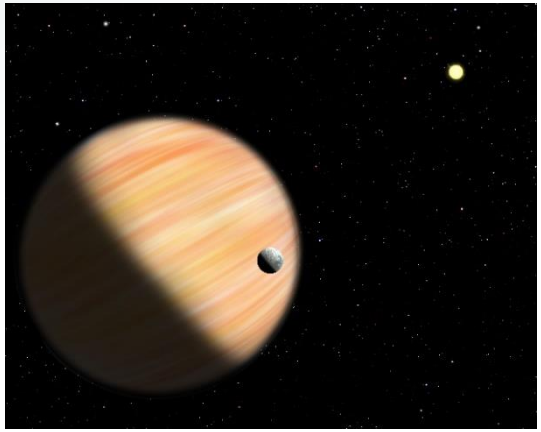
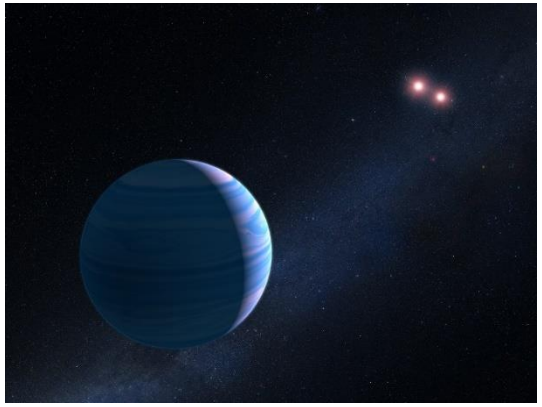
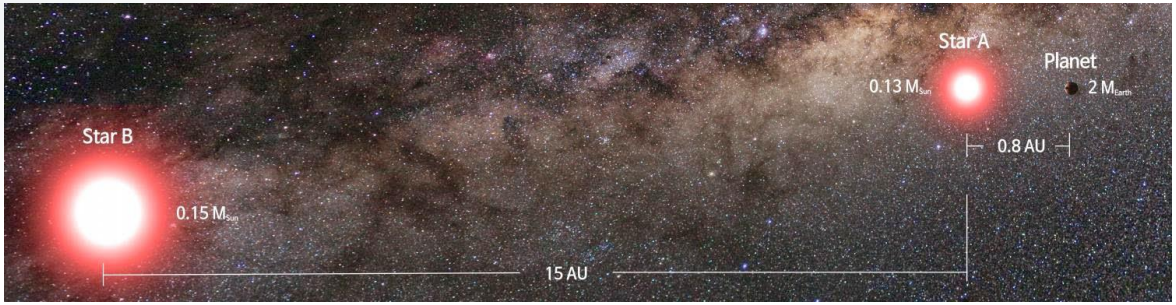
MICROLENSING PLANET DISCOVERIES

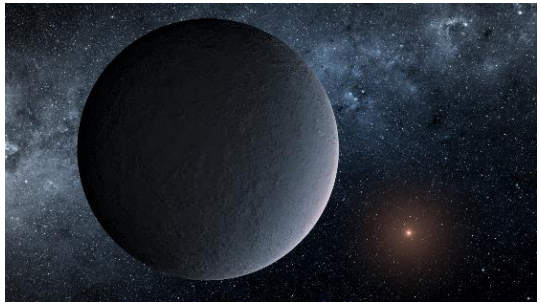




Yossi Shvartzvald

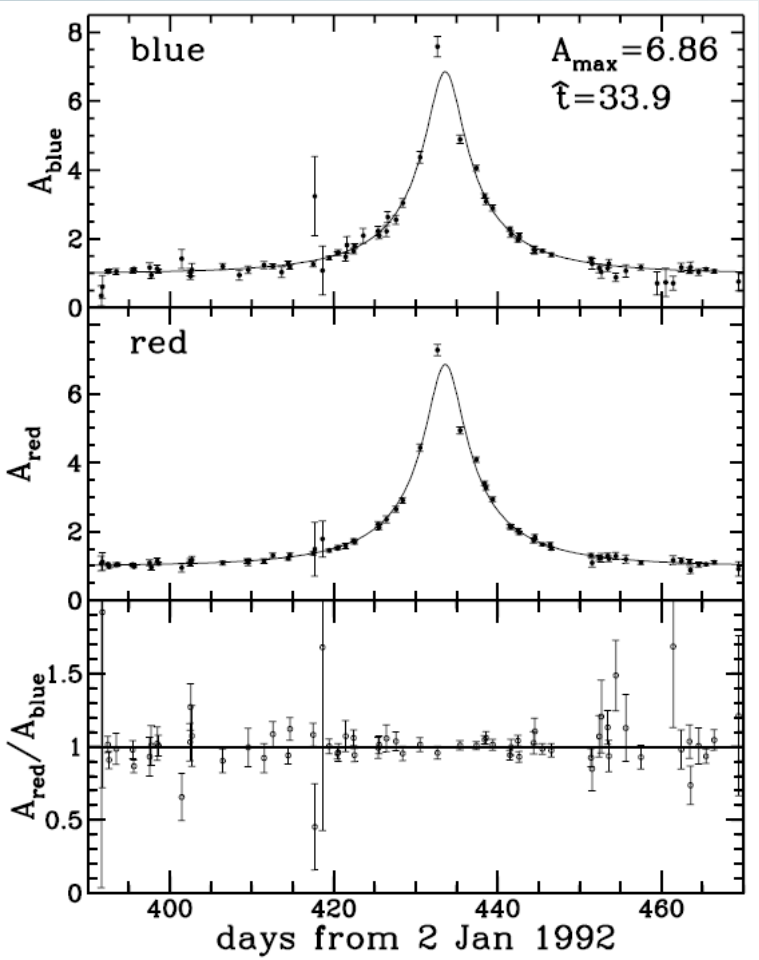
NPP Fellow at JPL





Prehistory

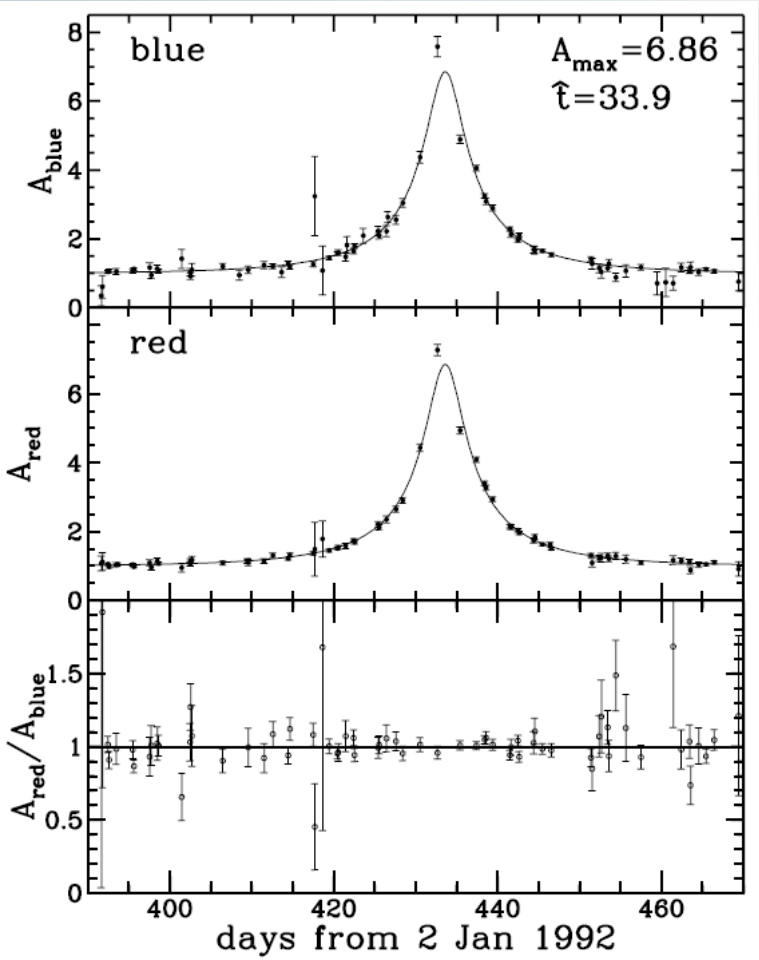
MACHO LMC-1



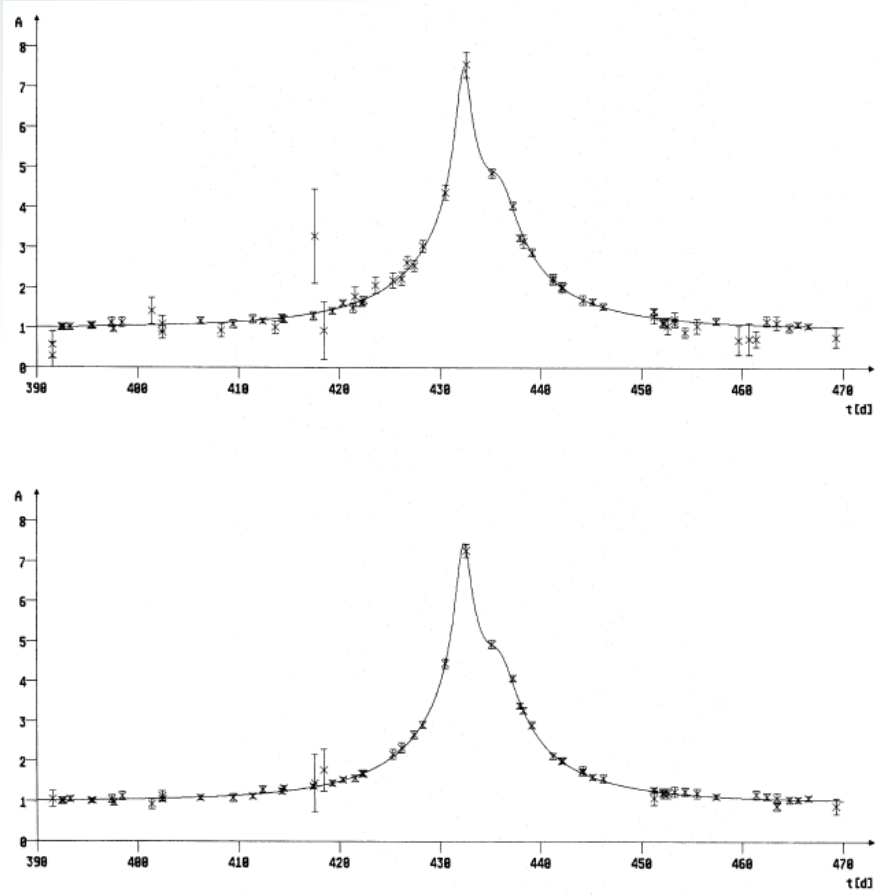
Alcock et al. 1993

Prehistory

MACHO LMC-1

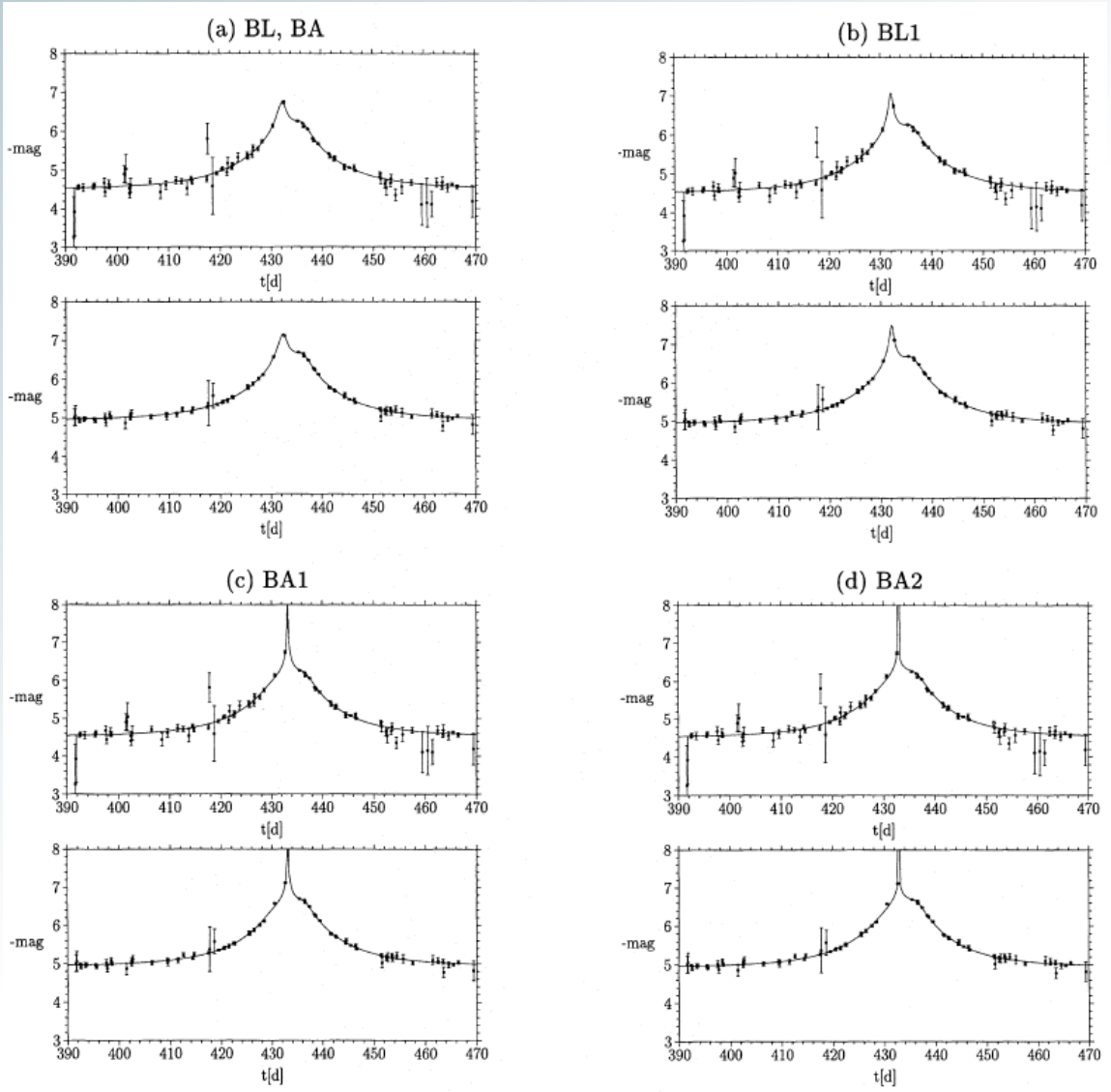


Alcock et al. 1993



Dominik & Hirshfeld 1994

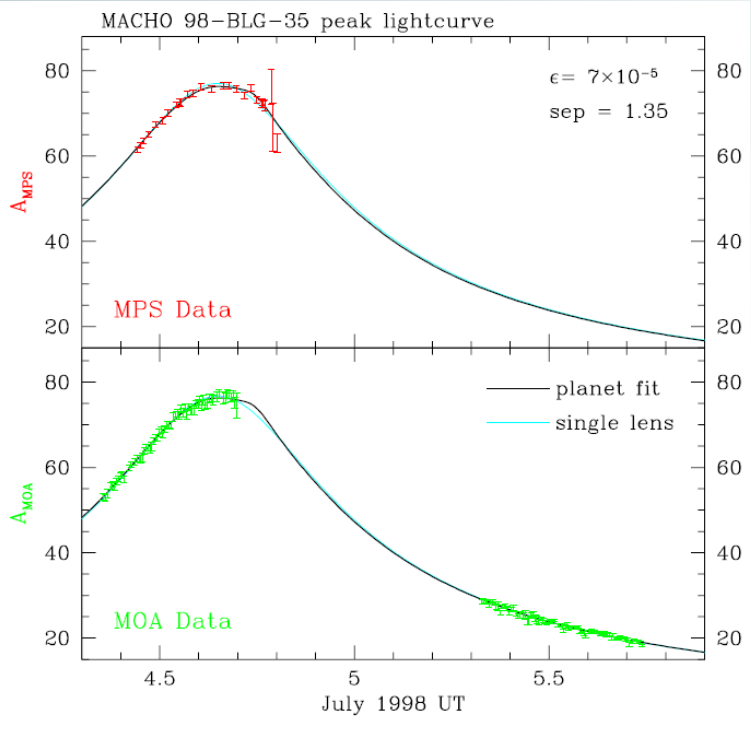
Prehistory



Dominik & Hirshfeld 1996

Prehistory

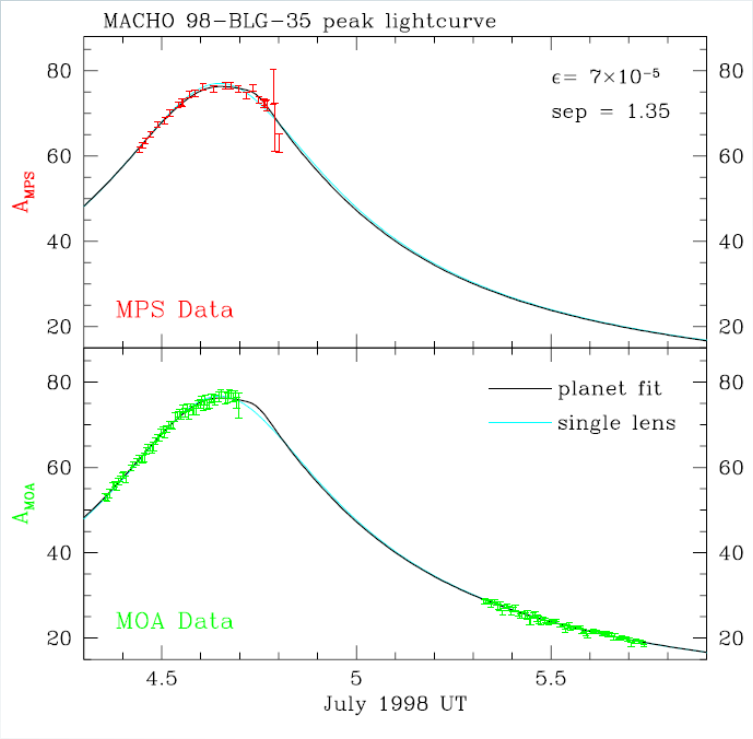
MACHO-98-BLG-35



Rhie et al. 2000

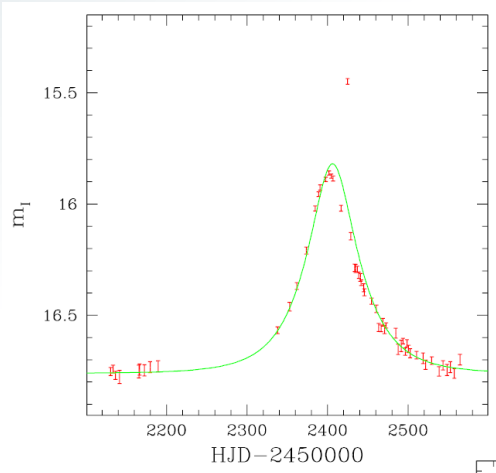
Prehistory

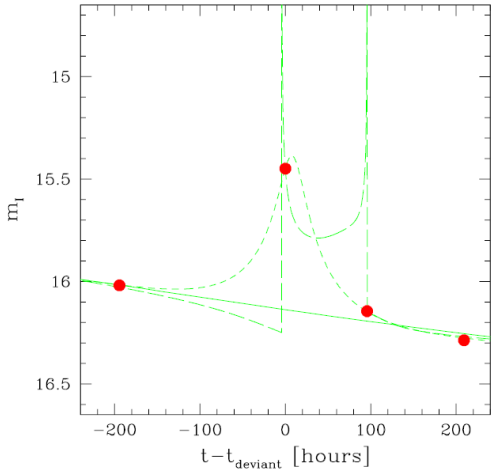
MACHO-98-BLG-35



Rhie et al. 2000

OGLE-2002-BLG-055

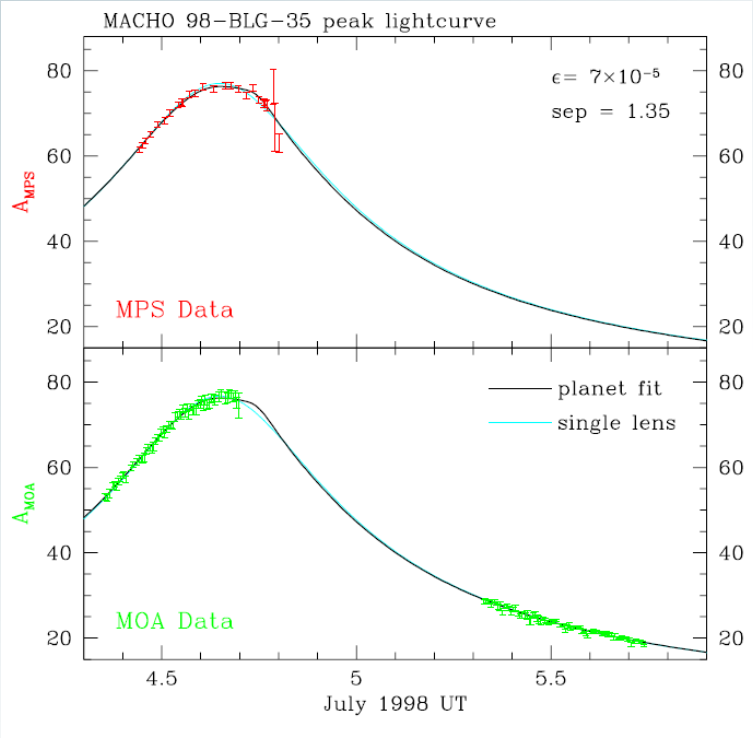




Jaroszynsky & Paczynski 2002

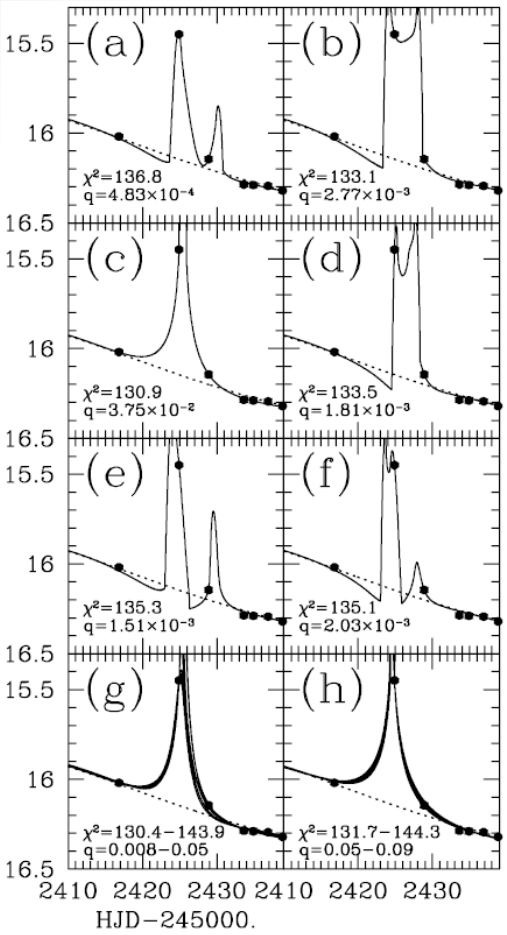
Prehistory

MACHO-98-BLG-35



Rhie et al. 2000

OGLE-2002-BLG-055

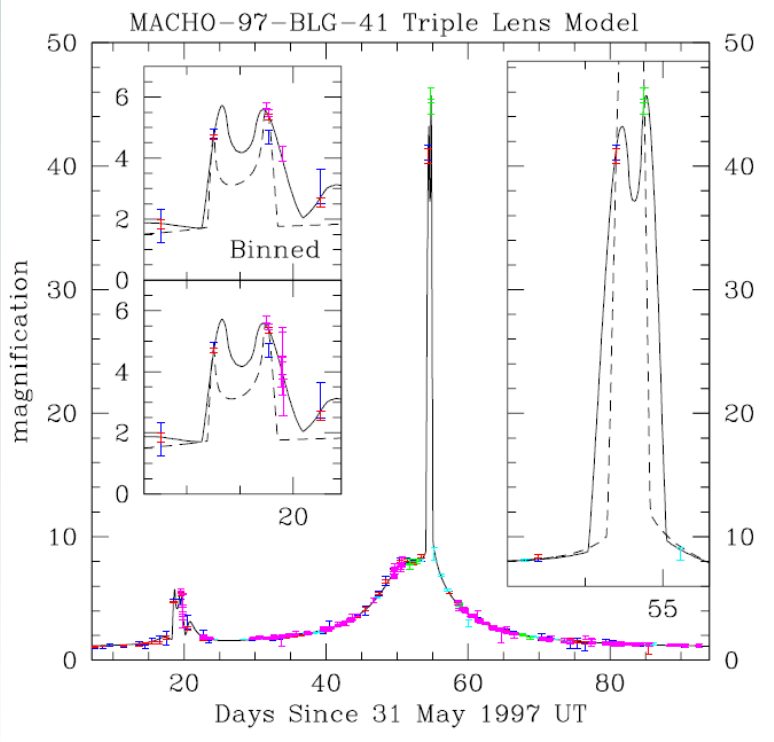


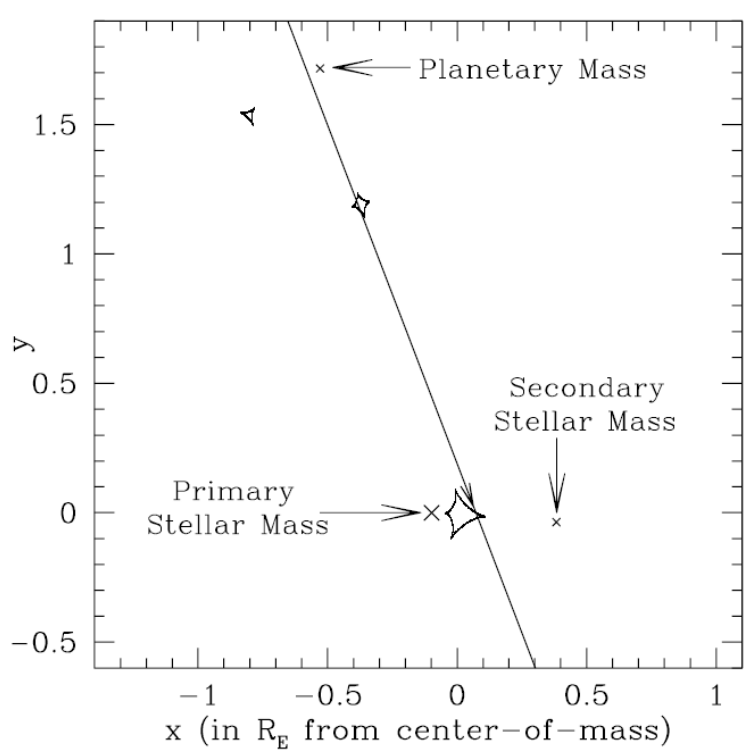
Gaudi & Han 2004

Prehistory

MACHO-97-BLG-41

First circumbinary planet!!



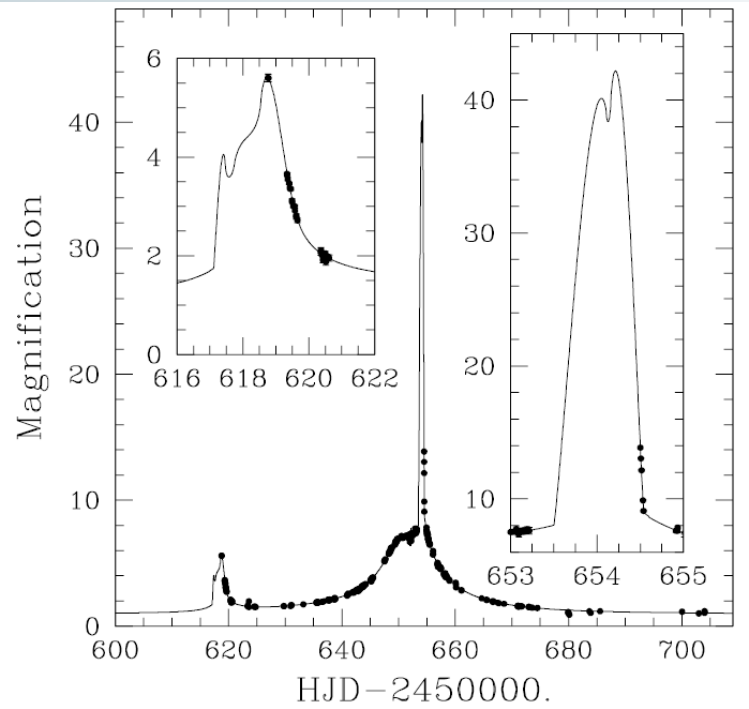


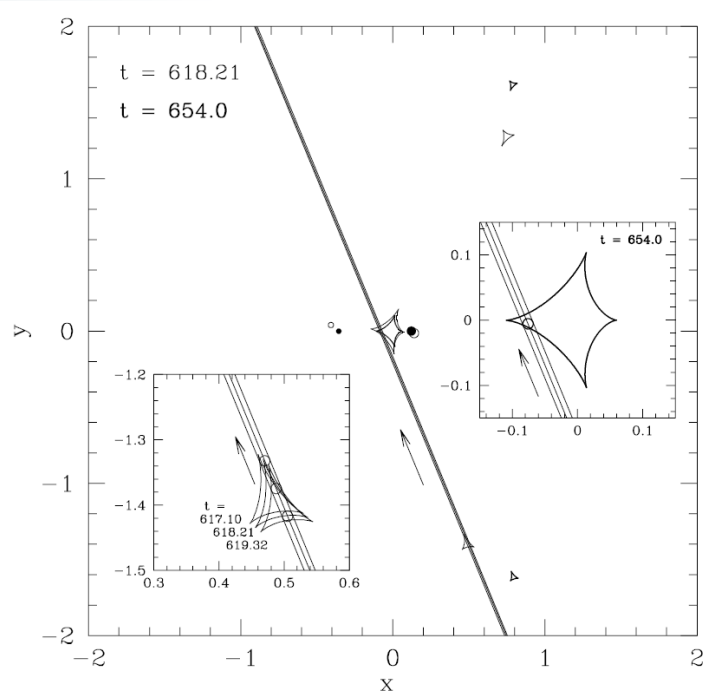
Bennett et al. 1999

Prehistory

MACHO-97-BLG-41

~~First circumbinary planet!!~~ => Rotation in a Binary Microlens

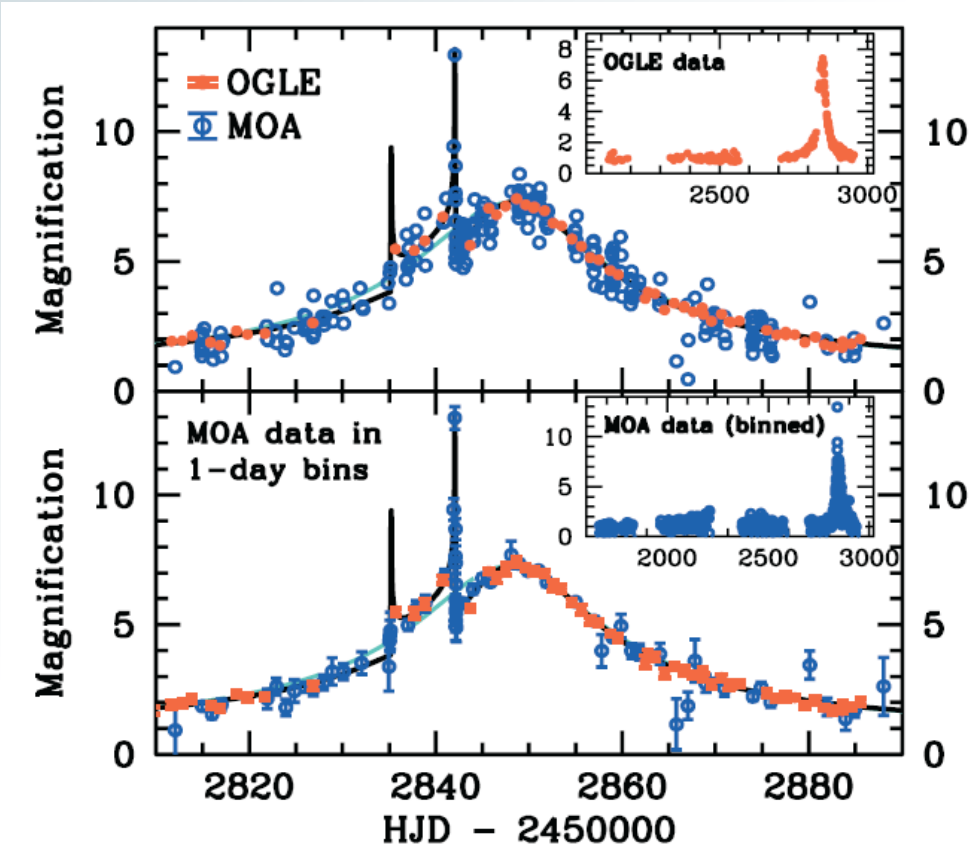




Alcock et al. 2000

The first microlensing planet

OGLE-2003-BLG-235/MOA-2003-BLG-53



Bond et al. 2004

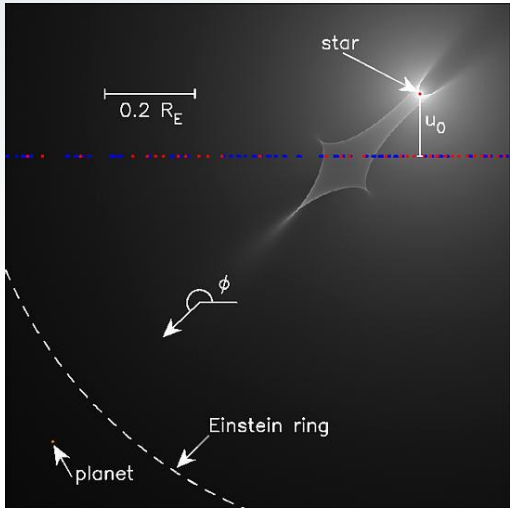
The first microlensing planet

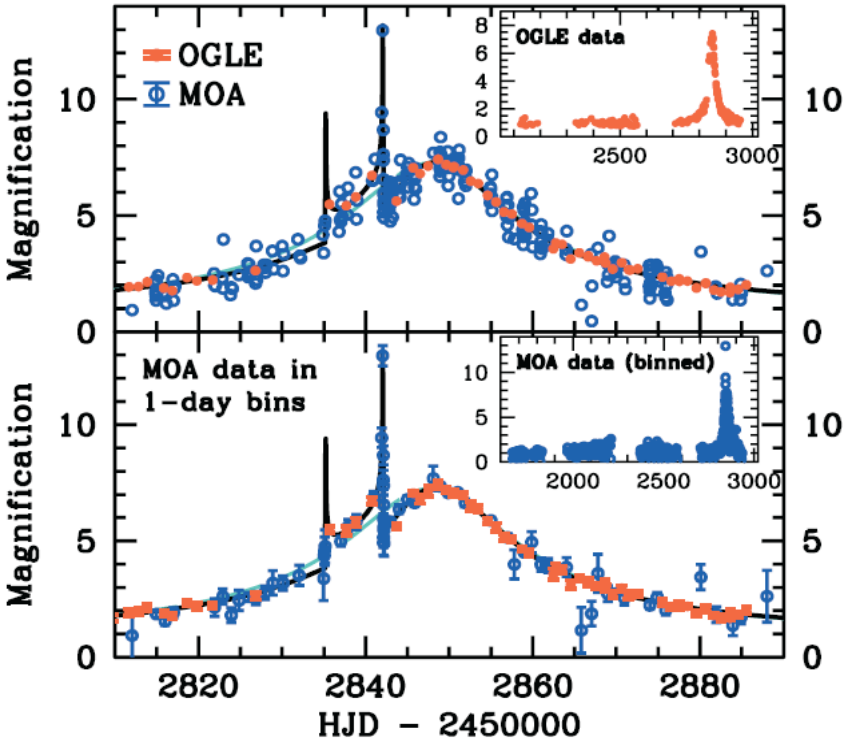
OGLE-2003-BLG-235/MOA-2003-BLG-53

Model parameters

t_E	$61.5 \pm 1.8\ [d]$
q	$3.9^{+1.1}_{-0.7} \times 10^{-3}$
s	1.120 ± 0.007

Resonant caustic





Bond et al. 2004

The first microlensing planet

OGLE-2003-BLG-235/MOA-2003-BLG-53

Model parameters

t_E	$61.5 \pm 1.8\ [d]$
q	$3.9^{+1.1}_{-0.7} \times 10^{-3}$
s	1.120 ± 0.007

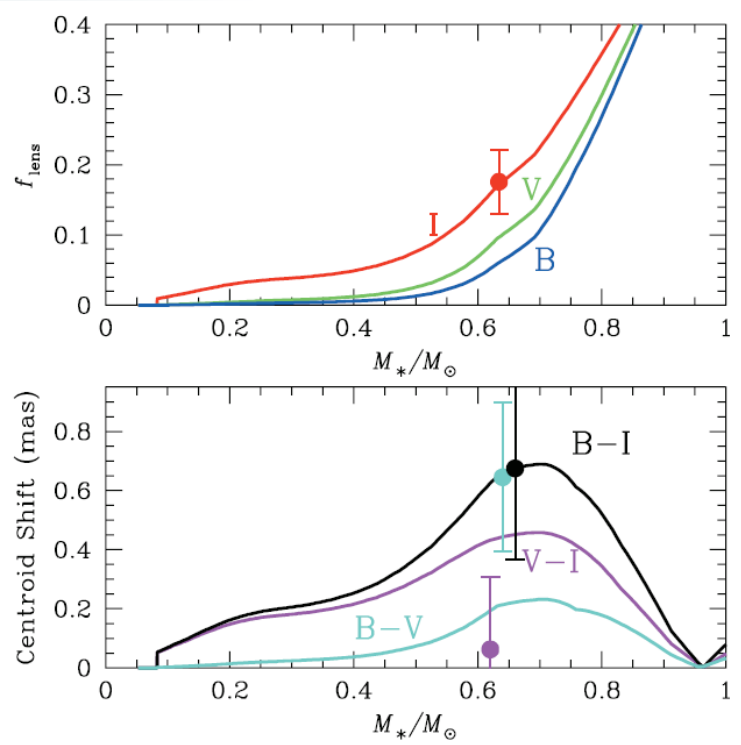
Bond et al. 2004

Physical properties

$m_{\rm planet}$	$2.6^{+0.8}_{-0.6}[M_J]$
$a_\perp$	$4.3^{+2.5}_{-0.8}[\rm AU]$
$M_{\rm host}$	$0.63^{+0.07}_{-0.09}[M_\odot]$

Bennett et al. 2006

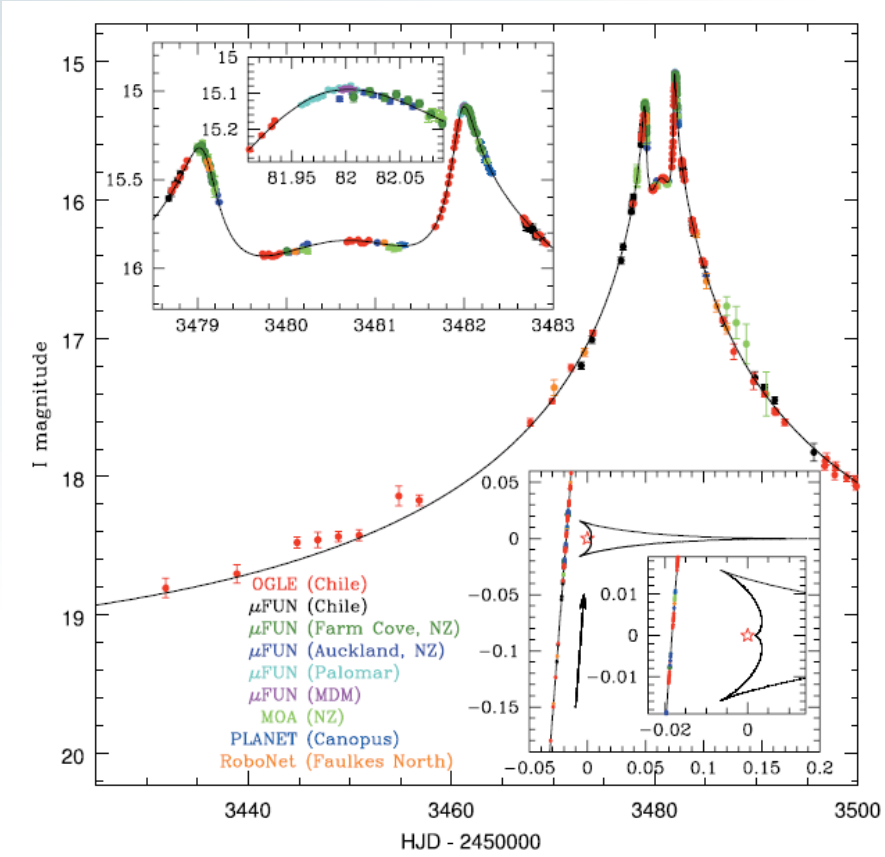
Host star identification using *HST*



Bennett et al. 2006

2nd microlensing planet – alert and follow-up

OGLE-2005-BLG-071



Udalski et al. 2005

2nd microlensing planet – alert and follow-up

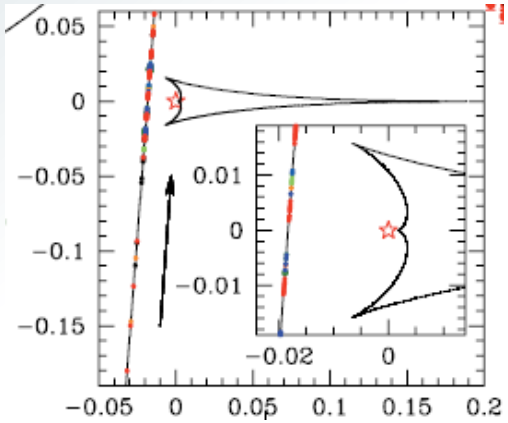
OGLE-2005-BLG-071

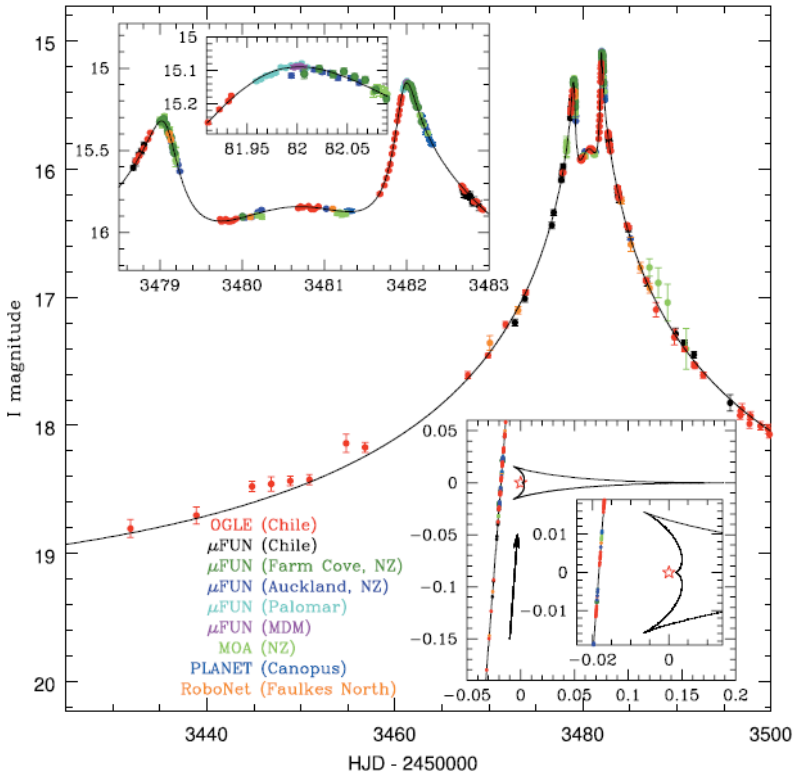
Model parameters

t_E	71 $[d]$
q	7.1 / 6.7×10^{-3}
s	1.29 / 0.76

Wide / Close

Central caustic





Udalski et al. 2005

2nd microlensing planet – alert and follow-up

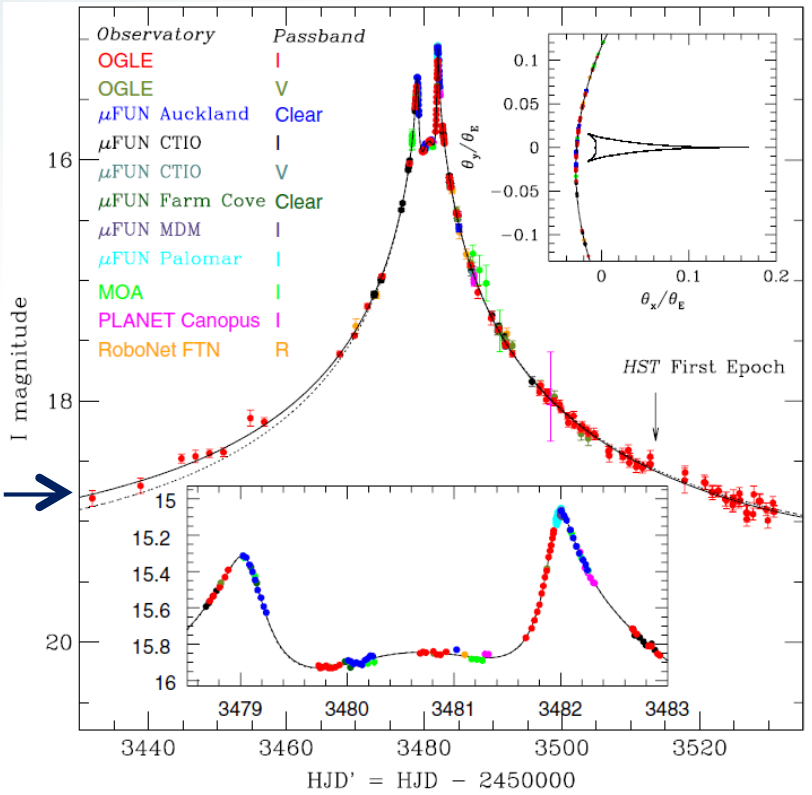
OGLE-2005-BLG-071

Model parameters

t_E	71 $[d]$
q	7.5 / 6.9×10^{-3}
s	1.31 / 0.76

Wide / Close

Microlens parallax →



Dong et al. 2009

2nd microlensing planet – alert and follow-up

OGLE-2005-BLG-071

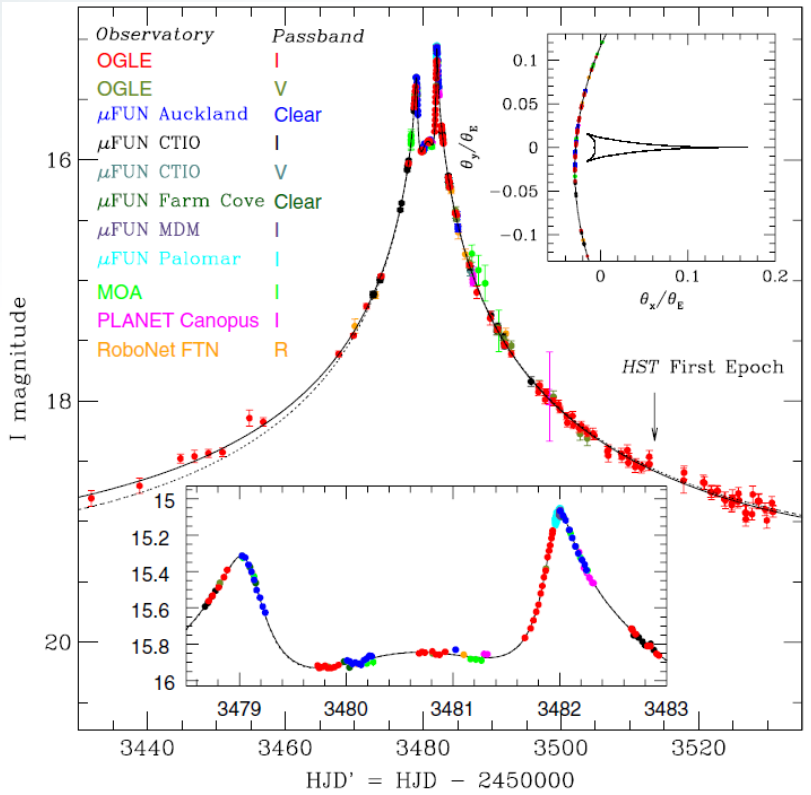
Model parameters

t_E	71 $[d]$
q	7.5 / 6.9×10^{-3}
s	1.31 / 0.76

Wide / Close

Physical properties

m_{planet}	3.8 / 3.4 $[M_J]$
$a_\perp$	3.6 / 2.1[AU]
M_{host}	0.46 $[M_\odot]$



Dong et al. 2009

2nd microlensing planet – alert and follow-up

OGLE-2005-BLG-071

Model parameters

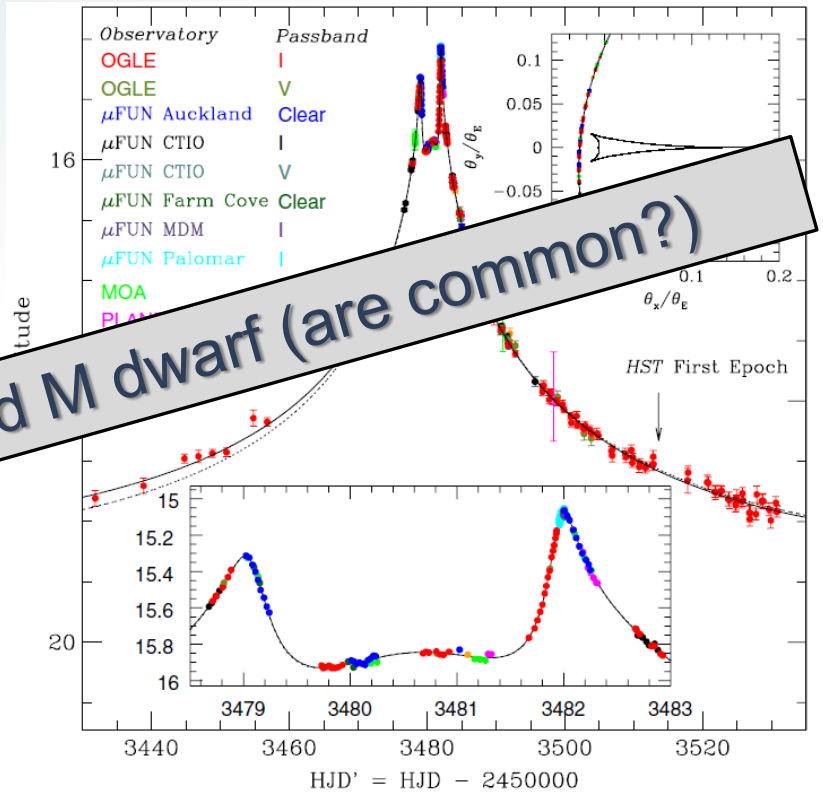
t_E	71 $[d]$
q	7.5 / 6.9×10^{-3}
s	1.31 / 0.76

Wide / Close

Pl… perties

$m_{\rm planet}$	3.8 / 3.4 $[M_J]$
$a_\perp$	3.6 / 2.1[AU]
$M_{\rm host}$	0.46 $[M_\odot]$

Super Jupiter around M dwarf (are common?)



Dong et al. 2009

Super Jupiters around M dwarfs

~20% of microlensing planet discoveries !!

Event	Host mass $[M_\odot]$	Planet mass $[M_J]$	Bayesian estimate?	Discovery Ref.
OGLE-2005-BLG-071	0.46 ± 0.04	3.8 ± 0.4		Udalski+(2005)
OGLE-2012-BLG-0406	0.44 ± 0.07	2.73 ± 0.43		Poleski+(2014)
MOA-2011-BLG-322	$0.39^{+0.45}_{-0.19}$	$11.6^{+13.4}_{-5.6}$	Yes	Shvartzvald+(2014)
OGLE-2008-BLG-355	$0.37^{+0.30}_{-0.17}$	$4.6^{+3.7}_{-2.2}$	Yes	Koshimoto+(2014)
OGLE-2015-BLG-0954	0.33 ± 0.12	3.9 ± 1.4		Shin+(2016)
MOA-2016-BLG-227	$0.29^{+0.23}_{-0.15}$	$2.8^{+2.2}_{-1.5}$	Partial	Koshimoto+(2017)
MOA-2009-BLG-387	$0.19^{+0.30}_{-0.12}$	$2.6^{+4.2}_{-1.6}$	Partial	Batista+(2011)
MOA-2010-BLG-073	0.16 ± 0.03	11.0 ± 2.0		Street+(2013)
OGLE-2013-BLG-0102	0.096 ± 0.013	12.6 ± 2.1		Jung+(2015)
OGLE-2012-BLG-0358	0.022 ± 0.002	1.85 ± 0.19		Han+(2013)

Super Jupiters around M dwarfs

~20% of microlensing planet discoveries !!

Event	Host mass [$M_\odot$]	Planet mass [M_J]	Bayesian estimate?	Discovery Ref.
OGLE-2005-BLG-071	0.46 ± 0.04	3.8 ± 0.4		Udalski+(2005)
OGLE-2012-BLG-0406	0.44 ± 0.07	2.73 ± 0.43		Poleski+(2014)
MOA-2011-BLG-322	$0.39^{+0.45}_{-0.19}$	11.6^{+13}		Shvartzvald+(2014)
OGLE-2008-BLG-355	$0.37^{+0.30}$		Yes	Koshimoto+(2014)
OGLE-2015-BLG-09		3.9 ± 1.4		Shin+(2016)
MOA	$0.29^{+0.23}_{-0.15}$	$2.8^{+2.2}_{-1.5}$	Partial	Koshimoto+(2017)
MOA-2009-BLG-387	$0.19^{+0.30}_{-0.12}$	$2.6^{+4.2}_{-1.6}$	Partial	Batista+(2011)
MOA-2010-BLG-073	0.16 ± 0.03	11.0 ± 2.0		Street+(2013)
OGLE-2013-BLG-0102	0.096 ± 0.013	12.6 ± 2.1		Jung+(2015)
OGLE-2012-BLG-0358	0.022 ± 0.002	1.85 ± 0.19		Han+(2013)

Super Jupiters around M dwarf are not rare

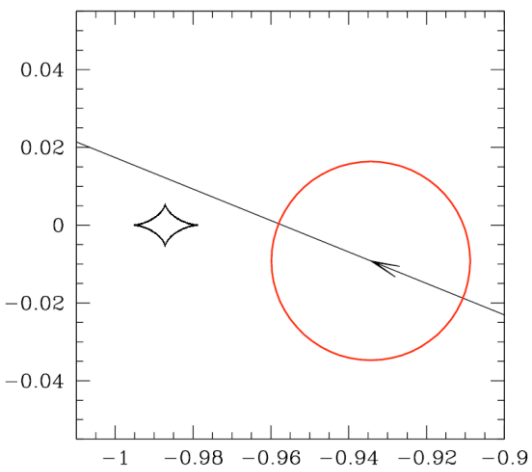
3rd microlensing planet

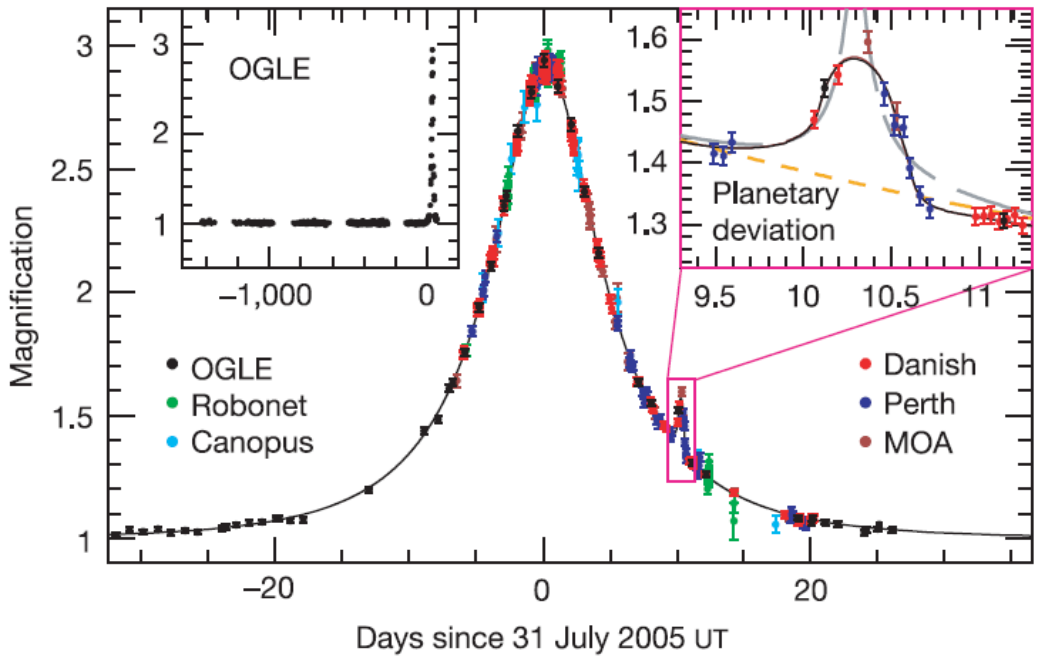
OGLE-2005-BLG-390

Model parameters

t_E	$11.0 \pm 0.1\ [d]$
q	$7.6 \pm 0.7 \times 10^{-5}$
s	1.61 ± 0.01

Planetary caustic





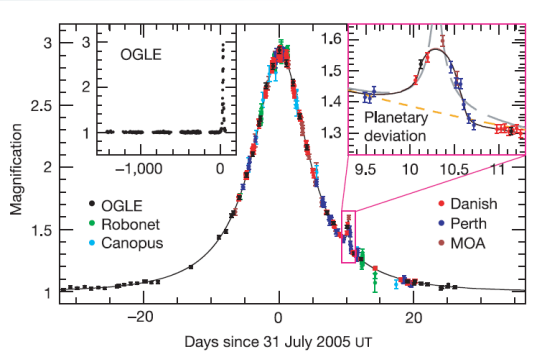
Beaulieu et al. 2006

3rd microlensing planet

OGLE-2005-BLG-390

Model parameters

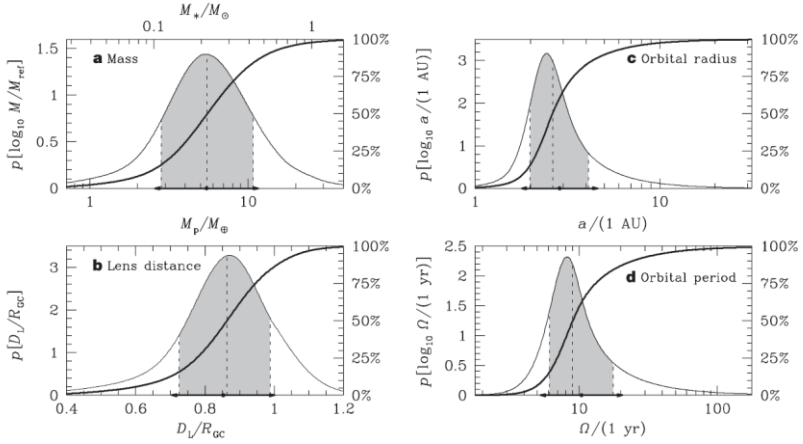
t_E	$11.0 \pm 0.1\ [d]$
q	$7.6 \pm 0.7 \times 10^{-5}$
s	1.61 ± 0.01



Physical properties

m_{planet}	$5.5^{+5.5}_{-2.7}\ [M_\oplus]$
$a_\perp$	$2.6^{+1.5}_{-0.6}[\text{AU}]$
M_{host}	$0.22^{+0.21}_{-0.11}\ [M_\odot]$

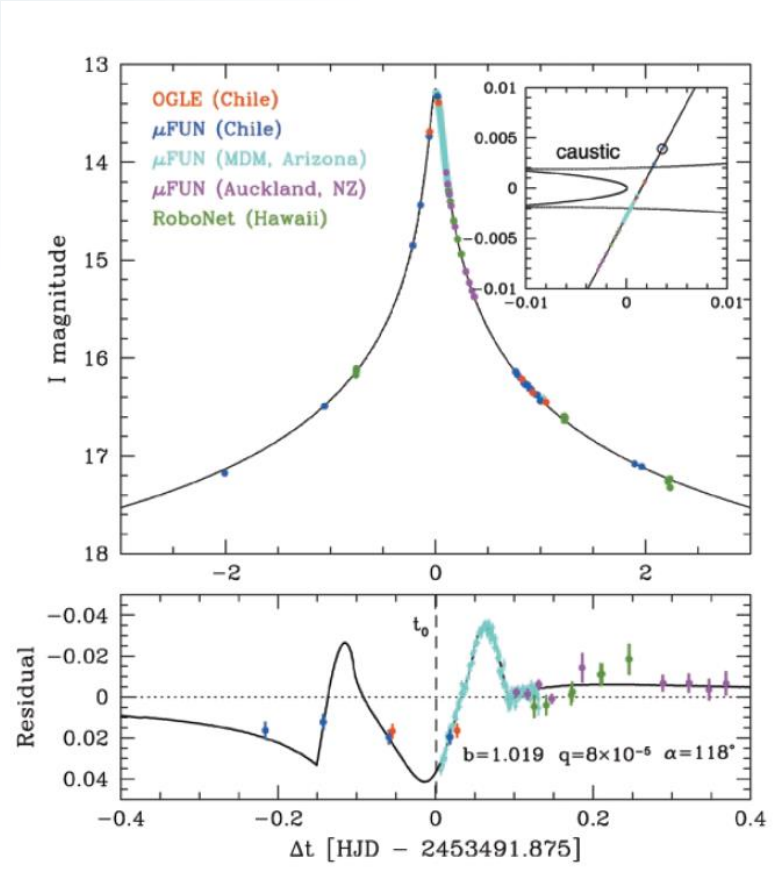
Bayesian analysis



Beaulieu et al. 2006

4th microlensing planet

OGLE-2005-BLG-169

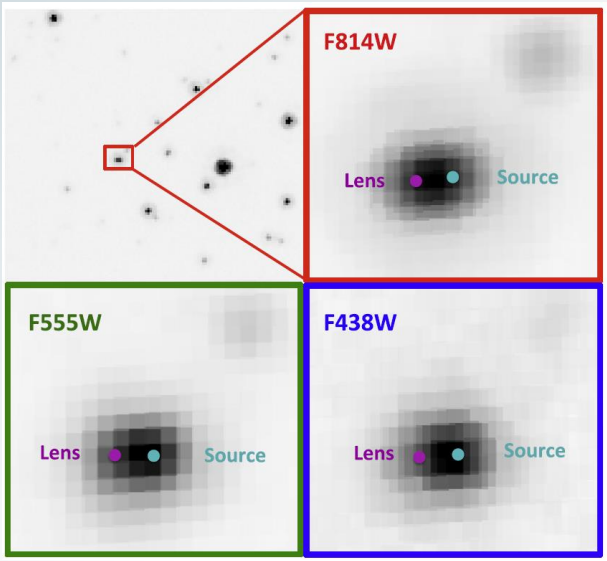


Gould et al. 2006

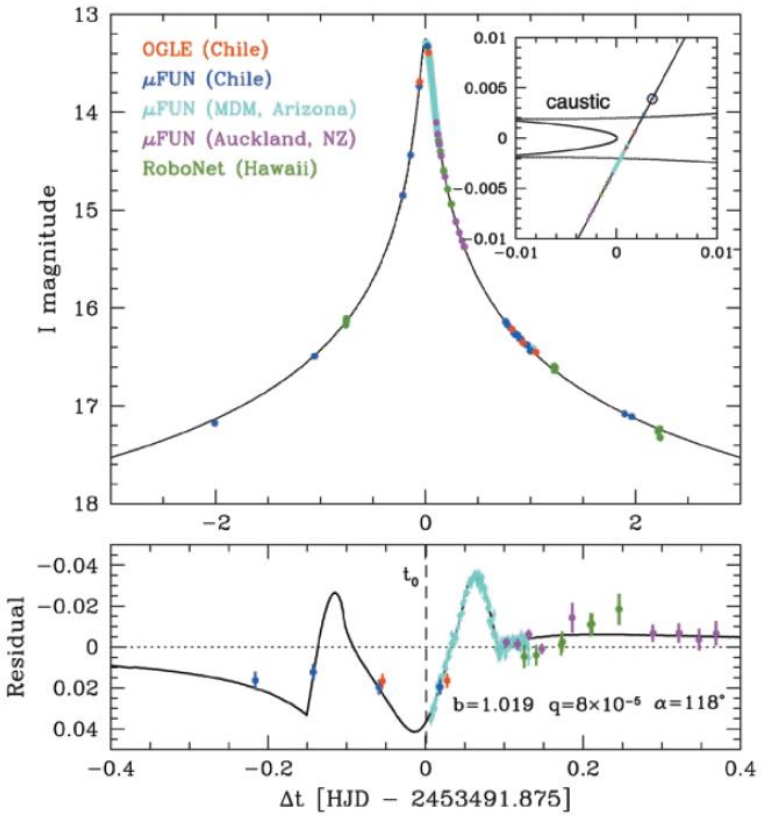
4th microlensing planet

OGLE-2005-BLG-169

HST – 6.4 years after the event



Bennett et al. 2015

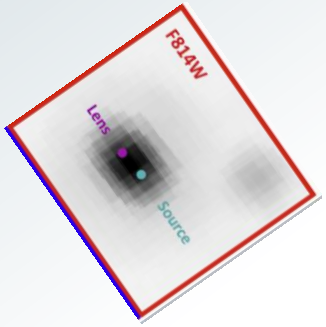


Gould et al. 2006

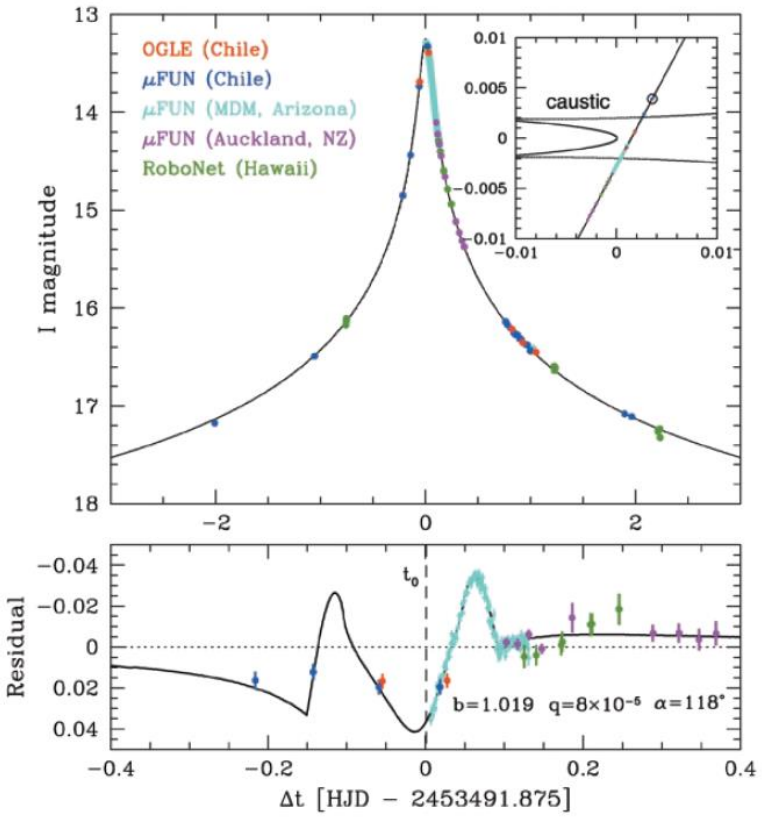
4th microlensing planet

OGLE-2005-BLG-169

HST – 6.4 years after the event



Bennett et al. 2015

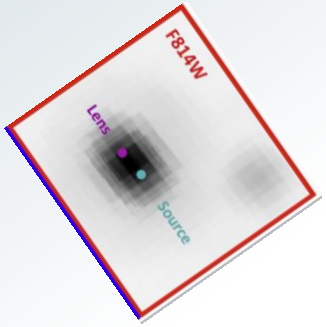


Gould et al. 2006

4th microlensing planet

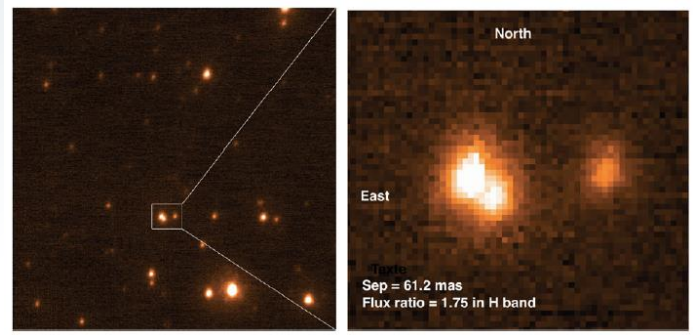
OGLE-2005-BLG-169

HST – 6.4 years after the event

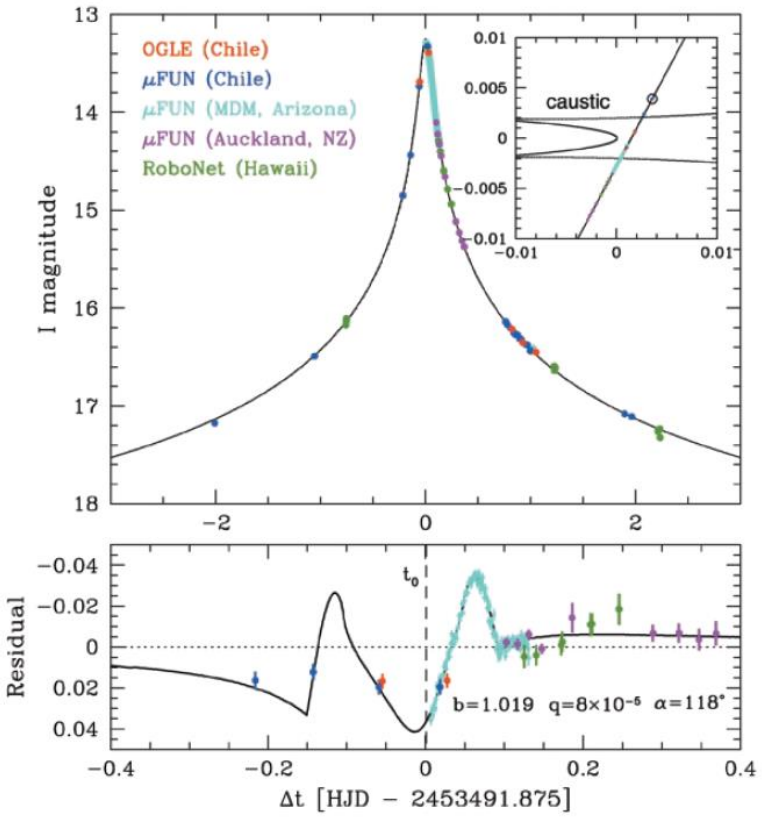


Bennett et al. 2015

Keck – 8.2 years after the event



Batista et al. 2015



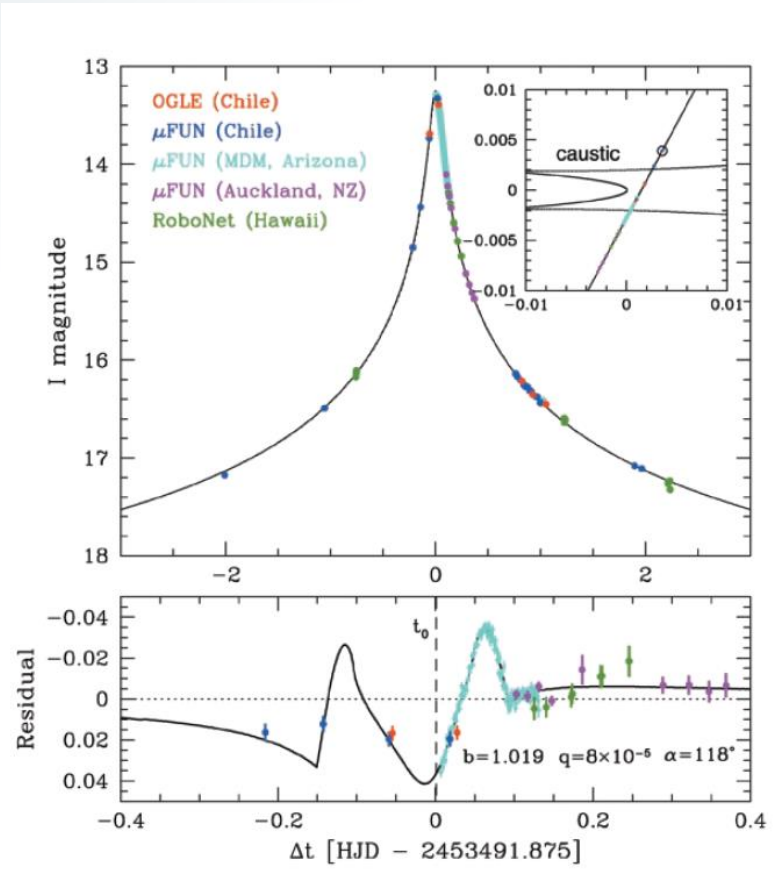
Gould et al. 2006

4th microlensing planet

OGLE-2005-BLG-169

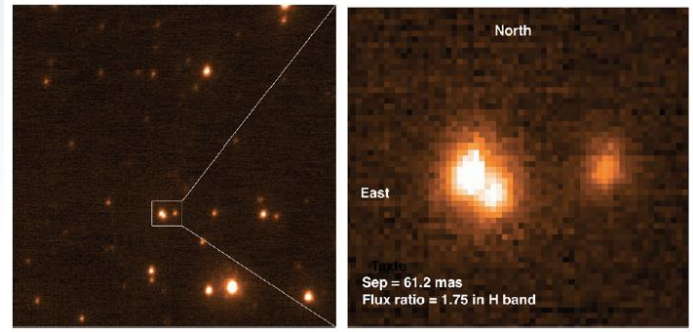
Physical properties

m_{planet}	$13.2 \pm 1.3[M_{\oplus}]$
$a_{\perp}$	$3.4 \pm 0.3[\text{AU}]$
M_{host}	$0.65 \pm 0.05[M_{\odot}]$



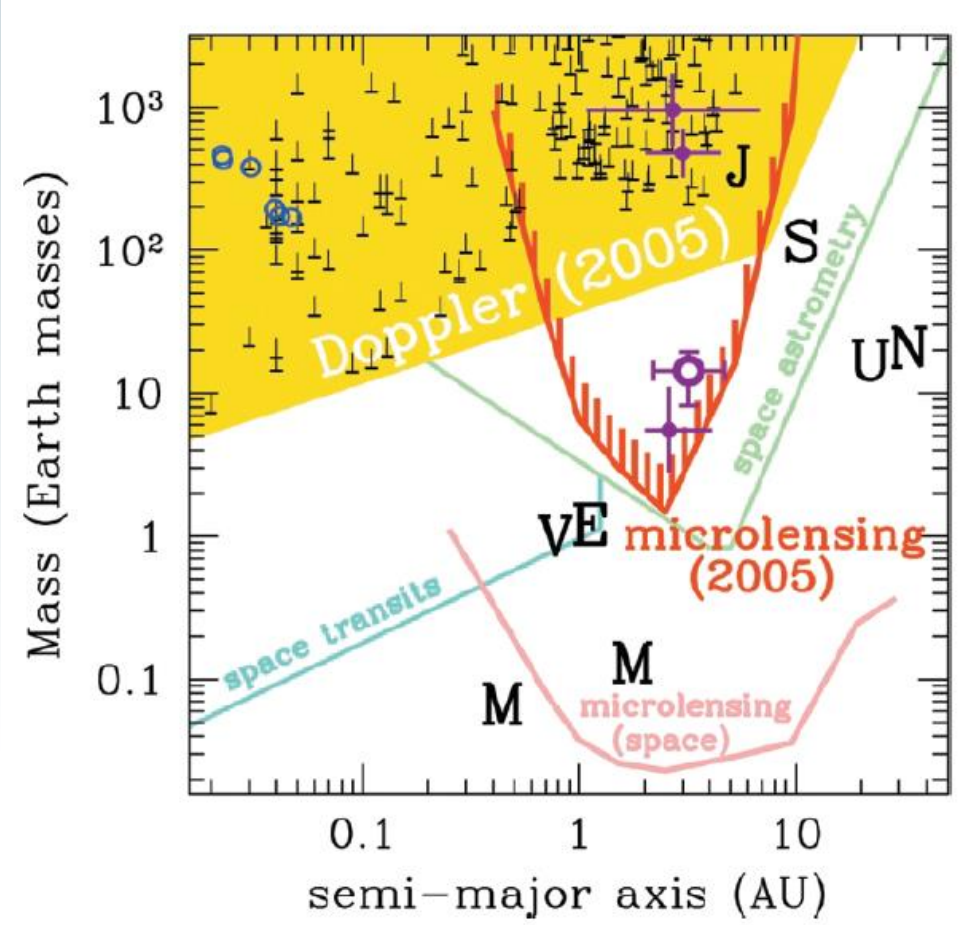
Gould et al. 2006

Keck – 8.2 years after the event



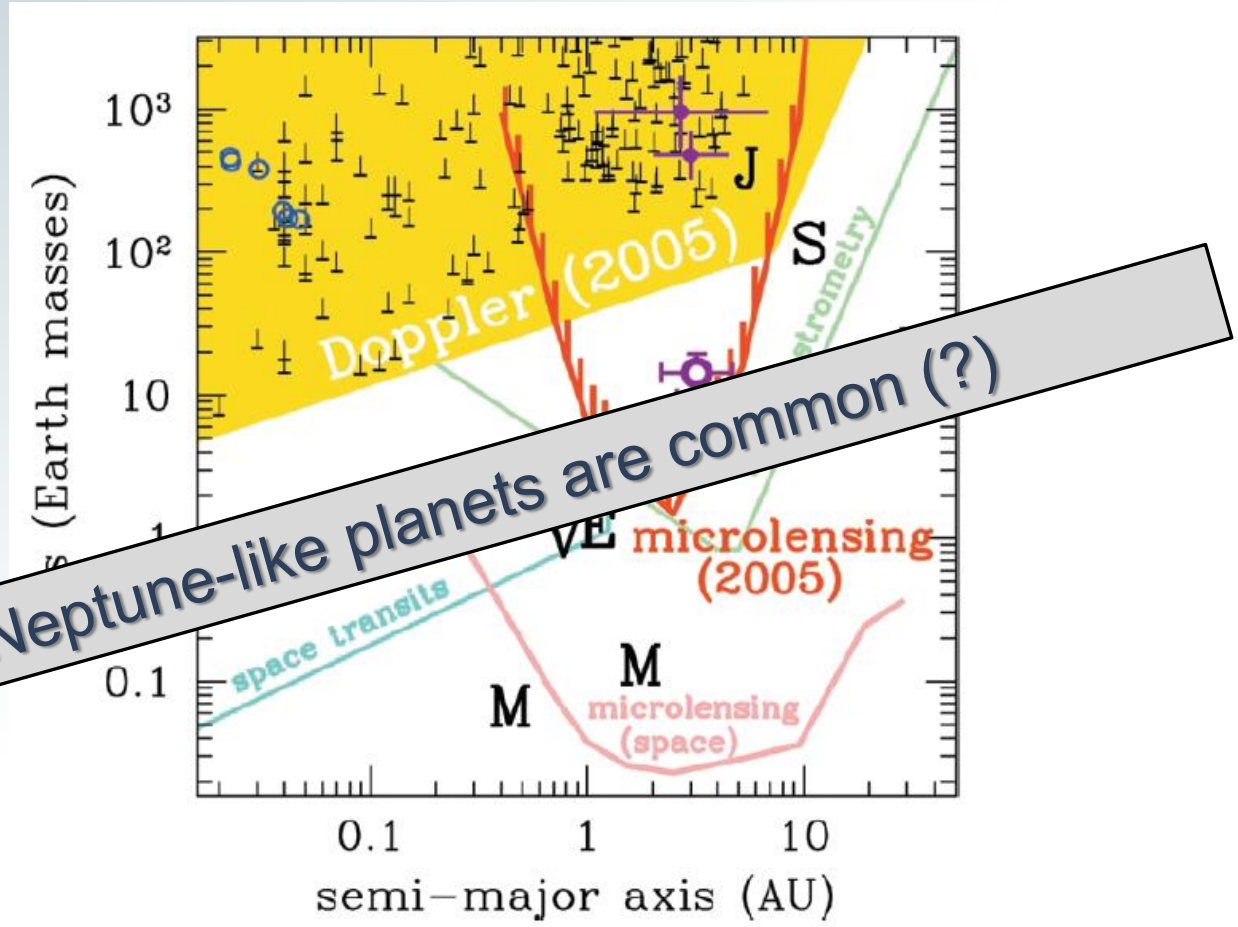
Batista et al. 2015

4th microlensing planet



Gould et al. 2006

4th microlensing planet



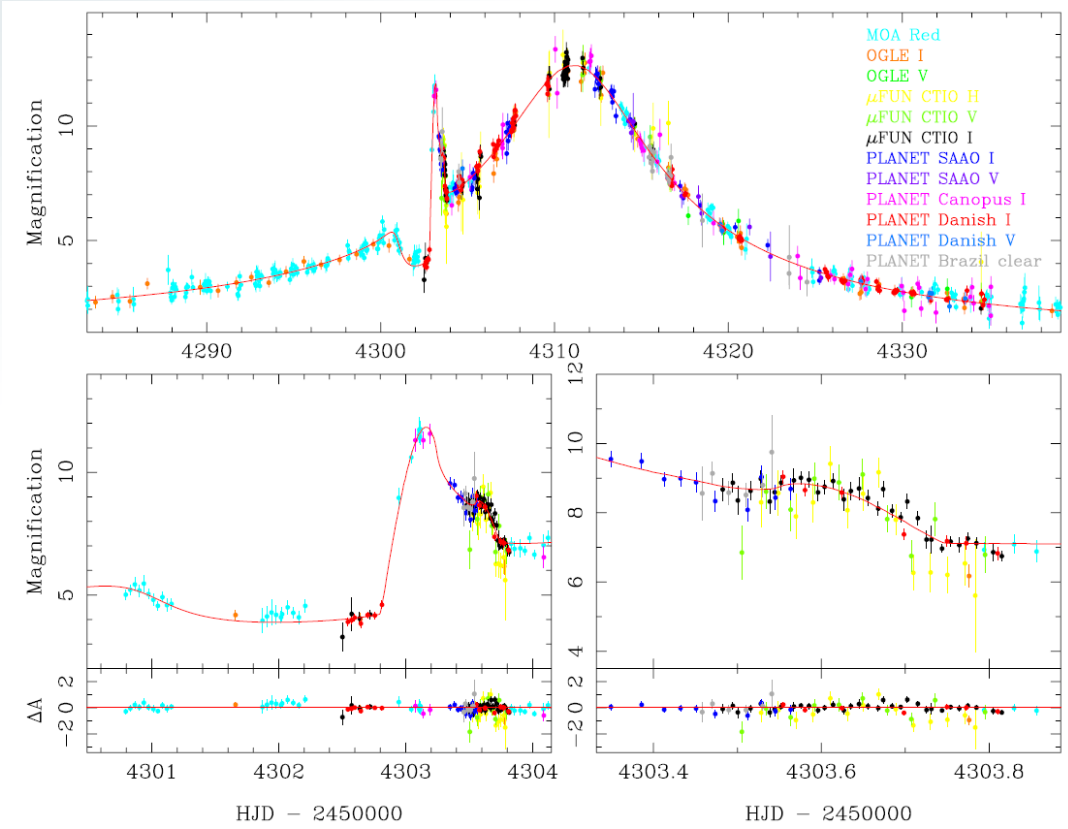
Gould et al. 2006

…10th microlensing planet

OGLE-2007-BLG-368

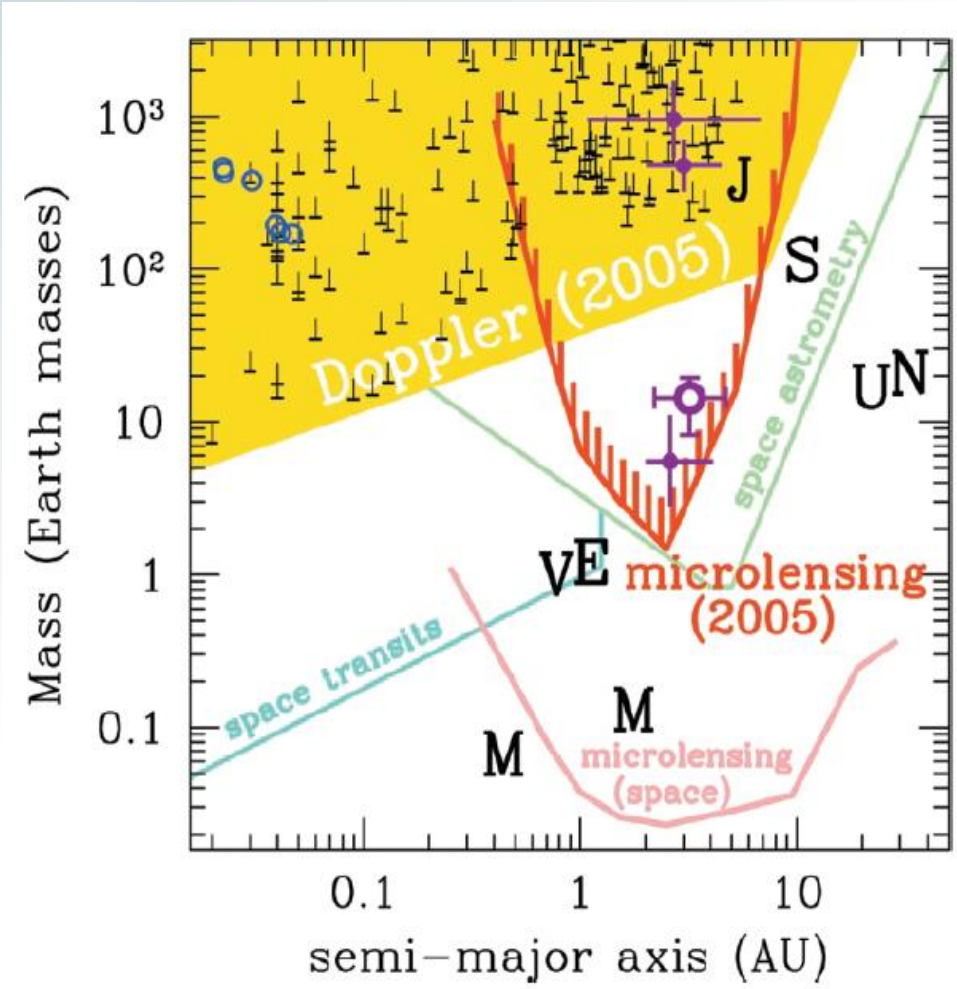
Physical properties

$m_{\rm planet}$	$20^{+7}_{-8}\ [M_\oplus]$
$a_\perp$	$3.3^{+1.4}_{-0.8}$[AU]
$M_{\rm host}$	$0.64^{+0.21}_{-0.26}\ [M_\odot]$



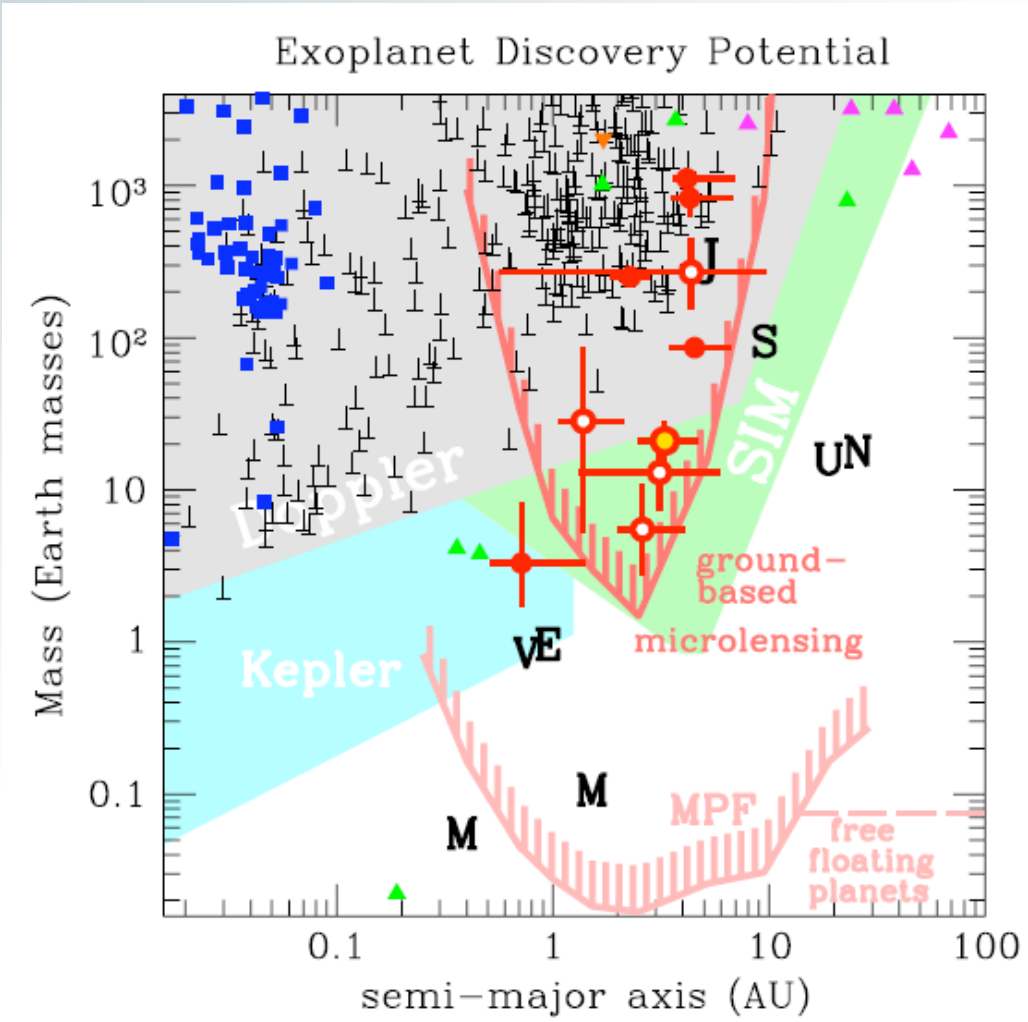
Sumi et al. 2010

10th microlensing planet



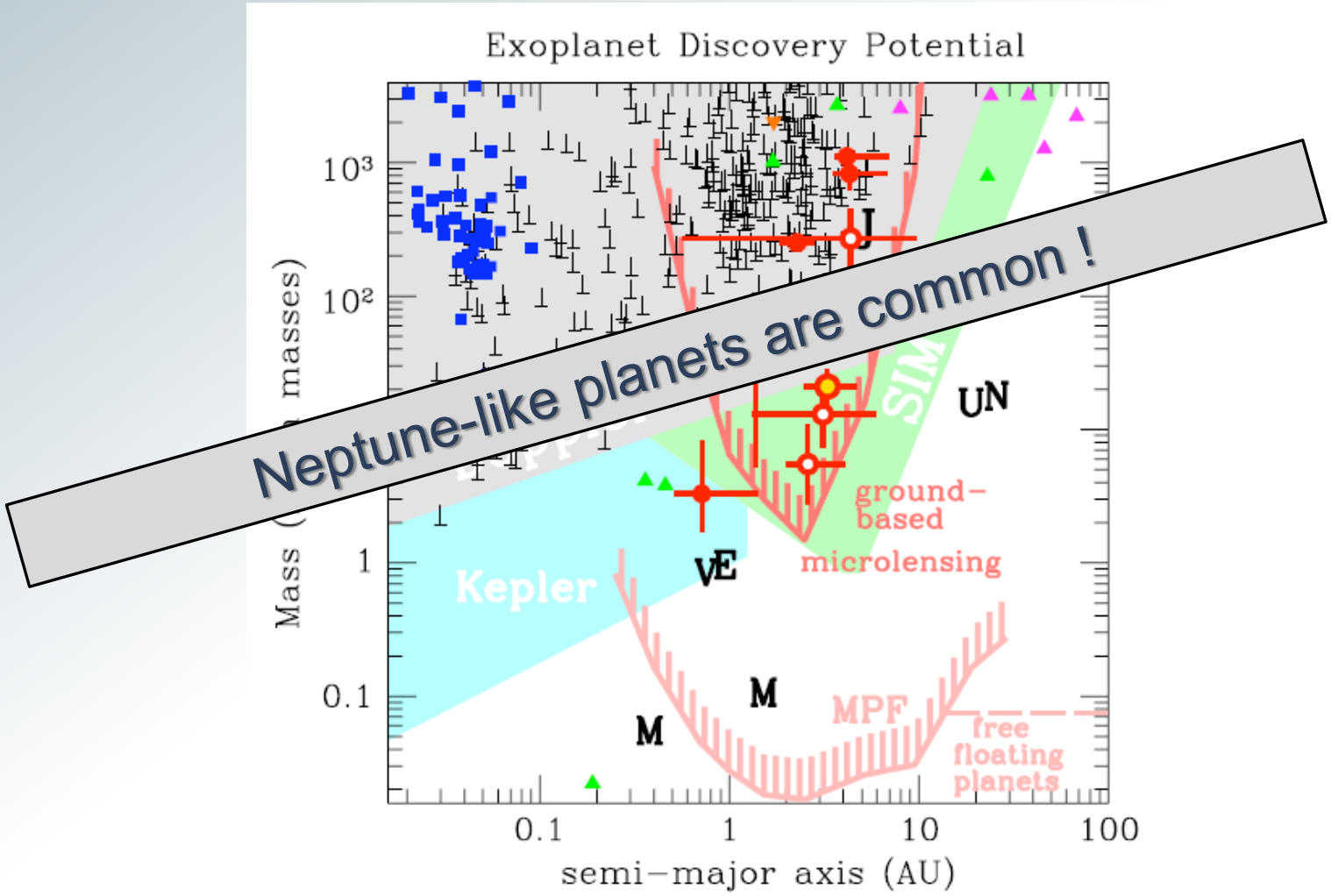
Gould et al. 2006

10th microlensing planet



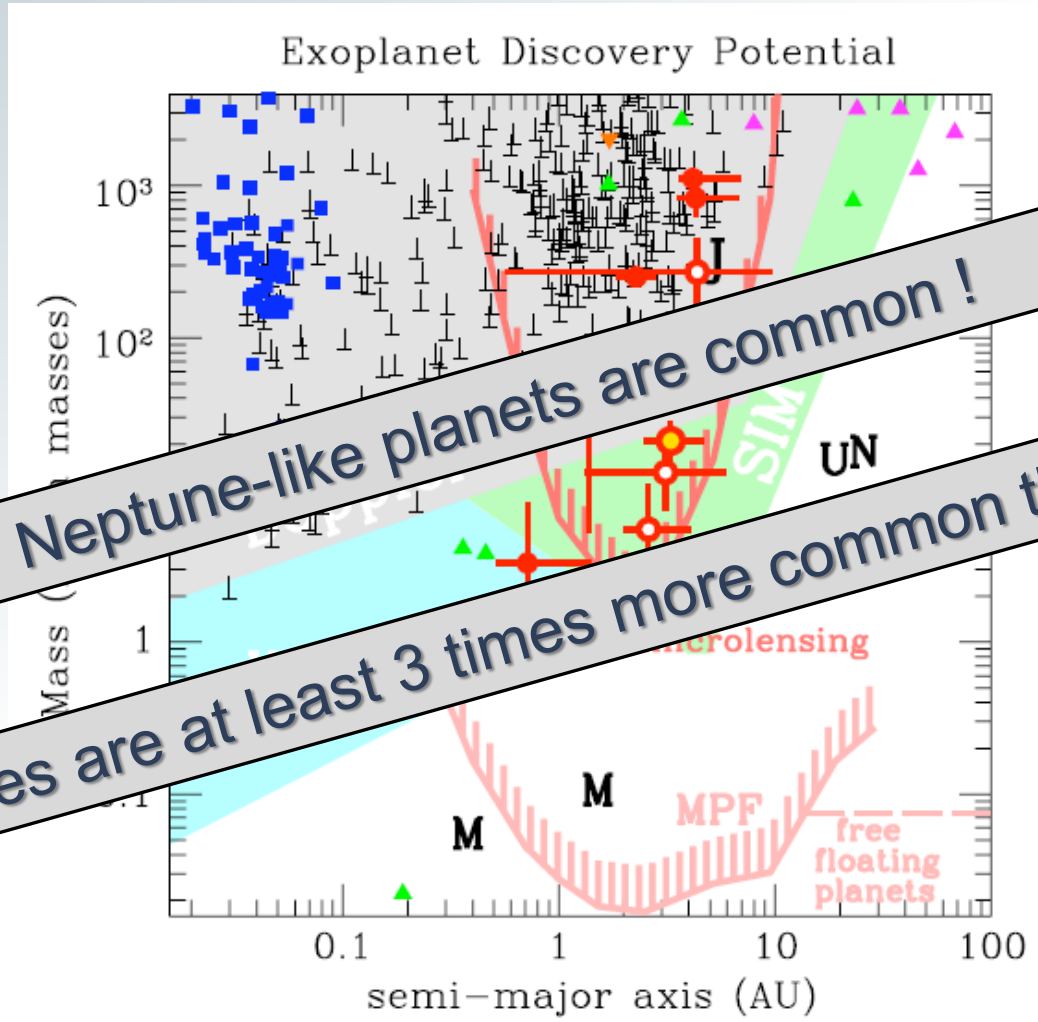
Sumi et al. 2010

10th microlensing planet



Sumi et al. 2010

10th microlensing planet

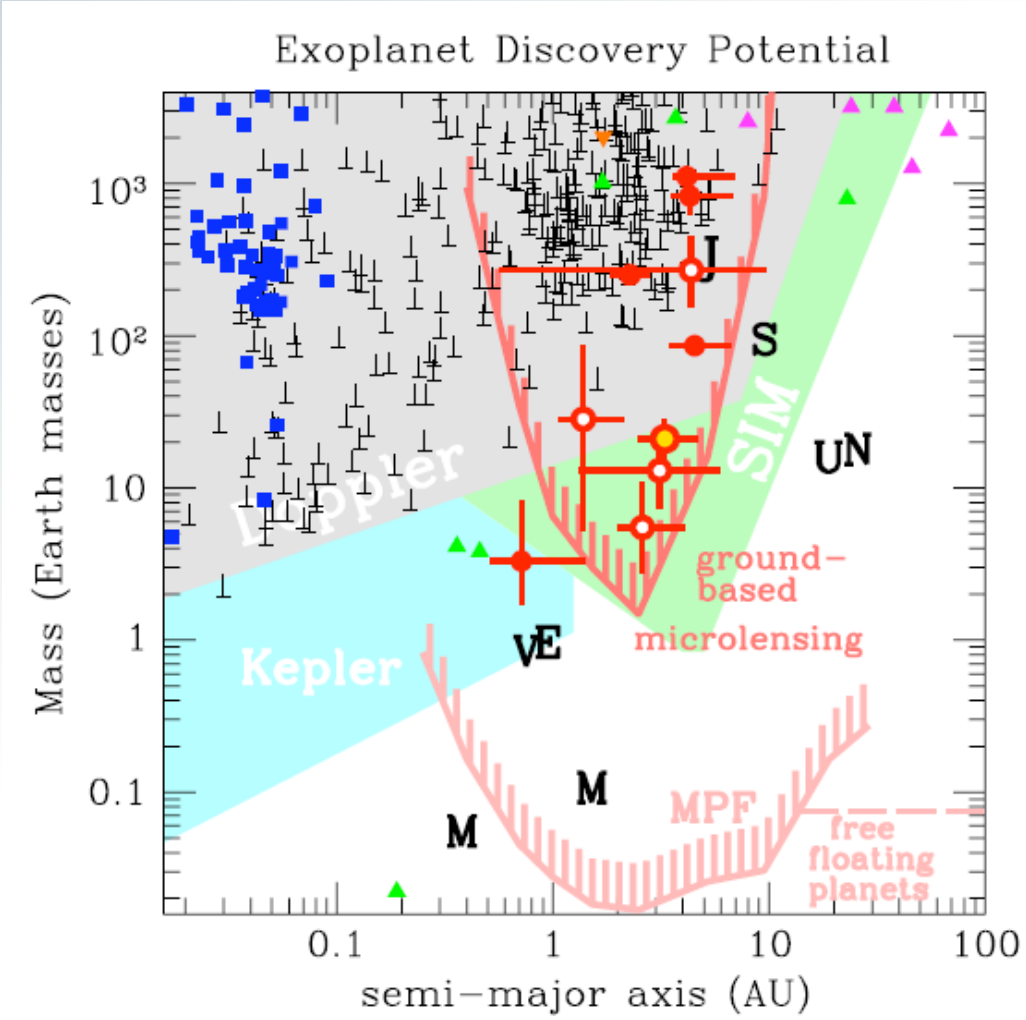


Neptune-like planets are common !

Neptunes are at least 3 times more common than Jupiters

Sumi et al. 2010

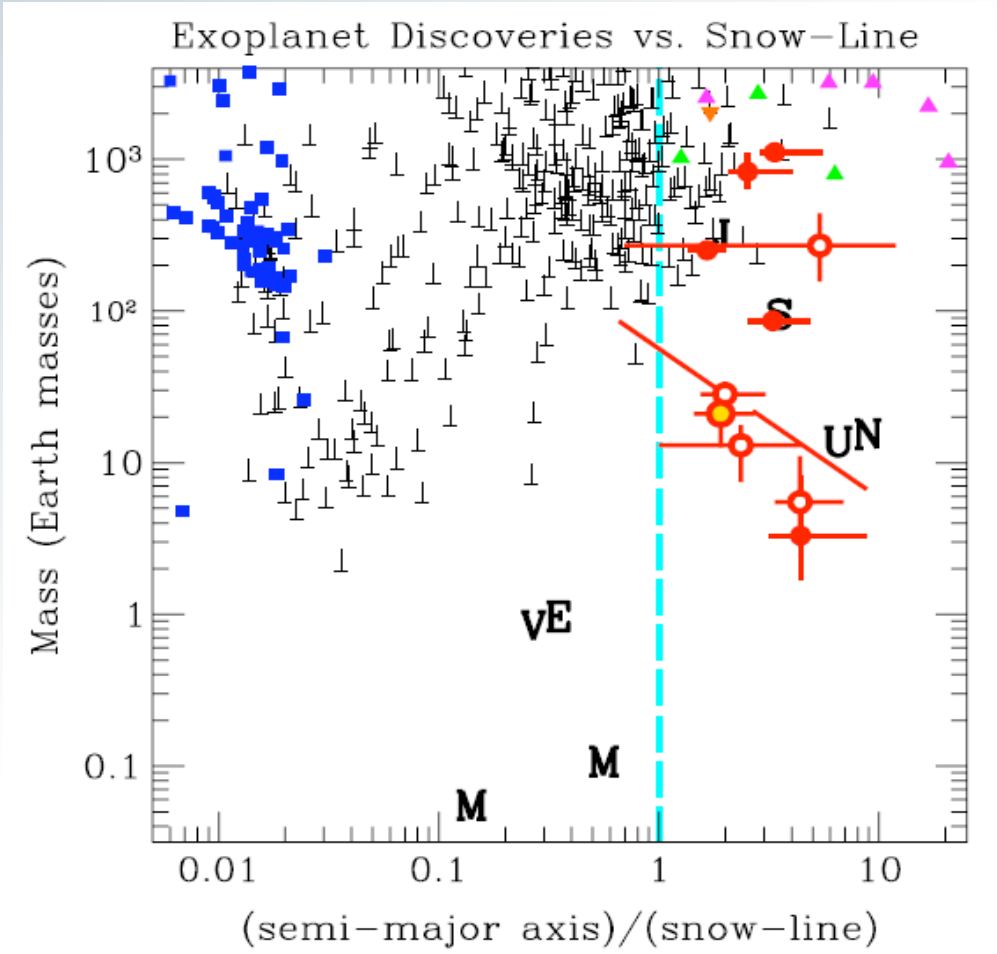
10th microlensing planet



But the hosts are different…

Sumi et al. 2010

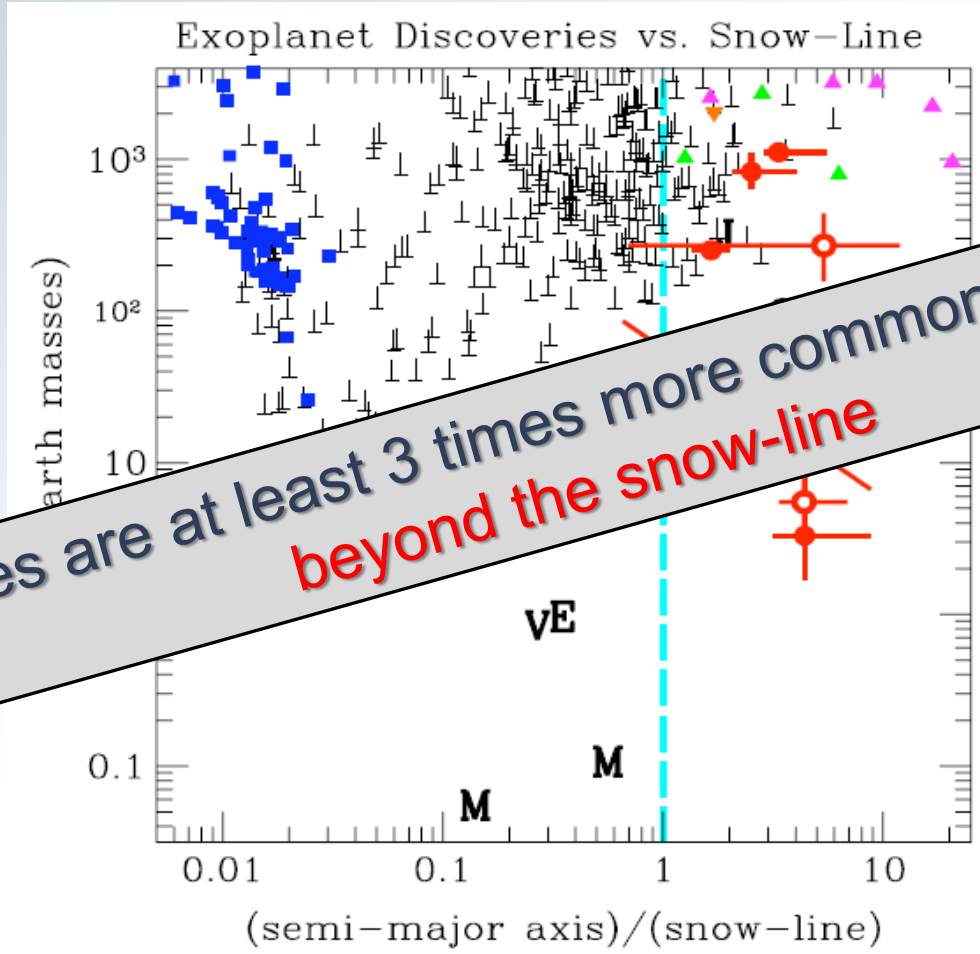
10th microlensing planet



…scaling to the host mass

Sumi et al. 2010

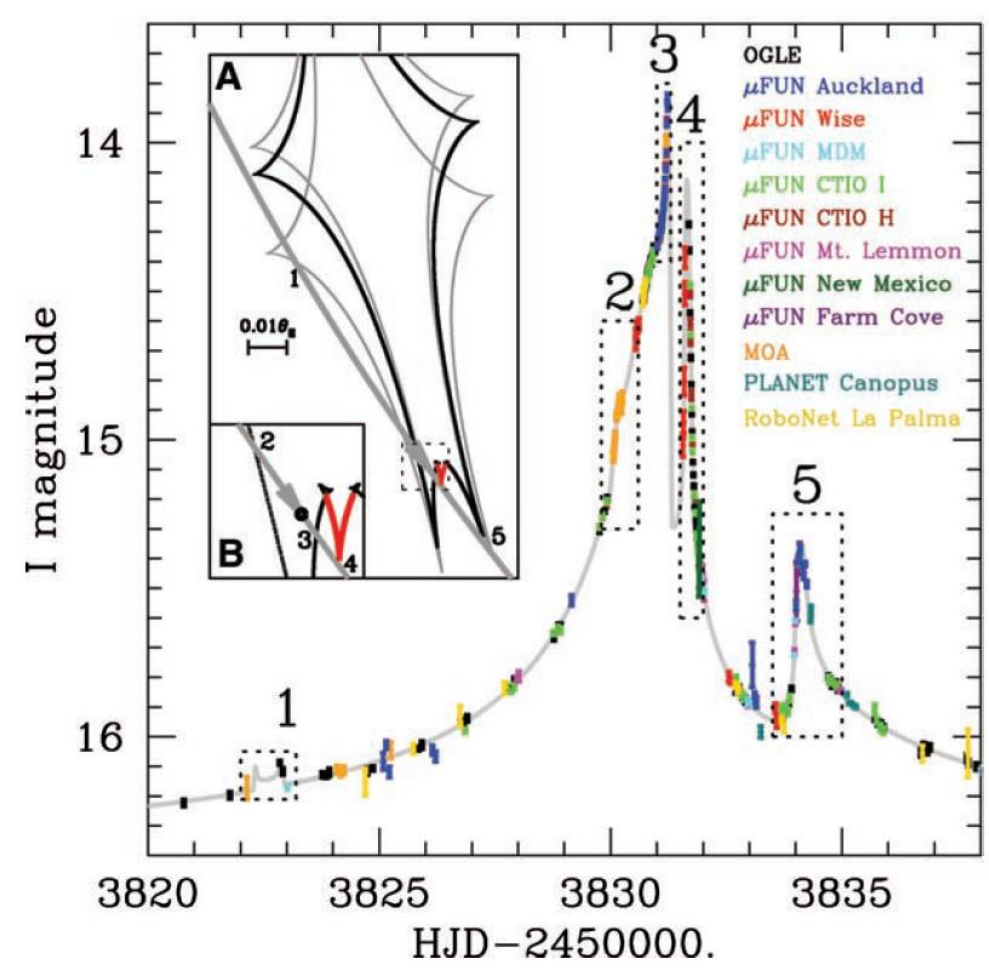
10th microlensing planet



Neptunes are at least 3 times more common than Jupiters beyond the snow-line

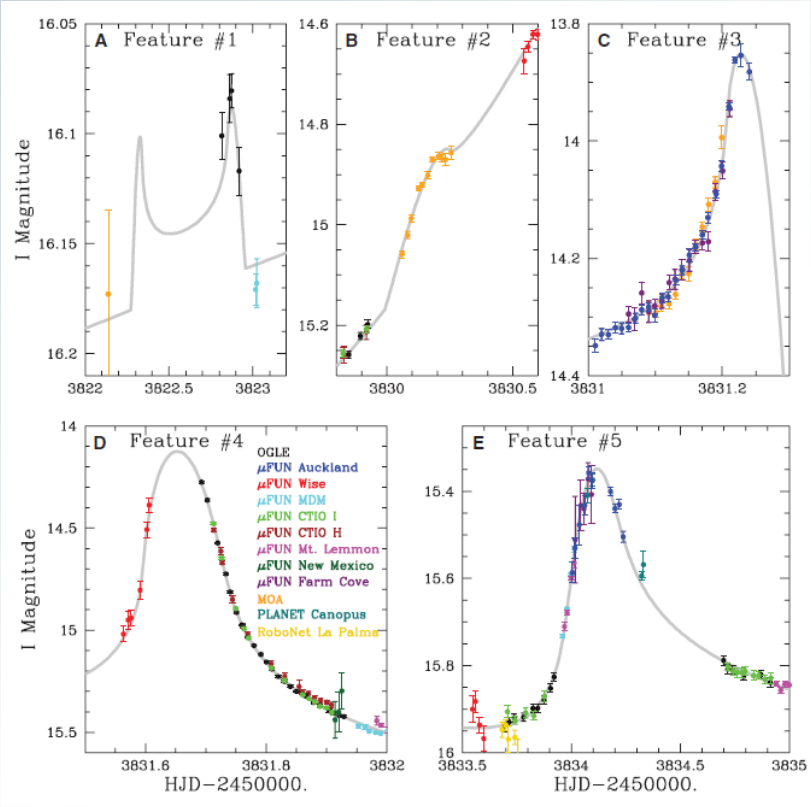
Sumi et al. 2010

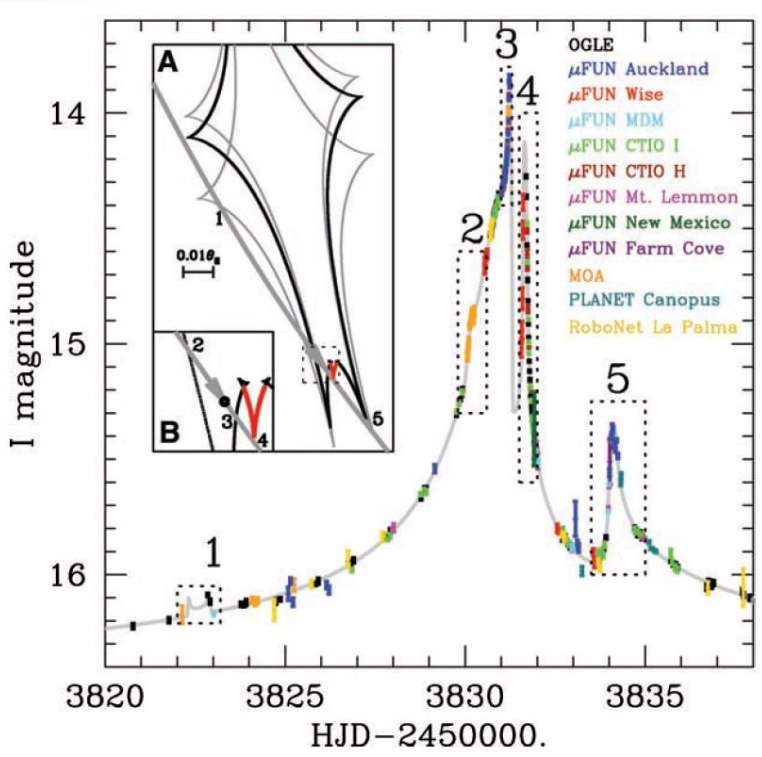
OGLE-2006-BLG-109



Gaudi et al. 2008

OGLE-2006-BLG-109

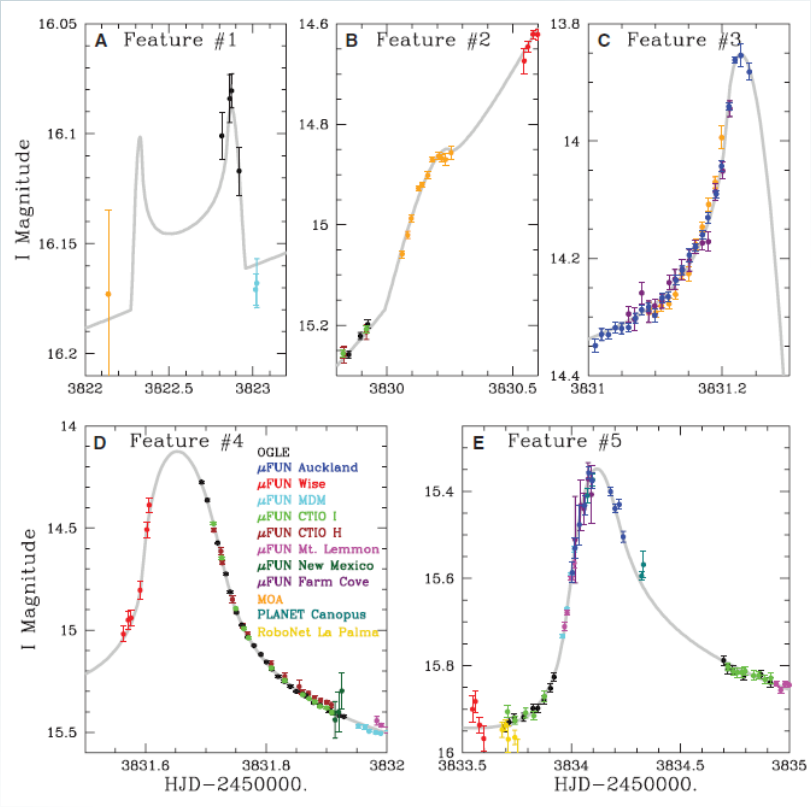


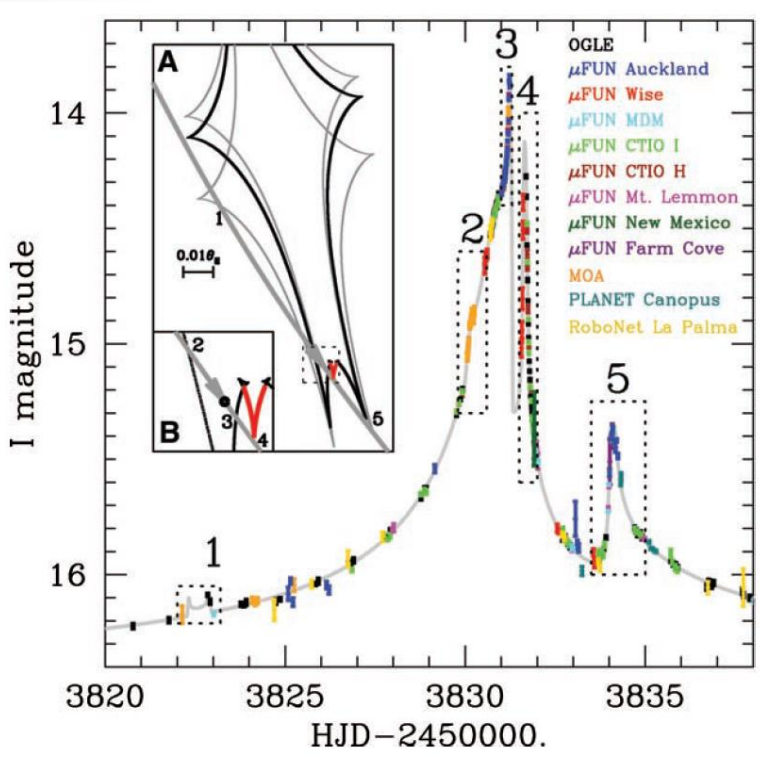


Gaudi et al. 2008

Two planet systems

OGLE-2006-BLG-109





Gaudi et al. 2008

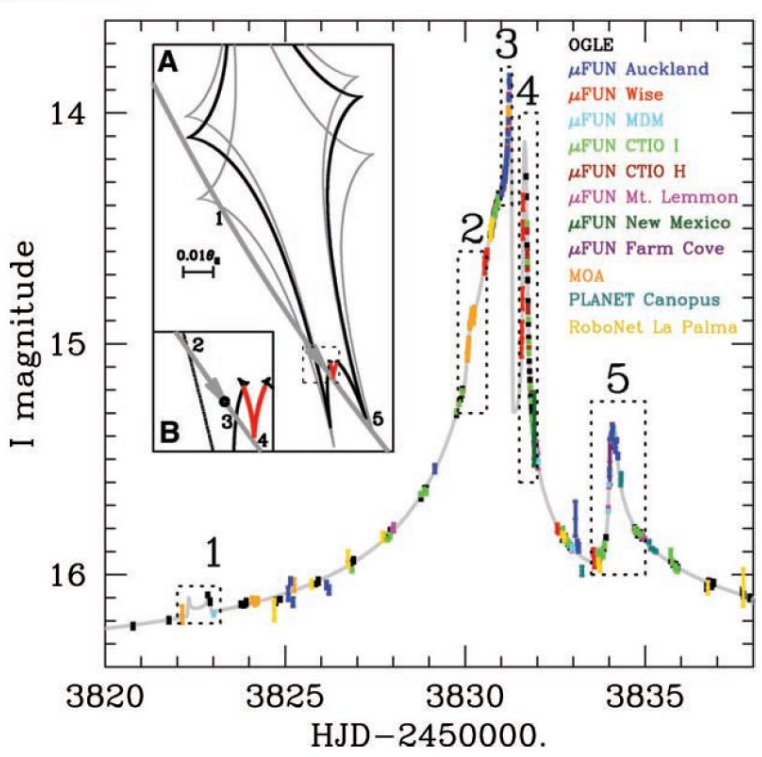
Two planet systems

OGLE-2006-BLG-109

Model parameters

m_b/M	1.35×10^{-3}
m_c/m_b	0.36
$a_{\perp,b}/a_{\perp,c}$	0.6

Gaudi et al. 2008



Two planet systems

OGLE-2006-BLG-109

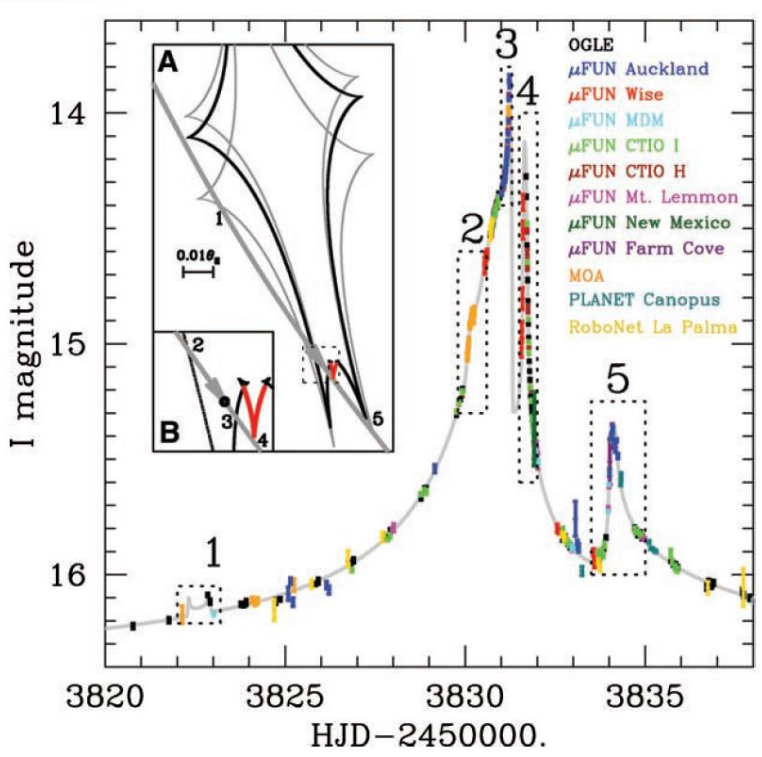
Model parameters

m_b/M	1.35×10^{-3}
m_c/m_b	0.36
$a_{\perp,b}/a_{\perp,c}$	0.6

Solar system

$m_j/M_\odot$	0.96×10^{-3}
m_s/m_j	0.30
a_j/a_s	0.5

Gaudi et al. 2008



Two planet systems

OGLE-2006-BLG-109

Model parameters

$m_{\rm b}/M$	1.35×10^{-3}
$m_{\rm c}/m_{\rm b}$	0.36
$a_{\perp,{\rm b}}/a_{\perp,{\rm c}}$	0.6

Solar system

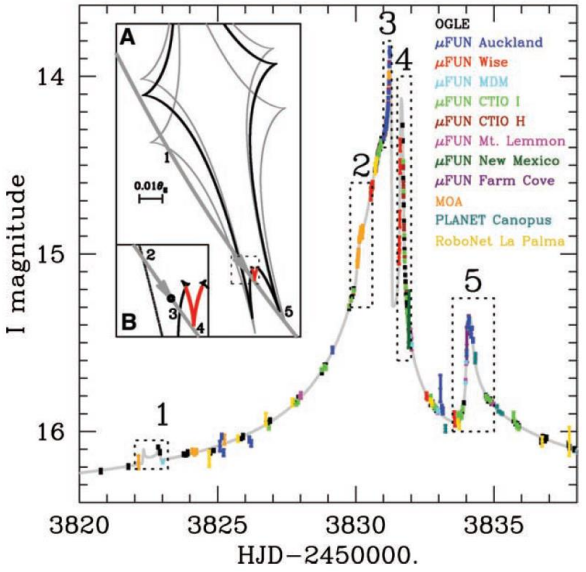
$m_{\rm j}/M_{\odot}$	0.96×10^{-3}
$m_{\rm s}/m_{\rm j}$	0.30
a_j/a_s	0.5

Gaudi et al. 2008

Physical properties

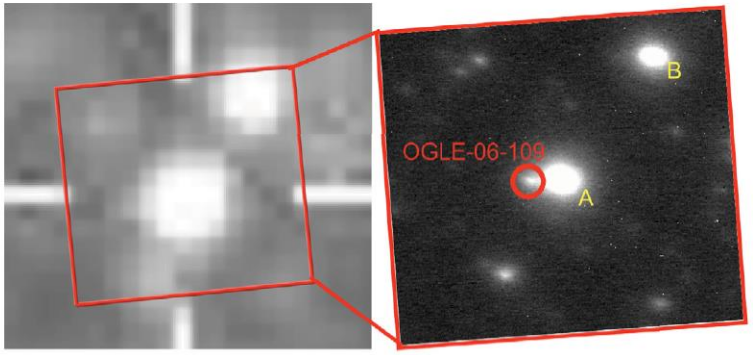
$m_{\rm b}$	$0.73 \pm 0.06[M_{\rm Jup}]$
$a_{\perp,{\rm b}}$	2.3 ± 0.5[AU]
$m_{\rm c}$	$0.75 \pm 0.06[M_{\rm Sat}]$
$a_{\perp,{\rm c}}$	$4.5^{+1.1}_{-1.0}$[AU]
$M_{\rm host}$	$0.51^{+0.05}_{-0.04}\ [M_{\odot}]$

Bennett et al. 2010



OGLE

Keck



Two planet systems

OGLE-2006-BLG-109

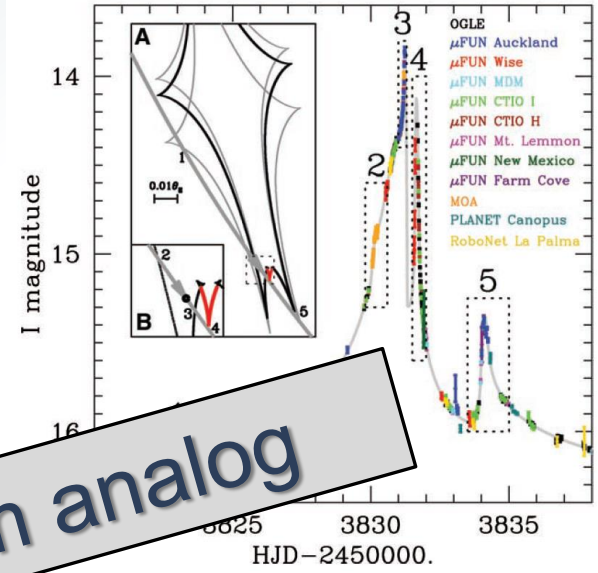
Model parameters

$m_{\rm b}/M$	1.35×10^{-3}
$m_{\rm c}/m_{\rm b}$	0.36
$a_{\perp,{\rm b}}/a_{\perp,{\rm c}}$	0.6

Solar system

$m_{\rm j}/M_{\odot}$	0.96×10^{-3}
$m_{\rm s}/m_{\rm j}$	0.30
a_j/a_s	0.5

Gaudi et al. 2008



Physical properties

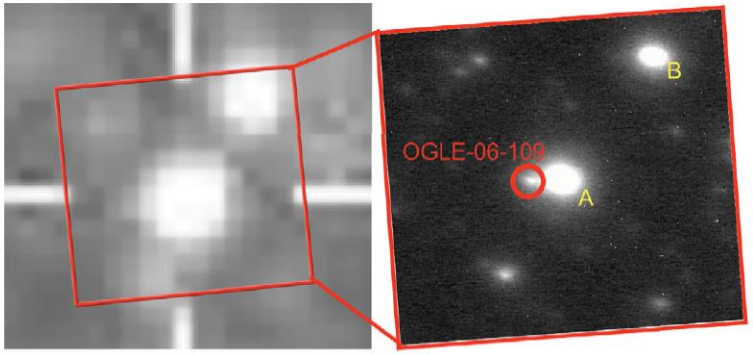
$m_{\rm b}$	$0.73 \pm 0.06[M_{\rm Jup}]$
$a_{\perp,{\rm b}}$	2.3 ± 0.5[AU]
$m_{\rm c}$	$0.75 \pm 0.06[M_{\rm Sat}]$
$a_{\perp,{\rm c}}$	$4.5^{+1.1}_{-1.0}$[AU]
$M_{\rm host}$	$0.51^{+0.05}_{-0.04}\ [M_{\odot}]$

Bennett et al. 2010

Solar system analog

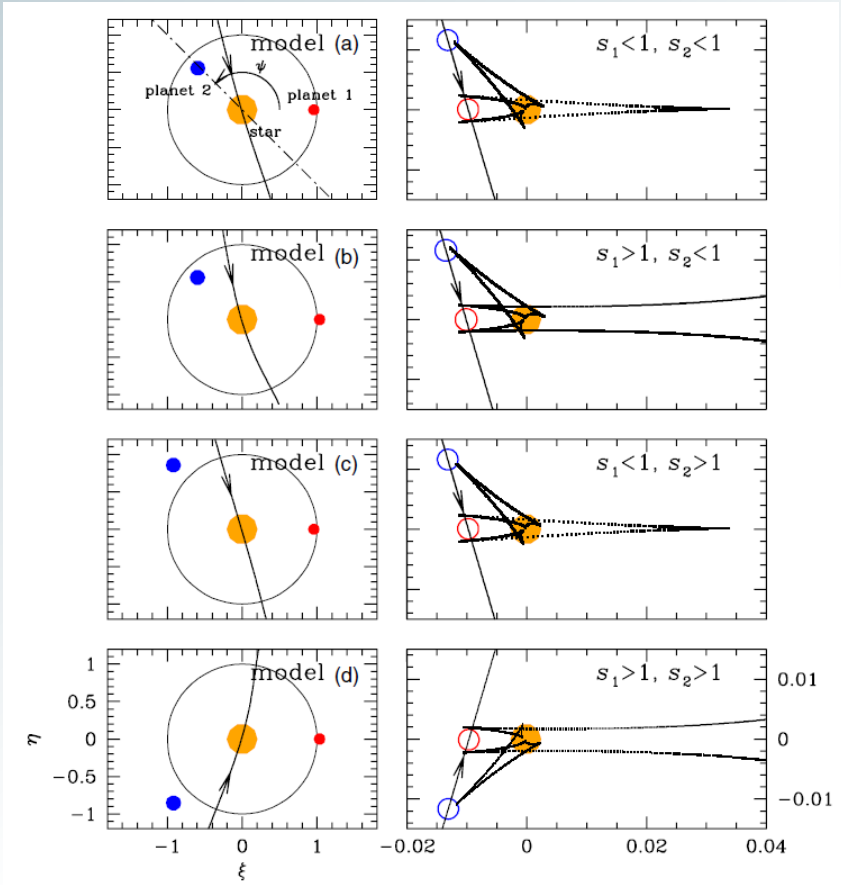
OGLE

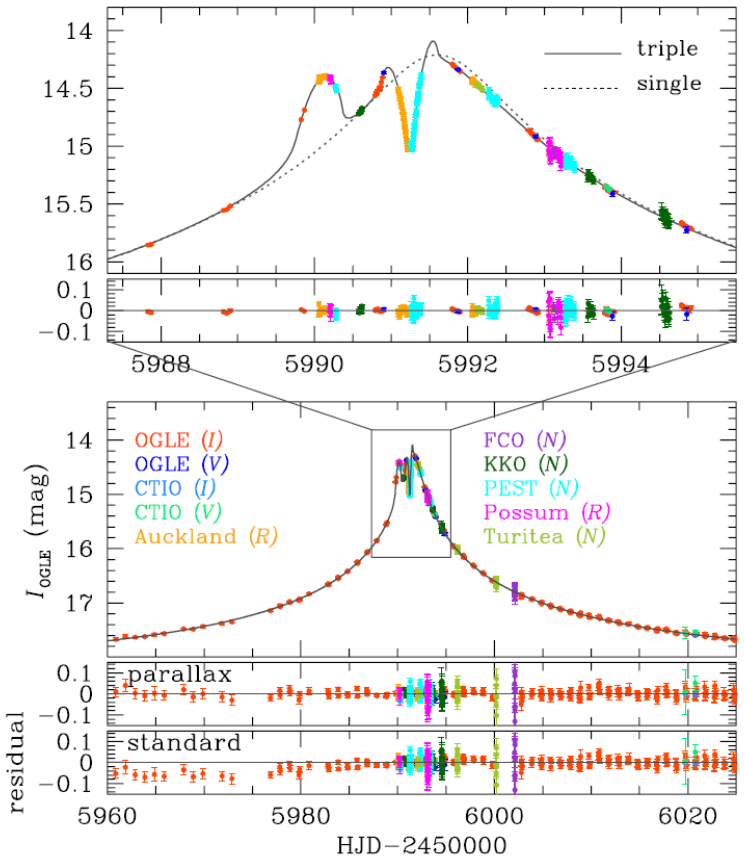
Keck



Two planet systems

OGLE-2012-BLG-0026





Han et al. 2013

Two planet systems

OGLE-2012-BLG-0026

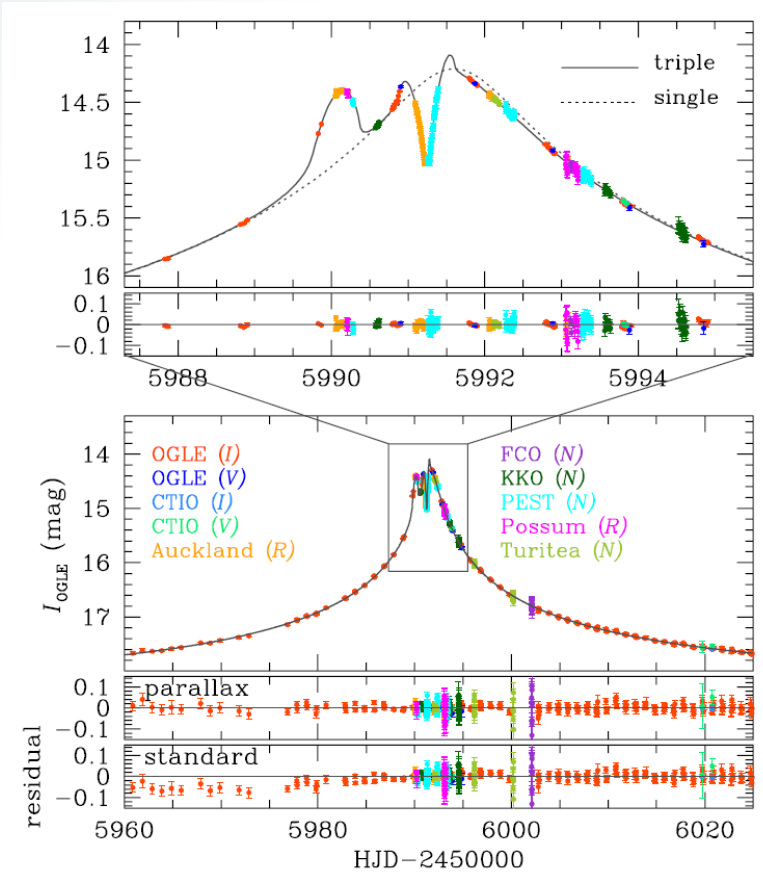
Model parameters

$m_{\rm b}/M$	0.8×10^{-3}
$m_{\rm c}/m_{\rm b}$	0.17
$a_{\perp,{\rm b}}/a_{\perp,{\rm c}}$	0.8/1.2

Solar system

$m_{\rm j}/M_{\odot}$	0.96×10^{-3}
$m_{\rm s}/m_{\rm j}$	0.30
a_j/a_s	0.5

Han et al. 2013



Two planet systems

OGLE-2012-BLG-0026

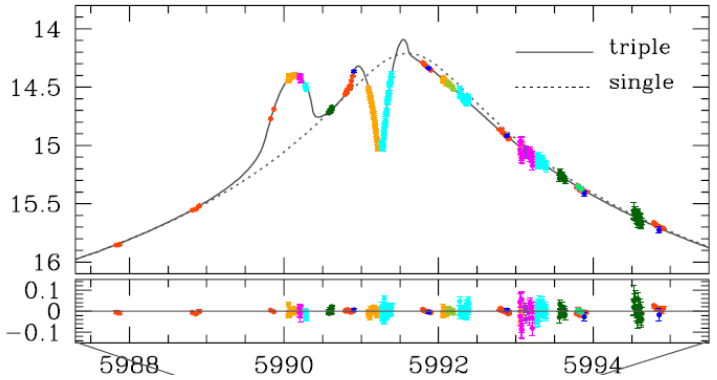
Han et al. 2013

Model parameters

$m_{\rm b}/M$	0.8×10^{-3}
$m_{\rm c}/m_{\rm b}$	0.17
$a_{\perp,{\rm b}}/a_{\perp,{\rm c}}$	~~0.8~~/1.2

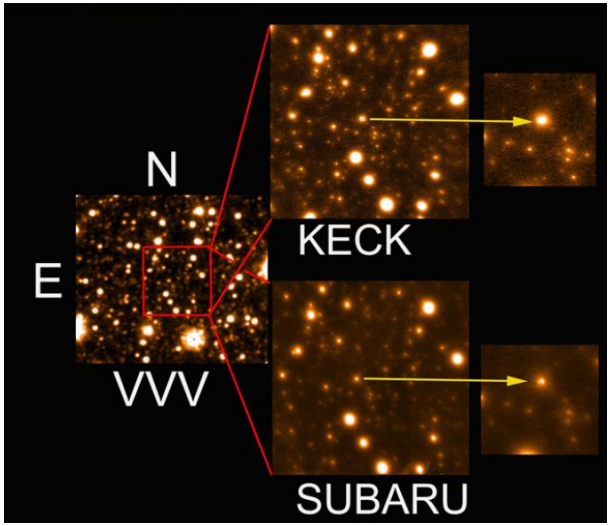
Solar system

$m_{\rm j}/M_{\odot}$	0.96×10^{-3}
$m_{\rm s}/m_{\rm j}$	0.30
a_j/a_s	0.5



Physical properties

$m_{\rm b}$	0.80 ± 0.07	0.86 ± 0.06	$[M_{\rm Jup}]$
$a_{\perp,{\rm b}}$	4.16 ± 0.45	4.8 ± 0.7	[AU]
$m_{\rm c}$	0.39 ± 0.02	0.40 ± 0.02	$[M_{\rm Sat}]$
$a_{\perp,{\rm c}}$	3.94 ± 0.45	4.0 ± 0.5	[AU]
$M_{\rm host}$	1.06 ± 0.05	1.06 ± 0.05	$[M_{\odot}]$



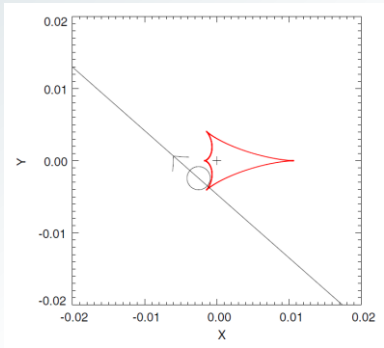
Beaulieu et al. 2016

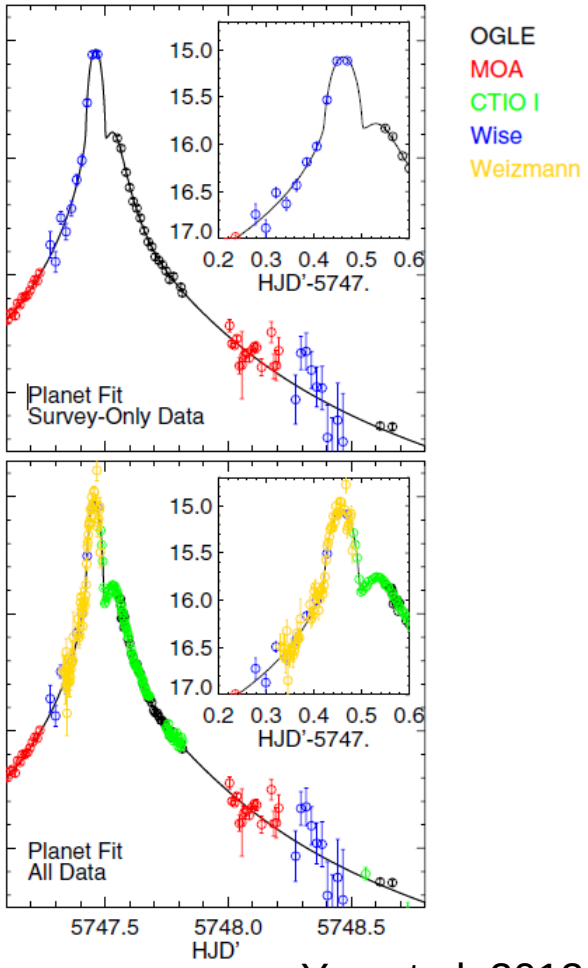
Second generation microlensing surveys

MOA-2011-BLG-293

Model parameters

t_E	$22\ [d]$
q	5.3×10^{-3}
s	$0.55\ /\ 1.83$





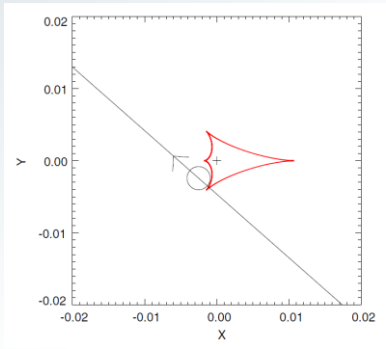
Yee et al. 2012

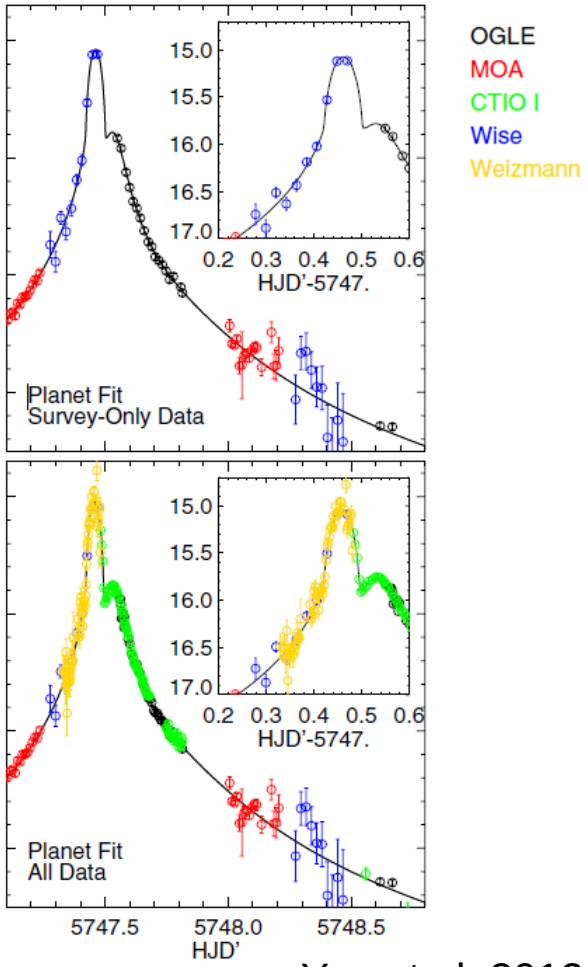
Second generation microlensing surveys

MOA-2011-BLG-293

Model parameters

t_E	22 $[d]$
q	5.3×10^{-3}
s	0.55 / 1.83

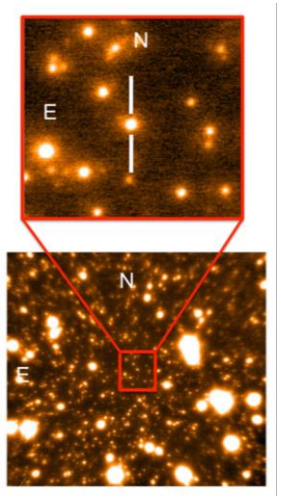




Physical properties

m_{planet}	4.8 $[M_J]$
$a_\perp$	1.1 / 3.7[AU]
M_{host}	0.86 $[M_\odot]$

Keck



Batista et al. 2014

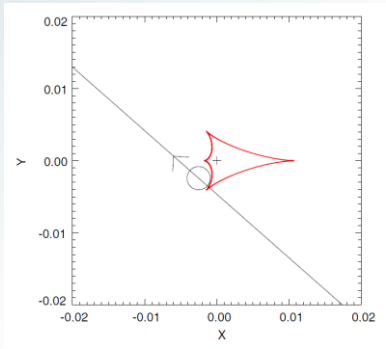
Yee et al. 2012

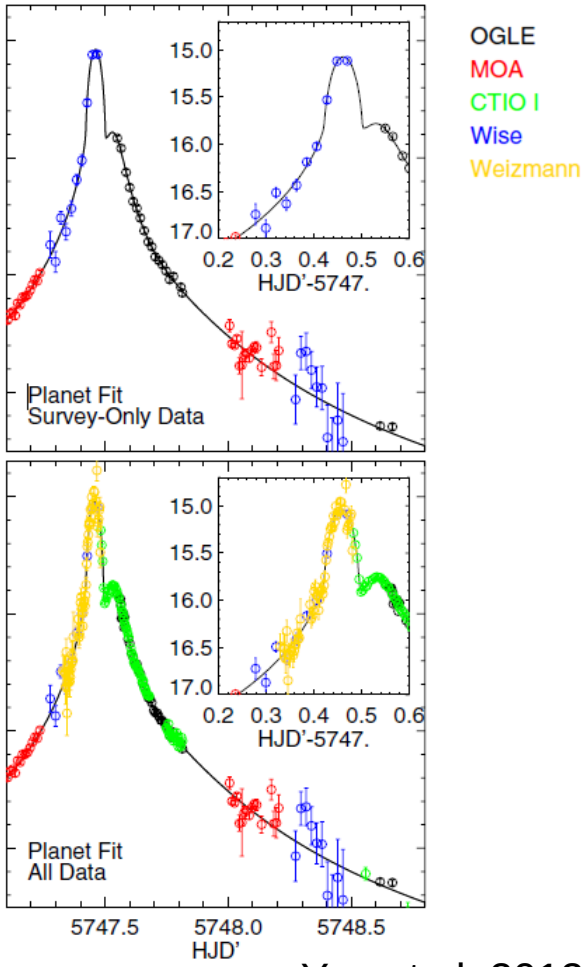
Second generation microlensing surveys

MOA-2011-BLG-293

Model parameters

t_E	22 $[d]$
q	5.3×10^{-3}
s	0.55 / 1.83

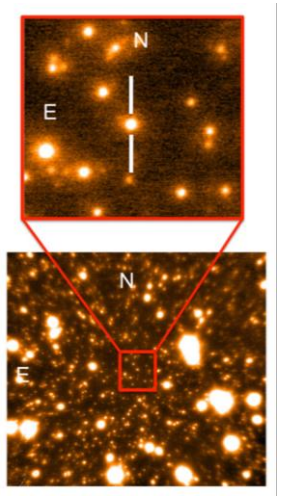




Physical properties

m_{planet}	4.8 $[M_J]$
$a_\perp$	1.1 / 3.7[AU]
M_{host}	0.86 $[M_\odot]$

Keck



Batista et al. 2014

Yee et al. 2012

Second generation microlensing surveys

MOA-2011-BLG-293

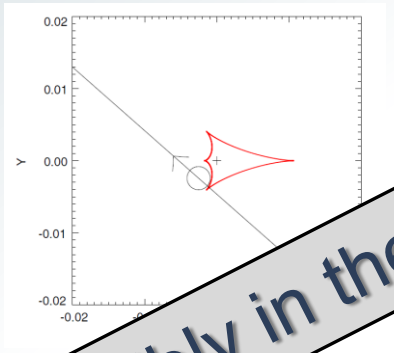
Model parameters

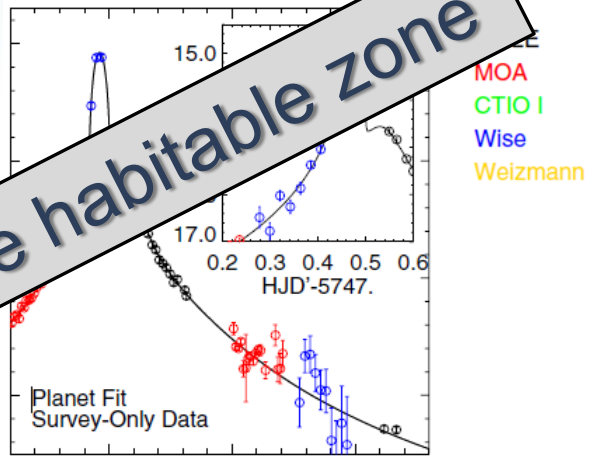
t_E	$22\ [d]$
q	5.3×10^{-3}
s	$0.55\ /\ 1.83$

Physical r… …s

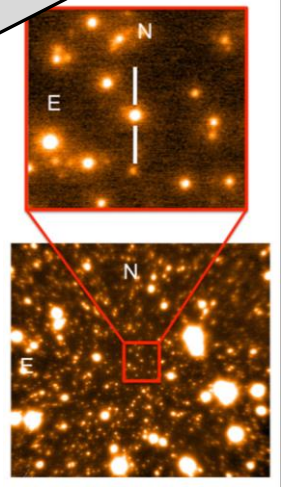
	$4.8\ [M_J]$
$a_\perp$	$1.1\ /\ 3.7$[AU]
$M_{\rm host}$	$0.86\ [M_\odot]$

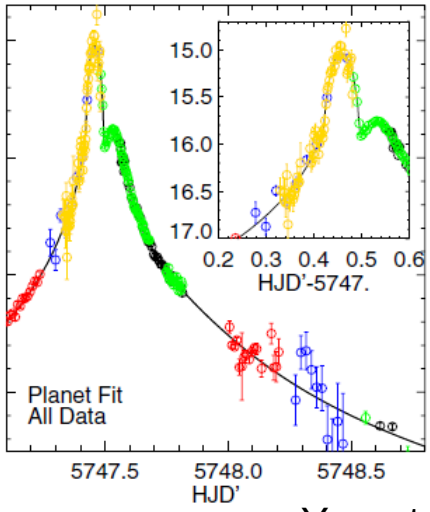
First μlensing planet possibly in the habitable zone





Keck

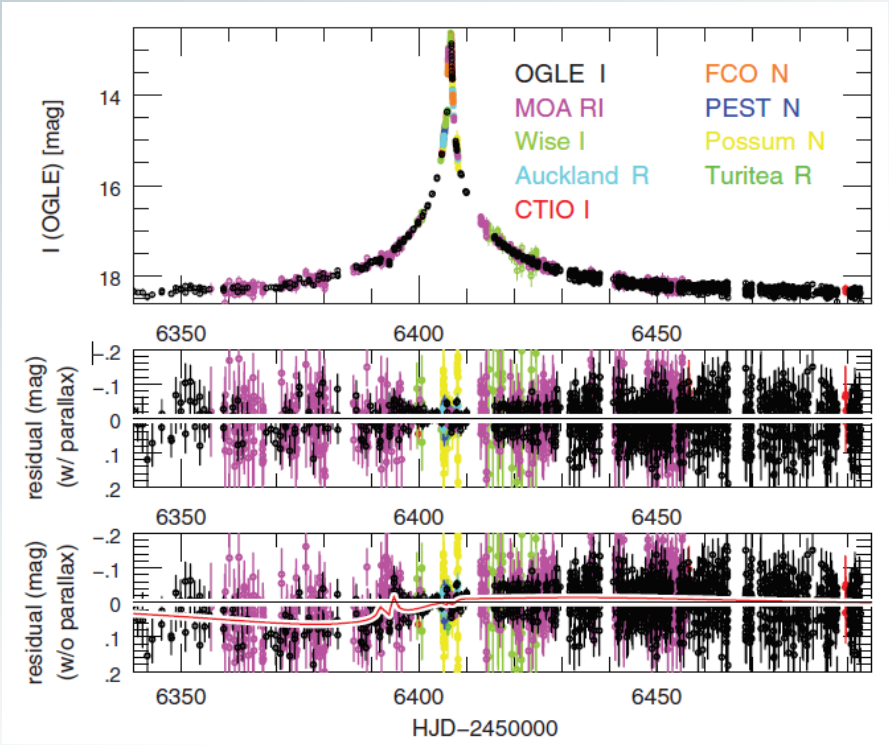


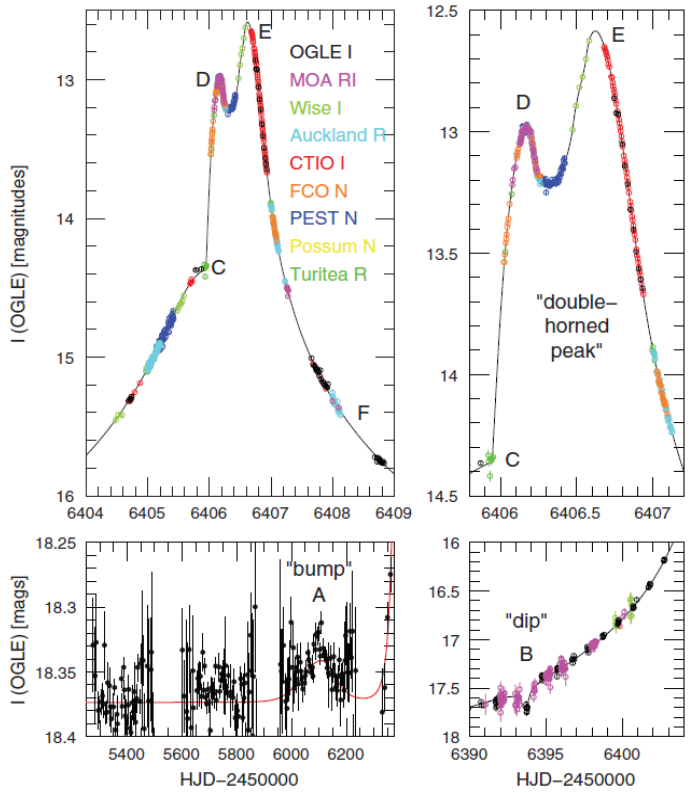


Batista et al. 2014

Yee et al. 2012

OGLE-2013-BLG-0341

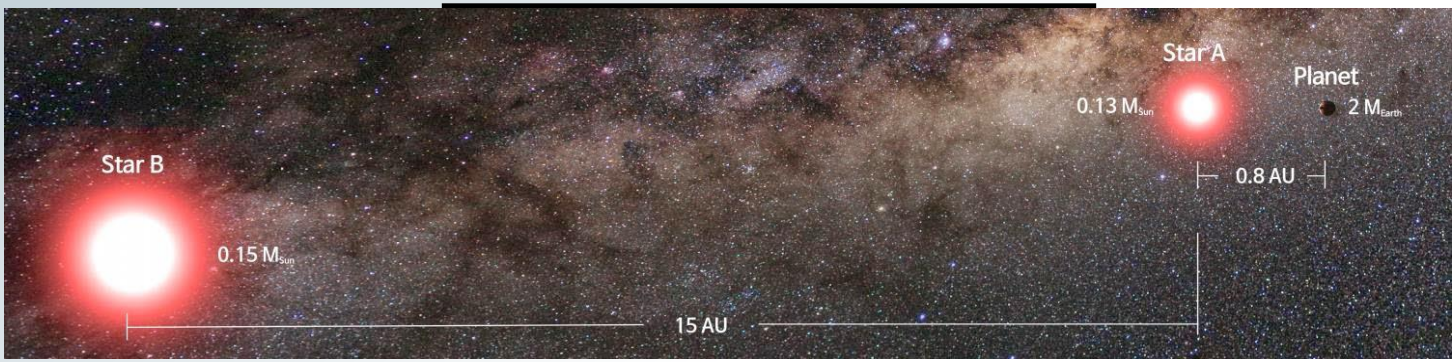




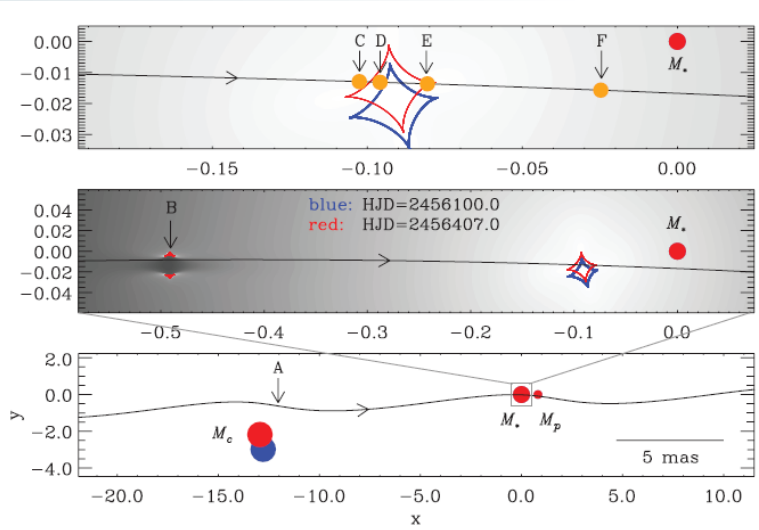
Gould et al. 2014

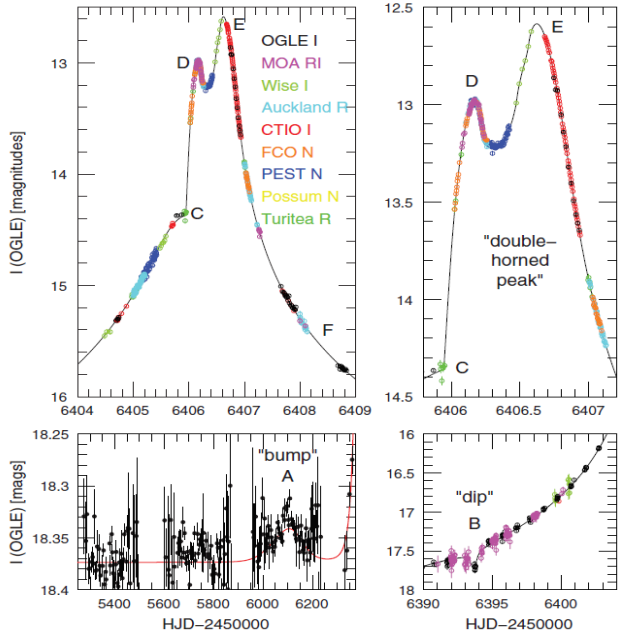
Planets in Binary-star systems

OGLE-2013-BLG-0341



Circum-secondary planet





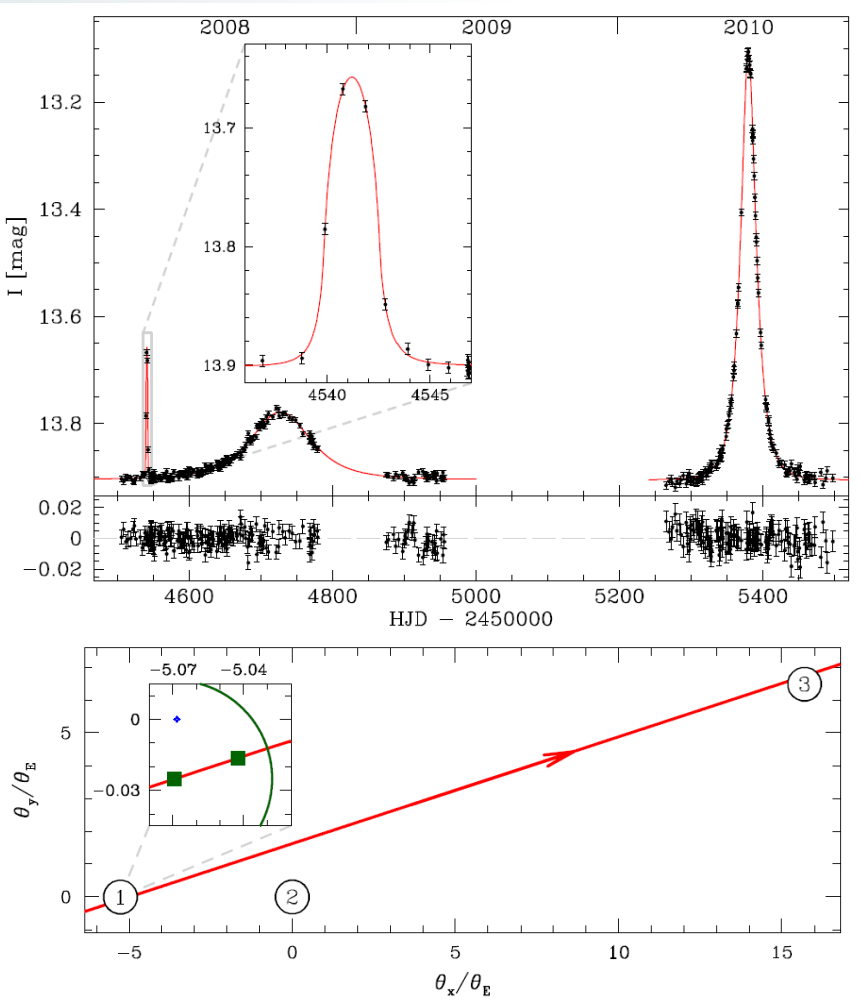
Gould et al. 2014

Planets in Binary-star systems

OGLE-2008-BLG-092

Circum-primary planet

4 M_{Uranus} at $\approx$ 18 AU orbit around a $0.7M_{\odot}$ primary star with a $0.15M_{\odot}$ secondery

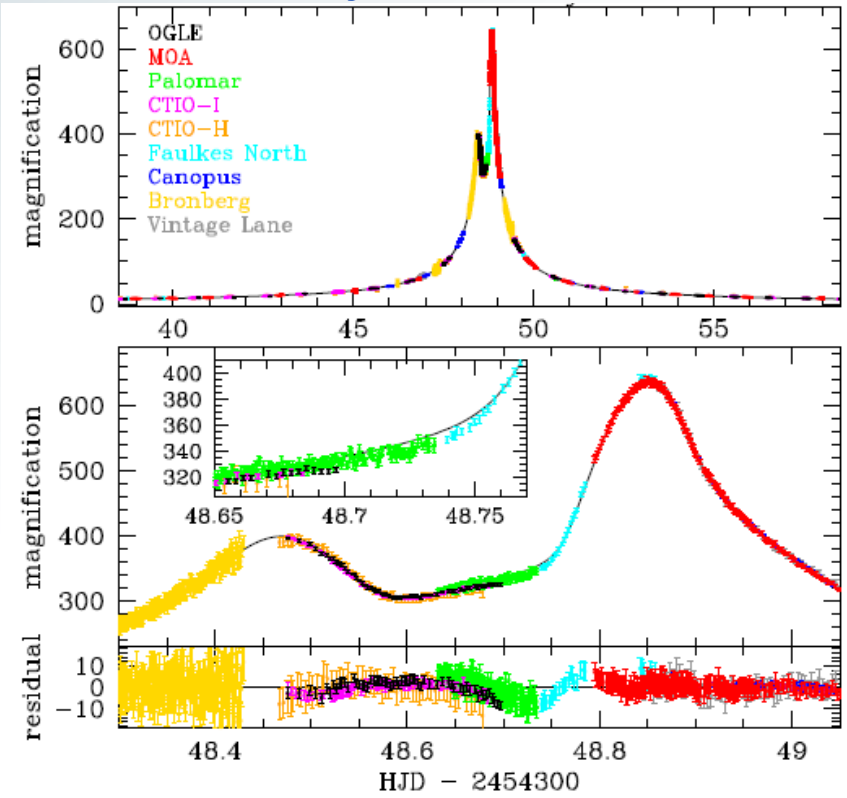


Poleski et al. 2014

Planets in Binary-star systems

OGLE-2007-BLG-349

Binary lens model

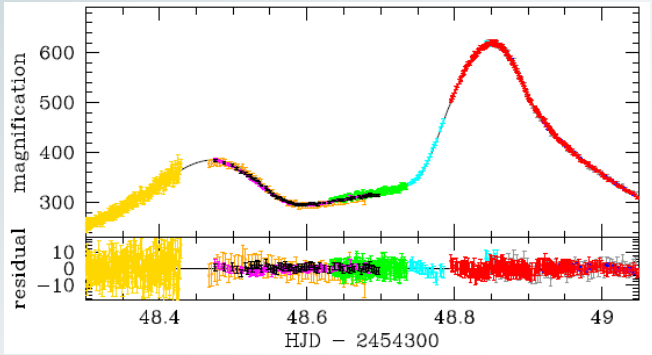


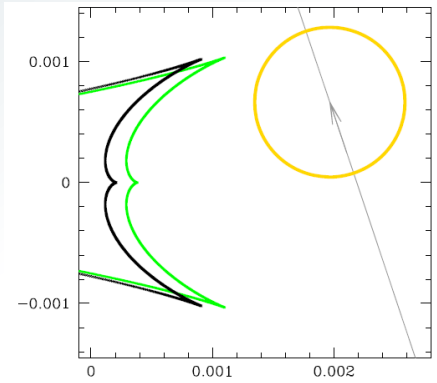
Bennett et al. 2016

Planets in Binary-star systems

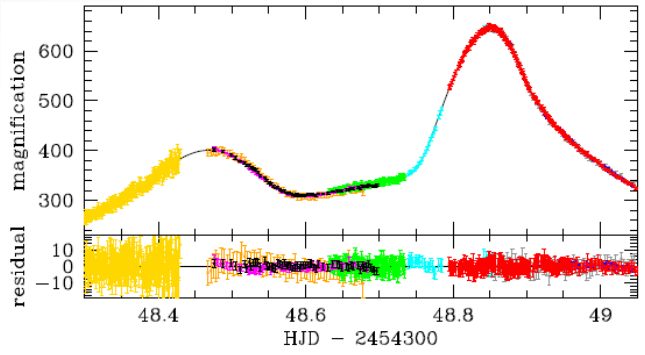
OGLE-2007-BLG-349

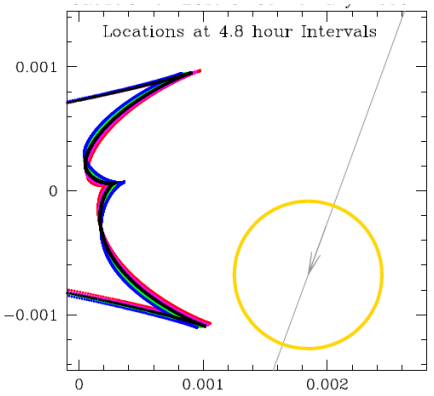
Two planet system





Circum-binary planet



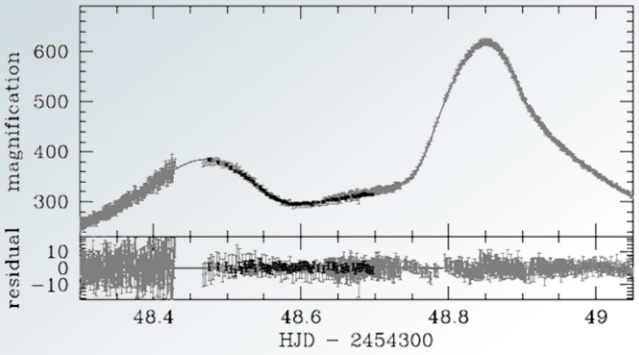


Bennett et al. 2016

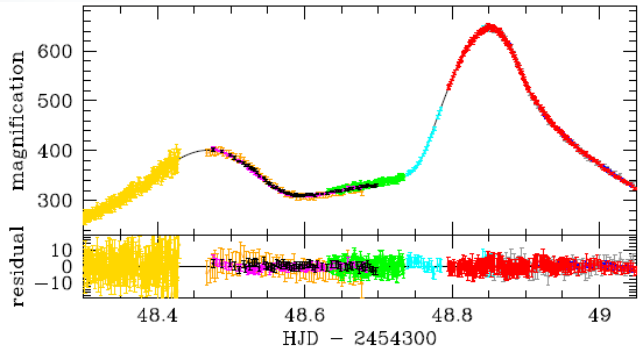
Planets in Binary-star systems

OGLE-2007-BLG-349

Two planet system

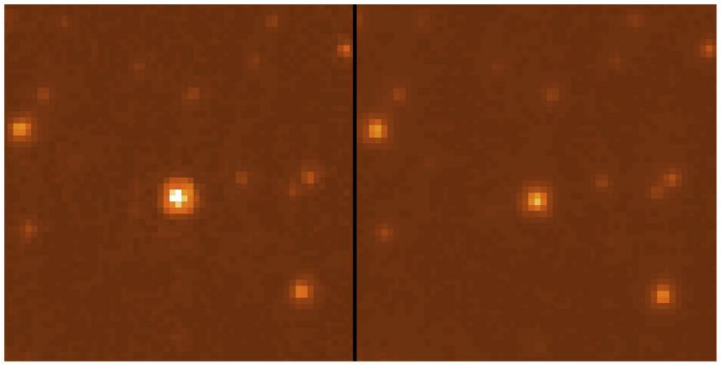


Circum-binary planet



HST

During the event After



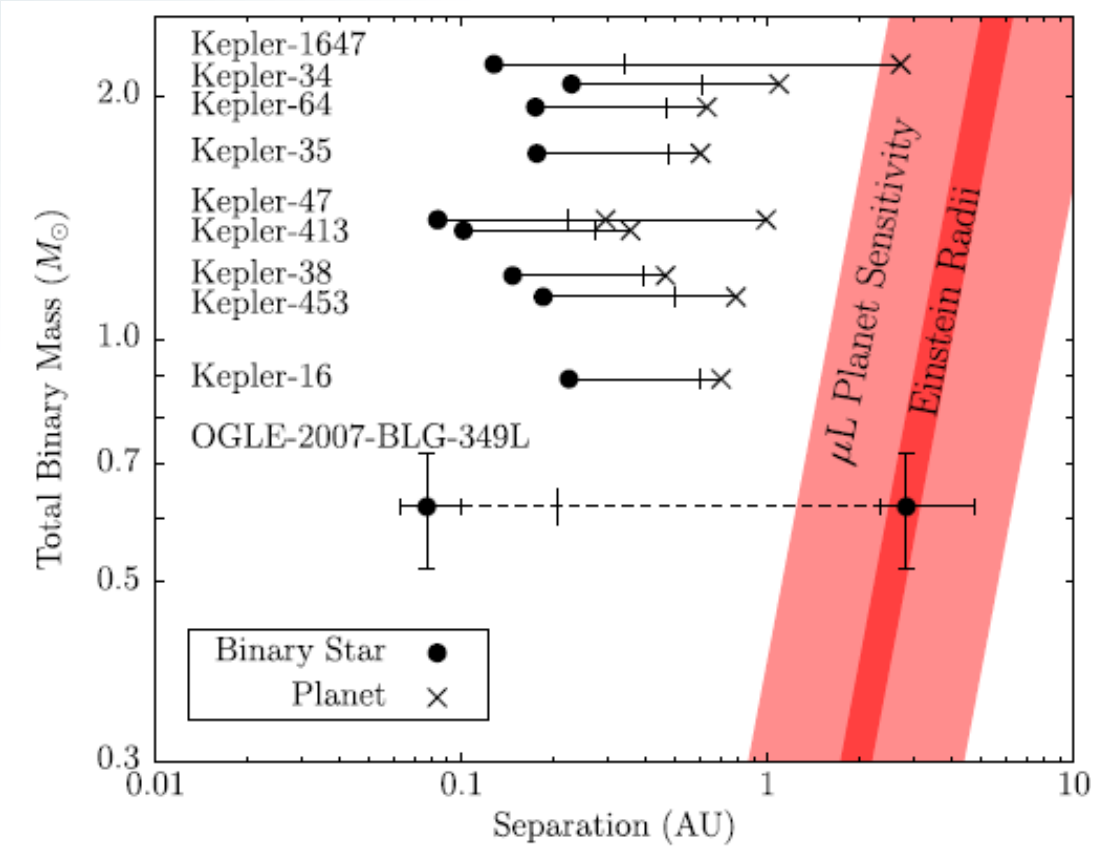
Bennett et al. 2016

Planets in Binary-star systems

OGLE-2007-BLG-349

80 $M_\oplus$ at 2.6 AU around a pair of M dwarfs in tight , 0.06 AU orbit

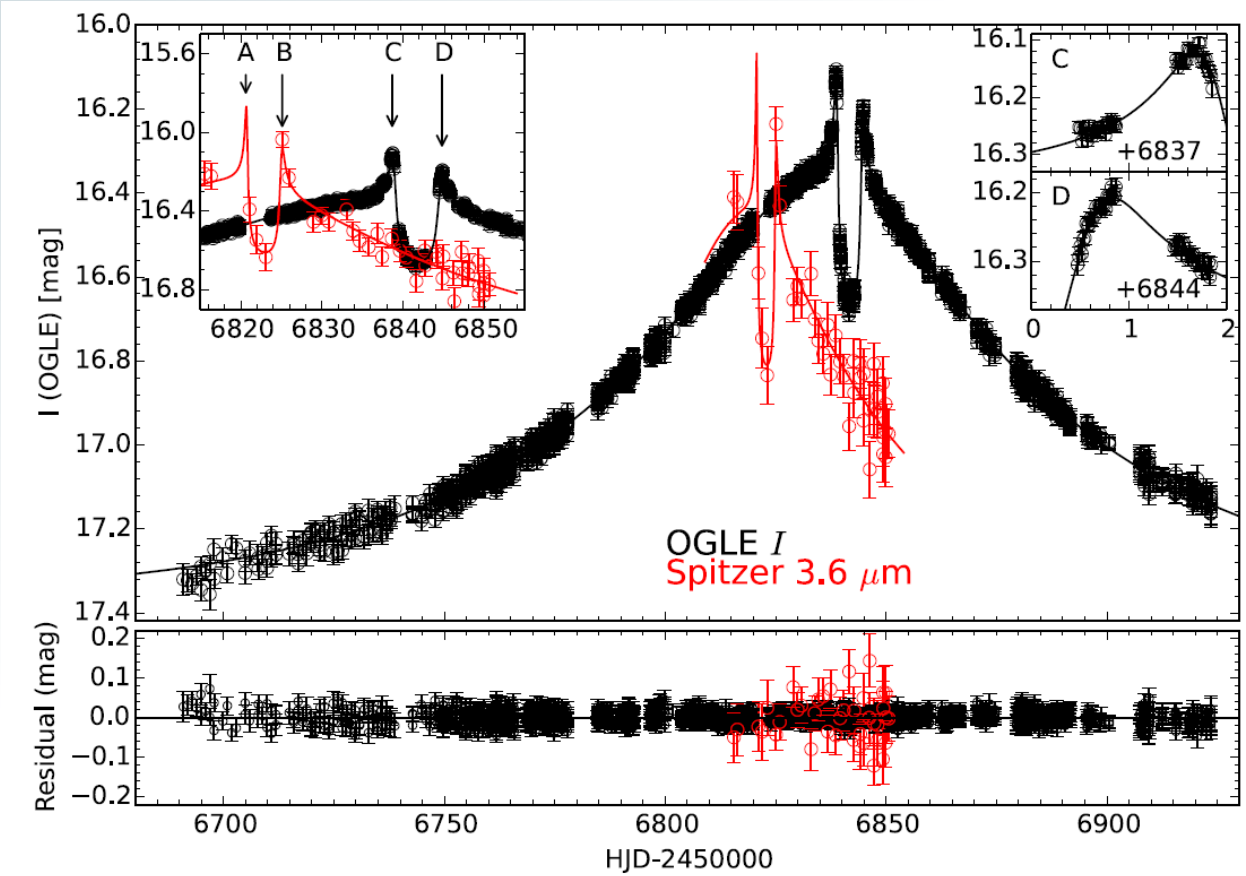
Circum-binary planet



Bennett et al. 2016

Spitzer as microlens parallax satellite

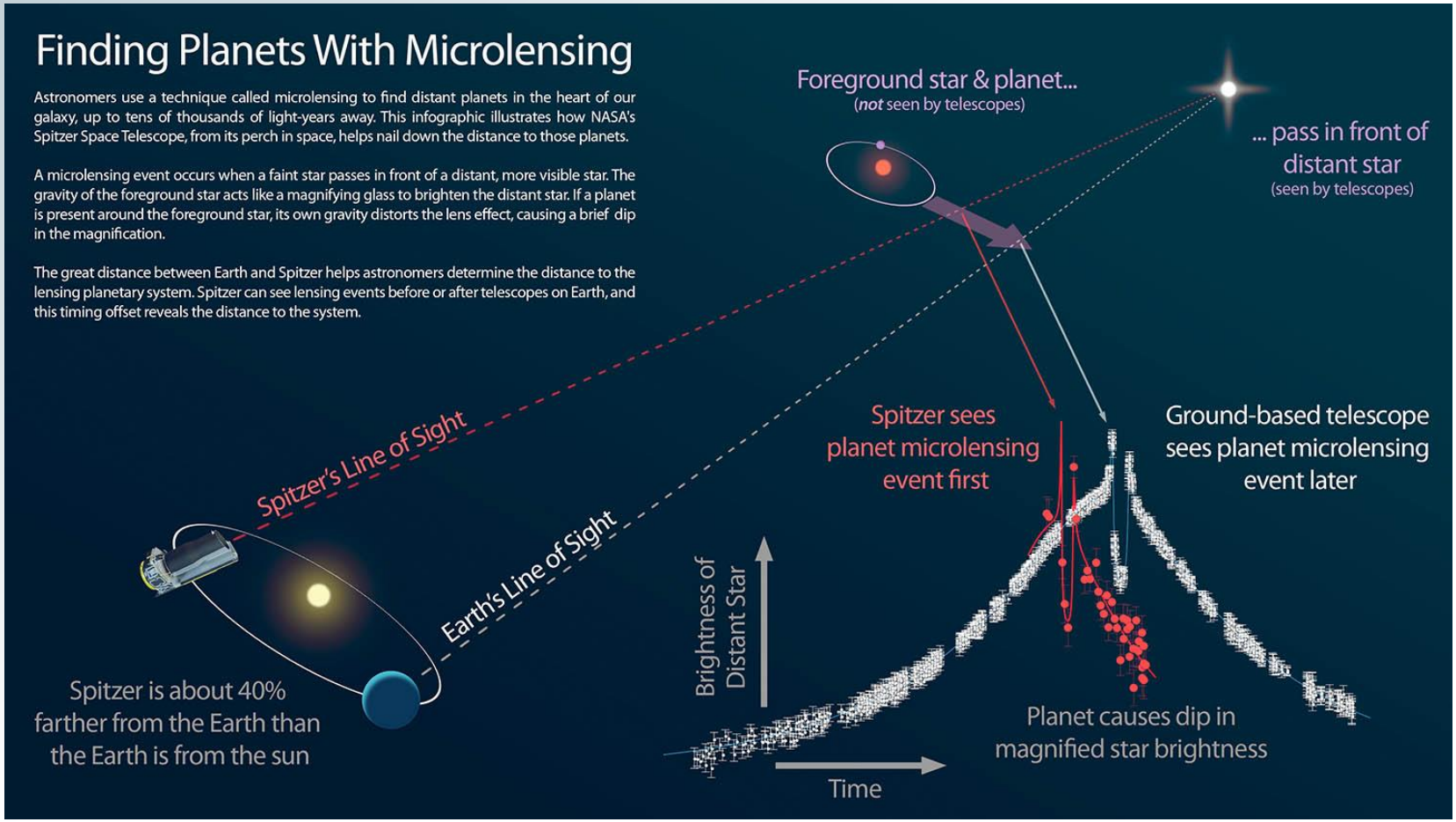
OGLE-2014-BLG-0124



Udalski et al. 2015

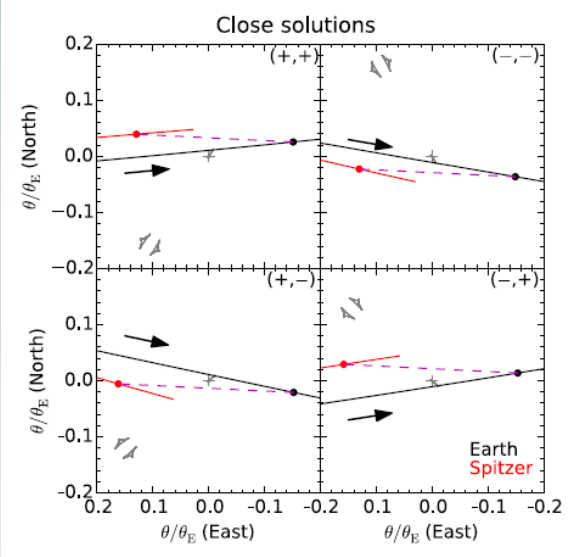
Spitzer as microlens parallax satellite

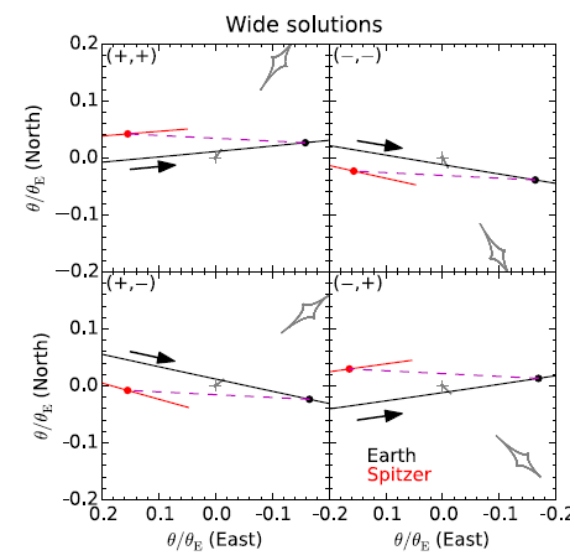
OGLE-2014-BLG-0124



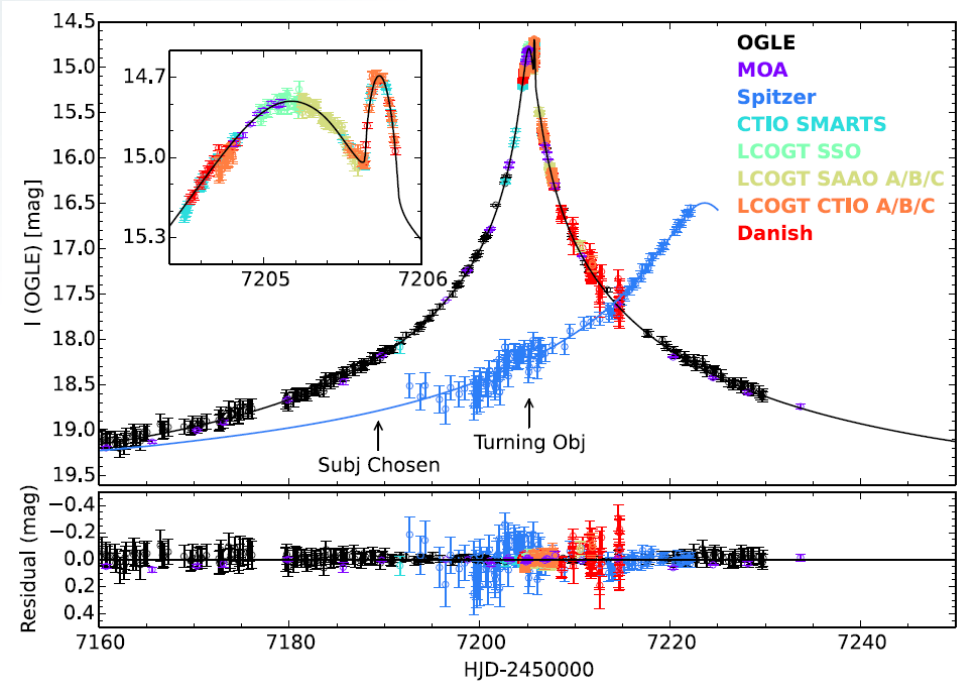
Udalski et al. 2015

Spitzer as microlens parallax satellite





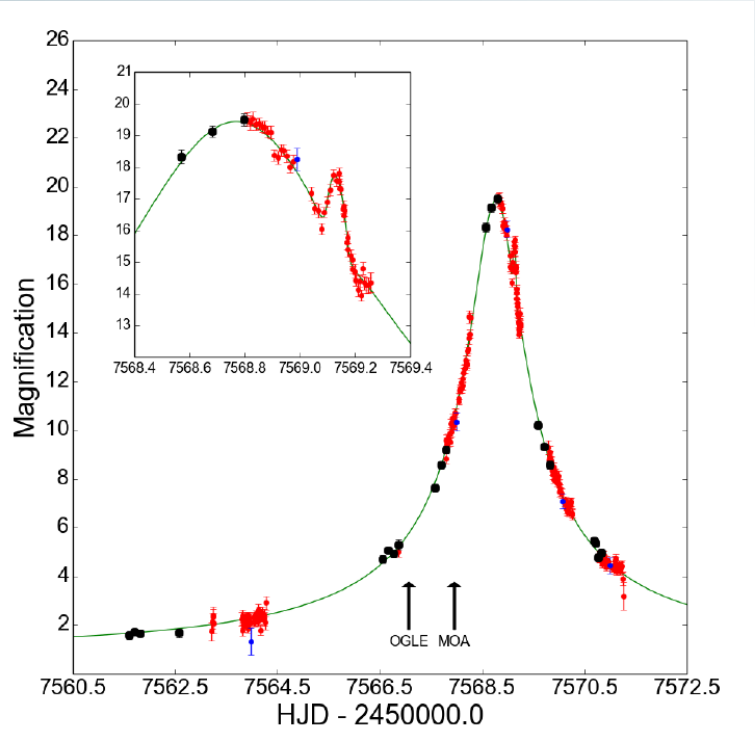
OGLE-2015-BLG-0966



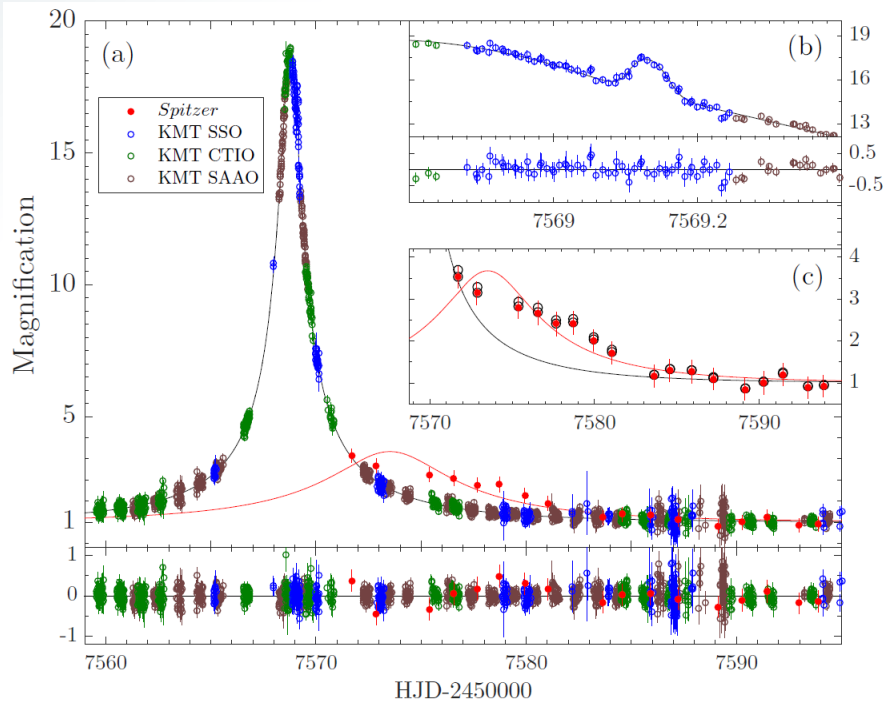
Street et al. 2016

Spitzer as microlens parallax satellite

OGLE-2016-BLG-1195



Bond et al. 2017



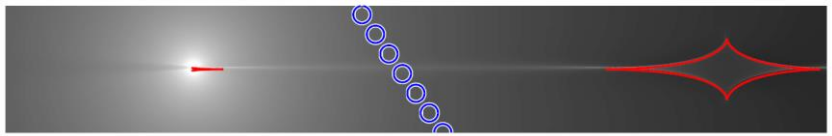
Shvartzvald et al. 2017

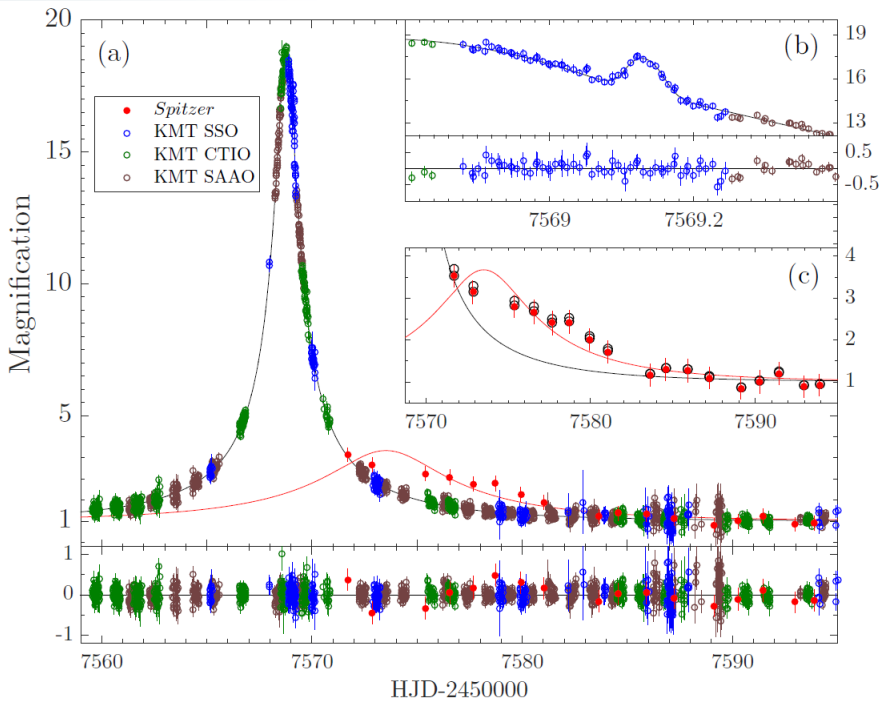
Spitzer as microlens parallax satellite

OGLE-2016-BLG-1195

Physical properties

$m_{\rm planet}$	$1.43^{+0.45}_{-0.32}[M_\oplus]$
$a_\perp$	$1.16^{+0.16}_{-0.13}[\rm AU]$
$M_{\rm host}$	$0.078^{+0.016}_{-0.012}[M_\odot]$





Shvartzvald et al. 2017

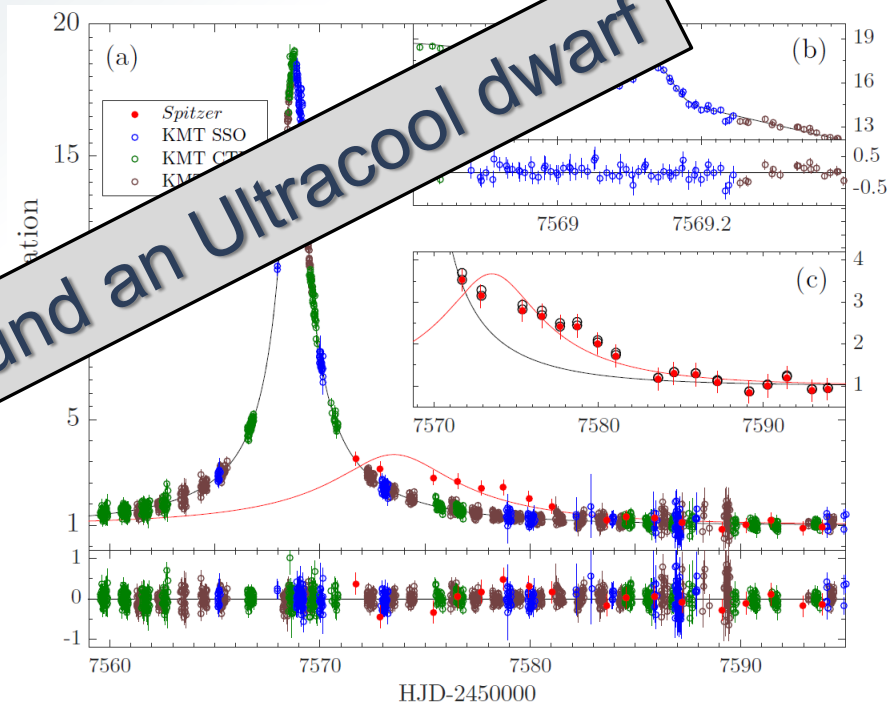
Spitzer as microlens parallax satellite

OGLE-2016-BLG-1195

Physical properties

$m_{\rm planet}$	$1.43^{+0.45}_{-0.32}[M_\oplus]$
$a_\perp$	$1.16^{+0.16}_{-0.13}[\mathrm{AU}]$
$M_{\rm host}$	$0.078^{+0.016}_{-0.012}[M_\odot]$

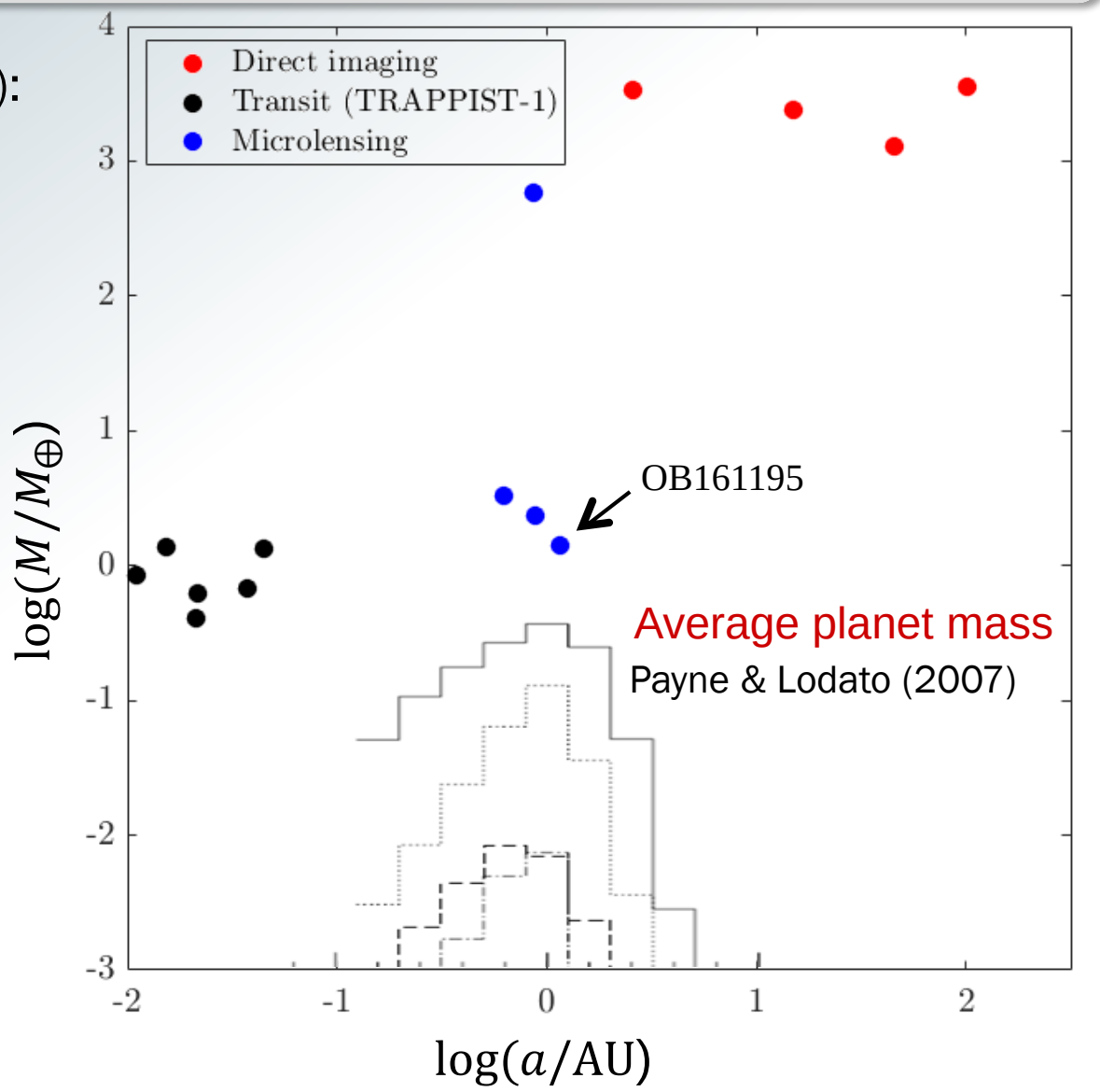
Earth at 1 AU around an Ultracool dwarf



Shvartzvald et al. 2017

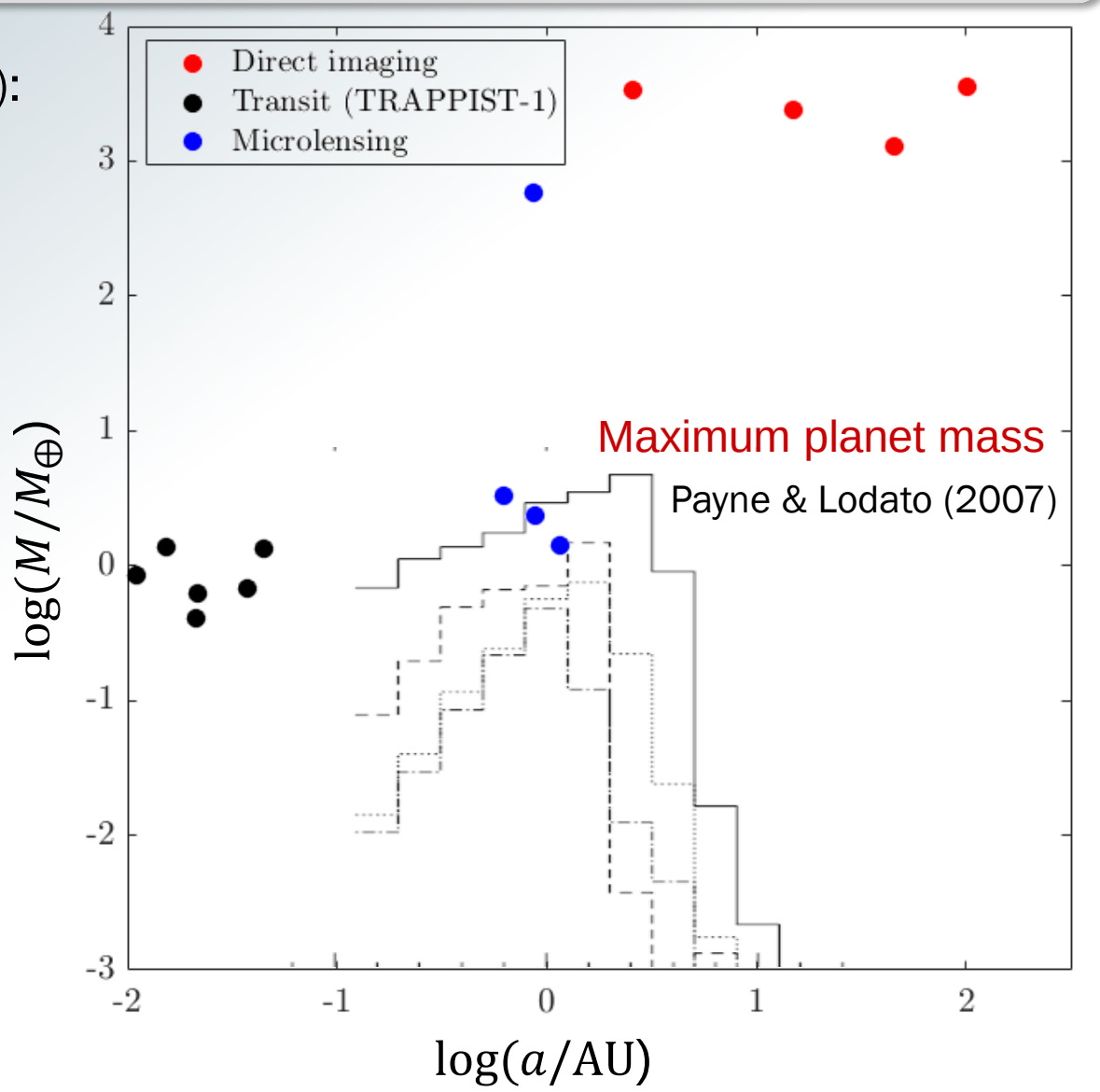
Planet formation around ultracool dwarfs

- Payne & Lodato (2007): Core accretion models around $0.05 M_{\odot}$ star
- Observationally challenging…



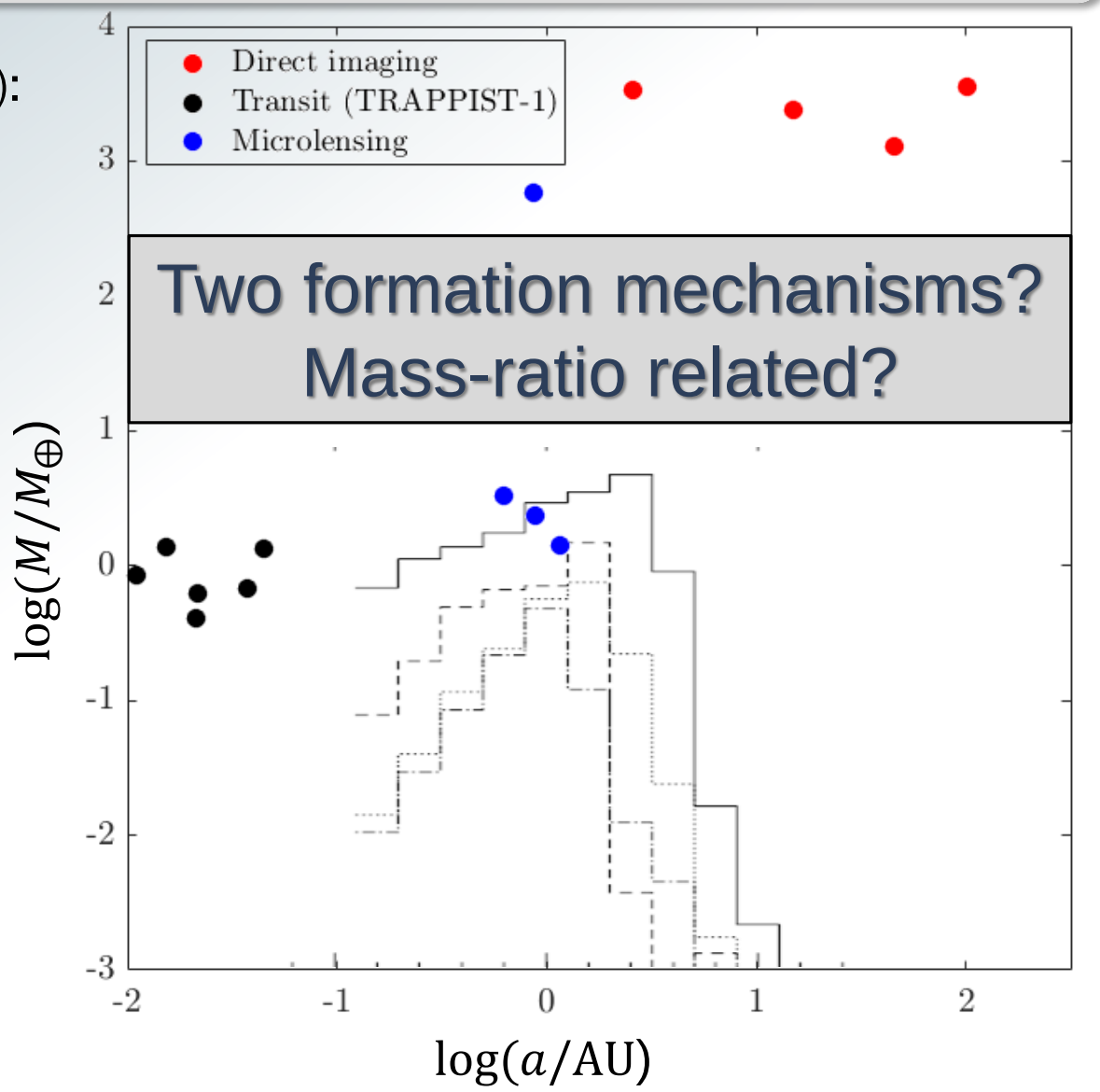
Planet formation around ultracool dwarfs

- Payne & Lodato (2007): Core accretion models around $0.05 M_{\odot}$ star
- Observationally challenging…



Planet formation around ultracool dwarfs

- Payne & Lodato (2007): Core accretion models around 0.05$M_\odot$ star
- Observationally challenging…



Microlensing planet discoveries vs. year