Gravitational Microlensing:

A powerful method for the detection of extrasolar planets

Joachim Wambsganss

(ZAH – Zentrum für Astronomie der Universität Heidelberg)

June 6, 2011

Bad Honnef

Gravitational Microlensing:

A powerful method for the detection of extrasolar planets

- Basics of Gravitational Microlensing
- Searching for Extrasolar Planets
- Searching for Extrasolar Planets with Microlensing ?
- Searching for Extrasolar Planets with Microlensing !
- **Finding Extrasolar Planets with Microlensing**
- Current Status & Future Directions of Microlensing

Gravitational Microlensing

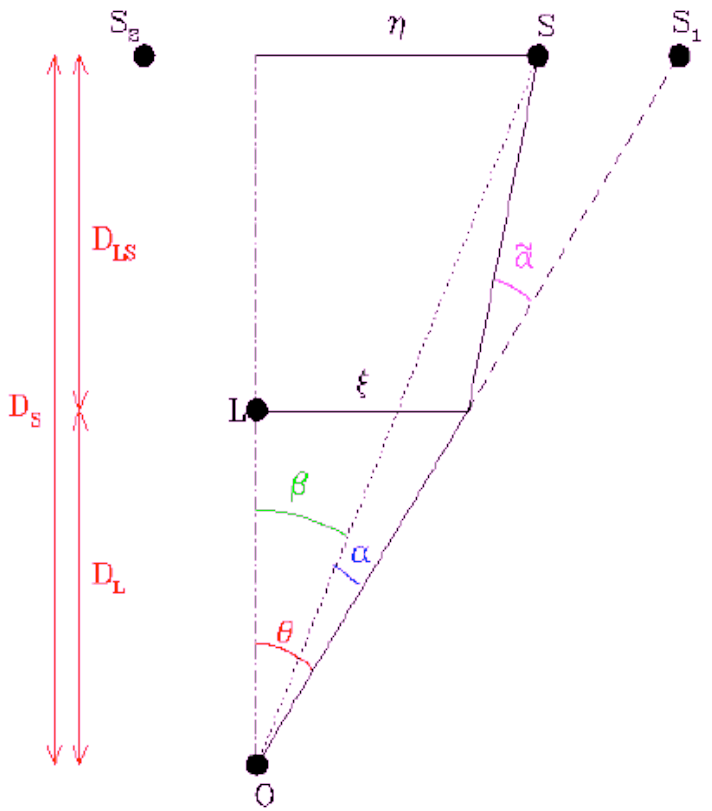
Einstein 1936:

DECEMBER 4, 1936 — SCIENCE

LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

"There is not great chance of observing this phenomenon."

Gravitational Lensing

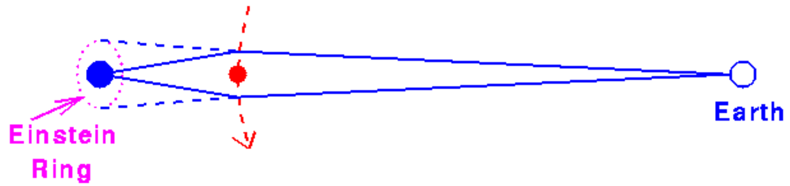


"Lens equation":

$$\vec{\theta} D_S = \vec{\beta} D_S + \vec{\hat{\alpha}} D_{LS}$$

Einstein radius:

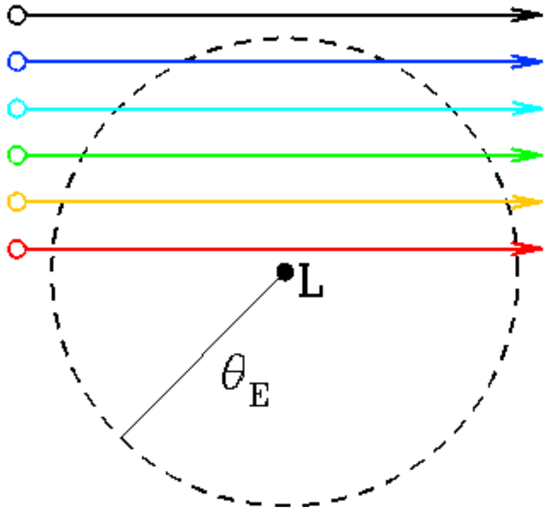
$$\theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S}}$$



Einstein radius for star in Milky Way:

$$\theta_E \approx 0.5 \sqrt{\frac{M}{M_\odot}} \text{ milliarcsec}$$

Galactic Microlensing

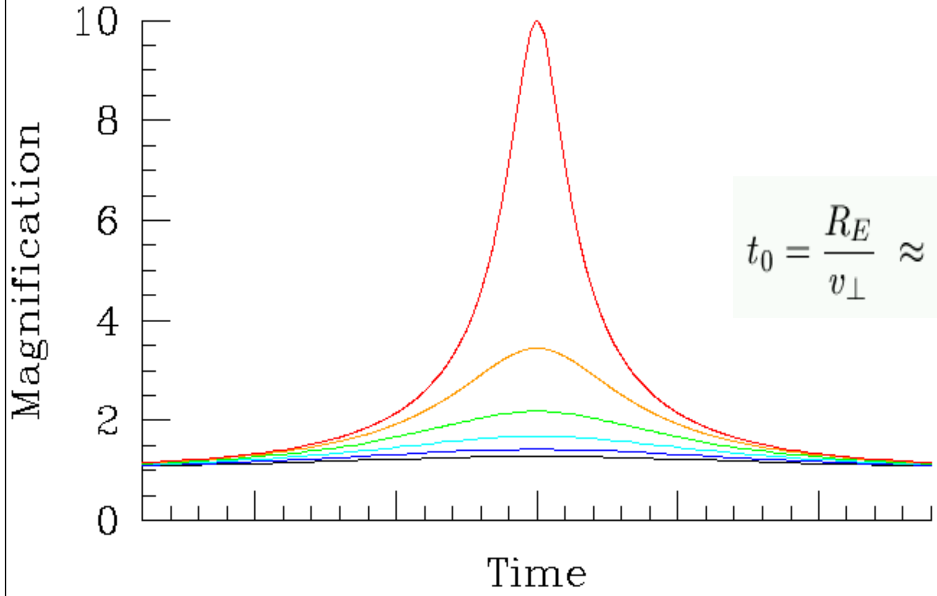


Einstein (1936), Paczynski (1986):

$$\mu_{1,2} = \left(1 - \left[\frac{\theta_E}{\theta_{1,2}}\right]^4\right)^{-1} = \frac{u^2+2}{2u\sqrt{u^2+4}} \pm \frac{1}{2}$$

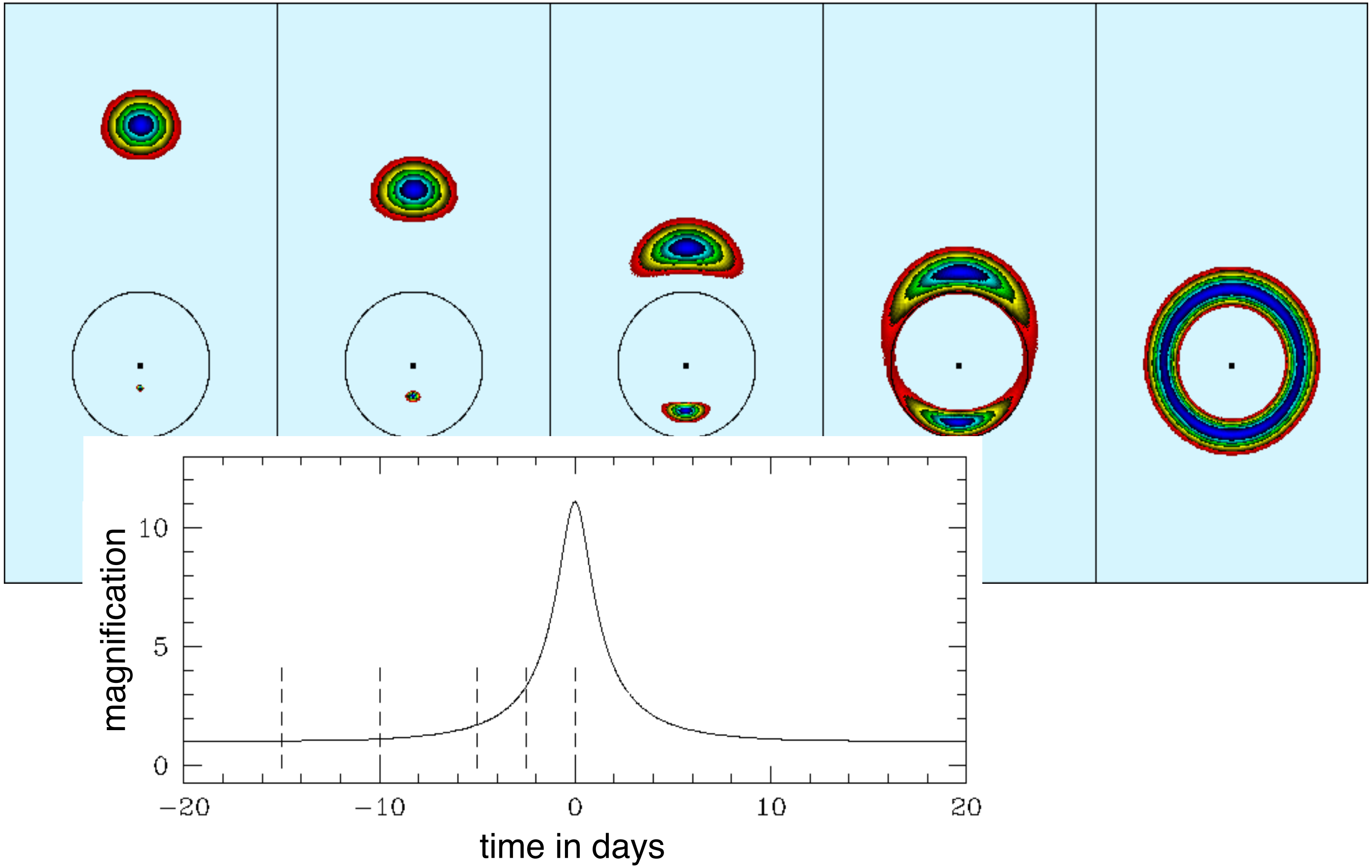
(where $u = \beta/\theta_E$)

$$\mu = \mu_1 + \mu_2 = \frac{u^2+2}{u\sqrt{u^2+4}}$$



$$t_0 = \frac{R_E}{v_\perp} \approx \; 0.214 \; \text{yr} \; \sqrt{\frac{M}{M_\odot}} \sqrt{\frac{D_L}{10\text{kpc}}} \sqrt{1 - \frac{D_L}{D_S}} \left(\frac{v_\perp}{200\text{km/sec}}\right)^{-1}$$

Galactic Microlensing



unresolved lightcurve

What is Gravitational **Micro**lensing?

Gravitational microlensing is the action of **compact** objects of **small mass** along the line of sight to **distant sources**

what is “small mass” ?

$\Rightarrow \quad 10^{-6} < M/M_\odot < 10^3$

what is “compact” ?

⇒ (much) smaller than Einstein radius

what are the “distant sources”?

⇒ quasars, stars

How can we observe *micro*-lensing ?

Einstein angle ($\theta_E = 0.5 \sqrt{(M/M_\odot)}$ milliarcsec) << telescope resolution !

$\Rightarrow$ image splitting not directly observable!

However, microlensing affects:

- **apparent magnitude (magnification)**
- (emission/absorption line shape)
- center-of-light position

AND these effects change with time due to relative motion of source, lens and observer:

$\Rightarrow$ microlensing is a **dynamic** phenomenon! It is observable:

- **photometrically**
- (spectroscopically)
- astrometrically

Galactic Microlensing

- Microlensing by stars in the Milky Way (Halo):
  proposed by Paczynski (1986) as a test for compact dark matter

- Idea:
  - monitor (background) stars in LMC or Milky Way Bulge
  - occasionally a random (foreground) star passes in front and magnifies background star in characteristic way
  - problem: **very** small probability for stellar ML events (of order $\mathbf{10^{-6}}$)

THE ASTROPHYSICAL JOURNAL, 374:L37–L40, 1991 June 20

Microlensing by Planets (Mao & Paczynski 1991):

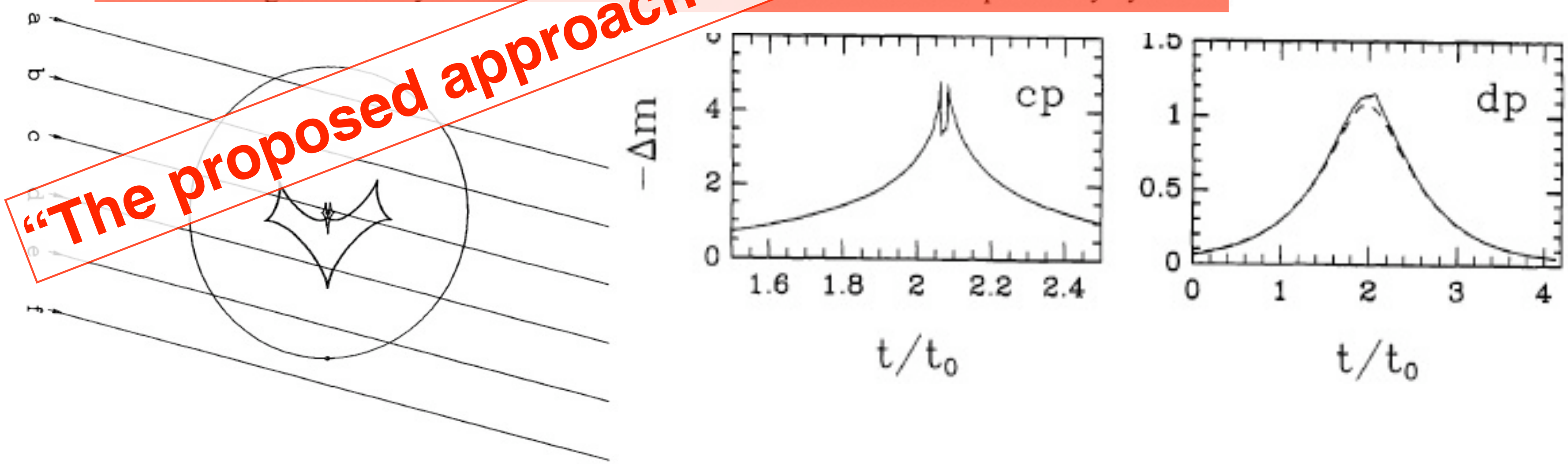
GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

SHUDE MAO AND BOHDAN PACZYŃSKI
Princeton University Observatory, Princeton, NJ 08544
Received 1991 March 12; accepted 1991 April 2

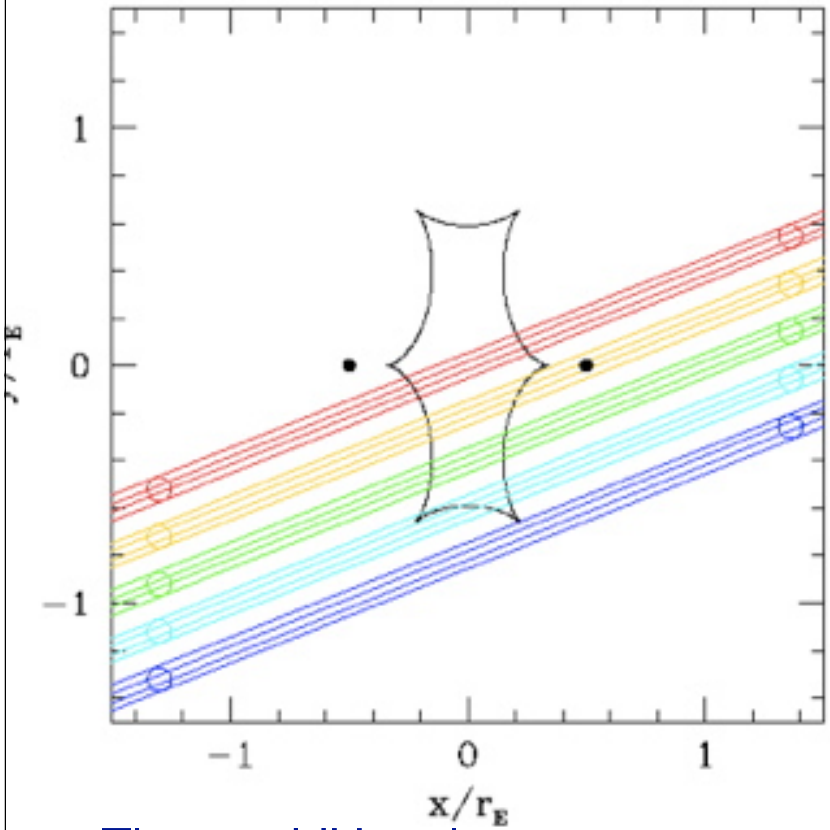
ABSTRACT

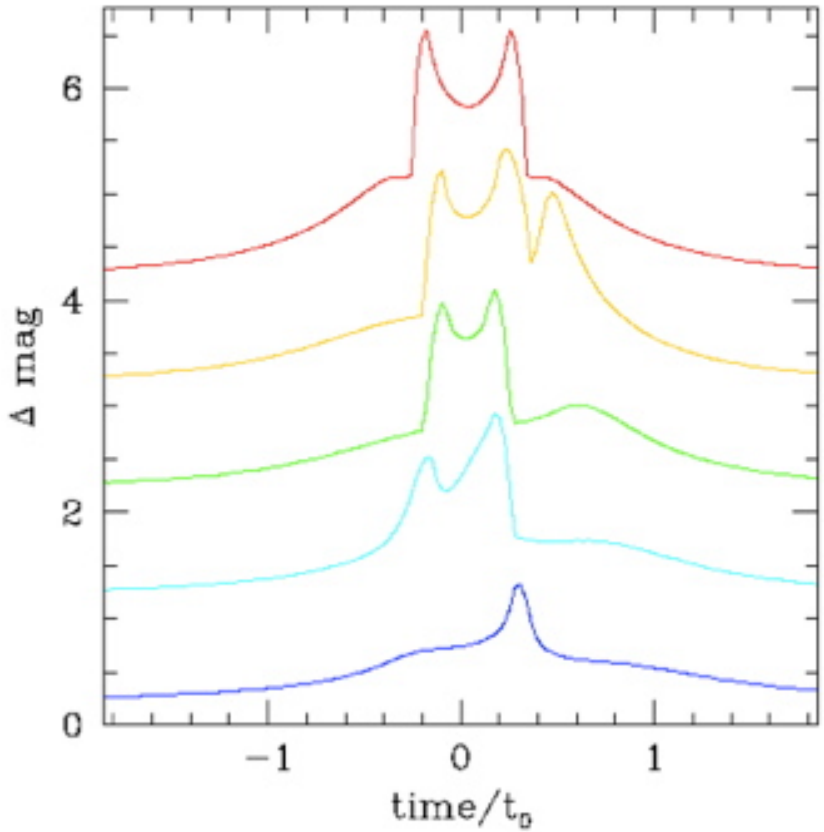
Almost all stars are in binary systems. When the separation between the two components is comparable to the Einstein ring radius corresponding to the combined mass of the binary acting as a gravitational lens, then an extra pair of images can be created, and the light curve of a lensed source becomes complicated. We estimate that ~10% of all lensing episodes of the Galactic bulge stars will strongly display the binary nature of the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems.

"The proposed approach is difficult, but not hopeless."



Microlensing by Double Lenses
(Mao & Paczynski 1991, Sackett 1995):





Three additional parameters:

1) mass ratio q
2) separation d
3) angle Φ

⇒ very large variety of light curves!

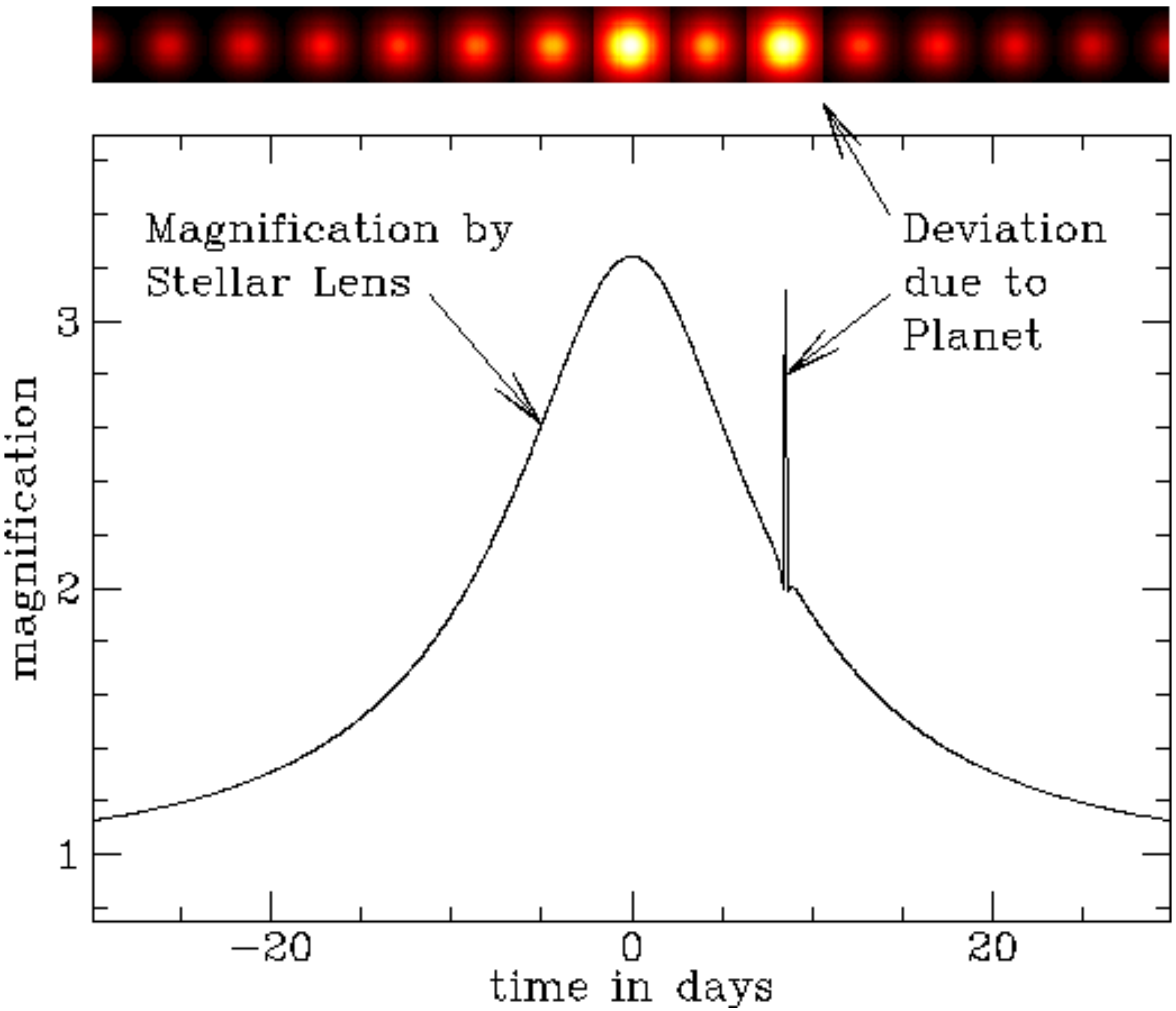
Microlensing by Planets (Mao & Paczynski 1991):

In Gravitational Lensing:

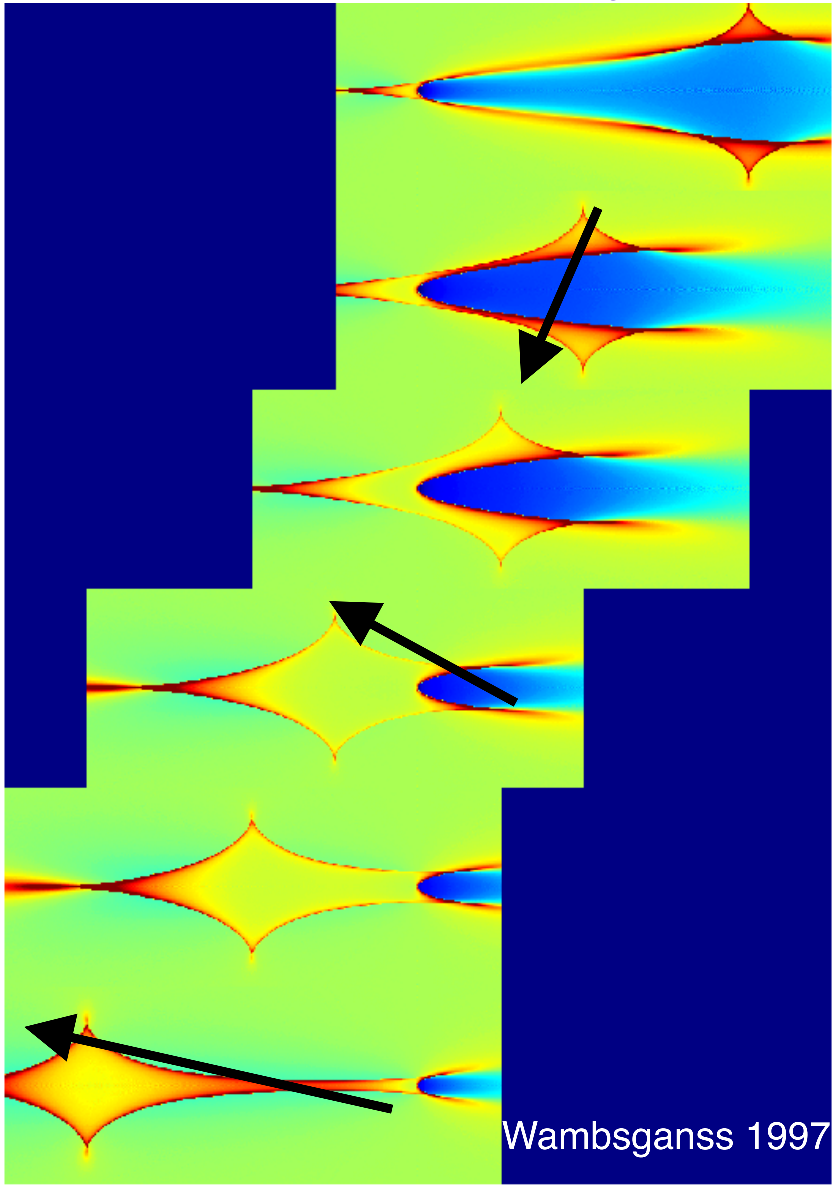
$$2 \neq 1 + 1$$

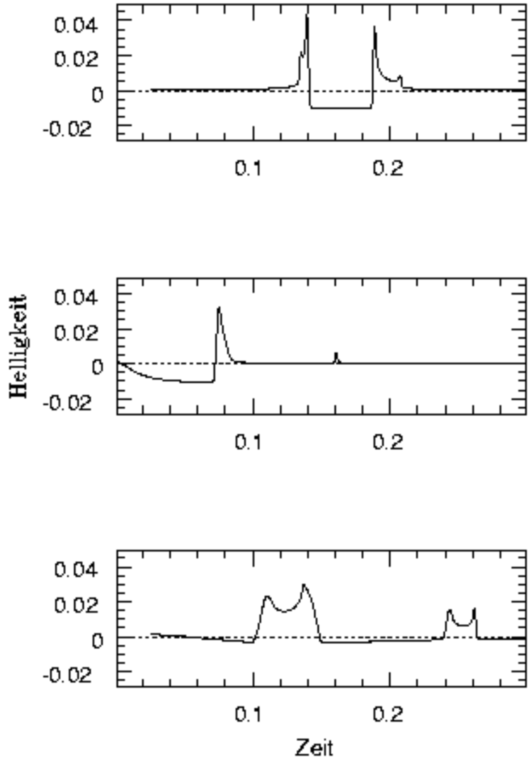
$$2 \gg 1 + 1$$

Microlensing by Planets (schematically):



Microlensing by Planets (quantitatively):

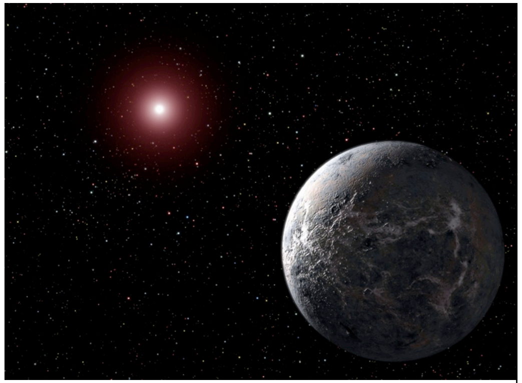




Saturn-like planet at about 1 AU
("resonant lensing")

Typical duration of planetary deviation:
10 - 30 hours !!!

Searching for Extrasolar Planets



First discovery in 1995 (Mayor & Queloz), >550 exoplanets known as of June 6, 2011, various search techniques employed:

⇒ **Francesco Pepe & Michael Perryman**

- radial velocity measurements (»Doppler-Wobble«): **high precision** spectroscopy ⇒ **Artie Hatzes**
- positional measurements: **high precision** astrometry
- brightness measurements: **high precision** photometry
  - transits (temporarily getting fainter) ⇒ **Magali Deleuil**
  - gravitational microlensing (temporarily getting brighter)
- pulsar timing: **high precision** time measurements
- direct imaging: **high precision**, high contrast imaging

⇒ **http://exoplanet.eu**

Searching for Extrasolar Planets

First discovery in 1995 (Mayor & Queloz), >550 exoplanets known as of June 6, 2011, various search techniques employed:

⇒ **Francesco Pepe & Michael Perryman**

- radial velocity measurements (»Doppler-Wobb…
  high precision spe… …ie Hatzes
- positional measur…
- bri…
  …Deleuil
- pulsa… …easurements
- direct … **precision**, high contrast imaging

Defining and cataloging exoplanets: The exoplanet.eu database

J. Schneider[1], C. Dedieu[2], P. Le Sidaner[2], R. Savalle[2], and I. Zolotukhin[234]

arXiv:1106.0586v1 [astro-ph.EP] 3 Jun 2011

⇒ **http://exoplanet.eu**

Searching for Exo-Planets with Microlensing?

Apparently a method with a lot of "disadvantages":

- probability for individual planet-lensing event very small: $\lesssim 10^{-8}$/star !
- duration of planetary deviation very short: (few) days → hours !
- planets are very distant (few kpc):
  - exact distance determination difficult/impossible !
  - subsequently no detailed investigation of planet possible !
- lightcurve shapes very diverse, characterization difficult, sometimes no unique relation to planet parameters !
- "one-and-only" event: no independent confirmation possible !

Searching for Exo-Planets with Microlensing?

Having heard all this,
why would anyone bother using

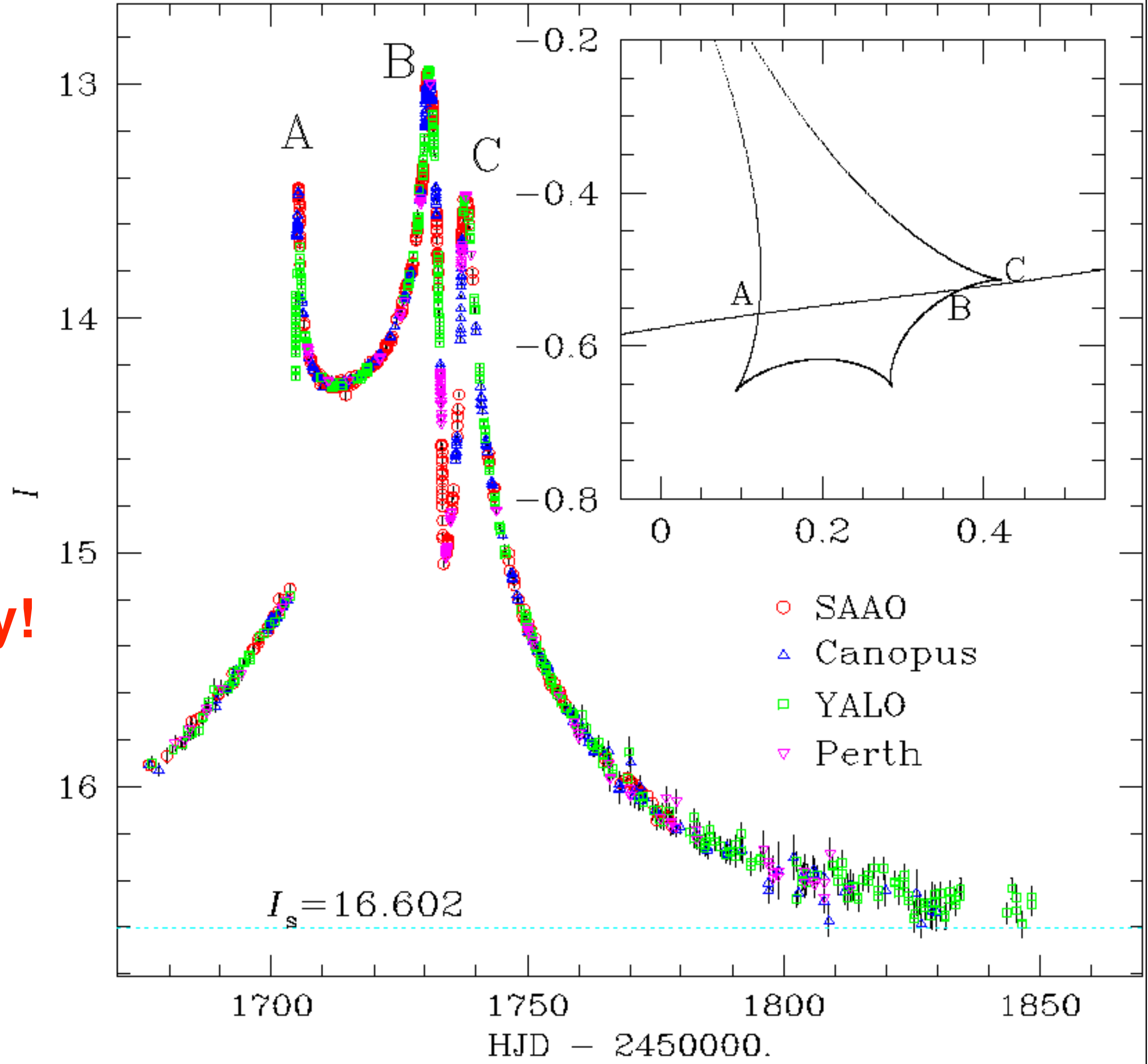
gravitational microlensing

in the search for extrasolar planets **???**

Searching for Exo-Planets with Microlensing!

"One-and-only" event:

no independent
confirmation ~~possible?~~
necessary!



Searching for Exo-Planets with Microlensing!

~~Apparently a method with a lot of "disadvantages":~~

These issues are no real problems:

- probability for individual planet-lensing event very small: $\lesssim 10^{-8}$ / star ! **yes, so what?**
- duration of planetary deviation very short: (few) days → hours ! **yes, so what?**
- planets are very distant (few kpc):
  - exact distance determination difficult/impossible ! **yes, possible!**
  - subsequently no detailed investigation of host star or planet possible ! **(partly possible!)**
- lightcurve shapes very diverse, characterization difficult, sometimes no unique relation to planet parameters ! **possible with good coverage!**
- "one-and-only" event: no independent confirmation possible ! **what about SNe or GRBs?**

.... just a question of coverage and signal-to-noise !!!

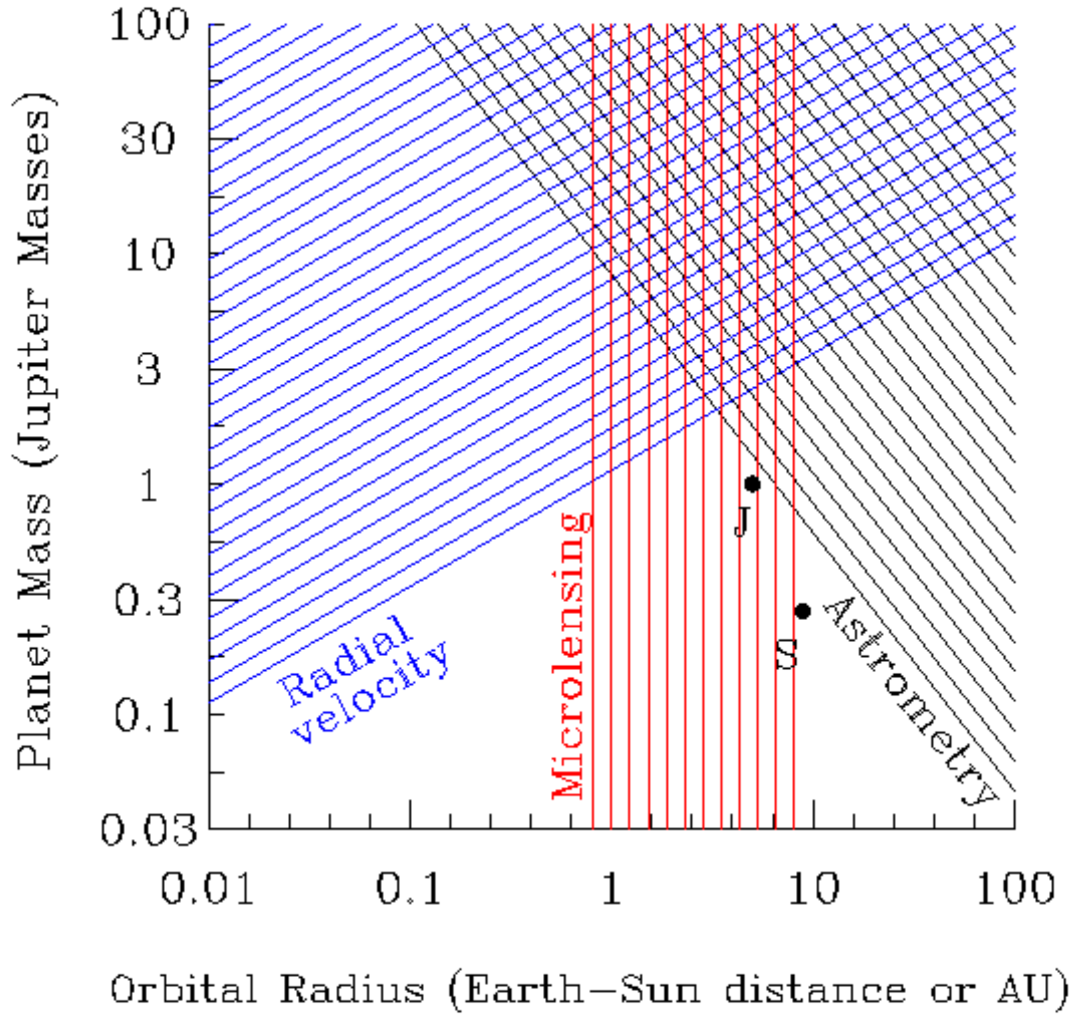
Searching for Exo-Planets with Microlensing!
The Advantages

- no bias for nearby stars
- sensitive to **ALL planet host stars** (no bias for planets around solar-type/main sequence stars)
- no strong bias for planets with large masses/short periods
- instantanous detection of (relatively) **large semi-major axes**
- Earth-bound observations sensitive down to **(almost) Earth-masses**
- most sensitive for planets within "**lensing zone**" (roughly corresponding to 0.5 AU $\leq a \leq$ 2.0 AU), overlap with "habitable zone"
- **multiple planet systems** detectable with high-magnification events
- only technique that can detect "**free-floating planets**"
- ultimately best **statistics** of galactic population of planets

$\Rightarrow$ Microlensing is a **very powerful/promising** method AND **complementary** to other planet search techniques!

Searching for Exo-Planets with Microlensing!

The Advantages



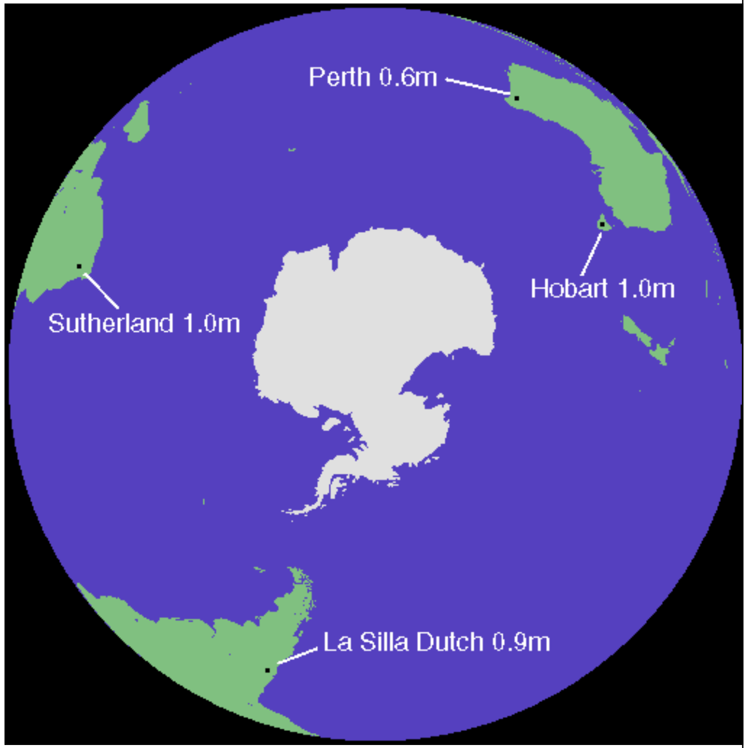
Searching for Exo-Planets with Microlensing!

The Strategy and the Teams

- Monitoring > 100 millions of bulge stars few times per week, use image subtraction, alert community on "anomalies":
  - **OGLE** - **O**ptical **G**ravitational **L**ens **E**xperiment: monitors 170 million stars regularly (!); about 800 alerts/season, 1.3m telescope (Chile)
  - **MOA** - **M**icrolensing **O**bservations in **A**strophysics: similar strategy, new 1.8m telescope (NZ), about 500 alerts/season
- Follow-up Networks: monitor "alerted events" with high frequency (few times per hour) and high accuracy:
  - **PLANET** - **P**robing **L**ens **A**nomaly NETwork/**RoboNET**:
    5 + x telescopes, mainly on Southern Hemisphere: good longitude coverage ("The 24 Hour Night Shift", P. Sackett), partly automated
  - ***μ*FUN - Micro**lensing **F**ollow-**U**p **N**etwork: one main telescope (Chile), many supplementary telescopes around the globe, including amateurs (25cm to 1.8m)

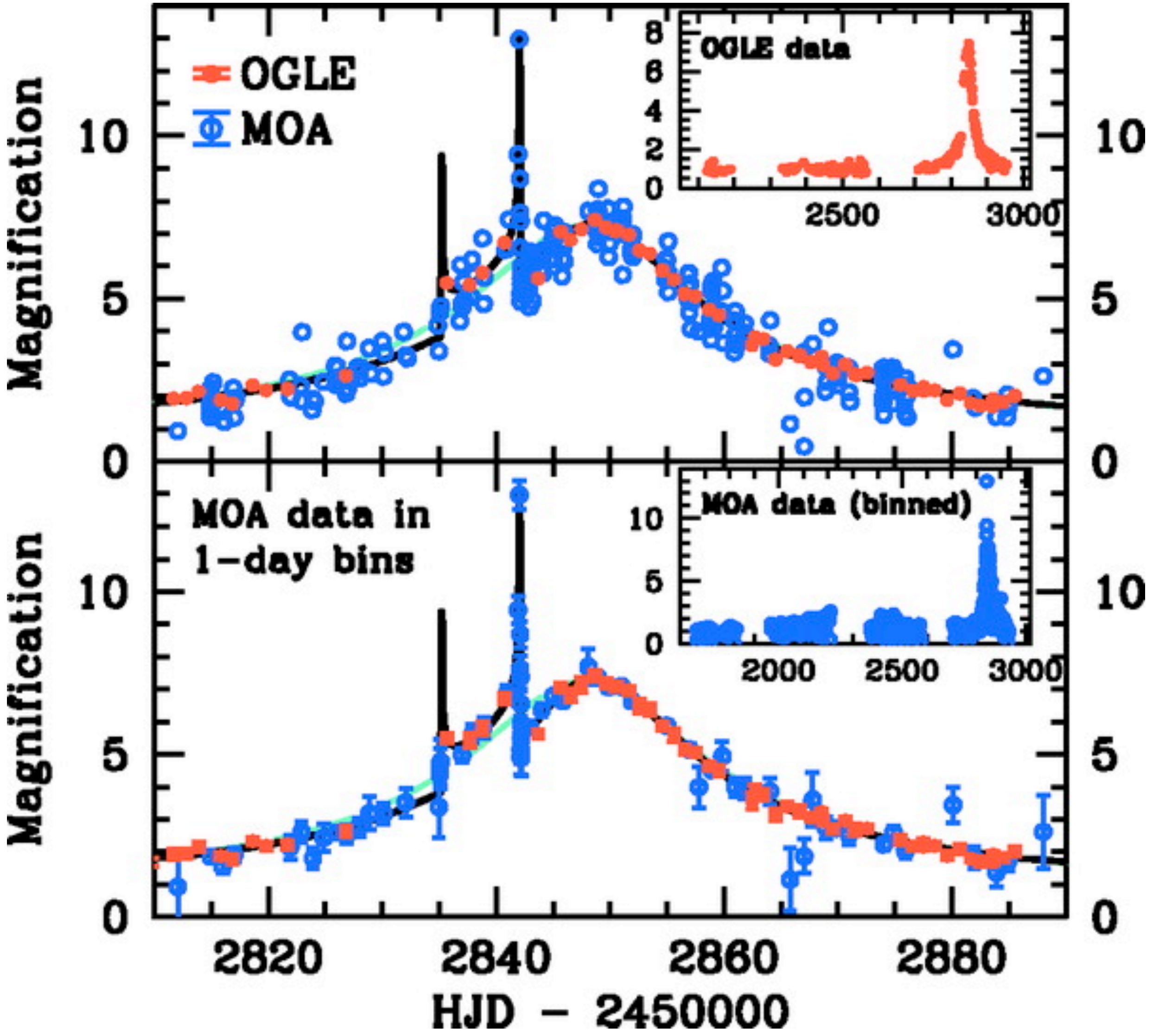
The PLANET - Team

PLANET - Probing Lens Anomaly NETwork: **“The 24 hour night shift”**

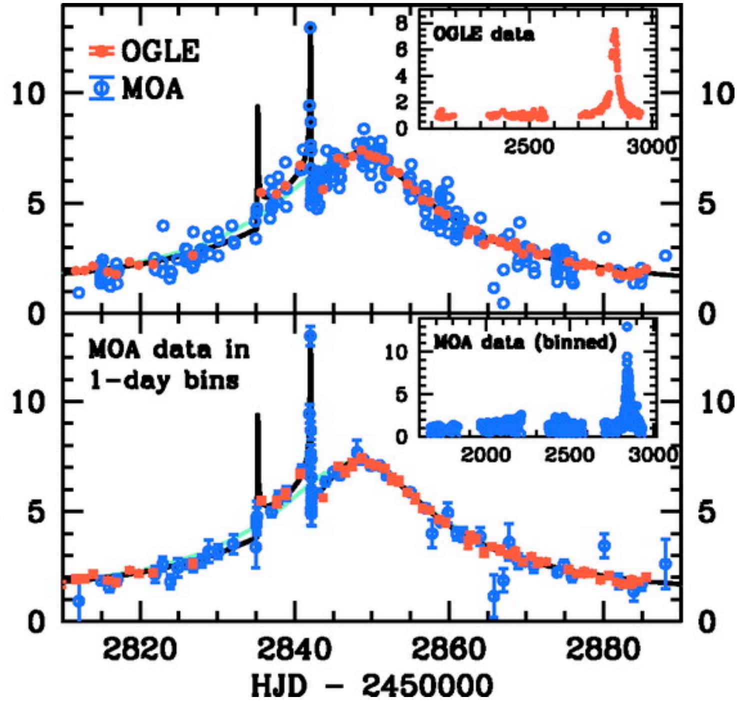


- international team, follows "alerts"
- about 30 astronomers worldwide (from Baltimore, Capetown, Christchurch, Copenhagen, Heidelberg, Hobart, Paris, Perth, Potsdam, St. Andrews ...)
- frequent monitoring of “alerted” microlensing events from 4 Southern telescope sites: "The 24 hour night shift" (Penny Sackett) in order to detect “anomalies”
- at any given time: PLANET follows about 20 events
- semi-automated coordination by “homebase” during bulge season

Finding Planets with Microlensing: First Detection!



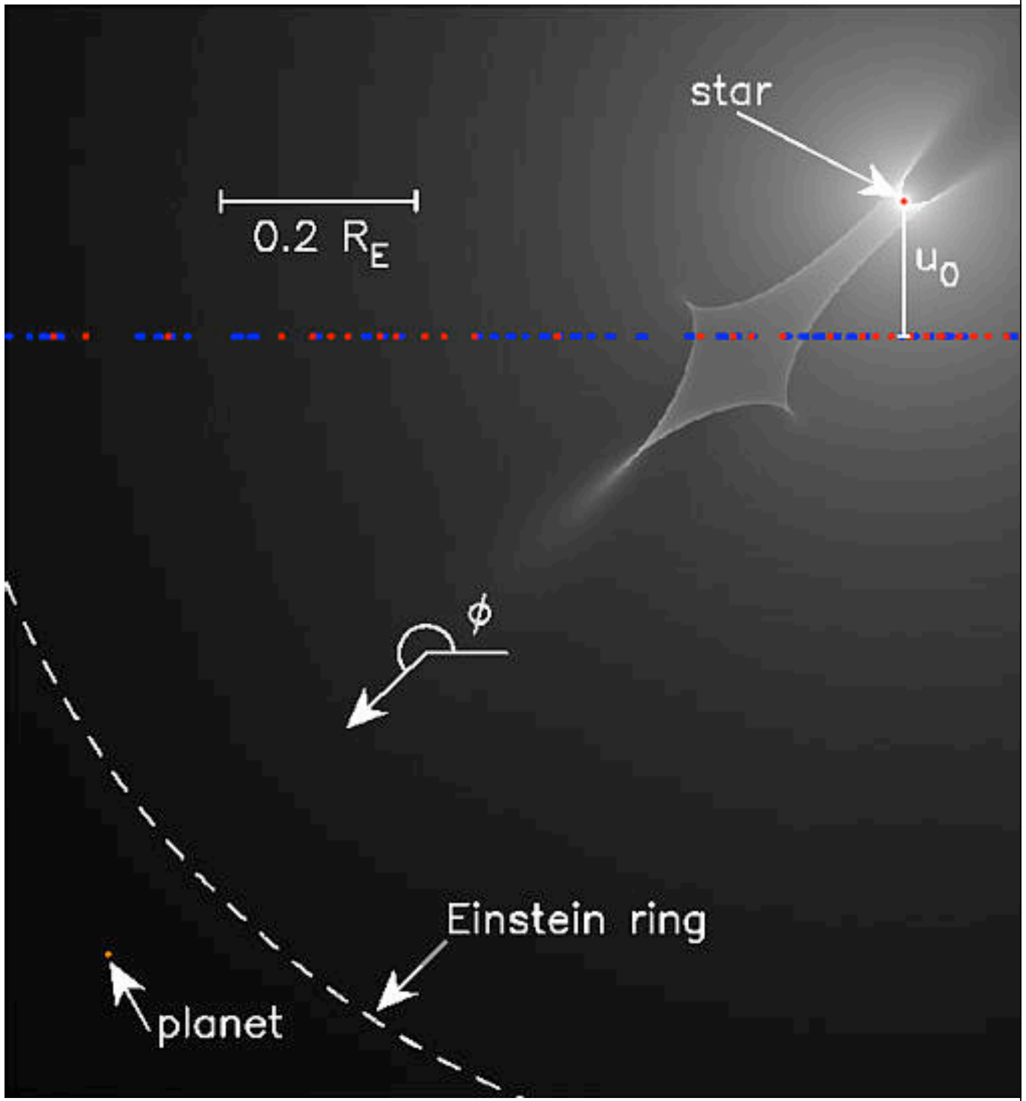
Finding Planets with Microlensing: First Detection!



OGLE-2003-BLG-235/
MOA-2003-BLG-053

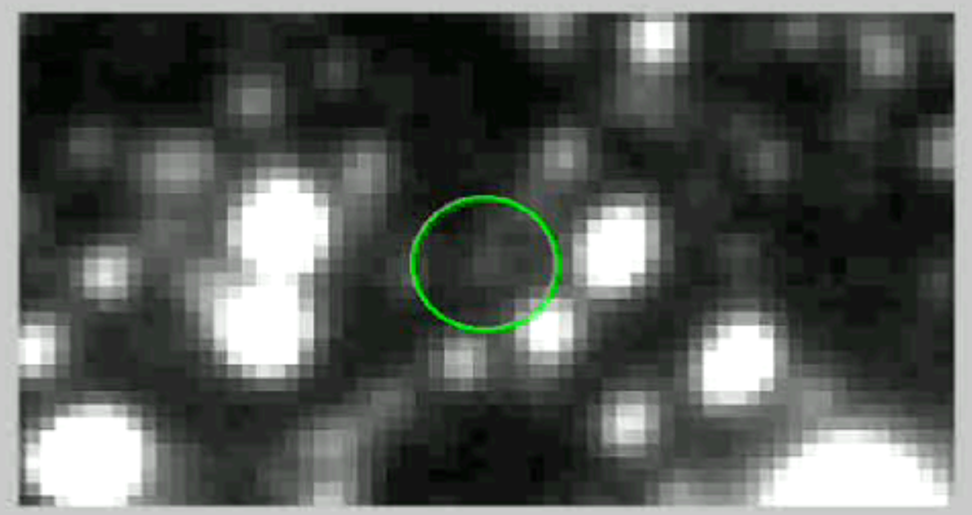
separation: about 3 AU
Mass: 2 Jupiter masses!

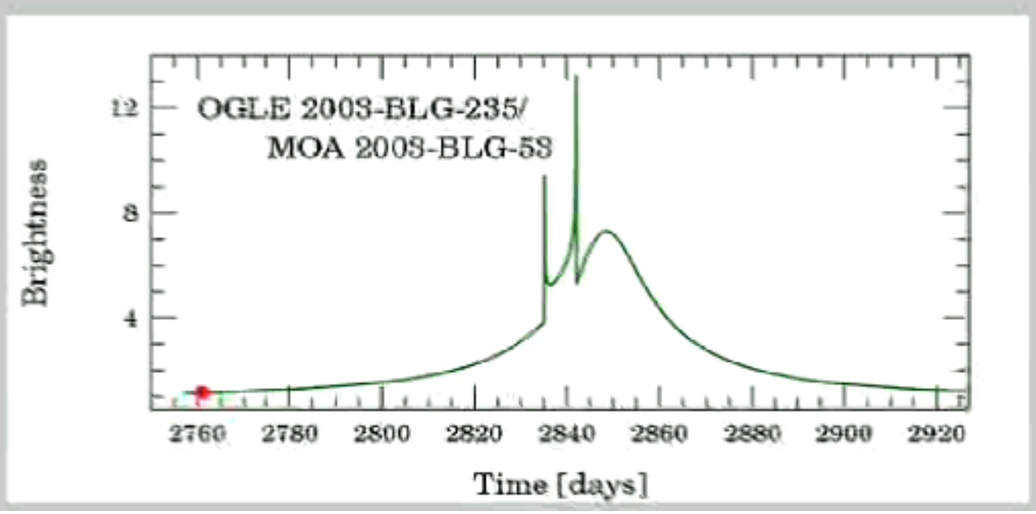
Bond et al. (April 2004)



Finding Planets with Microlensing: First Detection!

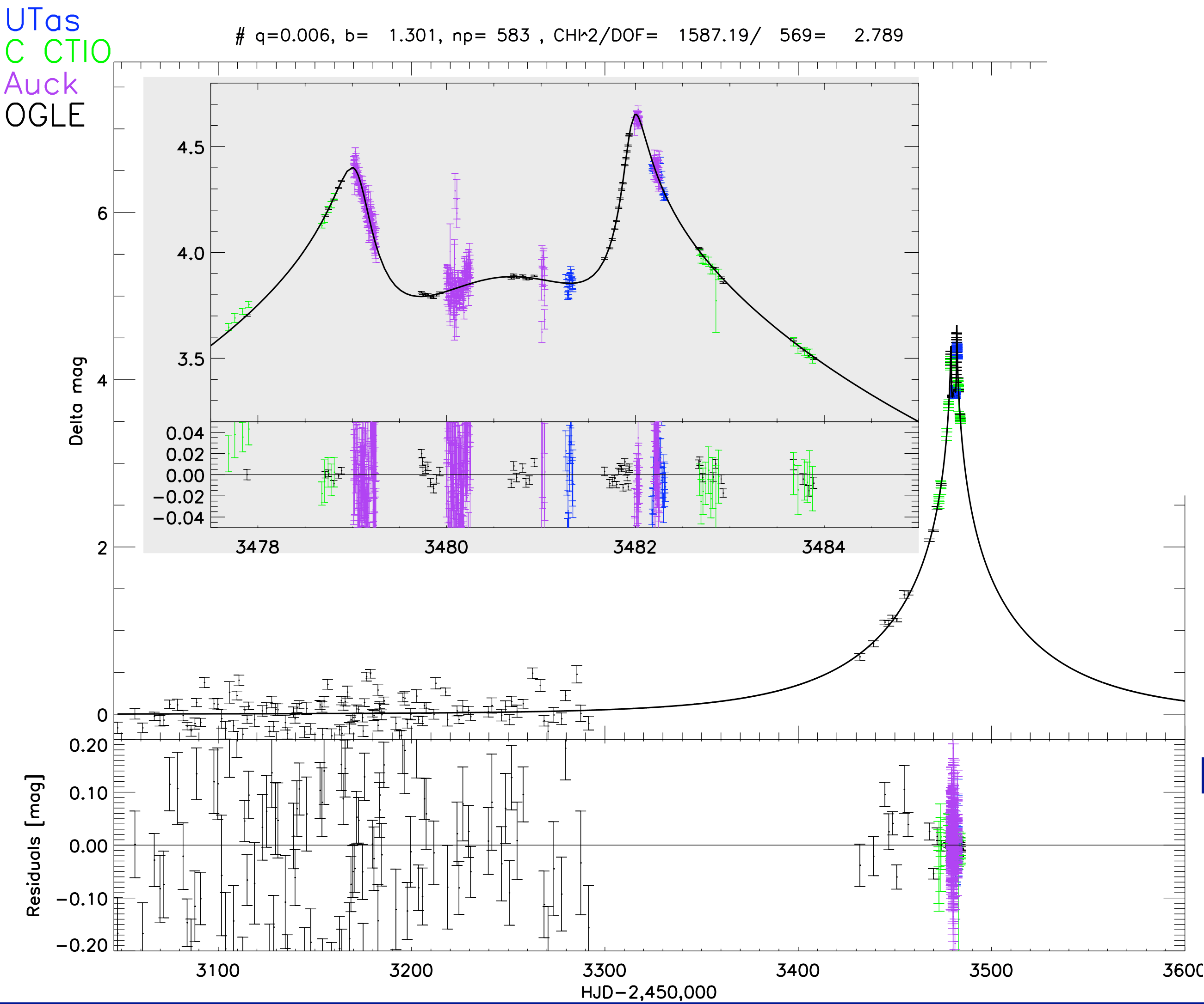
separation: about 3 AU
Mass: 2 Jupiter masses!





Bond et al.
(April 2004)

Finding Planets with Microlensing: Second Detection!



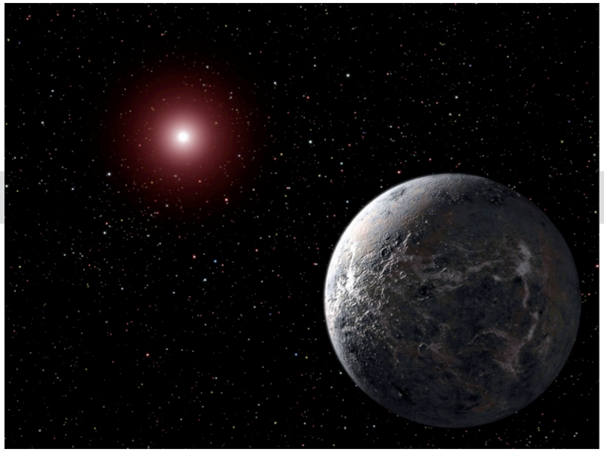
OGLE,μFUN,
MOA, PLANET

Udalski et al.
August 2005

Finding Planets with Microlensing: Third Planet!

Vol 439|26 January 2006|**doi:10.1038/nature04441**

nature

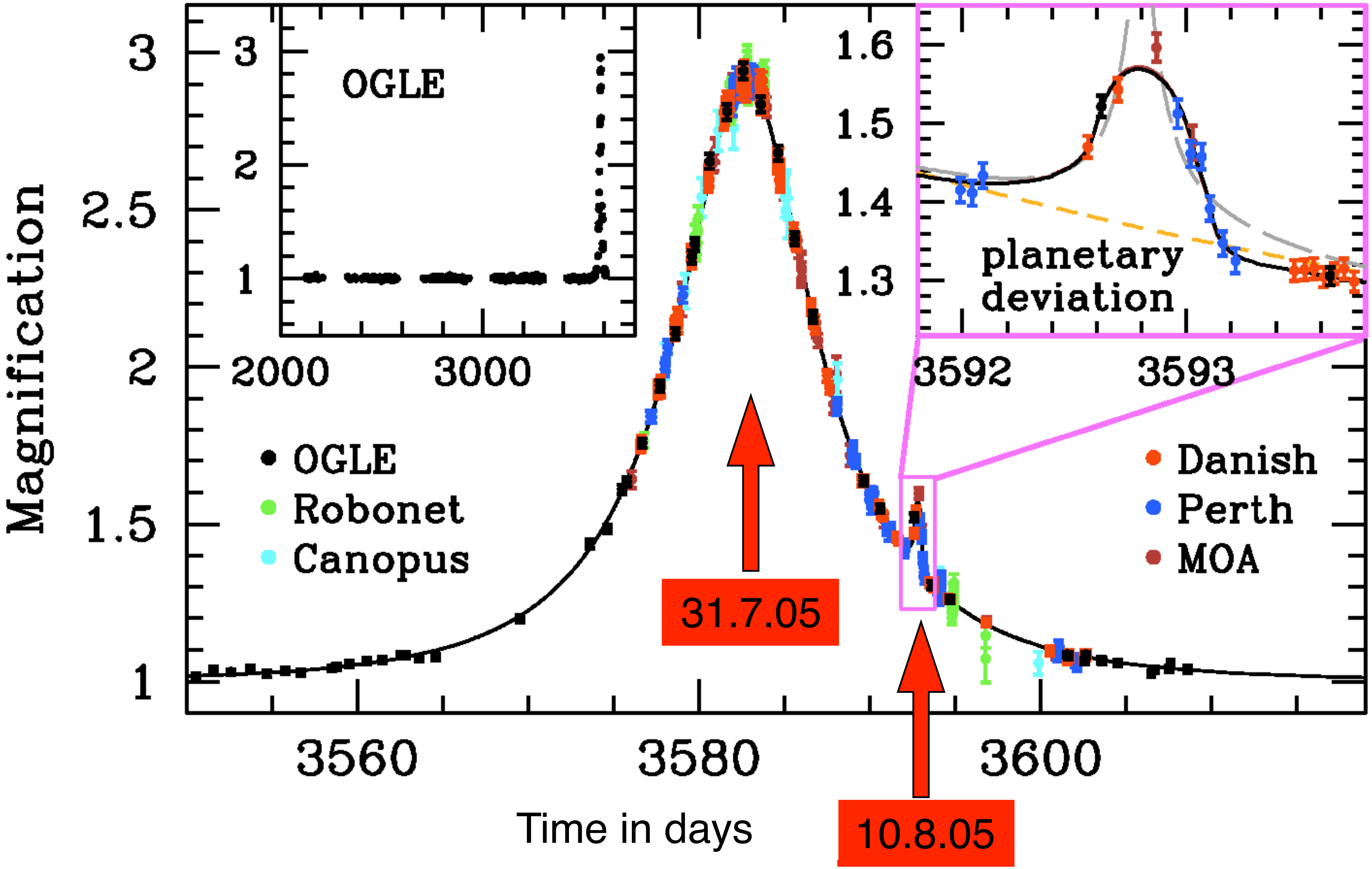


LETTERS

Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing

J.-P. Beaulieu[1,4], D. P. Bennett[1,3,5], P. Fouqué[1,6], A. Williams[1,7], M. Dominik[1,8], U. G. Jørgensen[1,9], D. Kubas[1,10], A. Cassan[1,4], C. Coutures[1,11], J. Greenhill[1,12], K. Hill[1,12], J. Menzies[1,13], P. D. Sackett[1,14], M. Albrow[1,15], S. Brillant[1,10], J. A. R. Caldwell[1,16], J. J. Calitz[1,17], K. H. Cook[1,18], E. Corrales[1,4], M. Desort[1,4], S. Dieters[1,12], D. Dominis[1,19], J. Donatowicz[1,20], M. Hoffman[1,19], S. Kane[1,21], J.-B. Marquette[1,4], R. Martin[1,7], P. Meintjes[1,17], K. Pollard[1,15], K. Sahu[1,22], C. Vinter[1,9], J. Wambsganss[1,23], K. Woller[1,9], K. Horne[1,8], I. Steele[1,24], D. M. Bramich[1,8,24], M. Burgdorf[1,24], C. Snodgrass[1,25], M. Bode[1,24], A. Udalski[2,26], M. K. Szymański[2,26], M. Kubiak[2,26], T. Więckowski[2,26], G. Pietrzyński[2,26,27], I. Soszyński[2,26,27], O. Szewczyk[2,26], Ł. Wyrzykowski[2,26,28], B. Paczyński[2,29], F. Abe[3,30], I. A. Bond[3,31], T. R. Britton[3,15,32], A. C. Gilmore[3,15], J. B. Hearnshaw[3,15], Y. Itow[3,30], K. Kamiya[3,30], P. M. Kilmartin[3,15], A. V. Korpela[3,33], K. Masuda[3,30], Y. Matsubara[3,30], M. Motomura[3,30], Y. Muraki[3,30], S. Nakamura[3,30], C. Okada[3,30], K. Ohnishi[3,34], N. J. Rattenbury[3,28], T. Sako[3,30], S. Sato[3,35], M. Sasaki[3,30], T. Sekiguchi[3,30], D. J. Sullivan[3,33], P. J. Tristram[3,32], P. C. M. Yock[3,32] & T. Yoshioka[3,30]

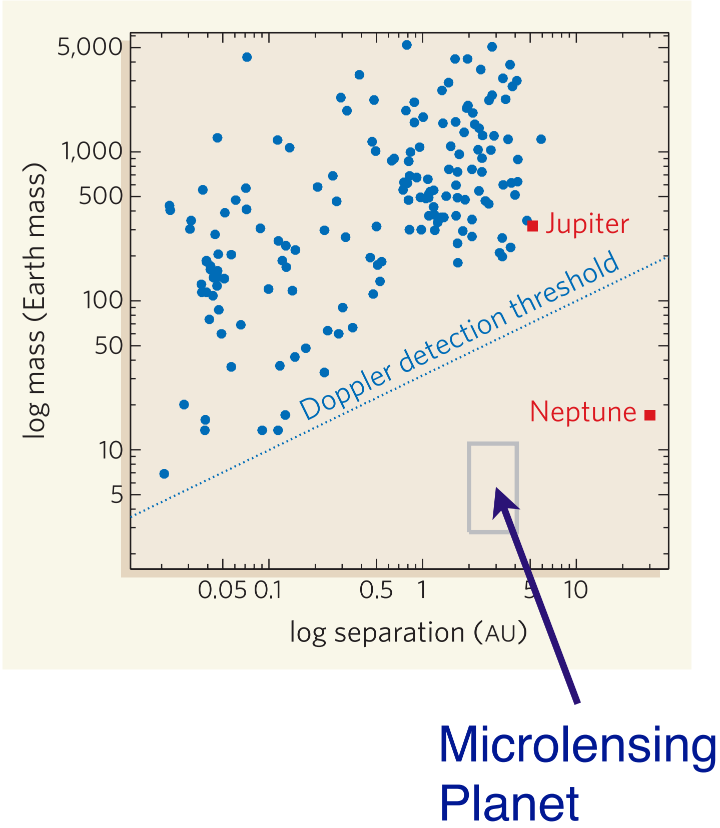
Finding Planets with Microlensing: Third Planet!



Finding Planets with Microlensing: Third Planet!

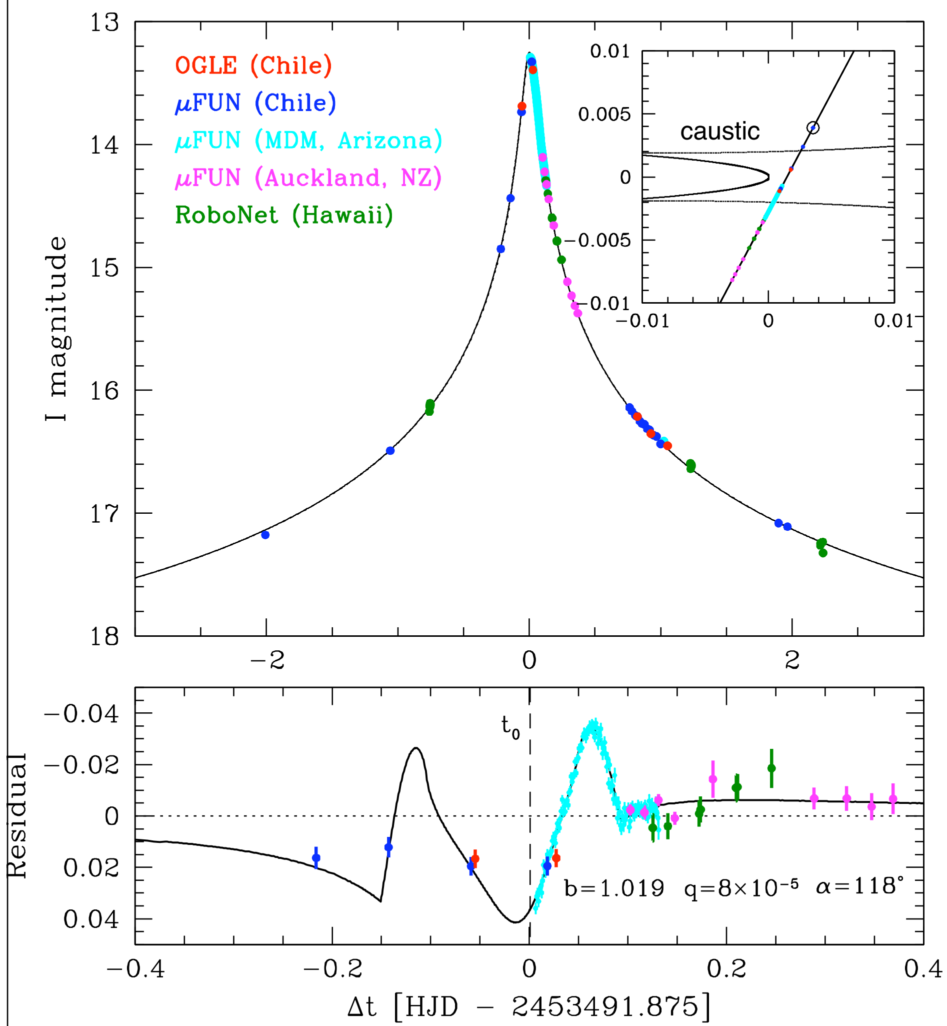
Microlensing event OGLE-2005-BLG-390:

- produced by star-plus-planet system with **mass ratio 7 × 10^{-5}**
- most likely (with model of Milky Way):
  - star of about 0.2 solar masses
  - planet of about 5.5 $^{+5.5}_{-2.7}$ Earth masses
  - (instantanous) separation 2.6 AU
  - orbital period 10 years



Finding Planets with Microlensing: Fourth Planet!

OGLE-2005-BLG-169: Gould et al. (2006)



Very high magnification event (μ= 800!)

separation d ≈ 2.7 AU

mass ratio: q = 0.00008
mass: m_{PL} = 13 $M_{\oplus}$

Implication: cool neptune's are common!

Finding Planets with Microlensing: Planets #5 and $6:

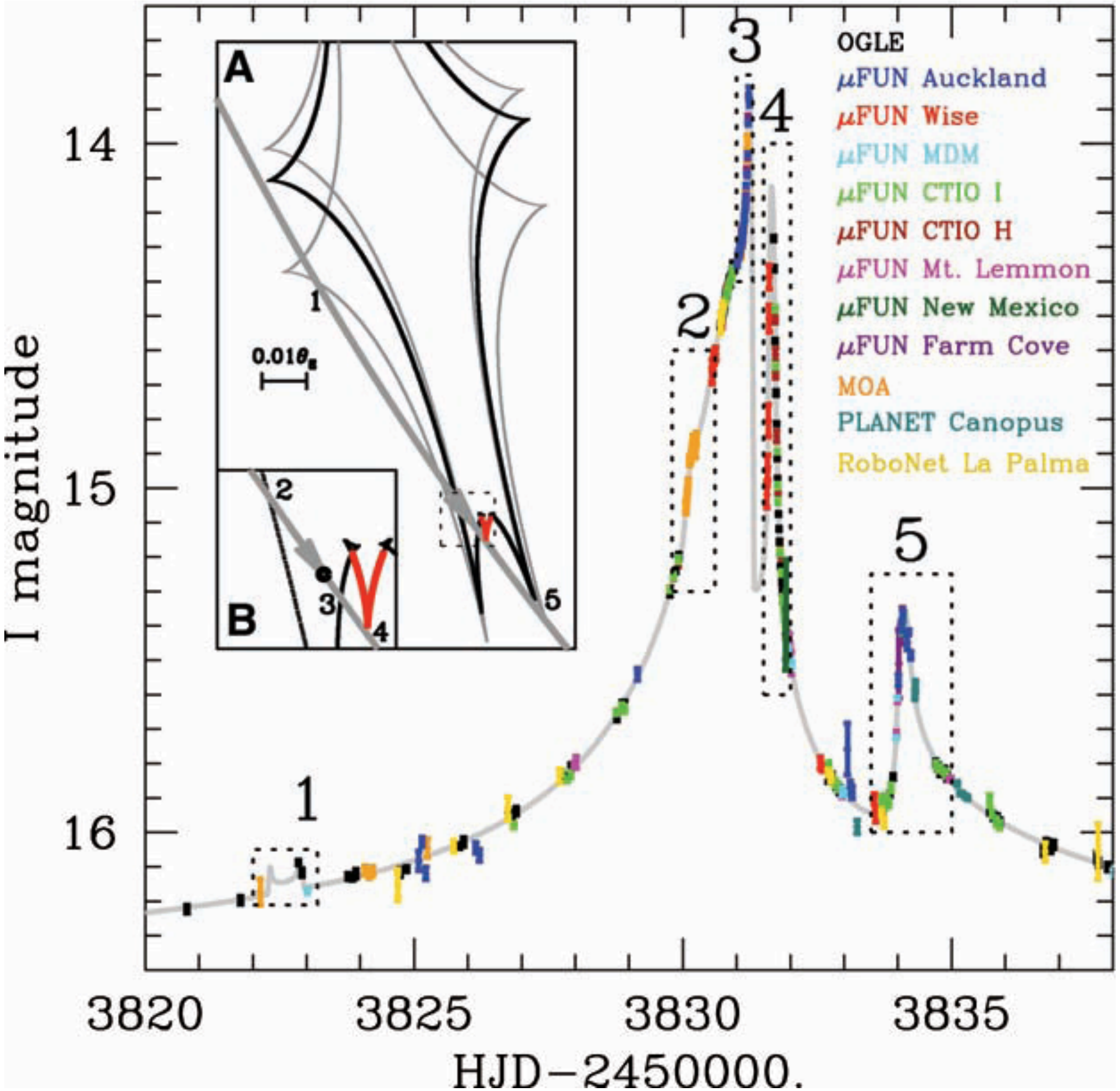
Discovery of a Jupiter/Saturn Analog with Gravitational Microlensing:

OGLE-2006-BLG-109Lb
OGLE-2006-BLG-109Lc

"We identify two planets with masses of ~0.71 and ~0.27 times the mass of Jupiter and orbital separations of ~2.3 and ~4.6 astronomical units orbiting a primary star of mass ~0.50 solar mass at a distance of ~1.5 kiloparsecs."

Gaudi et al. (Science, Feb 15, 2008)

Discovery of a Jupiter/Saturn Analog with Gravitational Microlensing

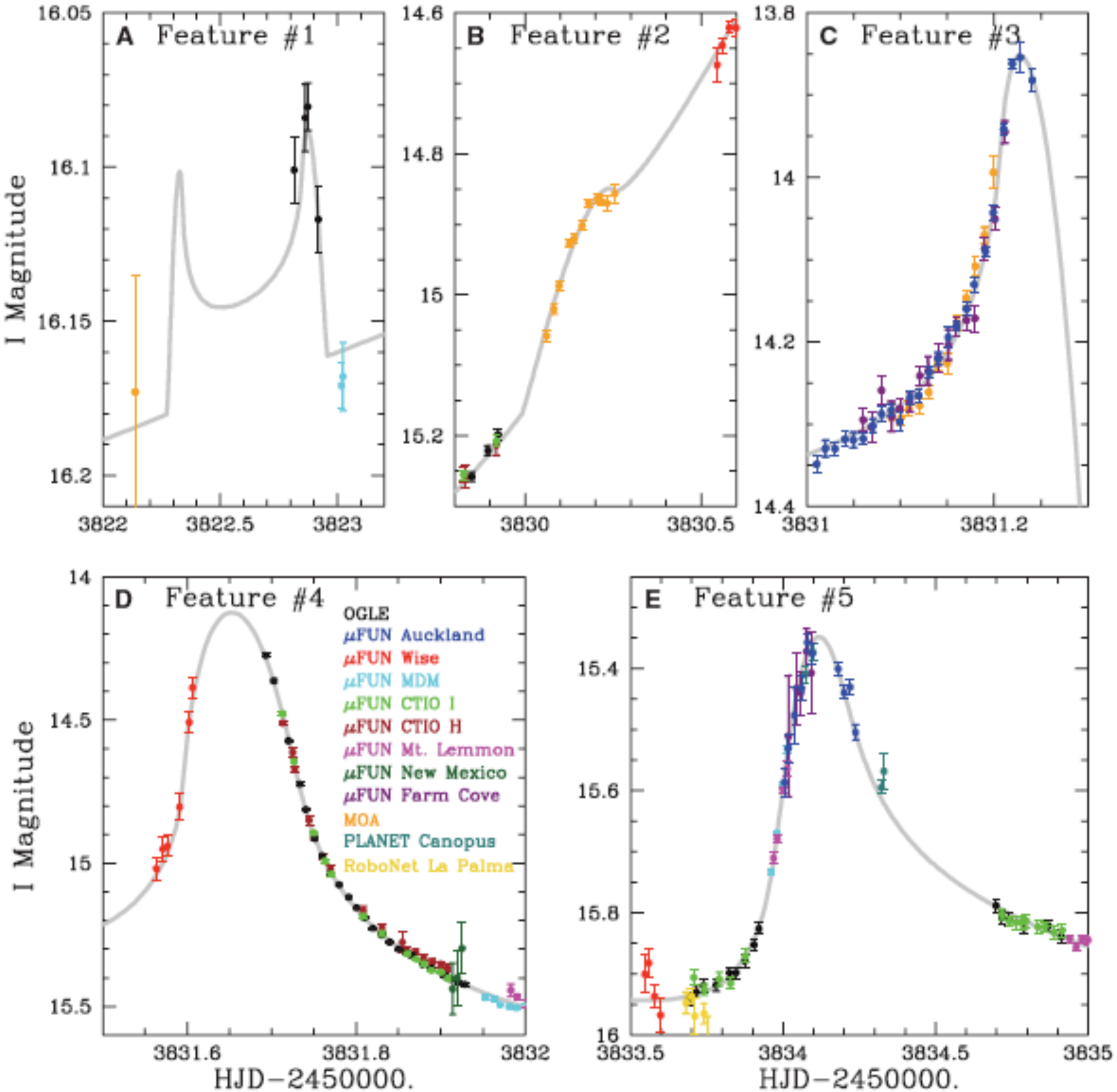


2742 data points
in 15 nights
from 12 different
observatories:

5 significant features

Gaudi et al.
(Science, Feb 15, 2008)

Discovery of a Jupiter/Saturn Analog with Gravitational Microlensing



Gaudi et al.
(Science, Feb 15, 2008)

Discovery of a Jupiter/Saturn Analog with Gravitational Microlensing

Gaudi et al. (Science, Feb 15, 2008)

Host star: $M \approx 0.5\, M_\odot$, $D_L \approx 1.5$ kpc

Two planets:

OGLE-2006-BLG-109Lb: $M \approx 0.71\, M_J$ $d \approx 2.3$ AU

OGLE-2006-BLG-109Lc: $M \approx 0.27\, M_J$ $d \approx 4.6$ AU

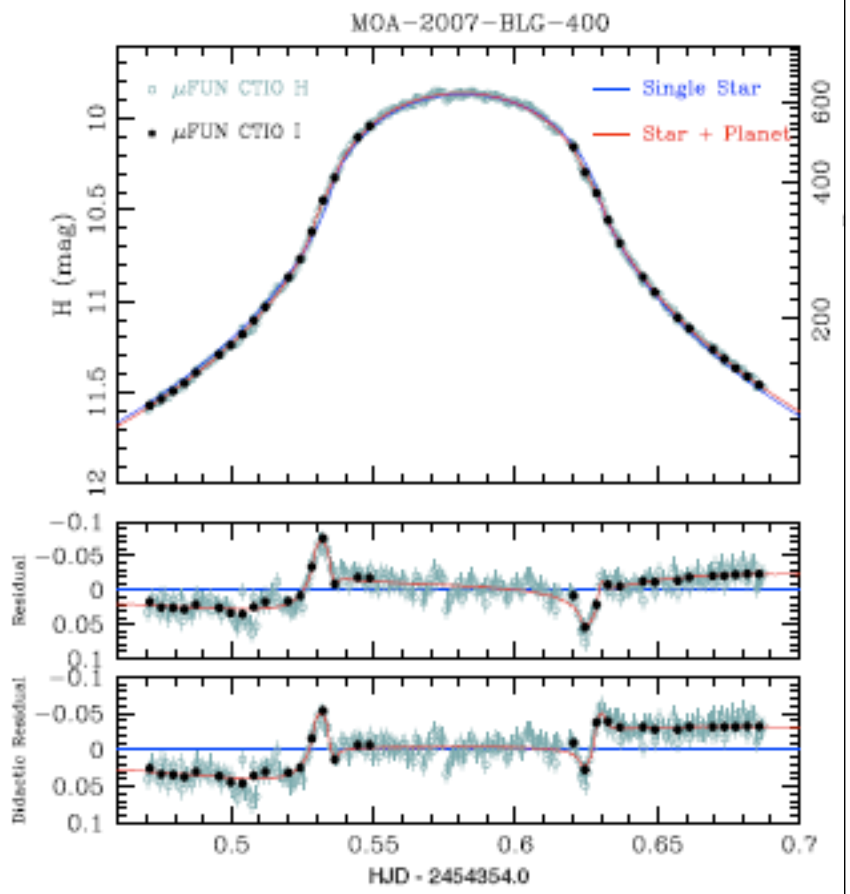
Mass ratio, separation ratio, equilibrium temperature of planets:
Quite similiar to Jupiter/Saturn system !

Detection of finite source effects and microlens parallax

Finding Planets with Microlensing: Eighth Planet!

MOA-2007-BLG-400: Cool, jovian-mass planet
(Dong et al. astro-ph/0809.2997)

high magnification event (m = 628)
very strong finite source effect:

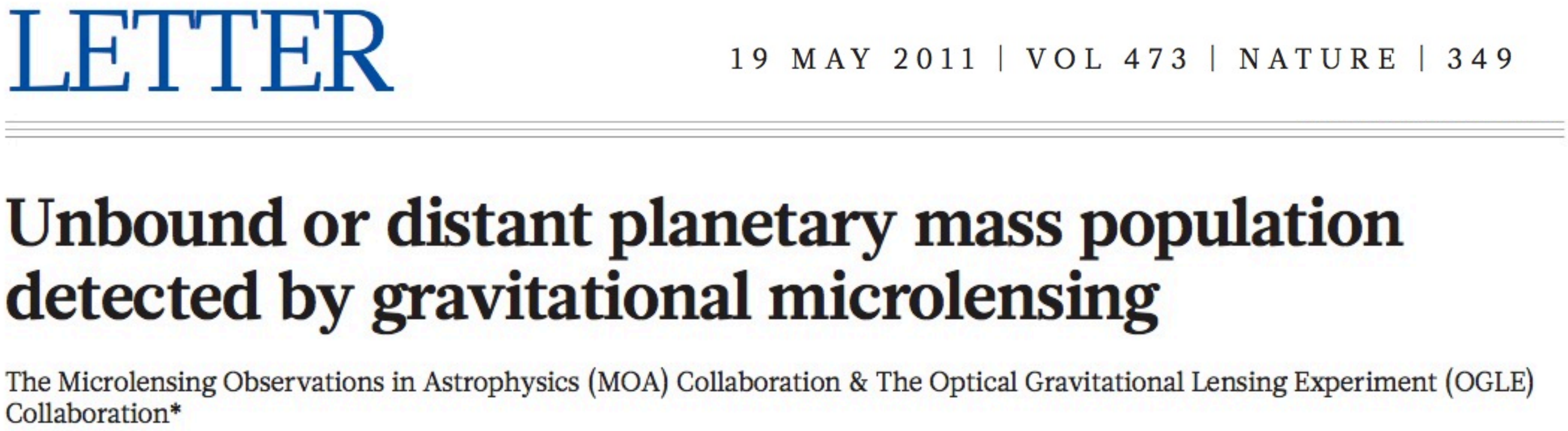


separation d ≈ (0.6 - 1.1) AU

mass ratio: $q = (2.6 \pm 0.4) \times 10^{-3}$

planet mass: $m_{PL} = (0.5 - 1.3)\ M_J$

Nature 473, 349 (May 19, 2011): Sumi et al.


LETTER

19 MAY 2011 | VOL 473 | NATURE | 349

Unbound or distant planetary mass population detected by gravitational microlensing

The Microlensing Observations in Astrophysics (MOA) Collaboration & The Optical Gravitational Lensing Experiment (OGLE) Collaboration*

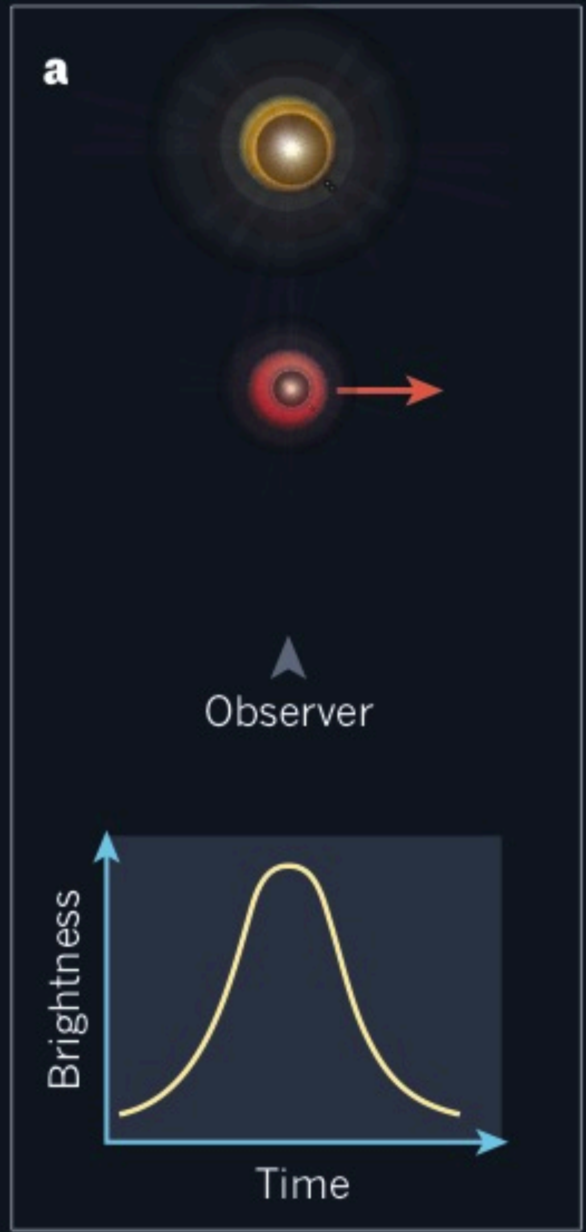


Figure from Wambsganss, J., Nature 473, 289 (2011)

Figure from Wambsganss, J., Nature 473, 289 (2011)

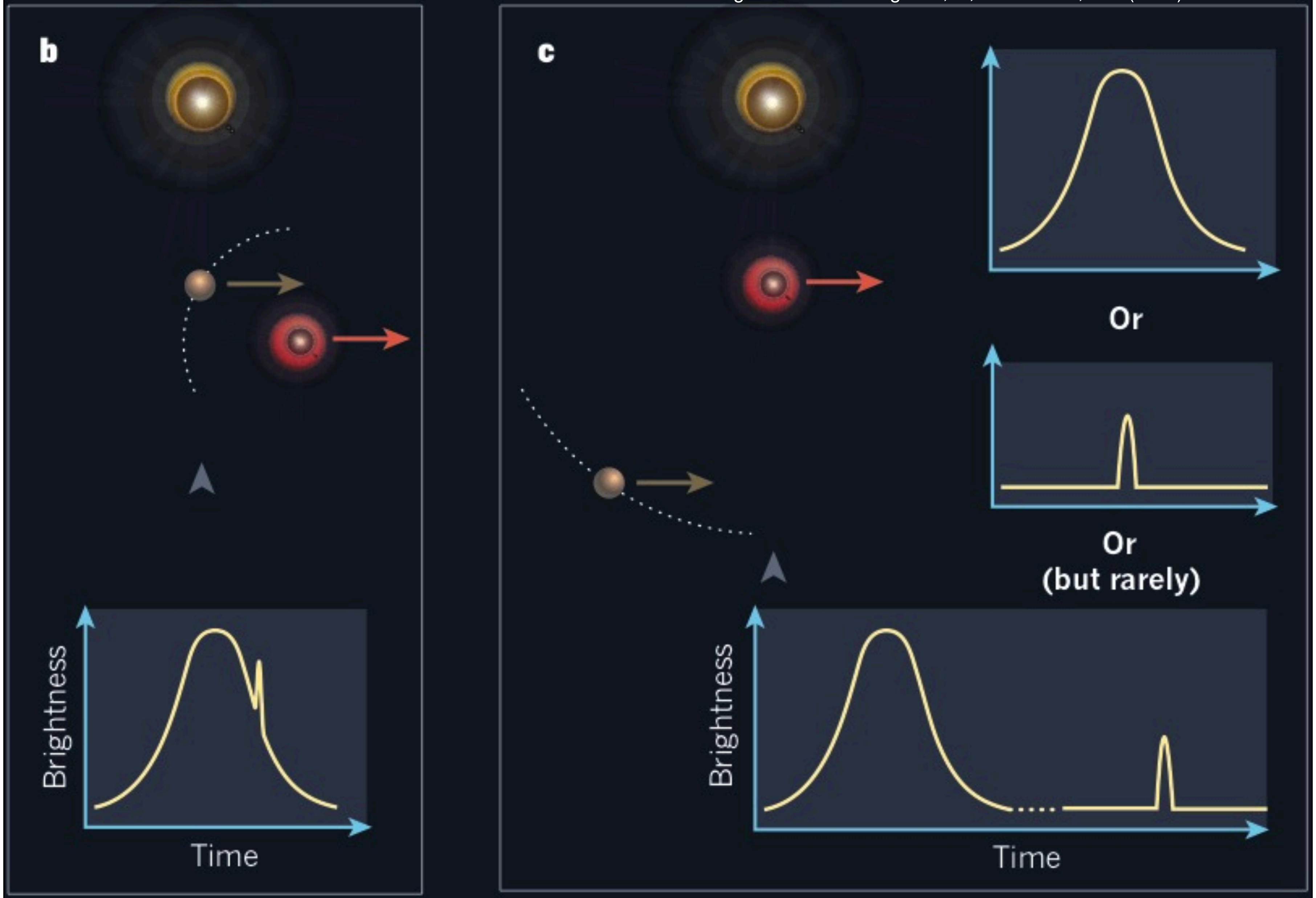
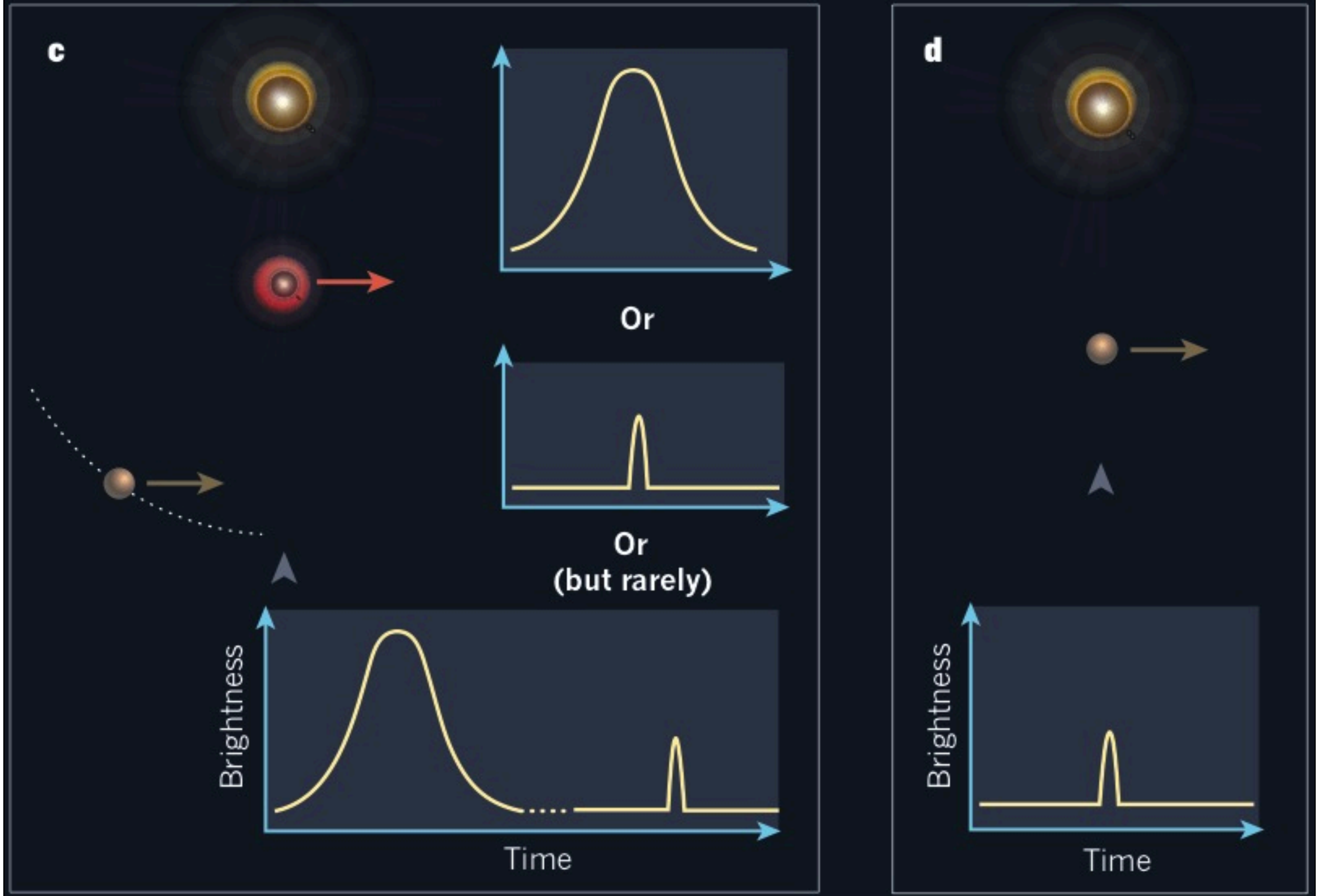
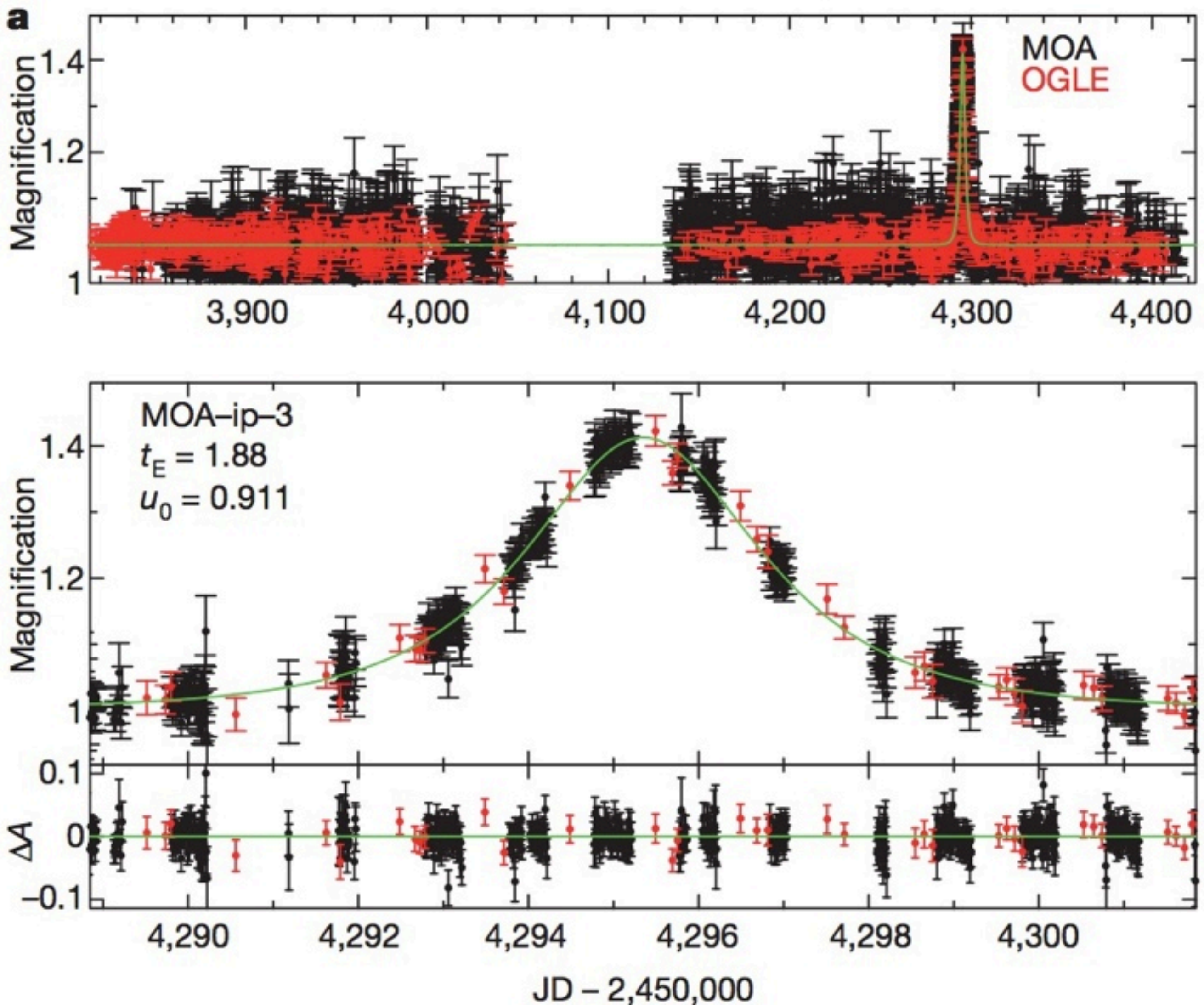


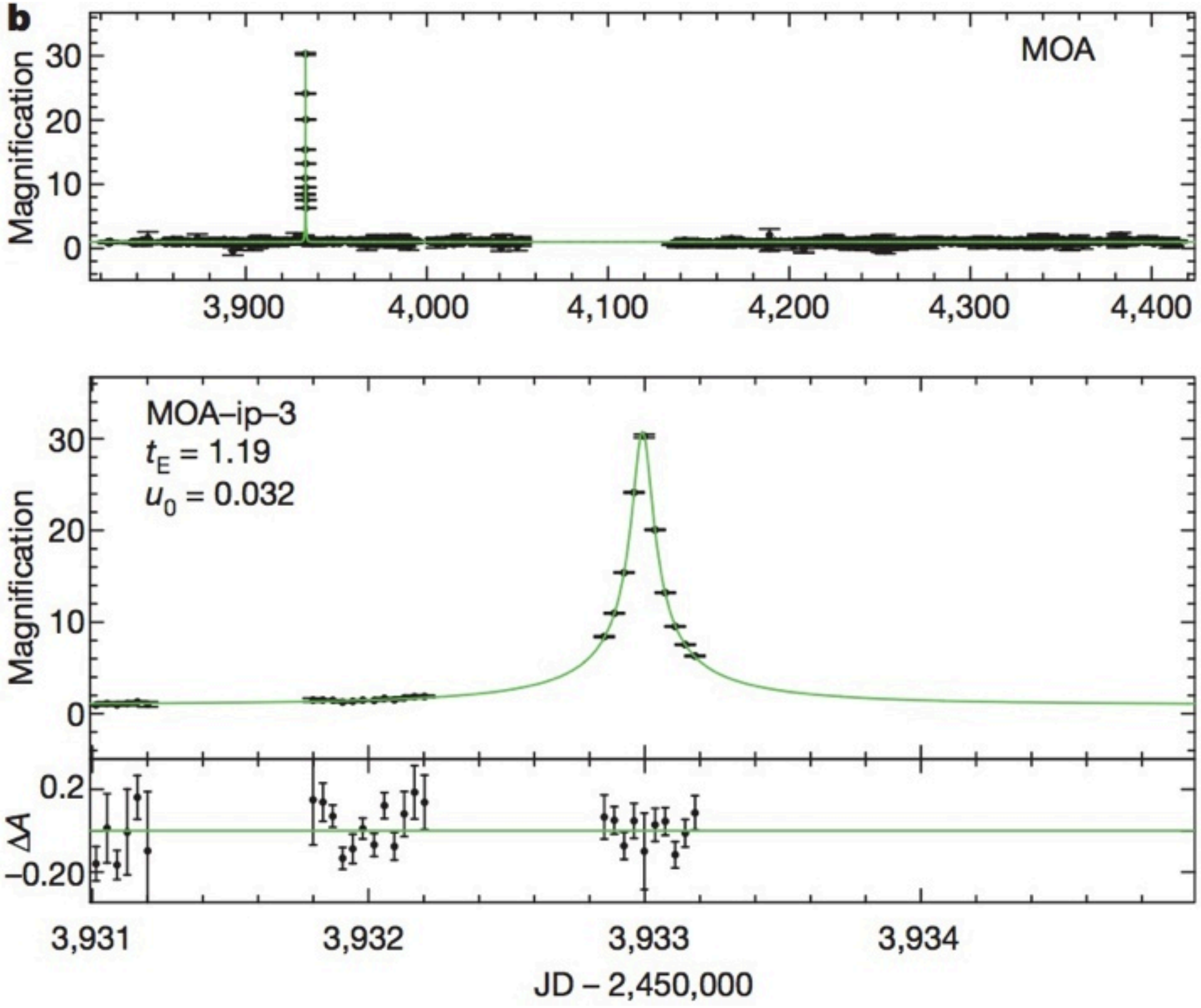
Figure from Wambsganss, J., Nature 473, 289 (2011)



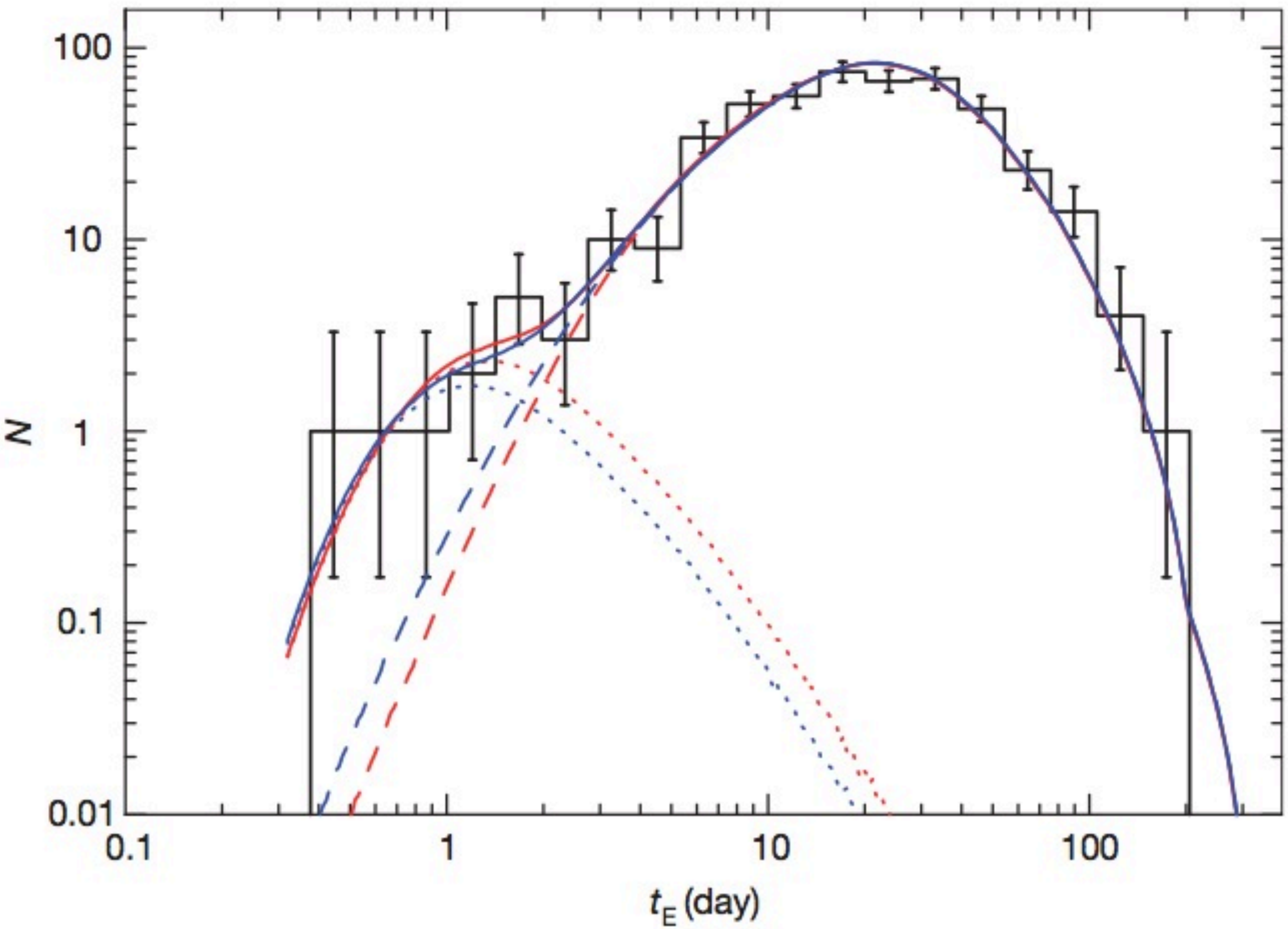
Nature 473, 349 (May 19, 2011): Sumi et al.



Nature 473, 349 (May 19, 2011): Sumi et al.



Nature 473, 349 (May 19, 2011): Sumi et al.



Nature 473, 349 (May 19, 2011):

ASTRONOMY

Bound and unbound planets abound

Two teams searching for extrasolar planets have jointly discovered a new population of objects: ten Jupiter-mass planets far from their host stars, or perhaps even floating freely through the Milky Way. SEE LETTER P.349

JOACHIM WAMBSGANSS

Two decades ago, we had no idea whether planets orbiting stars other than the Sun existed at all. Today, more than 500 exoplanets have been discovered, and the field of exoplanet research has advanced to become one of the most captivating branches of astronomy. Observational techniques now aim to address questions such as what the atmosphere and weather are like on some of these planets, and to determine their global statistical properties. On page 349 of this issue, the MOA and OGLE research teams[1] provide an exciting result for exoplanetary science: the discovery of a population of planets that have roughly the mass of Jupiter and separations from their putative host stars of at least ten times Earth's distance to the Sun.

LETTER 19 MAY 2011 | VOL 473 | NATURE | 349

Unbound or distant planetary mass population detected by gravitational microlensing

The Microlensing Observations in Astrophysics (MOA) Collaboration & The Optical Gravitational Lensing Experiment (OGLE) Collaboration*

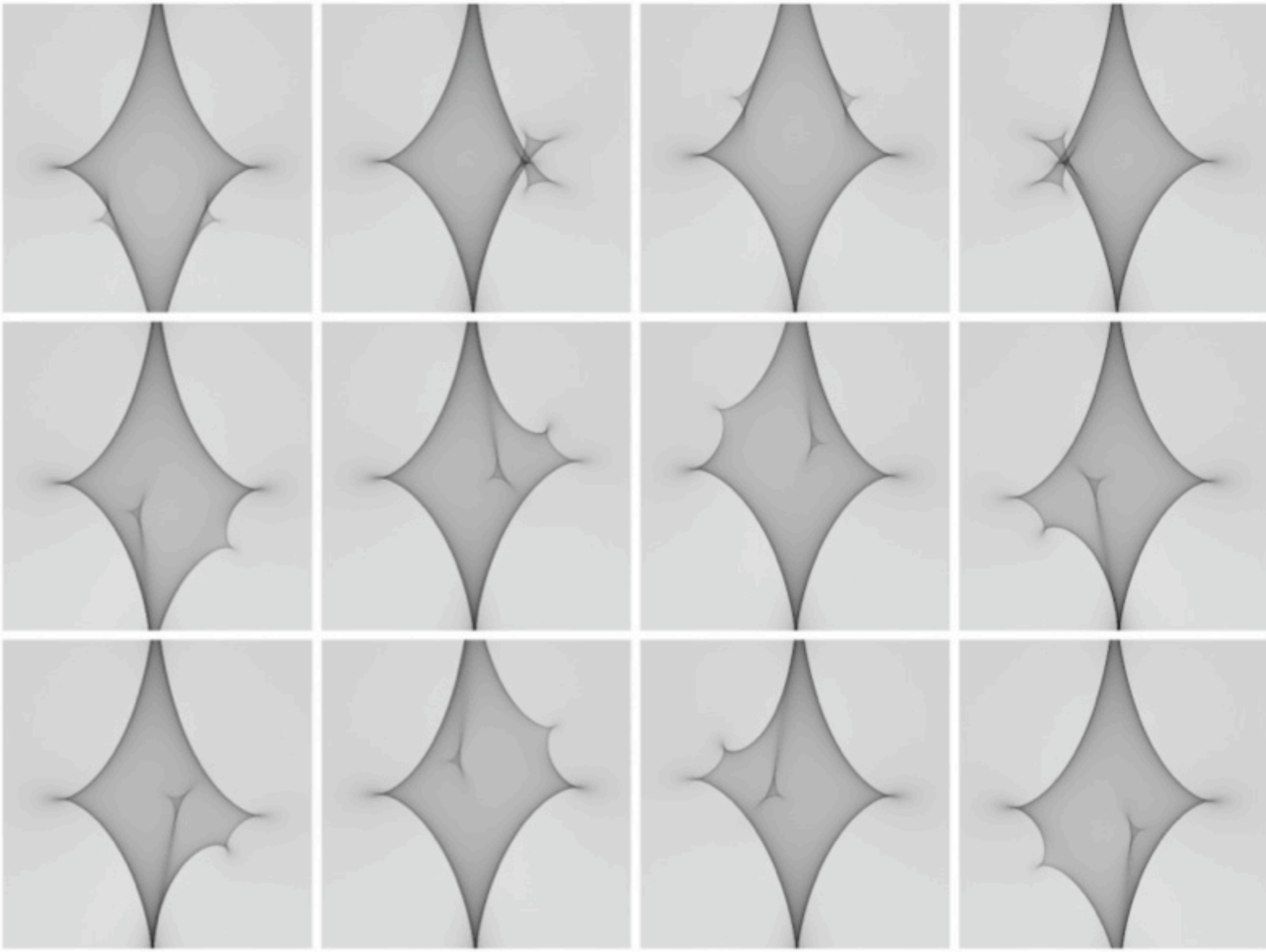
- 50 million bulge stars monitored for 2 years (2006/2007) with very high cadence: at least once per hour (>2000 data points)
- 474 **isolated** microlensing events detected
- **10** of those: **shorter than $t_E \leq$ 2 days** !

  $\Rightarrow$ $m \leq m_{Jupiter}$!

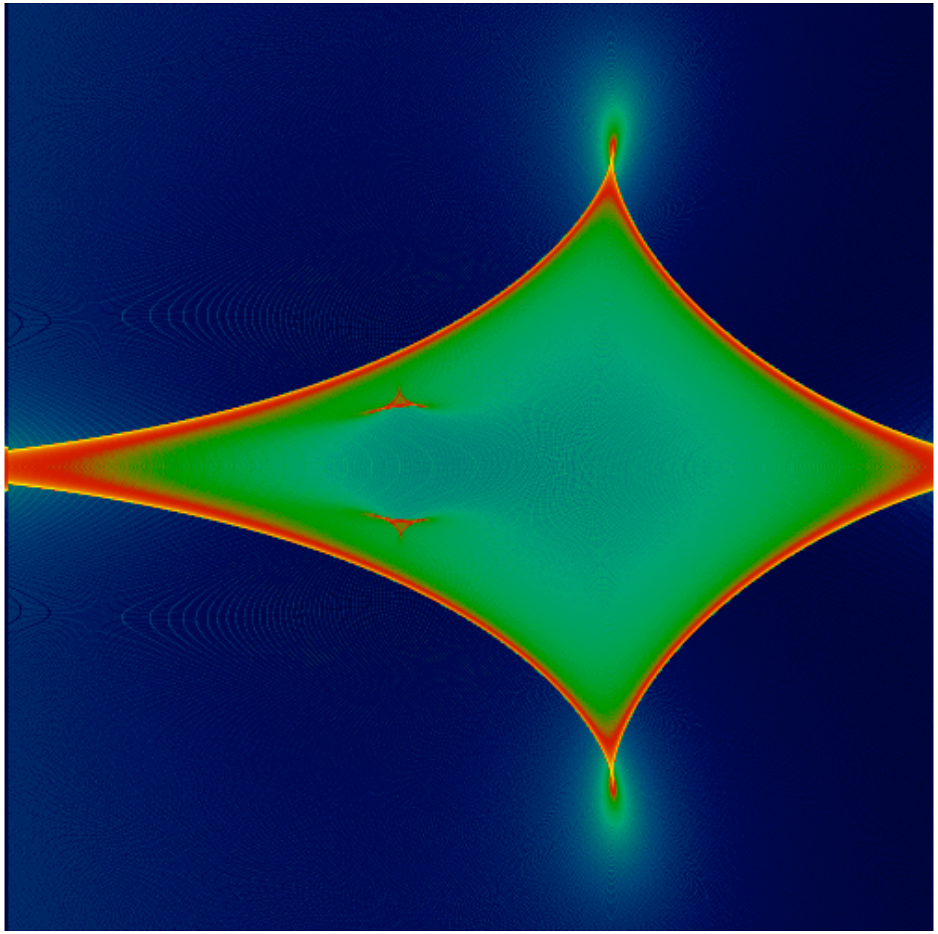
  $\Rightarrow$ $a \geq$ 10 AU !
- many more than expected: $1.8^{+1.7}_{-0.8}$ planets per main sequence star
- from direct imaging: $\leq$ 0.4 planets per main sequence star $\Rightarrow$

  $\Rightarrow$ ~ 1 Jupiter-mass planet per star free-floating through Milky Way !?!

Simulation: Microlensing by star-plus-planet-**plus-moon**!

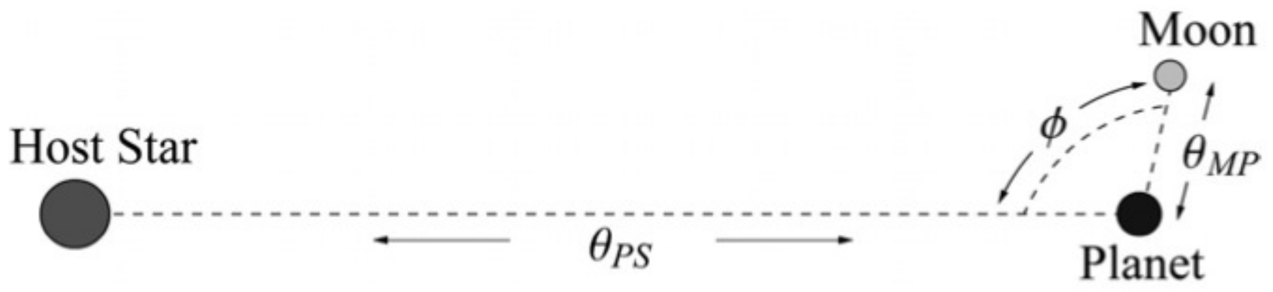


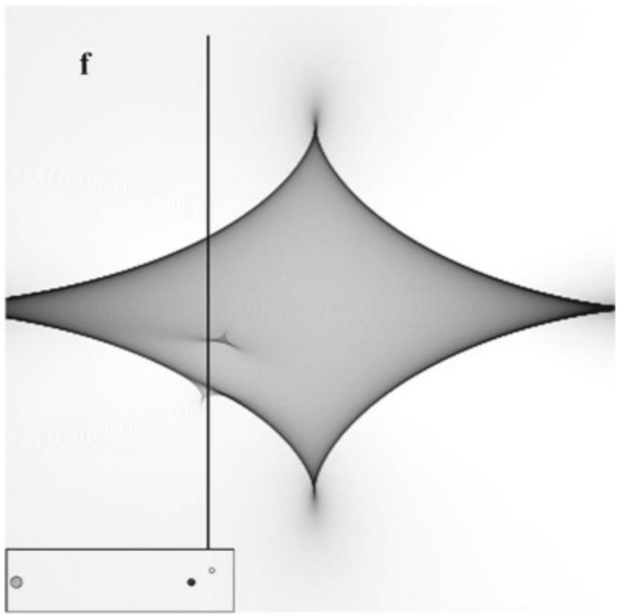
Star-plus-Planet-plus-Moon Caustic: Moon orbiting planet
(Liebig & Wambsganss, 2010)

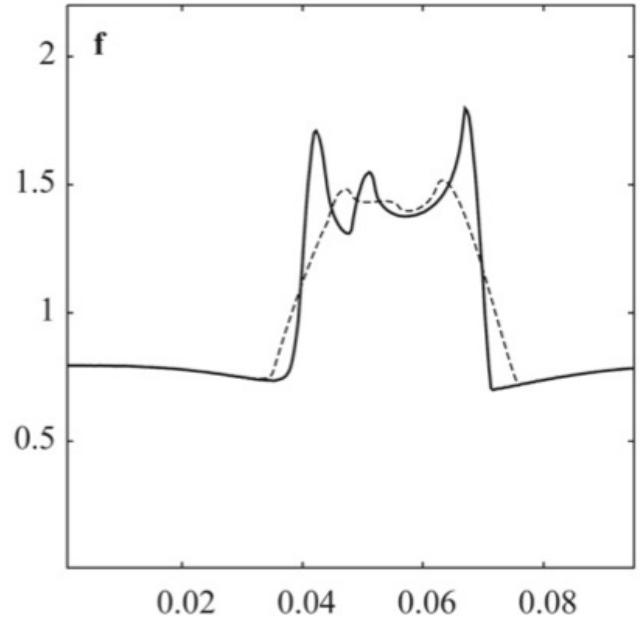


Star-plus-Planet-plus-Moon Caustic: Moon orbiting planet
(Liebig & Wambsganss, 2010)

Simulation: Microlensing by star-plus-planet-**plus-moon**!







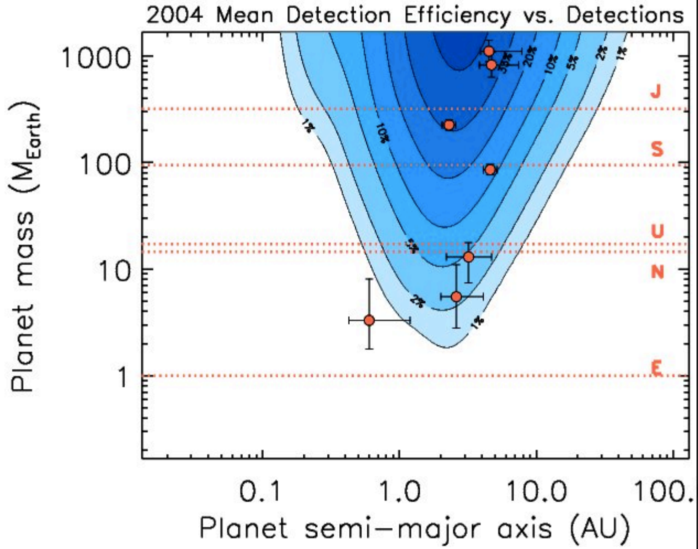
Star-plus-Planet-plus-Moon Caustic: Moon orbiting planet (Liebig & Wambsganss, 2010)

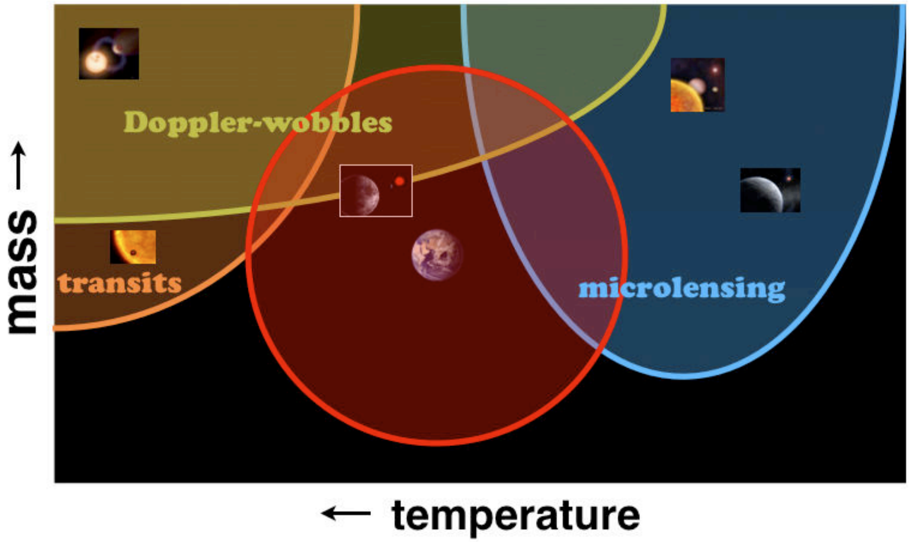
Current Status & Future Directions

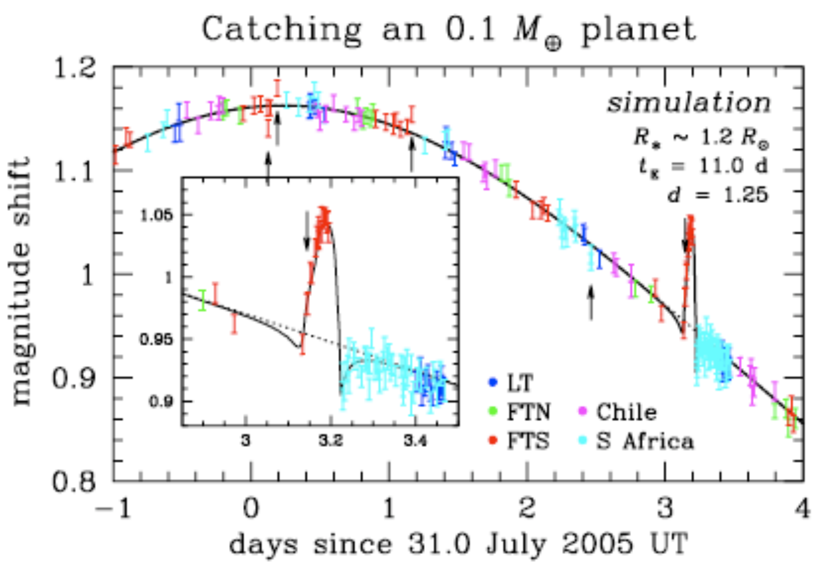
Recent "White Papers":

astro-ph/0808.004 (Dominik et al.)

astro-ph/0808.005 (Beaulieu et al.)







Current Status & Future Directions

Extrasolar planets (as of June 6, 2011)

552 planets
> 450 stars with planets
> 60 multiple planet systems

Among them:

11 [+ 10] microlensing planets
12 pulsar planets
124 transit planets
422 radial velocity planets

[from http://exoplanet.eu]

Microlensing and the Search for Exo-Planets

Gravitational Microlensing is a very competitive method for exoplanet search, detection & characterization; complementary to other techniques

- Very **encouraging results** so far:
  - more than a dozen (close) exoplanet detections with microlensing
  - indications of high abundance of low-mass, “cool” planets (“neptuns”)
  - very recently: >1 Jupiter-mass free-floating planet per MW star!
- Very **realistic next steps**:
  - improve and automate current survey/follow-up strategy
  - build wide-field, automated, world-wide 2m class telescope network
  - develop microlensing satellite telescope capabilities
- Very **promising future** prospects:
  - low(est) planet mass sensitivity!
  - unbiased with respect to host star!
  - confirming free-floating planets, detecting exo-moons!
  - ideal method for Galactic census of exoplanets!