Searching for Extrasolar Planets with Gravitational Microlensing

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Collaborators: Andy Gould (Ohio State) [MicroFUN], Andrzej Udalski (Warsaw) [OGLE], J.P. Beaulieu (IAP) [PLANET], Ian Bond (Massey) [MOA], Keith Horne (St. Andrews) [RoboNet]

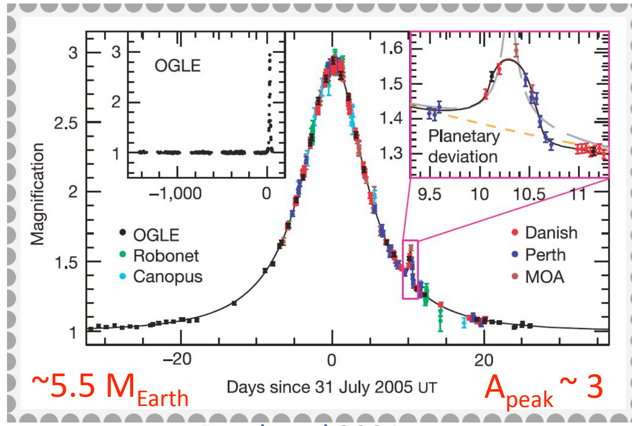
MicroFUN -- The Network in Which the Sun Never Rises (the Bulge *hopefully* Never Sets)

~20 sites, 30cm – 2m telescopes, and expanding …

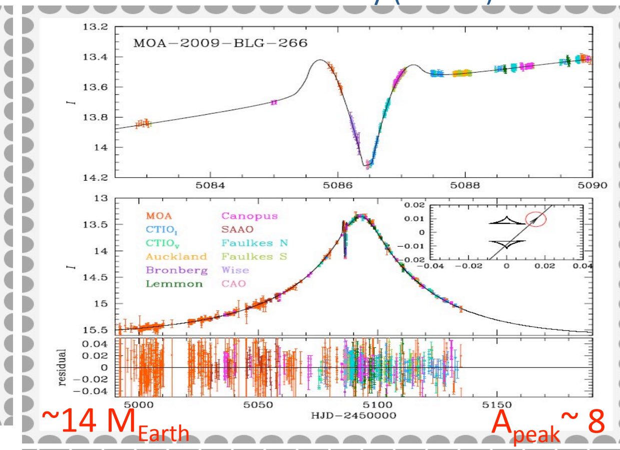
Stamp collecting microlensing planets

Gould & Loeb (1992) Planetary Caustics: Short blip anywhere on the light curve

Beaulieu et al 2006

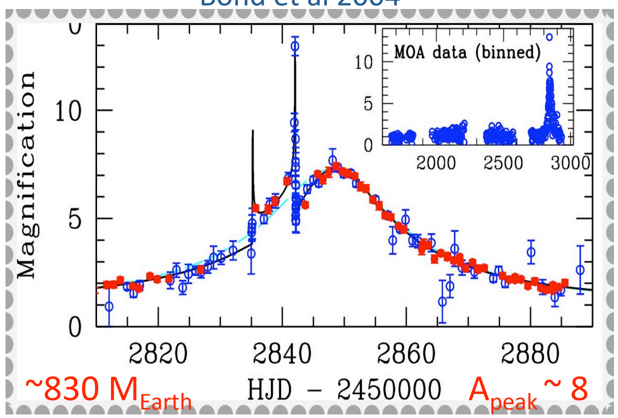


Preliminary (C. Han)

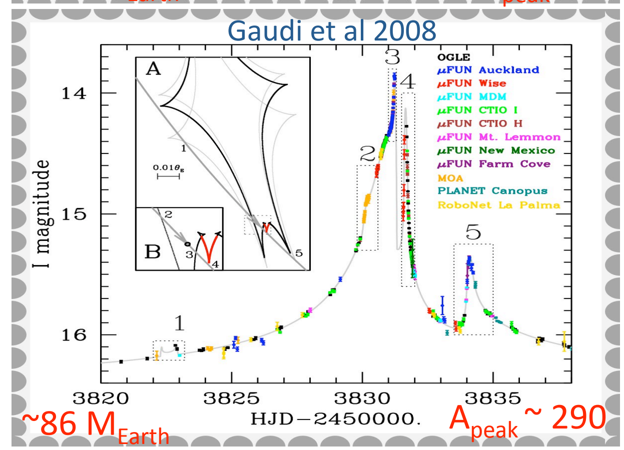


Mao & Paczynski (1991) Resonant Caustics:
Planet very close to Einstein Radius, Long time-scale perturbation, complicated deviations

Bond et al 2004

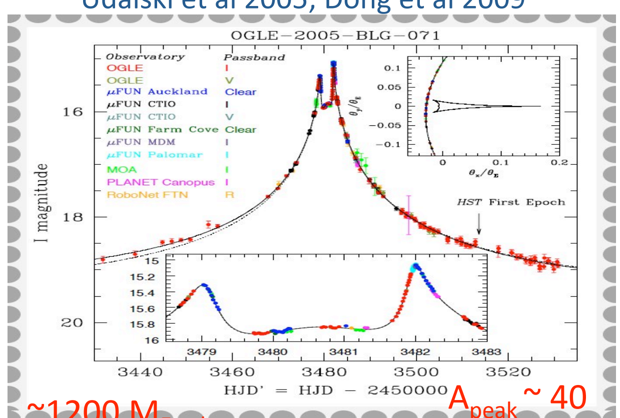


Gaudi et al 2008

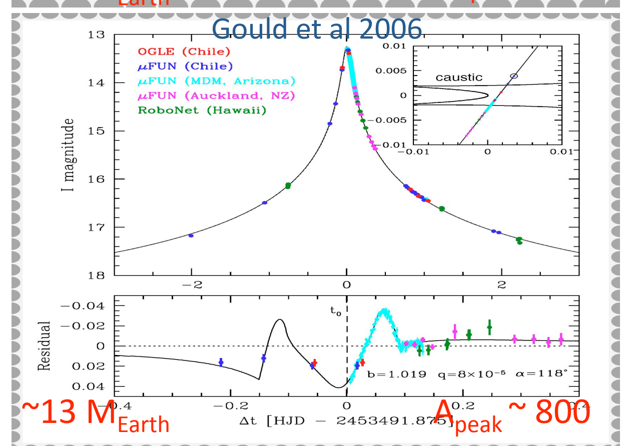


Griest & Safizadeh (1998) *Central Caustics:*
Perturbations close to the peak of High-Magnification Events

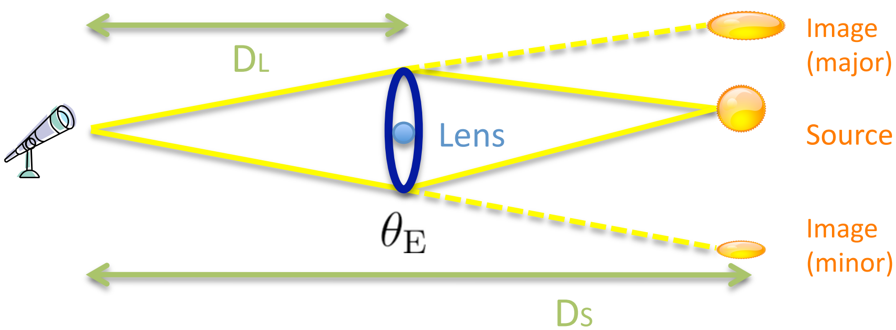
Udalski et al 2005; Dong et al 2009



Gould et al 2006



Microlensing Basics



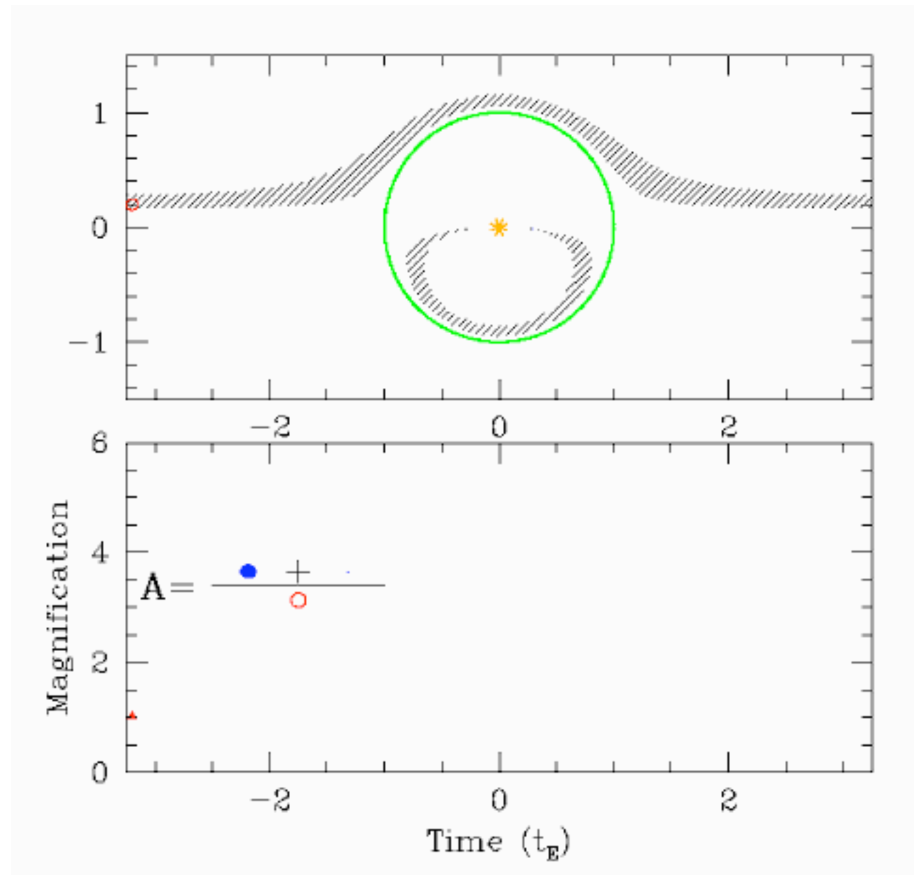
Angular Einstein Radius:

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

$$= 570\mu as(\frac{M}{0.5M_\odot})^{1/2}(\frac{D_{rel}}{12.5kpc})^{-1/2}$$

$$t_E = \theta_E / \mu_{LS} \sim 30 days$$

OGLE & MOA: ~1000 events per year by monitoring 10^8 stars



Credit: Scott Gaudi

Planetary Microlensing

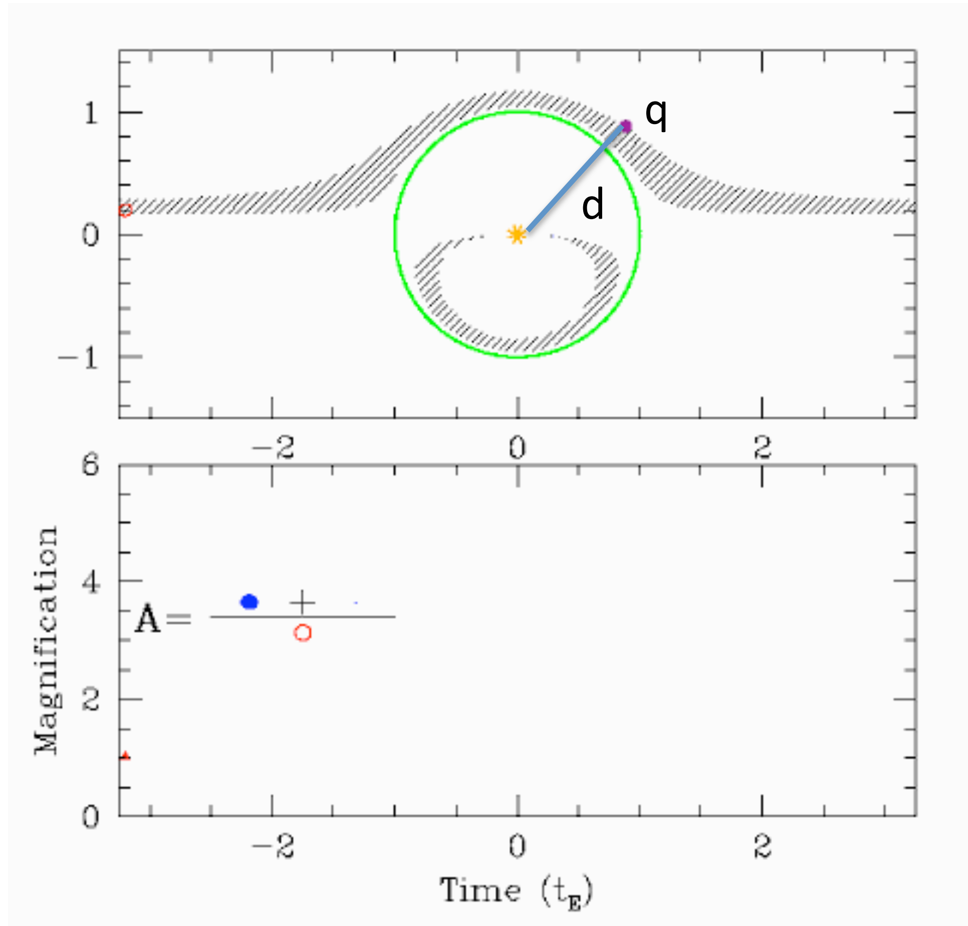
Mao & Paczynski (1991)
Gould & Loeb (1992)

-- Most sensitive to planets within from ~0.6 to ~1.6 r_E (= $\theta_E D_L$ ~ 3 AU)
–> Solar System Analogs!

Short timescale:

$$t_{planet} / t_E \sim \sqrt{M_{planet} / M_{star}} = \sqrt{q}$$

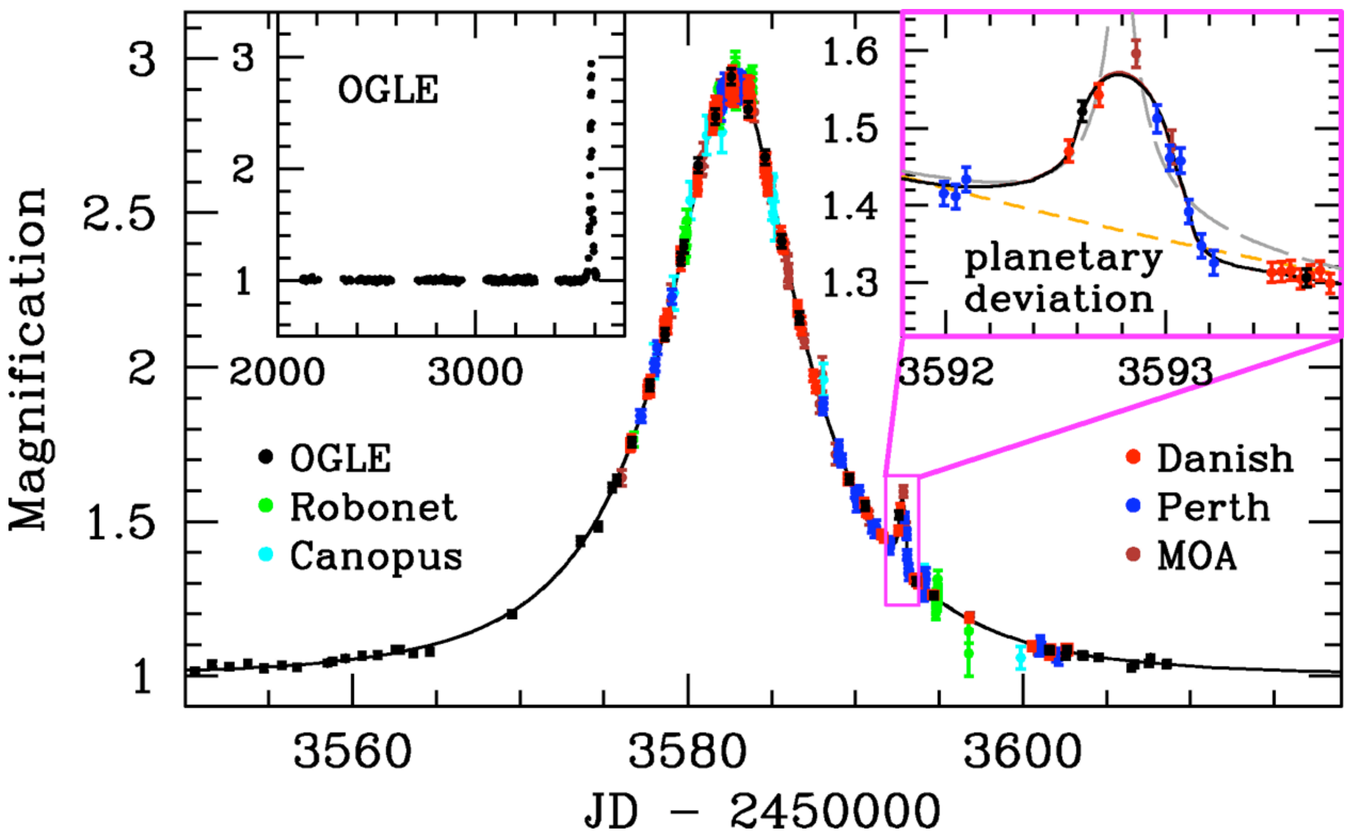
Intensive 24hr Monitoring of a Selective Number of Events



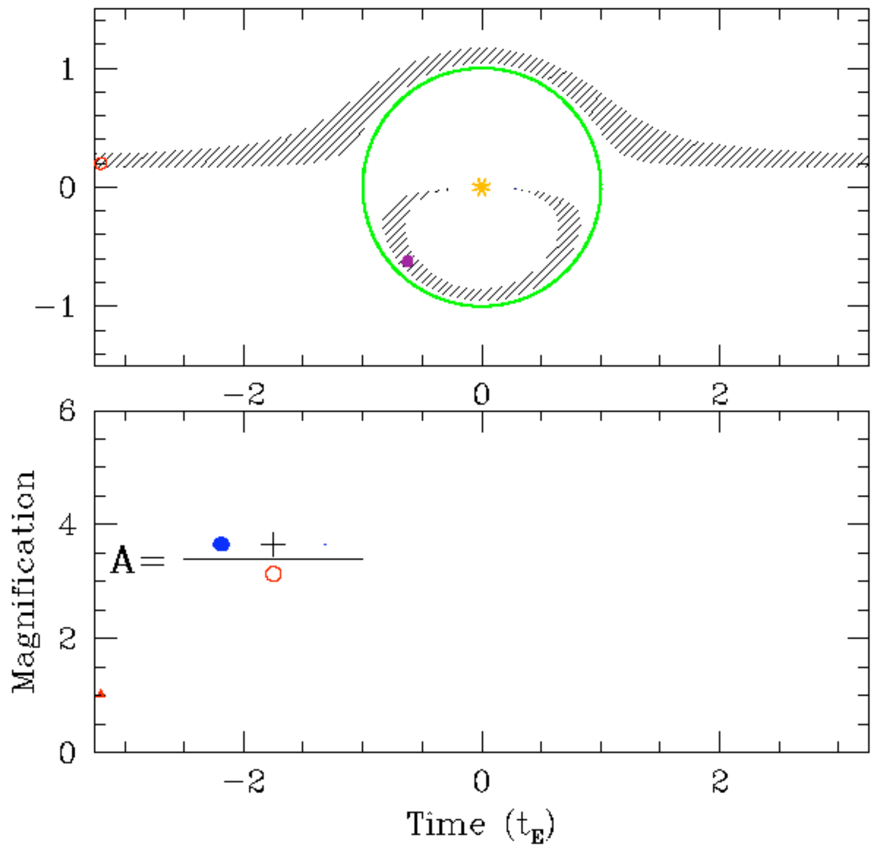
A *Classic* Gould & Loeb event

First Gould & Loeb type planet:
$q \sim 8 \times 10^{-5}$ $d \sim 1.6$
A cool Neptune: ~5.5 M_{Earth}, 2.6 AU, T~50K!

OGLE-2005-BLG-390 (Beaulieu et al. 2006, Nature, 439, 437)



Gould & Loeb Event -- Minor Image

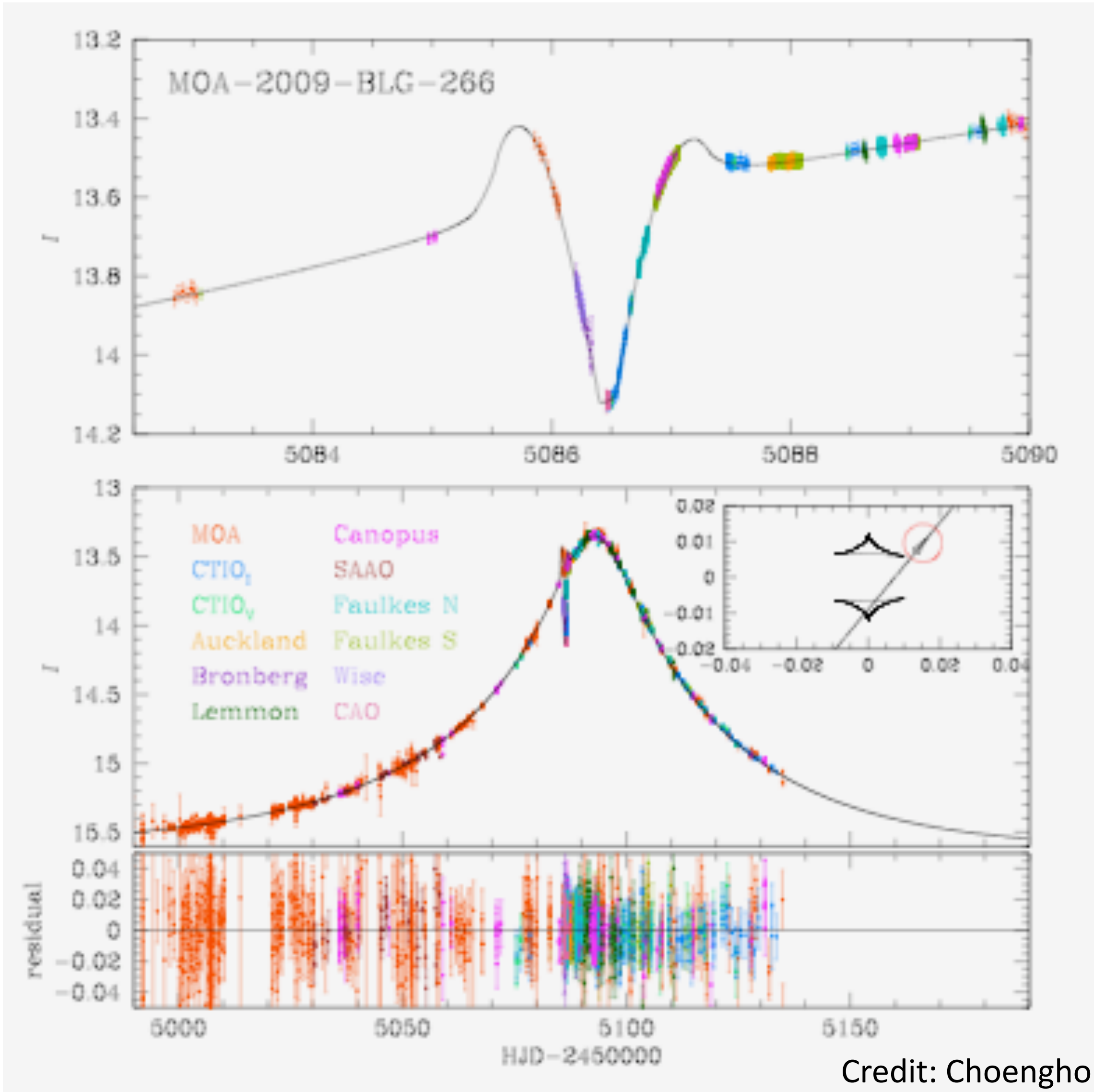


MOA-2009-BLG-266

The latest planet found by MOA + MicroFUN/PLANET

$q = 5 \times 10^{-5}$
$d = 0.9$

Preliminary:
$M_p \sim 14\ M_{Earth}$

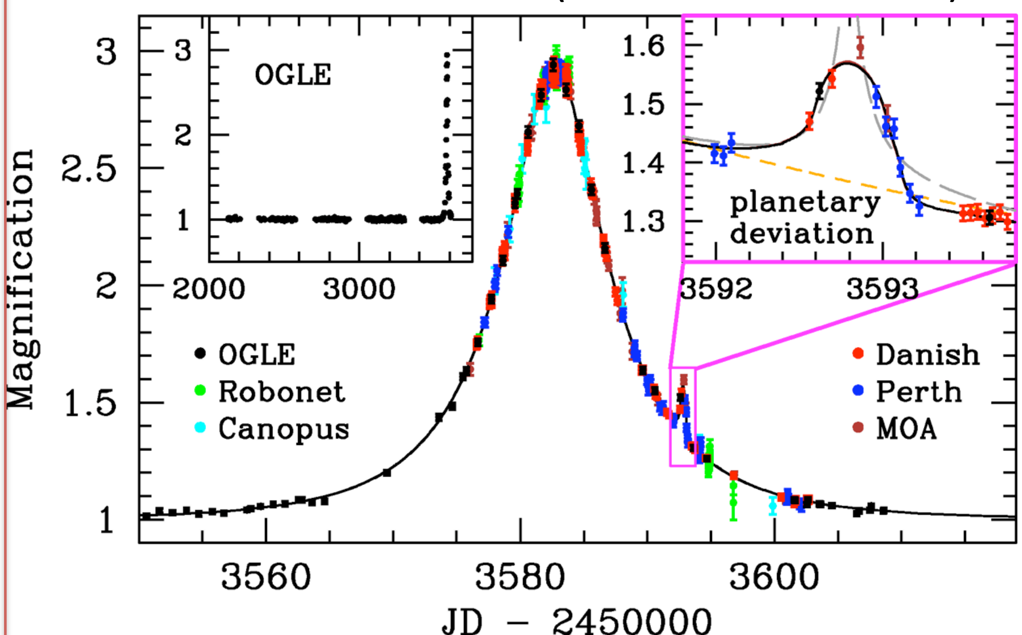


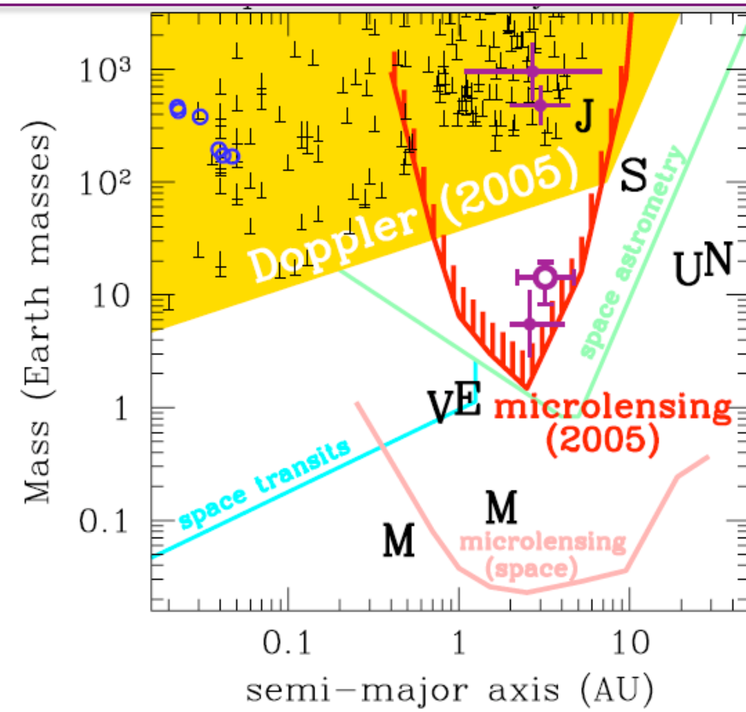
Credit: Choengho Han

Extrasolar Jupiter vs. Neptune

Gaudi et al. (2002) – NO planets from 43 events well observed by PLANET collaboration (1995-2000) :
< ~30% Jupiter around M dwarfs (at 95% conf)

First Gould & Loeb type planet:
A cool super Earth: ~5.5 M_{Earth}, 2.6 AU, T~50K!
OGLE-2005-BLG-390 (Beaulieu et al. 2006)





Small Number statistics, but implies:
Cold Neptunes Are Common!
~40% (16% - 69% at 90% conf)
(Gould et al. 2006)

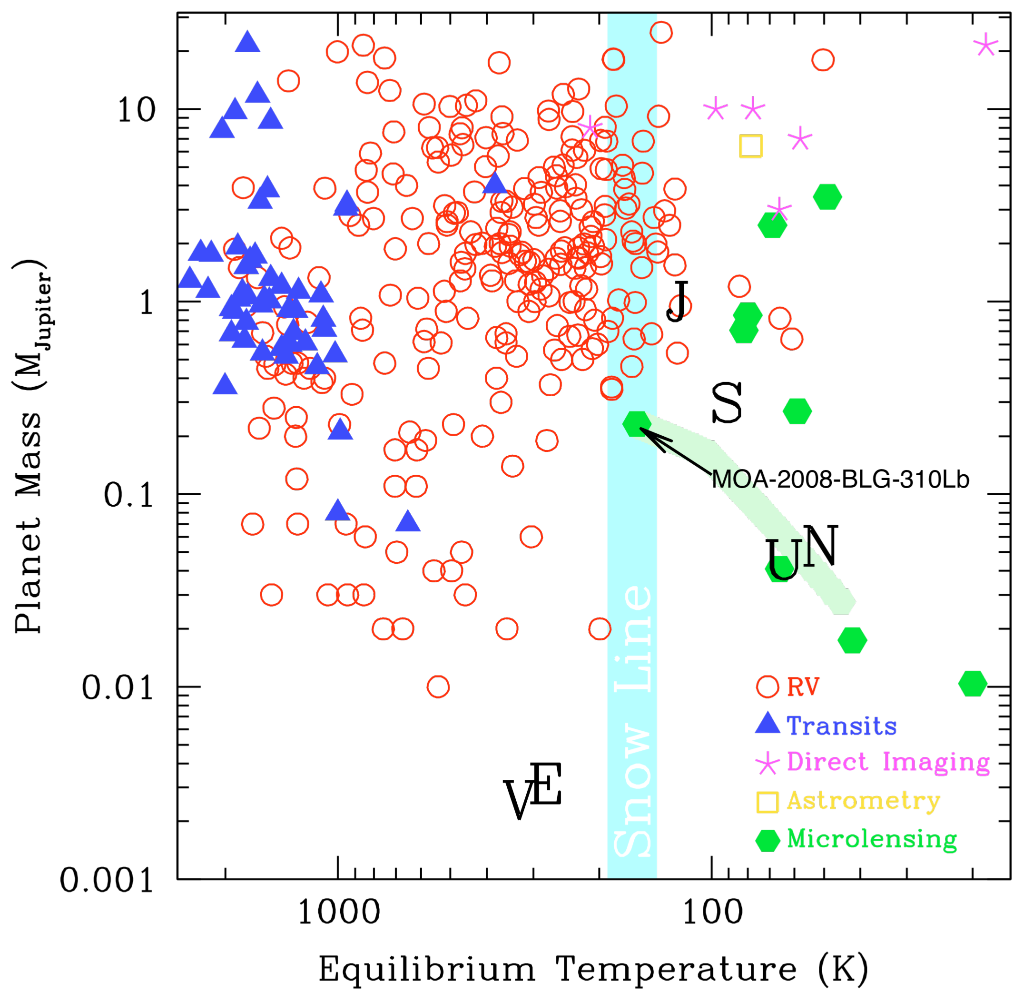
Why Microlensing?

•Planets down to Earth mass at a few AU (close to and beyond the snow line)

•Host stars – from M to G dwarfs + white dwarfs, brown dwarfs at ~1 – 8 kpc
(even potentially in M31)

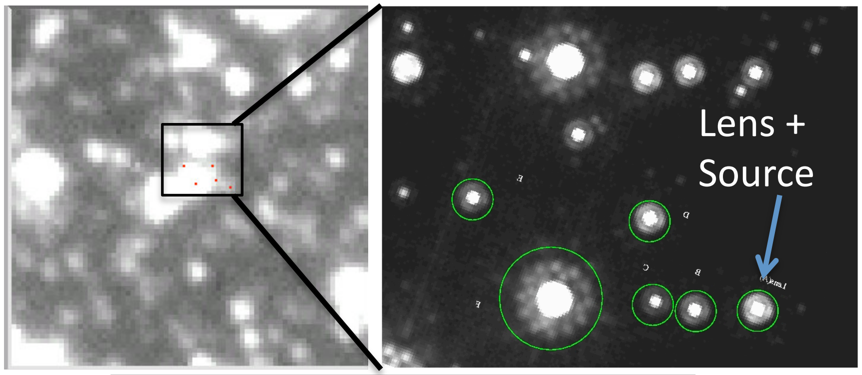
•Free floating planets (Juric & Tremaine 2008)

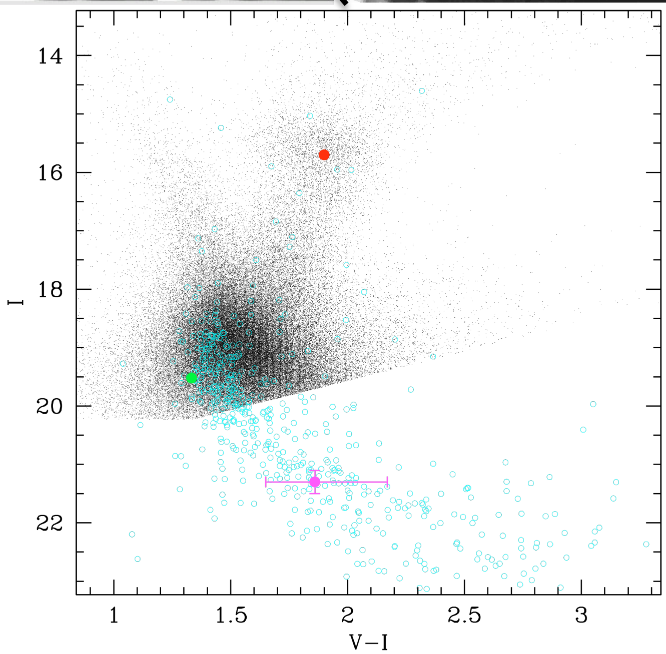
Speaking as a theorist, he [Scott Tremaine] notes that. “most every prediction by theorists about planetary formation has been wrong.”
-- Science Magazine, Jan 2002

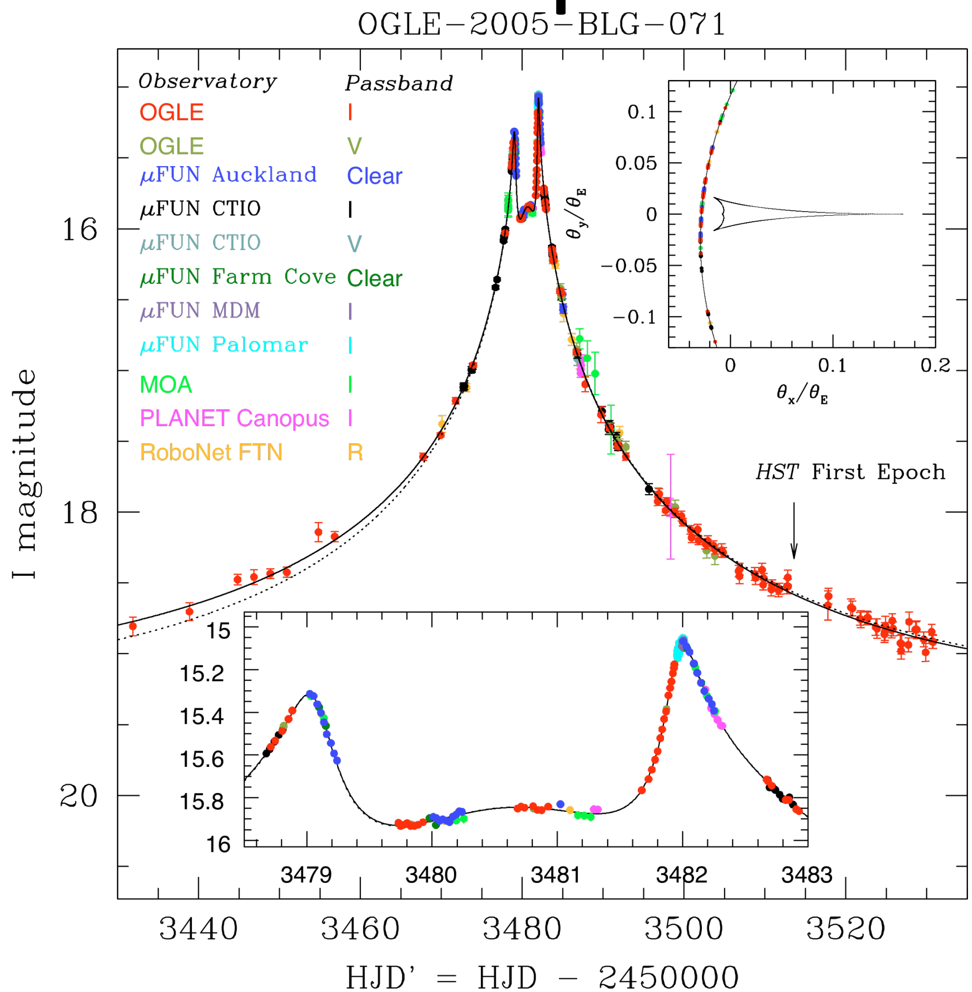


Janczak, Fukui, Dong et al., 2009, ApJ, Submitted, arXiv:0908.0529

The most massive M-dwarf planet?







Microlens Parallax + HST photometry & astrometry

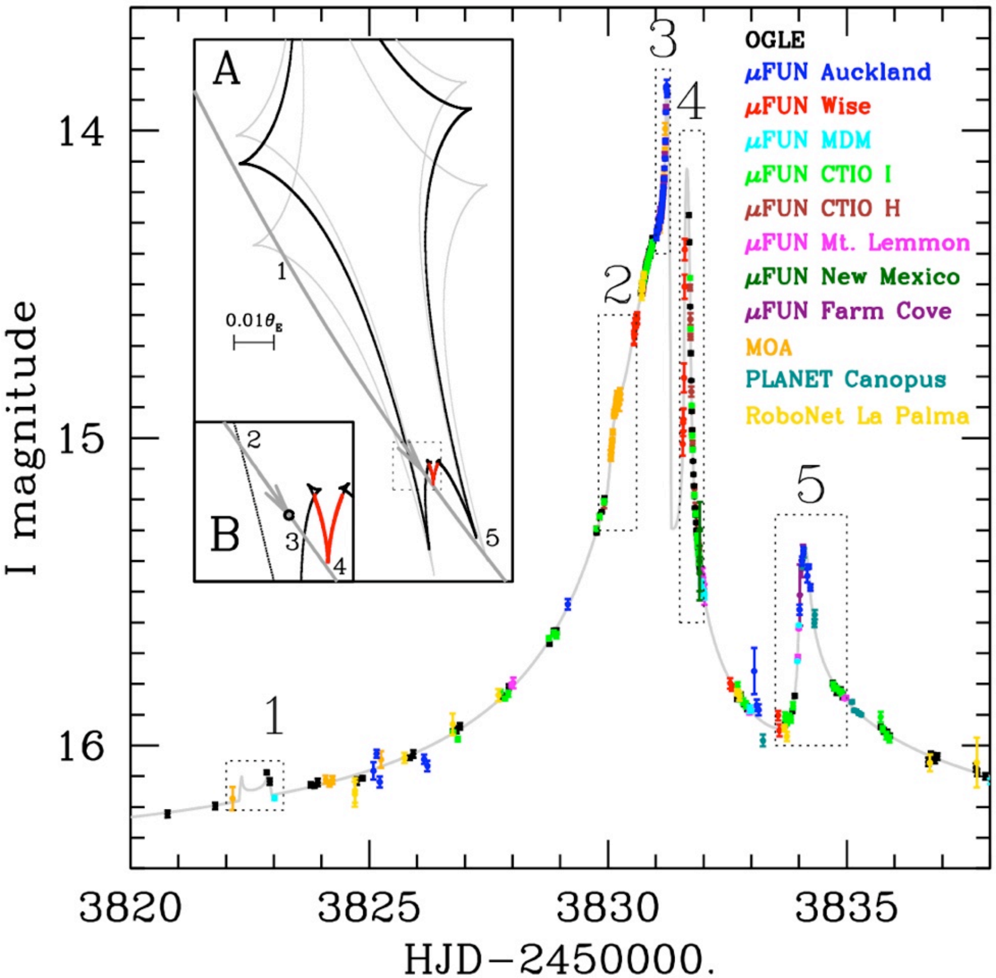
M = 0.46 ± 0.04 $M_\odot$ D_{lens} = 3.2 ± 0.4 kpc

M_p = 3.8 ± 0.4 M_J at 3.6 ± 0.2 AU

Discovery: Udalski, A. et al. 2005, ApJL, 628, 109

Characterization: Dong, S. et al. 2009, ApJ, 695, 970

The first Jupiter/Saturn Analog: OGLE-2006-BLG-109

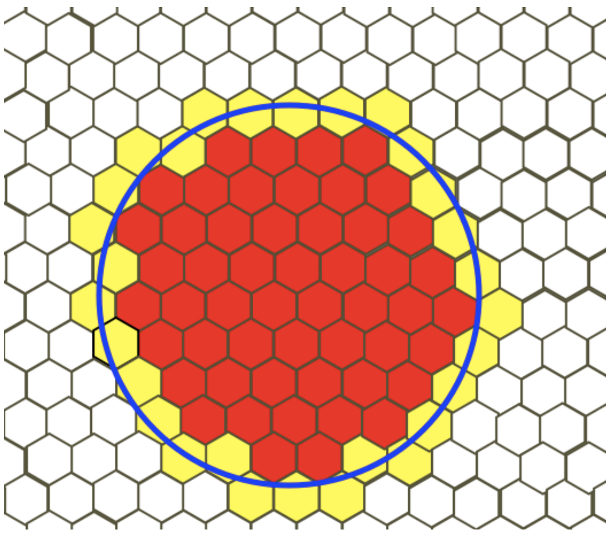


- A scaled version of our Solar System
- b: ~0.71 Jupiter Mass at ~2.3 AU

  c: ~0.27 Jupiter Mass at ~4.6 AU
- $M_* \sim 0.5\ M_\odot$

Gaudi et al. 2008, Science, 319, 927

An Efficient and Robust Algorithm



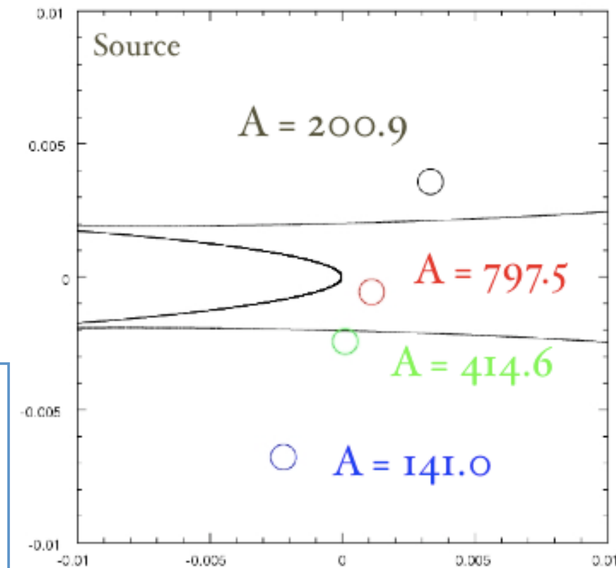
Dong, S., et al., 2006, ApJ, 642, 842 (Appendix A)
Dong, S. et al., 2009, ApJ, 698, 1826

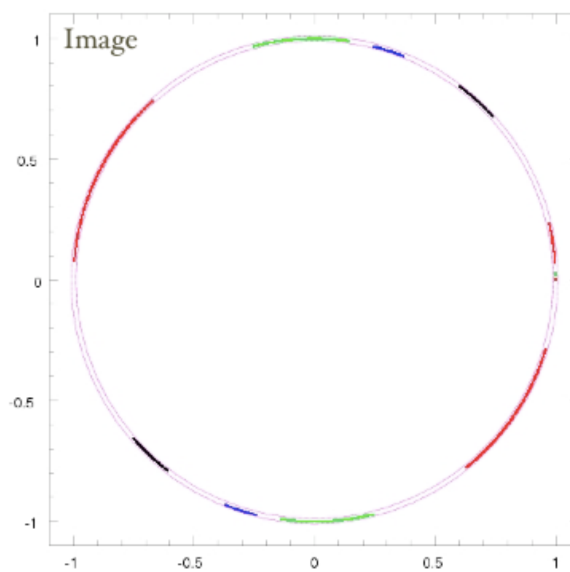
Loop-Linking (backup)combines contour integration and ray-shooting

(Hexagon-cell Magnification) Map-Making (workhorse):

• shoot rays from a narrow annulus on the image plane - reduce the overhead by orders of magnitude

•on the source plane, a combination of pixels and rays, with enhanced speed while preserving accuracy





Next-gen Survey in ~5 years

- A global ~2m wide-field telescope network
- A few thousands events per year with 10-20 min cadence, no human interference (solid statistics)
- ~40 η_{Earth} and 1-2 order of mag more Neptunes and Jupiters in 5-yr survey plus free floating planets
- Many more high-mag events (information rich: multi-planet system, precision mass, orbital motion, etc.)

Thank you!