Exoplanet Mass Measurements from Solar System Exploration Spacecraft

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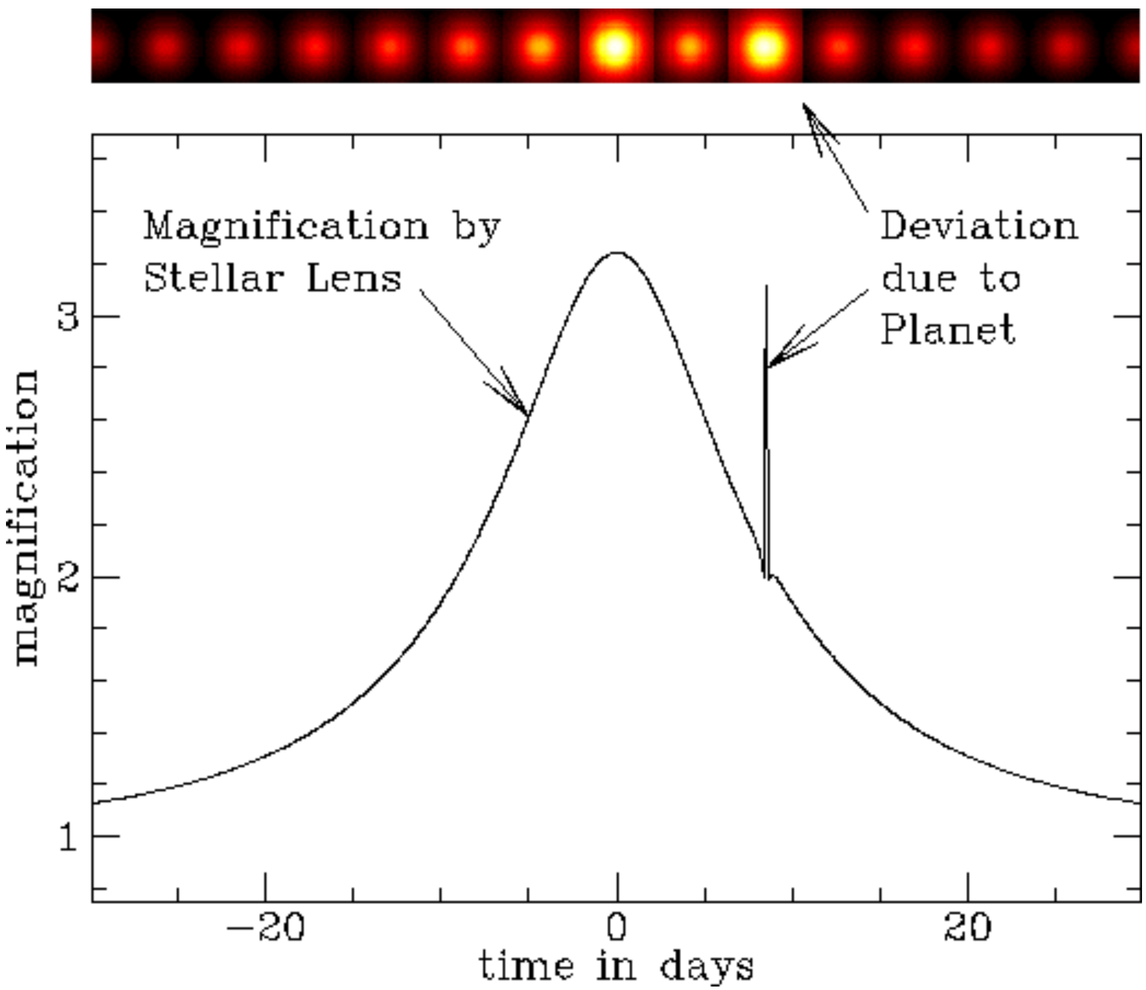
PLANET

Probing Lensing Anomalies NETwork



Many results
in collaboration with

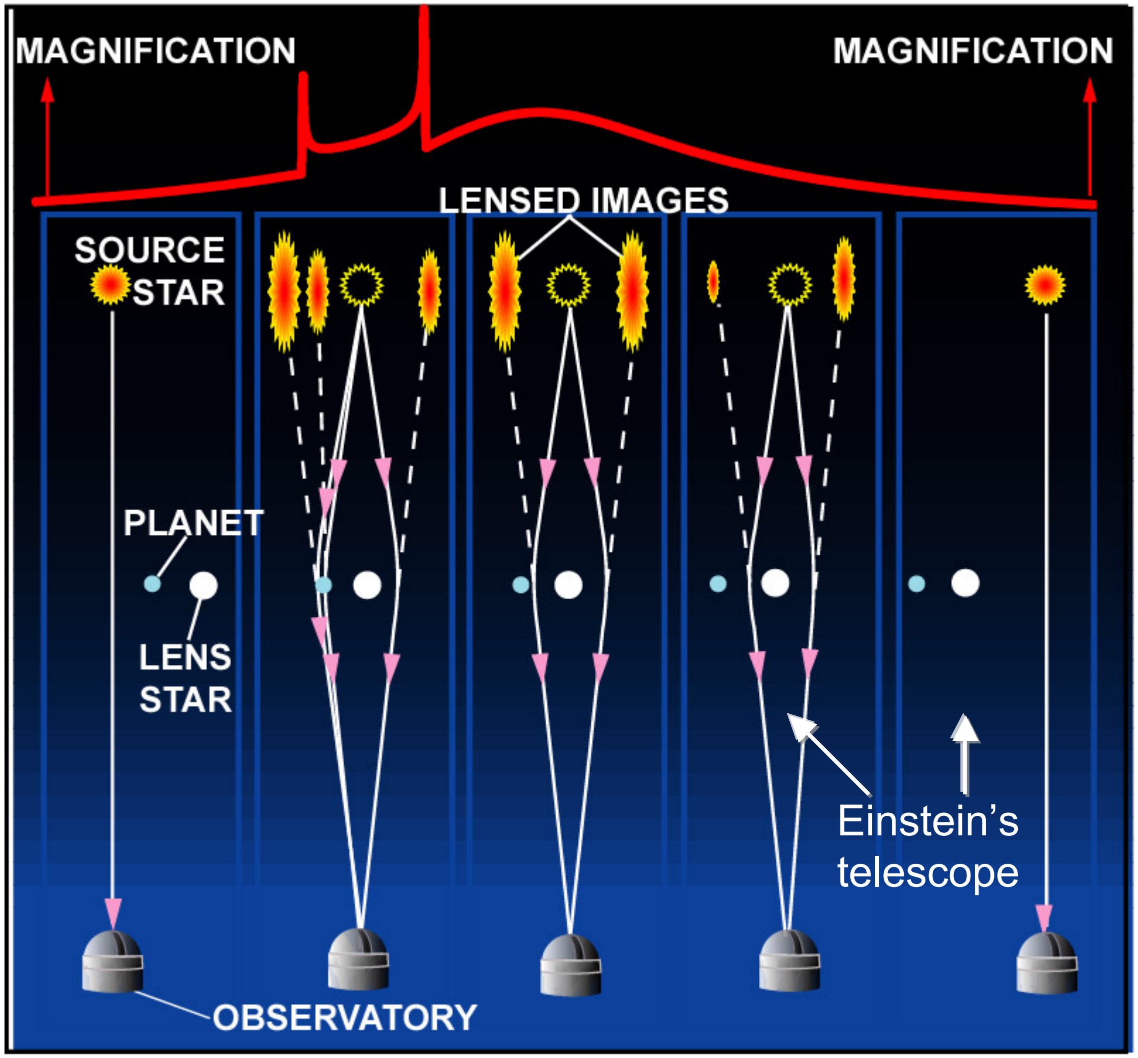
MicroFUN

Microlensing Follow-Up Network

OGLE

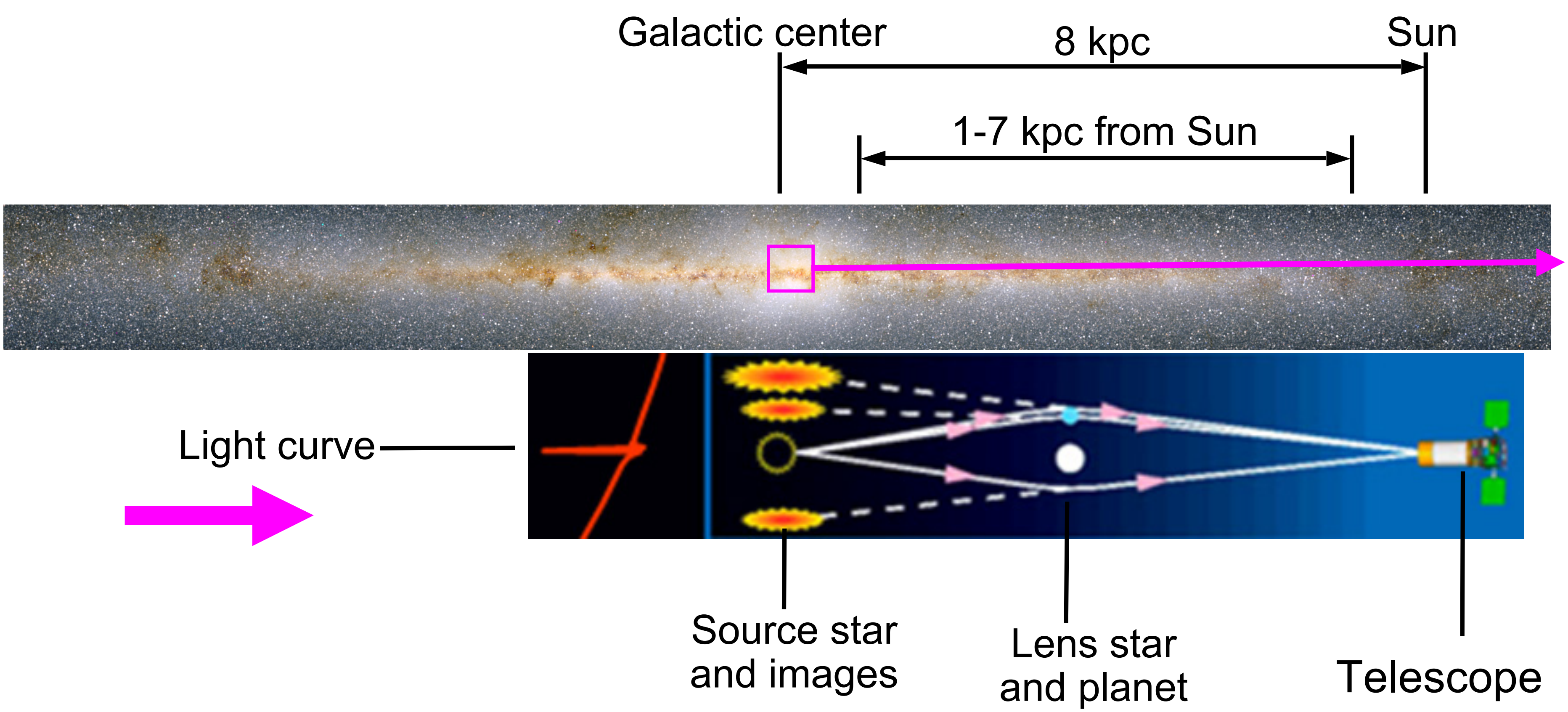
The Physics of Microlensing

- Foreground “lens” star + planet bend light of “source” star
- Multiple distorted images
  - Only total brightness change is observable
- Sensitive to planetary mass
- Low mass planet signals are rare – not weak
- Stellar lensing probability ~a few $\times 10^{-6}$
  - Planetary lensing probability ~0.001-1 depending on event details
- Peak sensitivity is at 2-3 AU: the Einstein ring radius, R_E



Key Fact: $1\ \text{AU} \approx \sqrt{R_{Sch} R_{GC}} = \sqrt{\frac{2GM}{c^2} R_{GC}}$

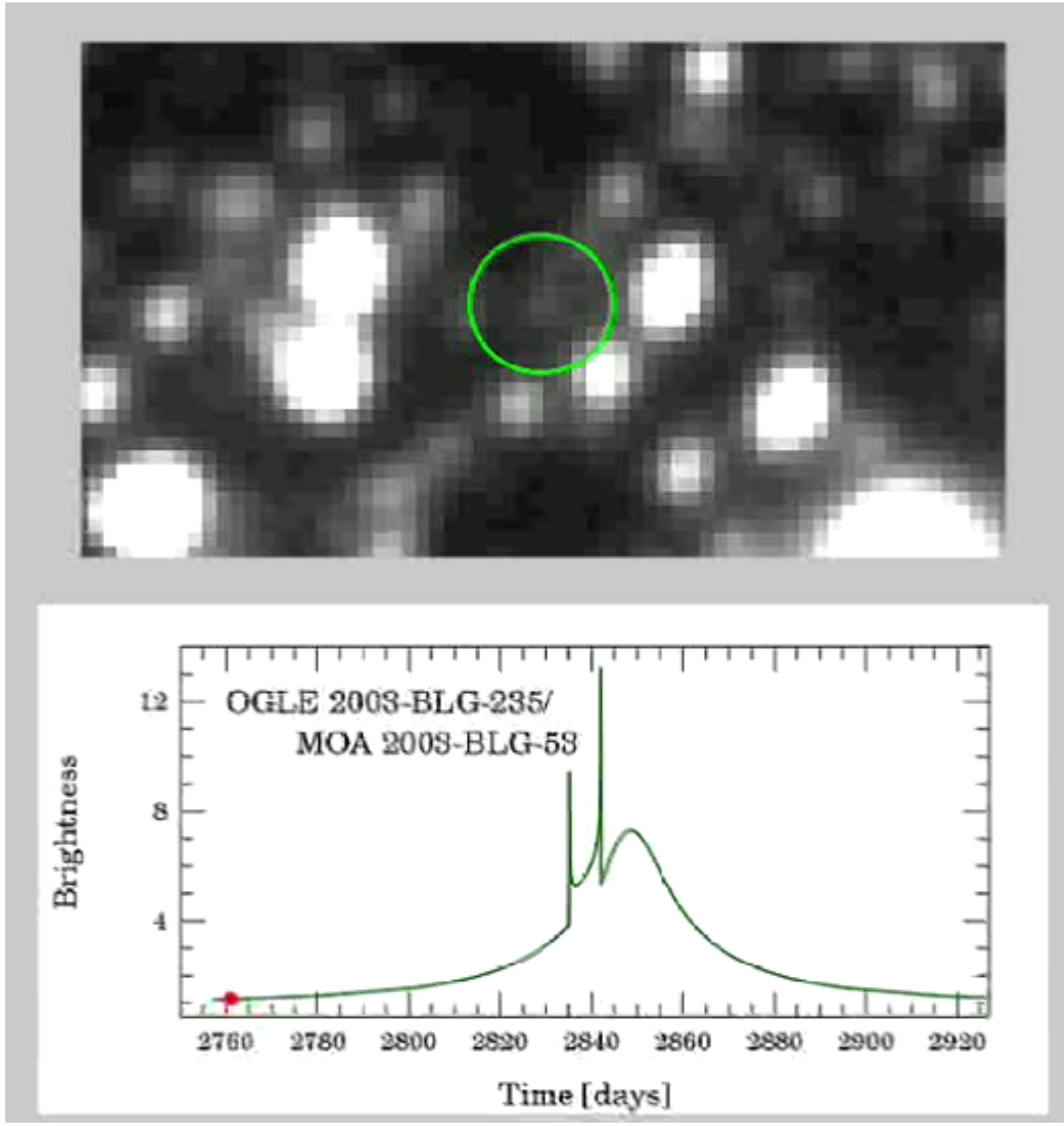
Microlensing Target Fields are in the Galactic Bulge



10s of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.

Simulated Lightcurve of 1st Planetary Event

Simulated version of actual data

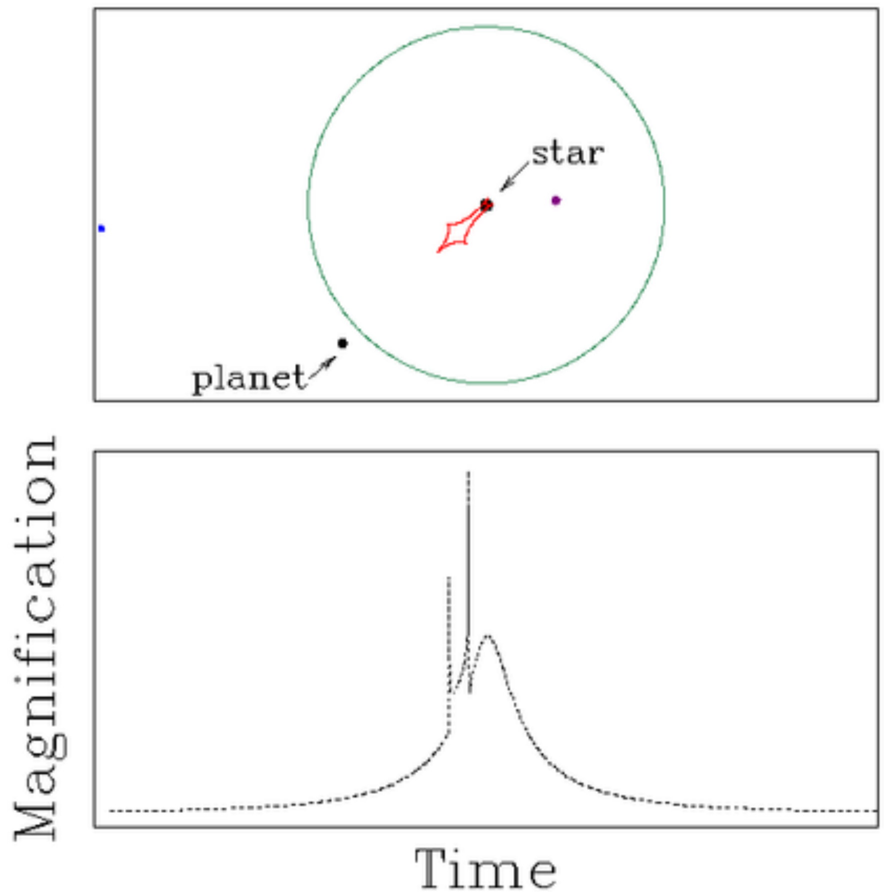


Best fit light curve simulated on an OGLE image

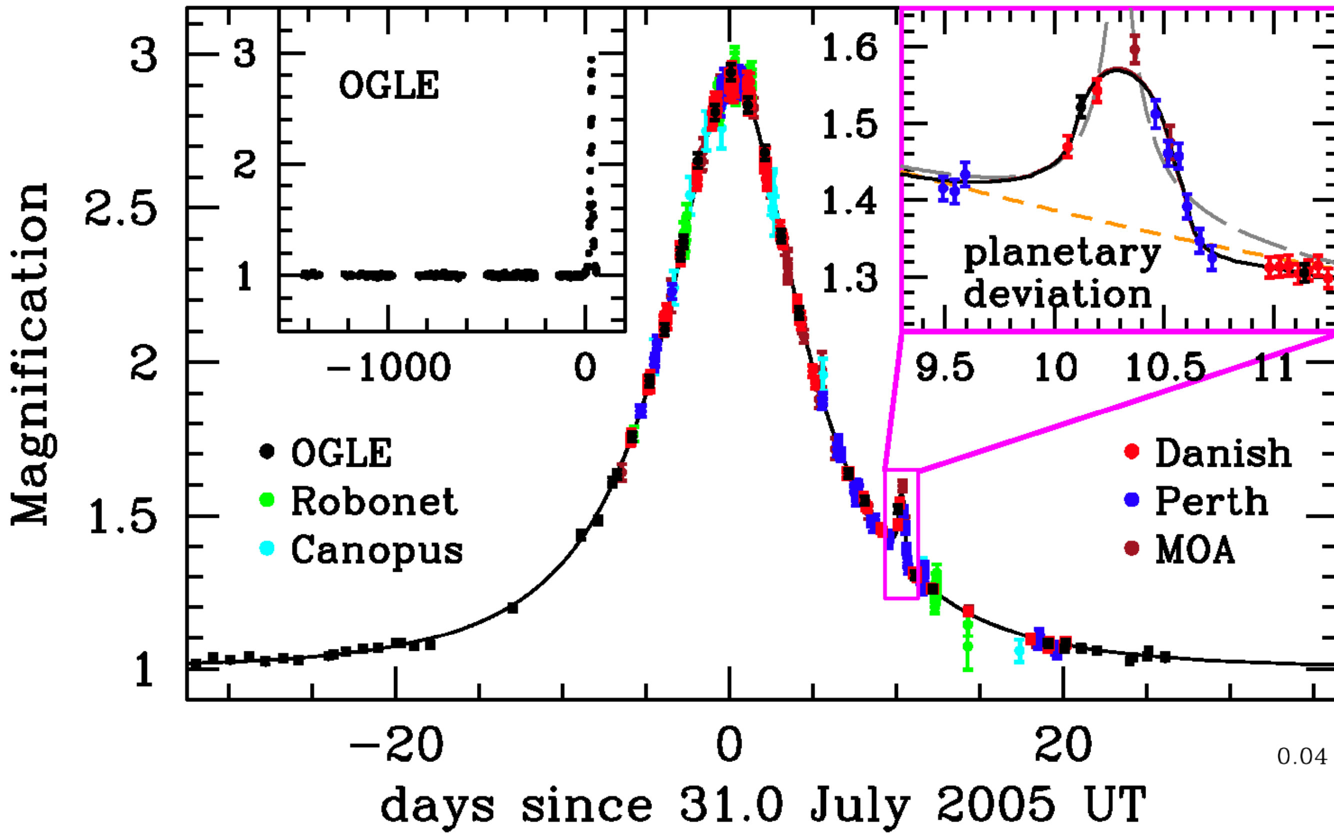
Lensed images at μarcsec resolution

View from telescope

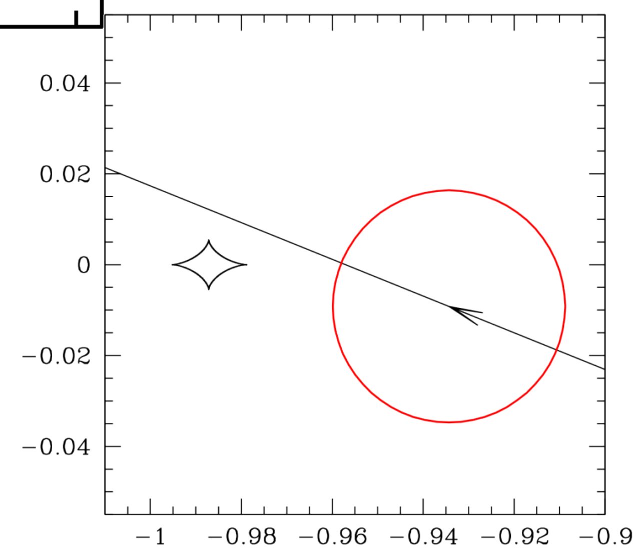
A planet can be discovered when one of the lensed images approaches its projected position.



OGLE-2005-BLG-390Lb - “lowest” mass exoplanet



A 5.5 $M_{\oplus}$ planet discovered by microlensing: OGLE-2005-BLG-390Lb. The lowest mass planet discovered when announced in 2006.

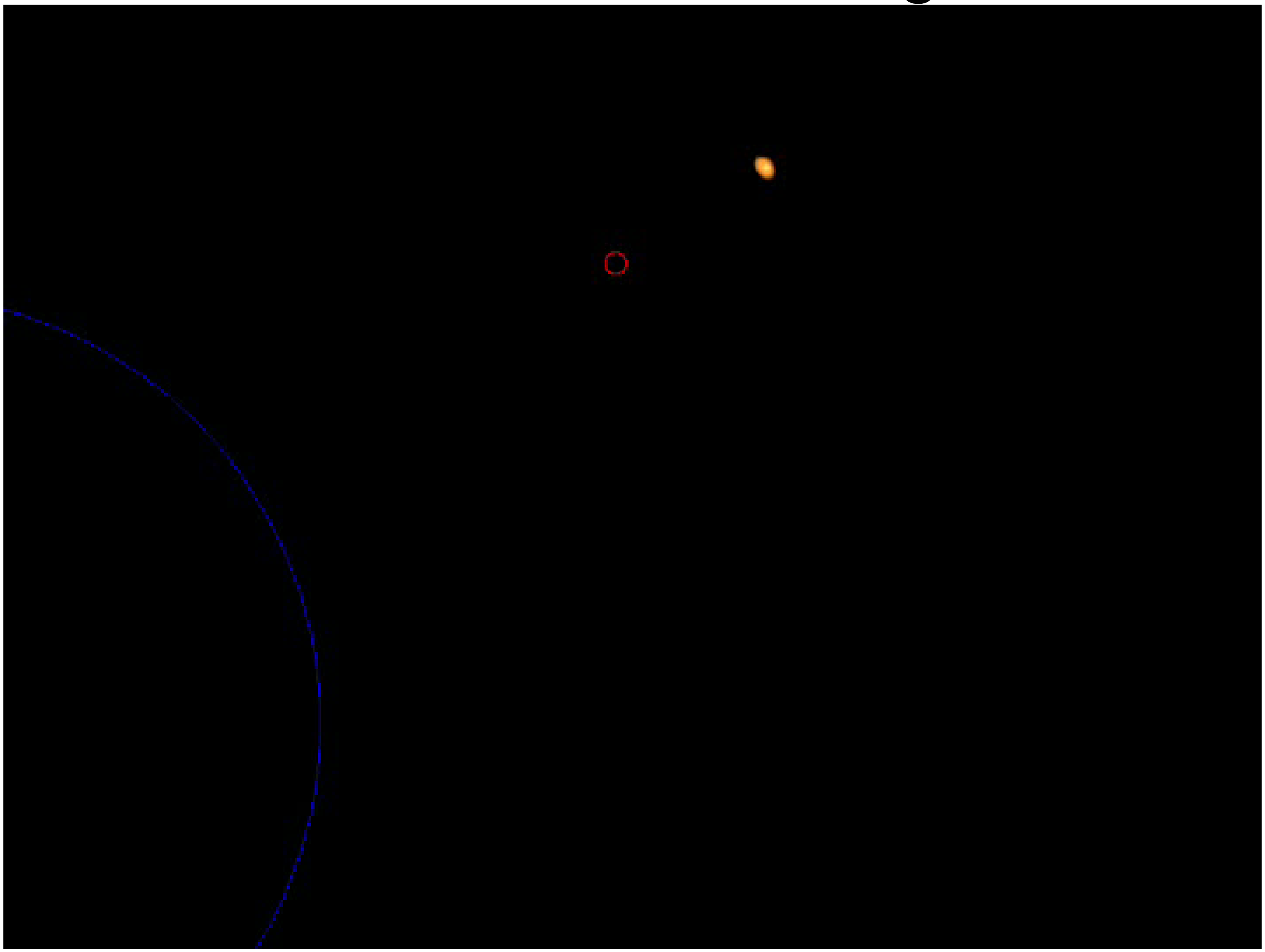


Source passes over caustic => significant finite source effect and clear measurement of t_*

Giant source star means lens star detection will be difficult

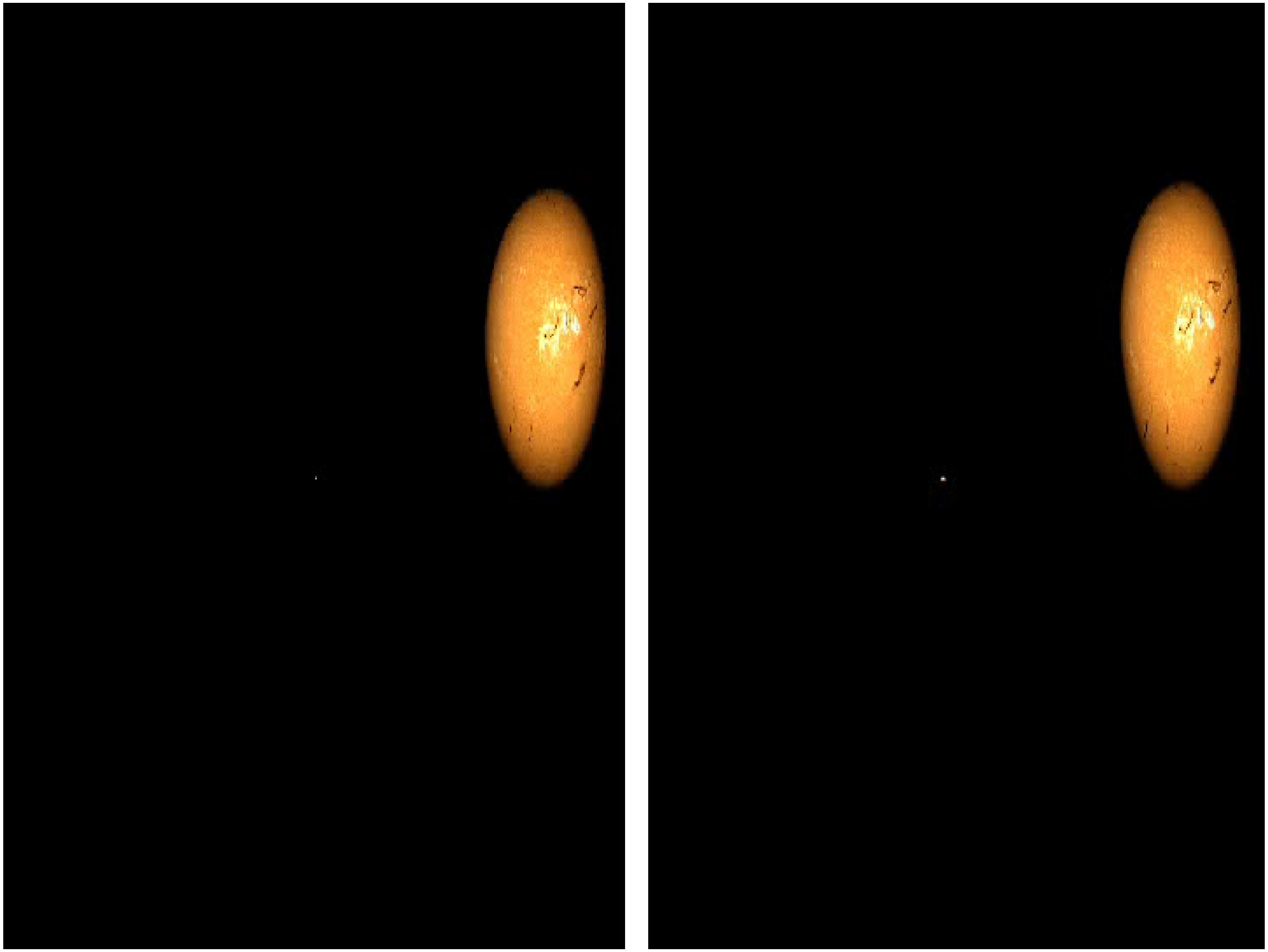
PLANET, OGLE & MOA Collaborations

OGLE-2005-BLG-390Lb at high resolution



- Simulated view from 10,000 km aperture space telescope
- H-α filter Solar images generate cool videos!

OGLE-2005-BLG-390Lb at high resolution

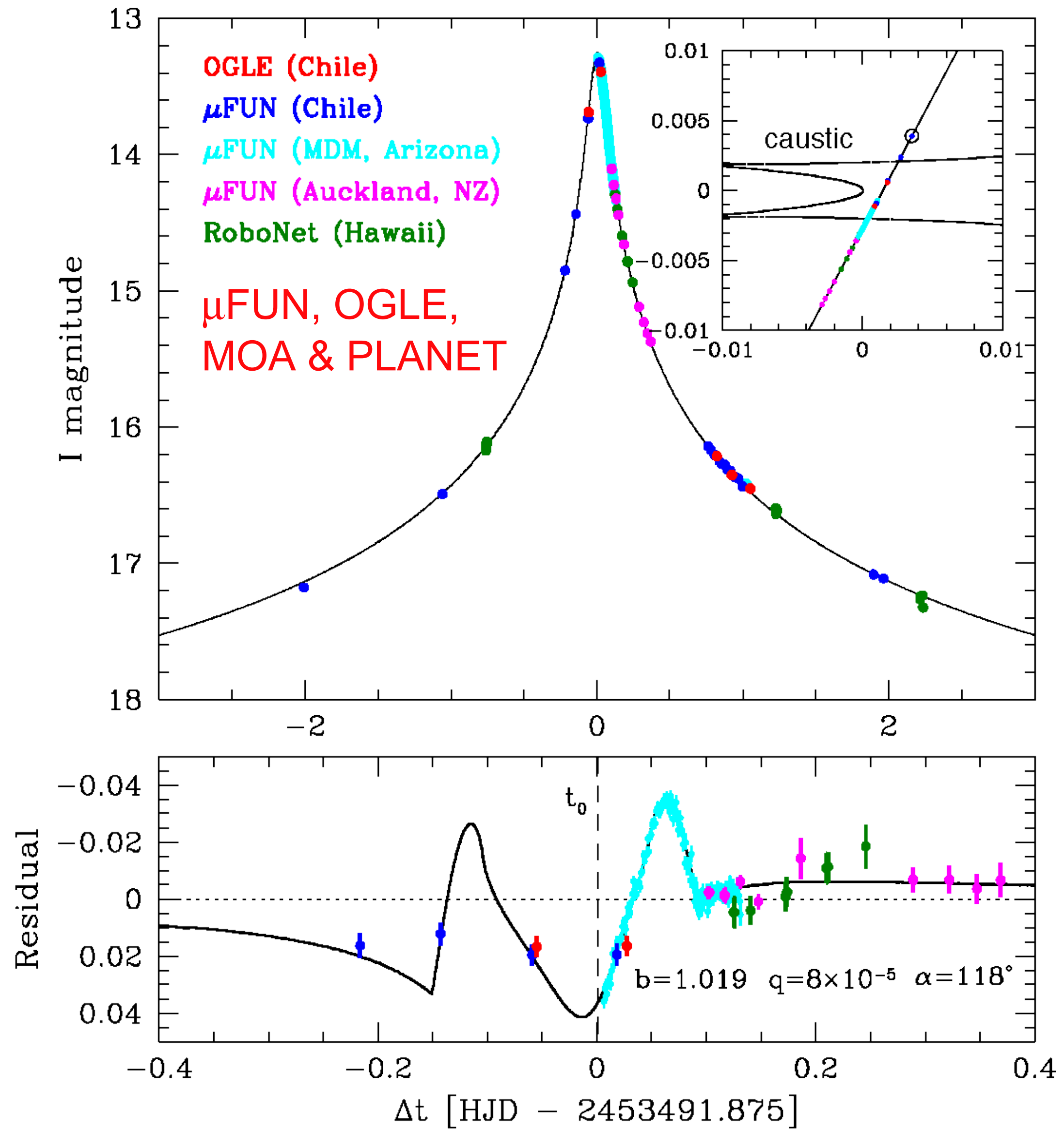


5.5 Earth-mass planet vs. 16.5 Earth-mass planet.

Only the total image area is observable. 5.5 Earth-mass is near limit for giant source.

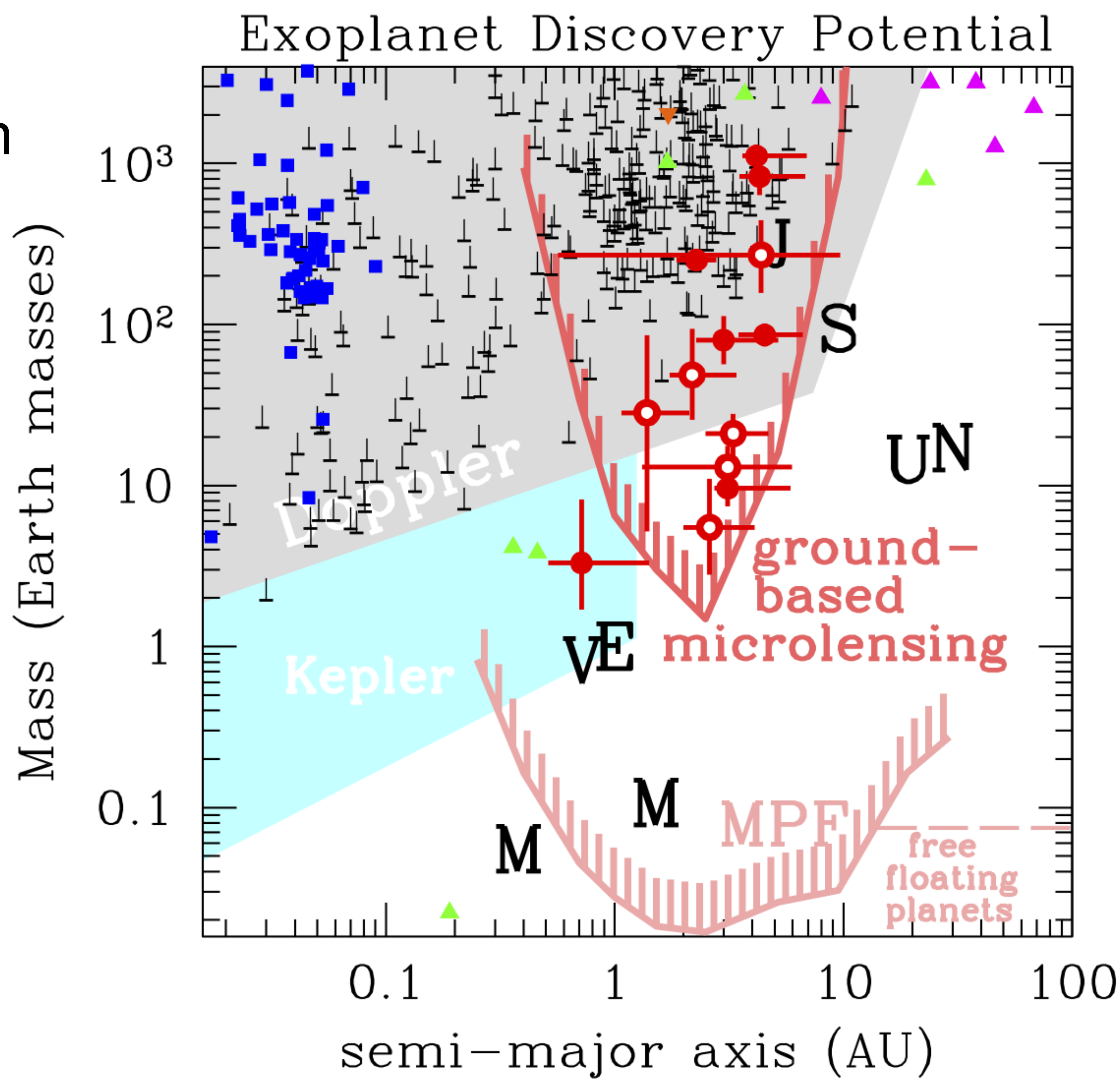
OGLE-2005-BLG-169Lb

- Detection of a ~13 $M_\oplus$ planet in a high magnification microlensing event
- Caustic crossing signal is obvious when light curve is divided by a single lens curve.
- Detection efficiency for ~10 $M_\oplus$ planets is << than for Jupiter-mass planets
  - 2/4 microlensing planets are super-Earths (~10 $M_\oplus$)
  - Super-Earths are much more common than Jupiters at 1-5 AU
  - ~37% of stars have super-Earths at 1.5-4.5 AU (> 16% at 90% confidence)



Microlensing Discoveries vs. Other Techniques

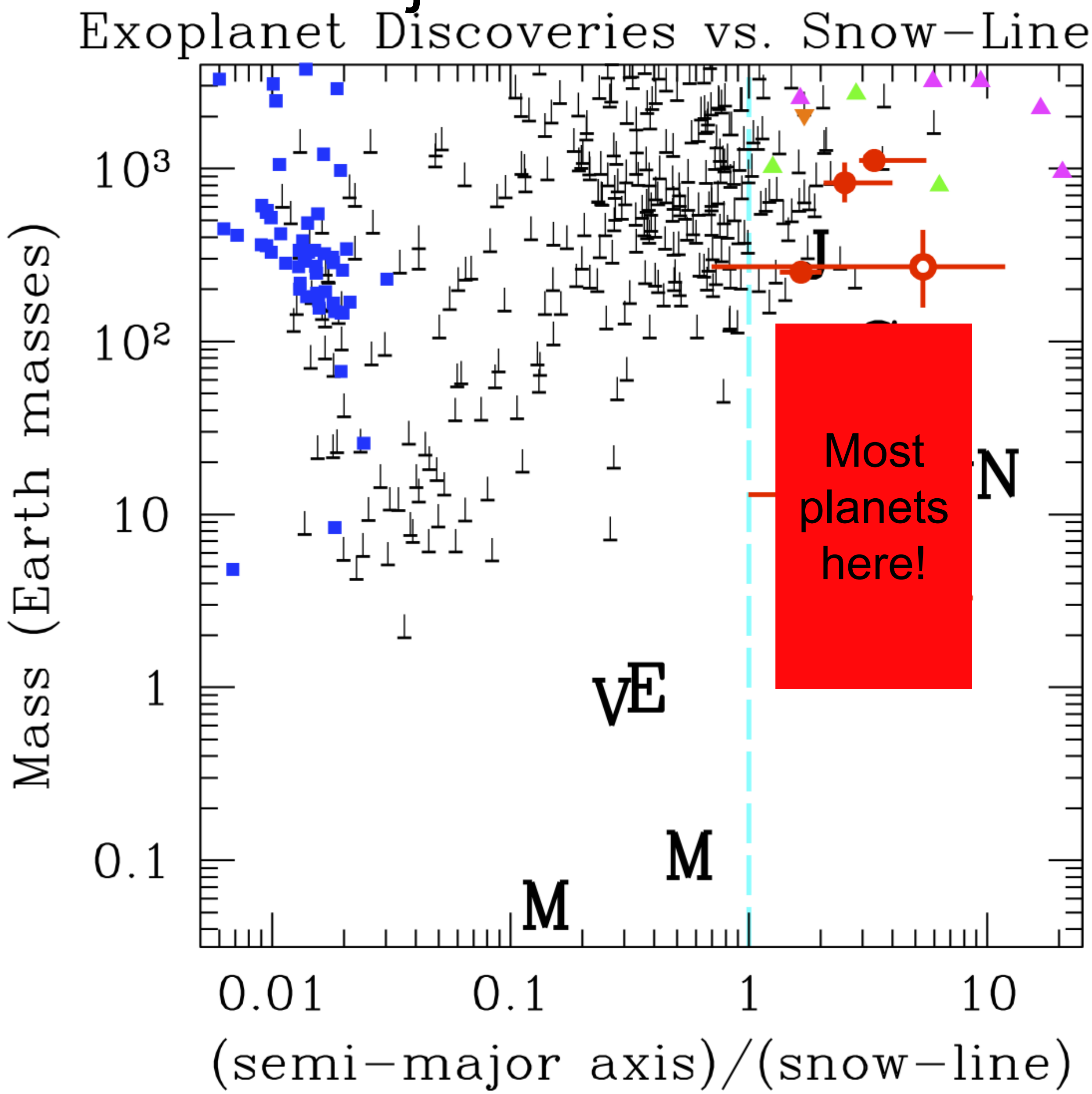
- Microlensing discoveries in red
- Doppler discoveries in black
- Transit discoveries shown as blue squares
- Direct detection, and timing are magenta and green triangles
- Microlensing opens a new window on exoplanets at 1-5 AU
  - Sensitivity approaching 1 Earth-mass



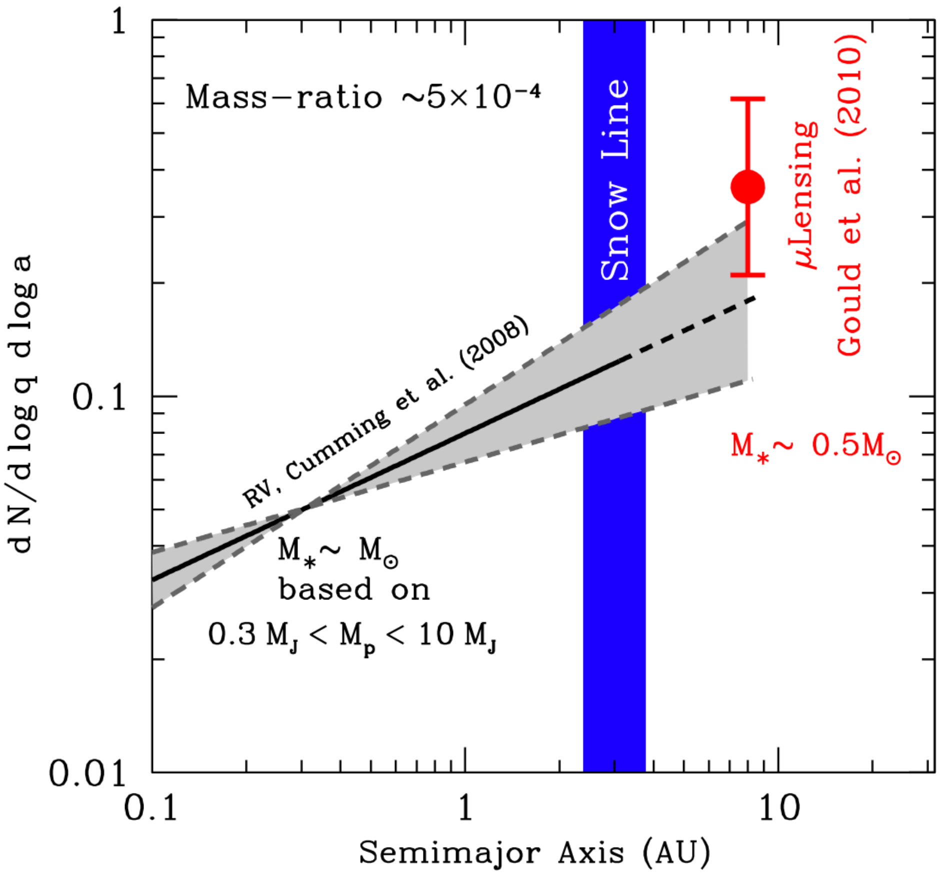
Planet mass vs. semi-major axis/snow-line

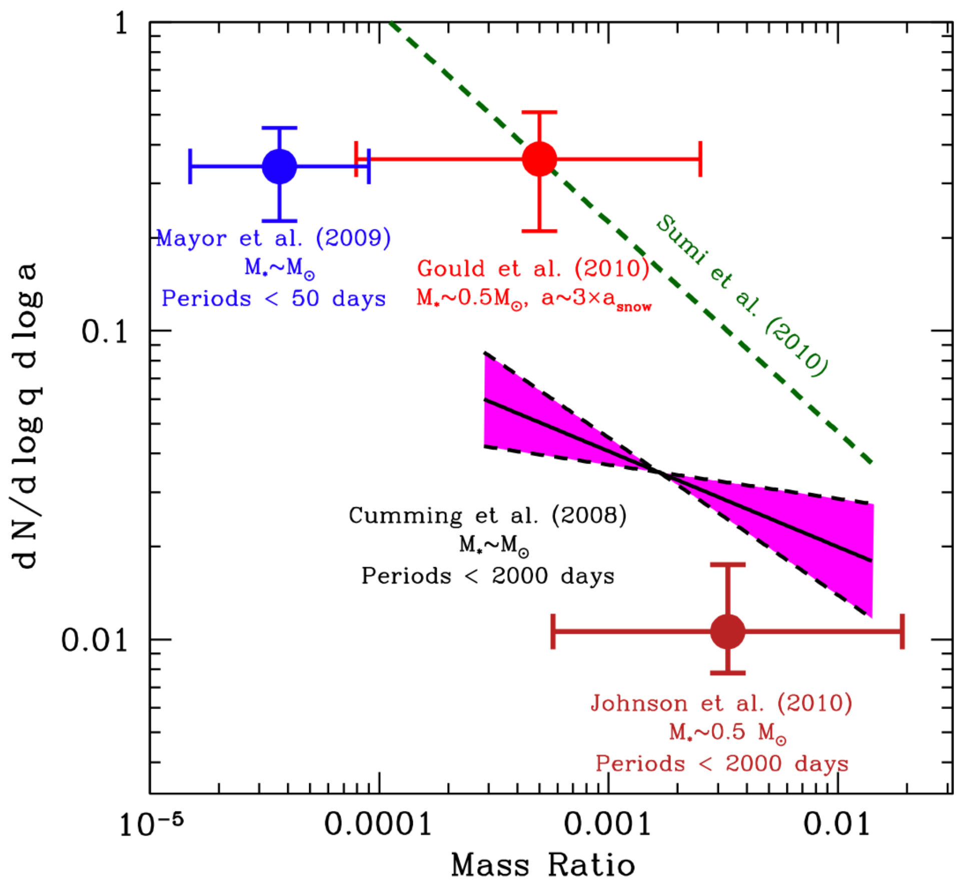
- "snow-line" defined to be 2.7 AU ($M/M_\odot$)
  - since L∝ M^2 during planet formation
- Microlensing discoveries in **red.**
- Doppler discoveries in black
- Transit discoveries shown as blue circles

- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered



Comparison of Statistical Results





Sumi et al. (2010) : $dN_p/d(\log q) \sim q^{-0.7}$

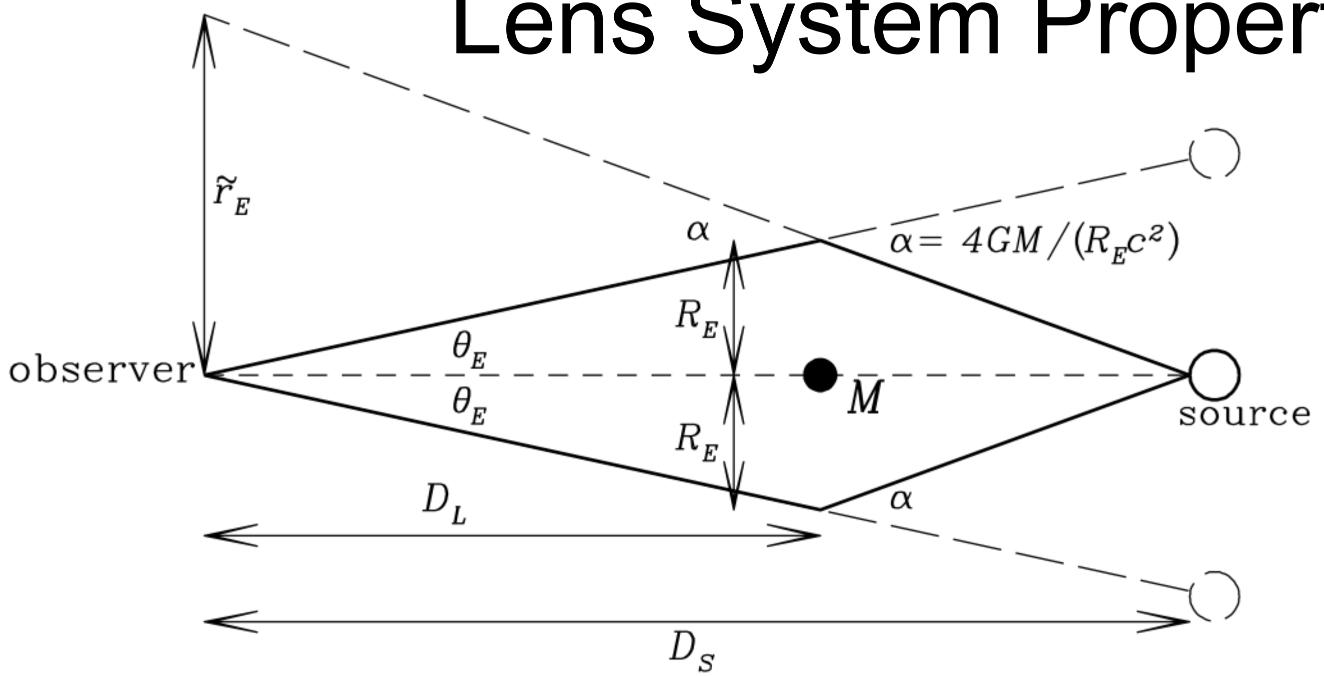
Gould et al. (2010) : $d^2N/d(\log q)\, d(\log a) = 0.36 \pm 0.15$

for $M \approx 0.5\, M_\odot$ and $q \approx 5 \times 10^{-4}$

Lens System Properties

- For a single lens event, 3 parameters (lens mass, distance, and velocity) are constrained by the Einstein radius crossing time, t_E
- There are two ways to improve upon this with light curve data:
  - Determine the angular Einstein radius : $\theta_E = \theta_* t_E / t_* = t_E \mu_{rel}$ where θ_* is the angular radius of the star and μ_{rel} is the relative lens-source proper motion
  - Measure the projected Einstein radius, $\tilde{r}_E$, with the microlensing parallax effect (due to Earth's orbital motion).

Lens System Properties



- Einstein radius : $P_E = \theta_* t_E / t_*$ and projected Einstein radius, $\tilde{r}_E$
  - t_* = the angular radius of the star
  - $\tilde{r}_E$ from the microlensing parallax effect (due to Earth's orbital motion).

$$R_E = \theta_E D_L \text{, so } \alpha = \frac{\tilde{r}_E}{D_L} = \frac{4GM}{c^2 \theta_E D_L} \text{. Hence } M = \frac{c^2}{4G} \theta_E \tilde{r}_E$$

Finite Source Effects & Microlensing Parallax Yield Lens System Mass

- If only θ_E or $\tilde{r}_E$ is measured, then we have a mass-distance relation.
- Such a relation can be solved if we detect the lens star and use a mass-luminosity relation
  - This requires HST or ground-based adaptive optics
- With θ_E, $\tilde{r}_E$, and lens star brightness, we have more constraints than parameters

mass-distance relations:

$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

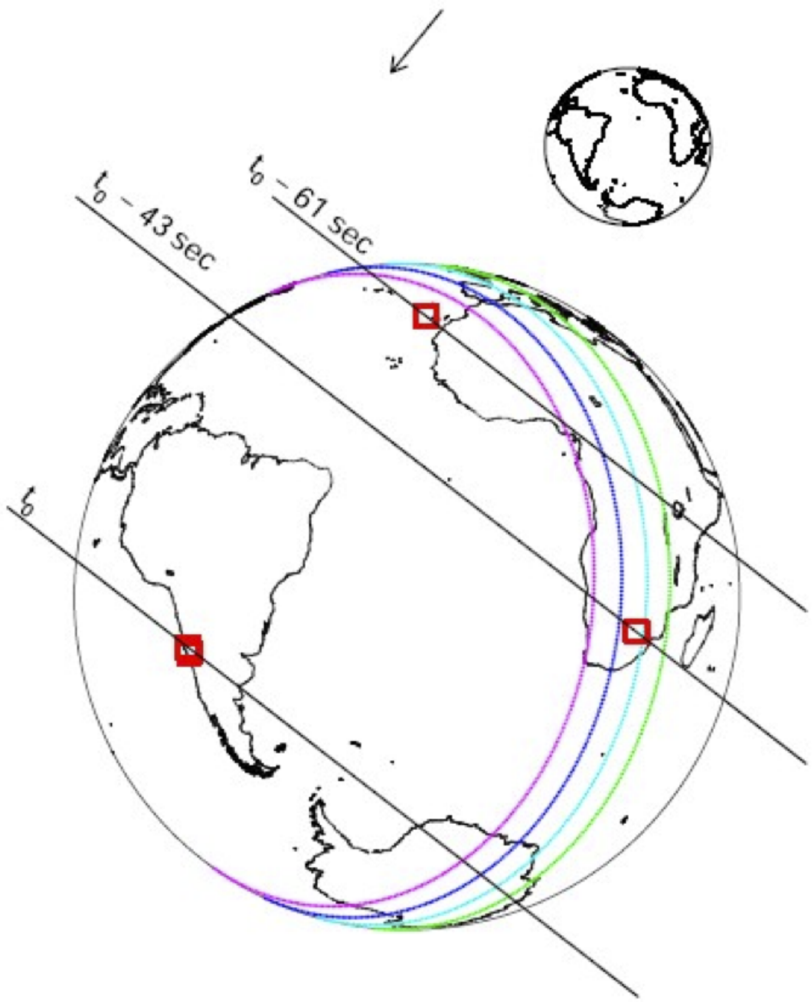
$$M_L = \frac{c^2}{4G}\tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E \theta_E$$

3 Ways to Measure Microlensing Parallax

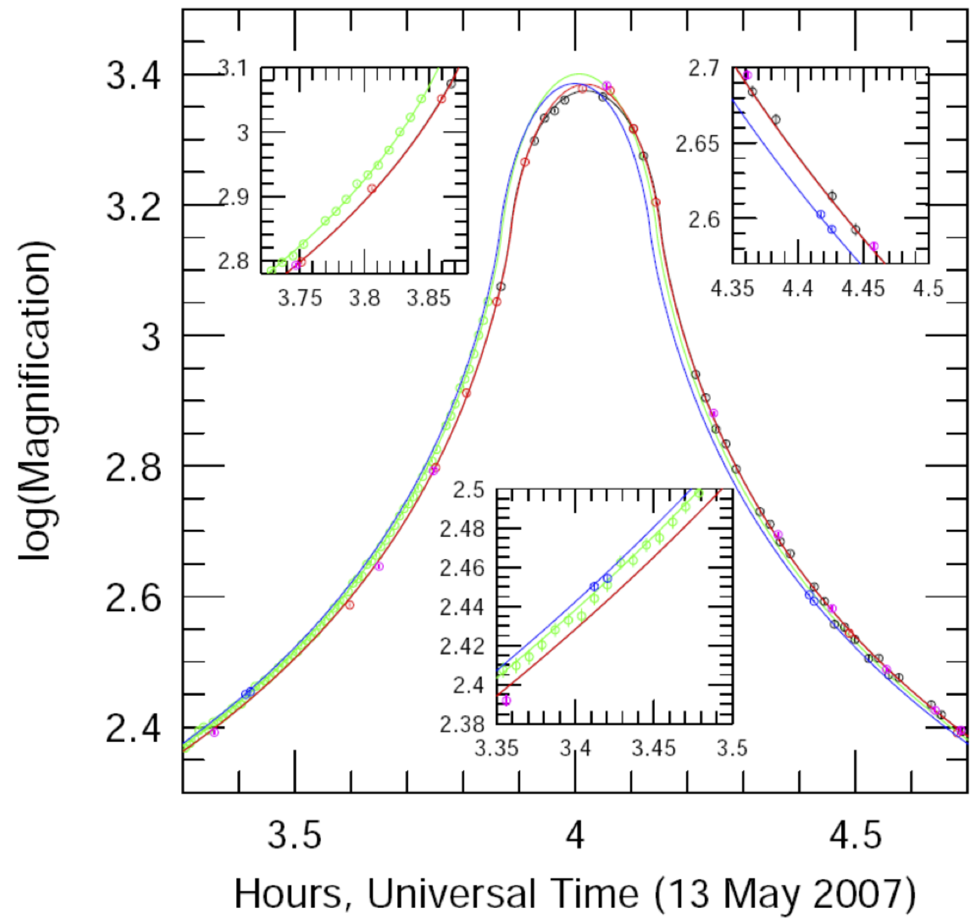
- Terrestrial - from different locations on the Earth
  - Requires very high magnification - rapid change in brightness
  - Measured for OGLE-2007-BLG-224 - disk brown dwarf
- Orbital motion of the Earth
  - Requires a long Einstein radius crossing time, $t_E \geq 100$ days
  - Measurable for some lenses in the Galactic disk, but not in the Galactic bulge
- From a Satellite far from Earth
  - Solar System missions provide “opportunities”
    - Cassini (late 1990’s)
    - Deep Impact 2004 (proposal)
  - OGLE-2005-SMC-1 measured by Spitzer
  - MOA-2009-BLG-266 - first planetary microlensing event with extra-terrestrial observations - by EPOXI (formerly Deep Impact) in Oct., 2009.

Terrestrial Microlensing Parallax



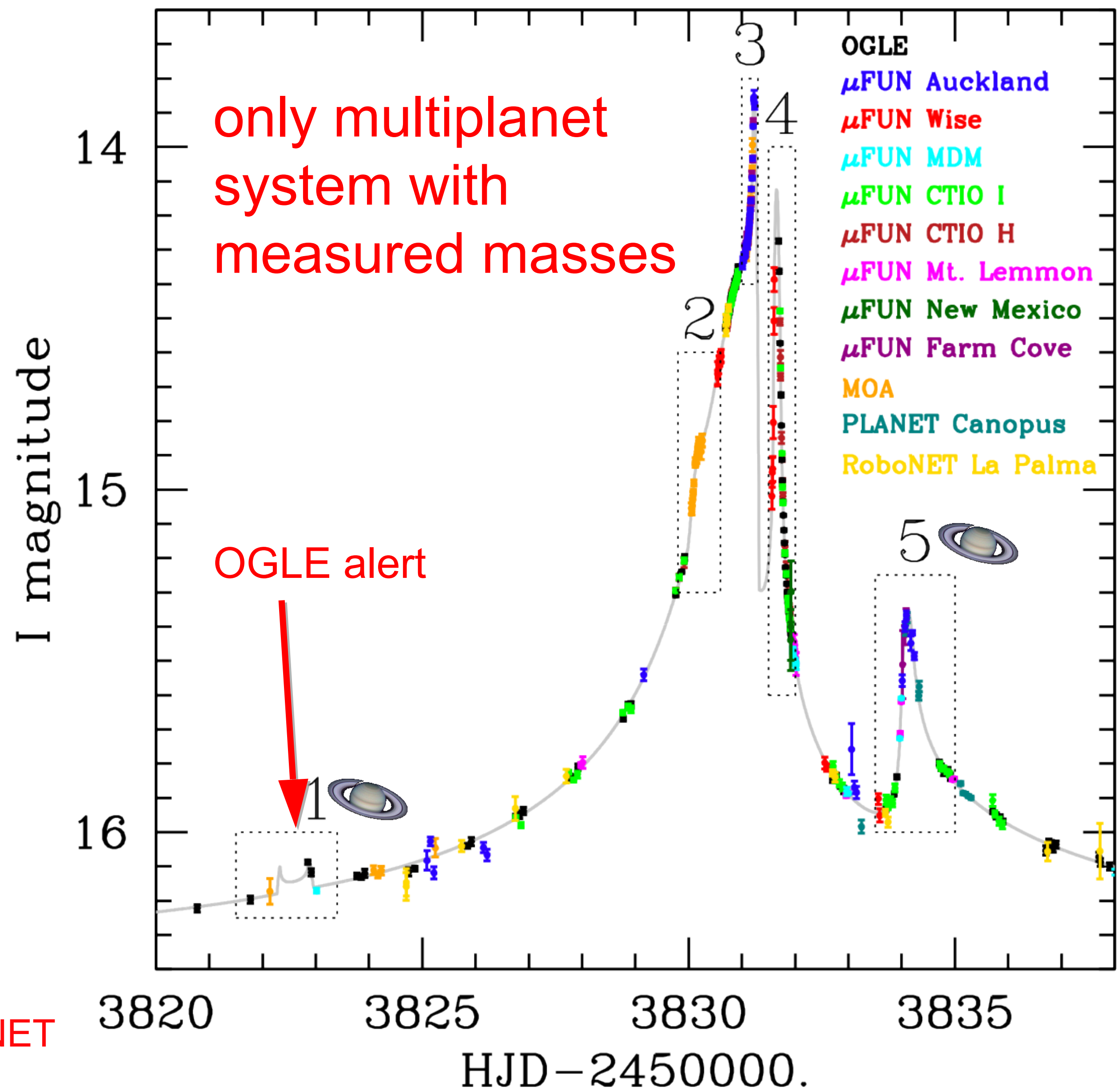
OGLE-2007-BLG-224

Canaries South Africa Chile



Double-Planet Event: OGLE-2006-BLG-109

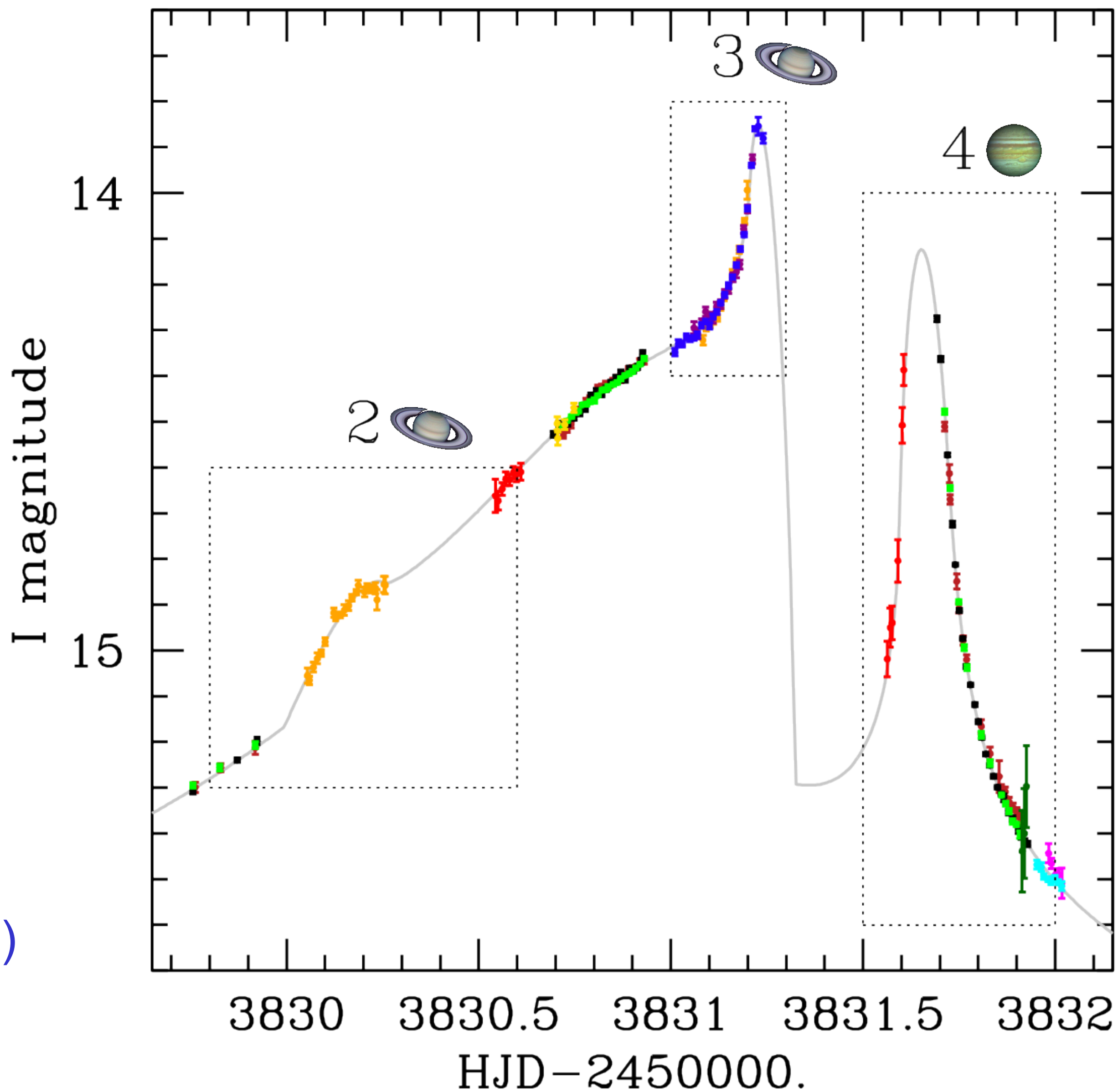
- 5 distinct planetary light curve features
- OGLE alerted 1st feature as potential planetary signal
- High magnification
- Feature #4 requires an additional planet
- Planetary signals visible for 11 days
- Features #1 & #5 require the orbital motion of the Saturn-mass planet



μFUN, OGLE, MOA & PLANET

OGLE-2006-BLG-109 Light Curve Detail

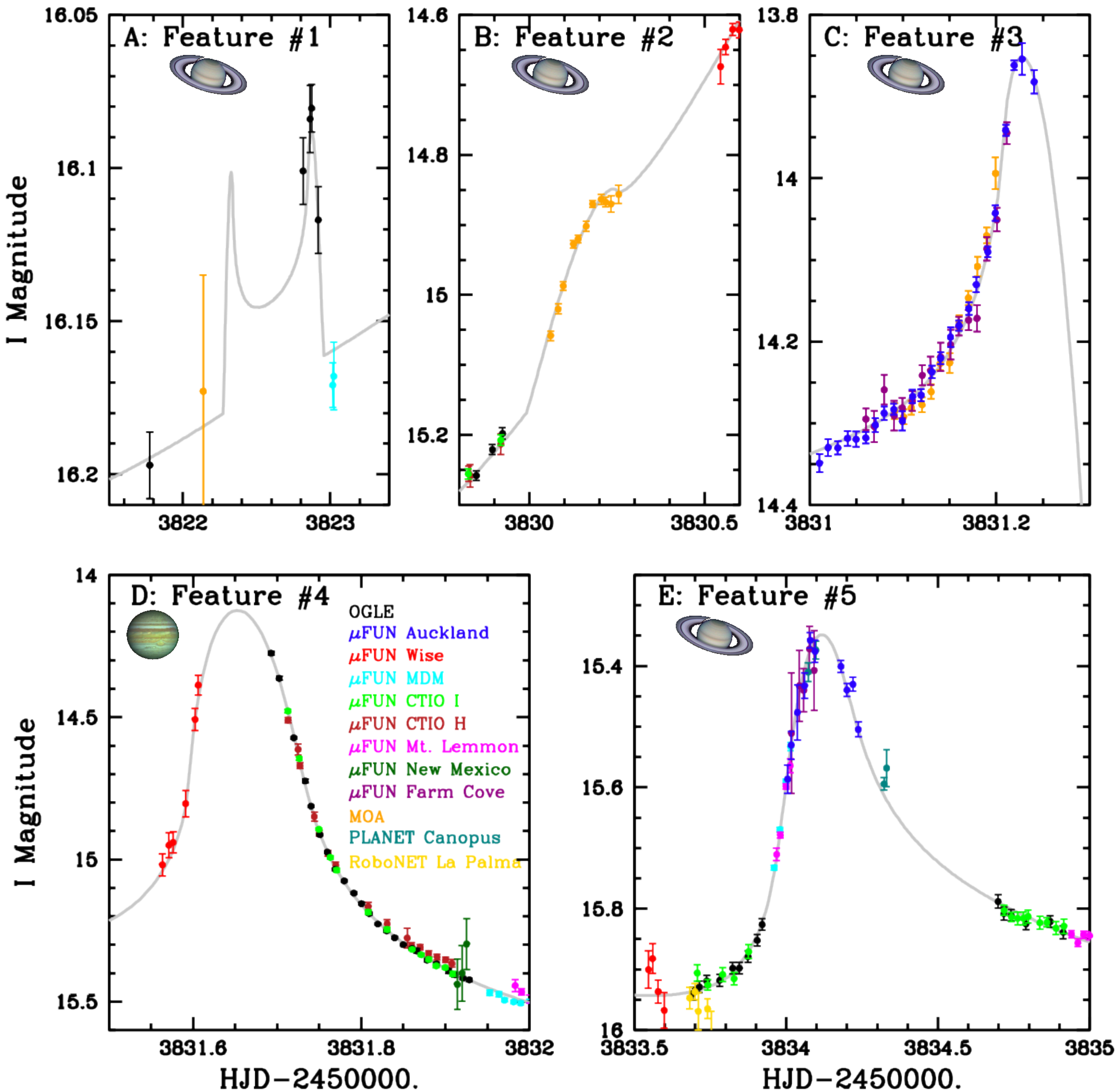
- OGLE alert on feature #1 as a potential planetary feature
- μFUN (Gaudi) obtained a model approximately predicting features #3 & #5 prior to the peak
- But feature #4 was not predicted - because it is due to the Jupiter - not the Saturn



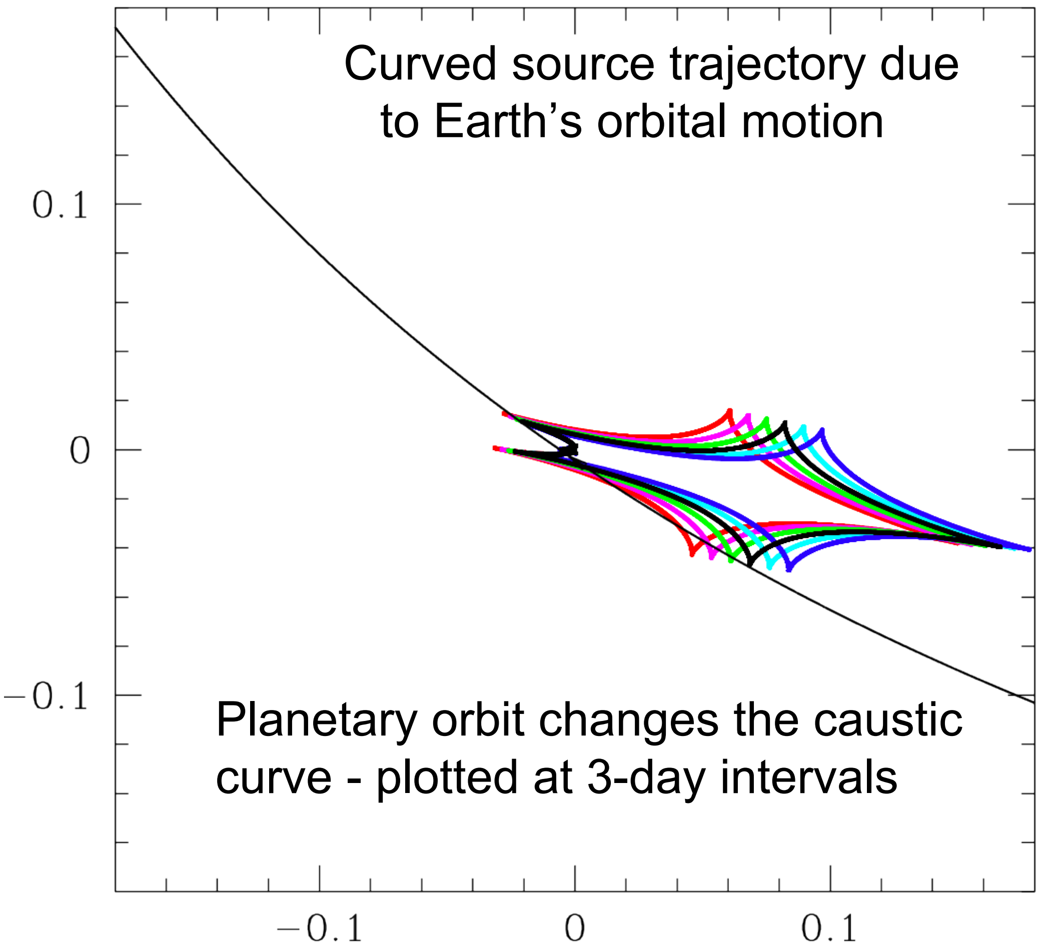
Gaudi et al (2008)
Bennett et al (2010)

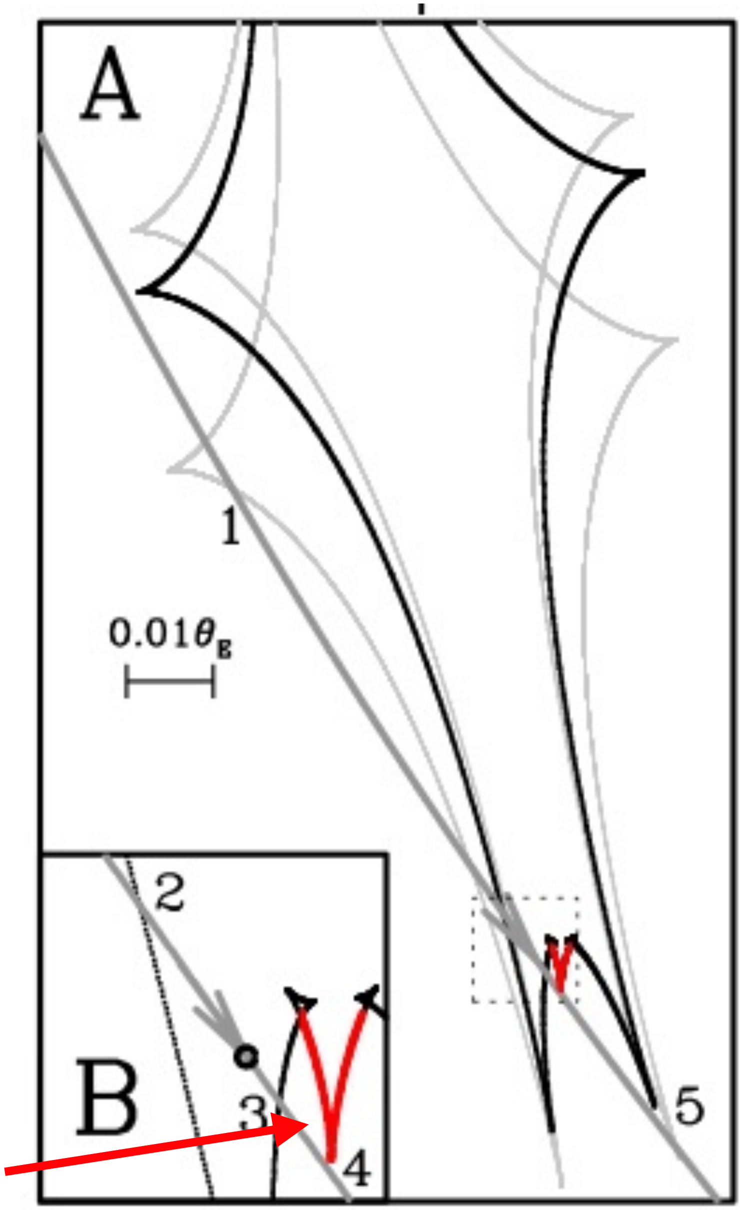
OGLE-2006-BLG-109 Light Curve Features

- The basic 2-planet nature of the event was identified during the event,
- But the final model required inclusion of orbital motion, microlensing parallax and computational improvements (by Bennett).



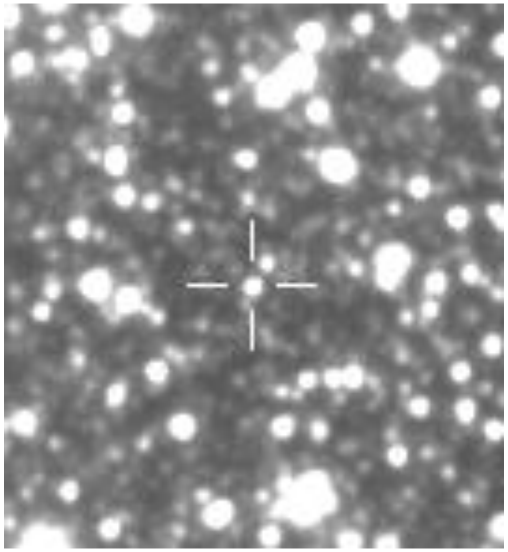
OGLE-2006-BLG-109Lb,c Caustics



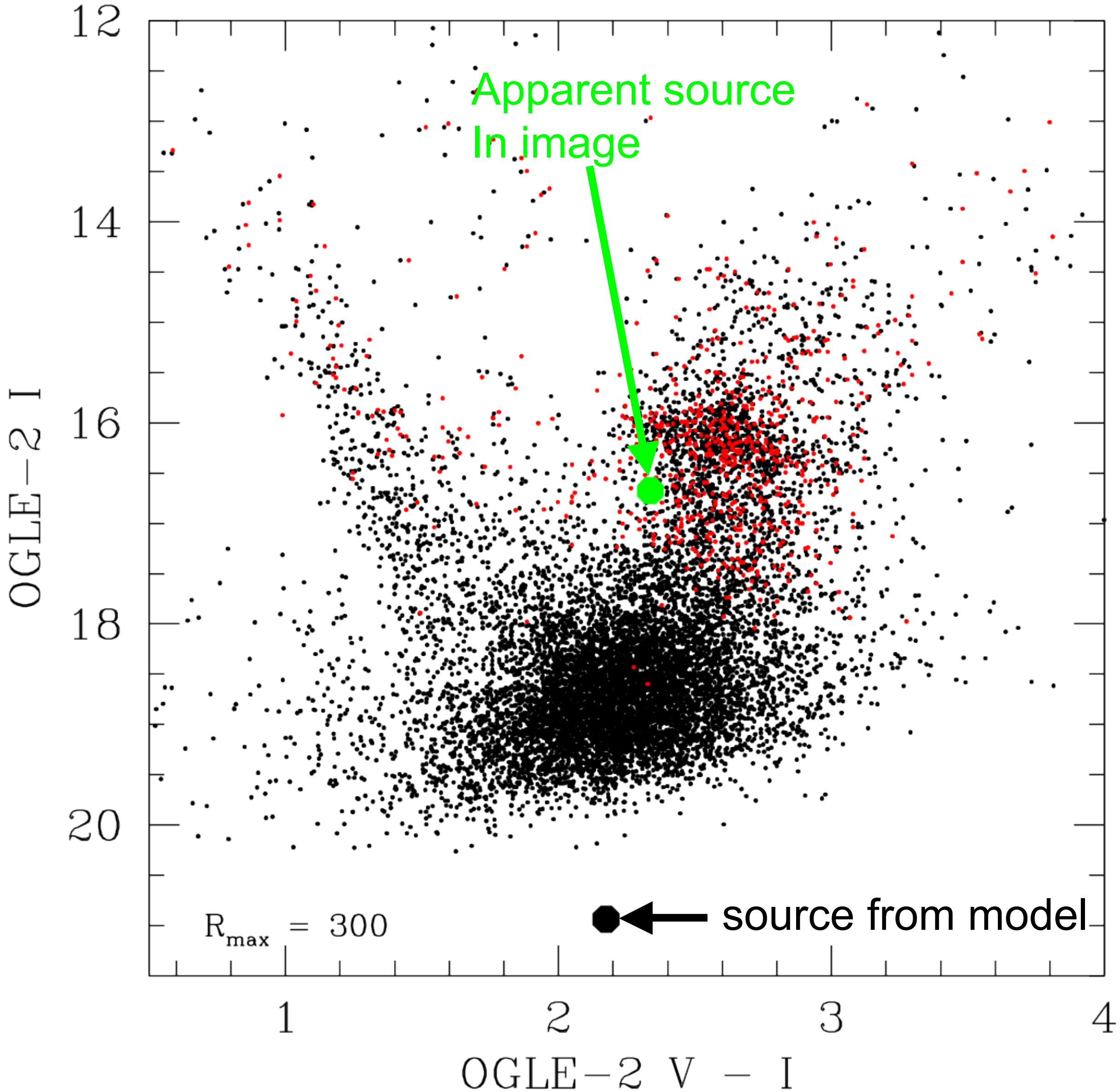


more analysis details later

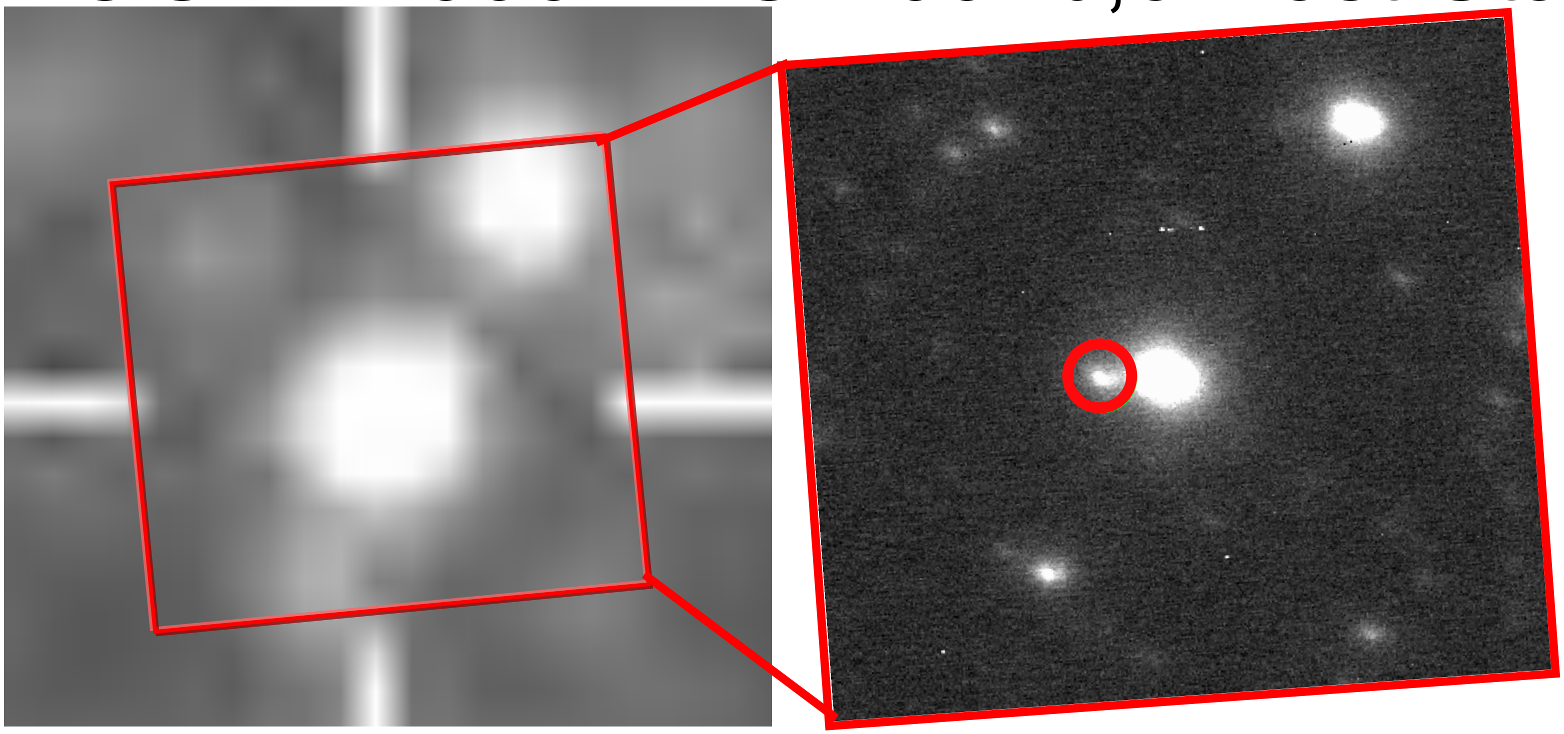
OGLE-2006-BLG-109 Source Star



The model indicates that the source is much fainter than the apparent star at the position of the source. Could the brighter star be the lens star?



OGLE-2006-BLG-109Lb,c Host Star



- OGLE images show that the source is offset from the bright star by 350 mas
- B. Macintosh: Keck AO images resolve lens+source stars from the brighter star.
- But, source+lens blend is 6× brighter than the source (from CTIO H-band light curve), so the lens star is 5× brighter than source.
  - H-band observations of the light curve are critical because the lens and source and not resolved
- Planet host (lens) star magnitude H ≈ 17.17
  - JHK observations will help to constrain the extinction toward the lens star

Only Multiplanet System with Measured Masses

Host star mass: $M_L = 0.52^{+0.18}_{-0.07} M_\odot$ from light curve model.

- Apply lens brightness constraint: $H_L \approx 17.17$.
- Correcting for extinction: $H_{L0} = 16.93 \pm 0.25$
  - Extinction correction is based on H_L-K_L color
  - Error bar includes both extinction and photometric uncertainties
- Lens system distance: $D_L = 1.54 \pm 0.13$ kpc

Host star mass: $M_L = 0.51 \pm 0.05 M_\odot$ from light curve and lens H-magnitude.

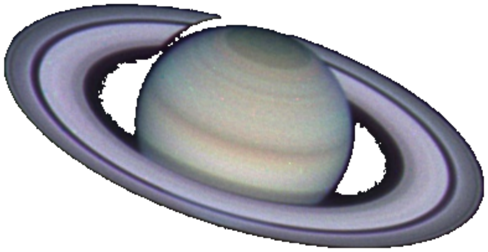
Other parameter values:

- "Jupiter" mass: $m_b = 0.73 \pm 0.06\ M_{Jup}$
  semi-major axis: $a_b = 2.3 \pm 0.5\,\mathrm{AU}$
- "Saturn" mass: $m_c = 0.27 \pm 0.03\ M_{Jup} = 0.90\ M_{Sat}$
  semi-major axis: $a_c = 4.5^{+2.2}_{-1.0}\,\mathrm{AU}$
- "Saturn" orbital velocity $v_t = 9.5 \pm 0.5$ km/sec
  eccentricity $\varepsilon = 0.15^{+0.17}_{-0.10}$
  inclination $i = 63 \pm 6°$

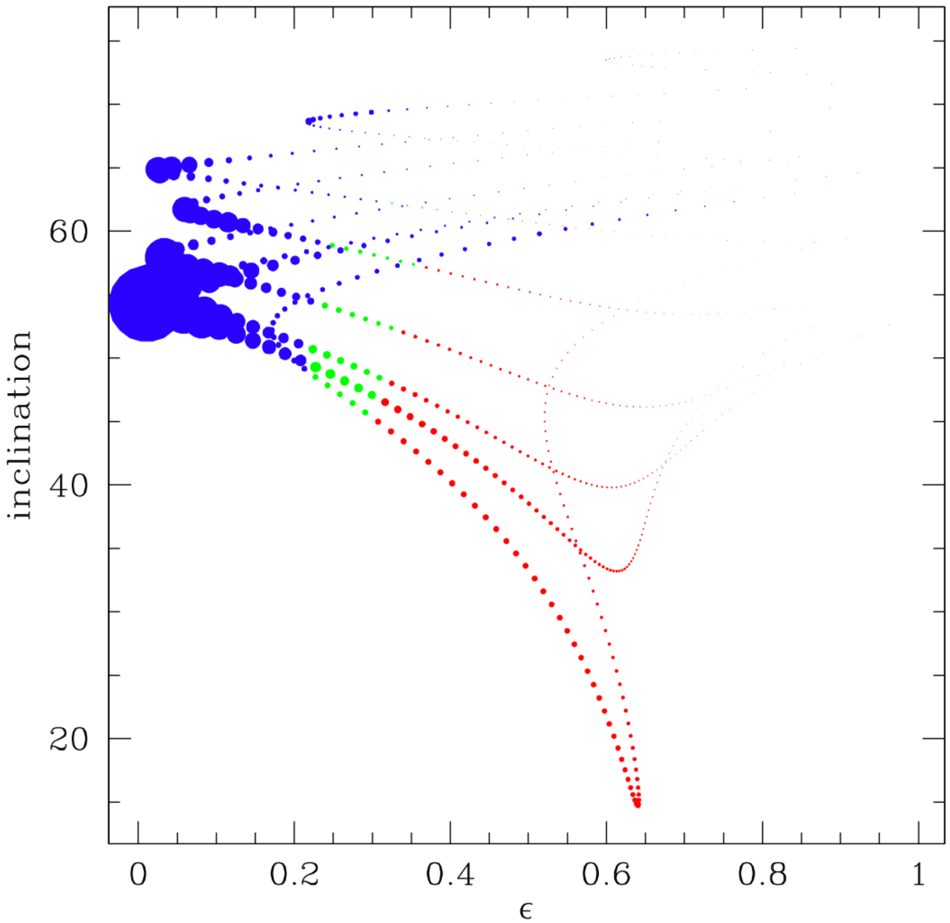
Orbital Motion Modeling

- 4 orbital parameters are well determined from the light curve
  - 2-d positions and velocities
  - Slight dependence on distance to the source star when converting to physical from Einstein Radii units
- Masses of the host star and planets are determined directly from the light curve
  - So a full orbit is described by 6 parameters (3 relative positions & 3 relative velocities)
  - A circular orbit is described by 5 parameters
- Models assume planetary circular motion
  - 2-d positions and velocities are well determined
  - Orbital period is constrained, but not fixed by the light curve
  - The orbital period parameter can be interpreted as acceleration or 3-d Star-Saturn distance (via $a = GM/r^2$)
- Details in Bennett et al (2010)

Full Orbit Determination for OGLE-2006-BLG-109Lc



- Series of fits with fixed orbital acceleration (weight with fit χ^2)
- Each fit corresponds to a 1-parameter family of orbits parameterized by v_z
  - unless $\frac{1}{2}\left(v_x^2 + v_y^2\right) - \frac{GM}{r} > 0$
- Assume the Jupiter orbits in the same plane and reject solutions crossing the Jupiter orbit or that are Hill-unstable
- Weight by prior probability of orbital parameters
  - planet is unlikely to be near periastron if ε >> 0



Families of solutions corresponding to best models at various values of a.

Full Orbit Determination for OGLE-2006-BLG-109Lc

- Full calculation using Markov chains run at fixed acceleration.
- Include only Hill-stable orbits
- results:

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

$$M_{Lc} = 0.27 \pm 0.03 M_J$$

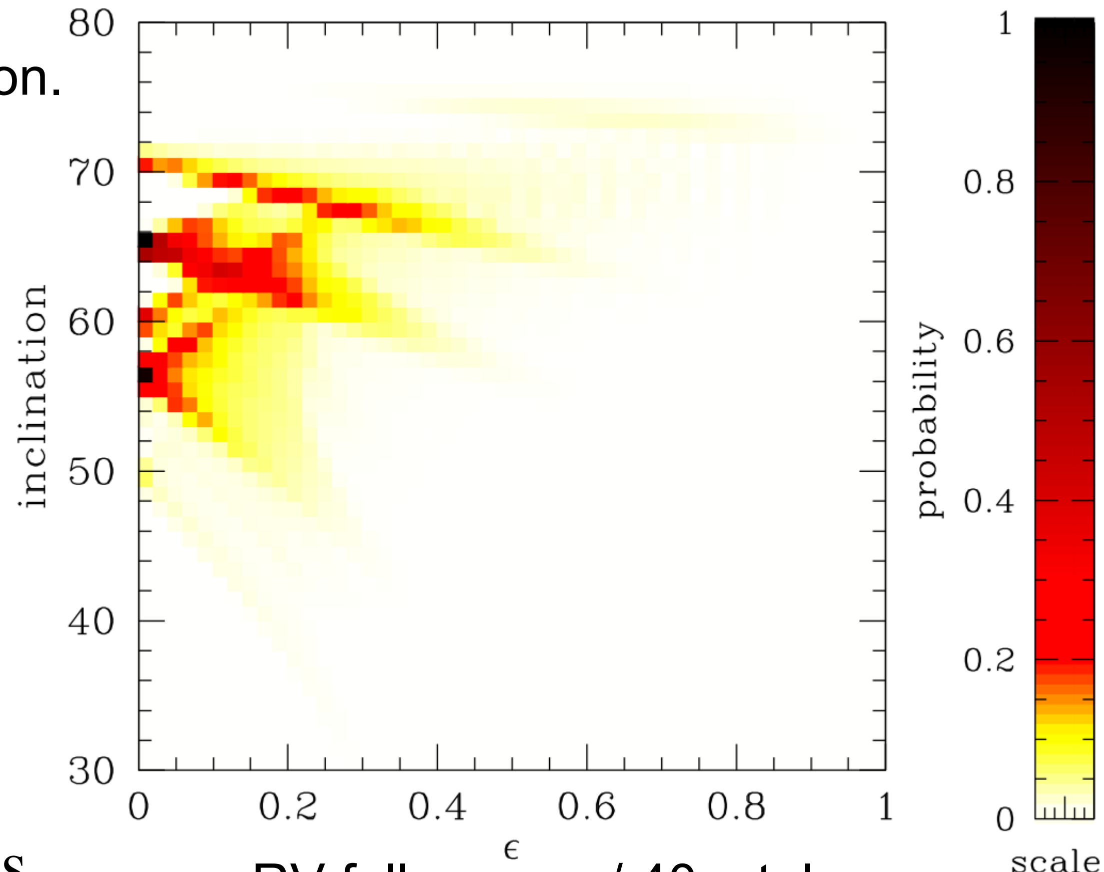
$$M_{Lb} = 0.73 \pm 0.07 M_J$$

$$a_{Lc} = 4.5^{+2.2}_{-1.0}\,\mathrm{AU}$$

$$a_{Lb} = 2.3 \pm 0.5\,\mathrm{AU}$$

$$\mathrm{inclination} = 64^{+4}_{-7}\ \mathrm{degrees}$$

$$\varepsilon = 0.15^{+0.17}_{-0.10}$$



- RV follow-up w/ 40m telescope
  - –K = 19 m/sec (H = 17.2)

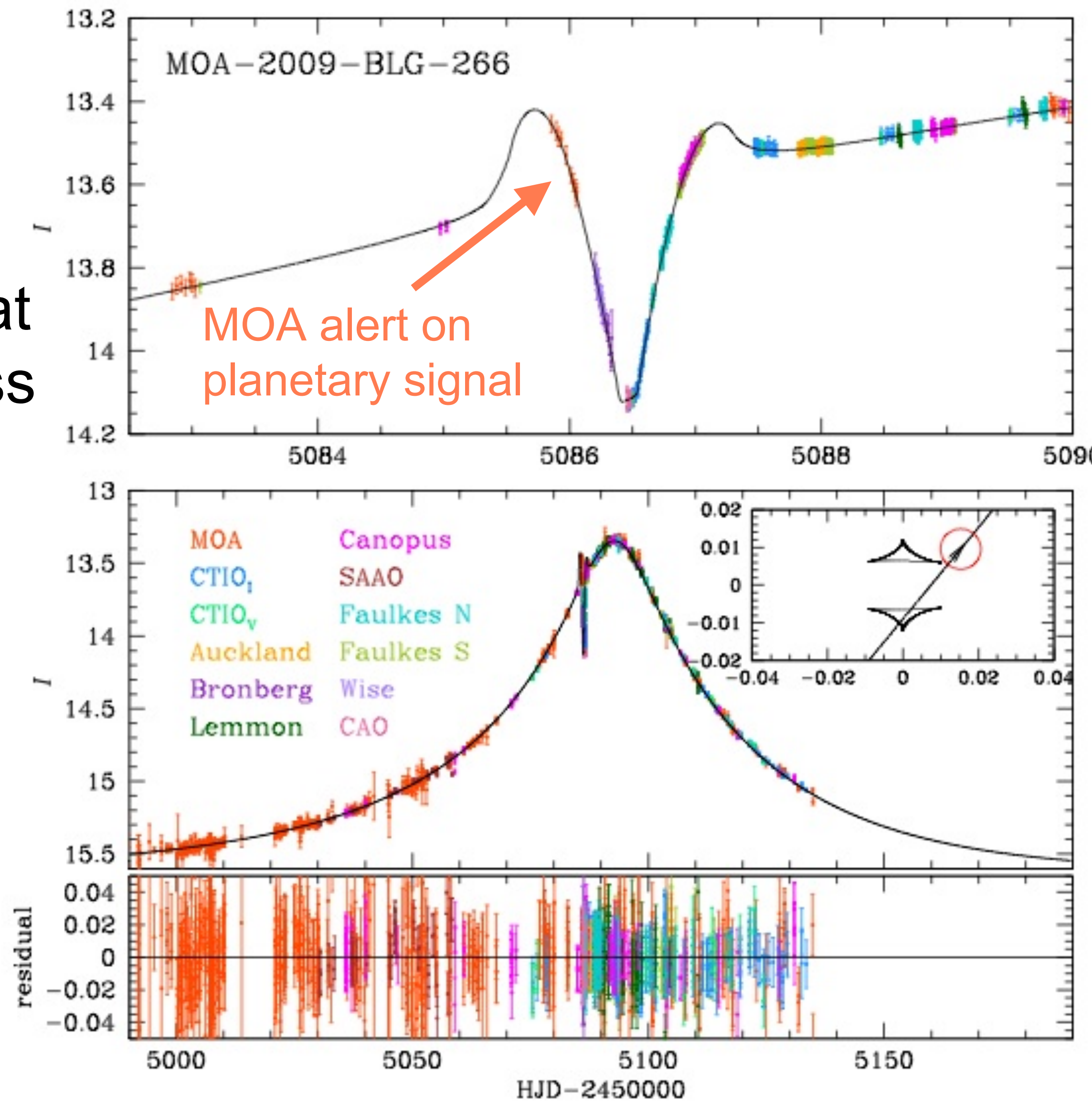
OGLE-2006-BLG-Lb,c Discovery Implications

- OGLE-2006-BLG-109L is the first lens system with a Jovian Planet which has very high sensitivity to additional Saturn-mass planets
  - OGLE-2003-BLG-235 and OGLE-2005-BLG-71 had much lower magnification
  - OGLE-2005-BLG-169 had only a Neptune (or Super-earth)
- Jupiter + Saturn systems may be common among systems with gas-giant planets
  - Radial velocity planets 47 UMa & 14 Her are similar systems with more massive planets.

Survey Discovery: MOA-2009-BLG-266

- Planet discovered by MOA on Sept. 11, 2009
- Lowest mass planet at > 0.05 AU with a mass measurement

  $\sim 10 M_{\oplus}$ at ~ 3AU
- Mass measurement from Deep Impact (now EPOXI) Spacecraft



Survey Discovery: MOA-2009-BLG-266

- Planet discovered by MOA on Sept. 11, 2009
- Low-mass planet
  - Probably $\sim 10 M_{\oplus}$
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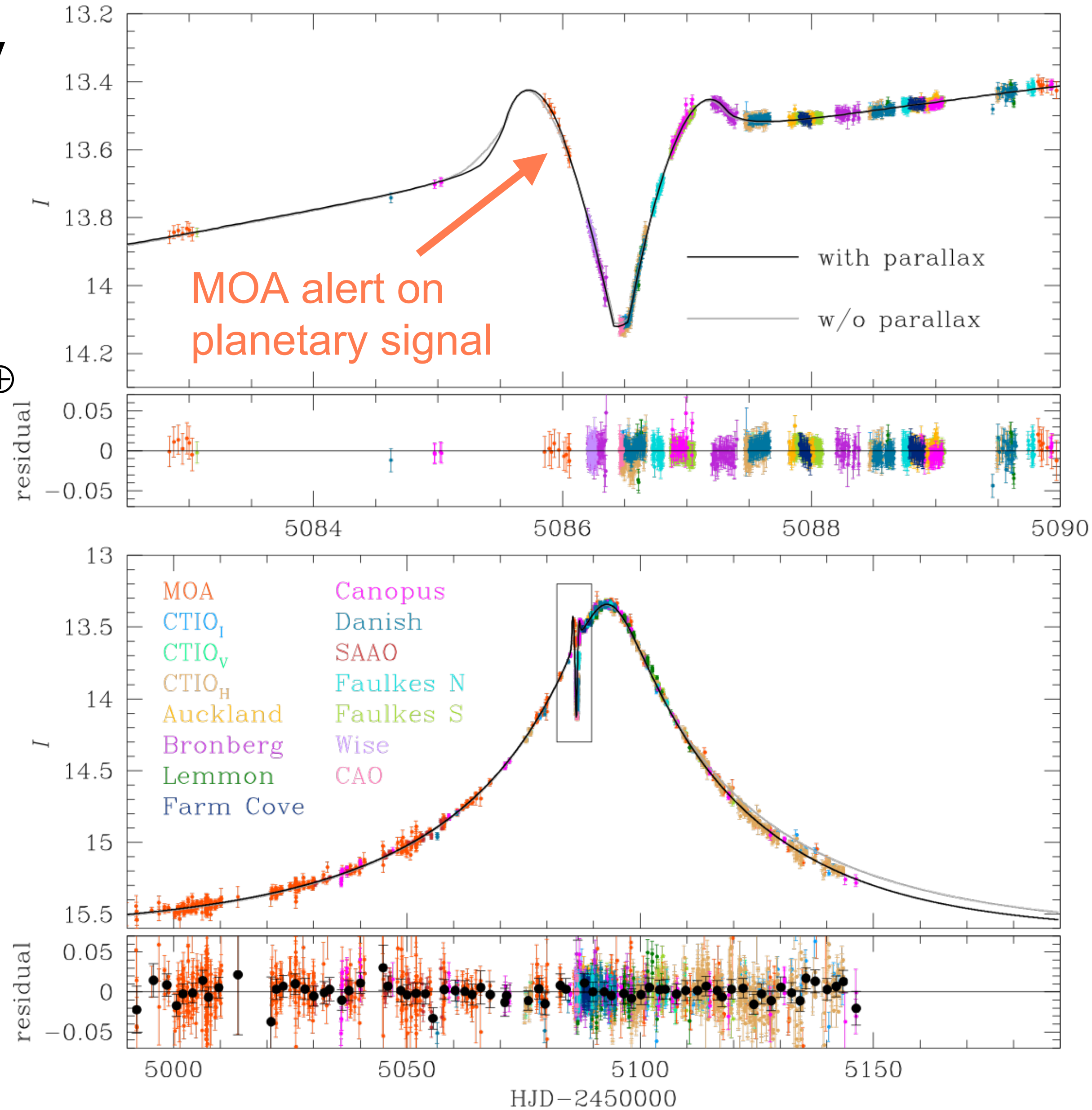
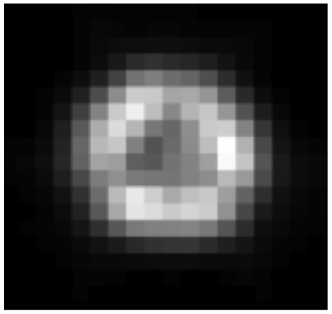


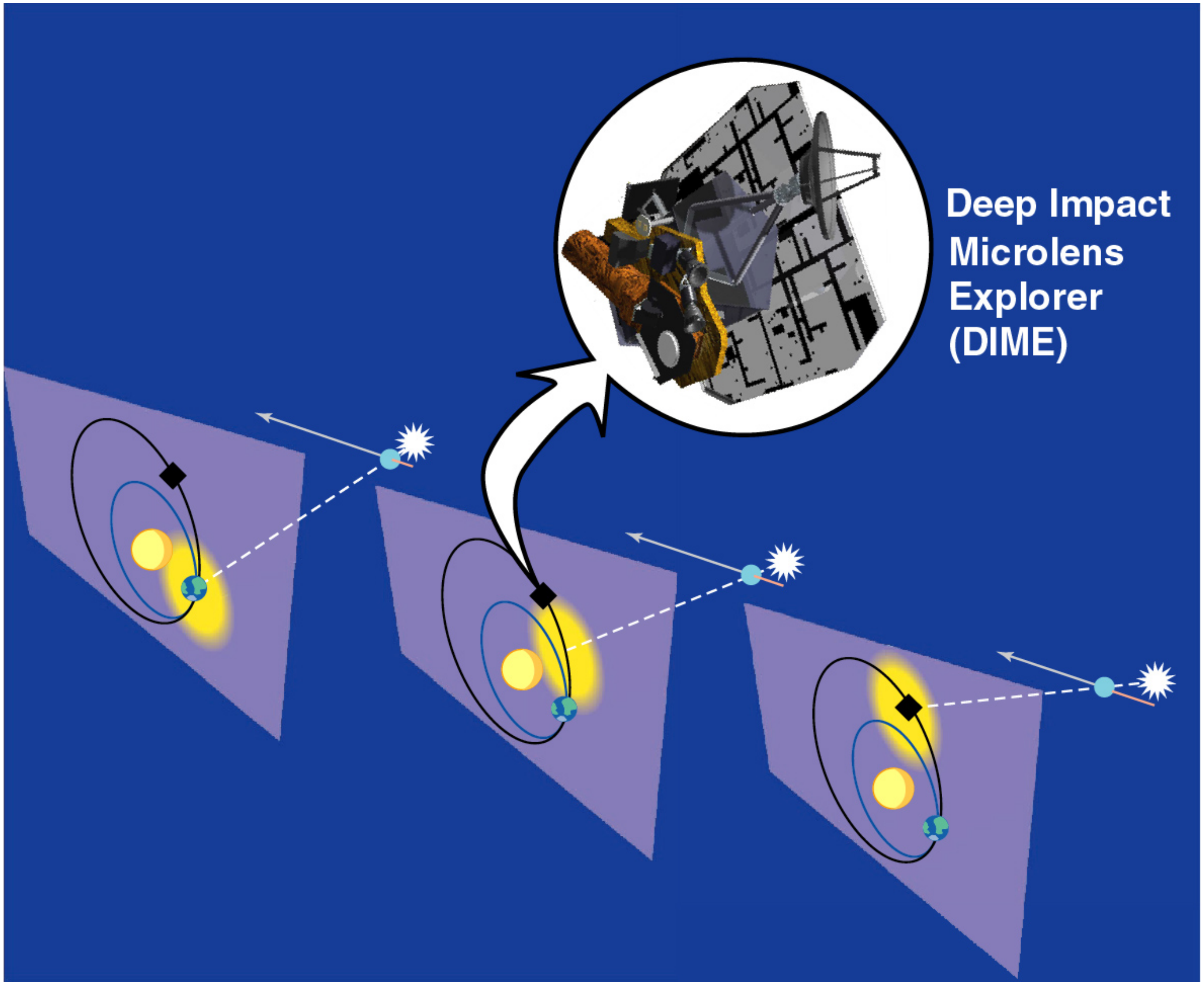
Space-Based Microlensing Parallax

2004: study LMC microlensing w/ DI imaging (proposed)

2009: Geometric exoplanet and host star mass measurements with DI



EPOXI PSF!



observations in Oct. - see Andy Becker's talk

Satellite Observations of Exoplanet Microlensing events

- Observe during host star lensing event
  - Targets are known only weeks to months before event is over
  - But most targets are within 5-10 degrees of the central Galactic bulge
  - Plan observations of a central bulge field, and update the coordinates just before the observations?
- Optimum Earth-satellite separation ~a few times smaller than Einstein Radius, R_E
  - But depends on detailed characteristics of the event
- Different event classes
  - Long events - months
  - Short events - 1-2 weeks
- Targets are usually “faint” I ~ 13-20
  - Long exposures, good pointing stability
  - Low precision photometry compared to transits

Long Exoplanet Microlensing events

- Long events - months
  - Planetary host stars in the Galactic disk and/or have high mass
    - High mass means M > 0.3 solar masses
  - Many have partial of full microlensing parallax measurements
  - Projected Einstein radius ~ 4 AU
  - Satellite observations to remove degeneracies in modeling
  - MOA-2009-BLG-266 is an example
    - 3 kpc away
    - Host mass = 0.5 or 0.7 solar masses
  - Best observed by a satellite 0.5-2 AU from the Earth in projected separation
    - e.g. Cassini in 2016 or 2017
    - Mars missions

Short Exoplanet Microlensing events

- Short events - 1-2 weeks
  - Host stars in the bulge and/or low mass (< 0.3 solar masses)
  - No microlensing parallax data from the ground
  - Projected Einstein radius 10-30 AU
  - Best observed by a satellite at 2-15 AU in projected separation
    - e.g. Cassini in 2011-2015
  - Usually no signal from the ground
  - A few observations from a 2nd satellite are sometimes helpful