Results from Microlensing Searches for Planets.

Scott Gaudi
The Ohio State University

Collaborative Efforts.

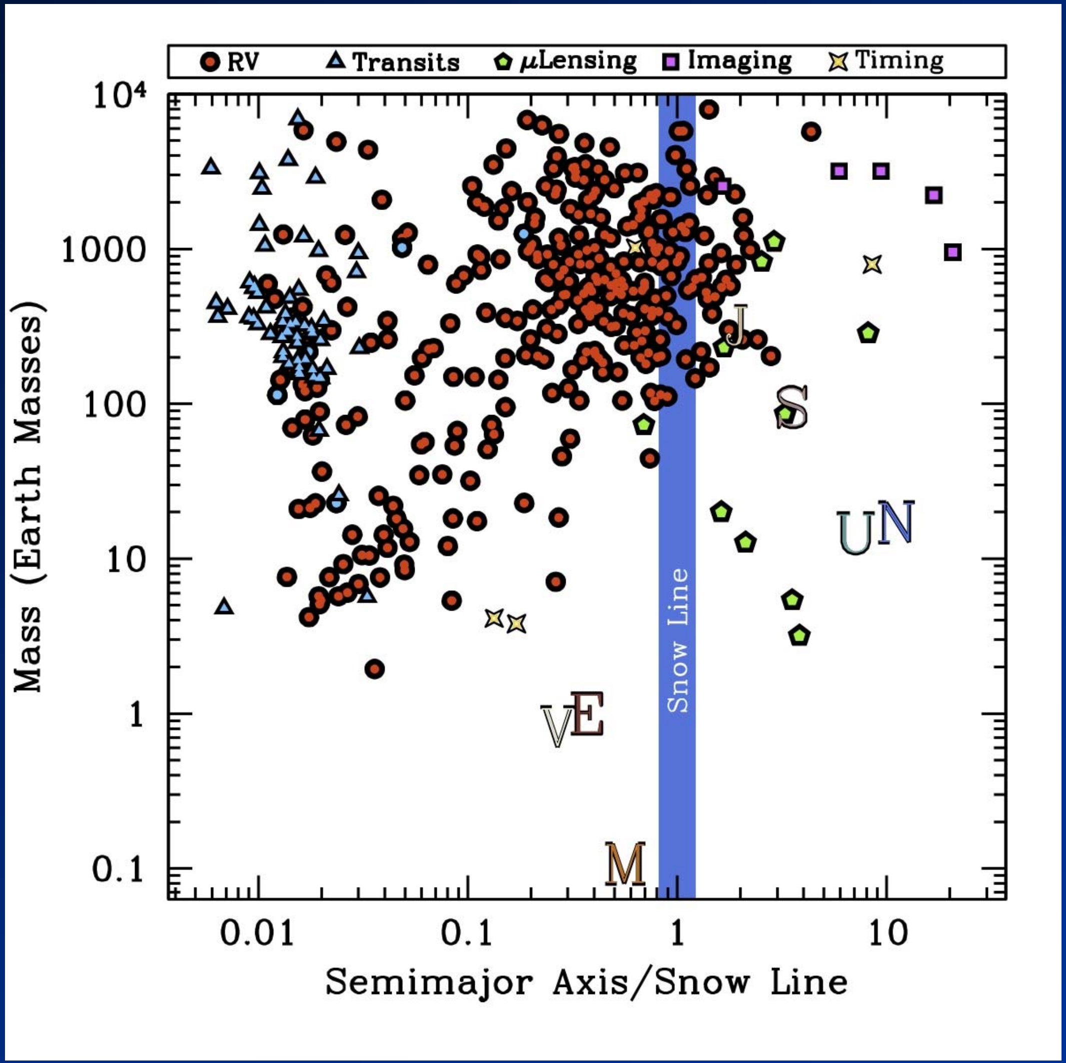
Worldwide Collaborations:

- **μFUN**
- **MiNDSTEP**
- **MOA**
- **OGLE**
- **PLANET**
- **RoboNet**

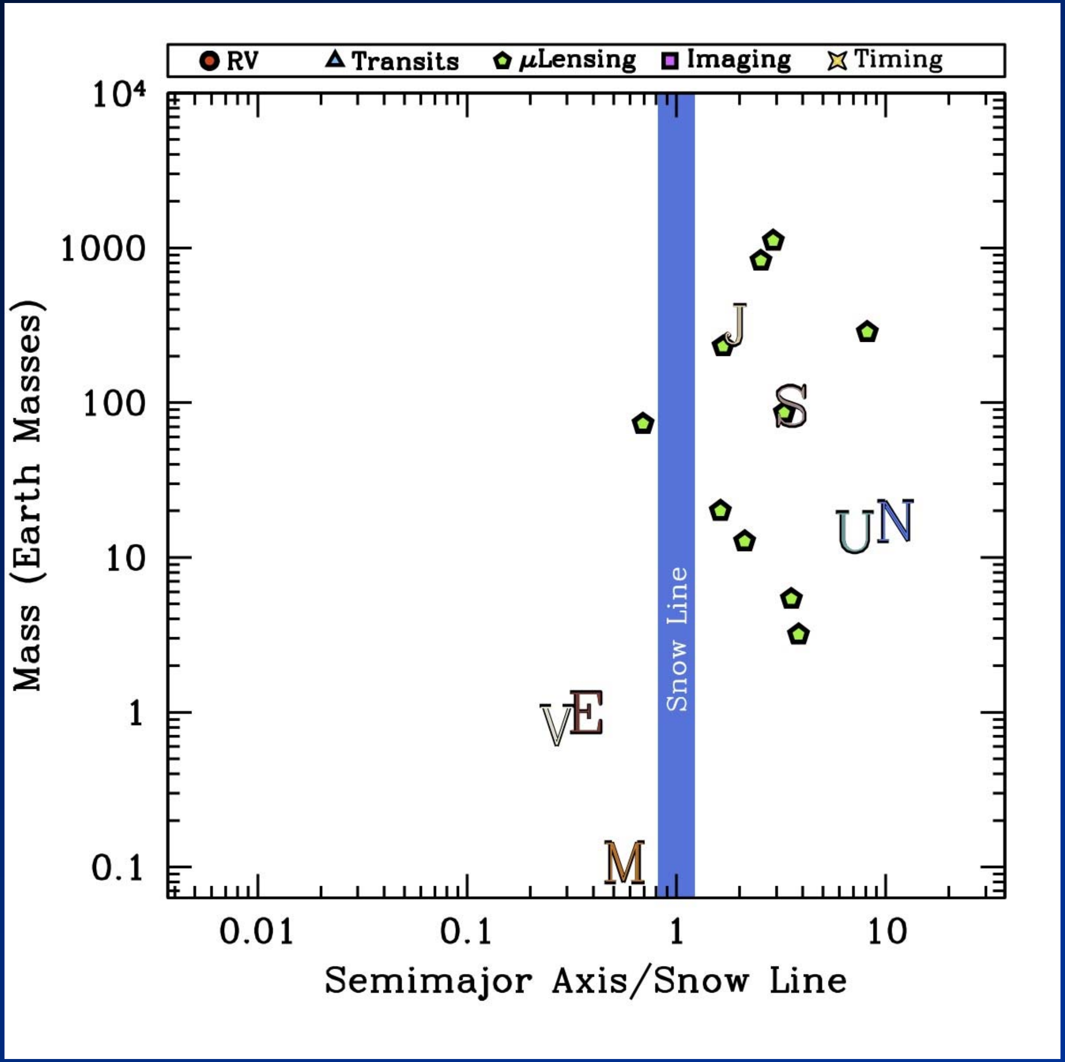
"Microlensing is a cult."

-Dave Koerner

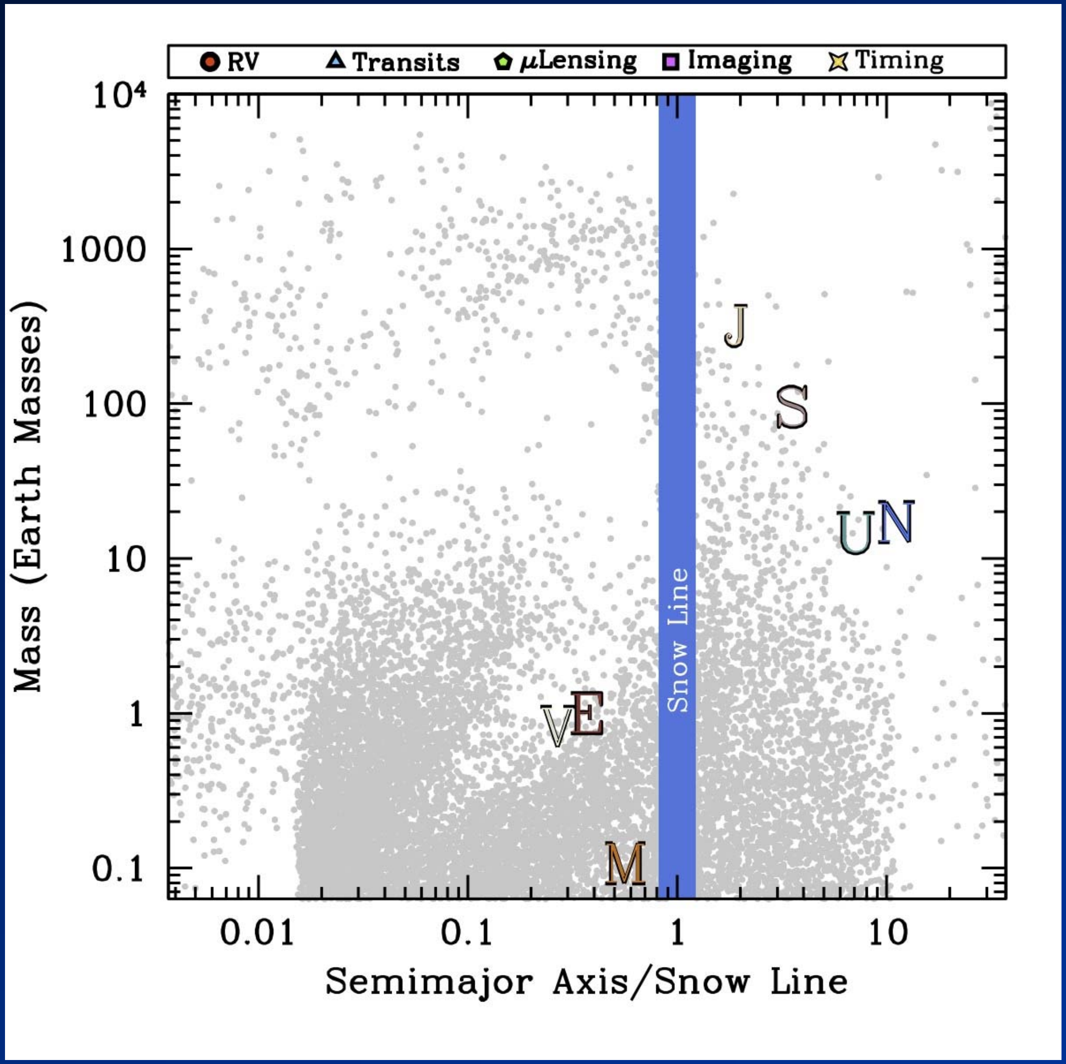
To the Snow Line… and Beyond!



To the Snow Line… and Beyond!

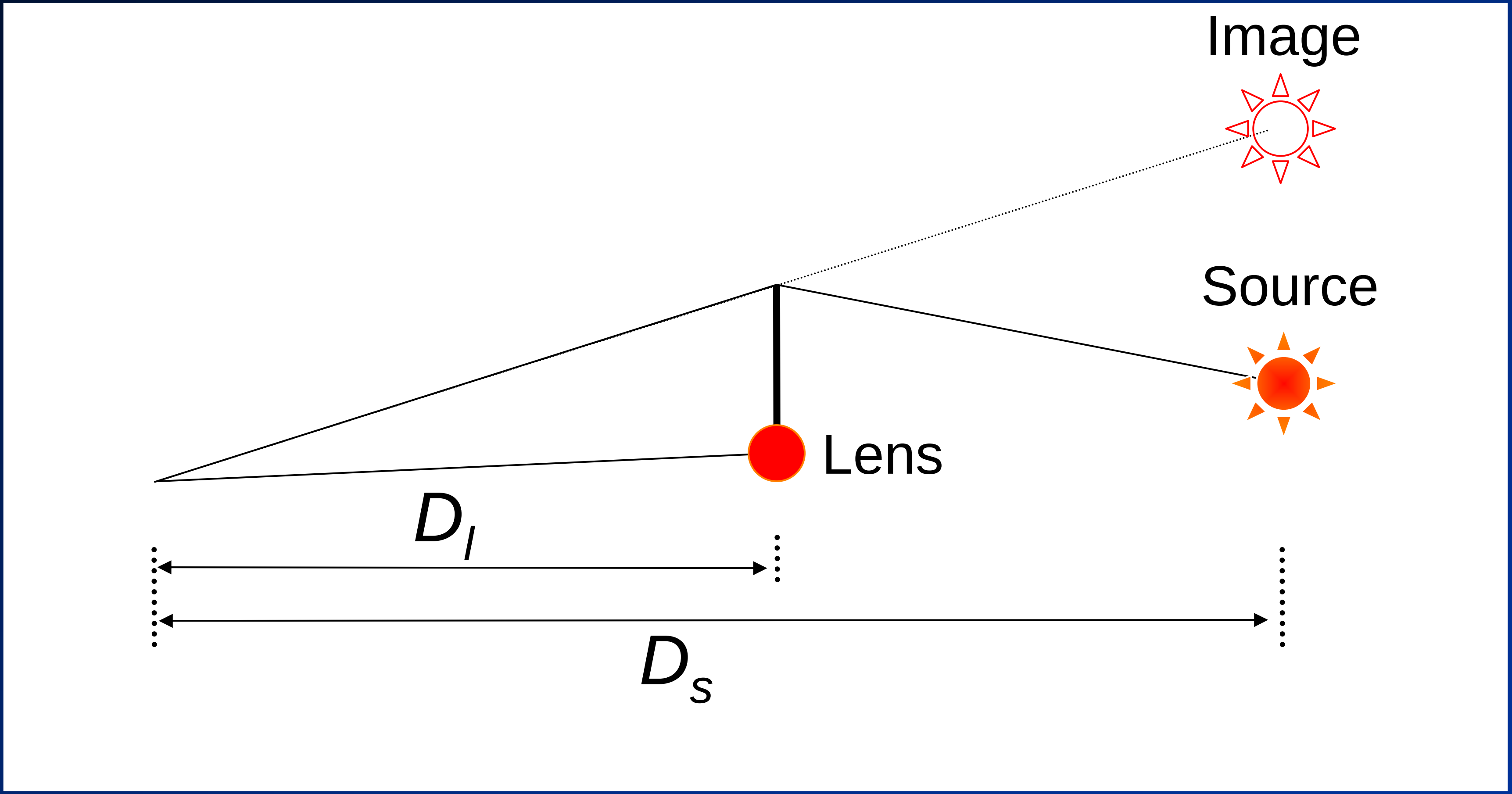


To the Snow Line… and Beyond!



(Ida & Lin)

Gravitational Lensing.



Rings and Images.

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_{OL}D_{OS}}} \sim 700\mu\text{as}\left(\frac{M}{0.5M_\odot}\right)^{1/2}$$

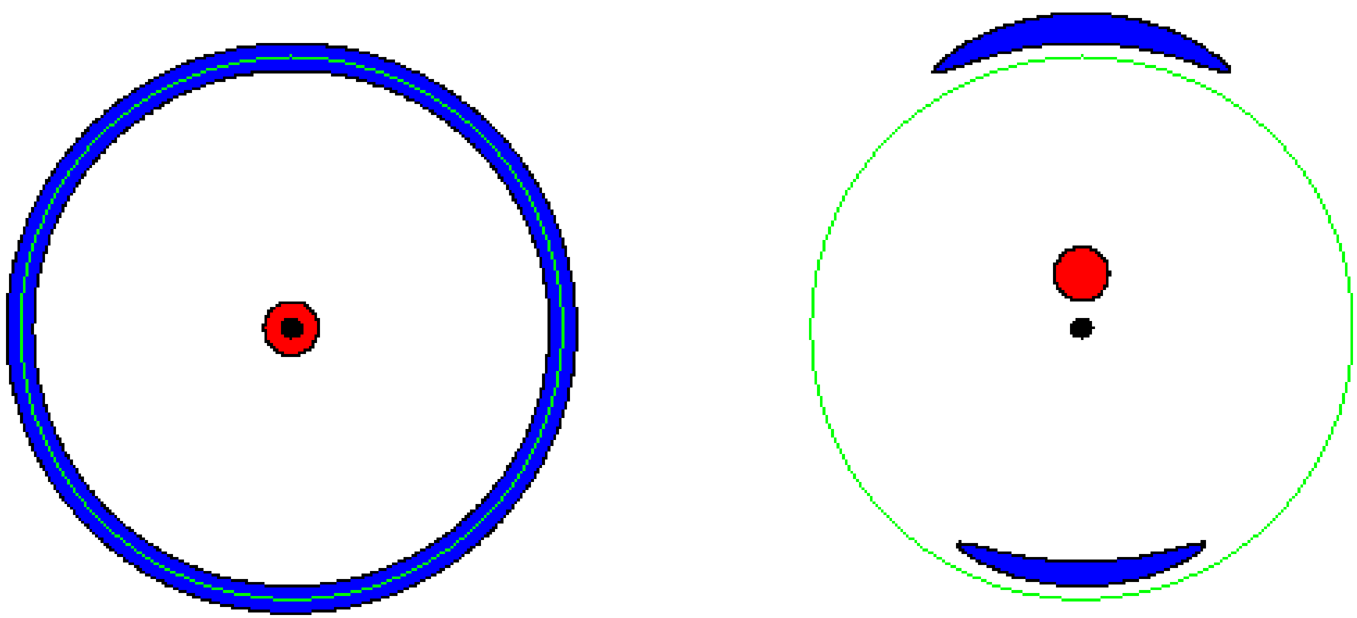
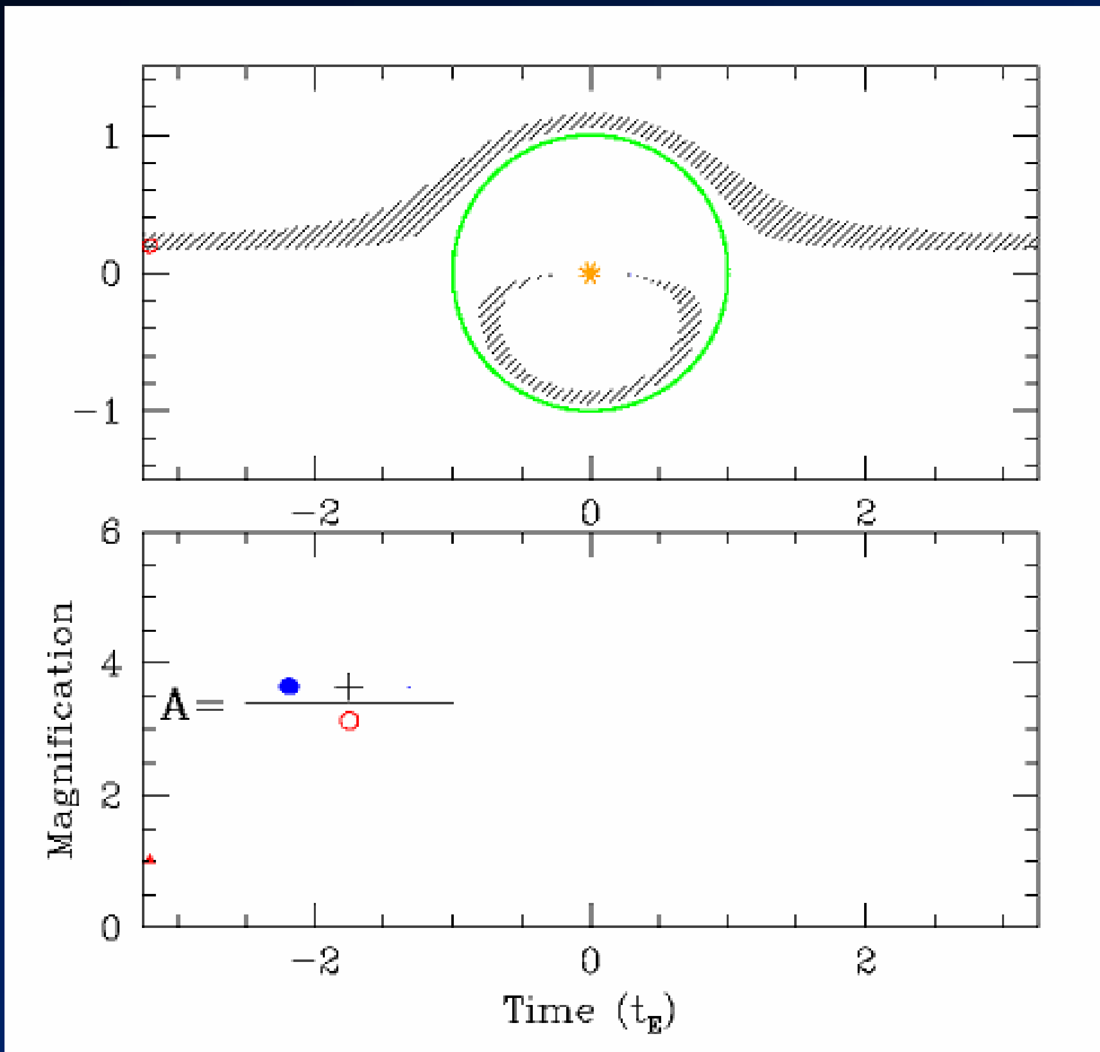
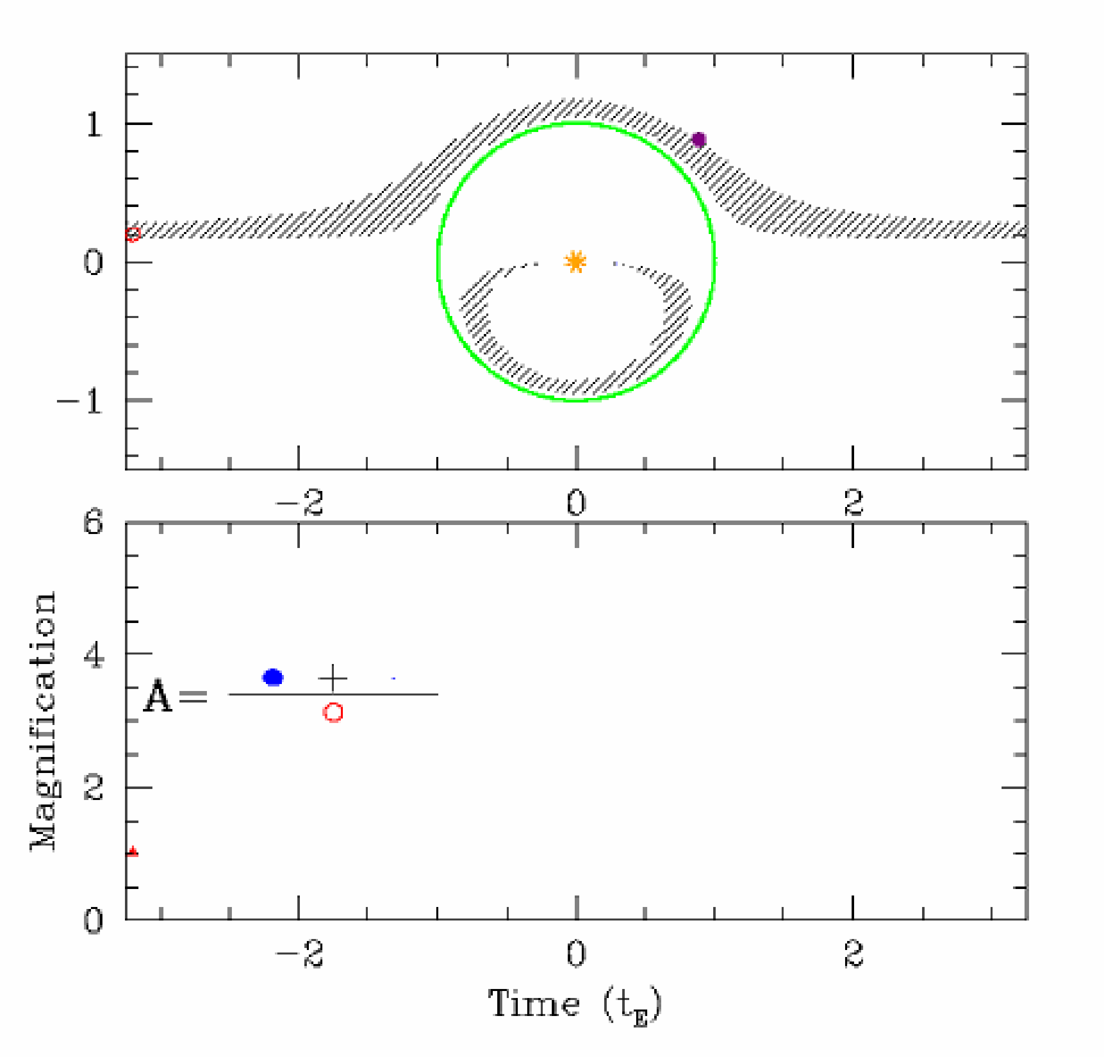


Image Separation $\approx 2\theta_E$ Magnification $= \dfrac{\text{Area of Image}}{\text{Area of Source}}$



$$t_E = \frac{\theta_E}{\mu} \approx 25 \text{ days} \left(\frac{M}{0.5 M_\odot} \right)^{1/2}$$



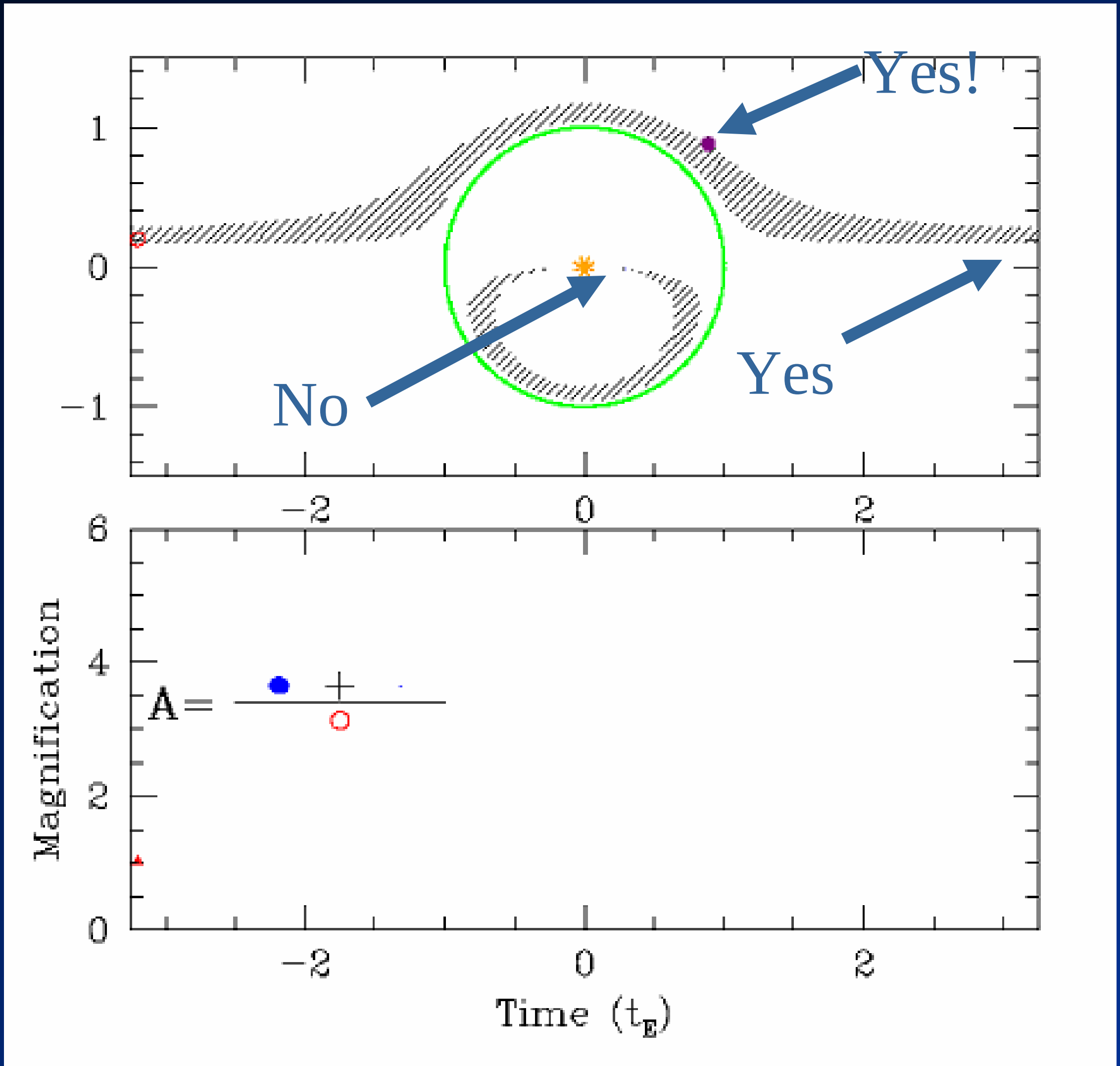
$$t_p = q^{1/2} t_E \approx 1 \text{ day} \left(\frac{M_p}{M_J}\right)^{1/2}$$

High-Magnification → High Efficiency

Maximized when

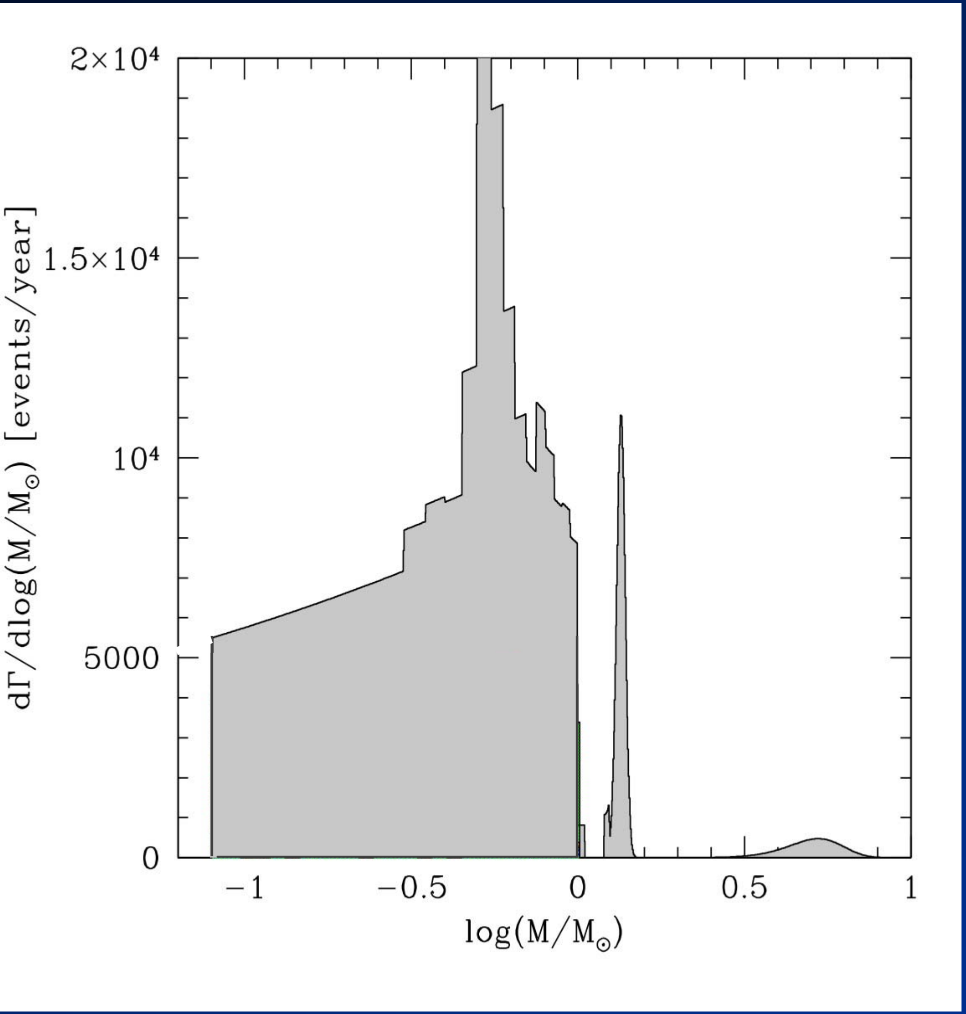
$$a \sim r_E = \theta_E D_l \sim 2.5\text{AU} \left(\frac{M}{0.5 M_\odot}\right)^{1/2}$$

Microlensing is directly sensitive to planet mass.



- Works by perturbing images
- Does not require light from the lens or planet.
- Sensitive to planets throughout the Galaxy (distances of 1-8 kpc)
- Sensitive to wide or **free-floating** planets
- Not sensitive to very close planets

Microlensing Host Stars?

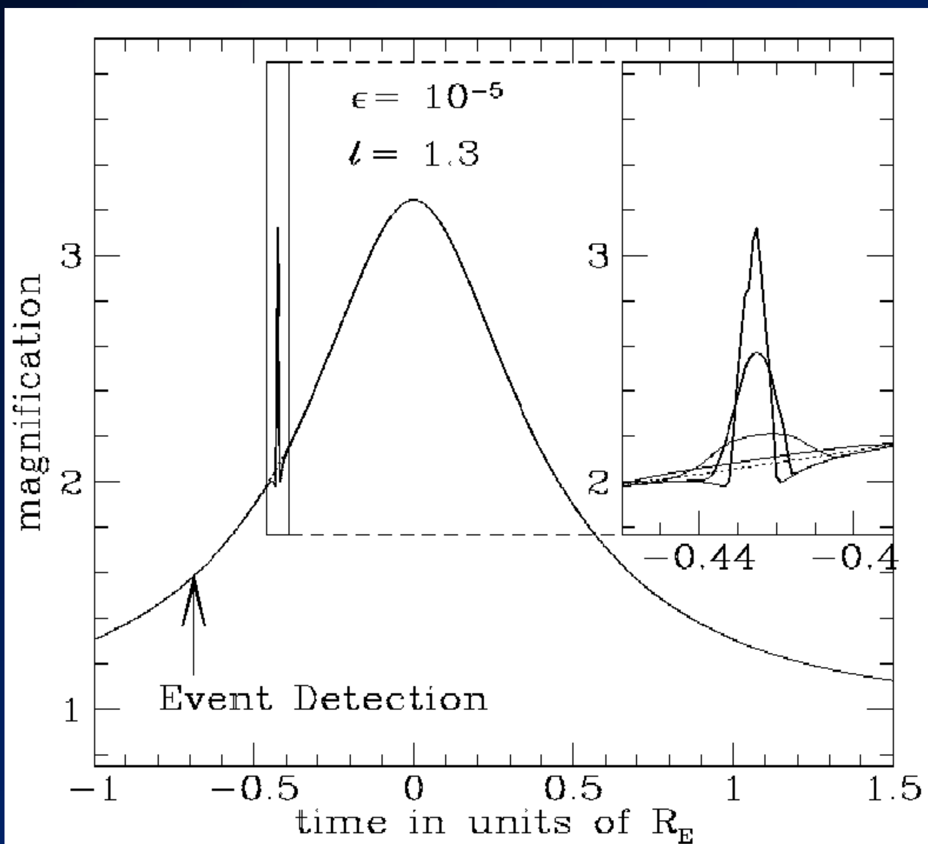


Sensitive to planets around:

- Main-sequence stars with $M < M_\odot$
- Brown dwarfs
- Remnants

Very Low-mass Planets

Large signals for low-mass planets.



(Bennett & Rhie 1996)

- Signals get rarer and briefer.

$$t_p = q^{1/2} t_E \approx 2\ \mathrm{hrs} \left(\frac{M_p}{M_{\circ\acute{U}}} \right)^{1/2}$$

- Probability ~ few %
- Mars-mass planets detectable **(!)**

Drink the Kool-Aid…

- Planets beyond the snow line.
  - Most sensitive at ~few $\times$ a_{snow}
- ***Very*** low-mass planets.
  - >10% Mars.
- Long-period and free-floating planets.
  - 0.5 AU - ∞
- Wide range of host masses.
  - BD, $M<M_{\odot}$, remnants
  - Typically 0.5 $M_{\odot}$
- Planets throughout the Galaxy.
  - 1-8 kpc

"I don't understand. You are looking for planets you can't see around stars you can't see."

-Debra Fischer
(c. 2000)

We lied to you.

- **We told you that we won't learn anything about the host stars.**
- ***This is not true*.**

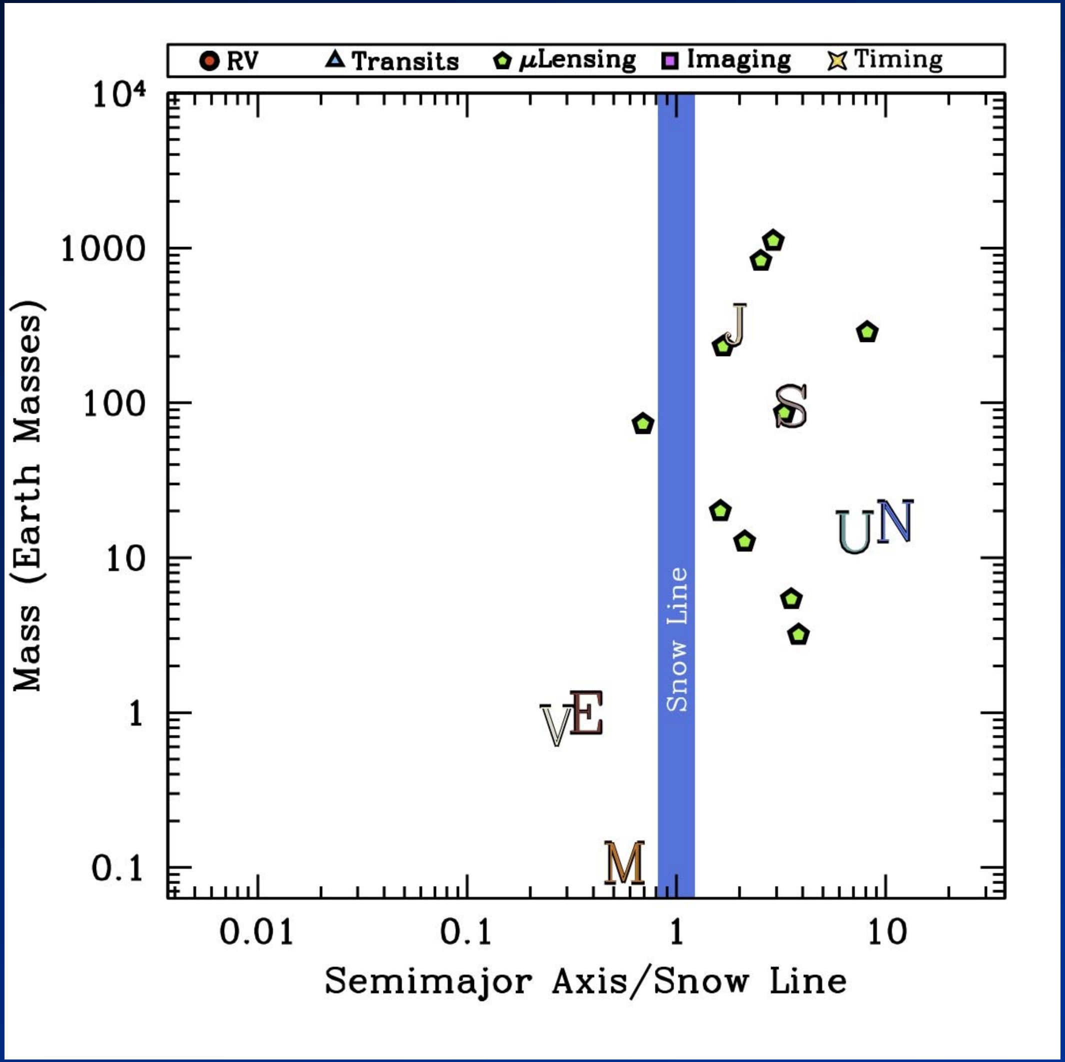
— Often can measure host star and planet masses to ~10-20%.

— Sufficiently bright to measure flux, color, and in some cases get spectra.

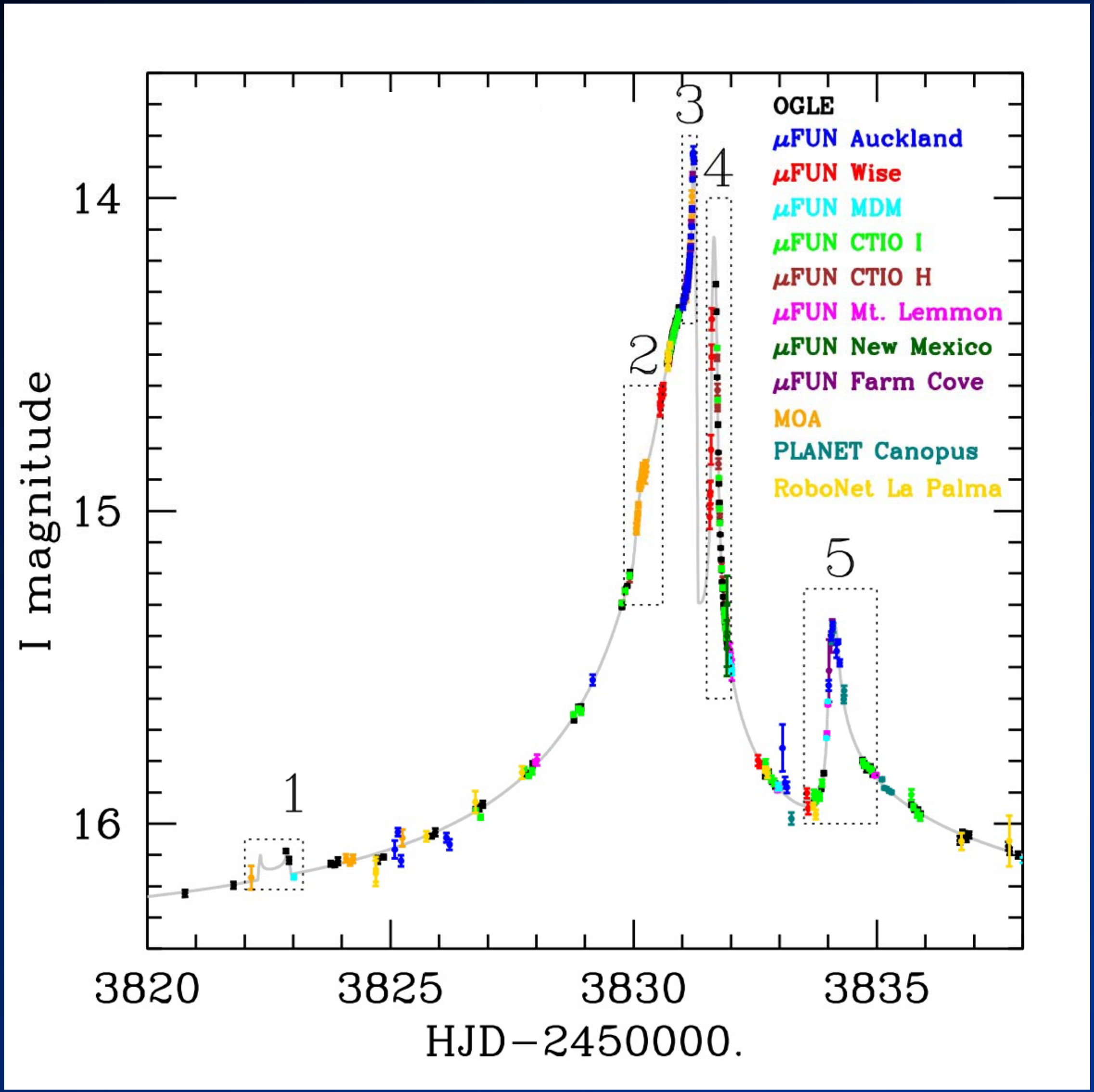
— In some cases can learn something about the orbit.

— Discoveries can be compared to nearby detections.

10 Detections.



A Multiple-Planet System.



- Single planet models fail.
- Two planets models work well.
- First multiple-planet system detected by microlensing.

(Gaudi et al 2008; Bennett et al, 2010)

Physical Properties.

Host:

Mass = $0.51 \pm 0.05\ M_{\odot}$

Luminosity ~ 5% $L_{\odot}$

Distance = 1510 ± 120 pc

Planet b:

Mass = $0.73 \pm 0.06\ M_{Jup}$

Semimajor Axis = 2.3 ± 0.5 AU

Planet c:

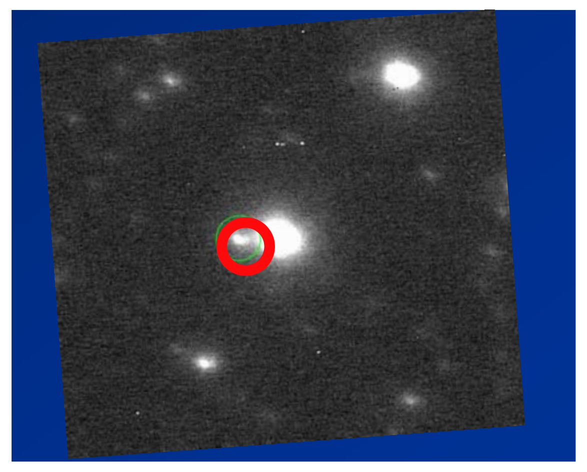
Mass = $0.27 \pm 0.02\ M_{Jup} = 0.90\ M_{Sat}$

Semimajor Axis = 4.6 ± 1.5 AU

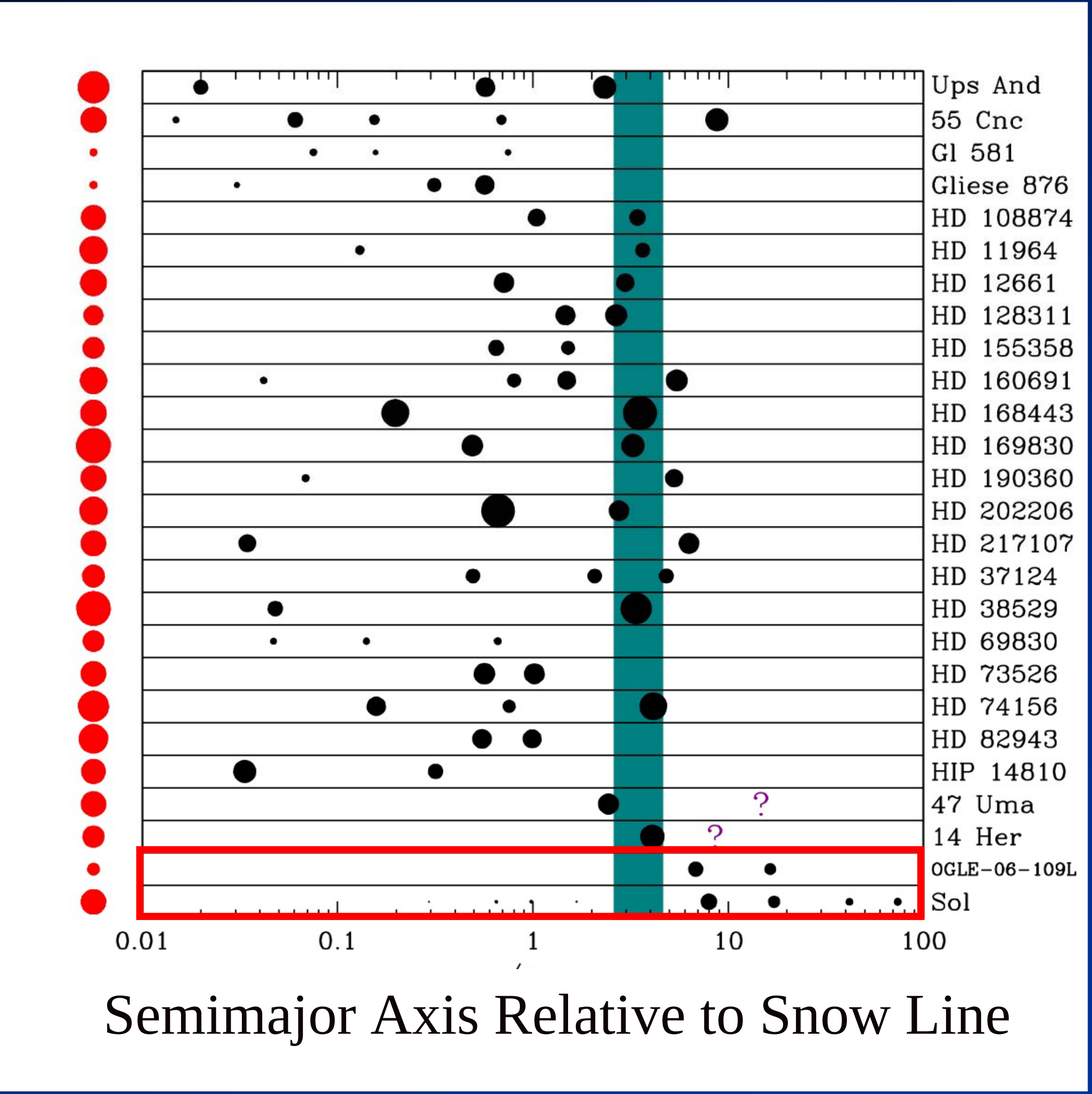
Eccentricity = 0.15+0.17-0.10

Inclination = 64+4-7 degrees

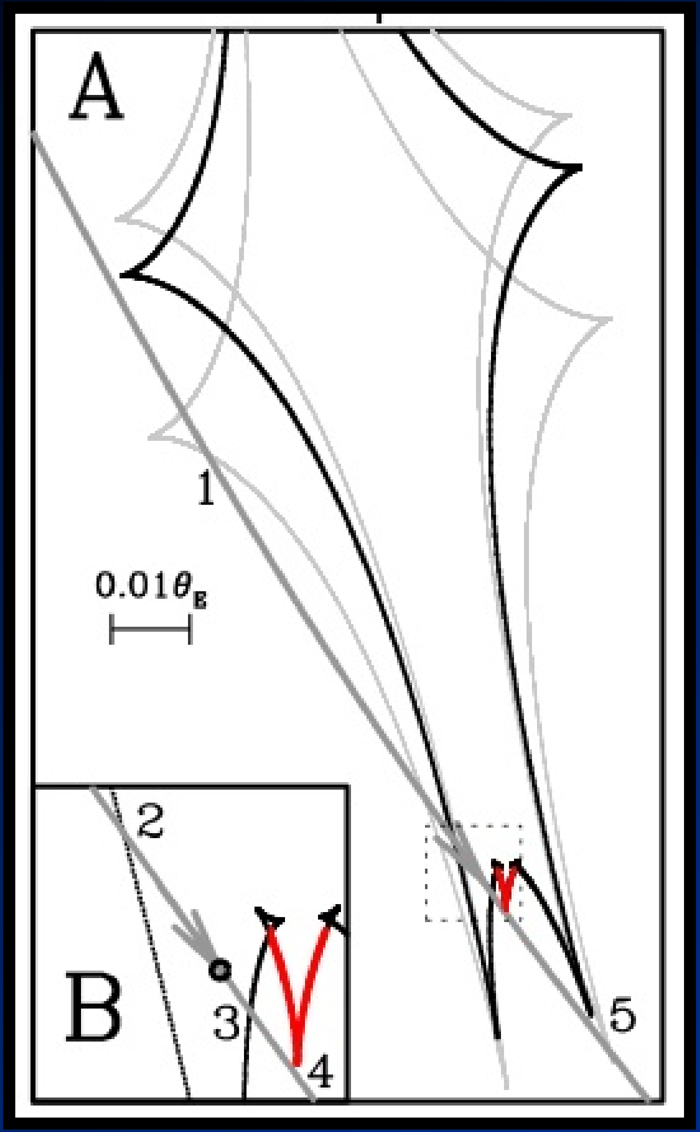
AO Imaging from Keck

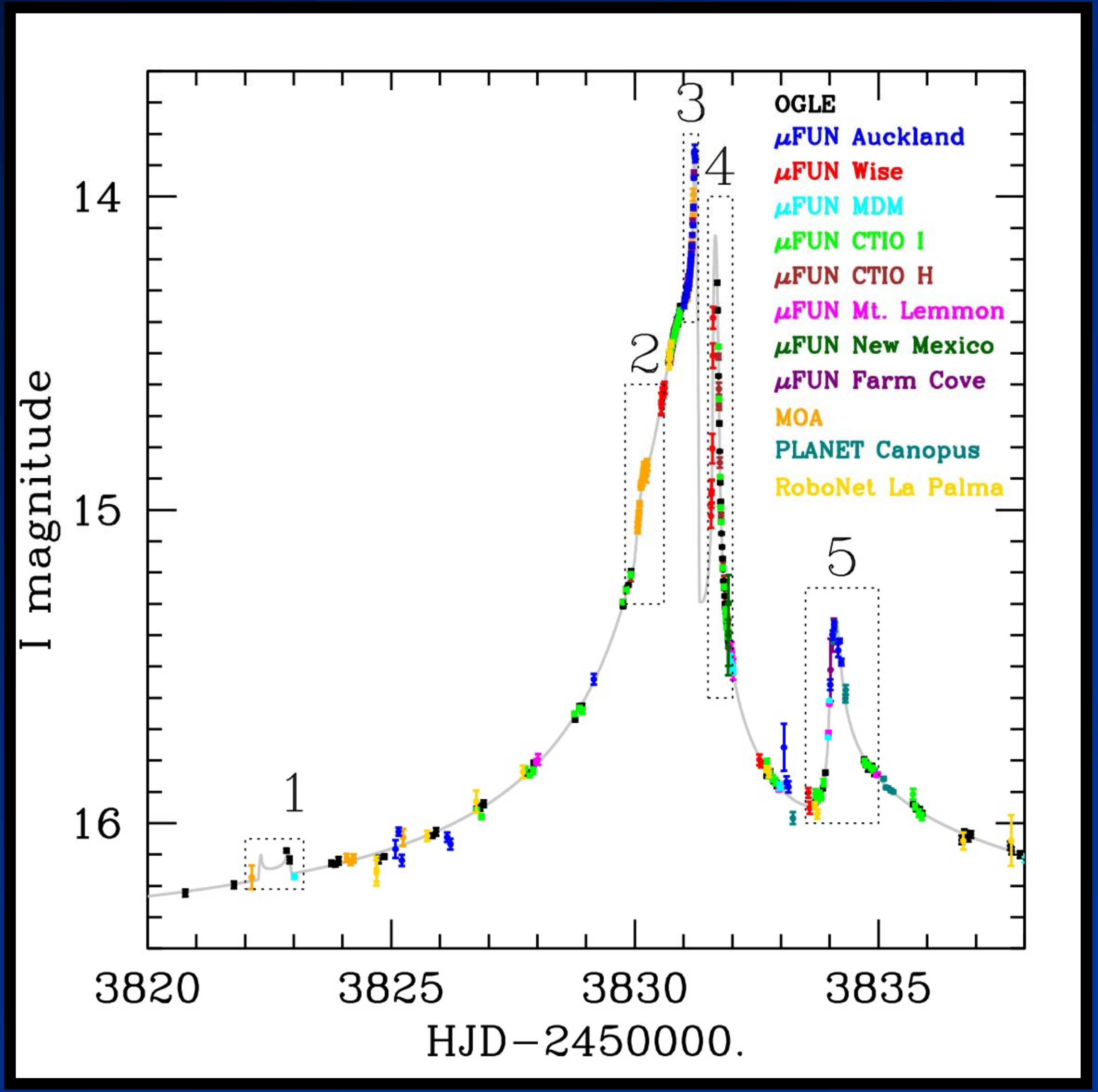


A Jupiter/Saturn Analog.



Orbital Motion.





What do we learn from orbital motion?

Measure 2 components of projected separation.

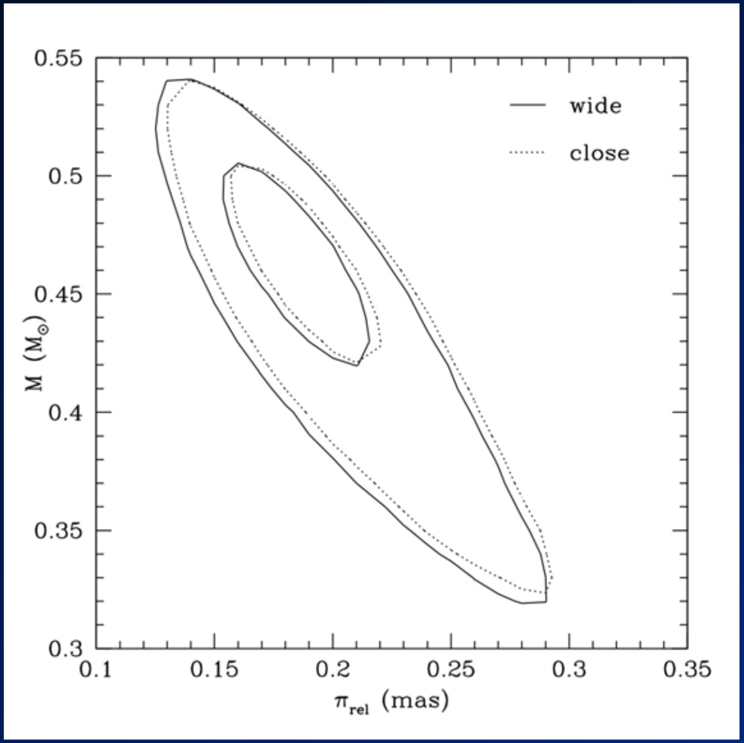
Measure 2 components of projected velocity.

Assuming circular orbits, determines inclination up to a 2-fold degeneracy.

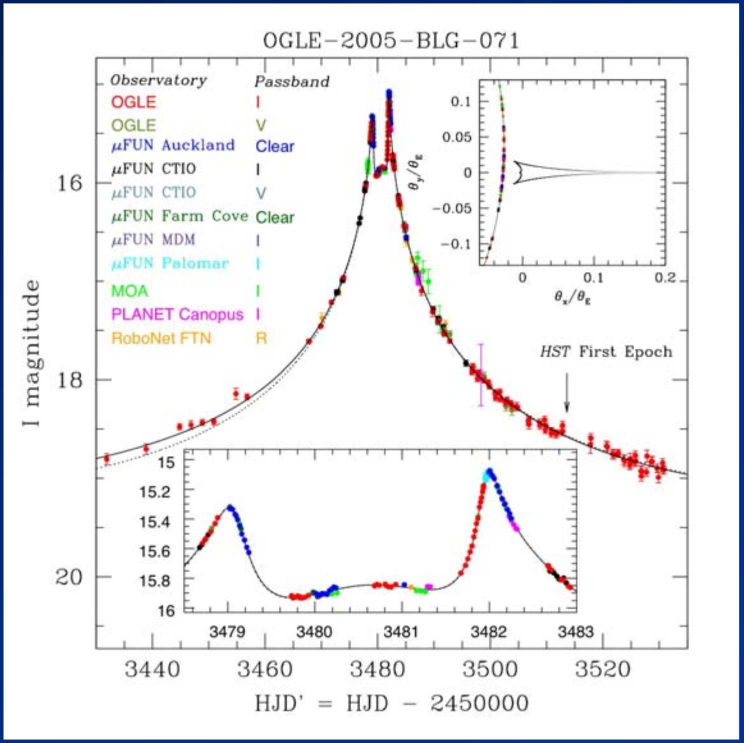
Acceleration breaks this degeneracy, and is weakly constrained.

Constraints on inclination and eccentricity.

The Most Massive M Dwarf Planet.



Dong et al. 2008



$$M = 0.46 \pm 0.04 M_\odot$$

$$D_l = 3.2 \pm 0.4 \text{ kpc}$$

$$v_{\rm LSR} = 103 \pm 15 \text{ km s}^{-1}$$

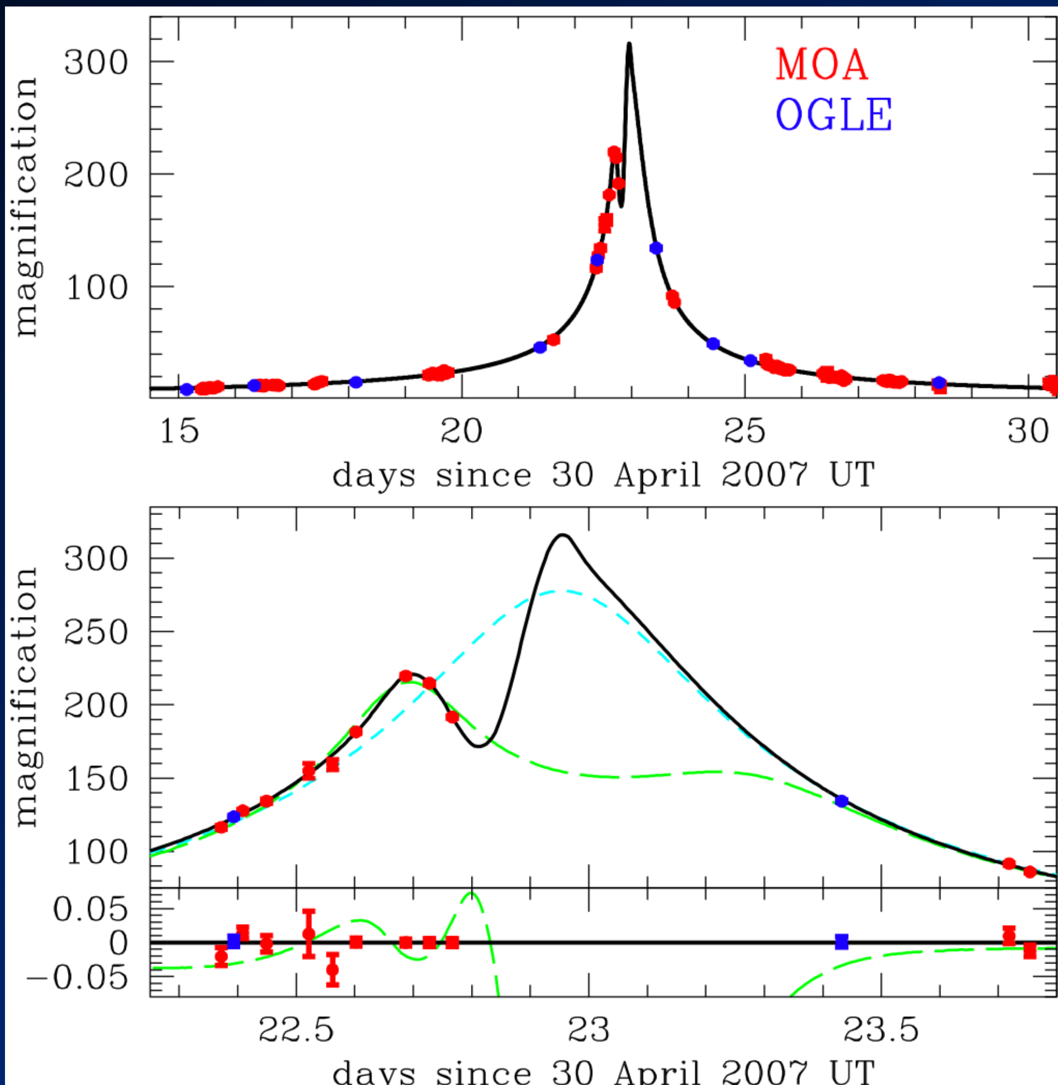
$$m = 3.8 \pm 0.4 M_{\rm Jup}$$

$$r_\perp = 3.6 \pm 0.2 \text{ AU}$$

$$T_{eq} \sim 50K$$

Low Mass Planet Orbiting a Sub-stellar Host.

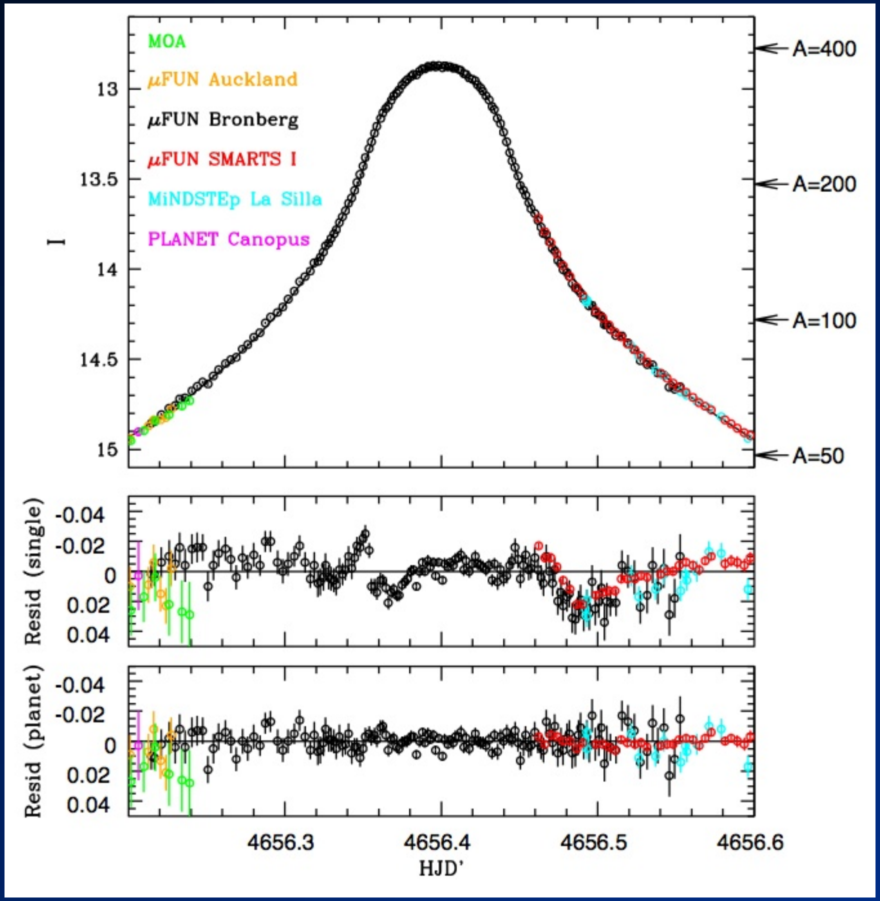
(Bennett et al 2008)

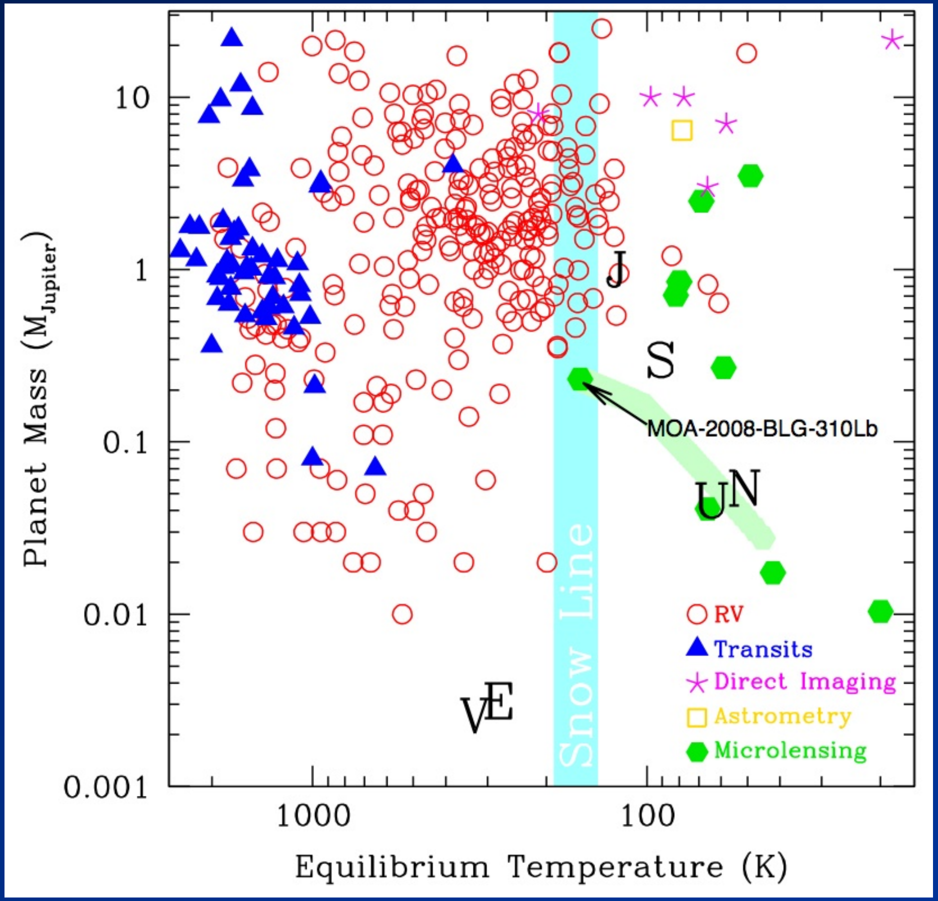


$$M = 0.06 \pm 0.03 M_{\odot}$$

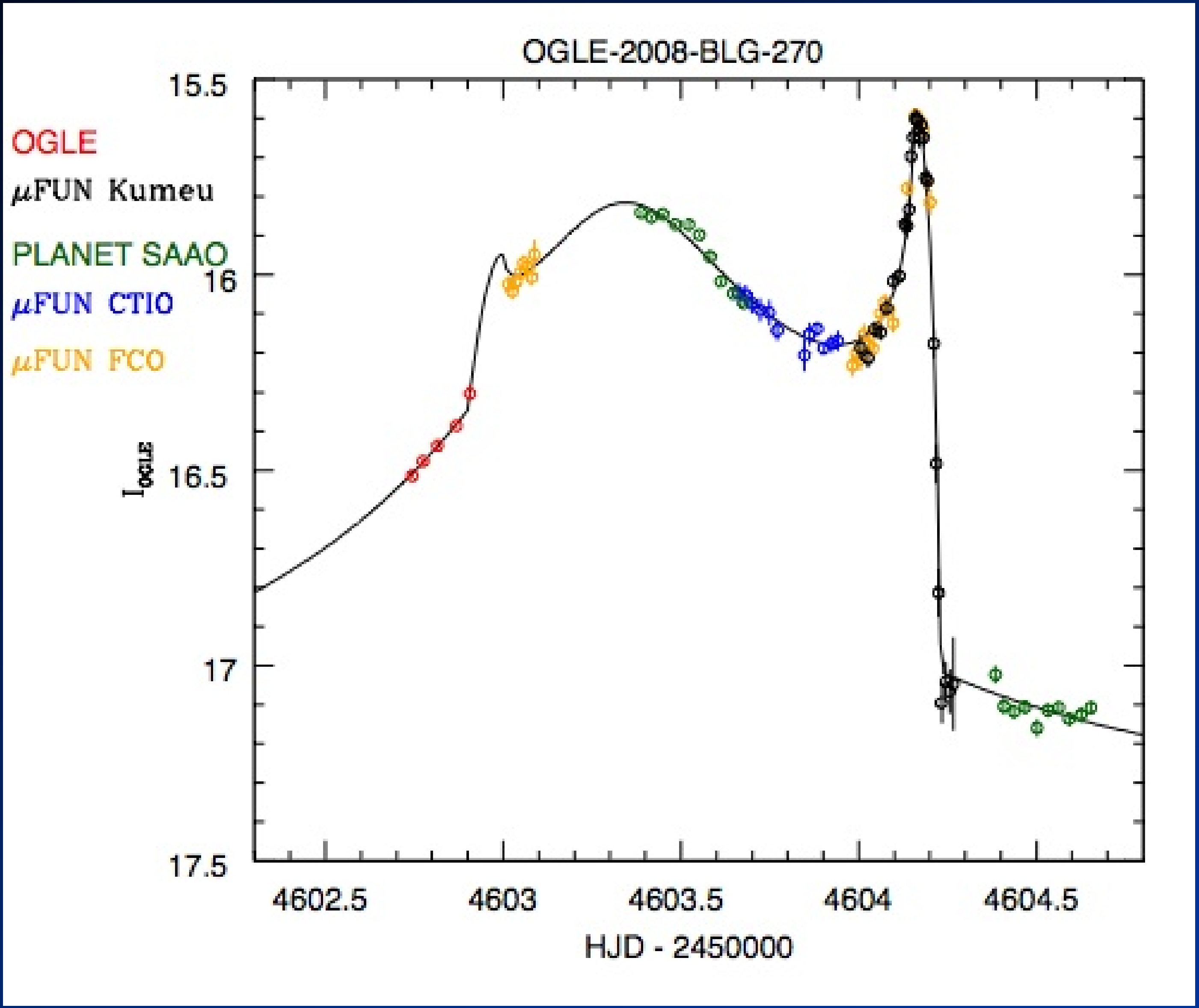
$$m = 3.3^{+4.9}_{-1.6} M_{\oplus}$$

Potential Galactic Bulge Planet.

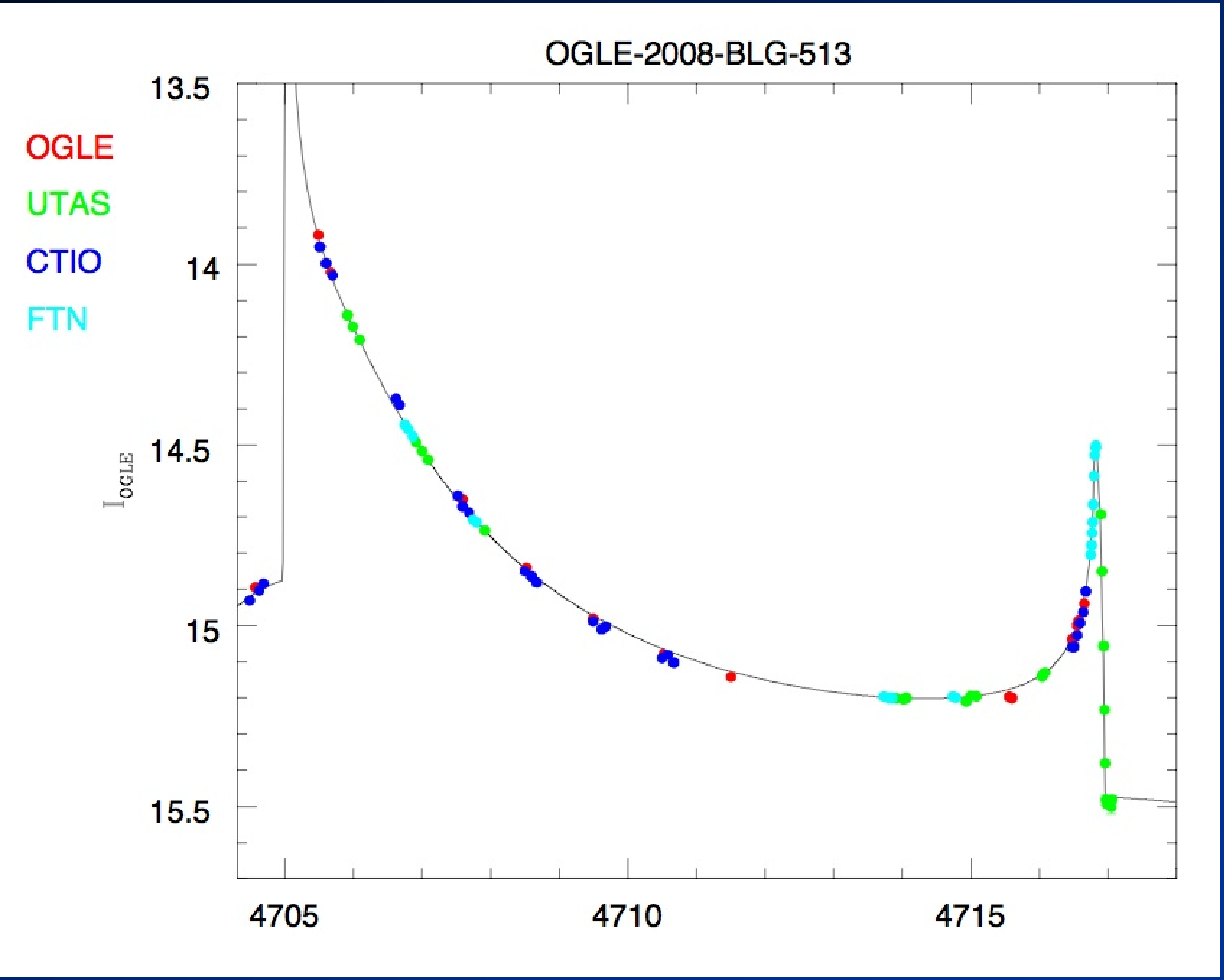




Janczak et al. 2009

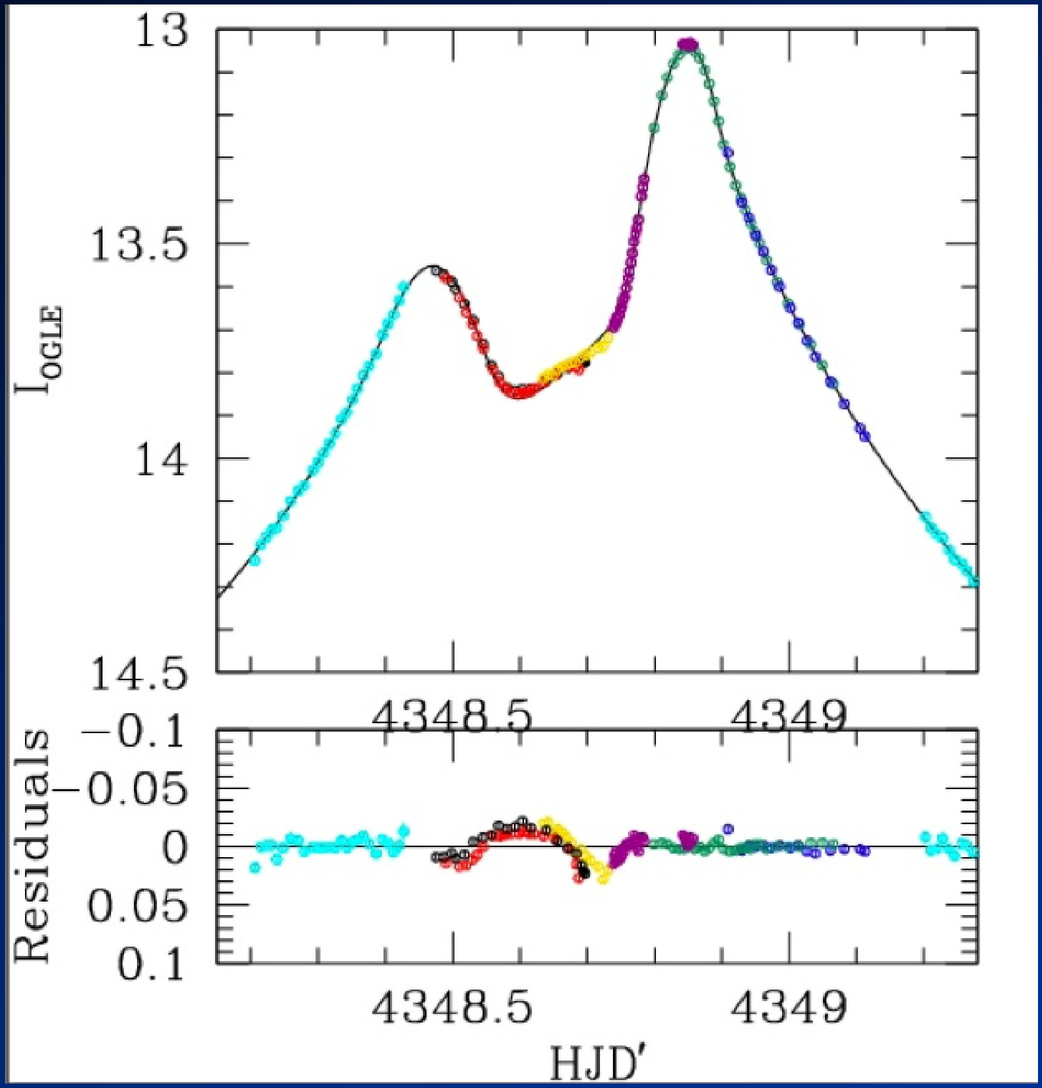


Jupiter-mass planet.

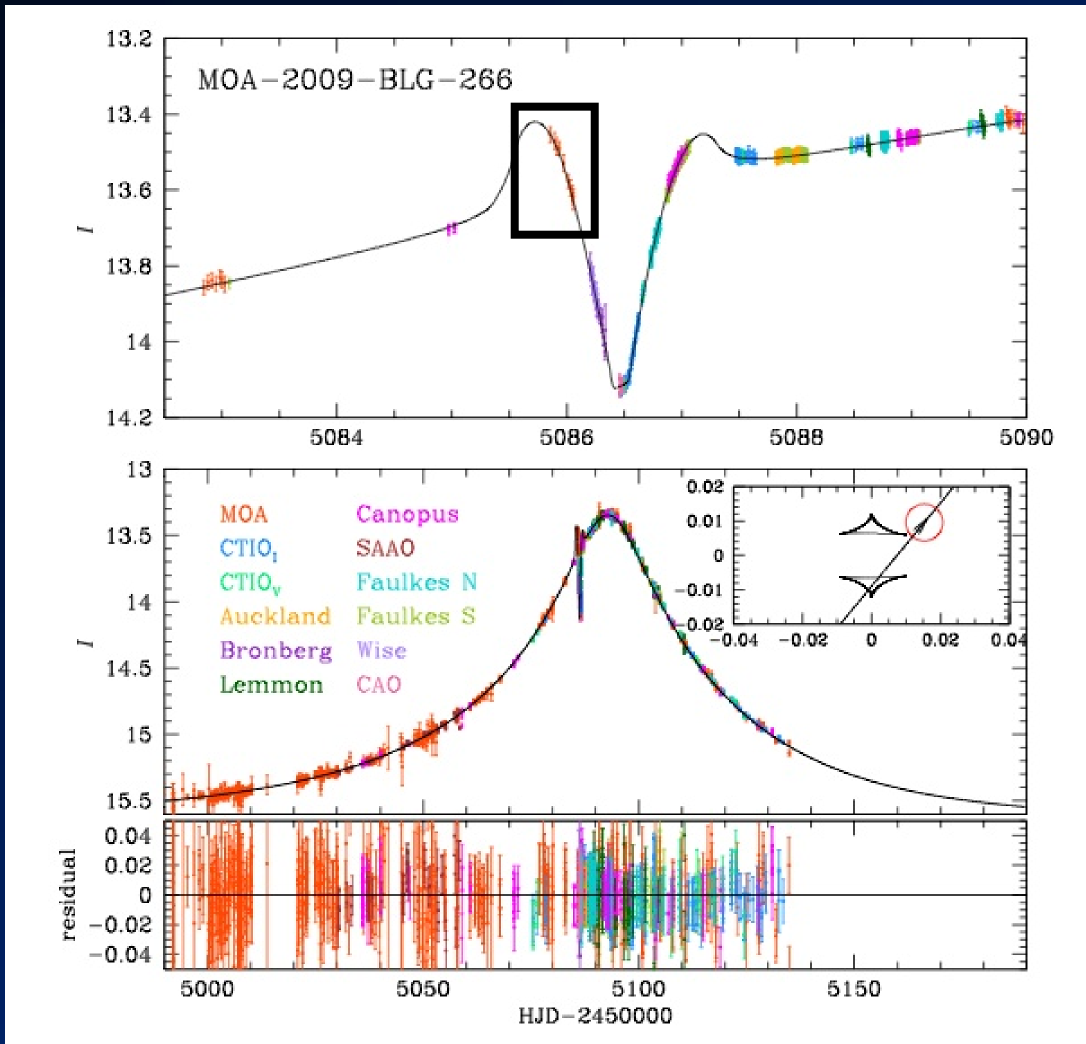


Brown dwarf companion?

(Yee et al., in prep.)



Another planetary system: Saturn + Earth?
Currently being analyzed by Subo Dong.



Host Star

$$M = 0.52 \pm 0.04\, M_{\odot}$$

$$D_L = 3.02 \pm 0.18 \text{ kpc}$$

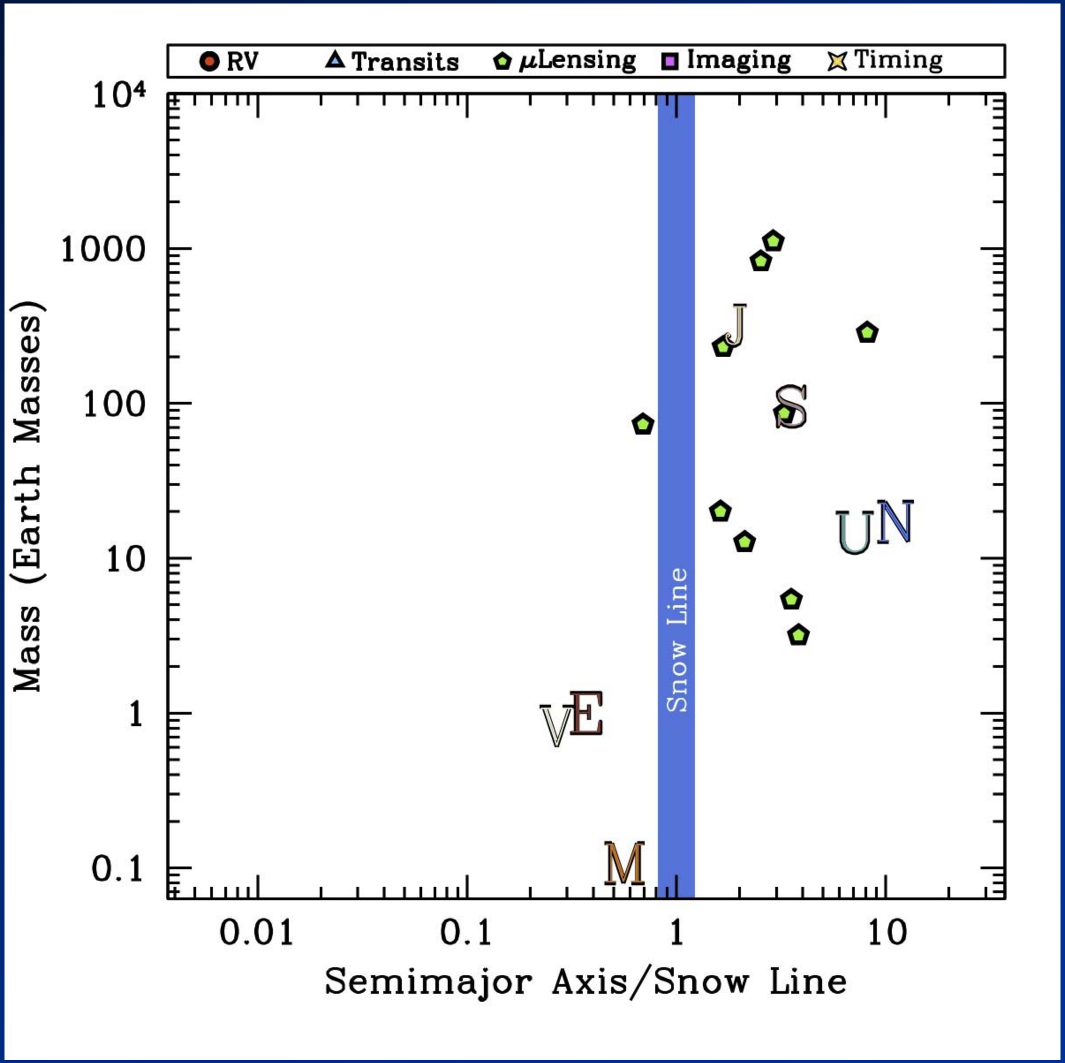
Planet

$$m = 9.2 \pm 0.7\, M_{\oplus}$$

$$a = 3.1^{+1.8}_{-0.4} \text{ AU}$$

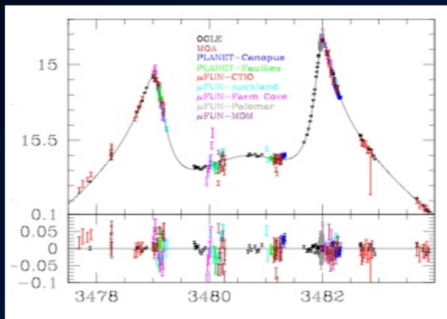
(MOA, μFUN, PLANET, RoboNET)

Demographics Beyond the Snow Line:



First Four Detections.

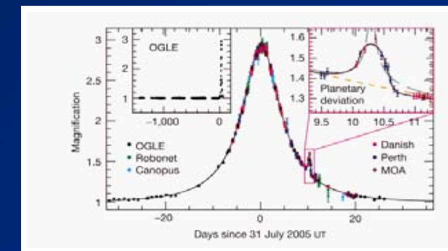
OGLE-2005-BLG-071
(Udalski et al 2005)



$M_p \sim 3.5 M_J, \;\; r \sim 3.6\text{AU}$

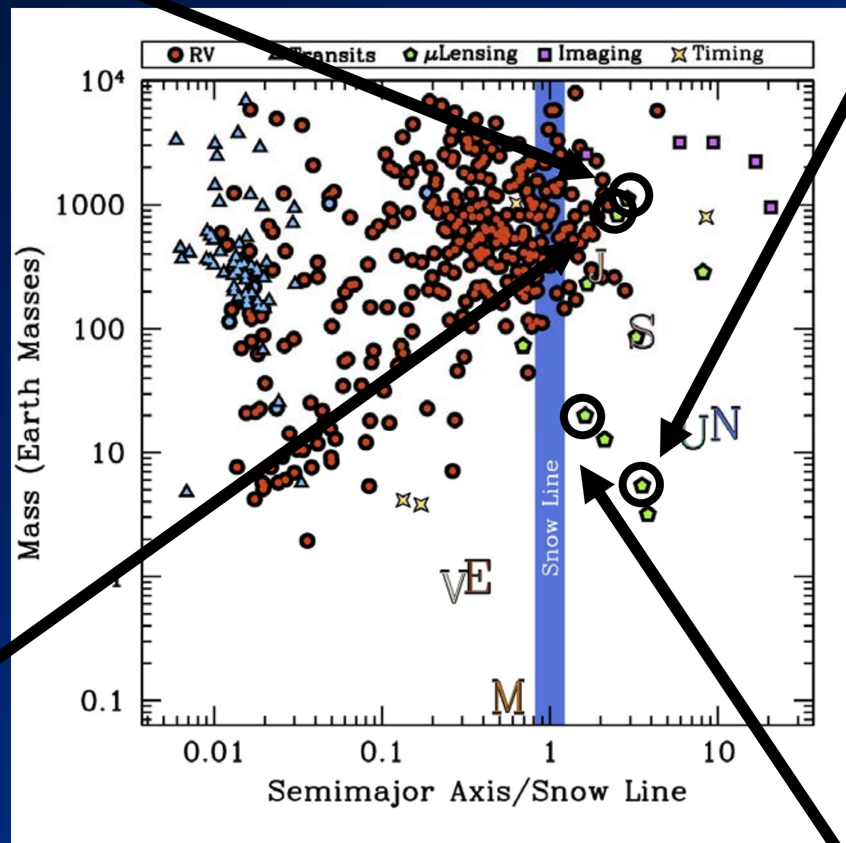
$M_* \sim 0.46 M_\odot, \;\; D_{OL} \sim 3.3$ kpc

OGLE-2005-BLG-390
(Beaulieu et al 2006)

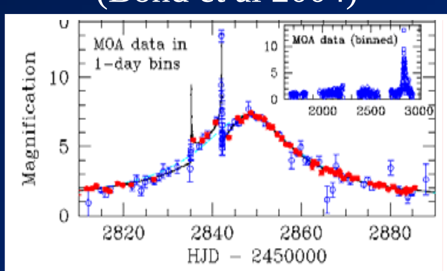


$M_p \sim 5.5 M_\oplus, \;\; r \sim 2.6\text{AU}$

$M_* \sim 0.22 M_\odot, \;\; D_{OL} \sim 6.6$ kpc



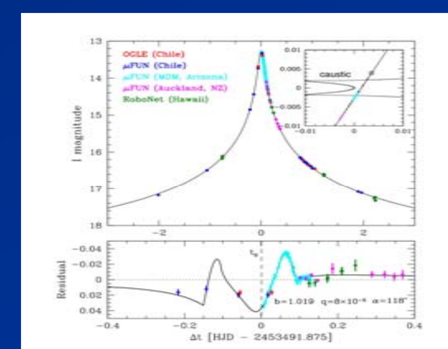
OGLE-2004-BLG-235
MOA-2004-BLG-53
(Bond et al 2004)



$M_p \sim 2.5 M_J, \;\; r \sim 4.3\text{AU}$

$M_* \sim 0.63 M_\odot, \;\; D_{OL} \sim 5.2$ kpc

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



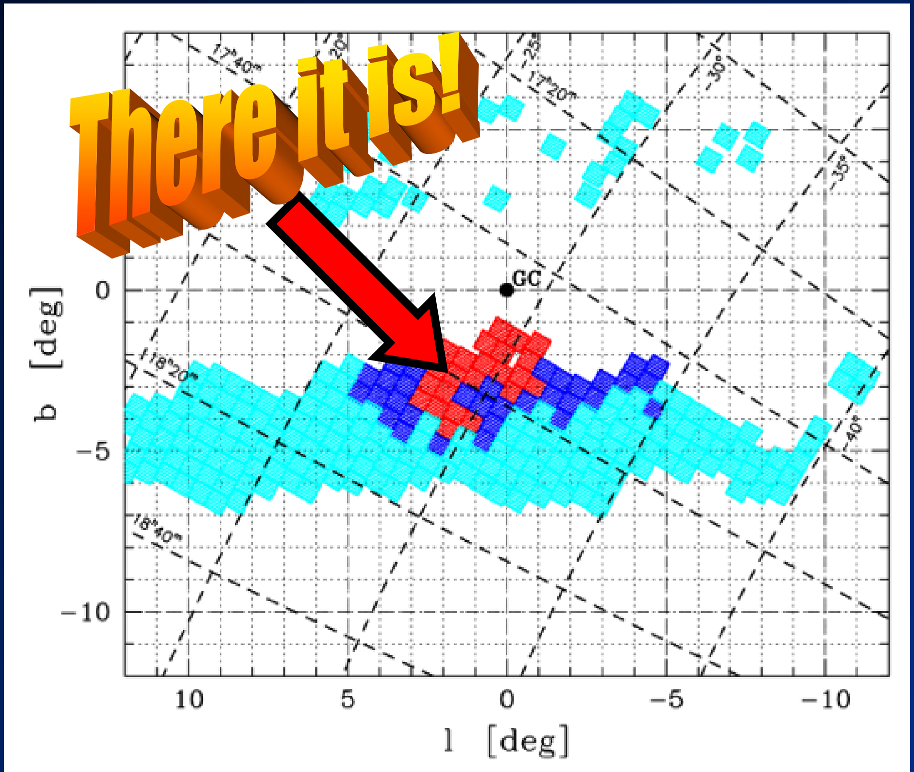
$M_p \sim 13 M_\oplus, \;\; r \sim 3.5\text{AU}$

$M_* = 0.5 M_\odot, \;\; D_{OL} = 2.7$kpc

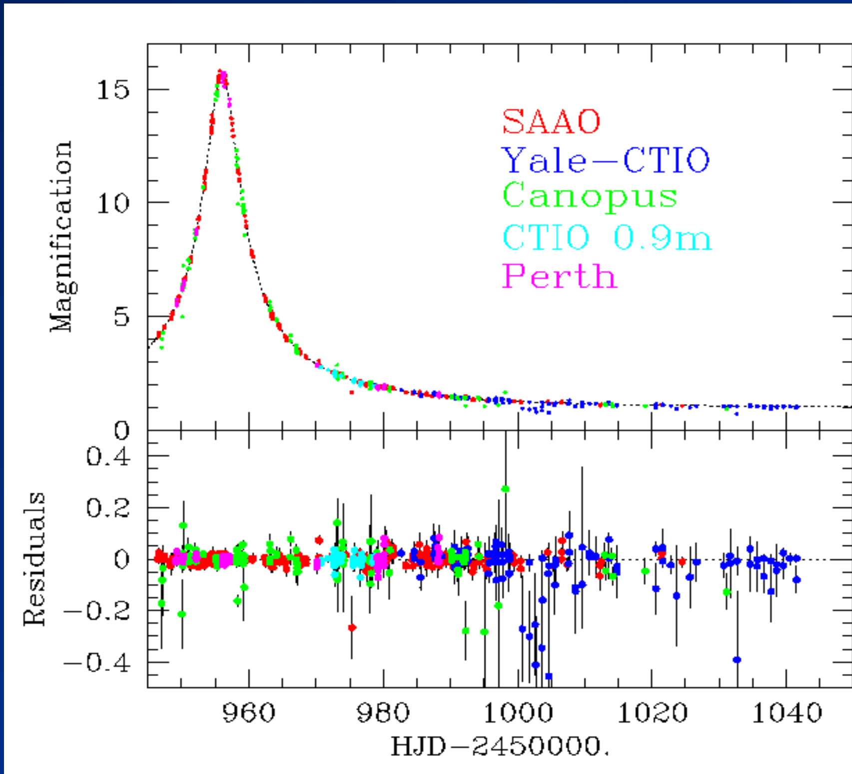
Two Jovian-mass planets

Two Neptune/Super Earth planets

How it is done: Alert/Follow-Up.



OGLE, MOA



(Albrow et al 2000)

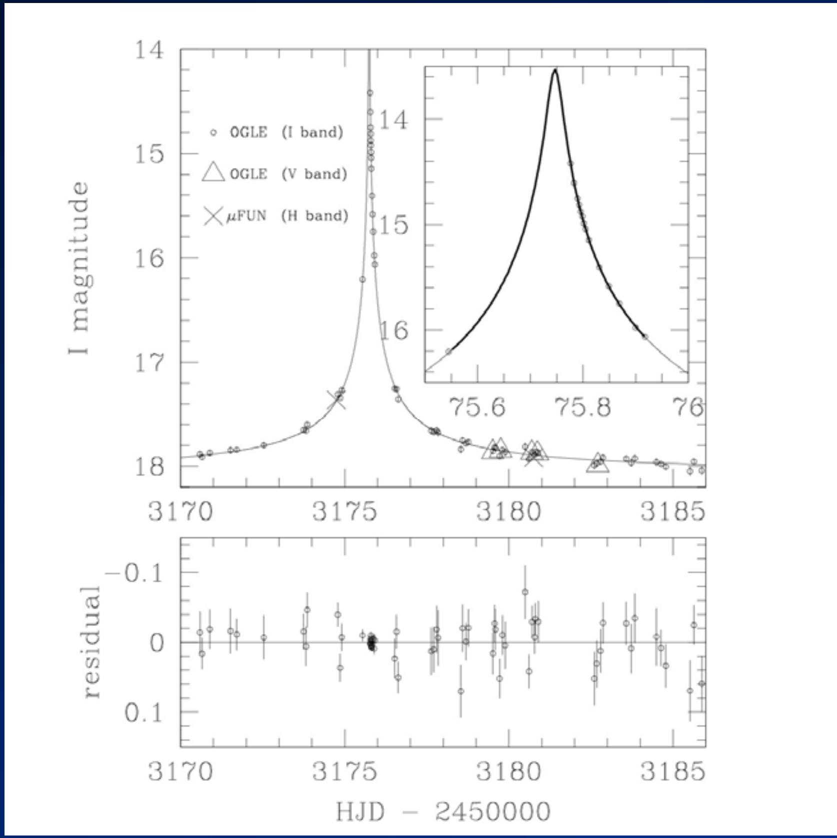
PLANET, μFUN, RoboNet, MiNDSTEp

Current Shoe-String, Slipshod μFUN Approach.

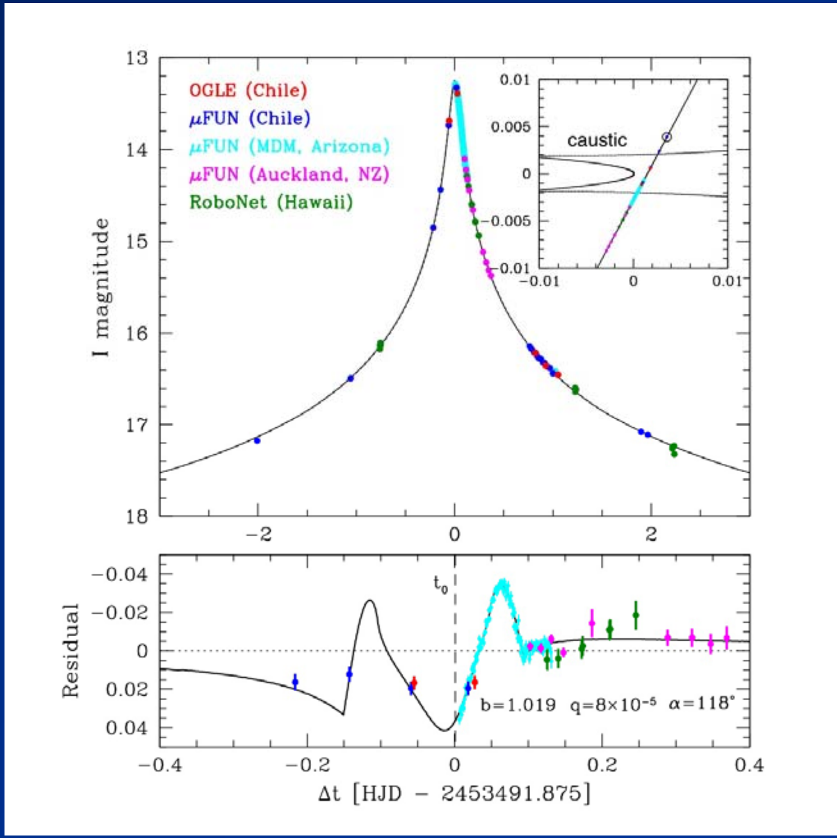
- Limited resources: shoe-string operation.
- Save money by employing enthusiastic amateurs.
- Focus on high-magnification events.
- Struggle to identify these real-time.
- Go all out!

“A Controlled Experiment” from Chaos.

The one that got away… …and the one that didn’t

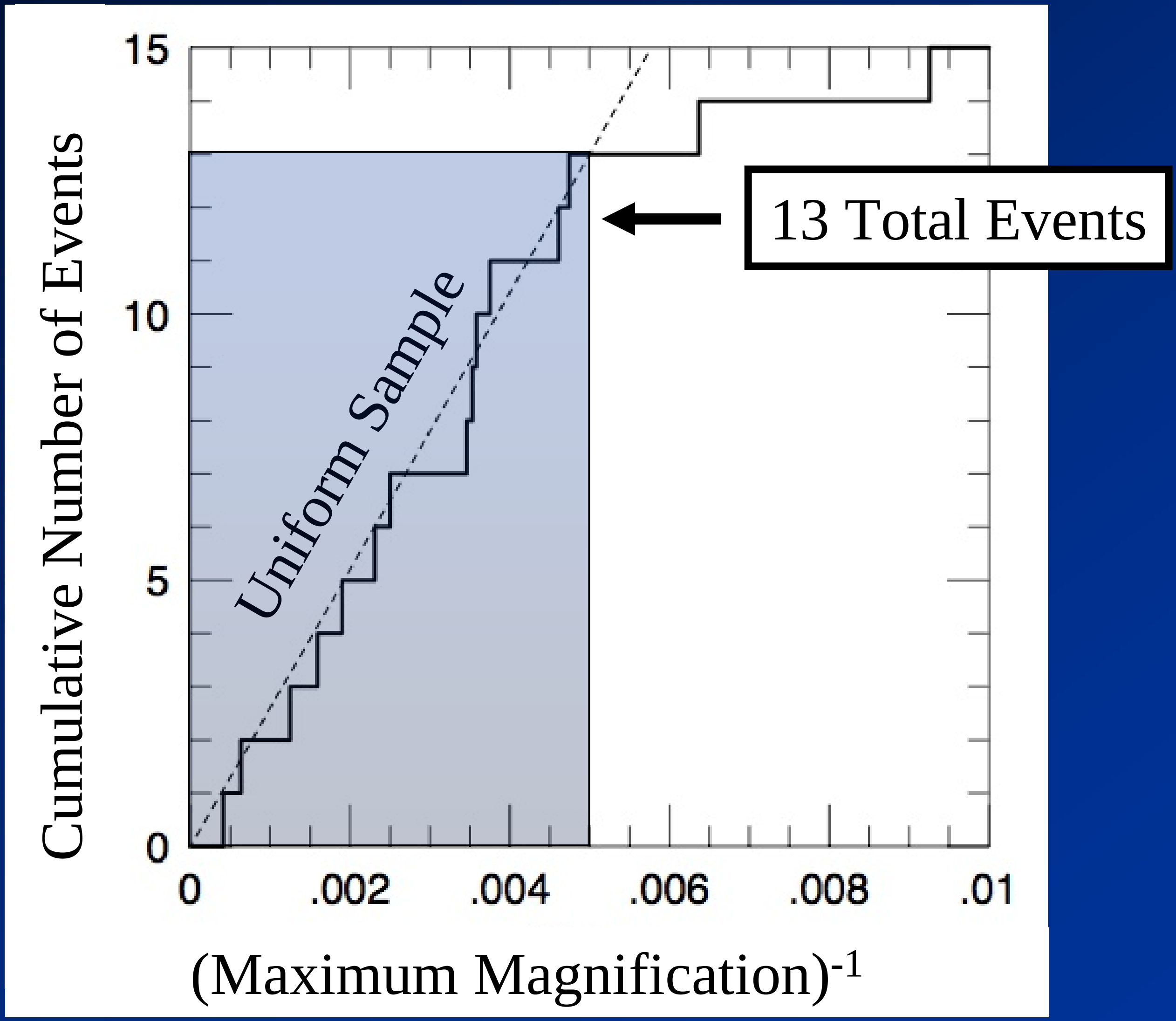


(Dong et al. 2006)

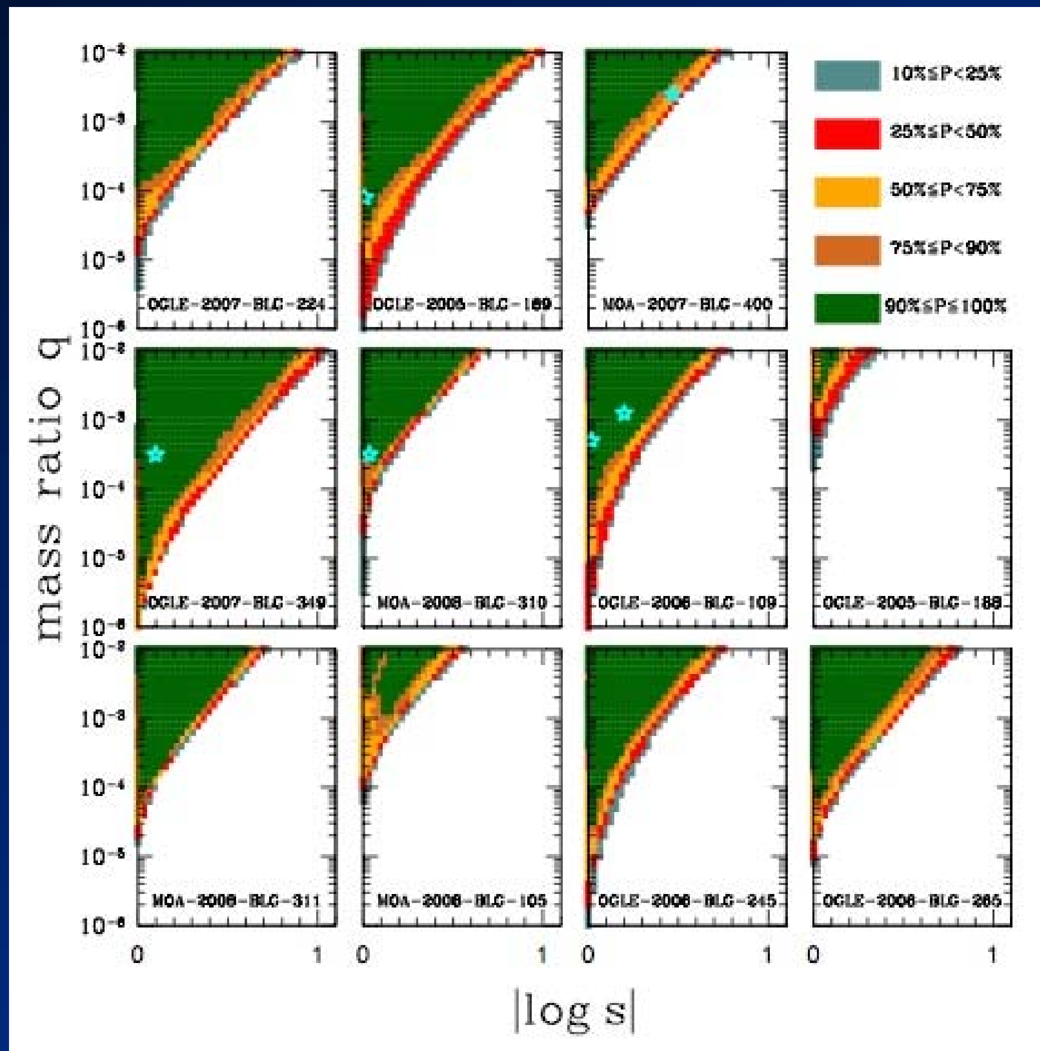


(Gould et al. 2006)

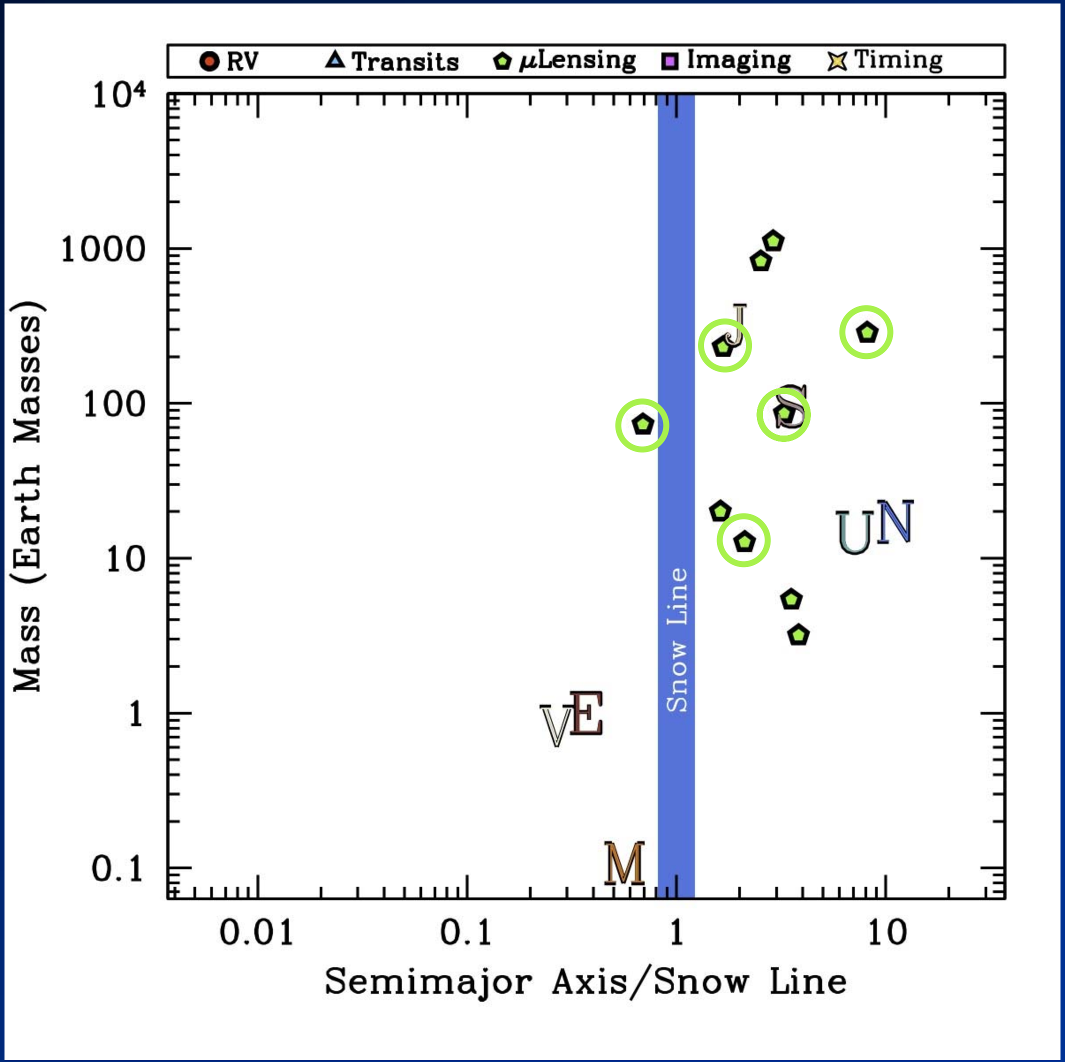
Uniform Sample.



Detection Efficiencies.

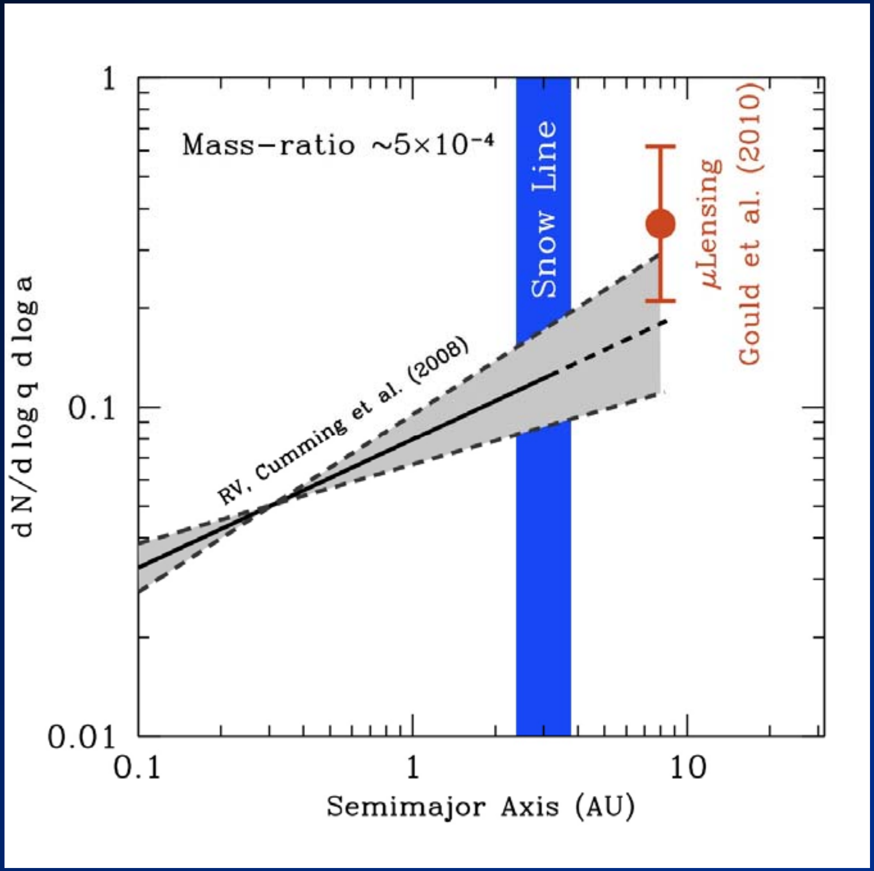


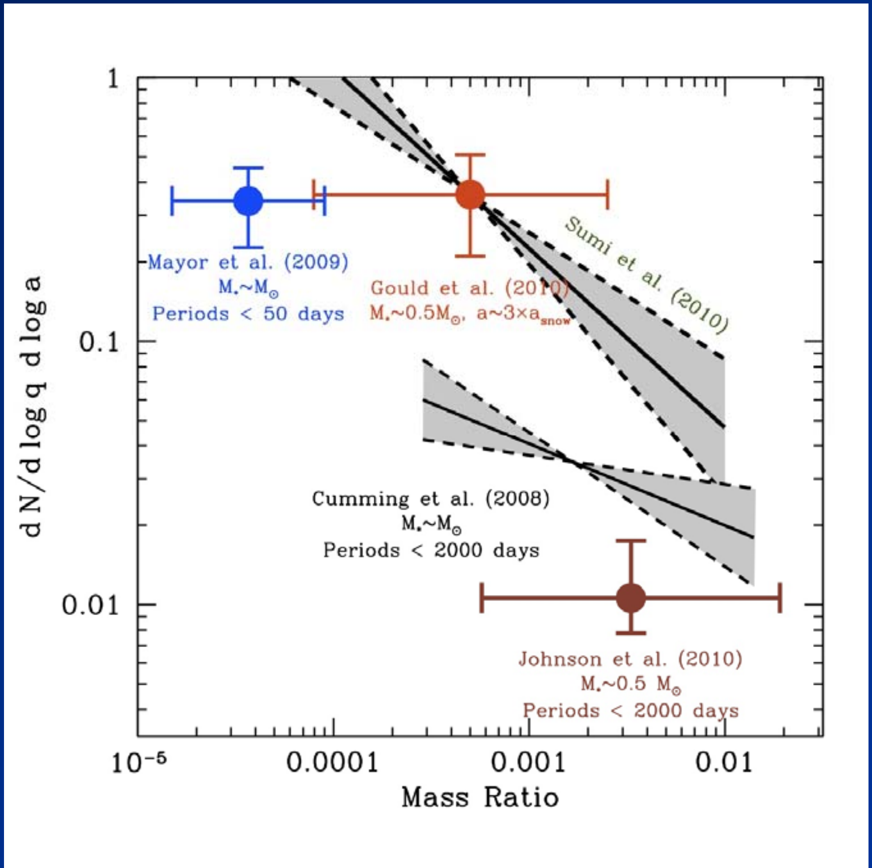
Detections.



(+ one detected but not yet published)

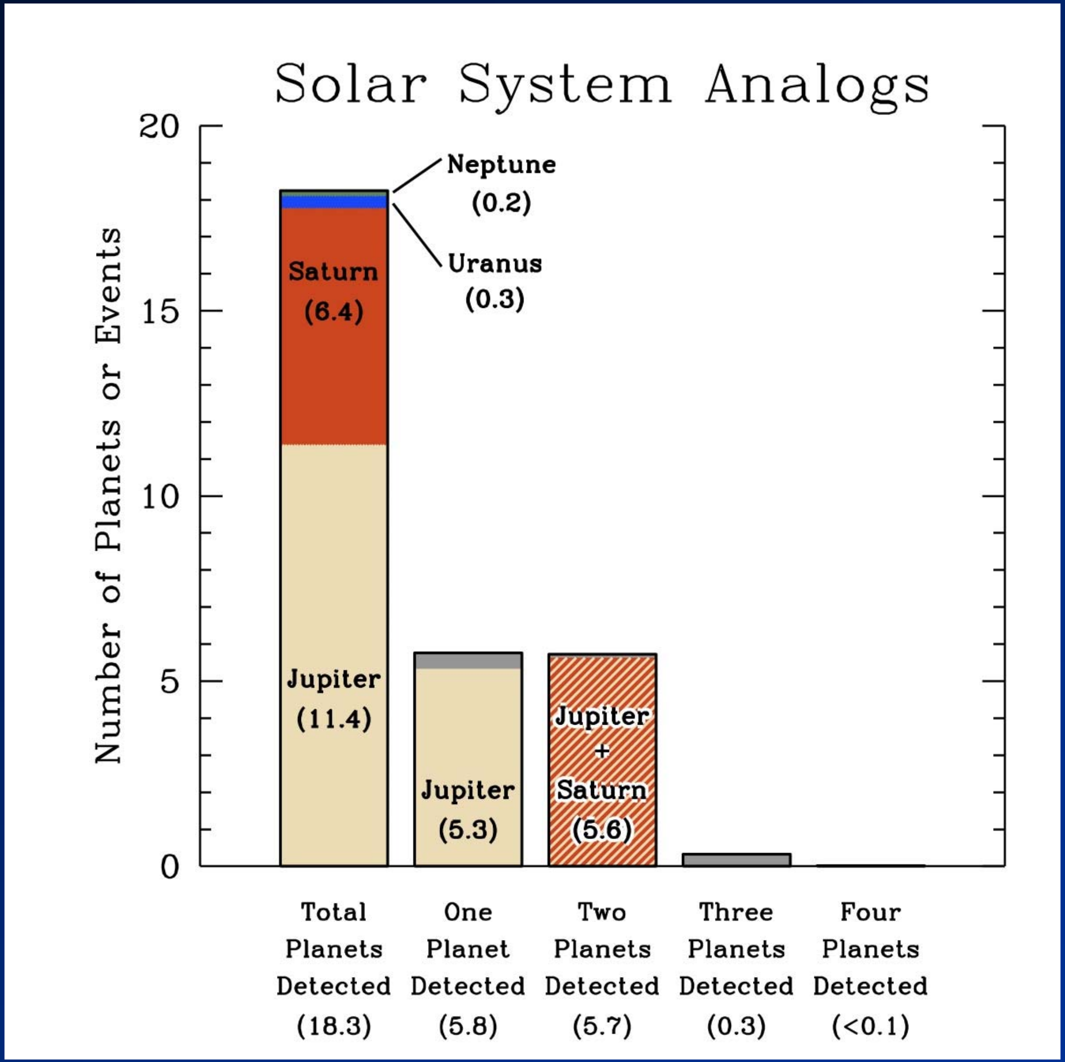
Frequency of Planets Beyond the Snow Line.





(Sumi et al. 2009, Gould et al. 2010, Bennett)

No Place Like Home?

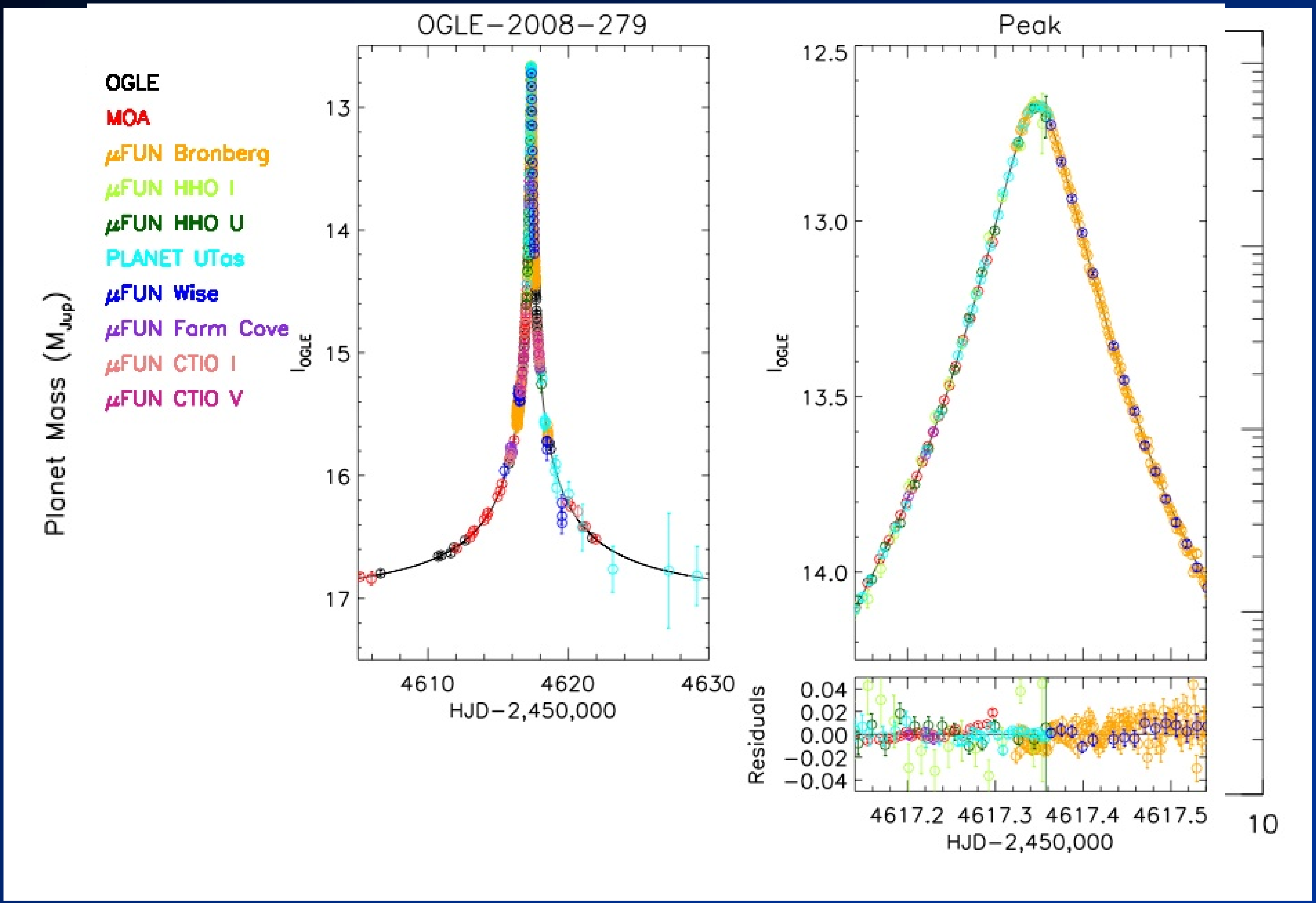


Frequency of Solar System Analogs: ~15% (Gould et al. 2010)

So what’s next?

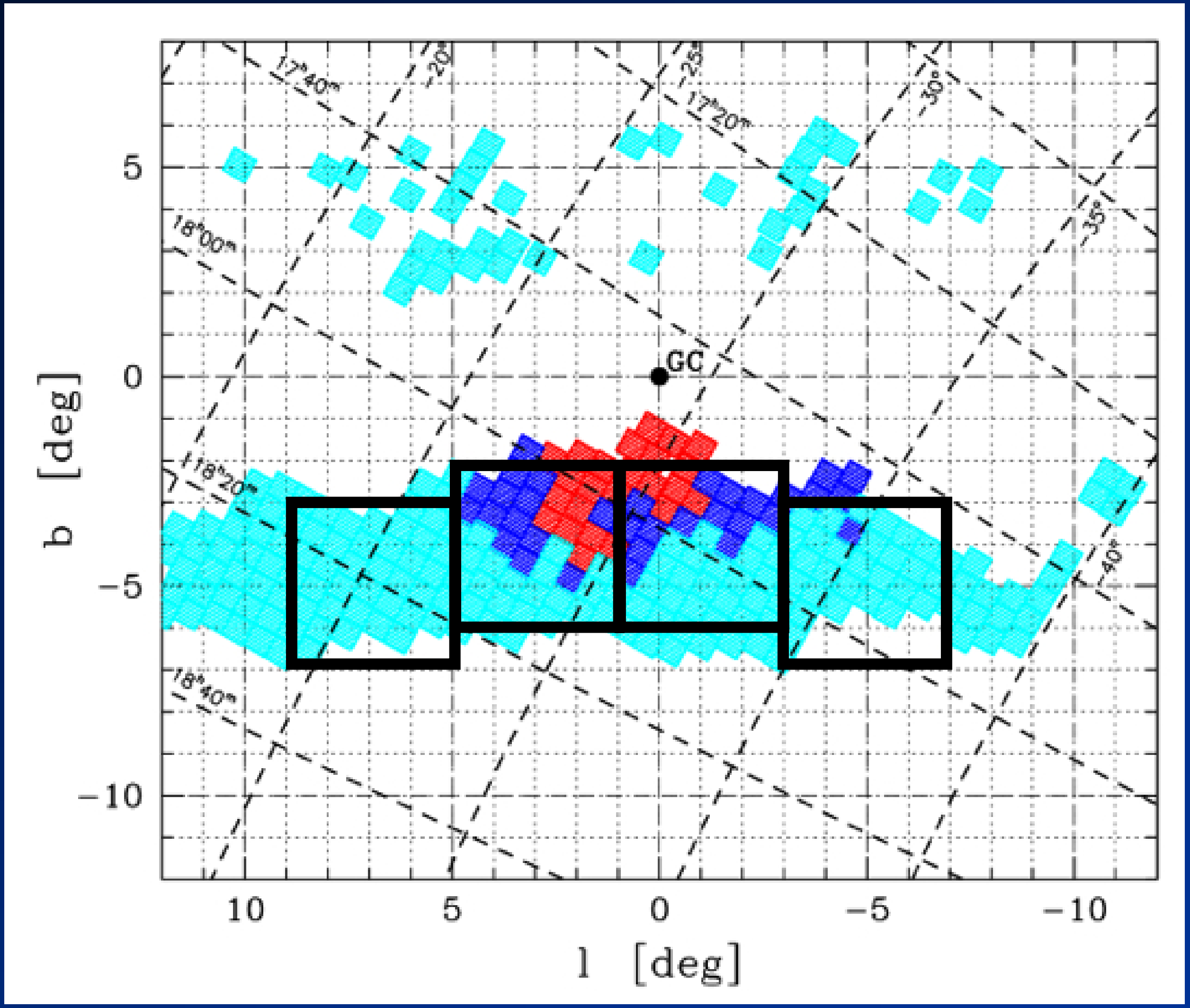
- **Ten announced so far:**
  - Six from 2003-2006
  - Four from 2007-2008
- **Seven more events with secure detections.**
- **17 likely planets discovered to date, in 16 systems.**
- **Can expect ~4 planets per year.**
- **Earth mass planets?**

Earths?



Yee et al. 2008

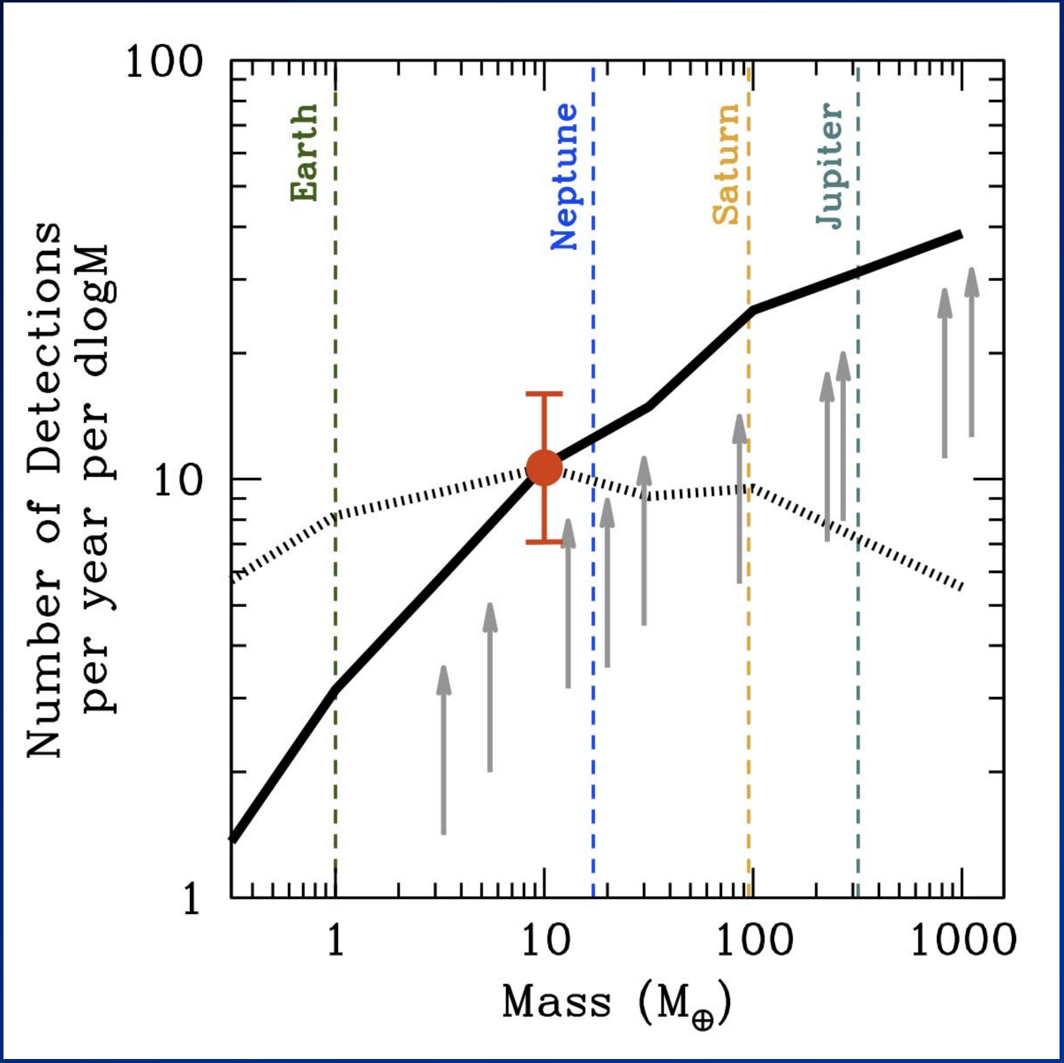
Wide-field Monitoring.



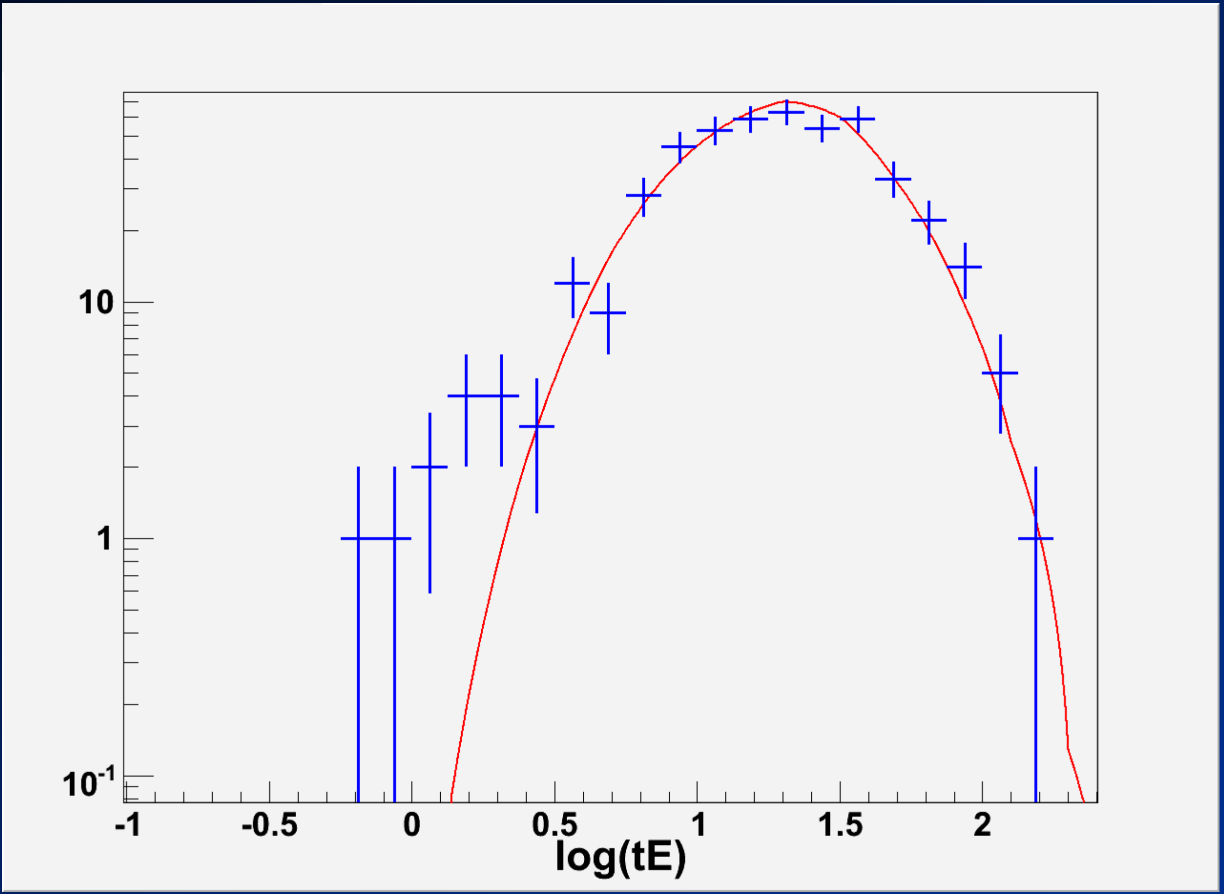
The Future is Now!

- **MOA-II (2006)**
  - 1.8m telescope, 2.18 sq. degree camera, NZ
- **OGLE -IV (2010)**
  - 1.3m telescope, upgrade to 1.4 sq. degree camera
- **Korean Microlensing Telescope Network (2012?)**
  - Approved ~$30M Korean initiative
  - Three telescopes:
    - South Africa
    - Chile
    - Australia

NextGen μLensing Survey.



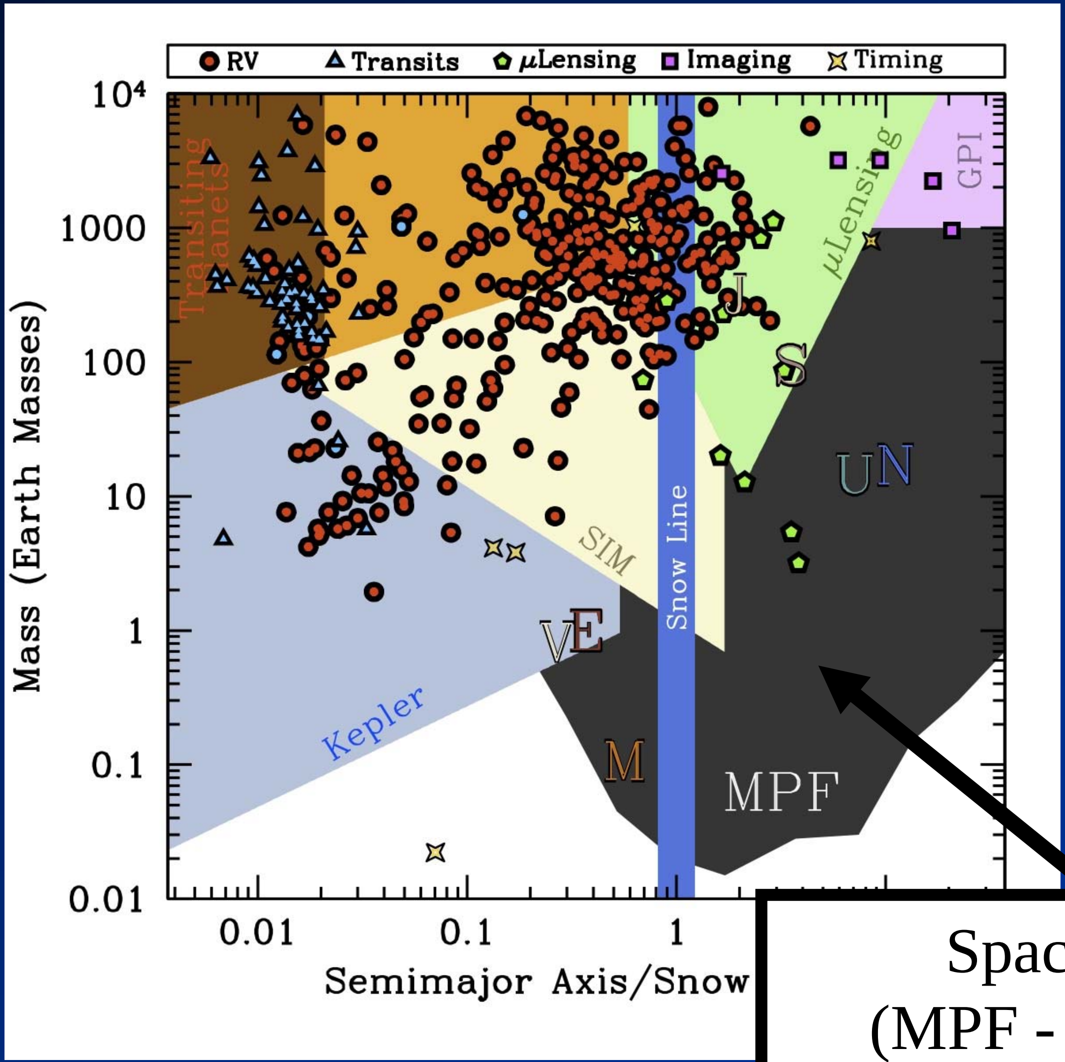
Free Floating Planets



(MOA Collaboration; Kamiya et al., in prep.)

- 2006-2007 data
- Excess of short events.
- 0.68 expected, 12 found.
- Wide or Free-floating planets?
- Mass Ratio ~0.005
- ~3 per star

Planet Search Synergy!



Space Survey
(MPF - Bennett, or
Joint ML/Weak Lensing)

Summary.

- Microlensing is sensitive to planets beyond the snow line, including low-mass planets.
- Contrary to popular belief, it is possible to learn a great deal about individual systems detected by microlensing.
- Results from microlensing surveys:
  - Cool Neptunes/Super Earths more common that Jupiter-mass planets.
  - Jovian companions are more common beyond the snow-line: most massive planets do not migrate (much).
  - Solar system analogs are probably not rare, nor are they likely the majority.
- Next-generation ground and space based surveys will tell us about the demographics of planetary systems.