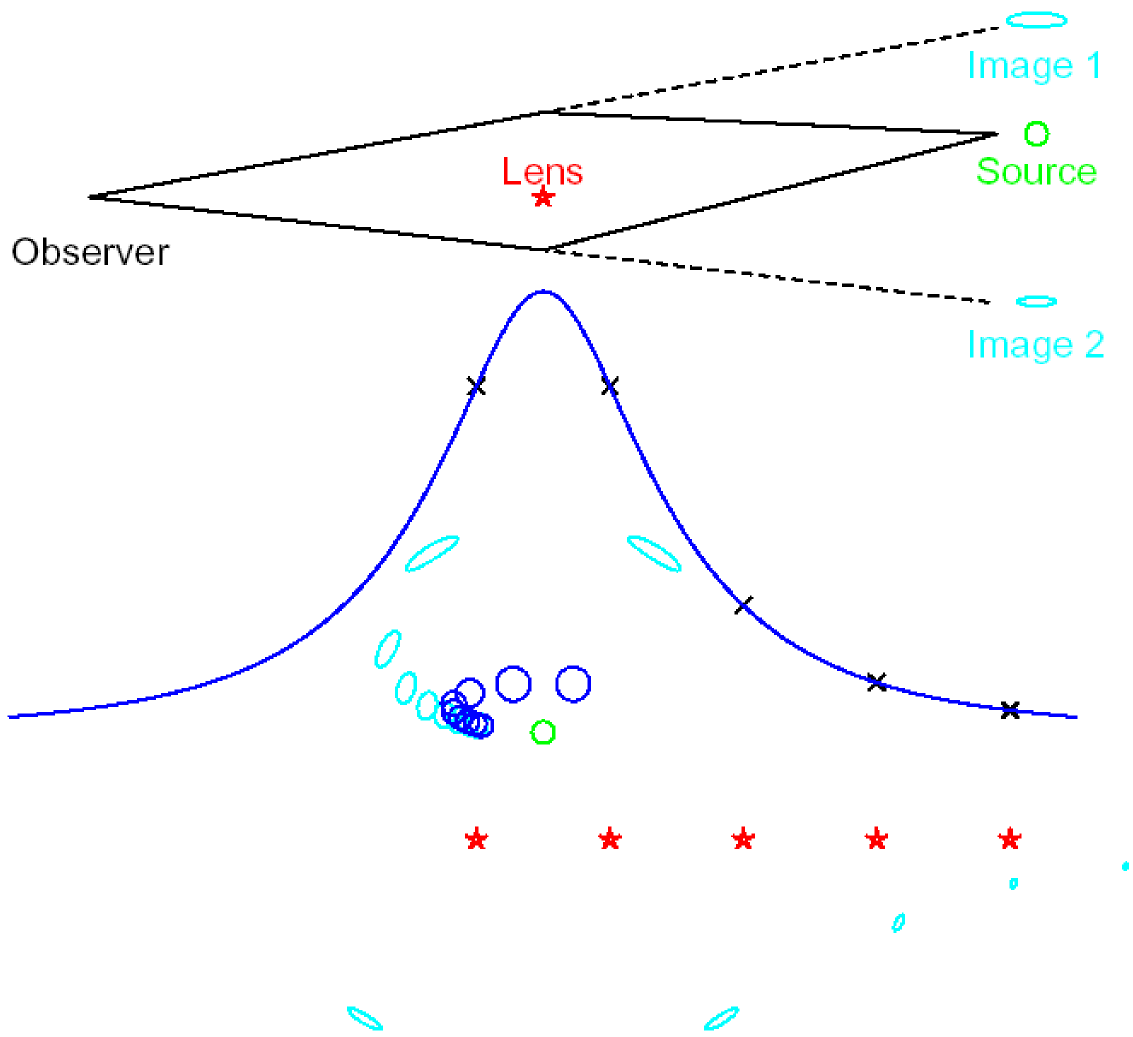
Microlensing V:

μlensing vs. World; Planet Frequency

Andy Gould (Ohio State)



Microlensing vs. Other Methods

No Light from Planet/Host System

- Distant planets
- Low-mass planets
- Free floating planets

Einstein-Ring/Snow-Line Coincidence

Host Rarely Seen

Usually Just a Snap Shot

Free-Floating Planets

Point-Lens Events w/o FFPs (short)

$$\Gamma \propto \int dM F(M) \int dD_L D_L^2 n(D_L) \int d^2\mu \mu f_\mu(\mu) \theta_{\rm E}(M, D_L)$$

$$t_{\rm E} = \frac{\theta_{\rm E}}{\mu}, \qquad \theta_{\rm E} = \sqrt{\kappa M \pi_{\rm rel}}$$

$$t_{\rm E}\ \text{small} \Rightarrow D_{LS} \ll D_S$$

$$dD_L D_L^2 n(D_L) \rightarrow dD_{LS} D_S^2 n(D_S) = K dD_{LS}; \quad \theta_{\rm E} \rightarrow \sqrt{\frac{\kappa \mathrm{AU}\, M}{D_S^2} D_{LS}}$$

$$\Gamma \propto \int dM F(M) M^{1/2} \int d^2\mu\, \mu f_\mu(\mu) \int d\ln D_{LS} D_{LS}^{3/2}$$

$$\frac{d\Gamma}{d\ln t_{\rm E}} \propto t_{\rm E}^3 \int dM F(M) M^{-1} \int d^2\mu \mu f_\mu(\mu)$$

Free-Floating Planets

Point-Lens Events w/o FFPs (long)

$$\Gamma \propto \int dM F(M) \int dD_L D_L^2 n(D_L) \int d^2\mu \mu f_\mu(\mu) \theta_{\rm E}(M, D_L)$$

$$t_{\rm E} = \frac{\theta_{\rm E}}{\mu}, \qquad \theta_{\rm E} = \sqrt{\kappa M \pi_{\rm rel}}$$

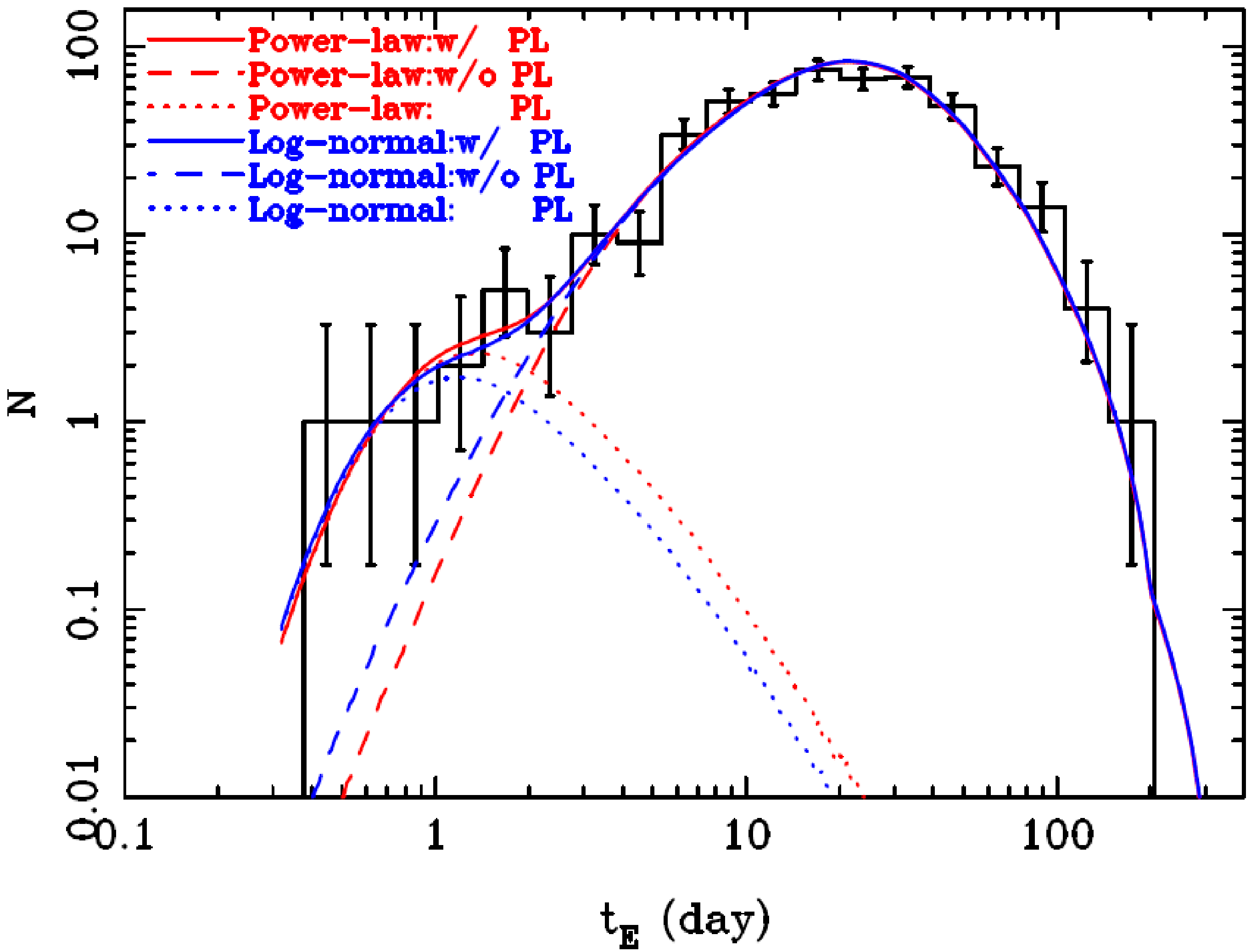
$$t_{\rm E} \text{ big} \Rightarrow \mu \rightarrow 0$$

$$d^2\mu \mu f_\mu(\mu) \rightarrow d\mu\, \mu^2 f_\mu(0) = K d \ln \mu\, \mu^3$$

$$\frac{d\Gamma}{d \ln t_{\rm E}} \propto t_{\rm E}^{-3} \int dM F(M) \int dD_L\, D_L^2 n(D_L) \theta_{\rm E}^4$$

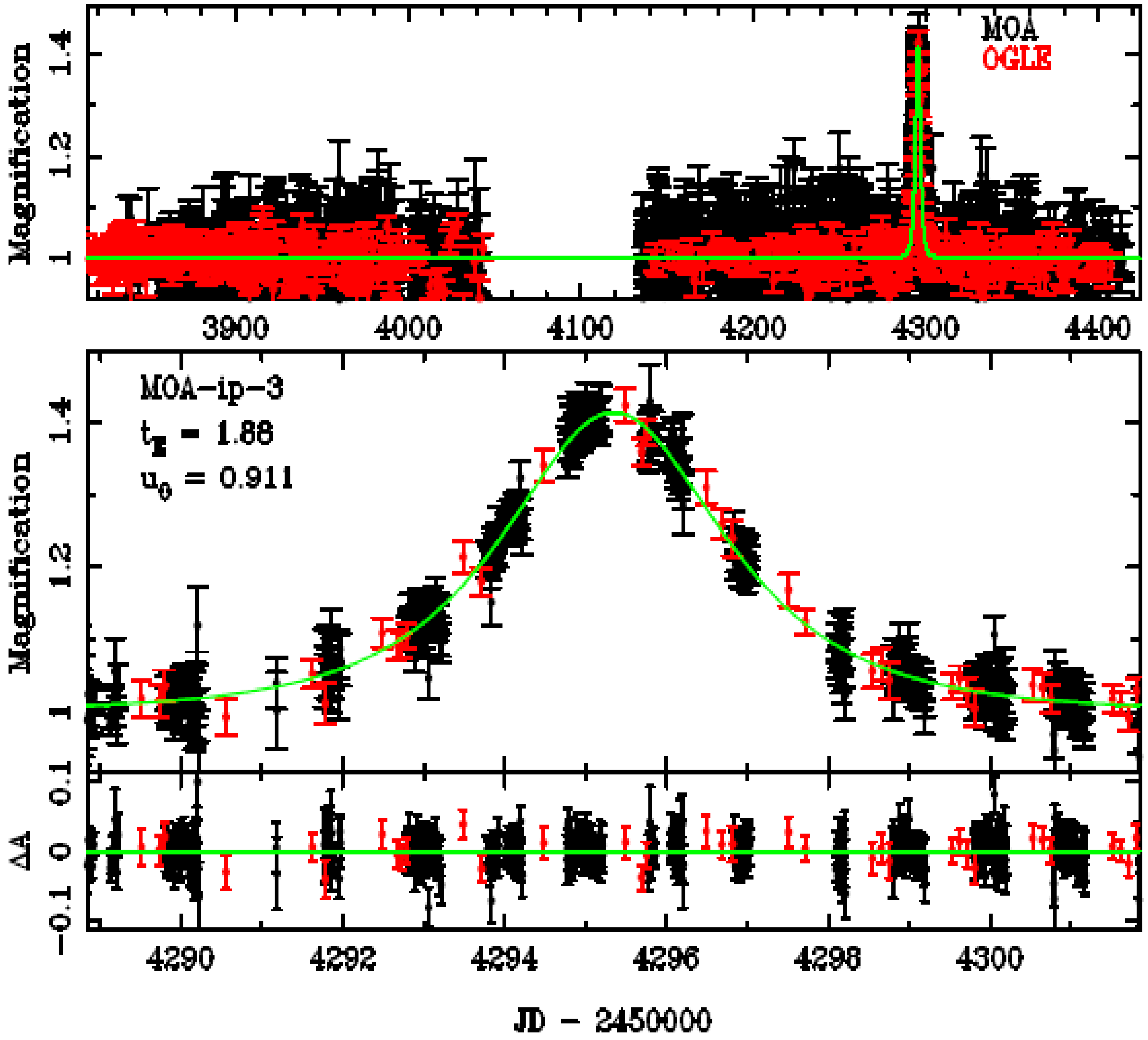
$$\frac{d\Gamma}{d \ln t_{\rm E}} \propto t_{\rm E}^{-3} \int dM F(M) M^2 \int dD_{LS}\, D_{LS}^2 n(D_{LS})$$

MOA Point-Lens Events

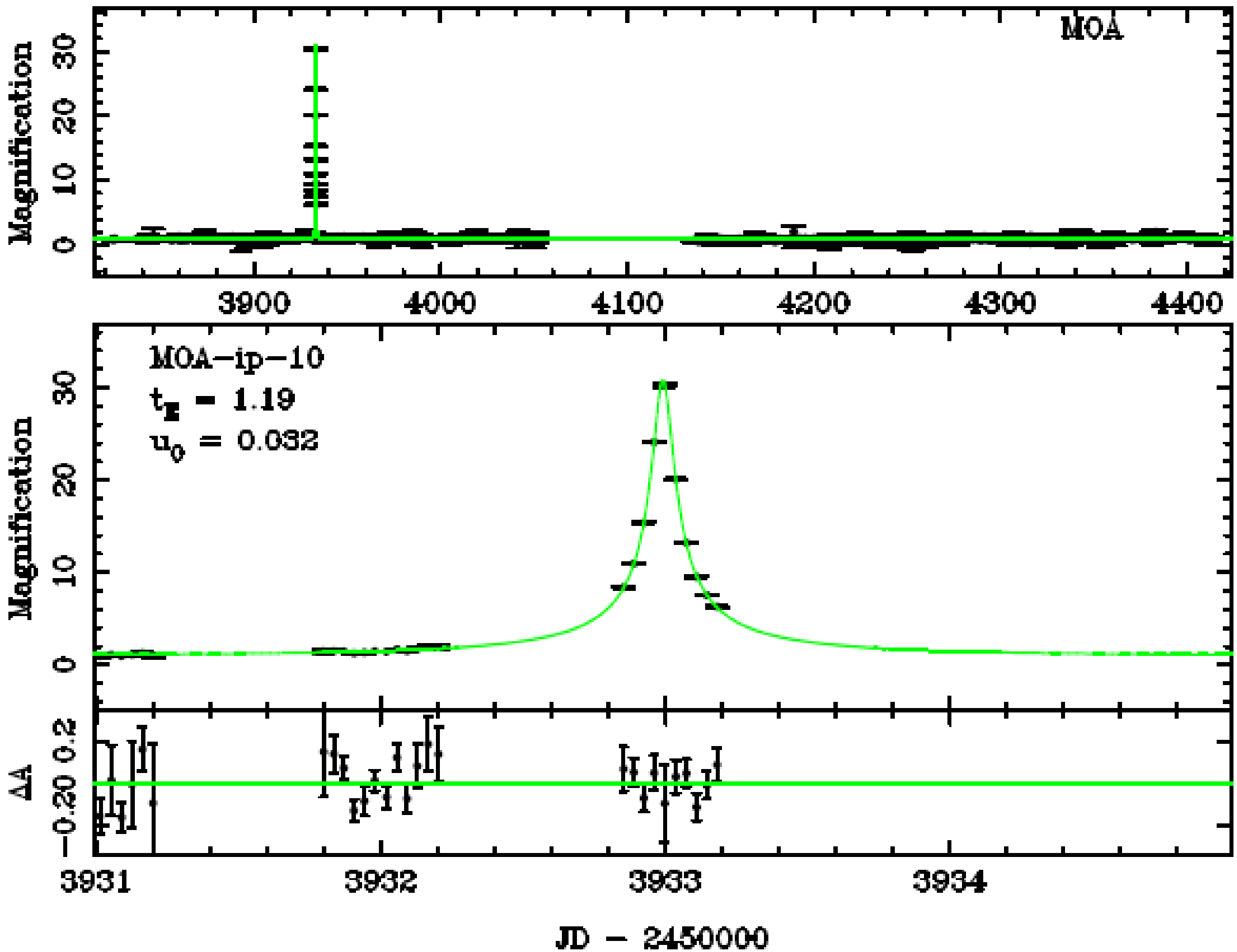


Sumi et al. 2011, Nature, 473, 349

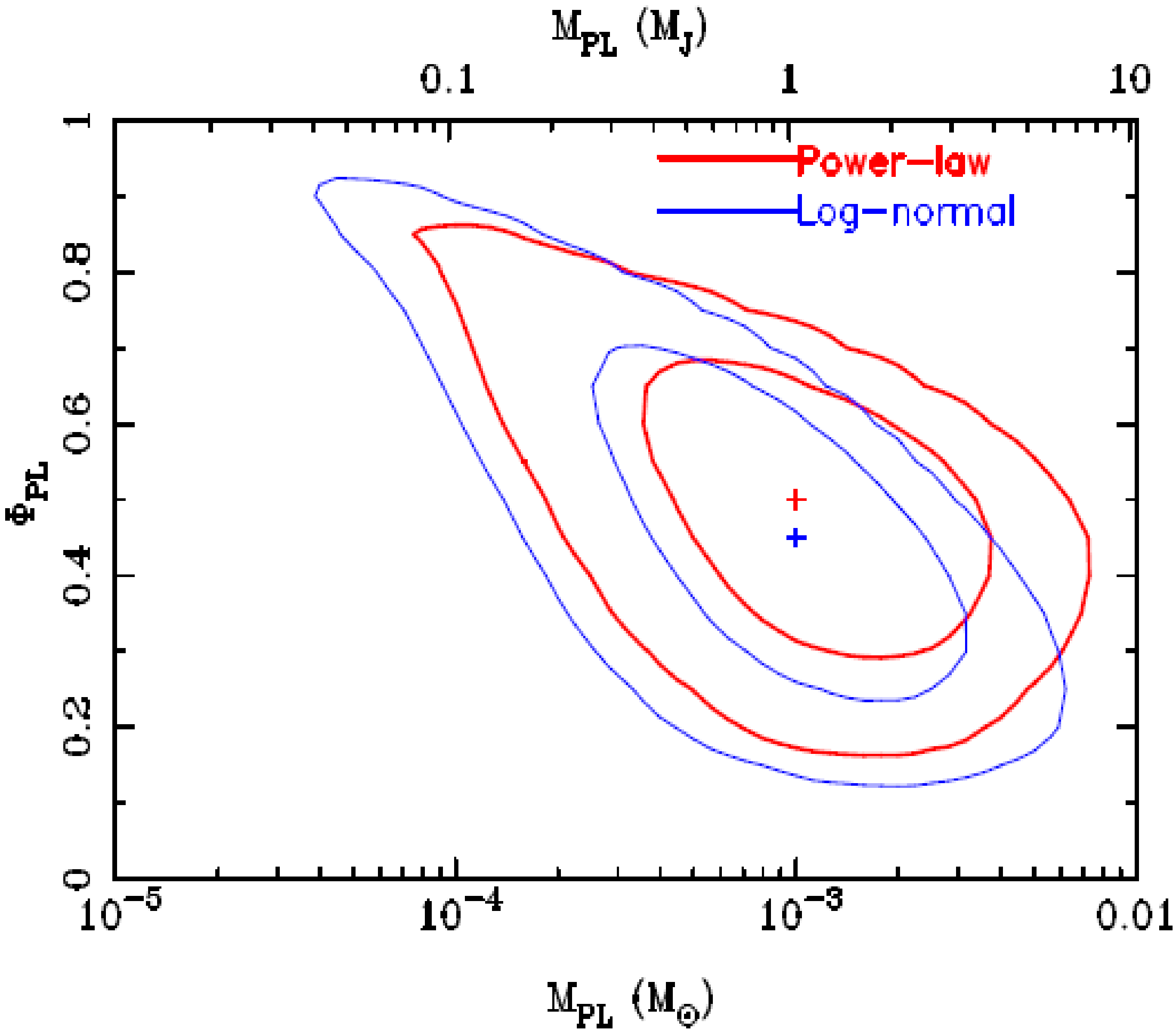
Sample Event 1



Sample Event 2



FFP Best-Fit Characteristics



Microlensing vs. Other Methods II: Bound-Planet Parameter Space

Sensitivity Peaks Just Beyond Snow Line

- Where giant planets are thought to form

Key characteristic: Einstein radius

$$r_{\rm E} = 4\,{\rm AU}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{D_L D_{LS}}{16\,{\rm kpc}^2}\right)^{1/2}$$

$$r_{\rm snow} = 2.7,\,{\rm AU}\frac{M}{M_\odot}$$

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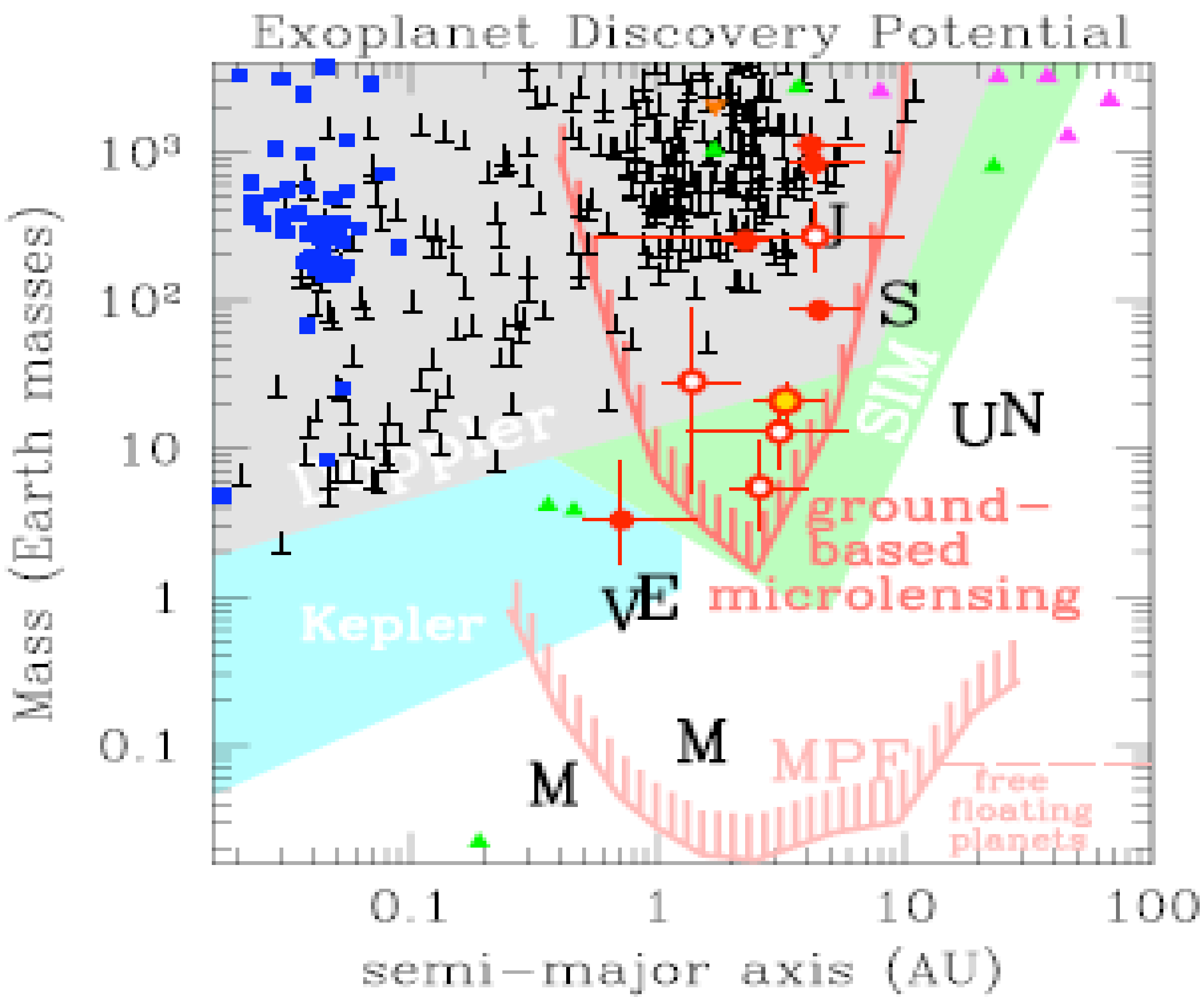
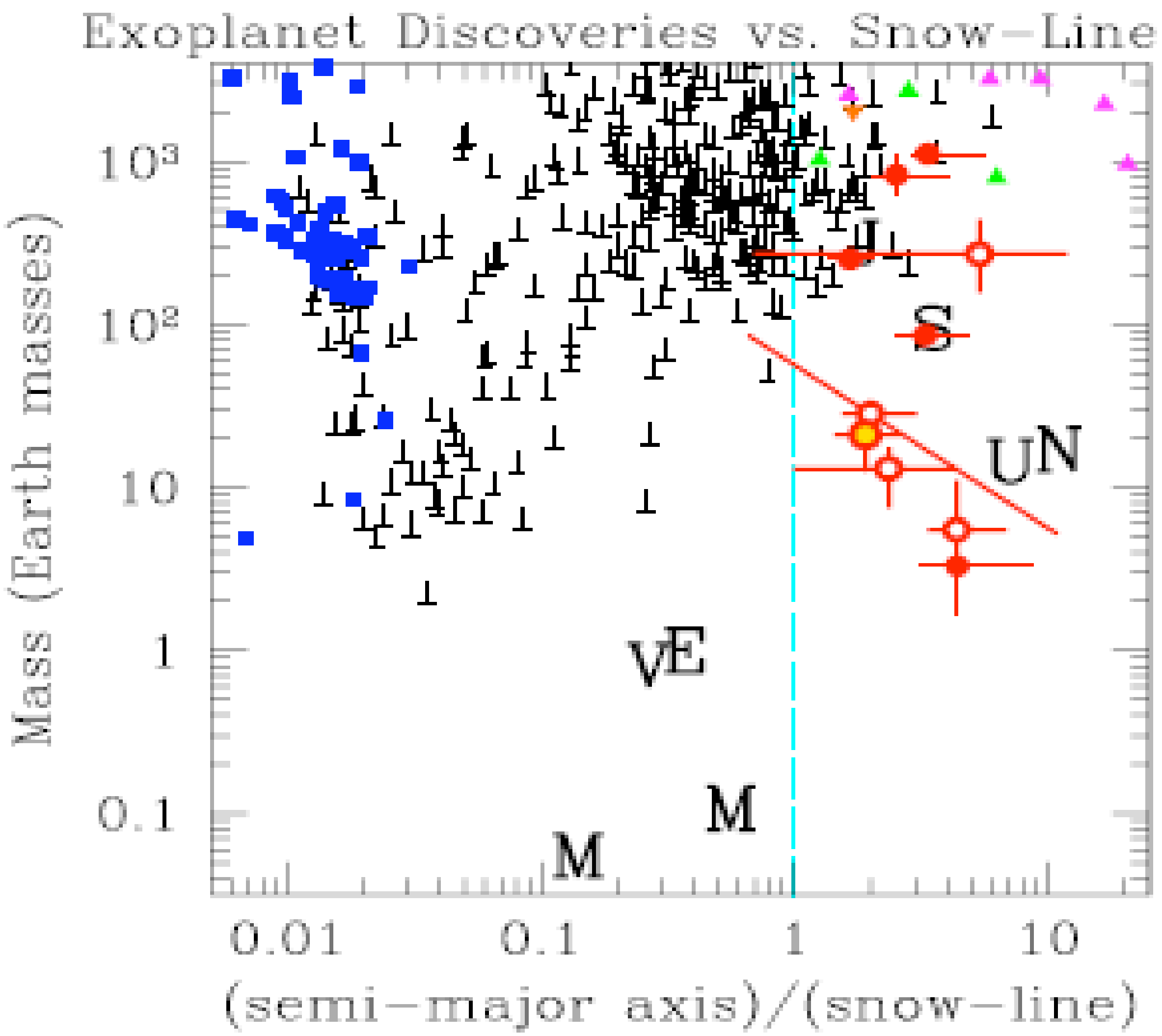
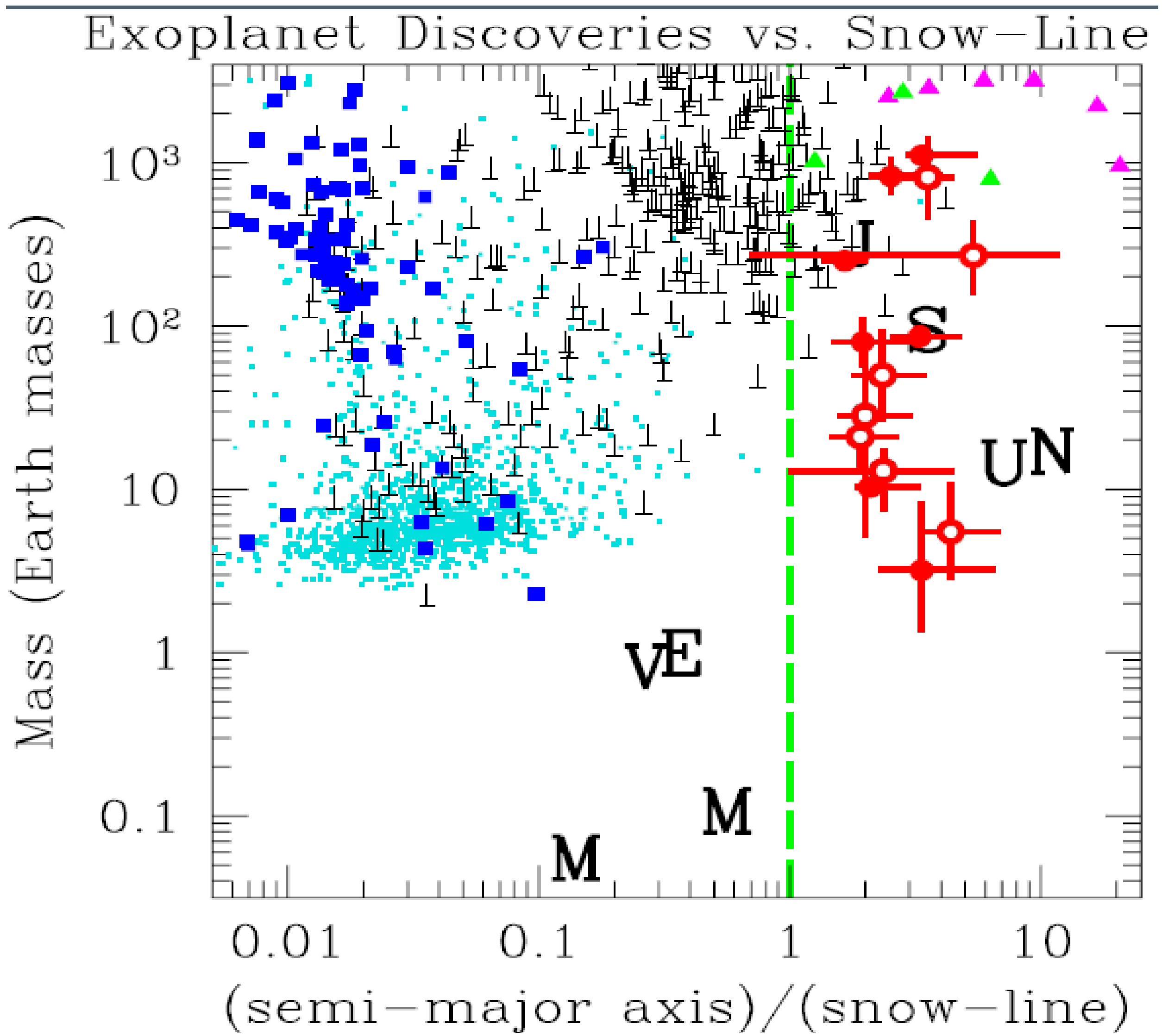
Planets 2010



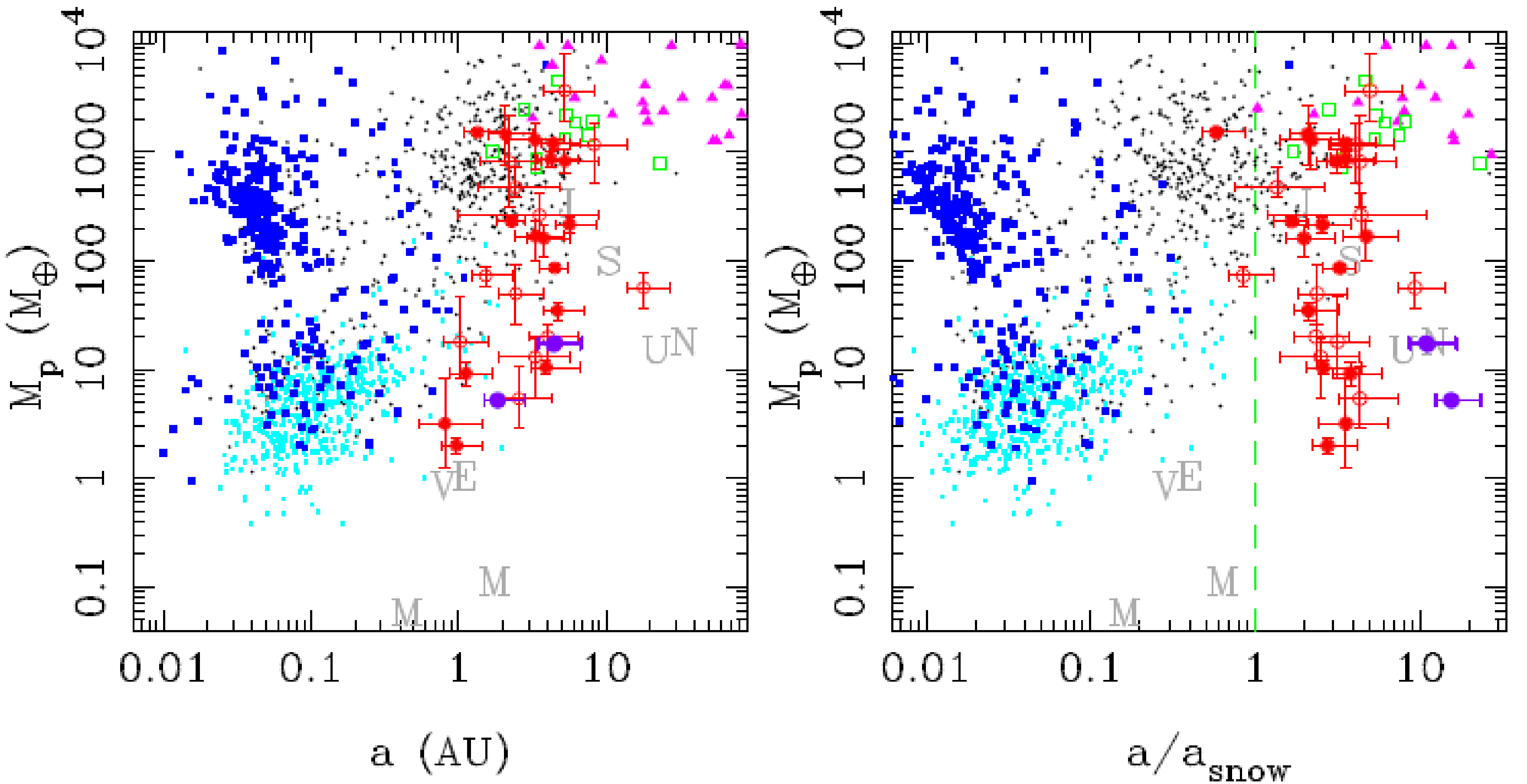
Planets 2010



Planets 2011



Planets 2015



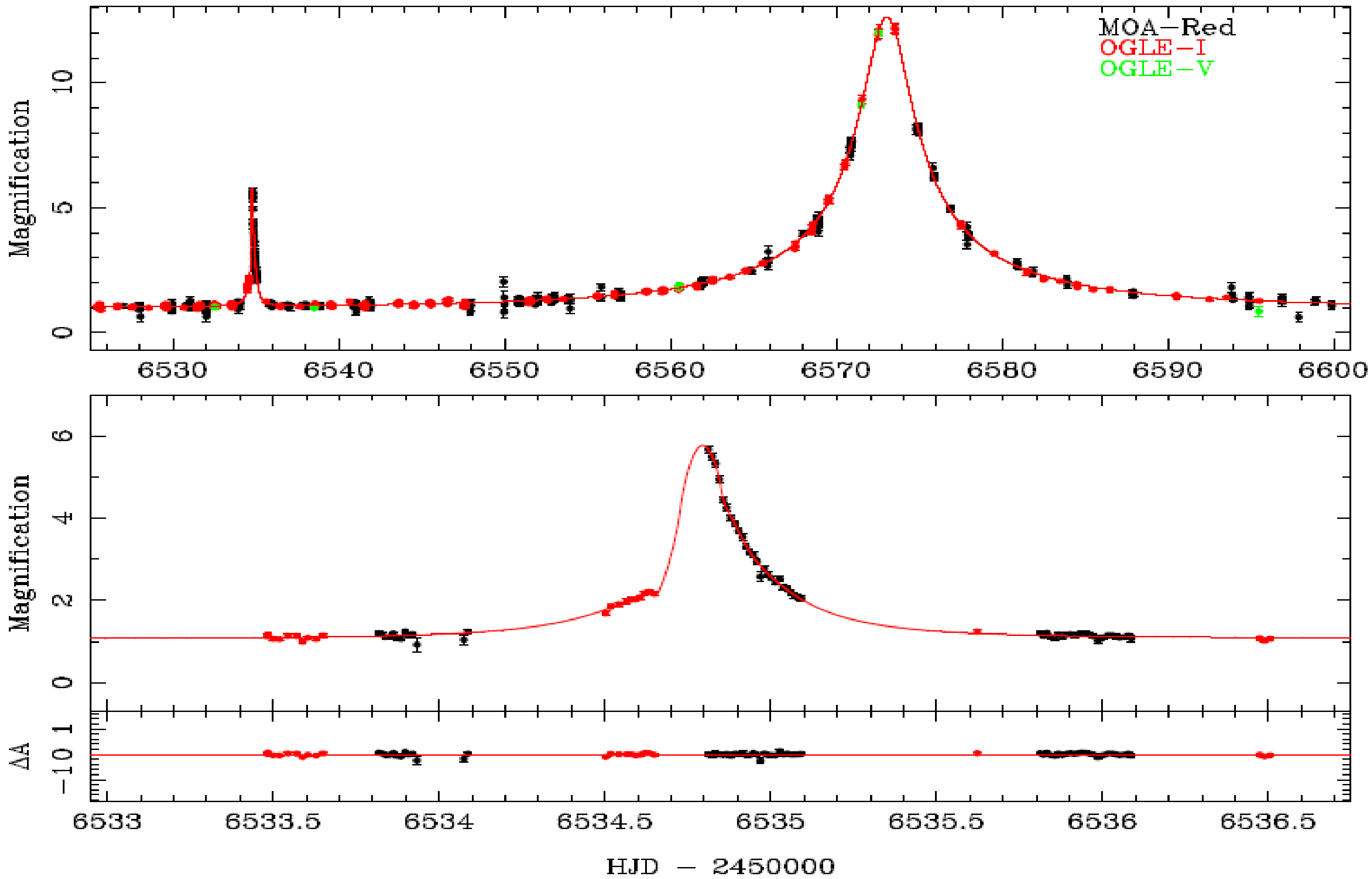
Microlensing vs. Other Methods III: Remote Planets

Crucial to Planet-Formation Theories

μlensing: Only Remote Planet Method

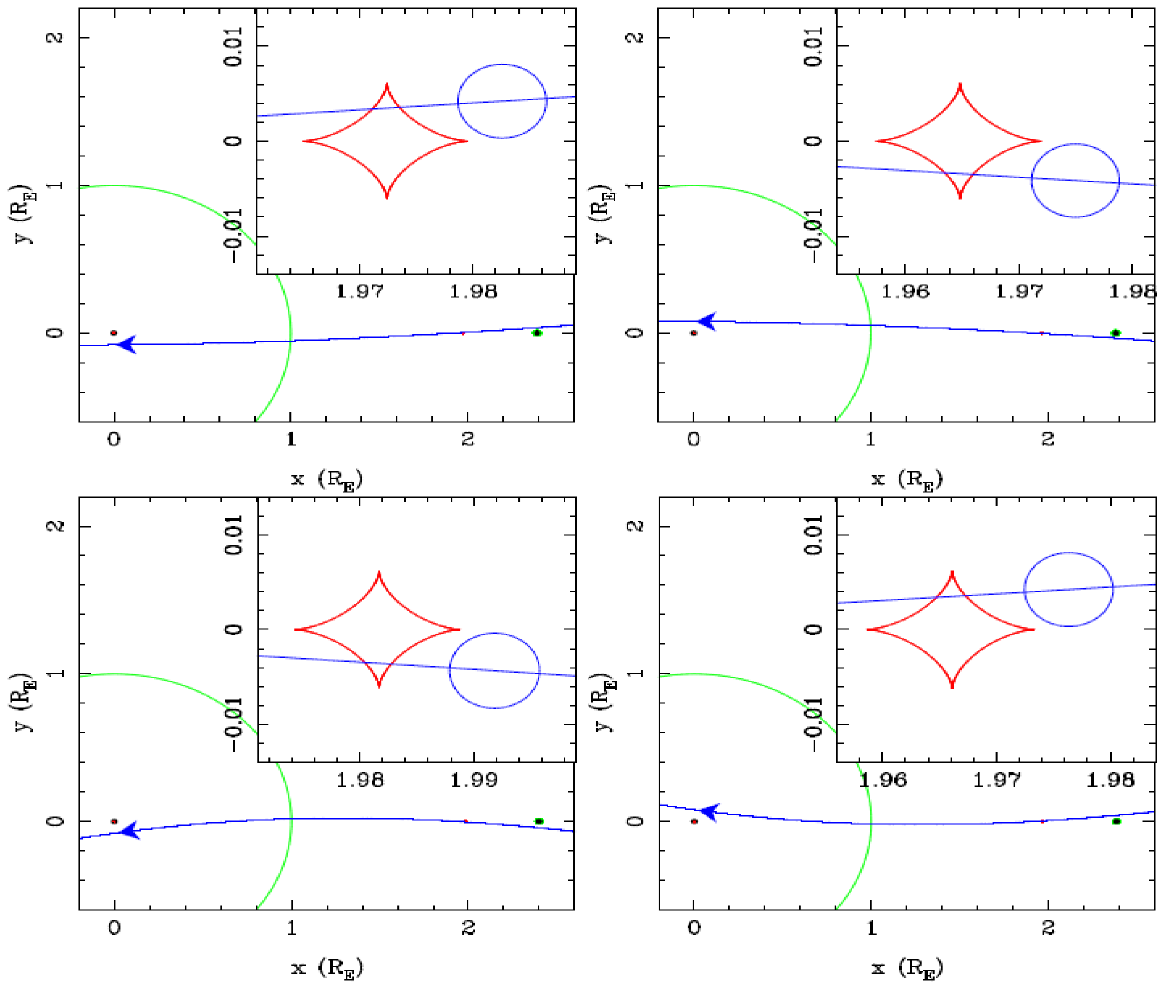
Key characteristic: “Almost” FFP

Remote Planets; “Neptune”



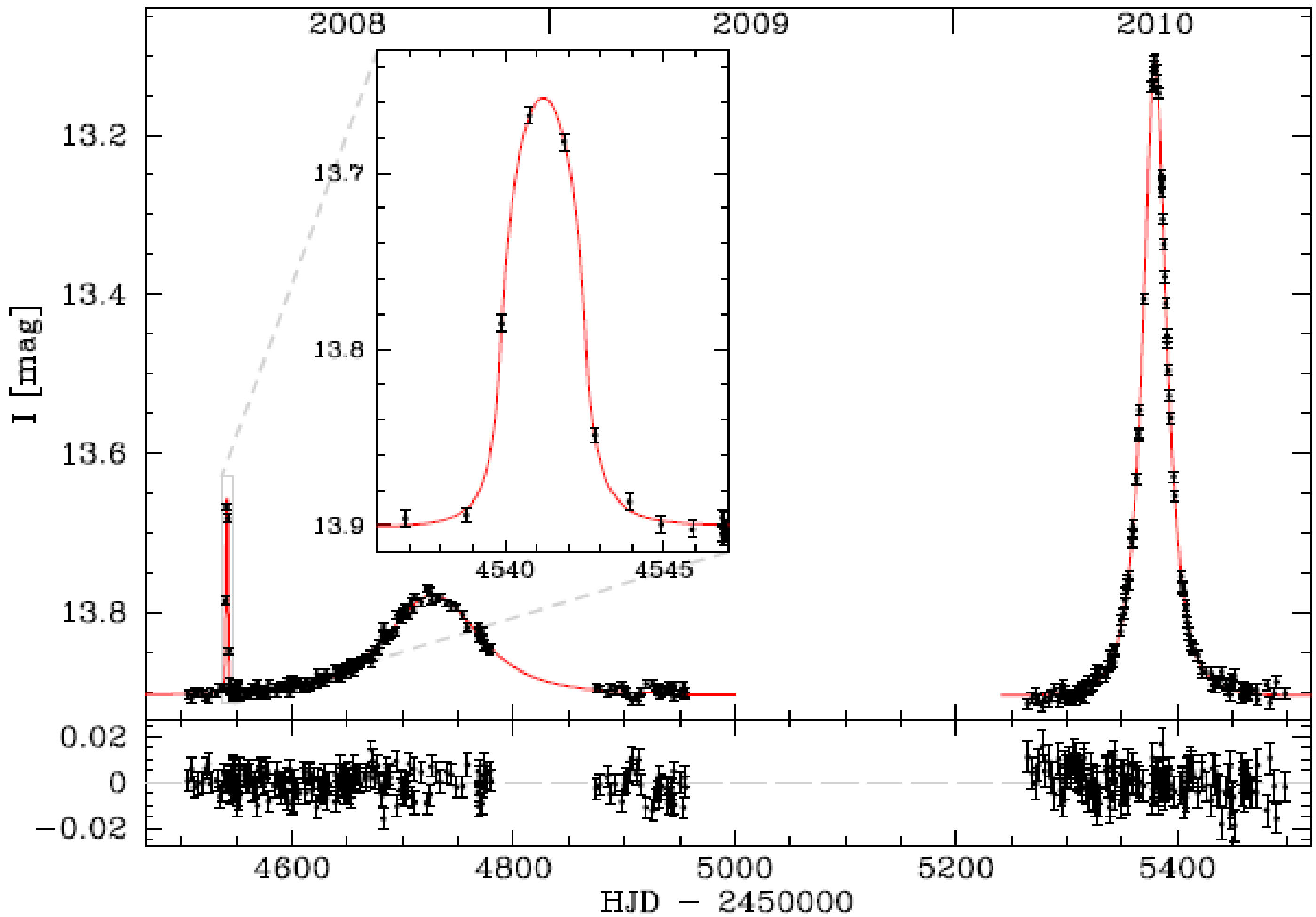
Sumi et al., in prep

Remote Planets; "Neptune"



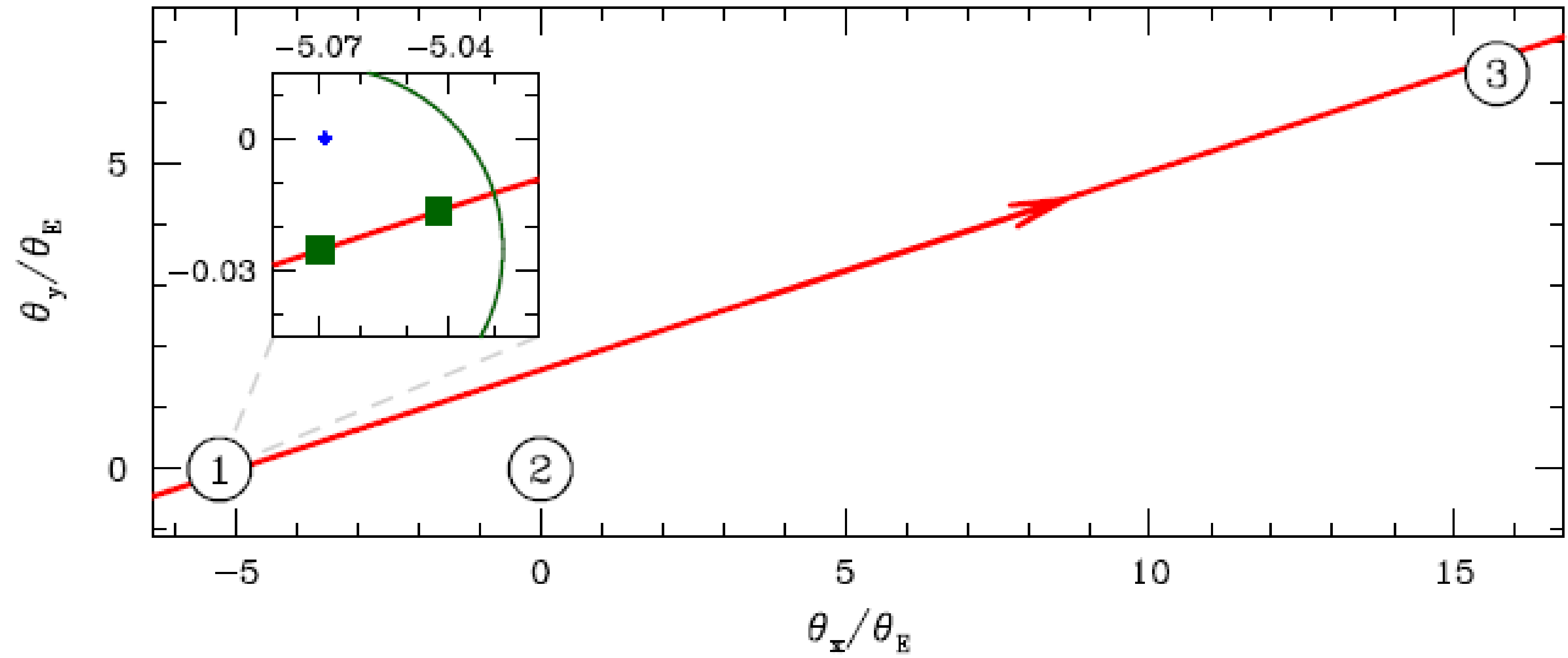
Sumi et al., (MOA-2013-BLG-605)

Remote Planets; “Uranus”



Poleski et al., (OGLE-2008-BLG-092)

Remote Planets; "Uranus"



Poleski et al., ApJ, 2014, 795, 42

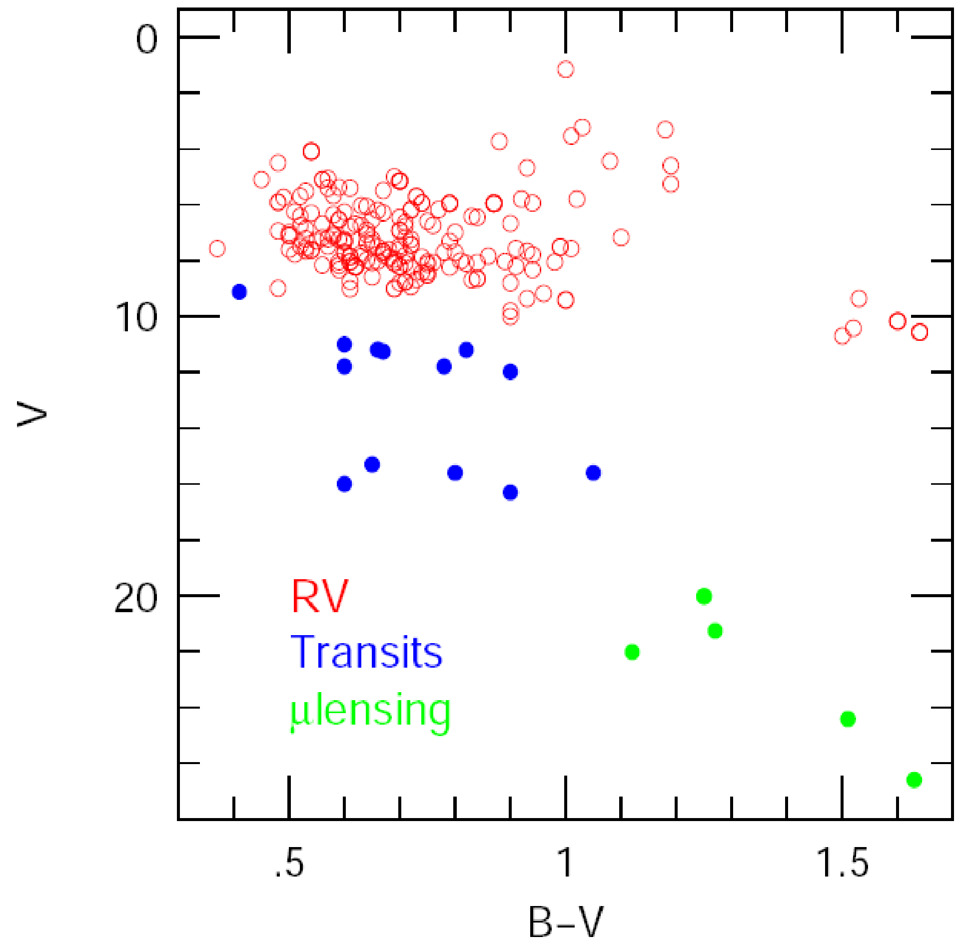
Microlensing vs. Other Methods IV: Faint/Dim Hosts

Other methods: struggle

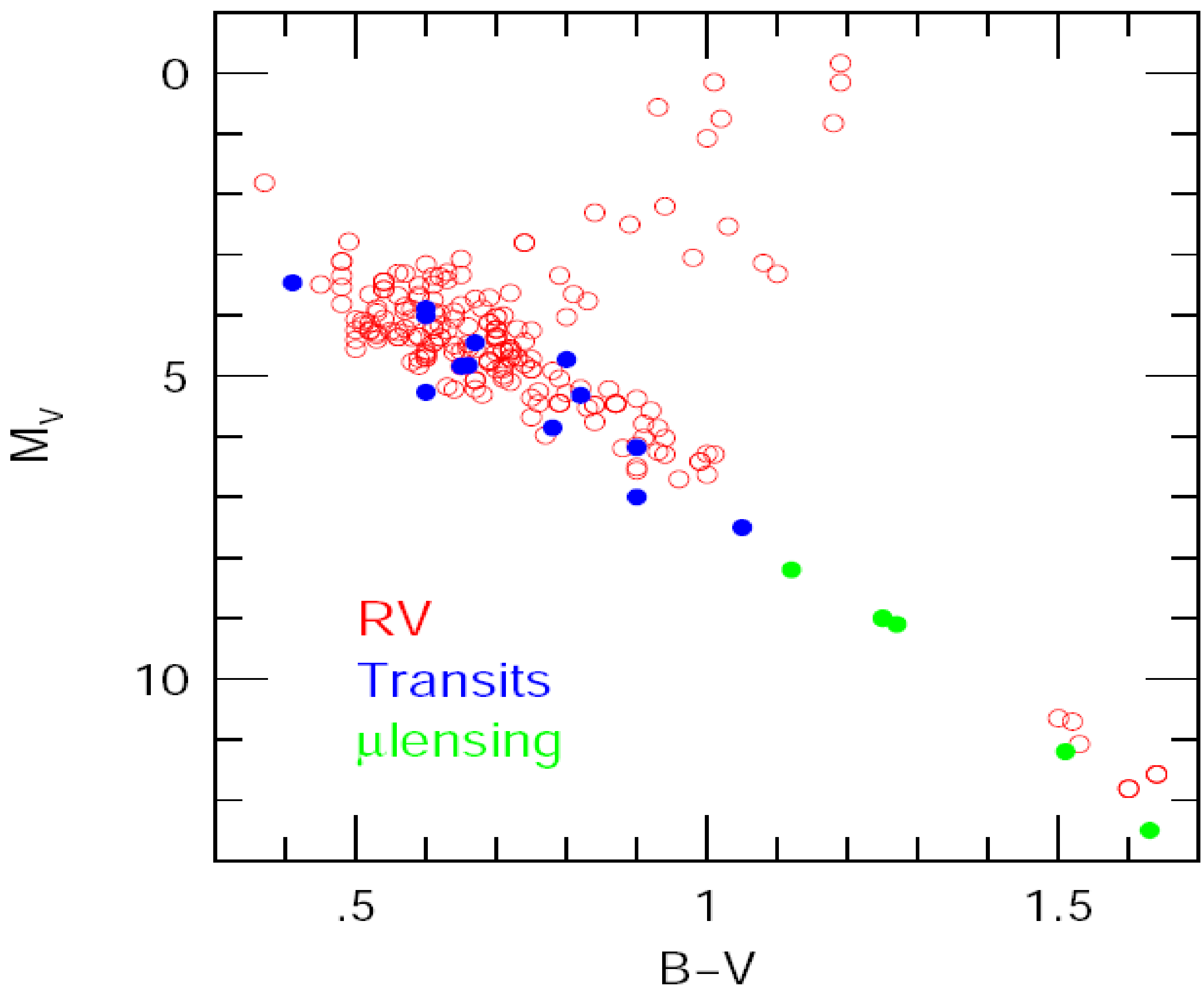
Microlensing: comes naturally

Key Characteristic: Mass/Not Light

Faint Hosts:
CMD (Apparent Mags)



Dim Hosts:
CMD (Absolute mags)



Microlensing vs. Other Methods IV:
Biggest Challenge: Host ID

Host superposed on source (glare)

Typically moves at 4 mas/yr

  10+ years to separately resolve

μlens masses require θ_E, π_E

  Usually: θ_E si; π_E non

  Hence: “Bayesian Estimates”

Bayesian Information Flow
(typical: finite source/no parallax)

Line of Sight toward Bulge Source known well

Proper motion $\mu = \theta_E/t_E$ known well

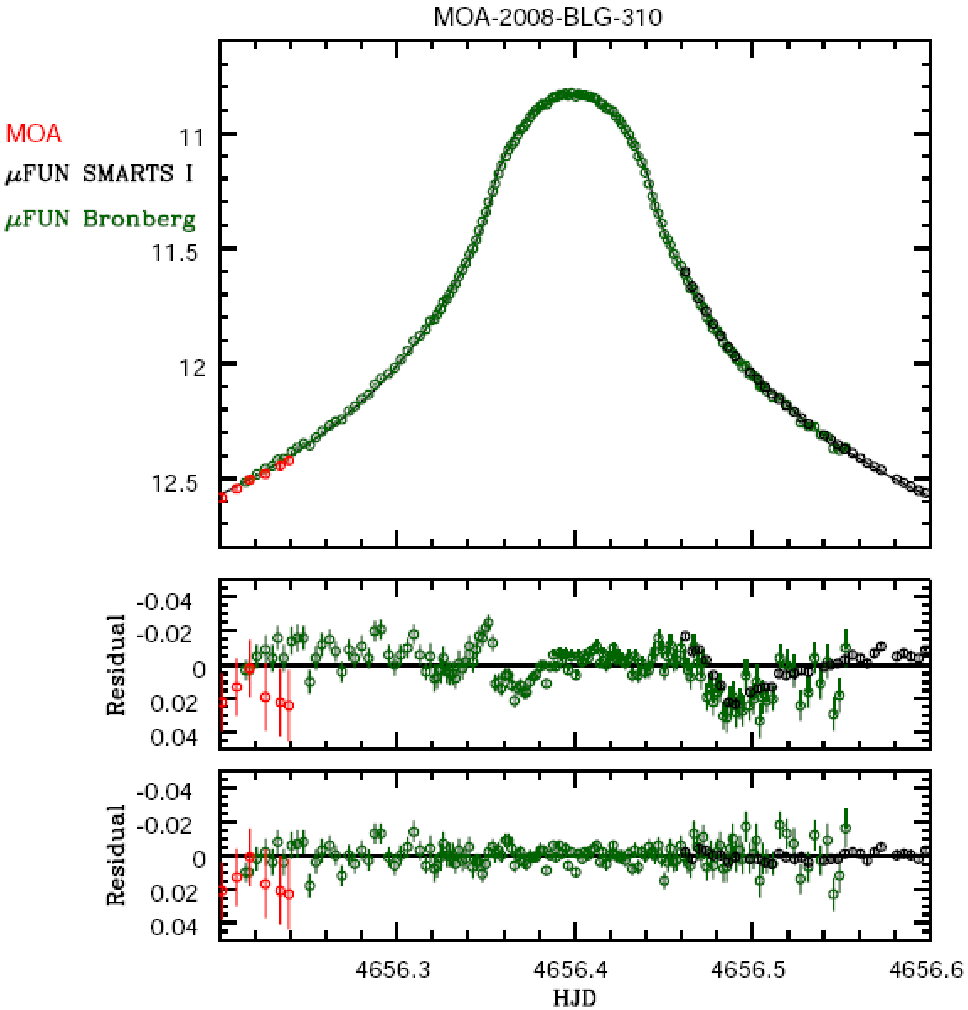
θ_E ==> $(M\ \pi_{rel})$ known well

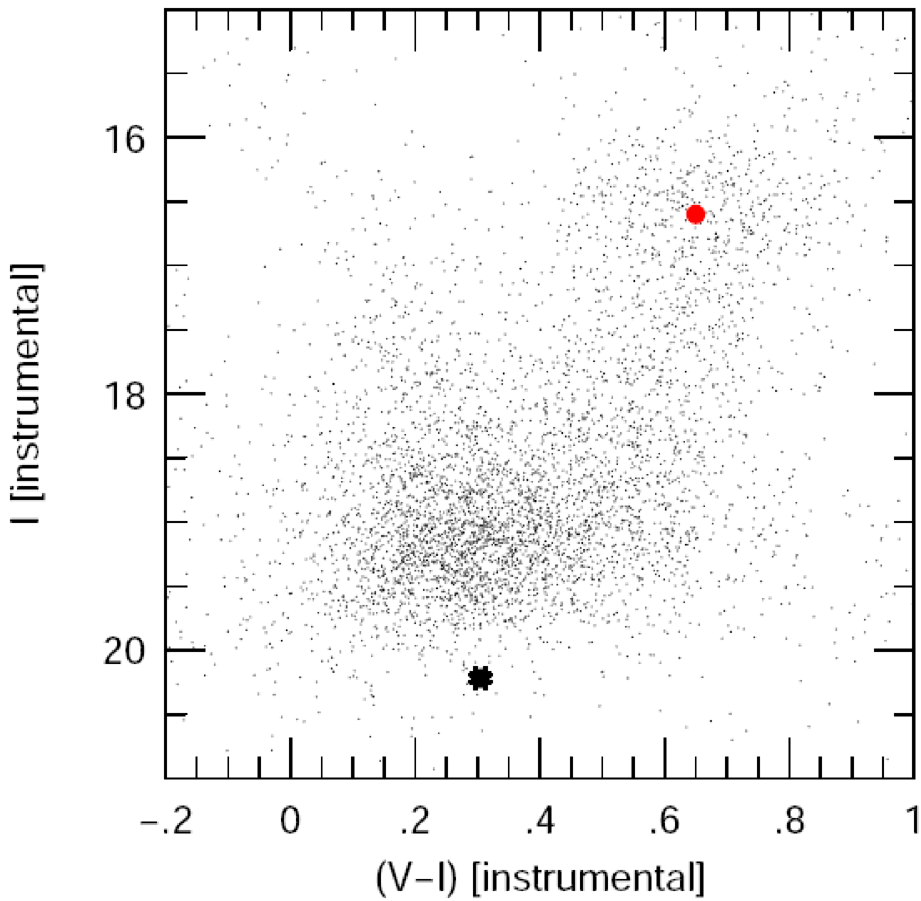
Galactic model favors bulge lenses, unless μ big

Galactic model favors low mass, unless θ_E big

MOA-2008-BLG-310

A Buried Planet

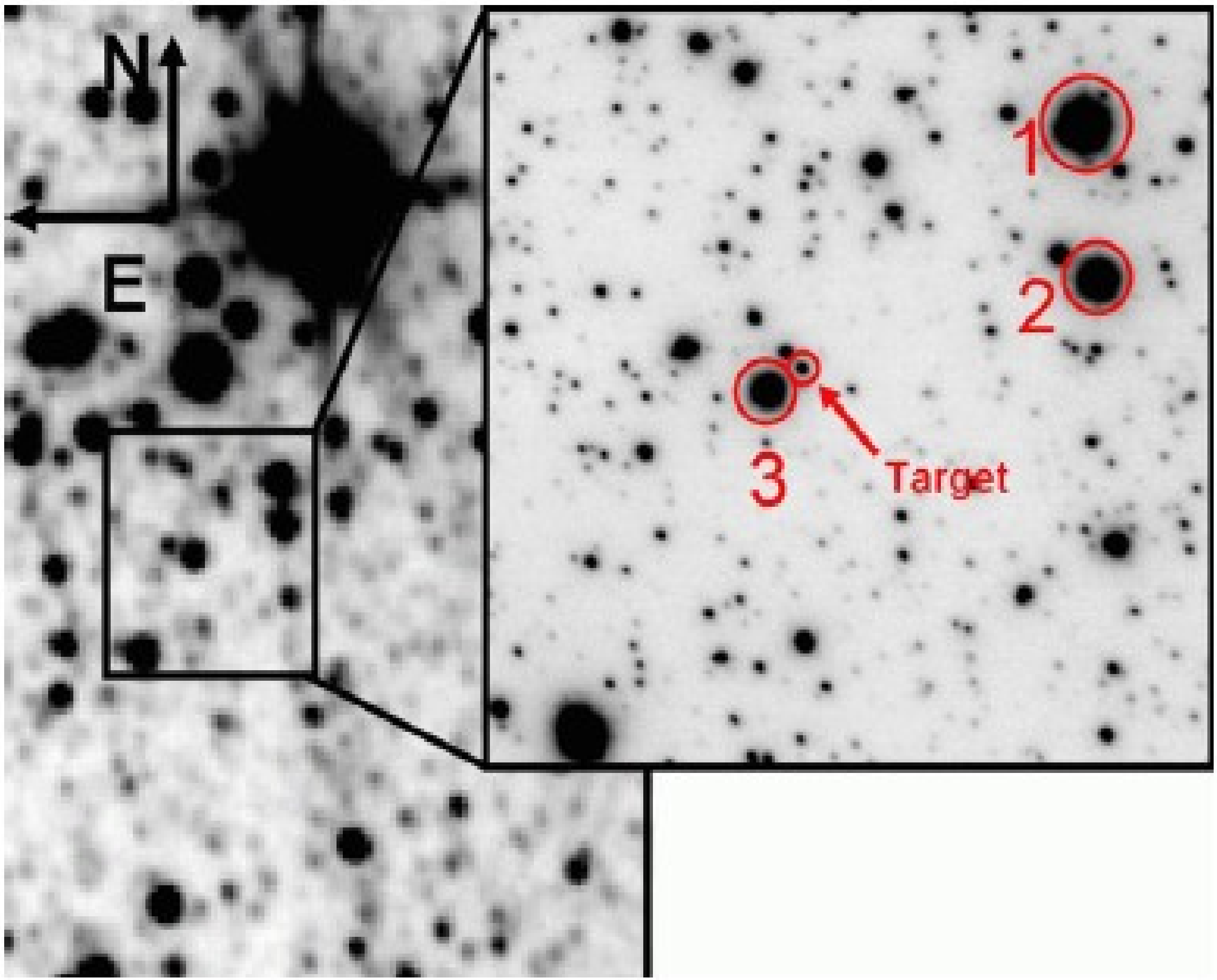




Janczak et al. 2010, ApJ, 711, 731

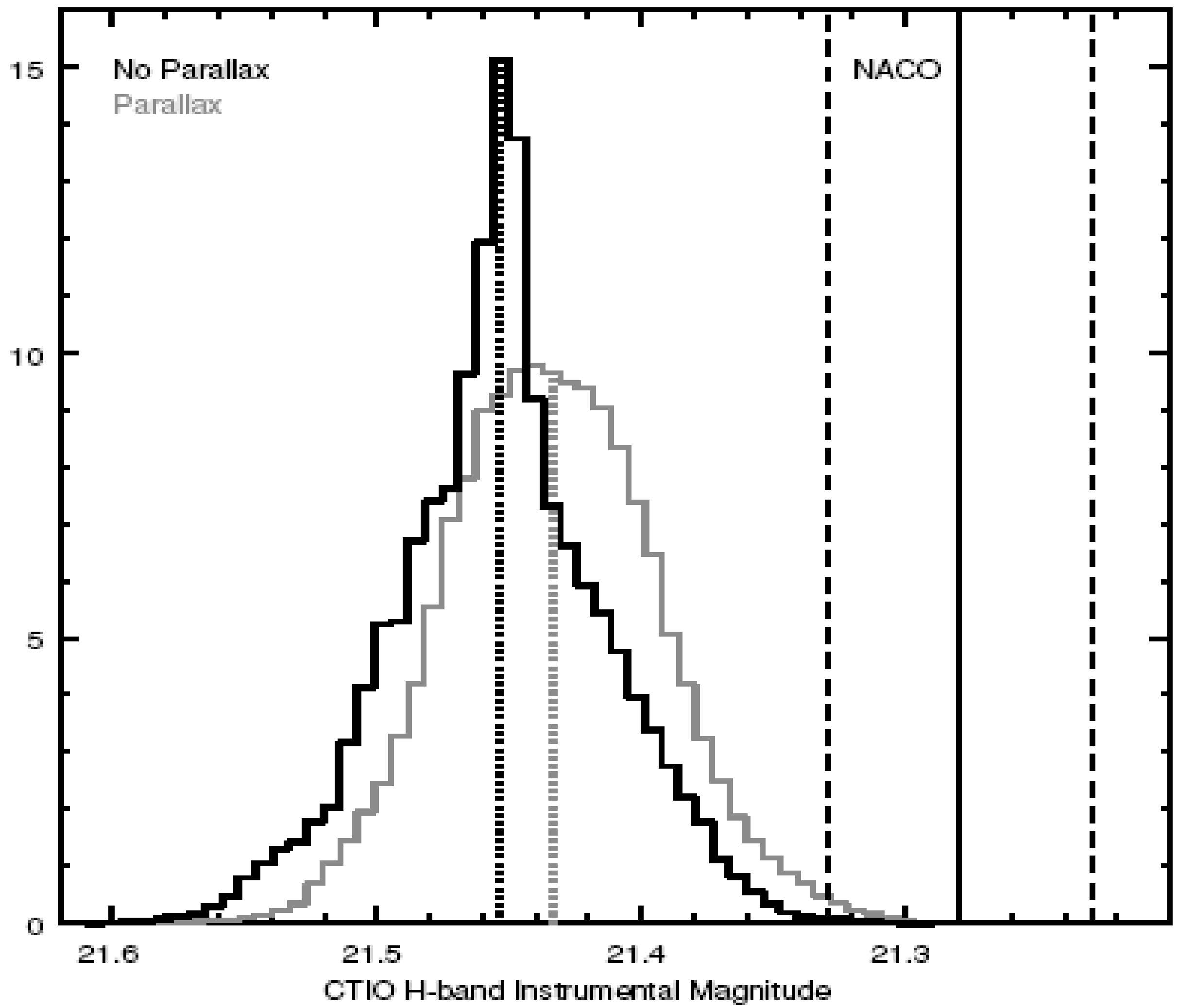
Extra Info: High Resolution Imaging

MOA-2008-BLG-310 (Janczak et al)

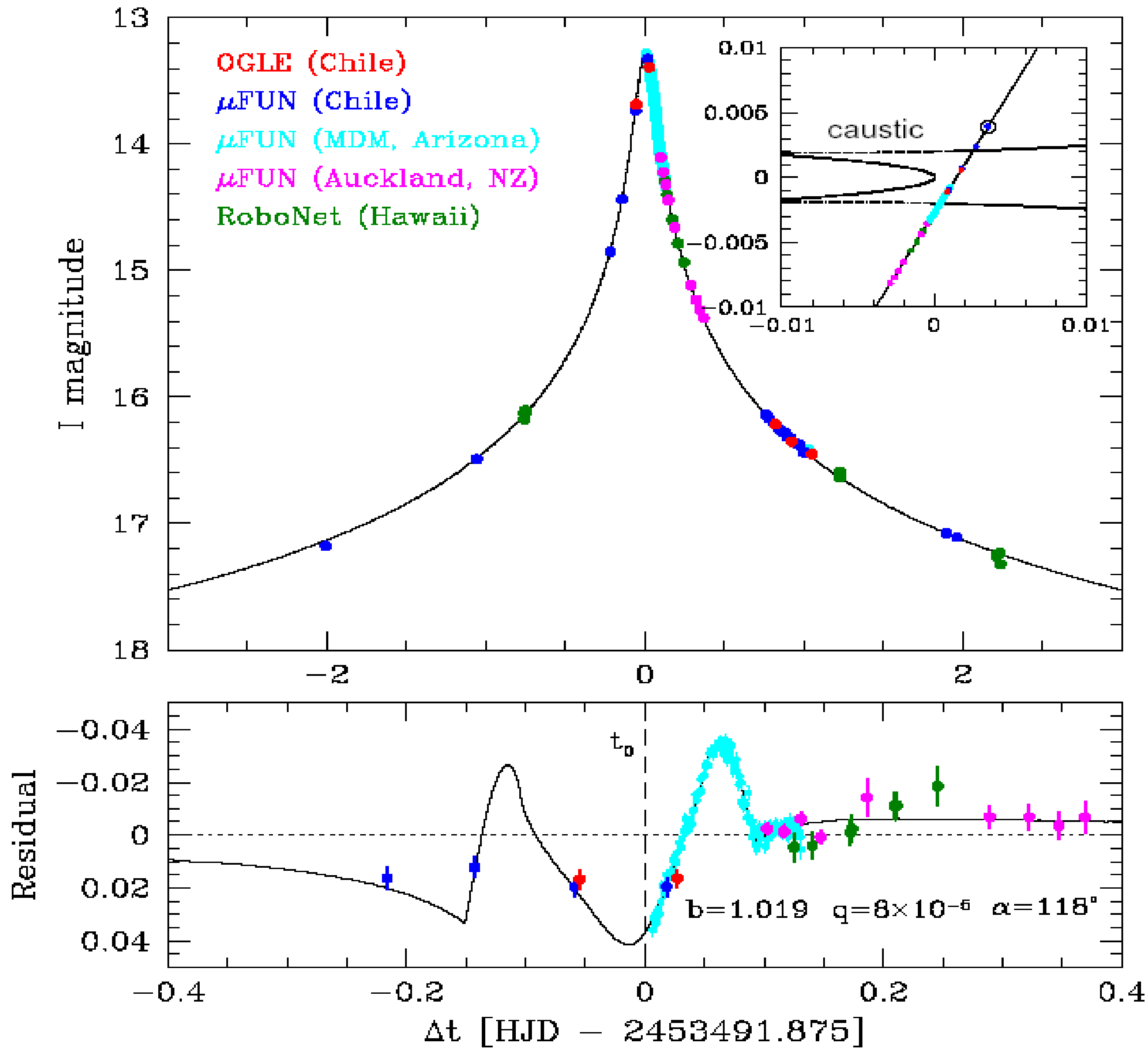


Extra Light Definitely Detected, but ..

Host, host-comp, source-comp, random?

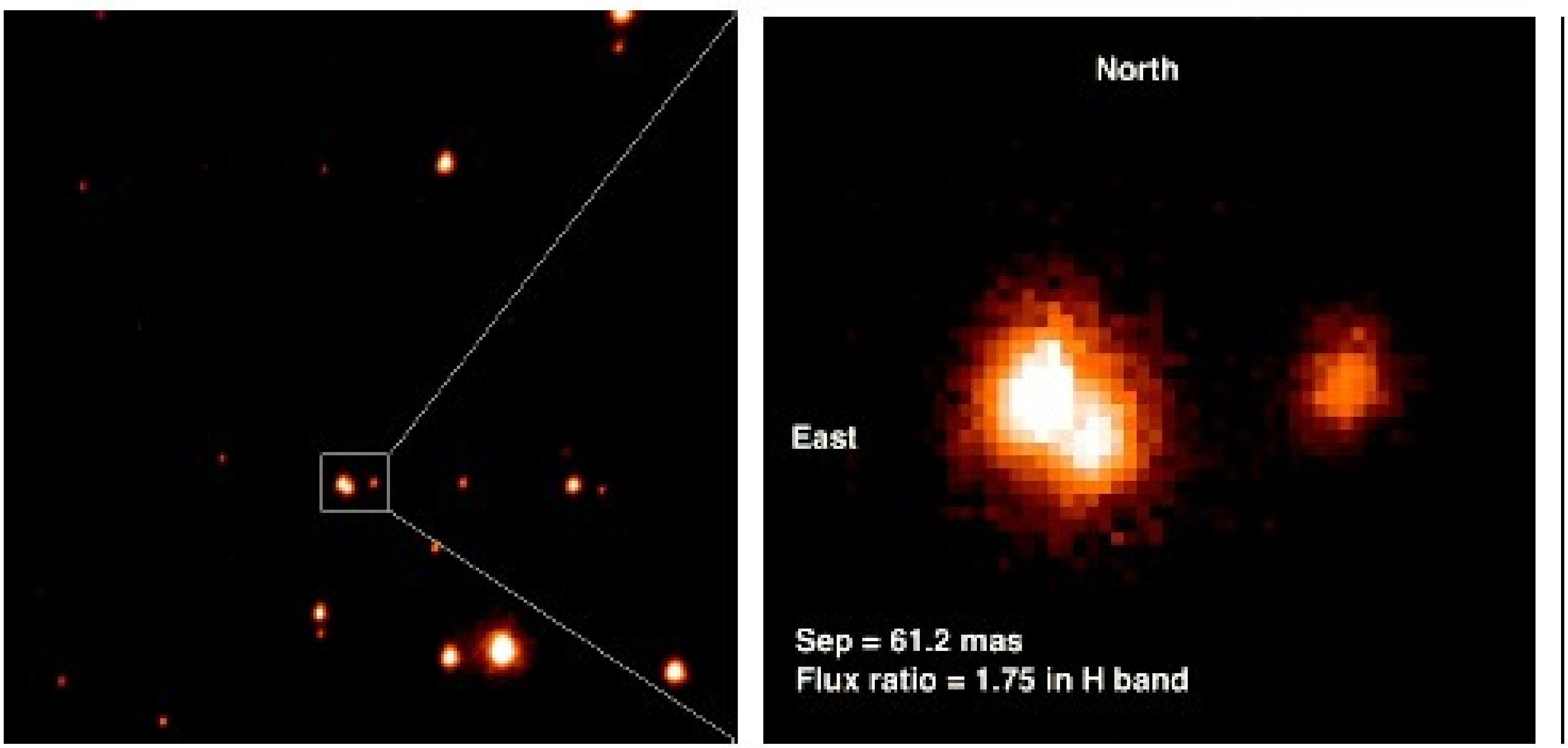


OGLE-2005-BLG-169:
Second High-Mag Event



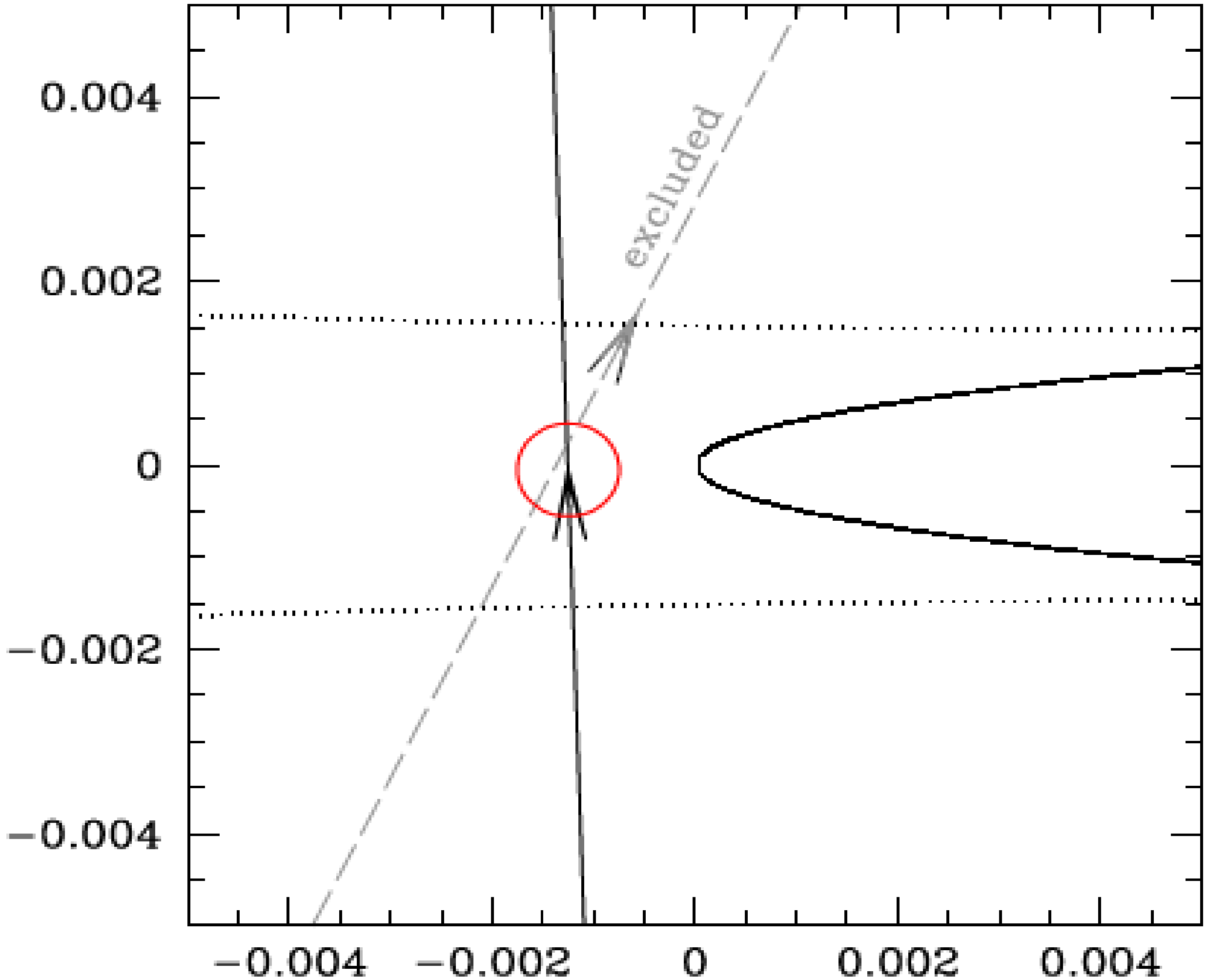
8 Years Later: Source-Lens Separate

Batista et al. 2015, ApJ, submitted



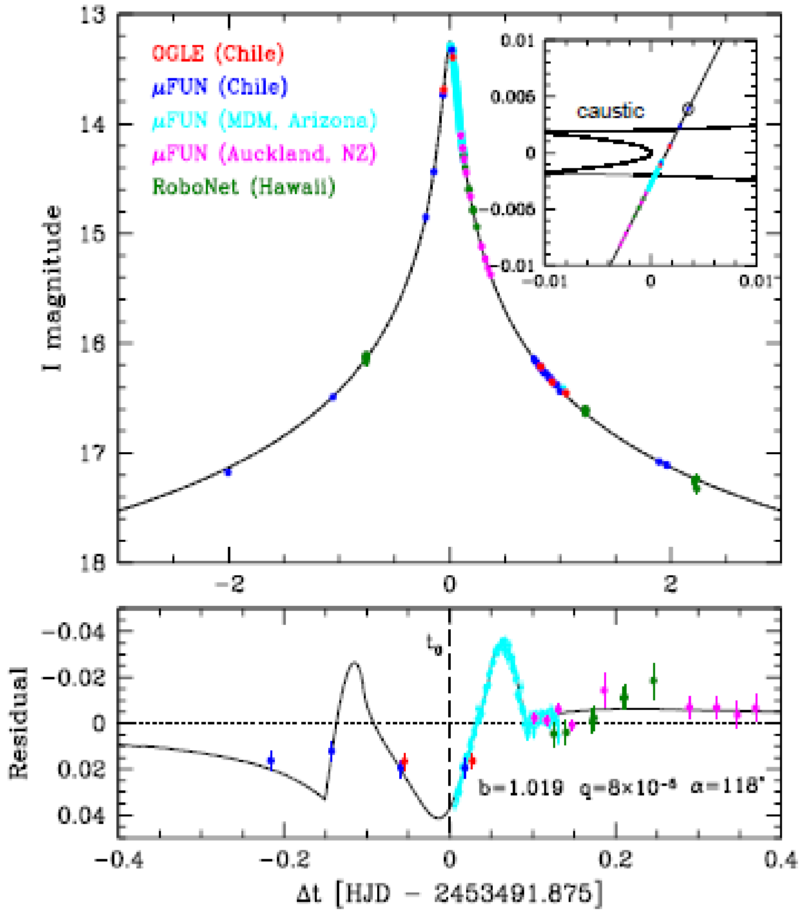
Source-Lens Proper Motion Measured

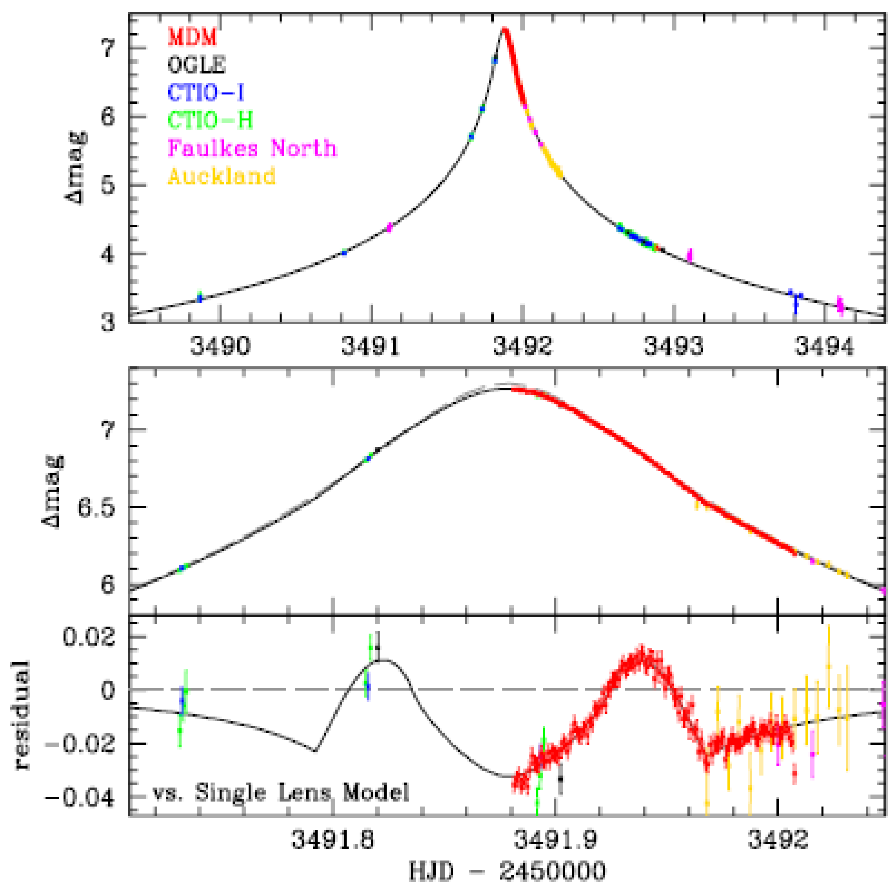
Batista et al. 2015, ApJ, submitted



Previously allowed solution excluded

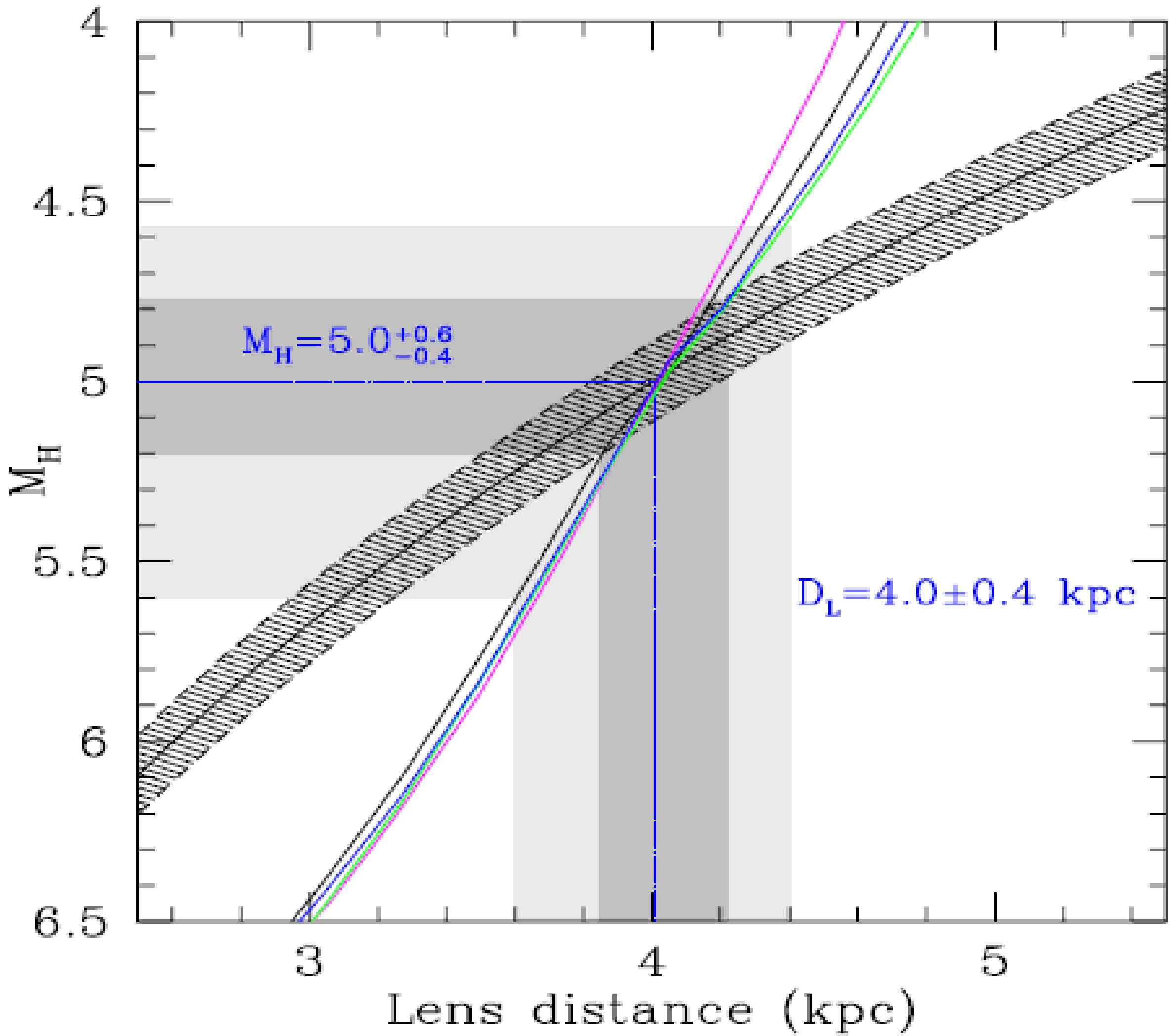
Batista et al. 2015, ApJ, submitted





Flux Measured (+θ_E) Yields M & D_L

Batista et al. 2015, ApJ, submitted



Physical parameters with 1-σ ranges

Parameter	Units	Value
D_L	kpc	4.0 ± 0.4
$M_{\rm host}$	$M_\odot$	0.65 ± 0.05
$m_{\rm planet}$	$M_\oplus$	13.2 ± 1.3
$r_\perp$	AU	3.4 ± 0.3
a	AU	~ 4.0

μlens Planet Frequency Estimates

Gould et al. 2010, ApJ, 720, 1073

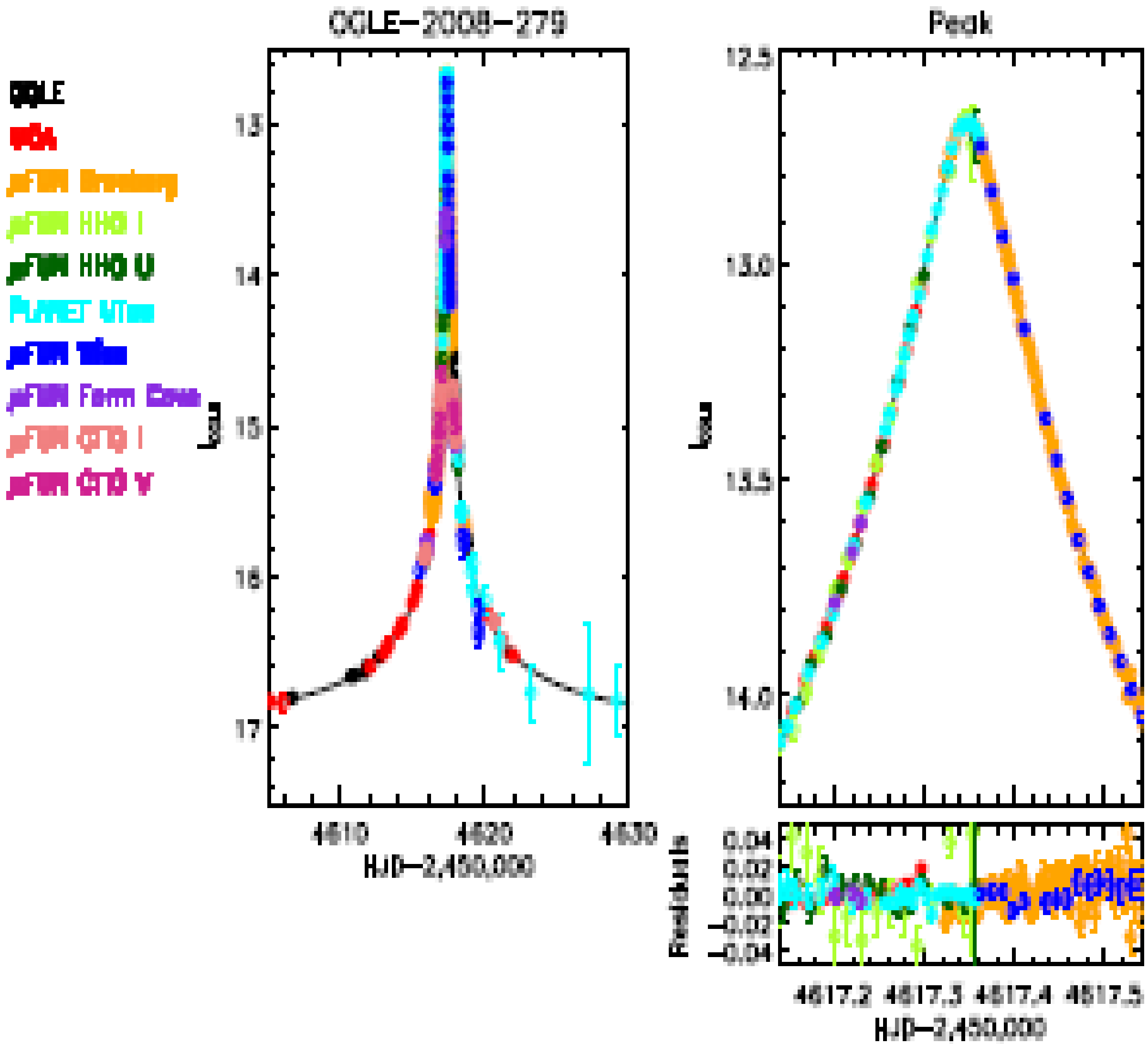
Cassan et al. 2012, Nature, 481, 167

Gould et al. (2010)

Sumi et al. 2010, ApJ, 710, 1641

OGLE-2008-BLG-279:

A = 1600

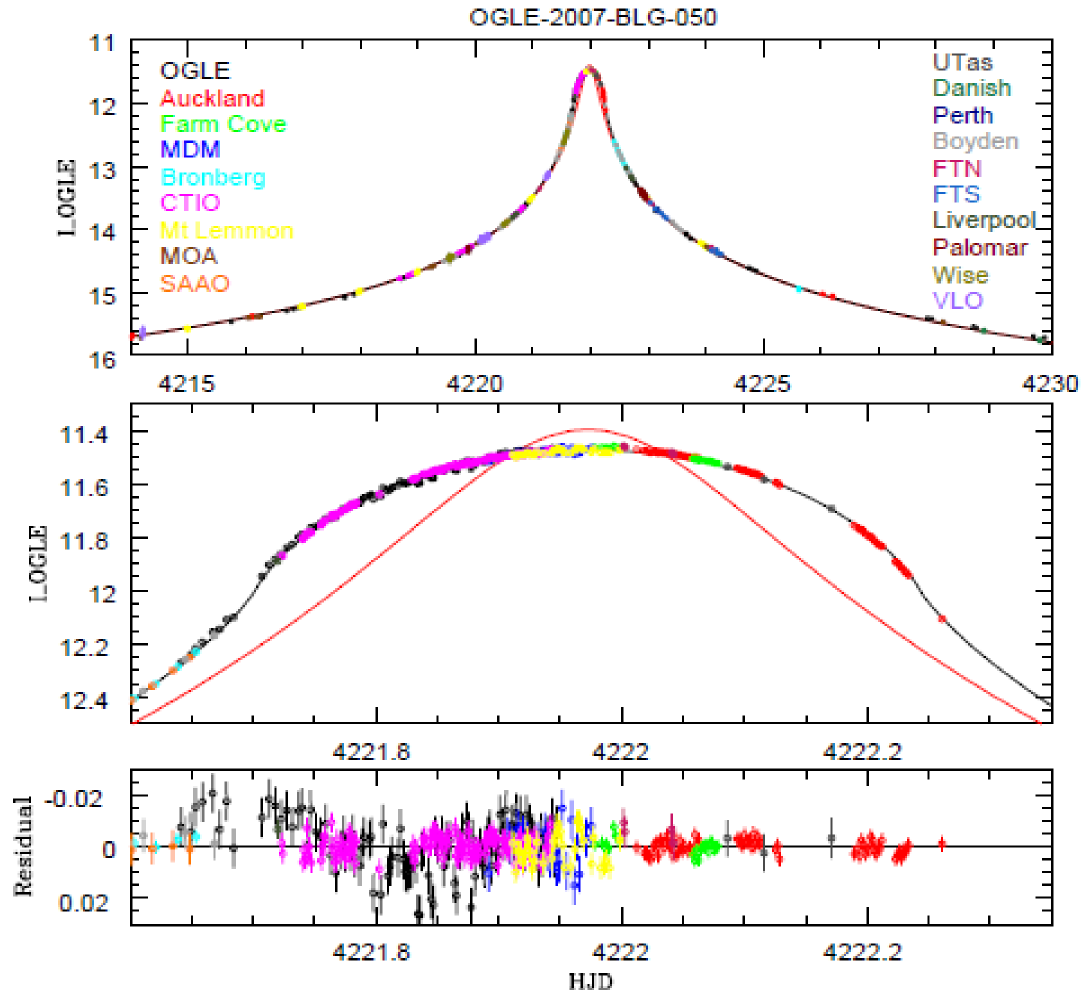


Yee et al. 2009, ApJ, 730, 2082

Jennifer Yee

OGLE-2007-BLG-050:

A = 432

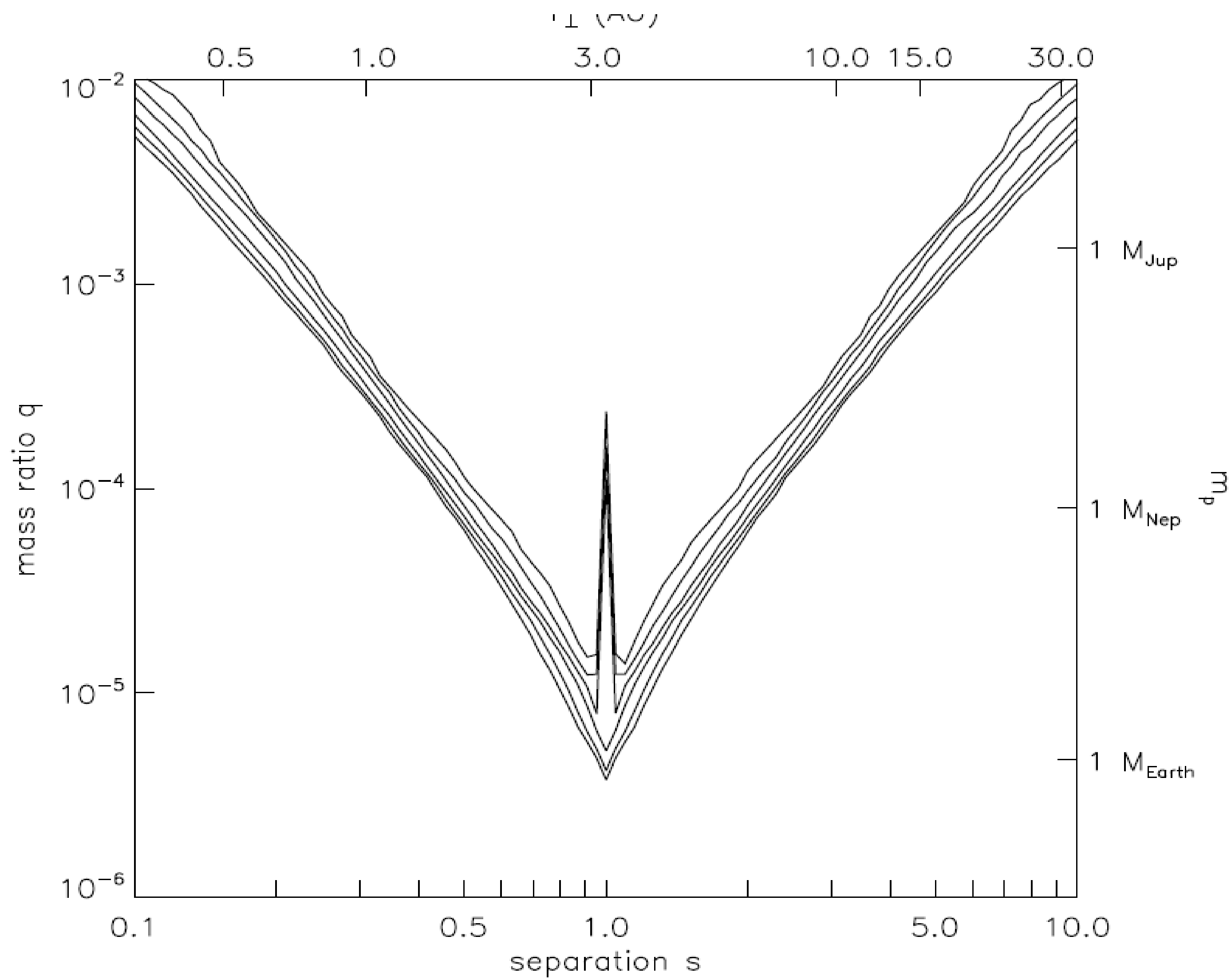


Batista et al. 2009, A&A, 508, 467

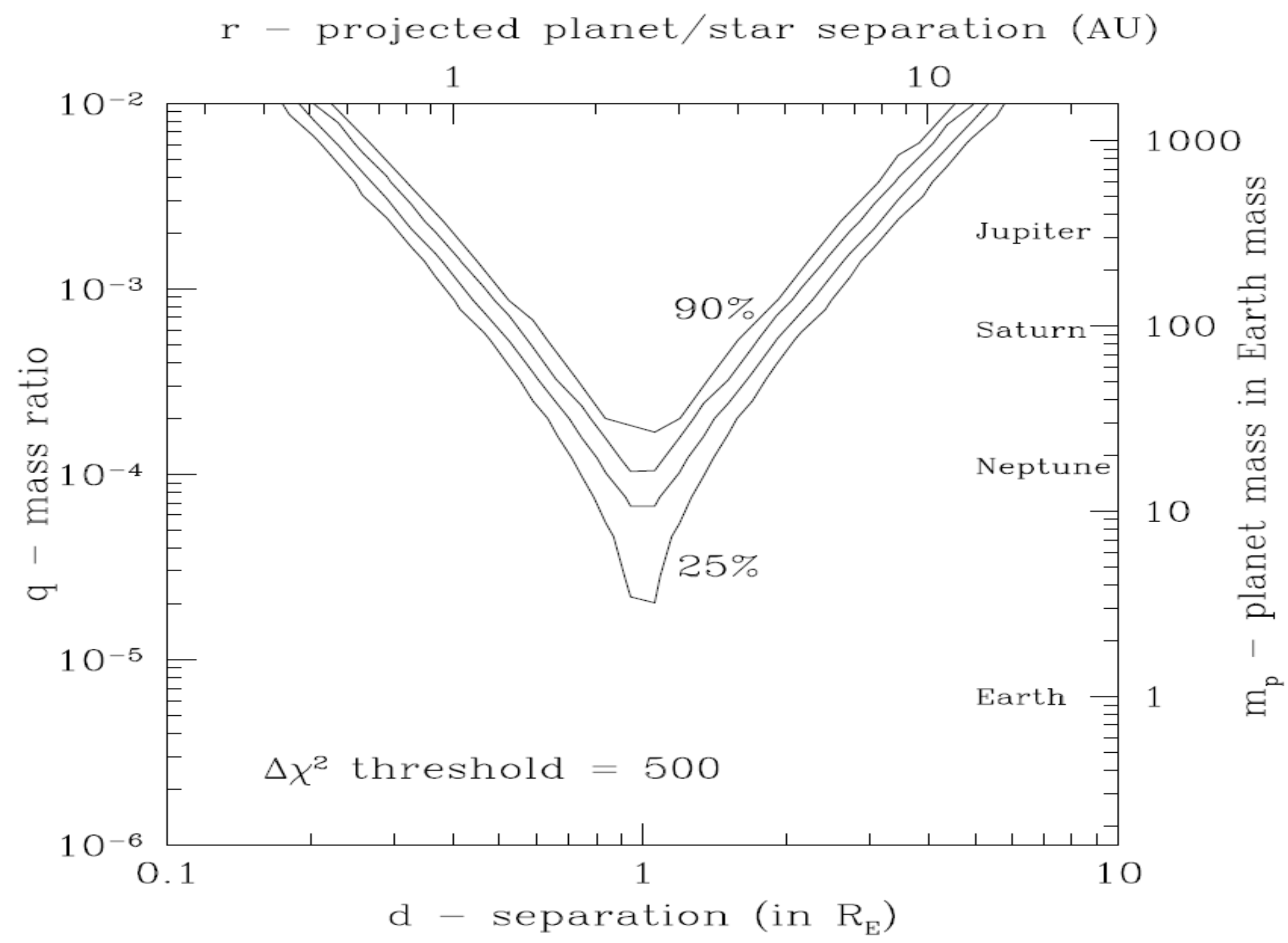
Virginie Batista

Planet Sensitivity

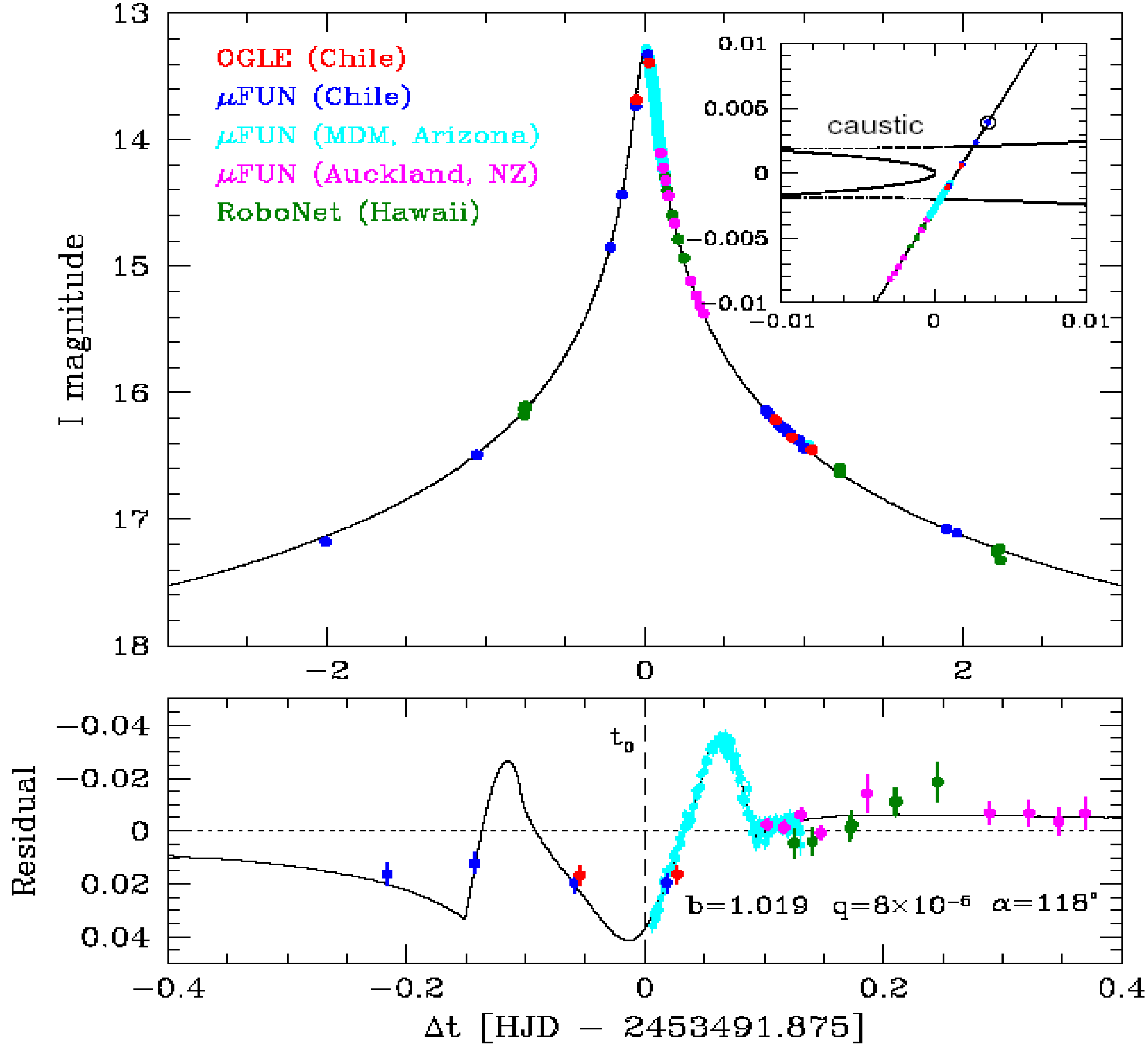
OGLE-2008-BLG-279



Planet Sensitivity
OGLE-2007-BLG-050



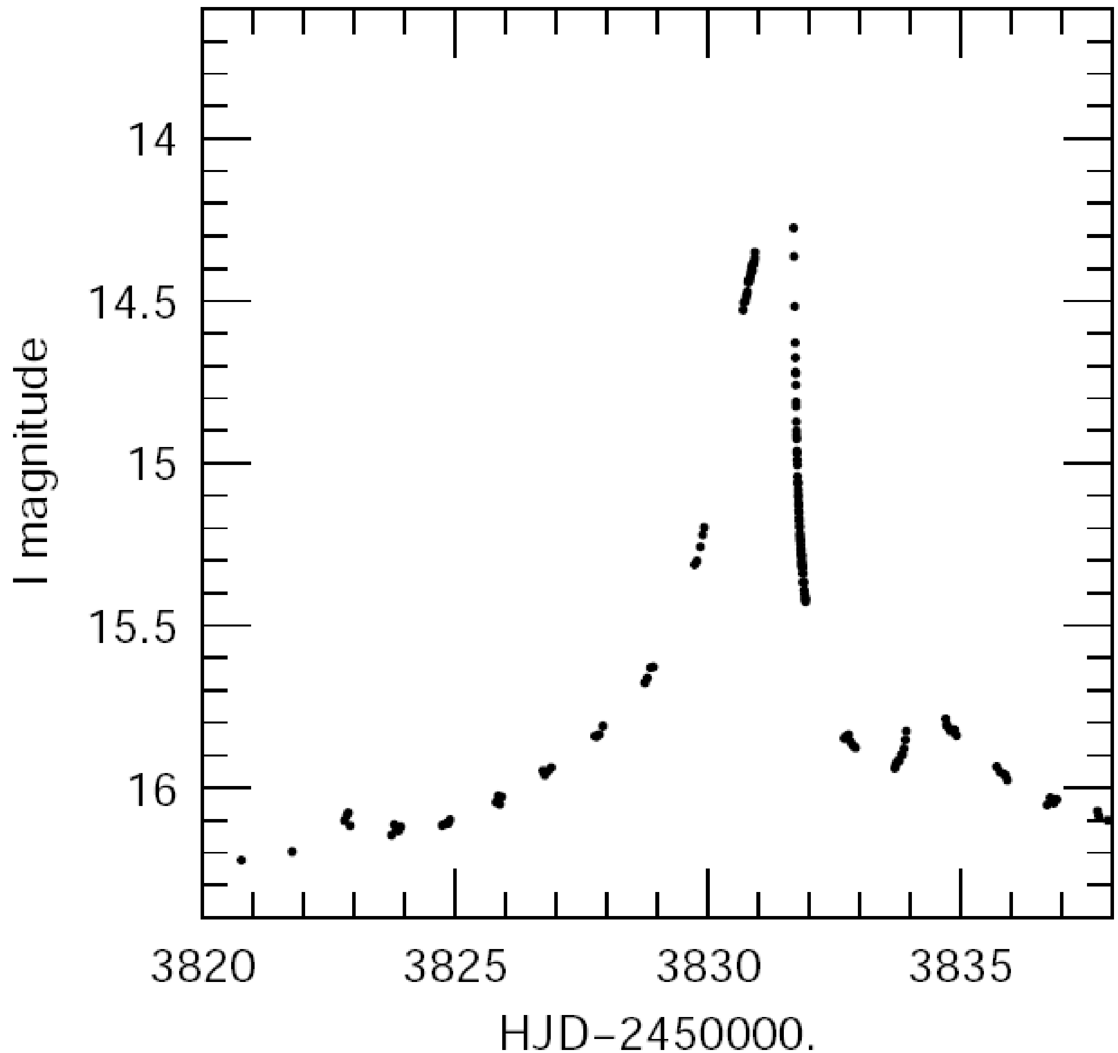
OGLE-2005-BLG-169:
First High-Mag Planet



Deokkeun An

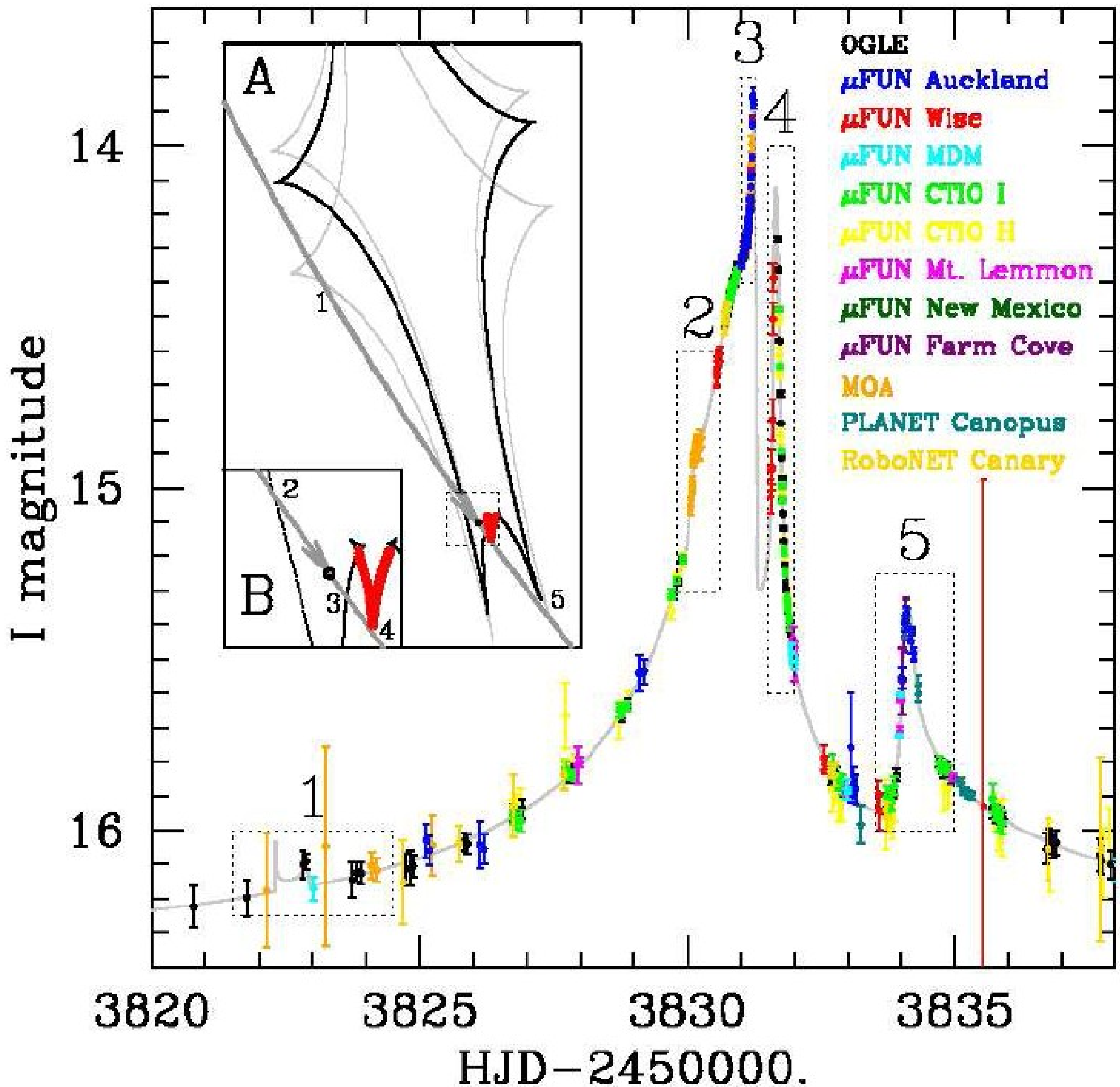
OGLE-2006-BLG-109:

2nd + 3rd High-Mag Planets (OGLE only)



OGLE-2006-BLG-109

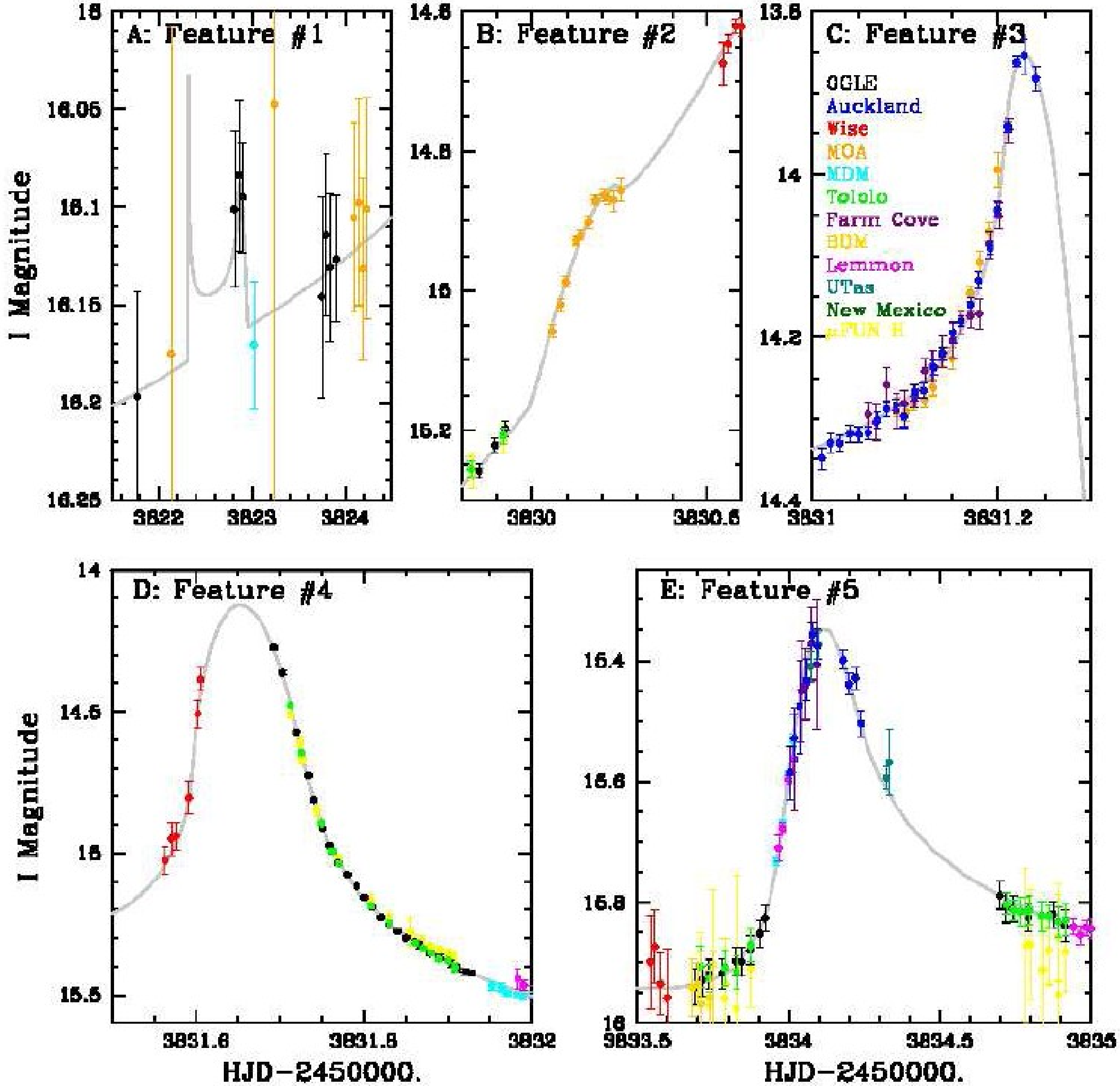
With Followup!



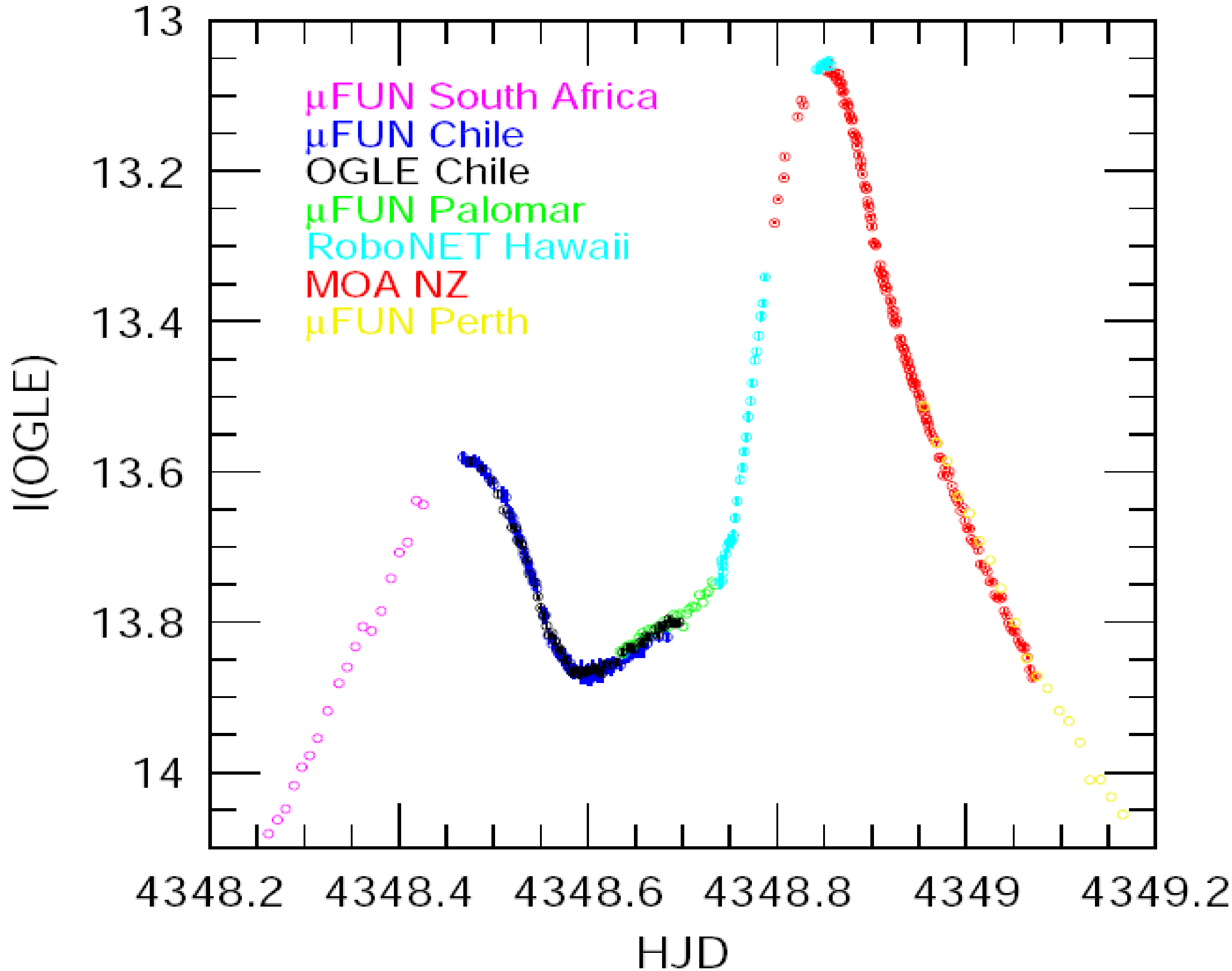
Gaudi et al. 2008, Science, 319, 927

Five Lightcurve Features

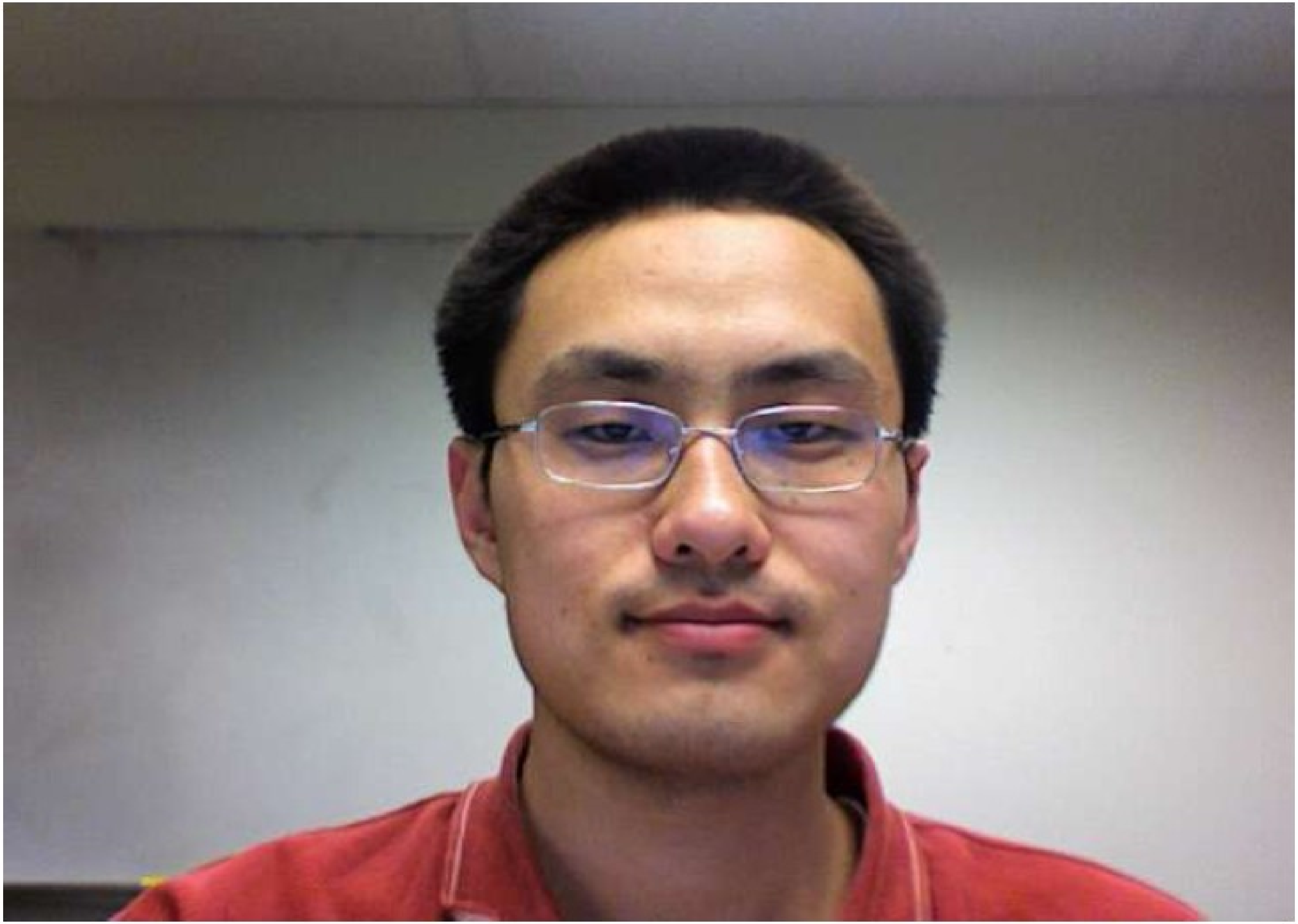
1+2+3+5=Saturn 4=Jupiter



OGLE-2007-BLG-349: Fourth High-Mag Planet (+)

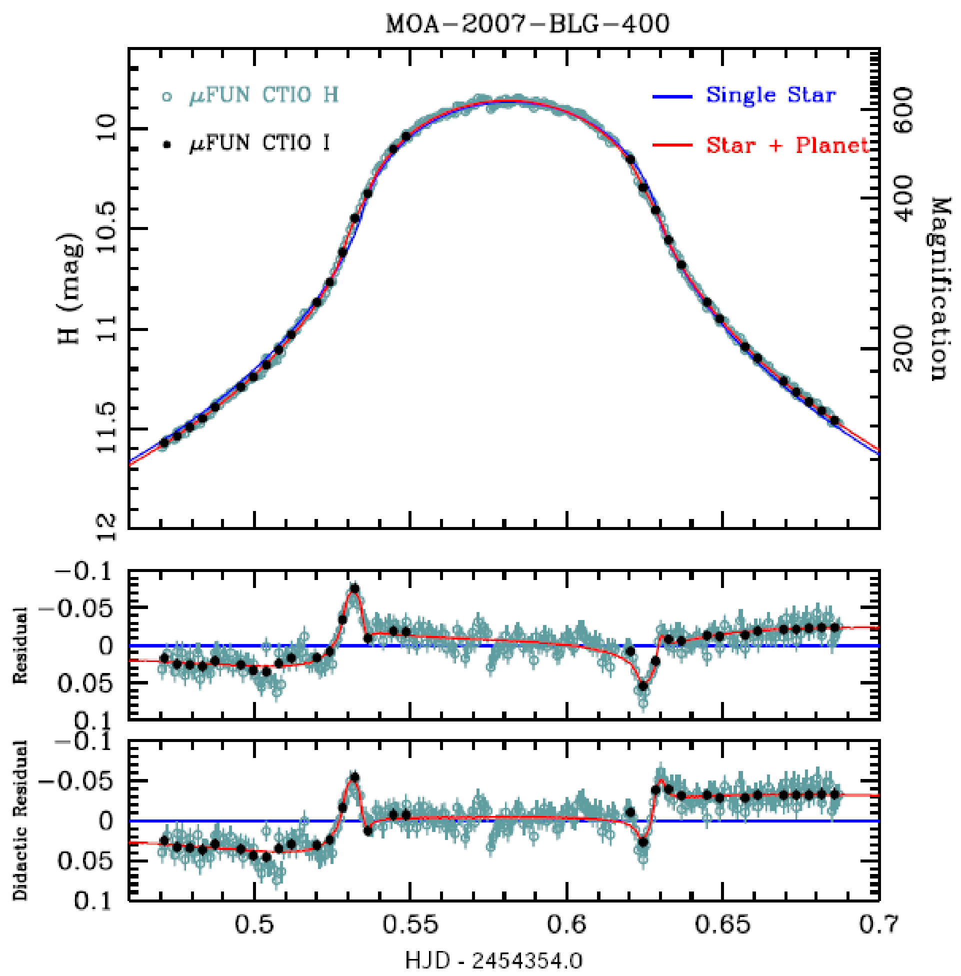


Subo Dong



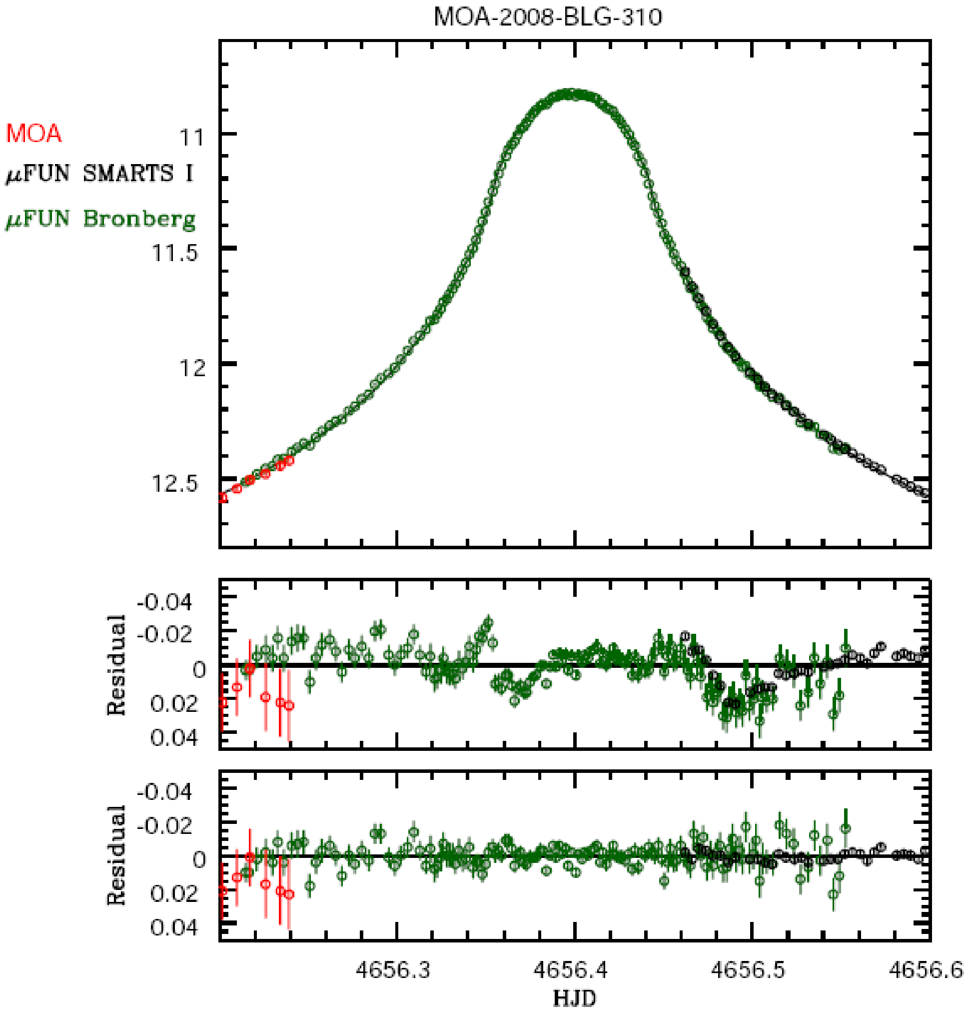
MOA-2007-BLG-400

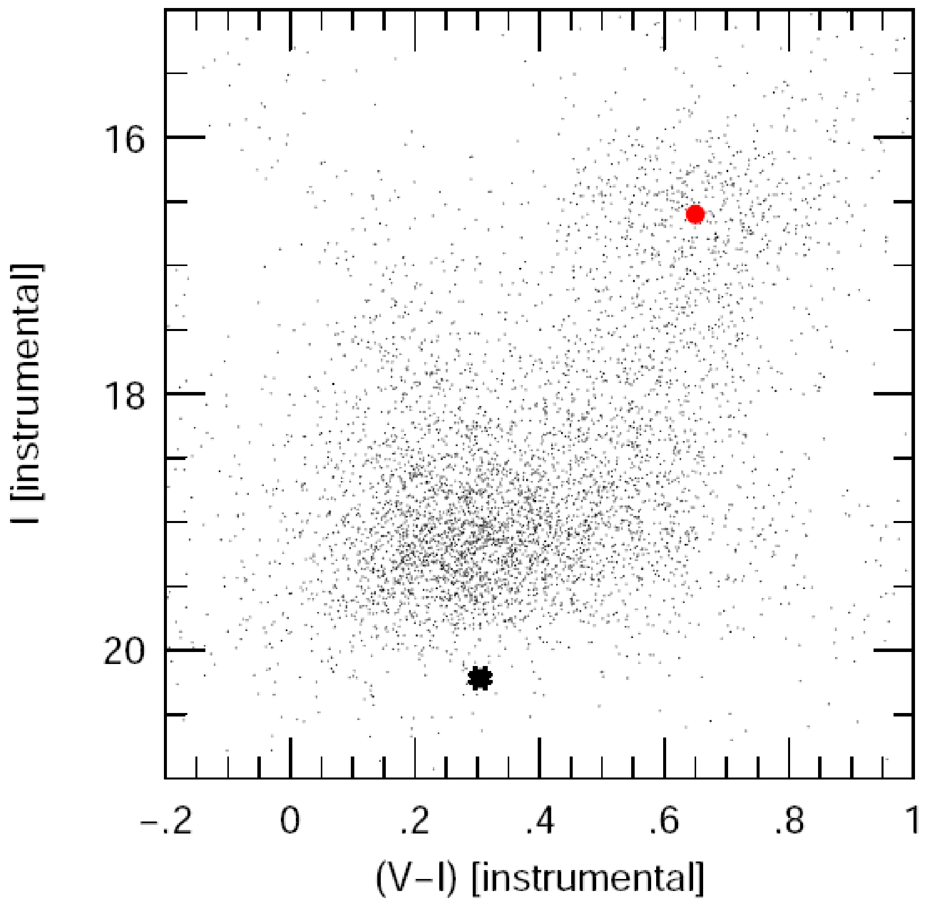
Fifth High-Mag Planet



MOA-2008-BLG-310

Sixth High-Mag Planet

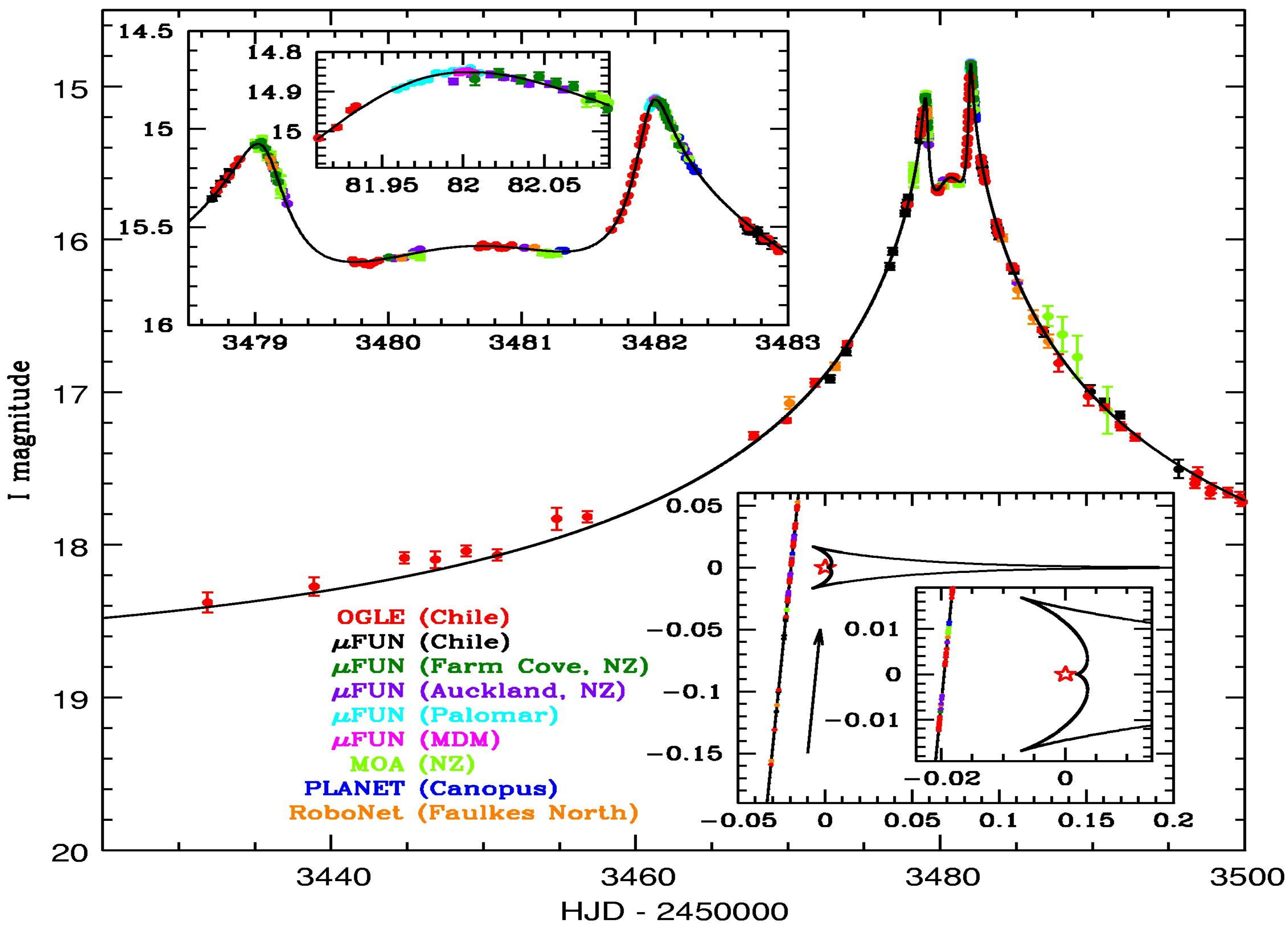




Janczak et al. 2010, ApJ, 711, 731

Julia Janczak

Second Microlensing Planet



Udalski et al. 2005, ApJ, 628, L109

Amateurs + Professionals

Grant, Ian, Jennie, Phil

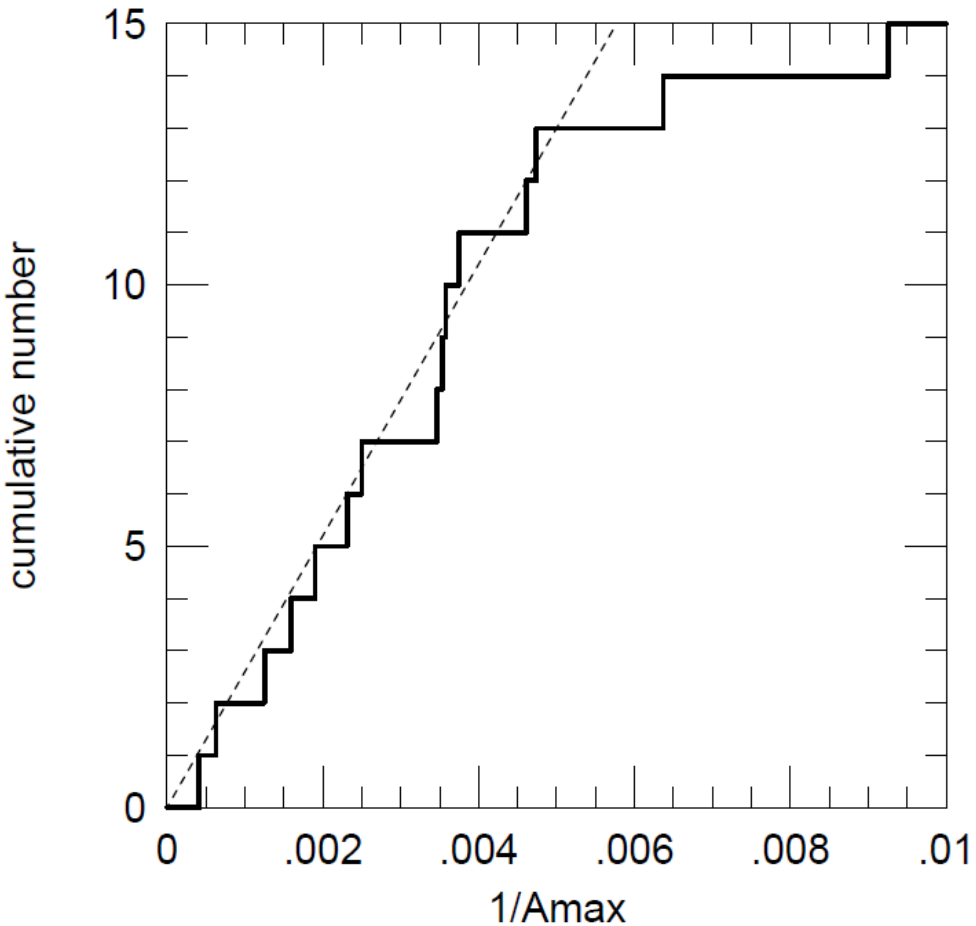
Amateurs + Professionals

"It just shows that you can be a mother, you can work full-time, and you can still go out there and find planets."

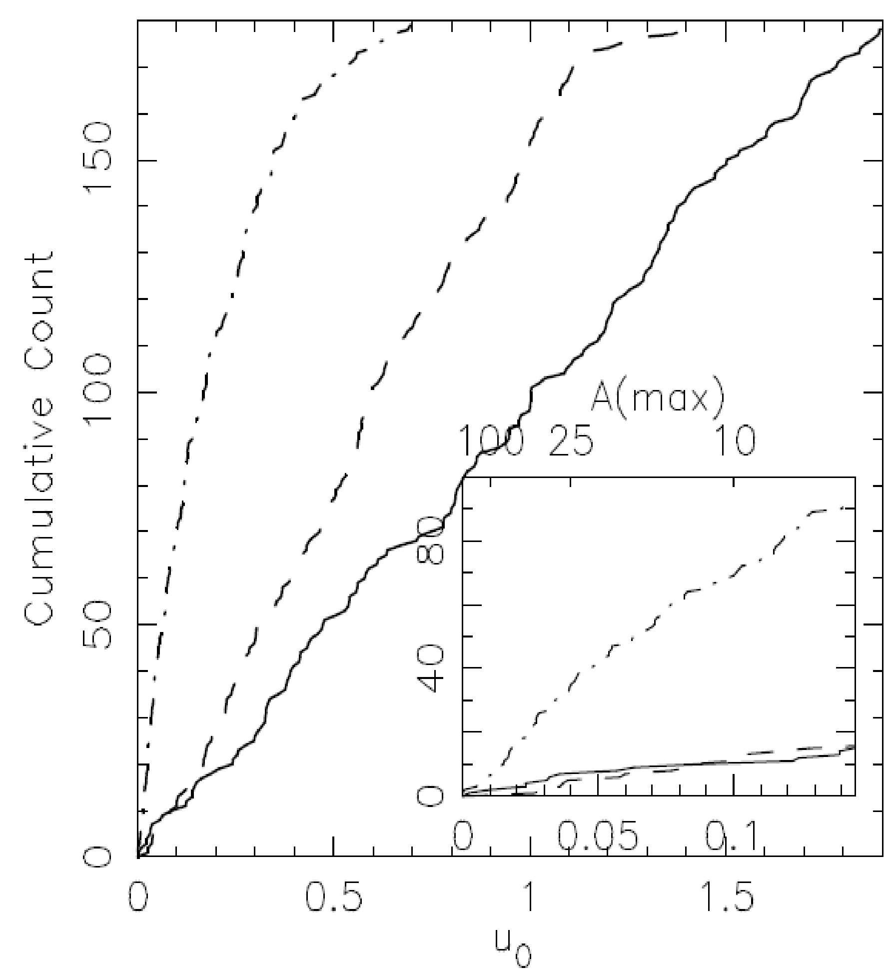
Jennie McCormick
(Amateur Astronomer, Auckland, New Zealand)

Well-covered events: fair sample (Amax>200)

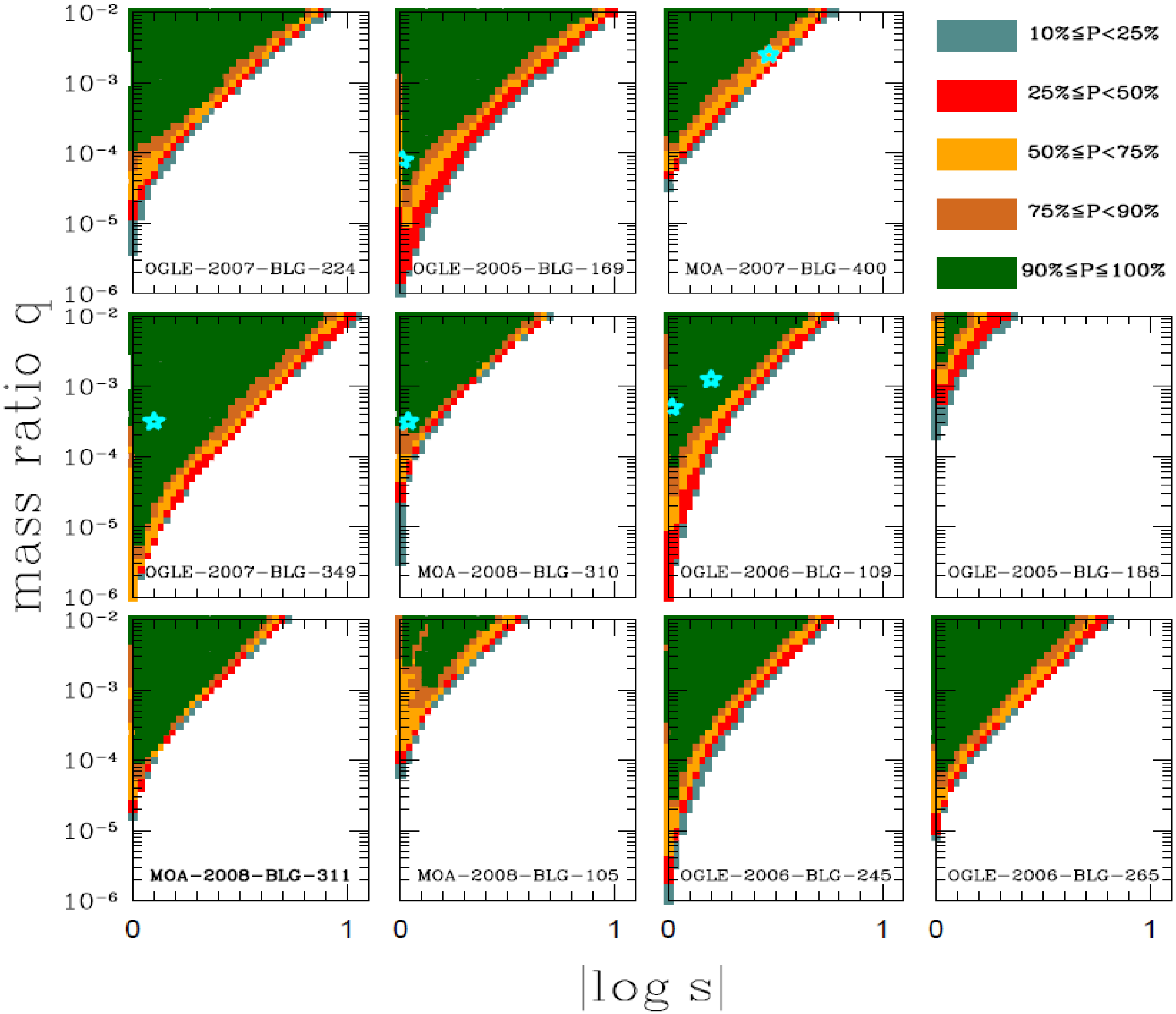
Well-Covered



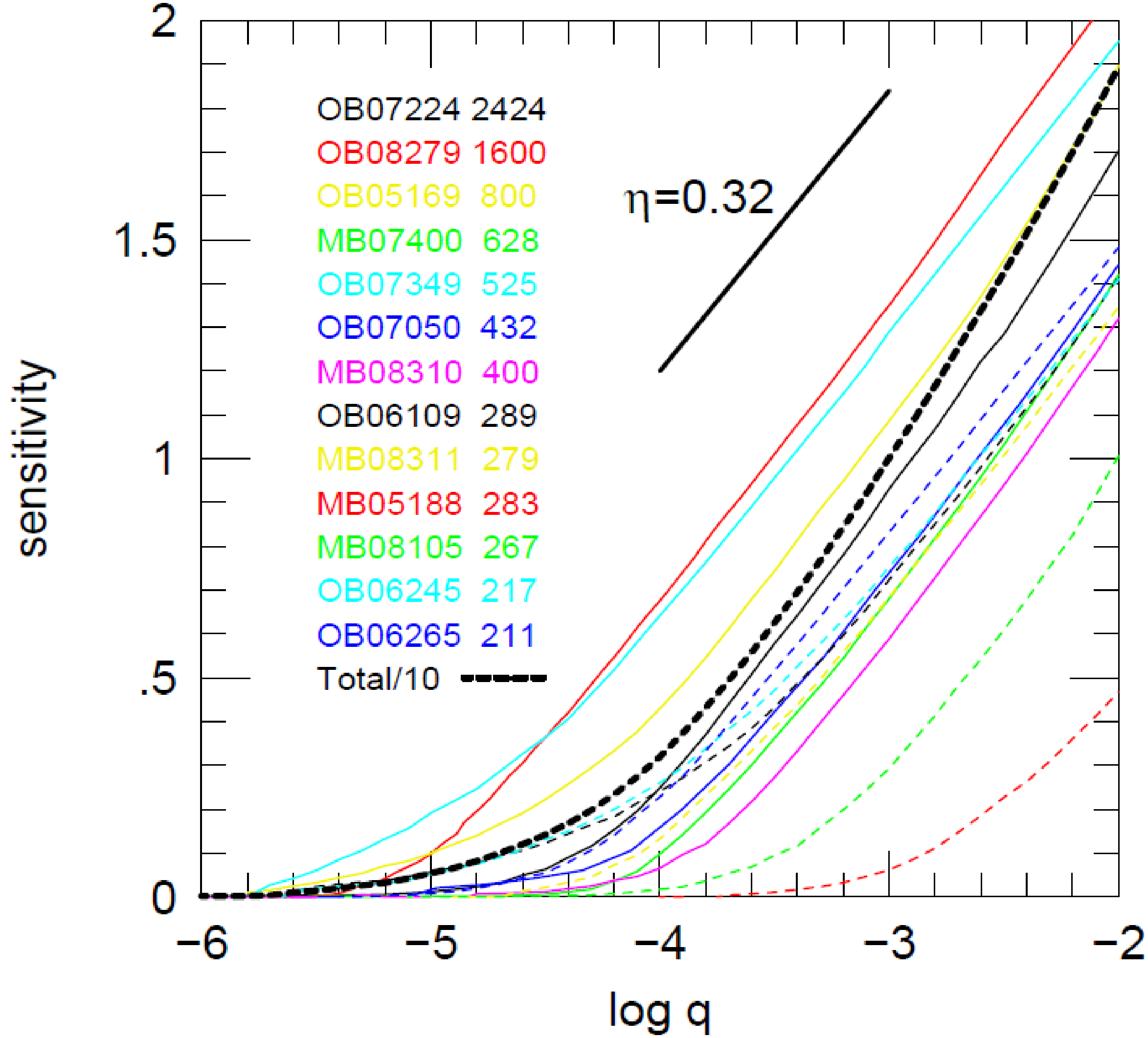
All Events



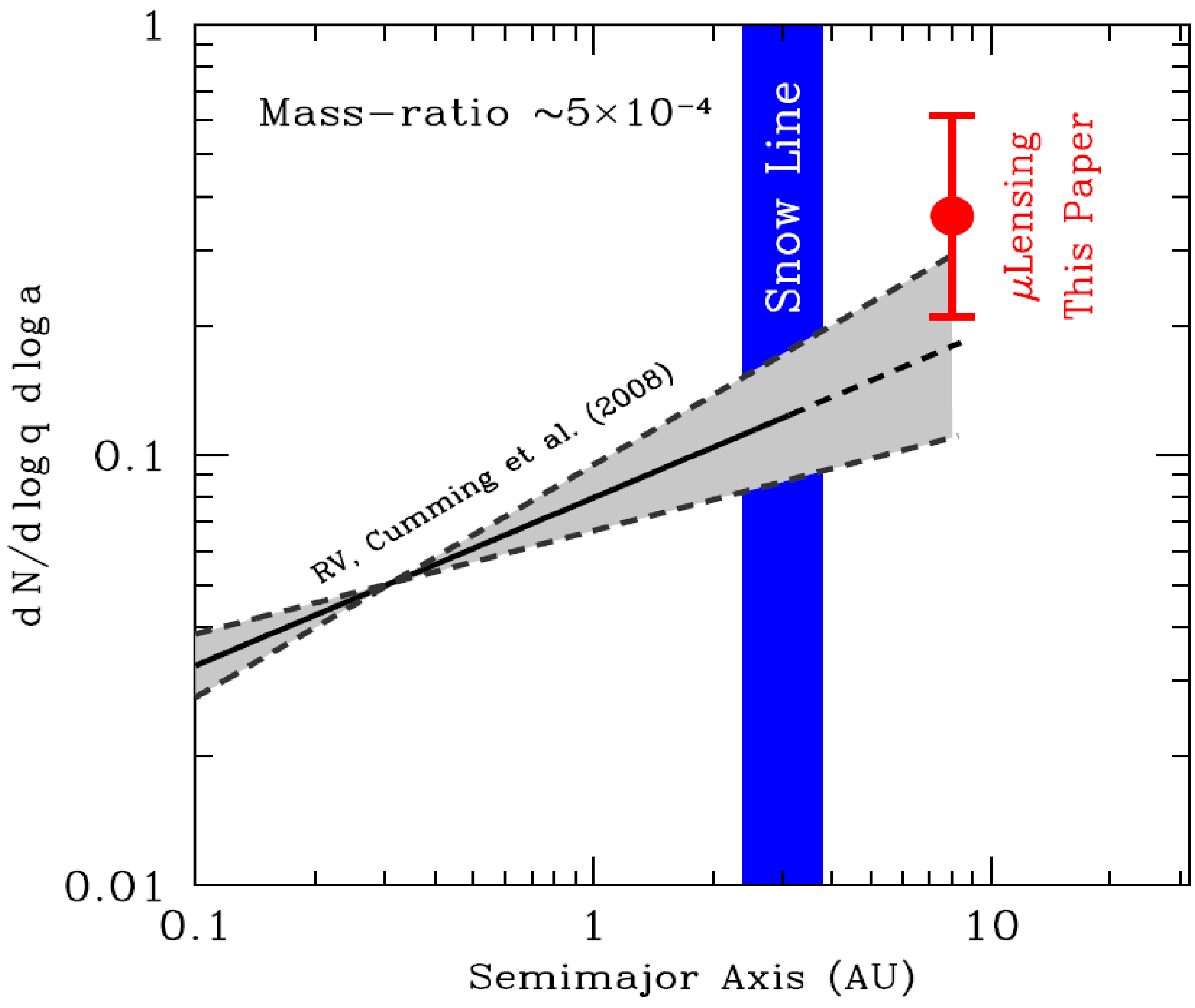
Planet Sensitivity Vs. Detections



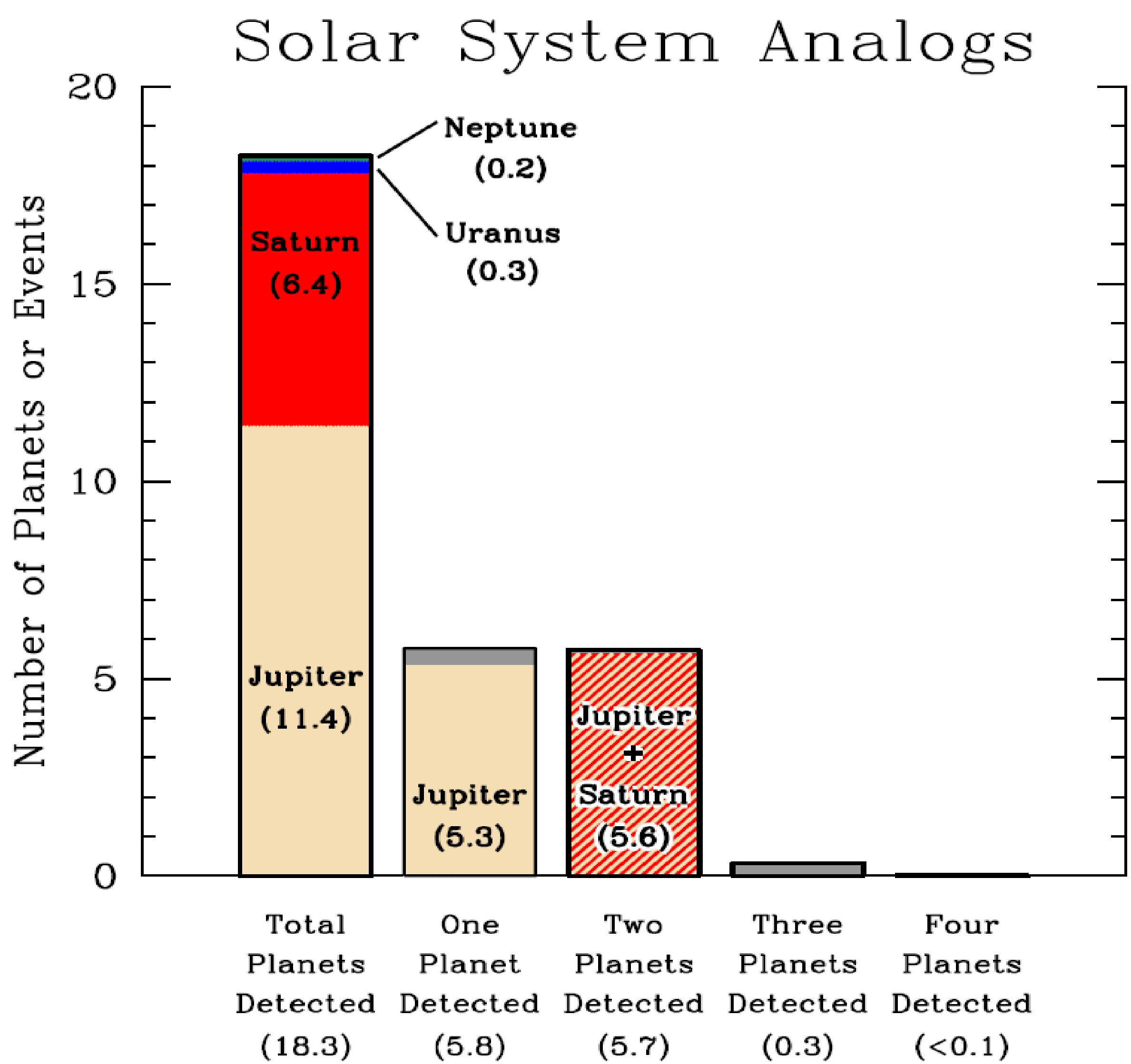
Planet Sensitivity Vs. Mass Ratio



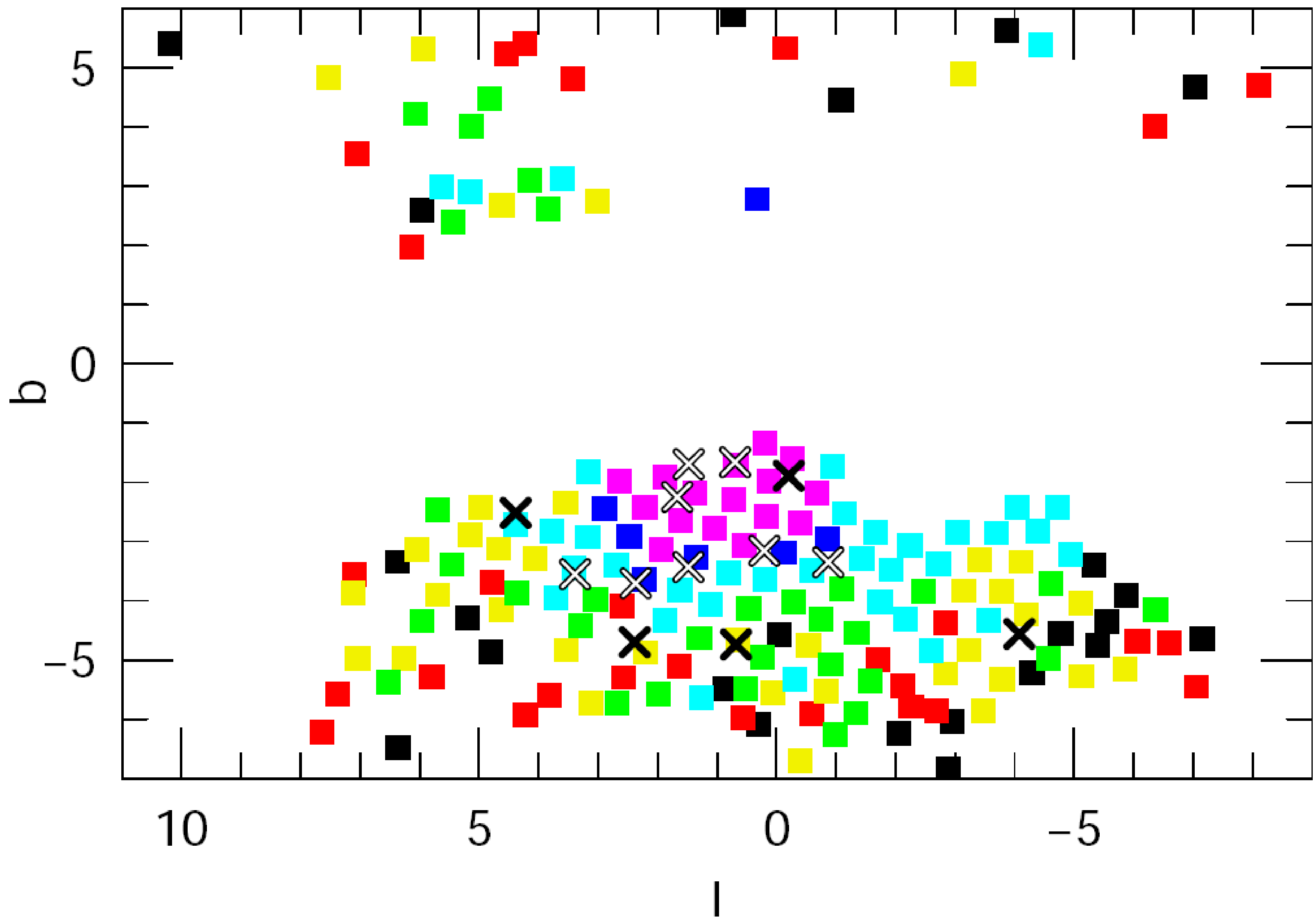
RV & Microlensing
Inside vs Outside Snow Line



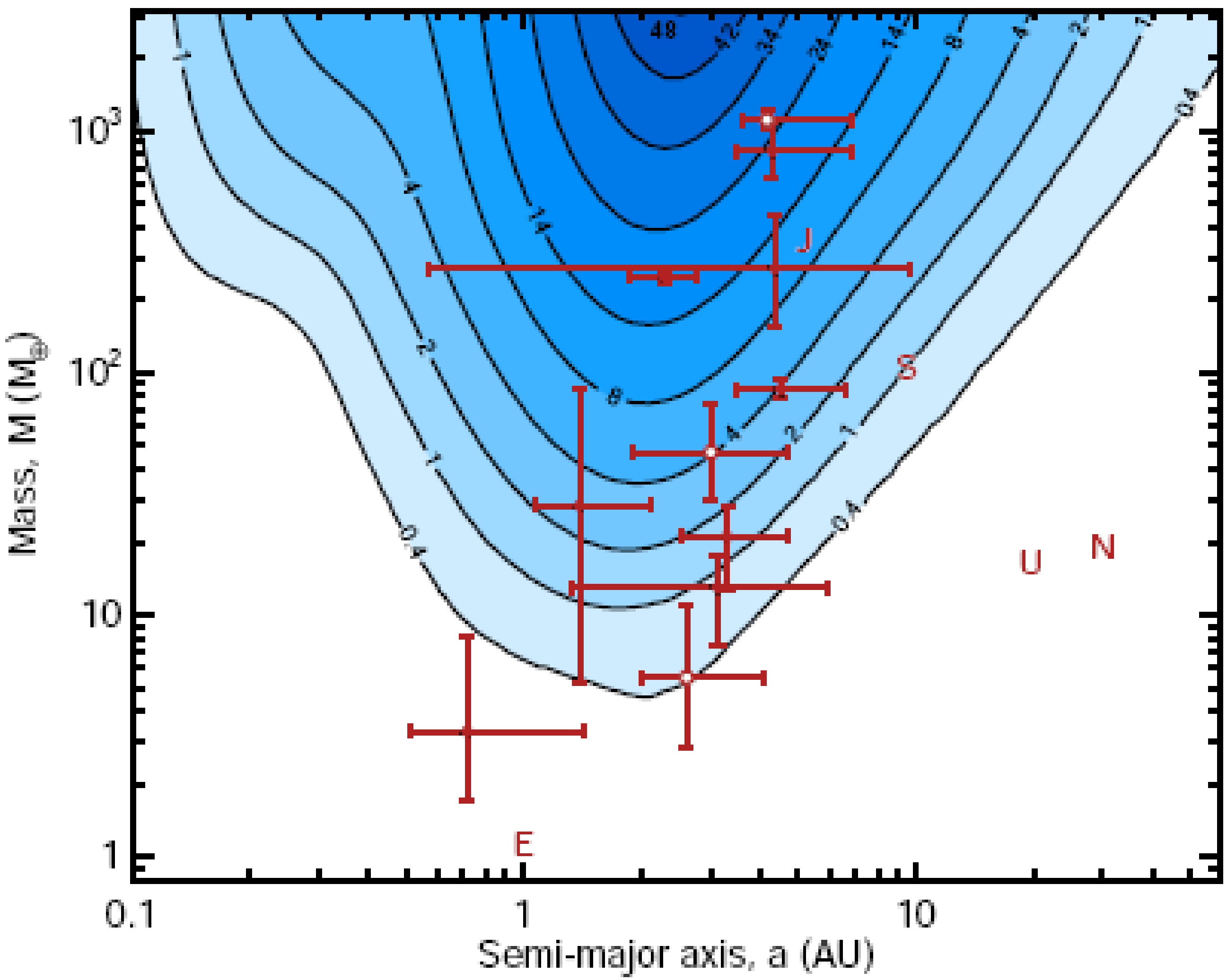
Solar System is Richer than Average ... But Not Dramatically So



Distribution of Planets on Sky



Combined Planet Frequency
Cassan et al (2012)



Combined Planet Frequency
Cassan et al (2012)