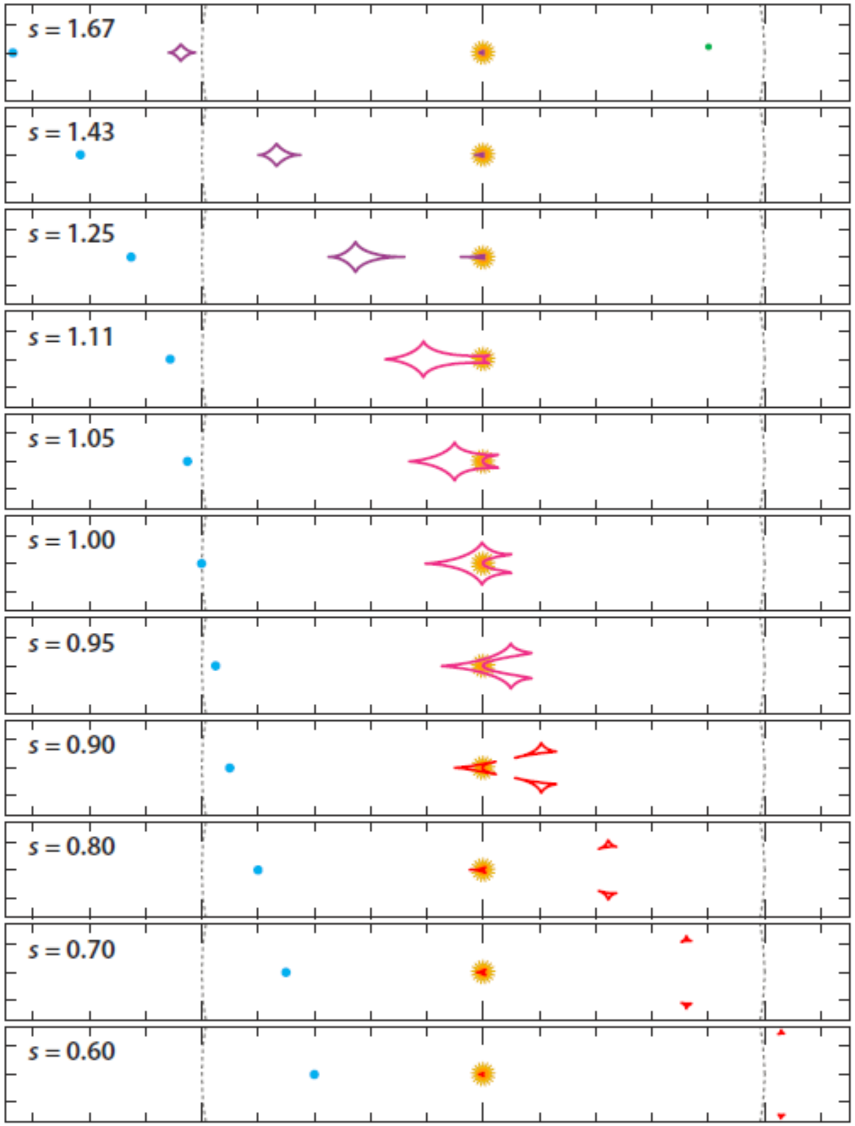
q ~ 0.003



Gaudi 2012

Caustics

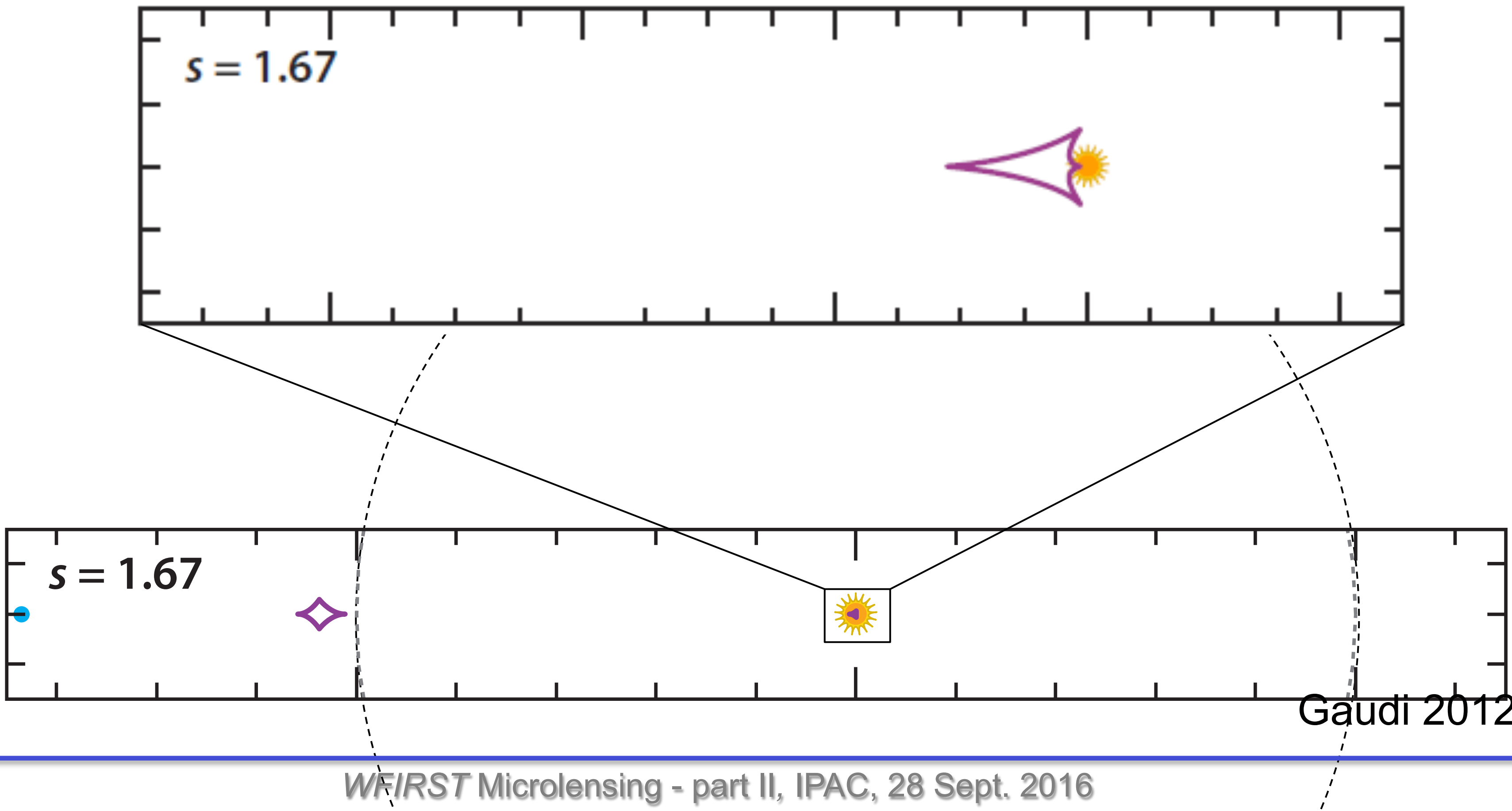
q ~ 0.003



Gaudi 2012

Caustics

q ~ 0.003



Gaudi 2012

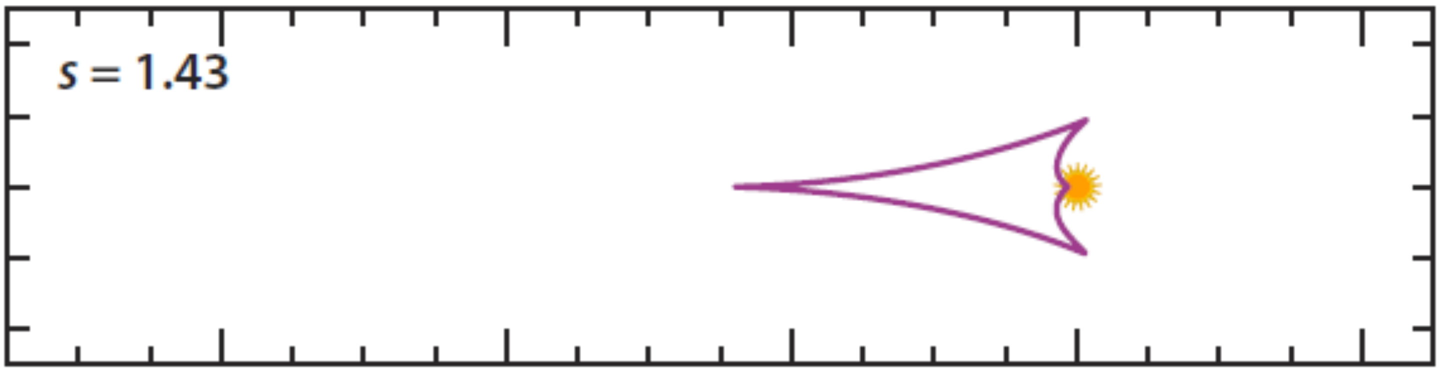
Caustics

q ~ 0.003

Gaudi 2012

Caustics

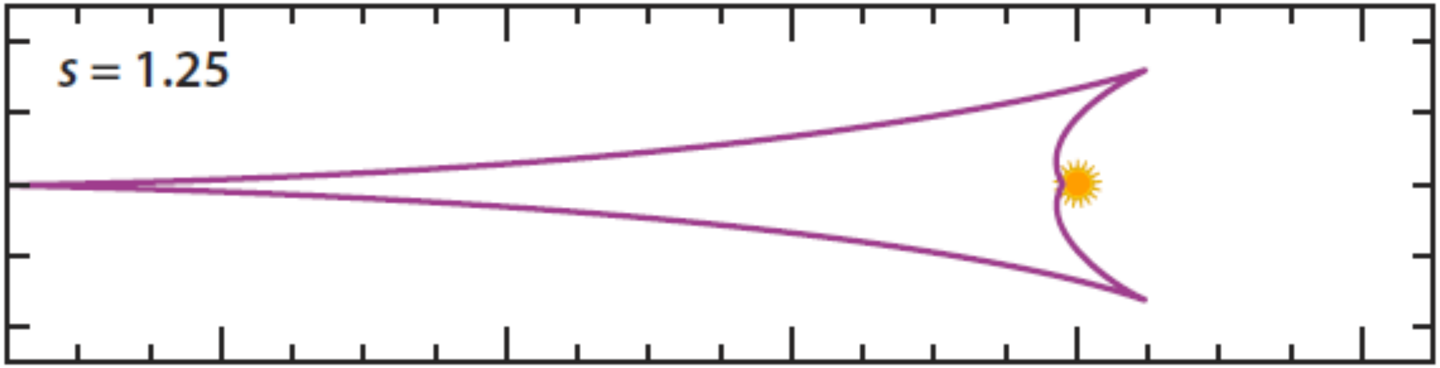
q ~ 0.003



Gaudi 2012

Caustics

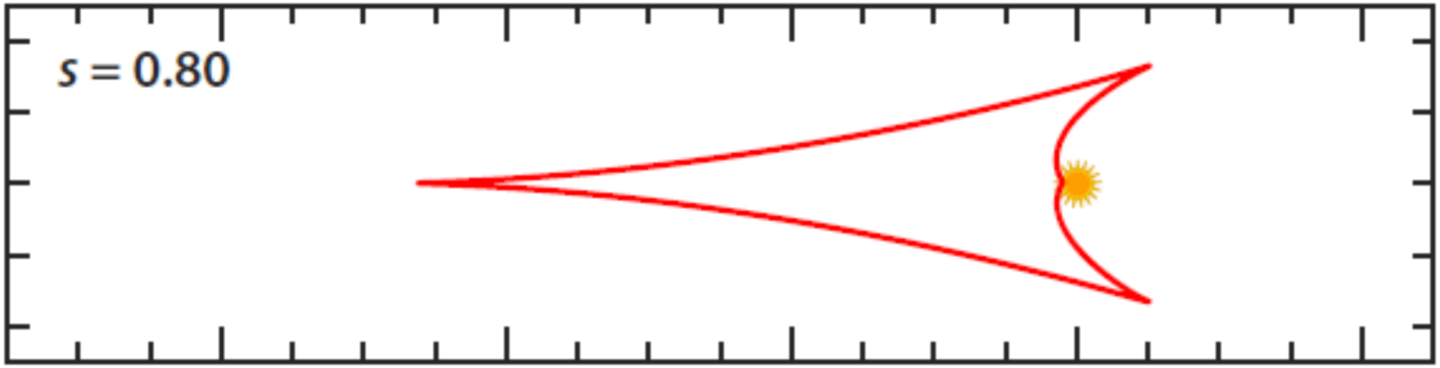
q ~ 0.003



Gaudi 2012

Caustics

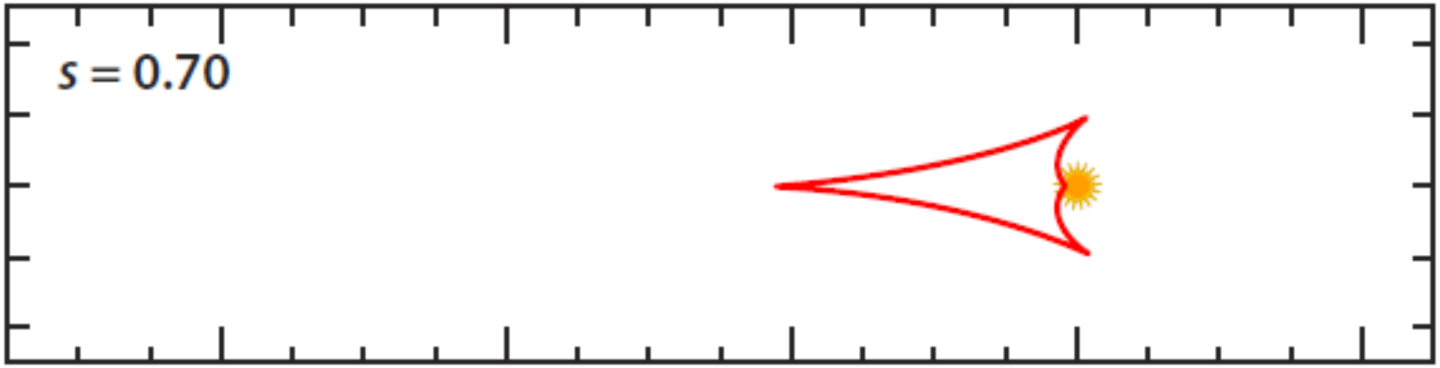
q ~ 0.003



Gaudi 2012

Caustics

q ~ 0.003



Gaudi 2012

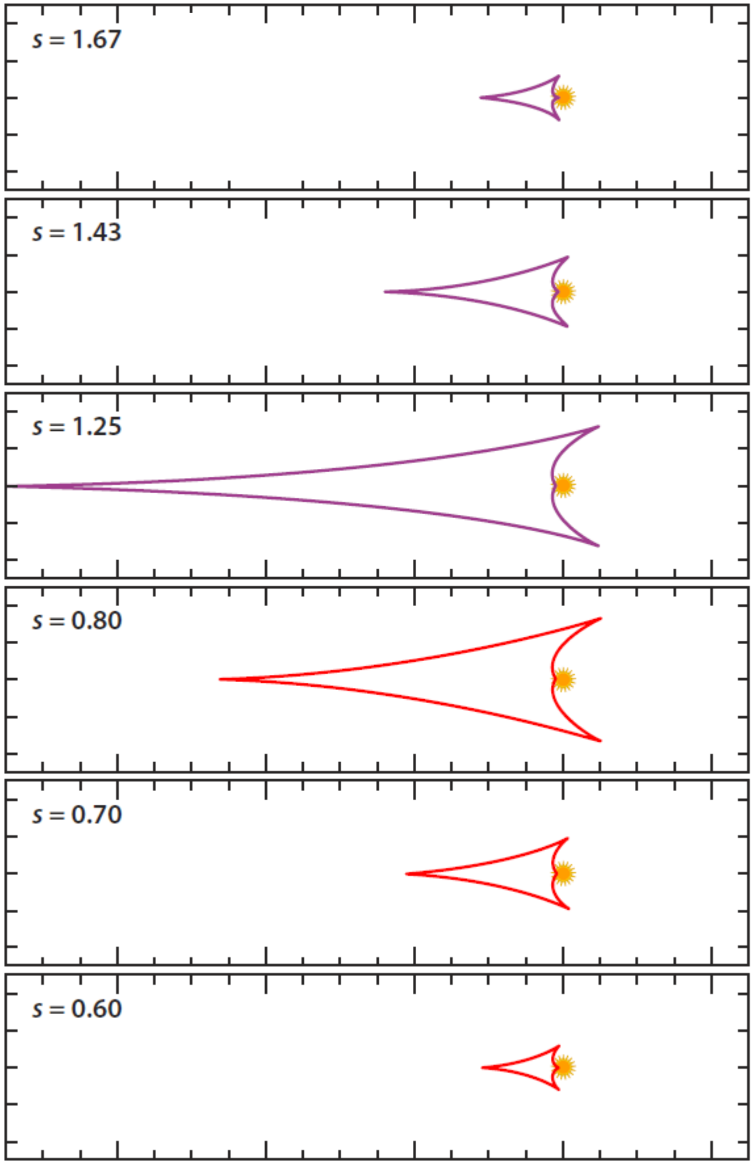
Caustics

q ~ 0.003

Gaudi 2012

Caustics

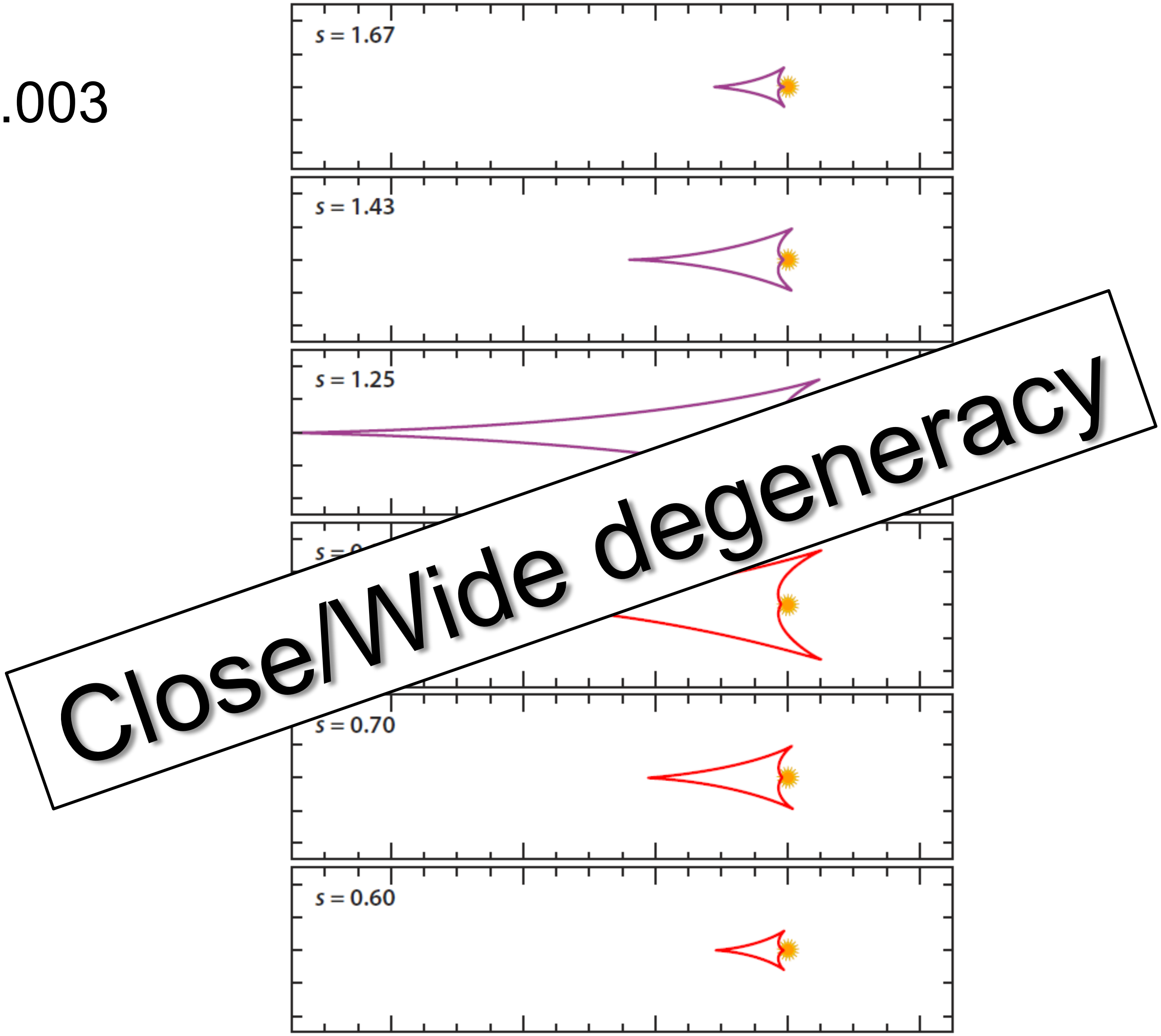
q ~ 0.003



Gaudi 2012

Caustics

q ~ 0.003



Gaudi 2012

Companion characterization

From lensing observables to physical parameters

Planet-Star mass ratio

$$q = \frac{M_P}{M_L}$$

Planet-Star separation

$$s = \frac{a_\perp}{r_E}$$

Event timescale

$$t_E\left(M_L, D_L, D_S, \mu_{rel}\right) = \frac{\theta_E}{\mu_{rel}}$$

From lensing observables to physical parameters

Planet-Star mass ratio

$$q = \frac{M_P}{M_L}$$

Planet-Star separation

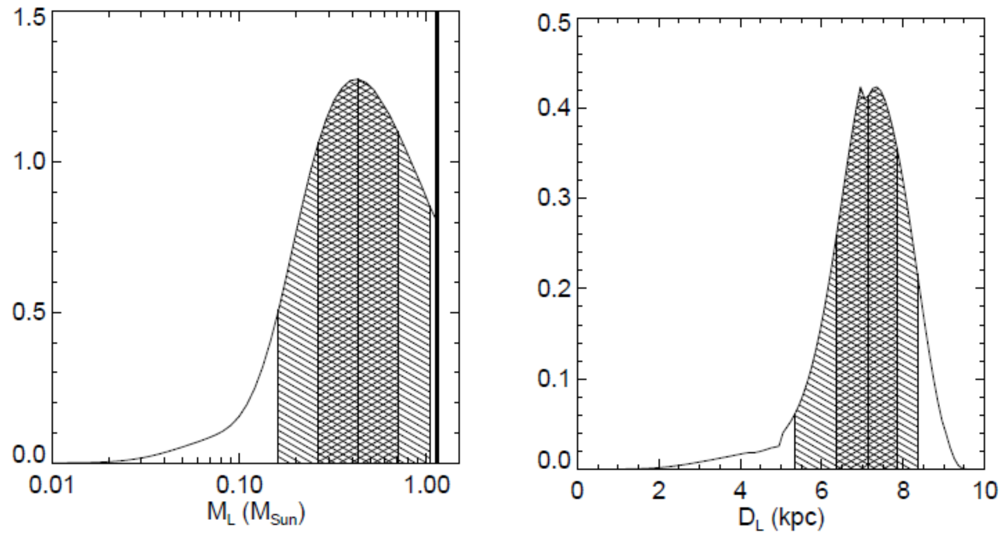
$$s = \frac{a_\perp}{r_E}$$

Event timescale

$$t_E\left(M_L, D_L, D_S, \mu_{rel}\right) = \frac{\theta_E}{\mu_{rel}}$$

Bayesian analysis

Assuming a Galactic model



Yee et al. 2012

From lensing observables to physical parameters

Planet-Star mass ratio

$$q = \frac{M_P}{M_L}$$

Planet-Star separation

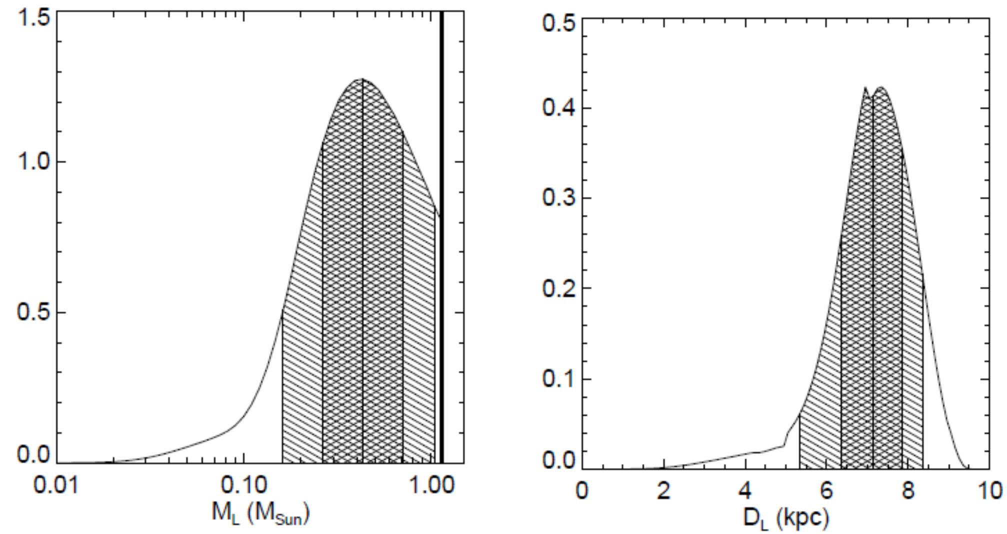
$$s = \frac{a_\perp}{r_E}$$

Event timescale

$$t_E\left(M_L, D_L, D_S, \mu_{rel}\right) = \frac{\theta_E}{\mu_{rel}}$$

Bayesian analysis

Assuming a Galactic model



Yee et al. 2012

MOA-2011-293:

t_E=22 [d], q=0.005, s=0.55/1.83

$\Rightarrow$ M_L=0.43 M_{sun}, D=7.1 kpc

$\Rightarrow$ m_p=2.5 M_{Jup}, $r_\perp$=1.0/3.4 AU

From lensing observables to physical parameters

Planet-Star mass ratio

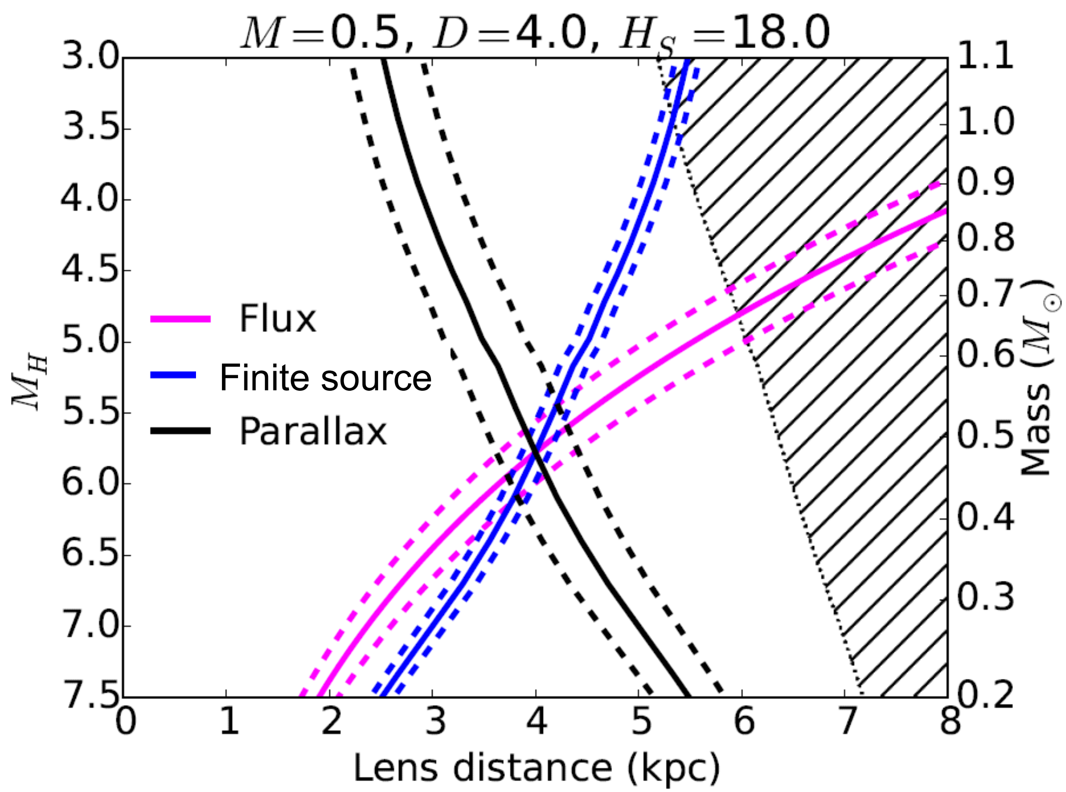
$$q = \frac{M_P}{M_L}$$

Planet-Star separation

$$s = \frac{a_\perp}{r_E}$$

Event timescale

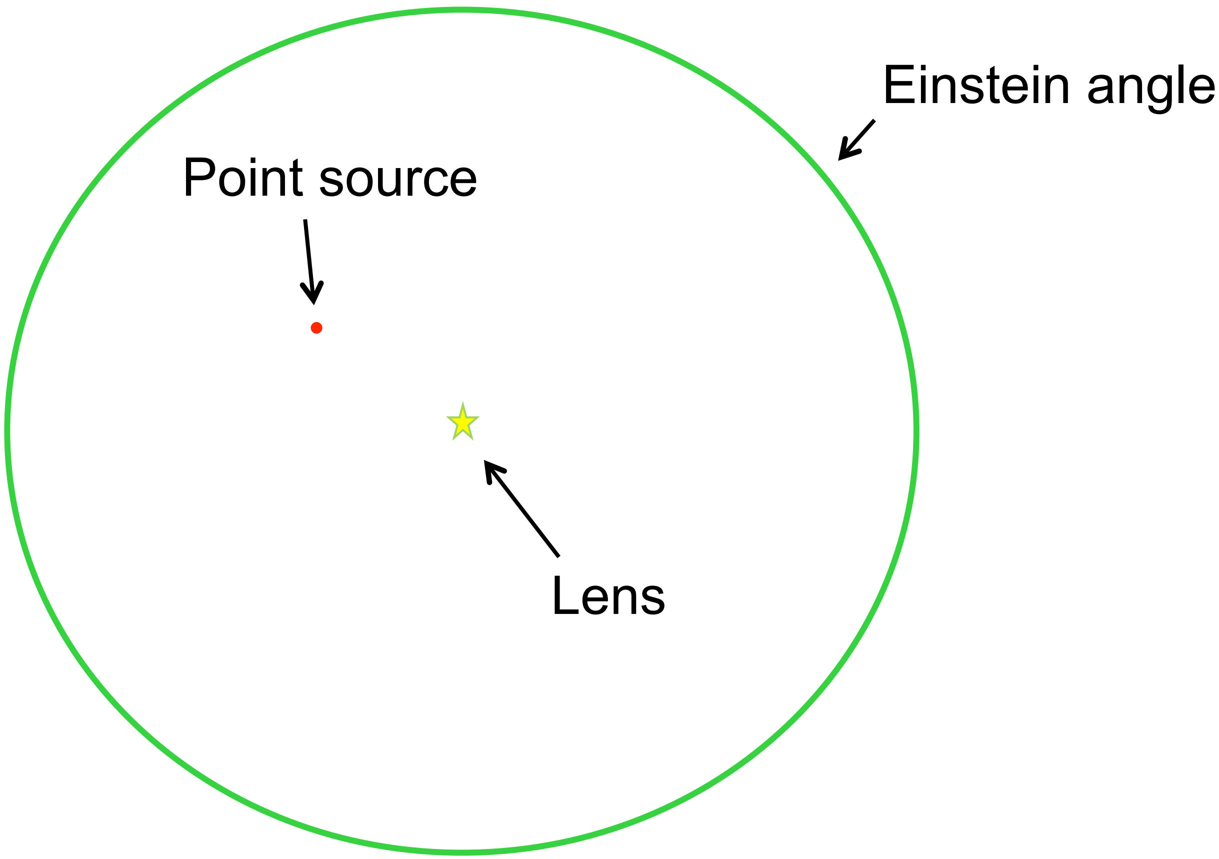
$$t_E\left(M_L, D_L, D_S, \mu_{rel}\right) = \frac{\theta_E}{\mu_{rel}}$$



Yee 2015

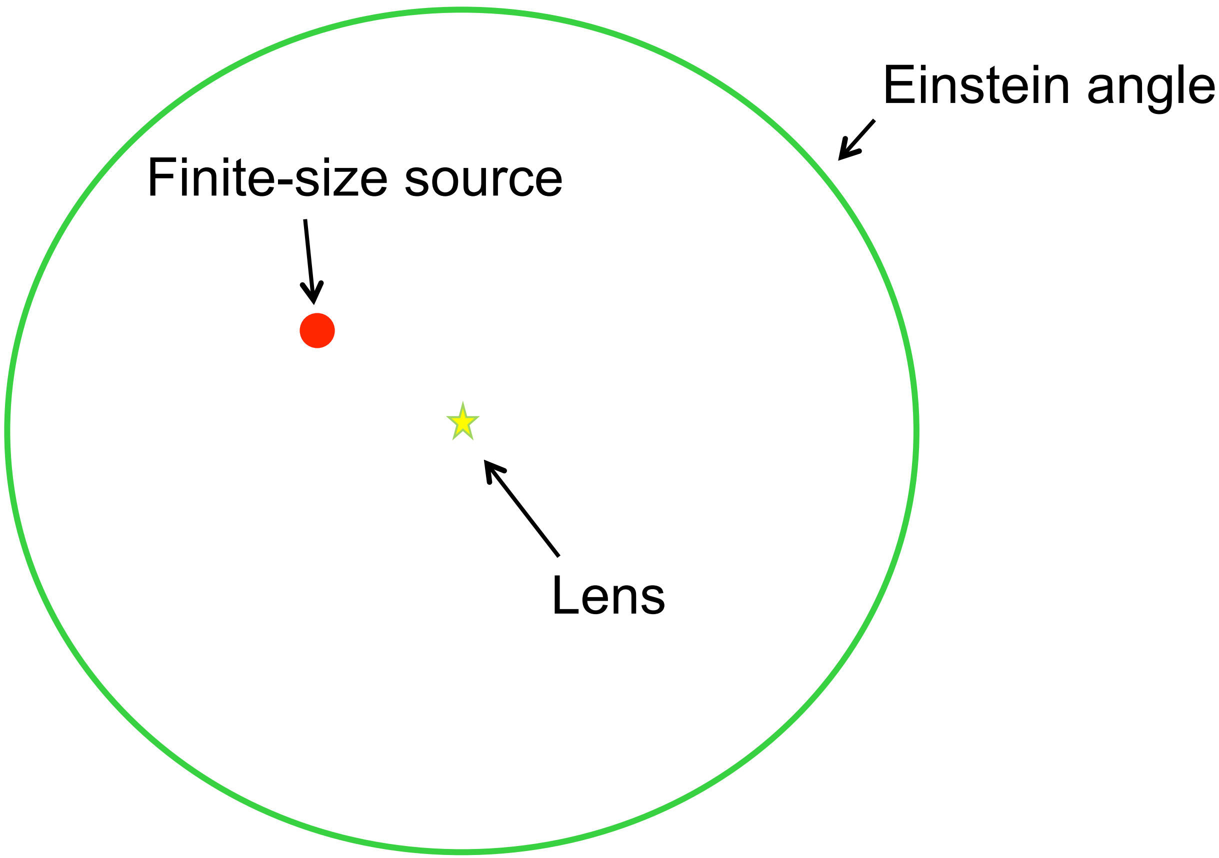
From lensing observables to physical parameters

- Finite source size $\rho_* = \dfrac{\theta_*}{\theta_E}$



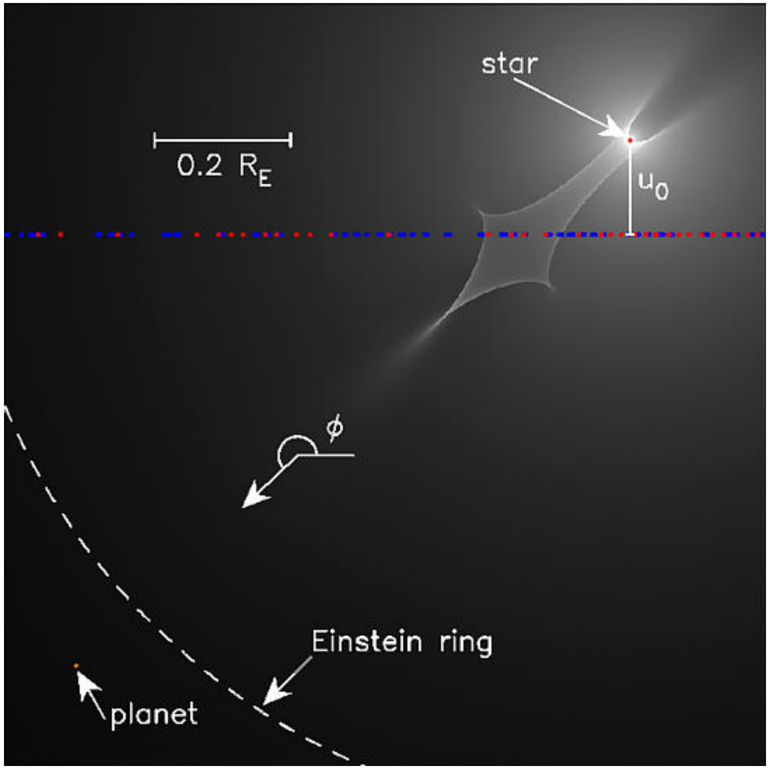
From lensing observables to physical parameters

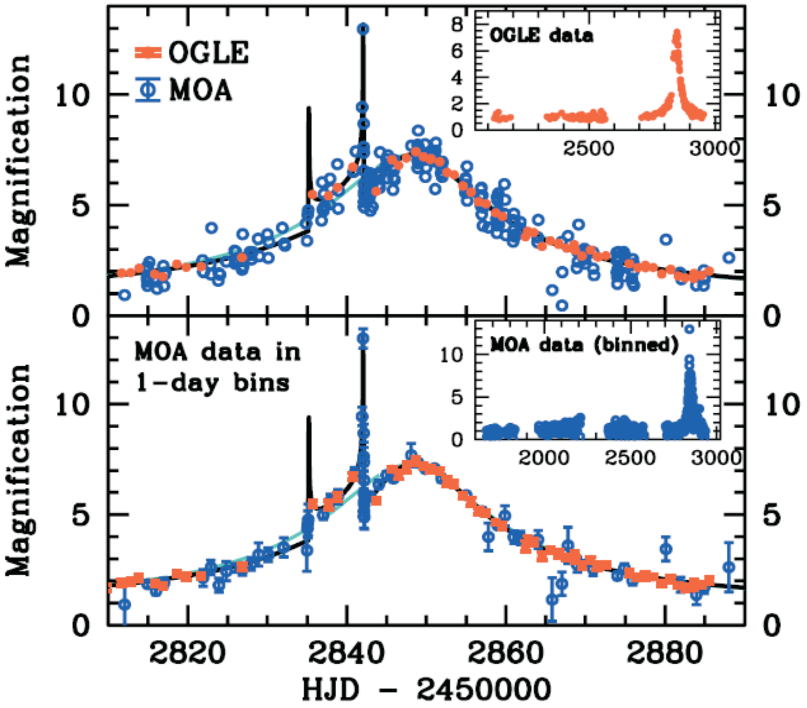
- Finite source size $\rho_* = \frac{\theta_*}{\theta_E}$



From lensing observables to physical parameters

- Finite source size $\rho_* = \frac{\theta_*}{\theta_E}$

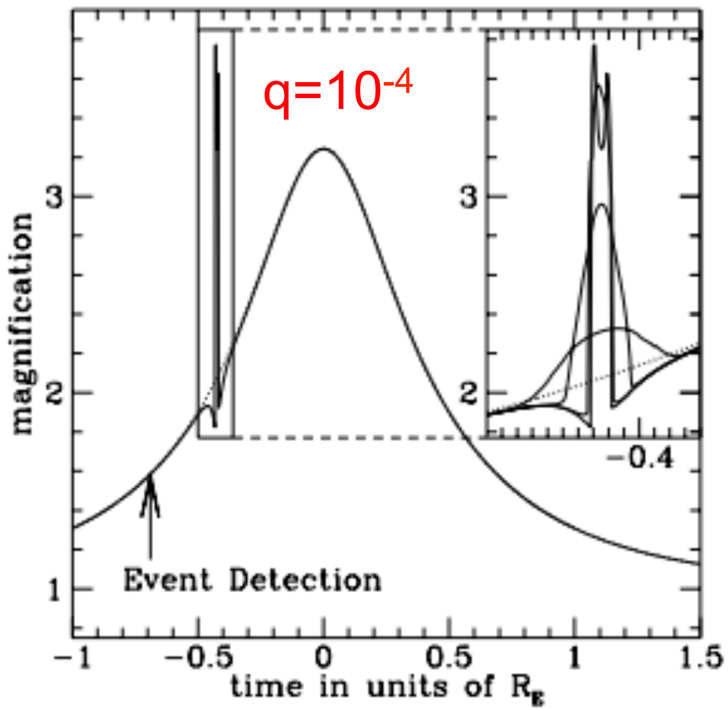




Bond et al. 2004

From lensing observables to physical parameters

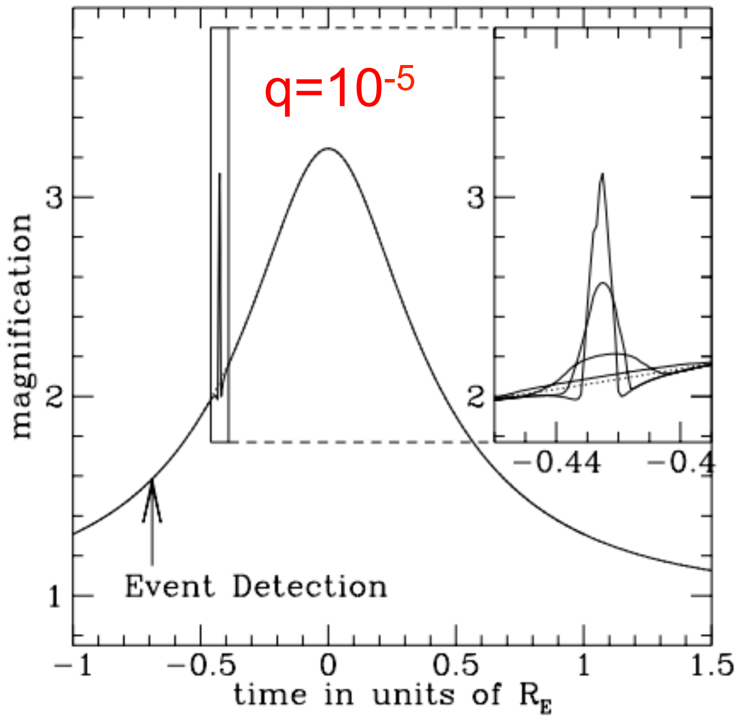
- Finite source size $\rho_* = \dfrac{\theta_*}{\theta_E}$

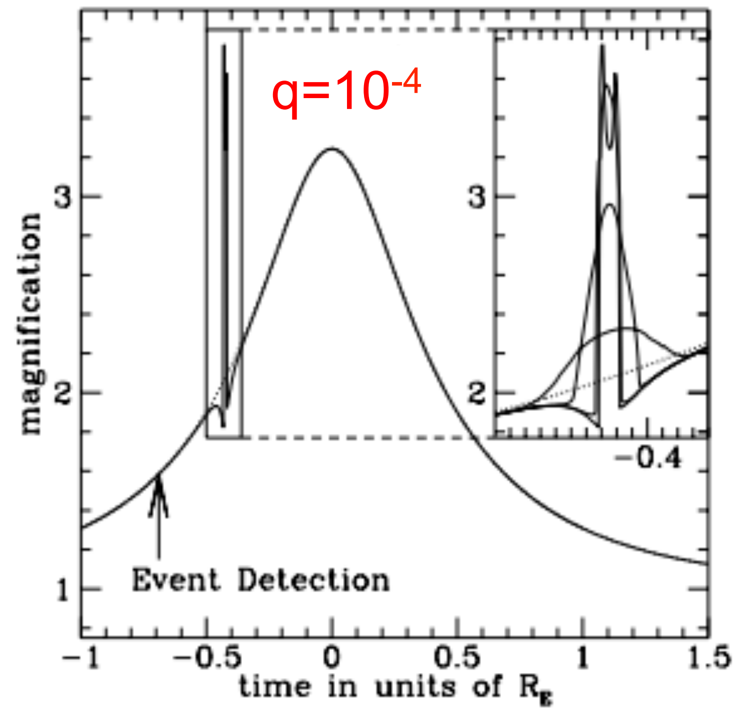


Bennett & Rhie 1996

From lensing observables to physical parameters

- Finite source size $\rho_* = \dfrac{\theta_*}{\theta_E}$



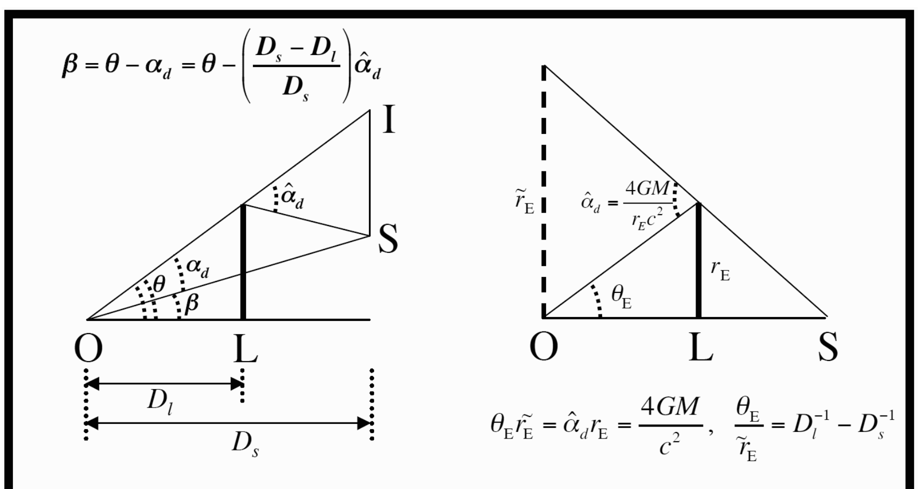


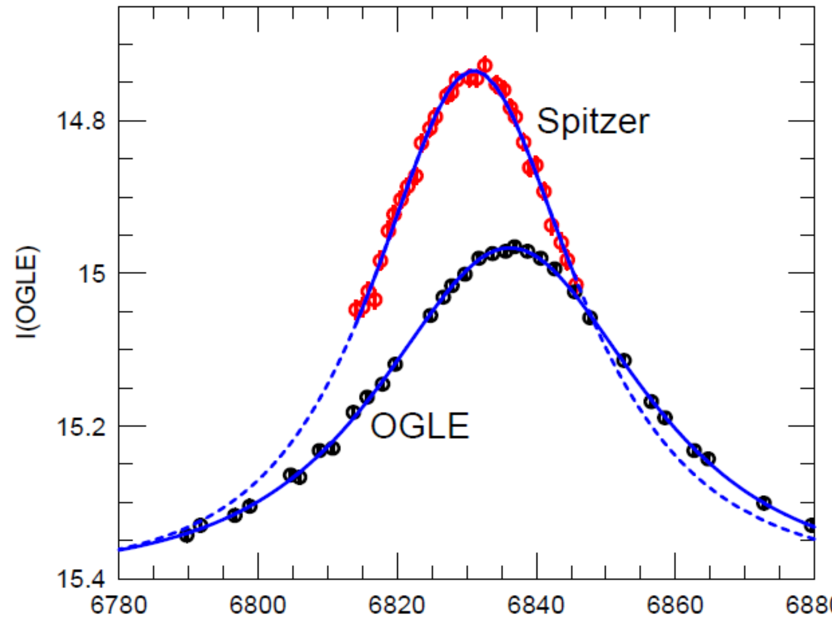
Bennett & Rhie 1996

From lensing observables to physical parameters

Satellite parallax

- Finite source size
- Microlens parallax $\pi_E = \frac{AU}{\tilde{r}_E}$



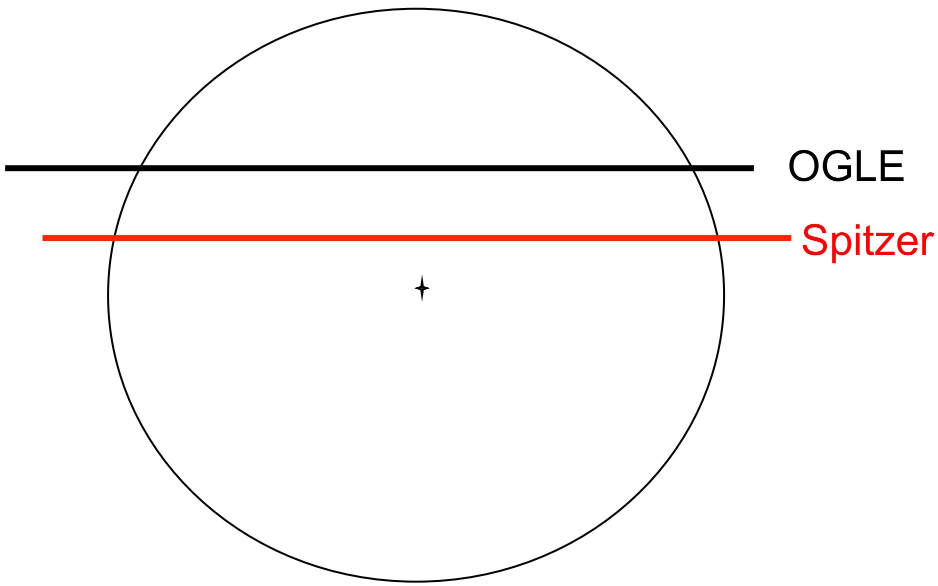


Yee et al. 2014

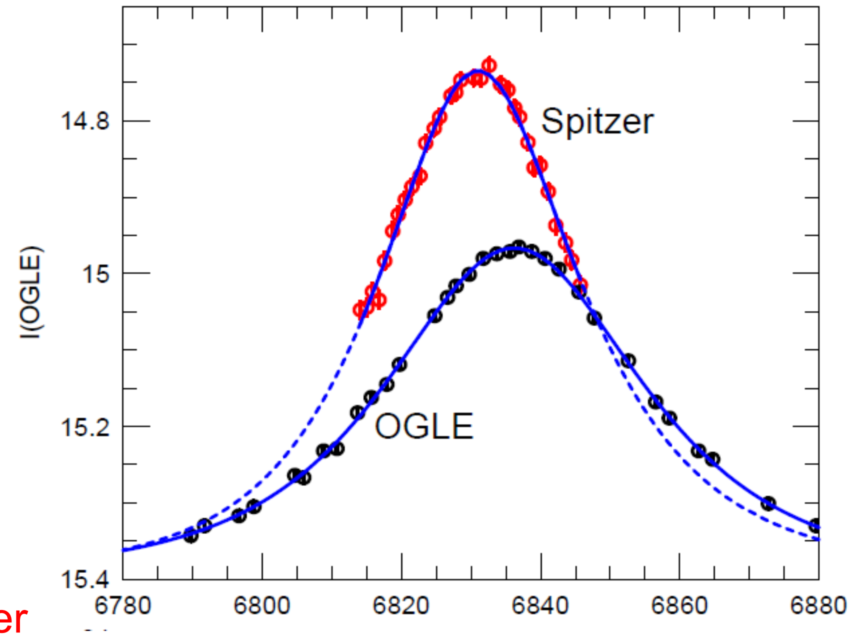
From lensing observables to physical parameters

- Finite source size
- Microlens parallax $\pi_E = \frac{AU}{\tilde{r}_E}$

Satellite parallax degeneracy



Satellite parallax

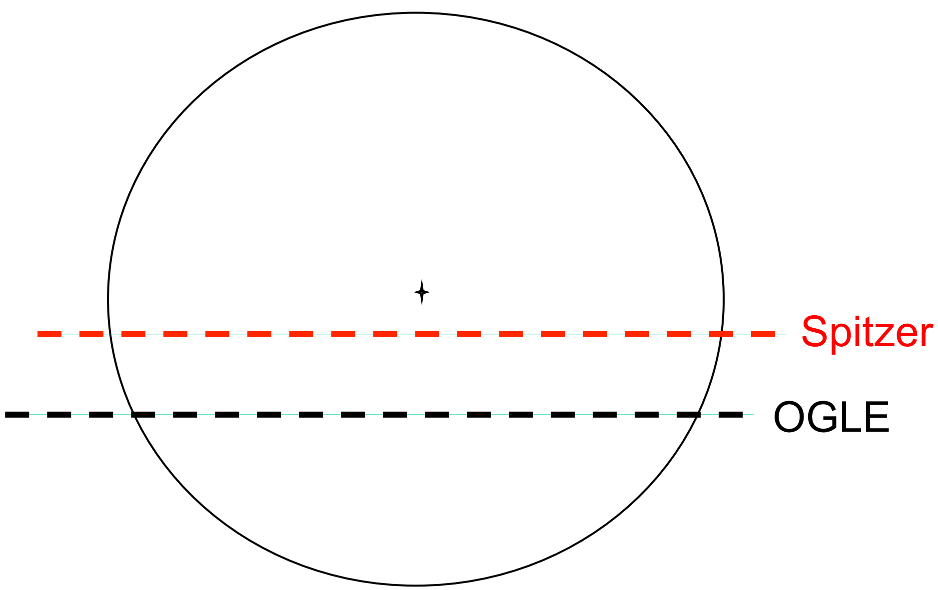


Yee et al. 2014

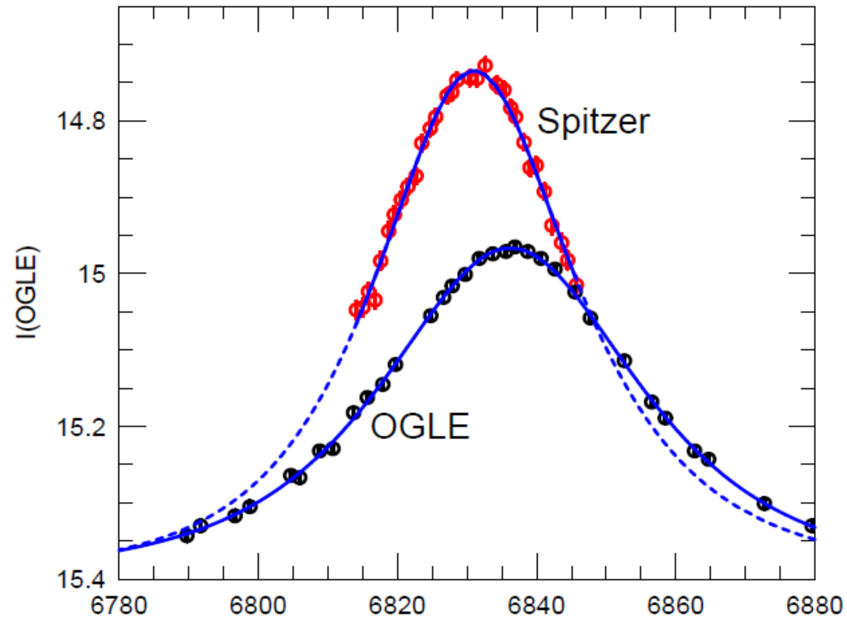
From lensing observables to physical parameters

- Finite source size
- Microlens parallax $\pi_E = \frac{AU}{\tilde{r}_E}$

Satellite parallax degeneracy



Satellite parallax



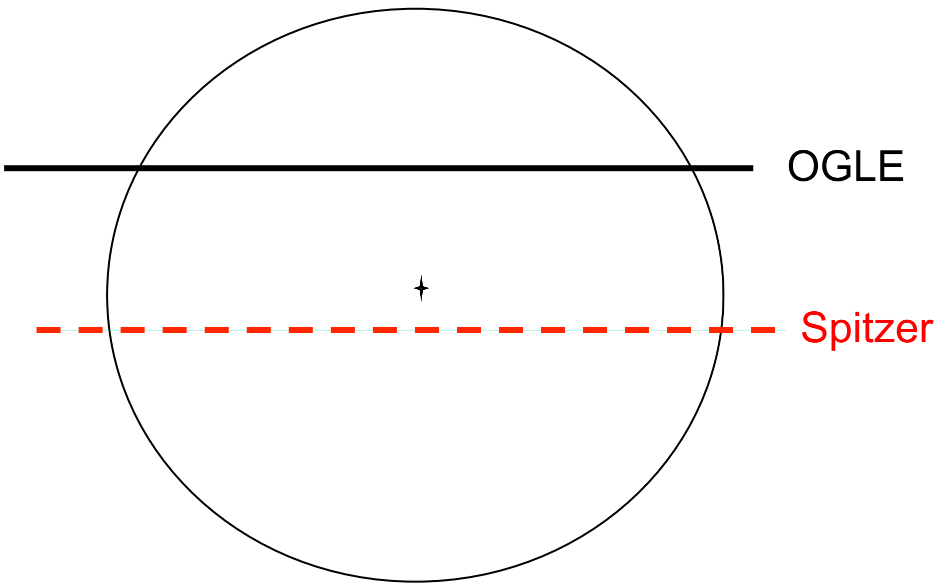
Yee et al. 2014

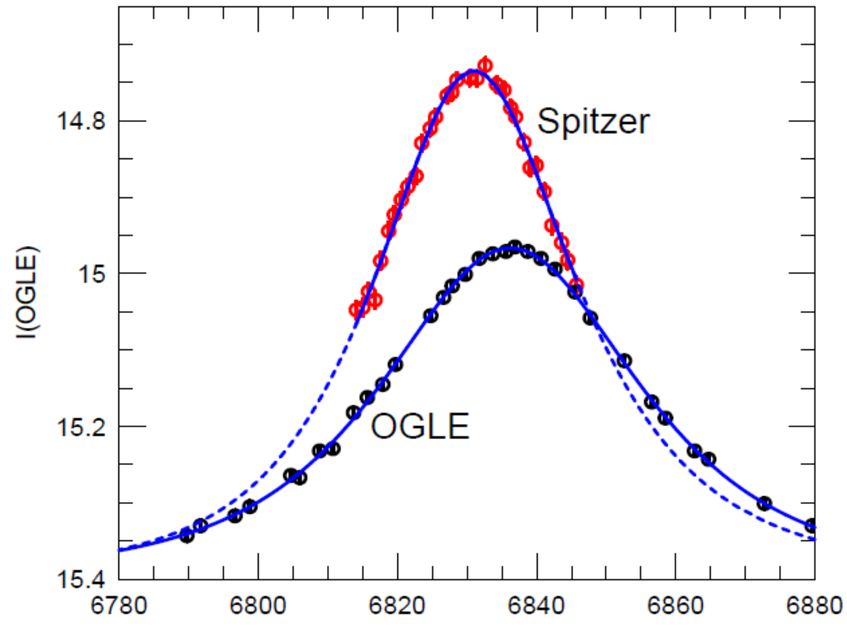
From lensing observables to physical parameters

Satellite parallax

- Finite source size
- Microlens parallax $\pi_E = \frac{AU}{\tilde{r}_E}$

<u>Satellite parallax degeneracy</u>



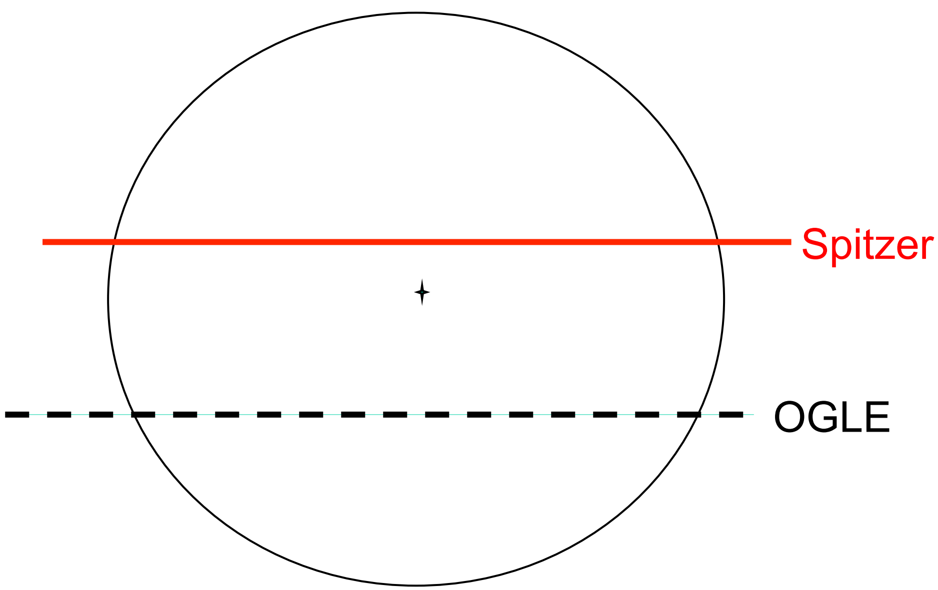


Yee et al. 2014

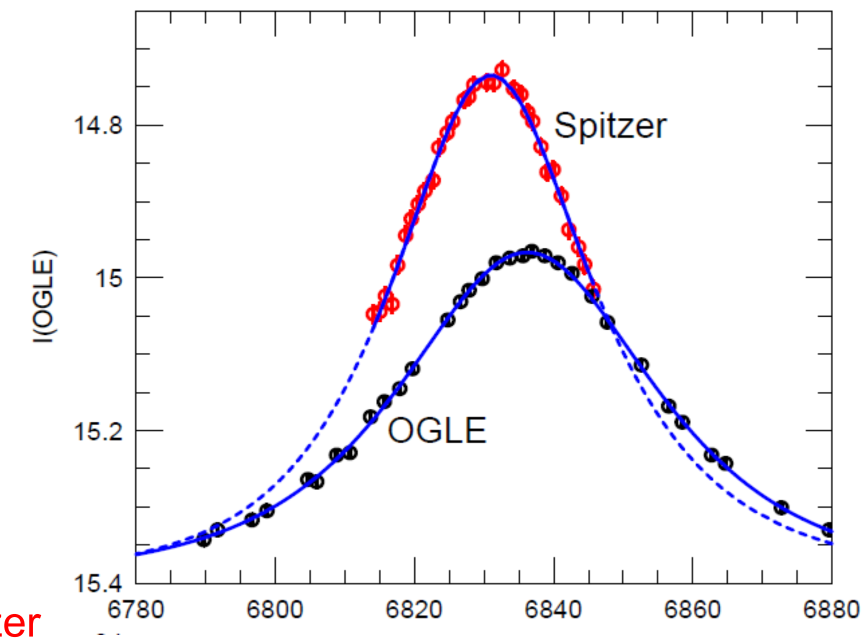
From lensing observables to physical parameters

- Finite source size
- Microlens parallax $\pi_E = \frac{AU}{\tilde{r}_E}$

Satellite parallax degeneracy



Satellite parallax



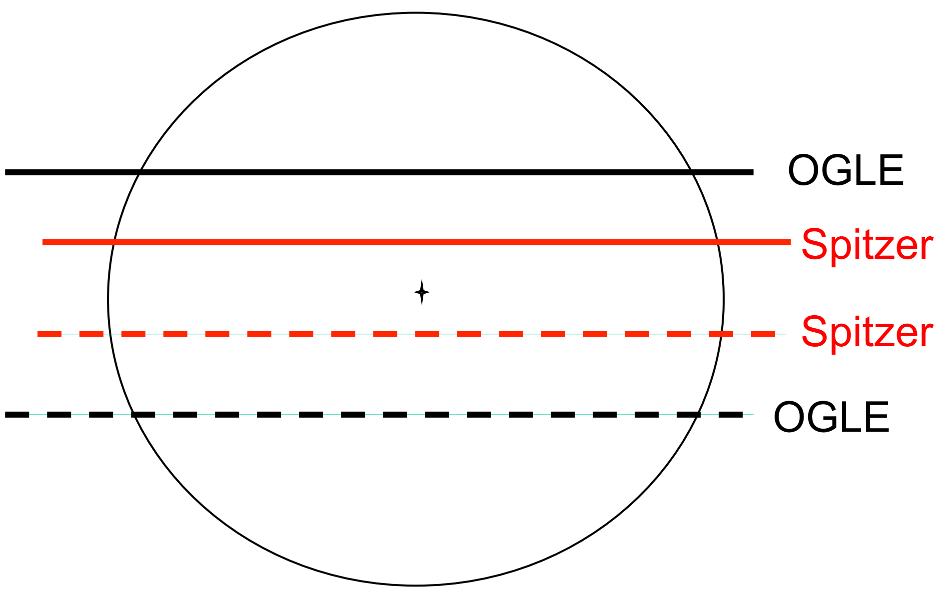
Yee et al. 2014

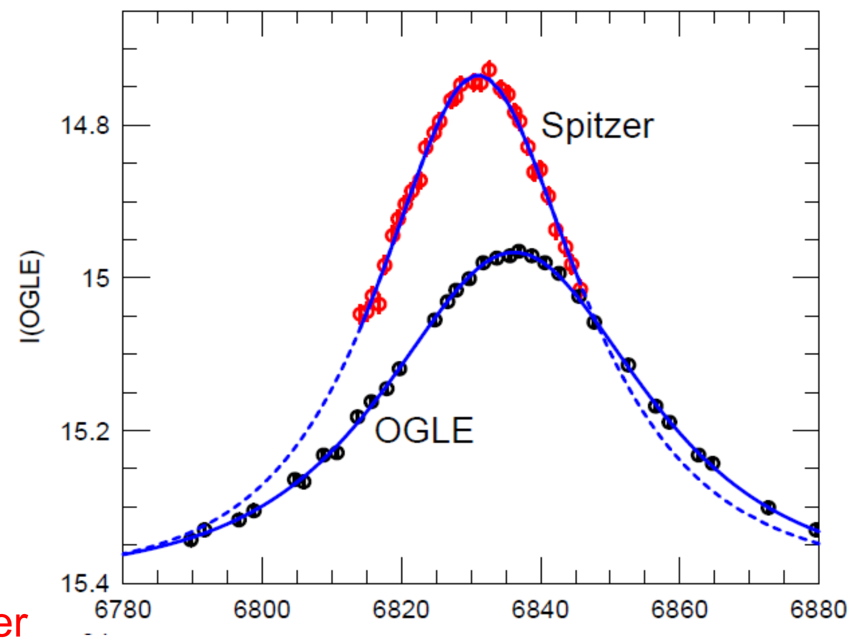
From lensing observables to physical parameters

Satellite parallax

- Finite source size
- Microlens parallax $\pi_E = \frac{AU}{\tilde{r}_E}$

Satellite parallax degeneracy





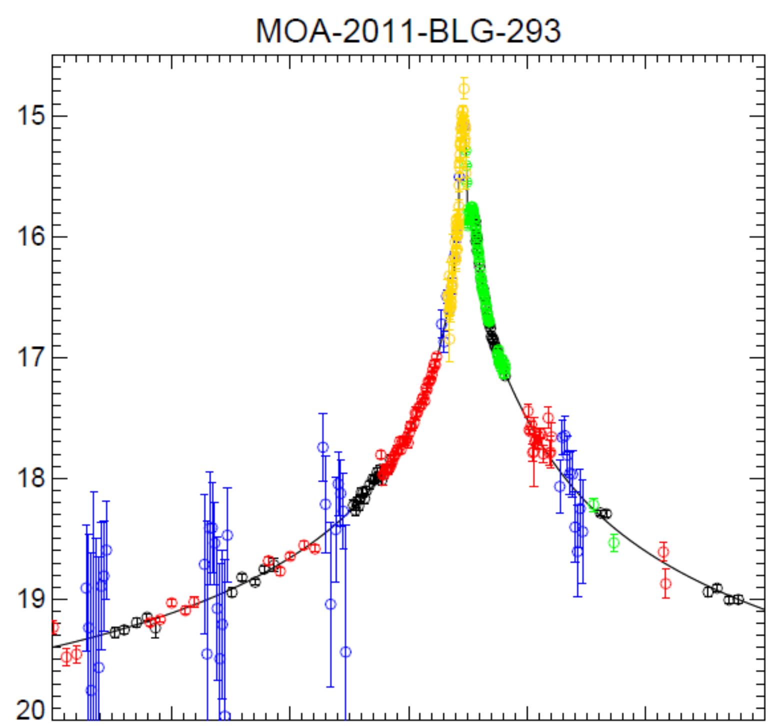
Yee et al. 2014

From lensing observables to physical parameters

- Finite source size
- Microlens parallax
- Lens flux

From lensing observables to physical parameters

- Finite source size
- Microlens parallax
- Lens flux
    - Source flux from model

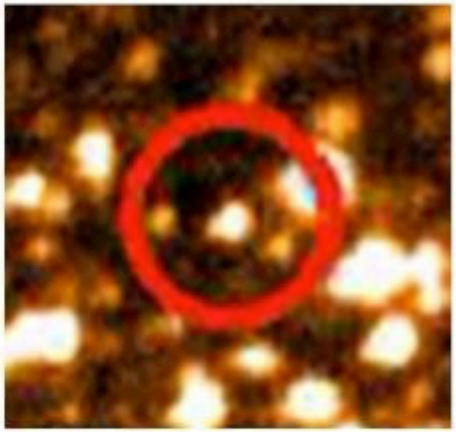


Yee et al. 2012

From lensing observables to physical parameters

- Finite source size
- Microlens parallax
- Lens flux
    - Source flux from model

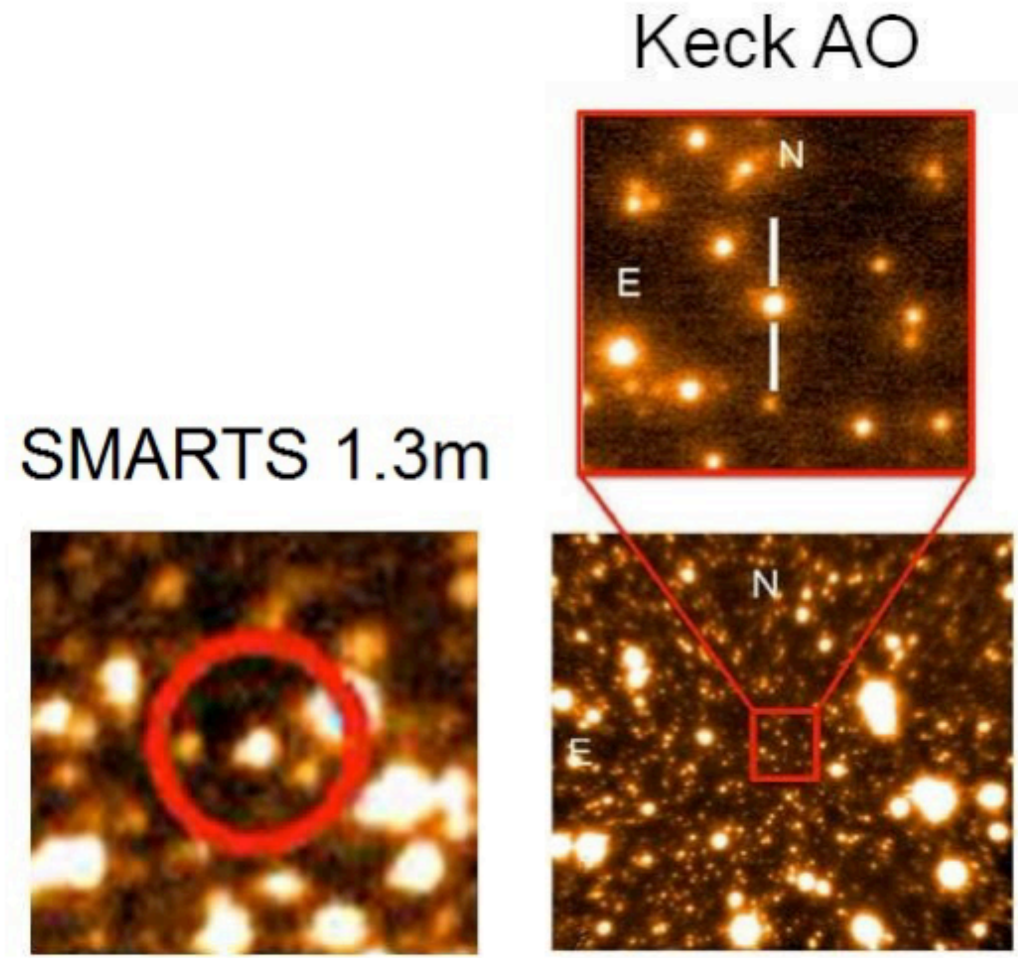
SMARTS 1.3m



Batista et al. 2014

From lensing observables to physical parameters

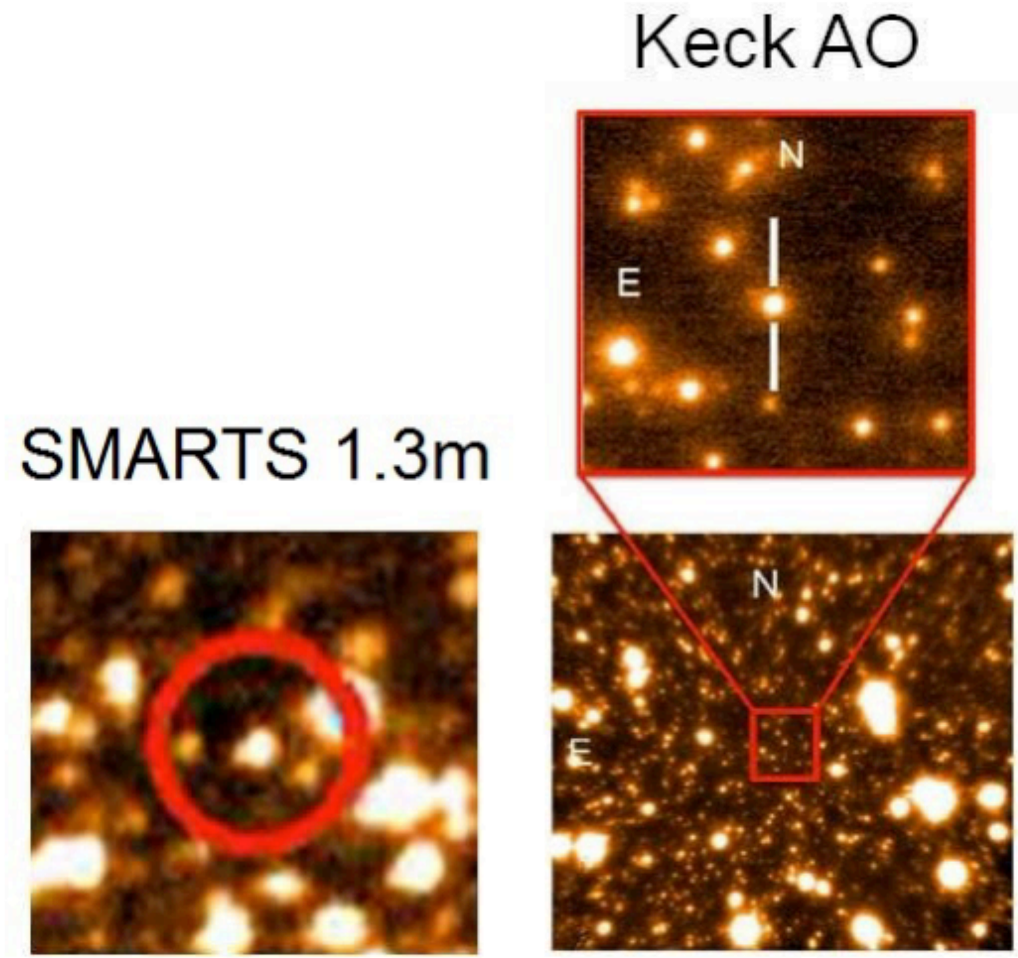
- Finite source size
- Microlens parallax
- Lens flux
    - Source flux from model
    - Source+lens flux from AO / HST



Batista et al. 2014

From lensing observables to physical parameters

- Finite source size
- Microlens parallax
- Lens flux
  - Source flux from model
  - Source+lens flux from AO / HST
  - Arithmetic……
  - Search for excess flux

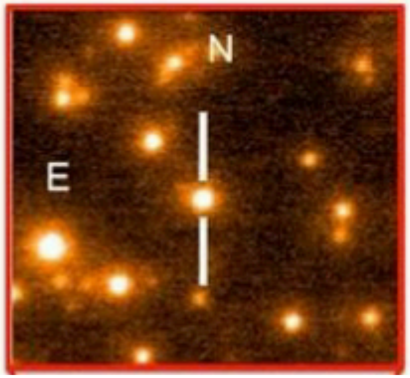


Batista et al. 2014

From lensing observables to physical parameters

- Finite source size
- Microlens parallax
- Lens flux
  - Source flux from model
  - Source+lens flux from AO / HST
  - Arithmetic……
  - Search for excess flux

Keck AO



<u>MOA-2011-293:</u>

Bayesian estimates:

⇒ M_L=0.43 M_{sun}, D=7.1 kpc

⇒ m_p=2.5 M_{Jup}, $r_\perp$=1.0/3.4 AU

Yee et al. 2012

From lens flux:

⇒ M_L=0.86 M_{sun}, D=7.7 kpc

⇒ m_p=4.8 M_{Jup}, $r_\perp$=1.1/3.6 AU

Batista et al. 2014

From lensing observables to physical parameters

- Finite source size
- Microlens parallax
- Lens flux
  - Source flux from model
  - Source+lens flux from AO / HST
  - Arithmetic……
  - Search for e…

Keck AO

First ML planet possibly in the habitable zone

<u>MOA-2011-293:</u>

Bayesi… …s:

… $0.43\ M_{sun}$, D=7.1 kpc

$\Rightarrow$ m_p=2.5 M_{Jup}, $r_\perp$=1.0/3.4 AU

Yee et al. 2012

From lens flux:

$\Rightarrow$ M_L=0.86 M_{sun}, D=7.7 kpc

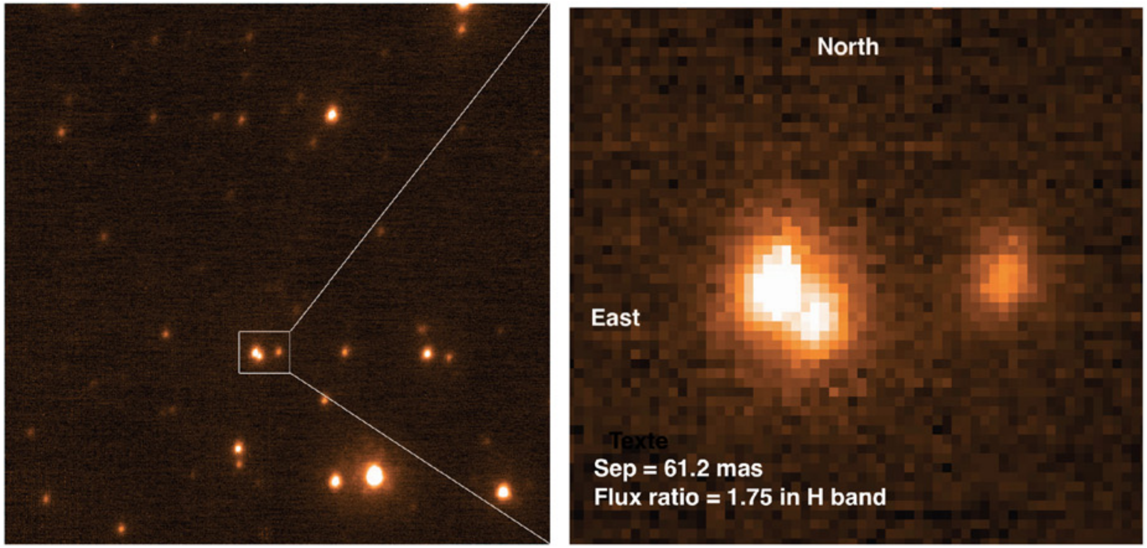
$\Rightarrow$ m_p=4.8 M_{Jup}, $r_\perp$=1.1/3.6 AU

Batista et al. 2014

From lensing observables to physical parameters

- Finite source size
- Microlens parallax
- Lens flux
    - Source flux from model
    - Source+lens flux from AO / HST
    - Arithmetic……
    - Search for excess flux
    - Source-lens separation

8.2 years after event OGLE-2005-169….



Batista et al. 2014

Microlensing basics

Planet-Star mass ratio

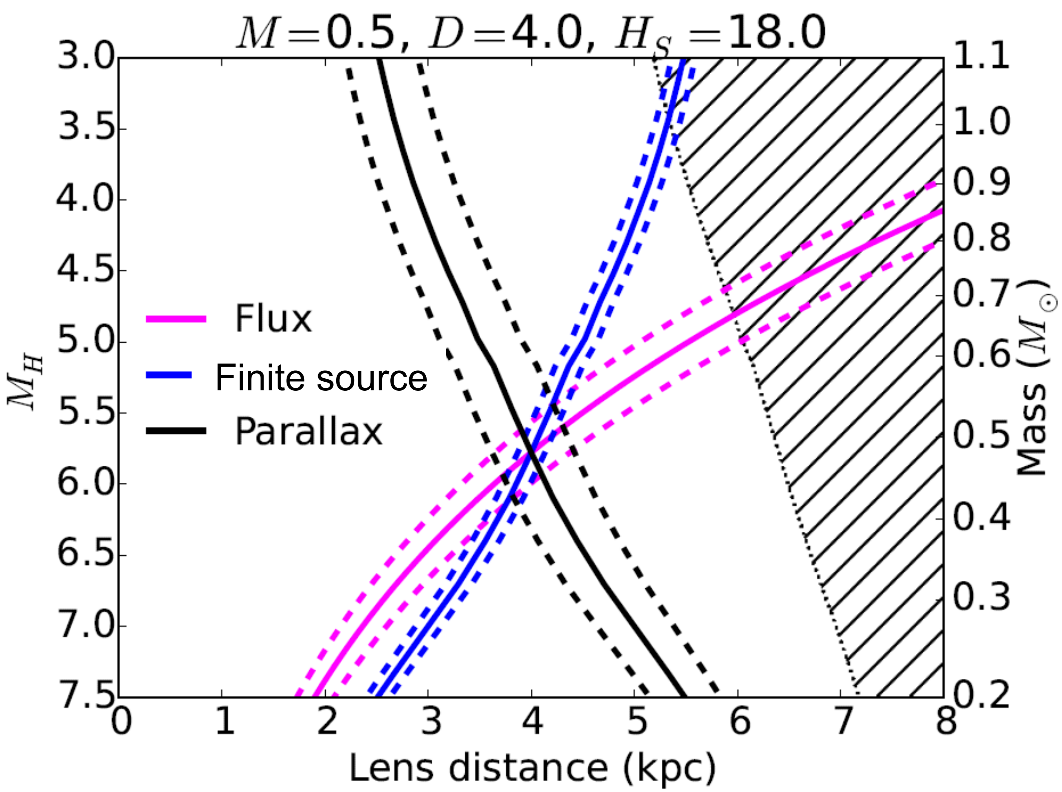
$$q = \frac{M_P}{M_L}$$

Planet-Star separation

$$s = \frac{a_\perp}{r_E}$$

Event timescale

$$t_E\left(M_L, D_L, D_S, \mu_{rel}\right) = \frac{\theta_E}{\mu_{rel}}$$

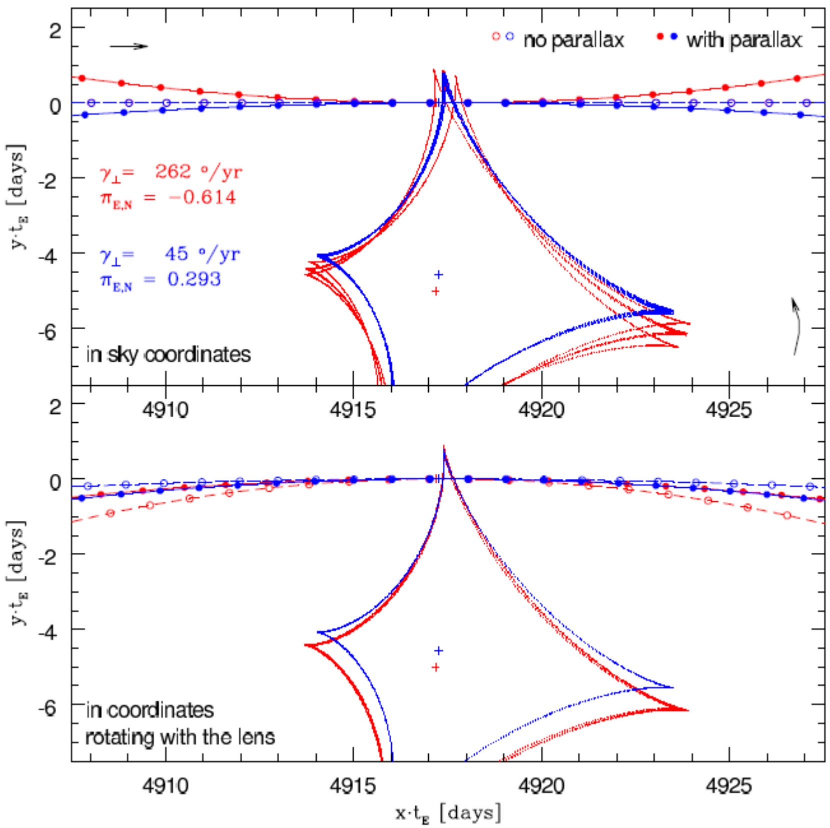


Yee 2015

Full Keplerian solution

Keplerian proposal

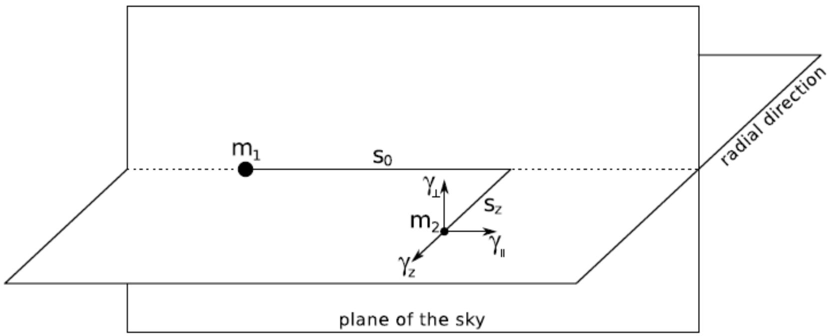
Lensing system orbital motion

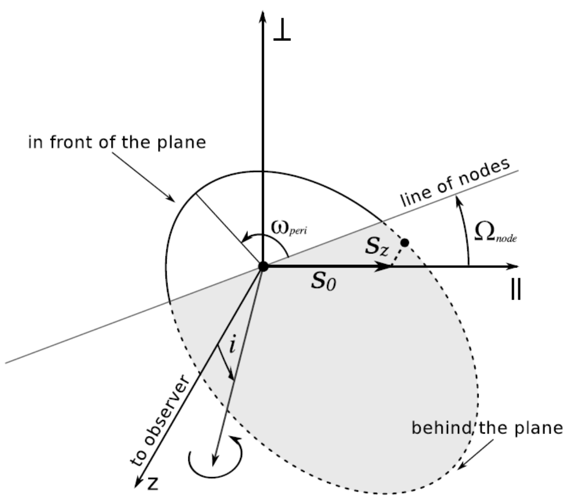


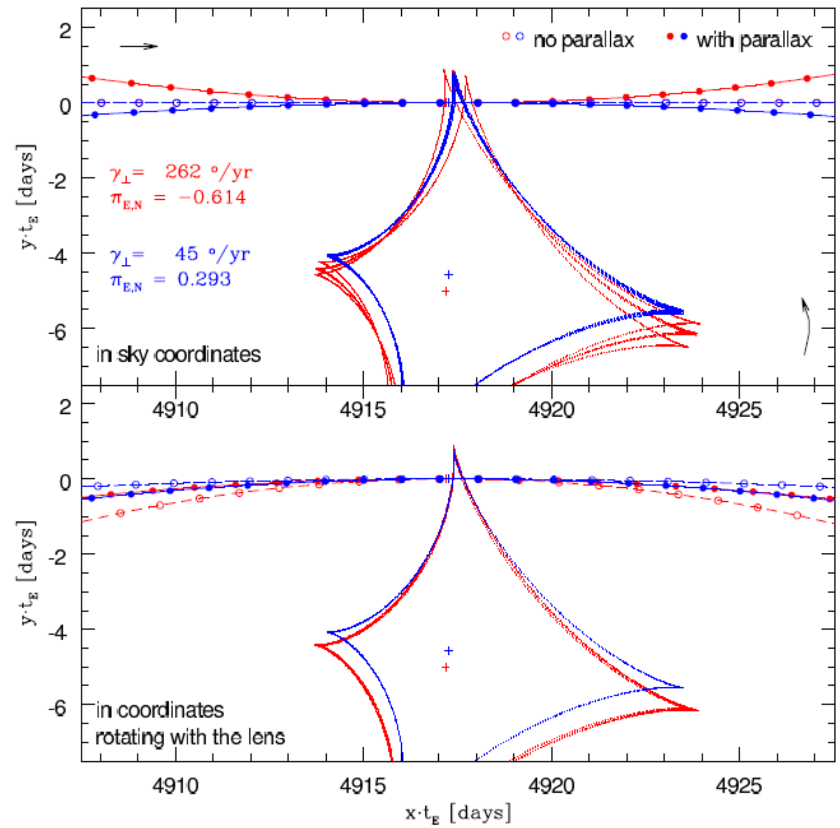
Skowron et al. 2011

Keplerian proposal

Lensing system orbital motion







Skowron et al. 2011


Ushering in the New Age of Microlensing from Space
February 1-3, 2017 • Pasadena Sheraton, Pasadena, CA
21st International Microlensing Conference
January 31, 2017 • Caltech, Pasadena, CA
1/2 day Microlensing Workshop
• Breaking results from K2's Campaign 9
• Progress in Spitzer's program of obtaining satellite parallaxes
• Ground-based surveys and advances in theory
• The revolutionary promise of the WFIRST mission for exoplanet science
SCIENTIFIC ORGANIZING COMMITTEE
Rachel Street, Chair (LCOGT)
Rachel Akeson (NExScI)
Tom Barclay (NASA Ames)
Jean-Philippe Beaulieu (IAS)
David Bennett (GSFC)
Valerio Bozza (University of Salerno)
Geoff Bryden (JPL)
Sean Carey (IPAC)
Scott Gaudi (Ohio State)
Andrew Gould (Ohio State)
Matthew Penny (Ohio State)
Takahiro Sumi (University of Osaka)
Motohide Tamura (University of Tokyo)
Andrzej Udalski (Warsaw University)
Jennifer Yee (Harvard-Smithsonian Center for Astrophysics)
http://nexsci.caltech.edu/conferences/2017/microlensing
mlens2017@ipac.caltech.edu