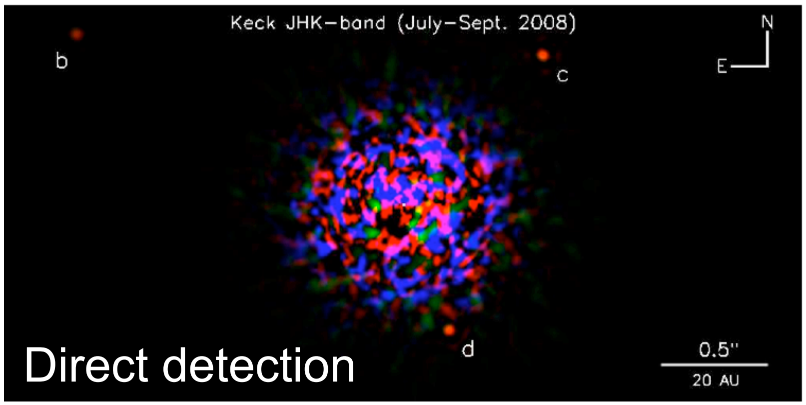
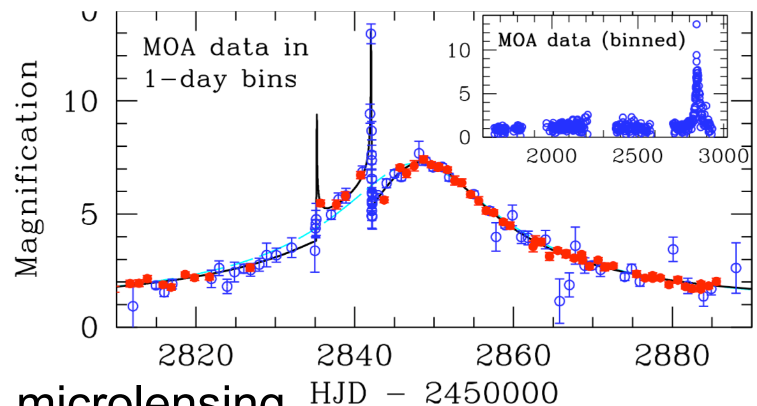
What Do We Need to Know About Planetary Architectures,

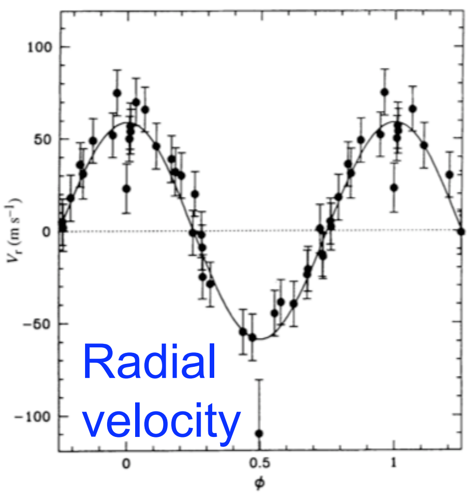
and

How Can We Attain This Information?



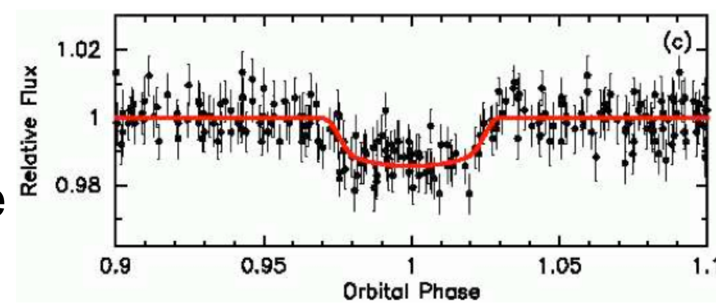


microlensing



David Bennett

University of Notre Dame



transit

What Do We Need to Know?

The main goal is exo-life

- If Fermi was right and alien life is common: Nothing!
  - just ask the aliens!


SPACE ALIEN BACKS BUSH FOR PRESIDENT!

WEEKLY WORLD NEWS

Same alien helped Clinton win top job in 1992!

WORLD EXCLUSIVE STORY AND PHOTOS!

- If SETI gets lucky!
  - maybe we can phone ET and ask?

- But, let's assume that we don't hear from ET

First Principles Requirements for Life

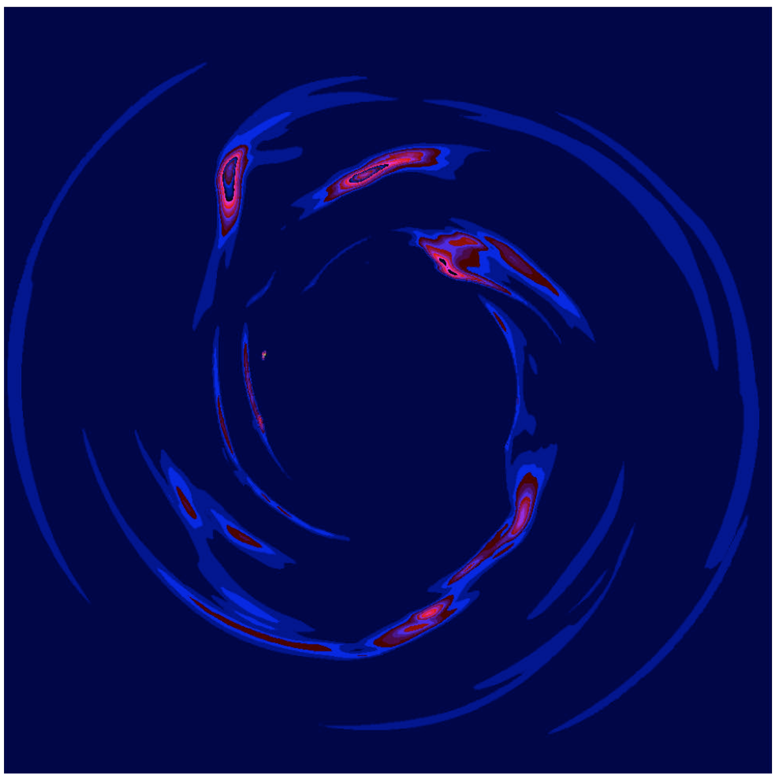
- ?
- we don’t really have a clue
- look for Earth-like life
  - requires liquid water
  - stellar radiation energy
  - standard habitable zone
- look for life where it is easy to look
  - late M-dwarfs
- But this is not enough
  - what if we don’t get lucky?

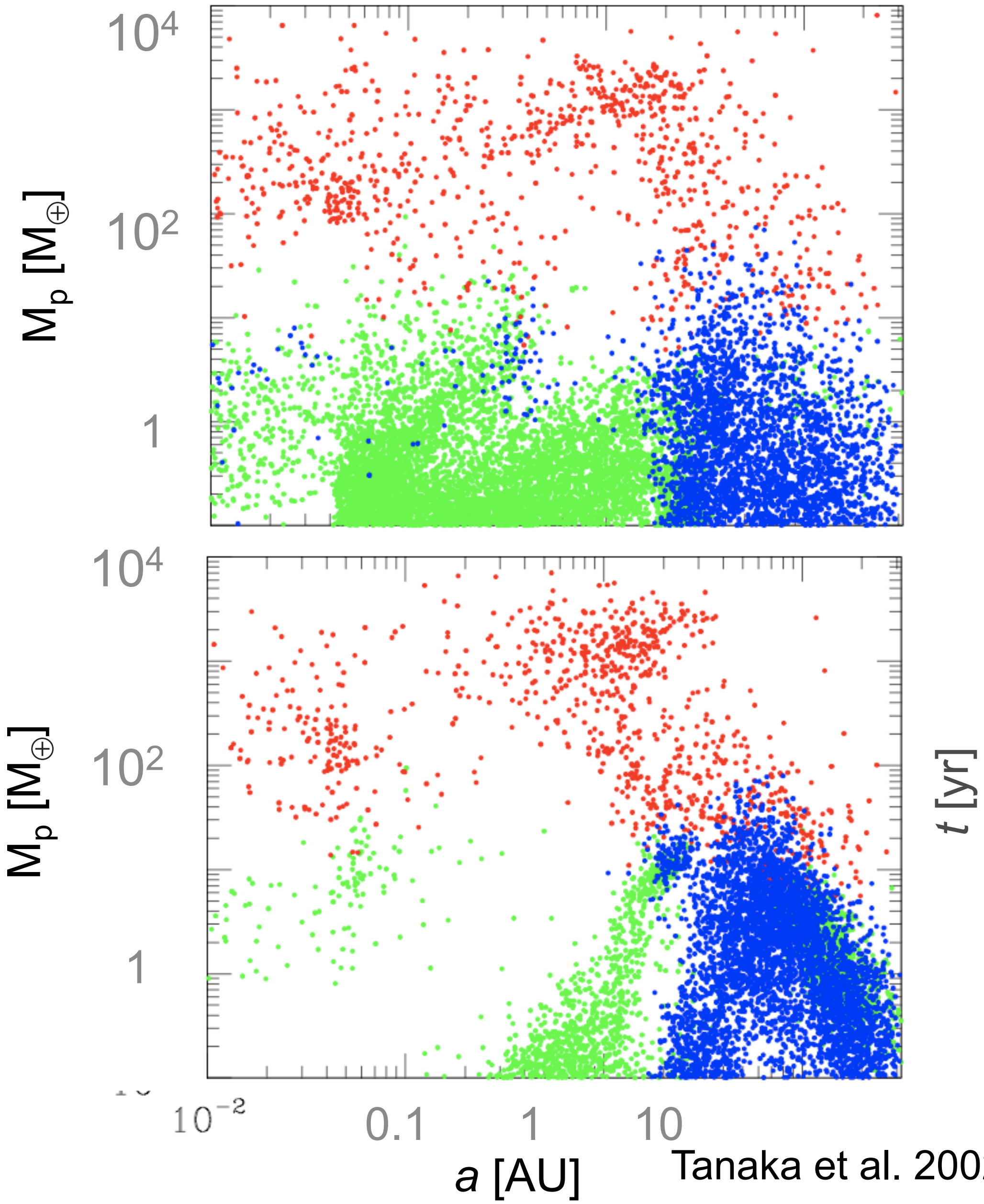
A Systematic Study of Planetary Systems

- Habitability is likely to depend on details of planet formation
  - delivery of water, but perhaps not too much
  - dynamical interactions might move planets in and out of HZ (i.e. to high eccentricity)
  - habitability may depend on properties of more massive planets in the system
- Information on nearby systems (TPF targets) is likely to be sparse
  - they are unlikely to transit, so we won't know the radius
  - mass may be poorly known
- We need a basic understanding of planet formation to understand the requirements for habitability

Planet Formation Theory

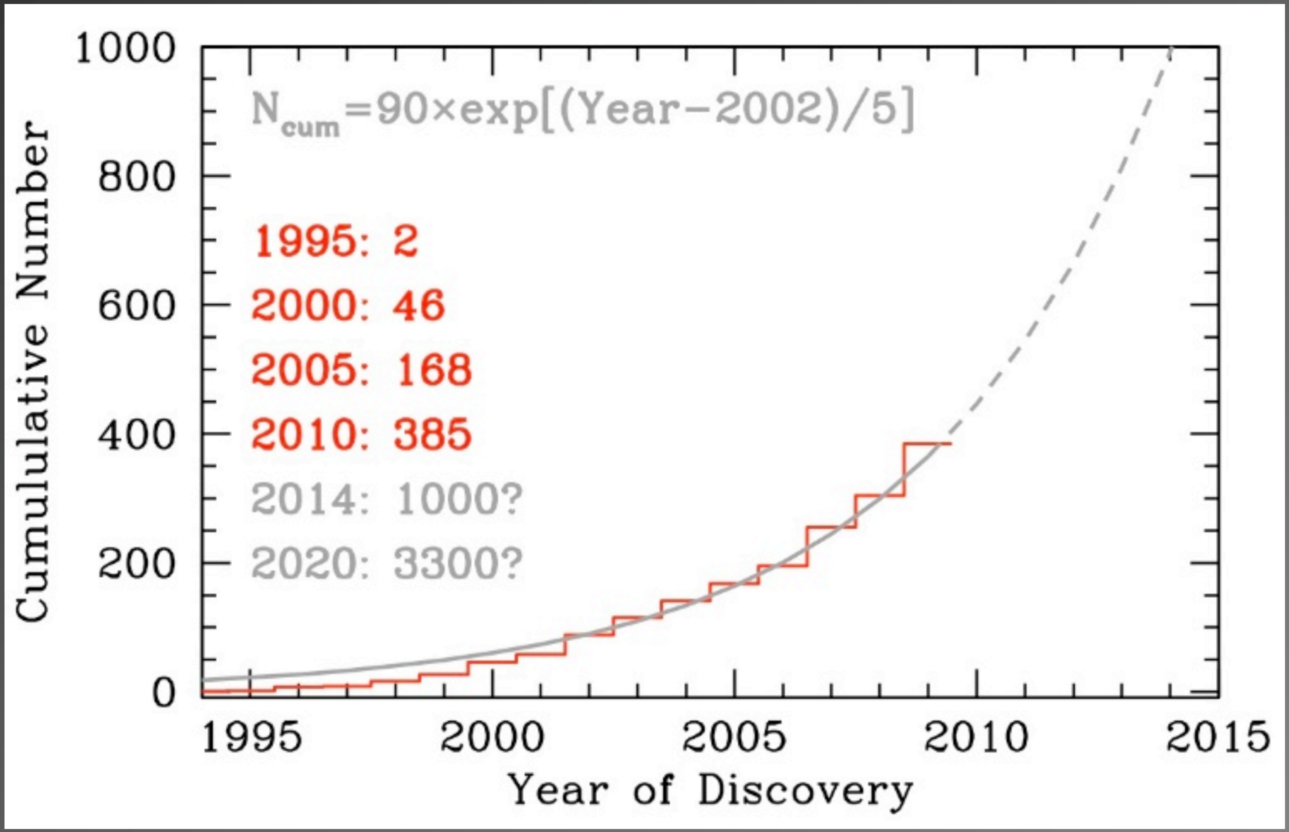
- much of the physics is too difficult to be calculated directly
- relies heavily on observations





Tanaka et al. 2002

The Demographics of Exoplanets.



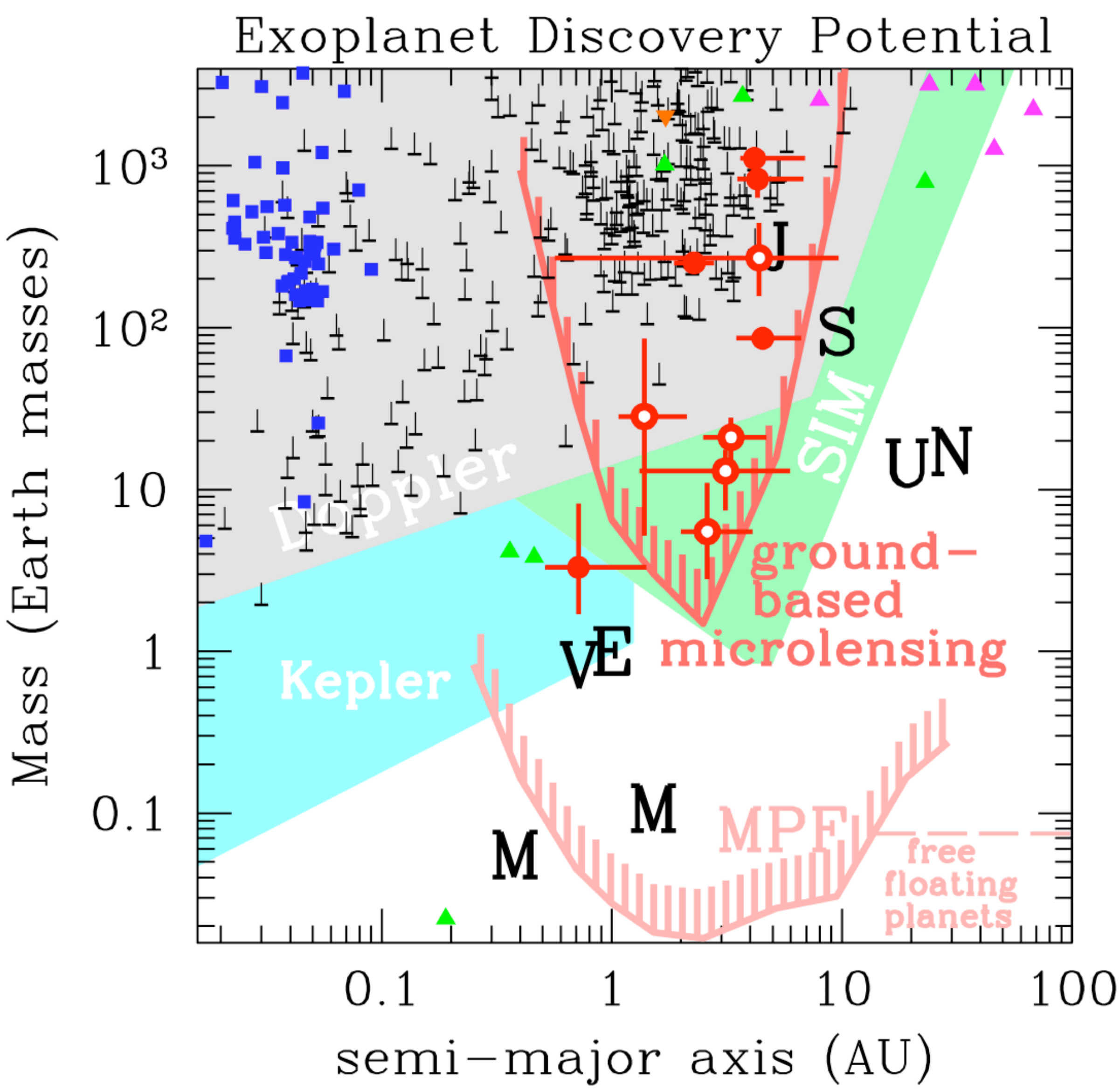
Scott Gaudi

The Ohio State University

Warner Prize Talk

Known Exoplanets by Detection Method

- Microlensing discoveries in red
- Doppler discoveries in black
- Transit discoveries shown as blue squares
- Direct detection, timing and astrometry are magenta, green, and orange 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 $L \propto M^2$ during planet formation
- Microlensing discoveries in **red.**
- Doppler discoveries in black
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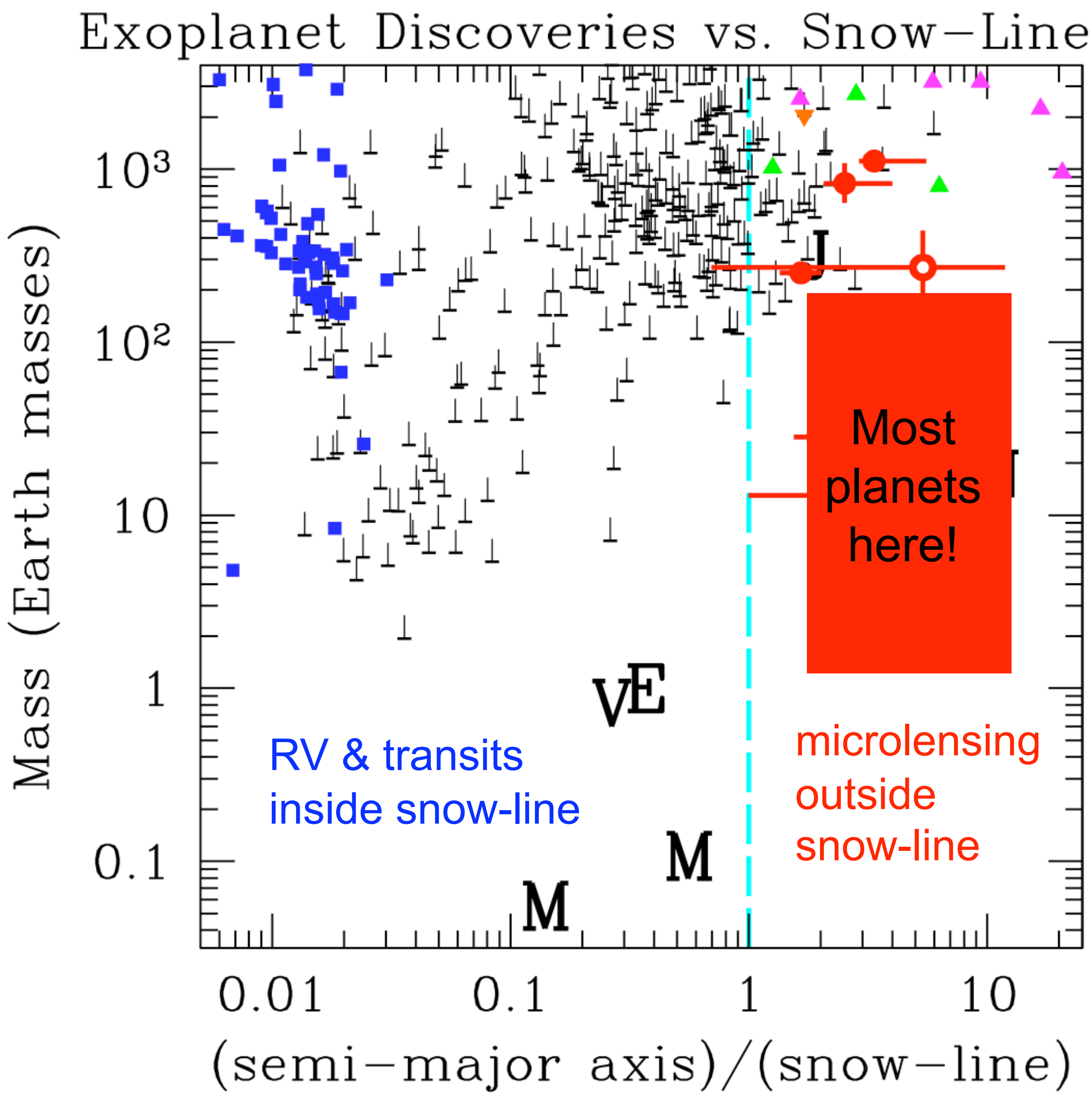
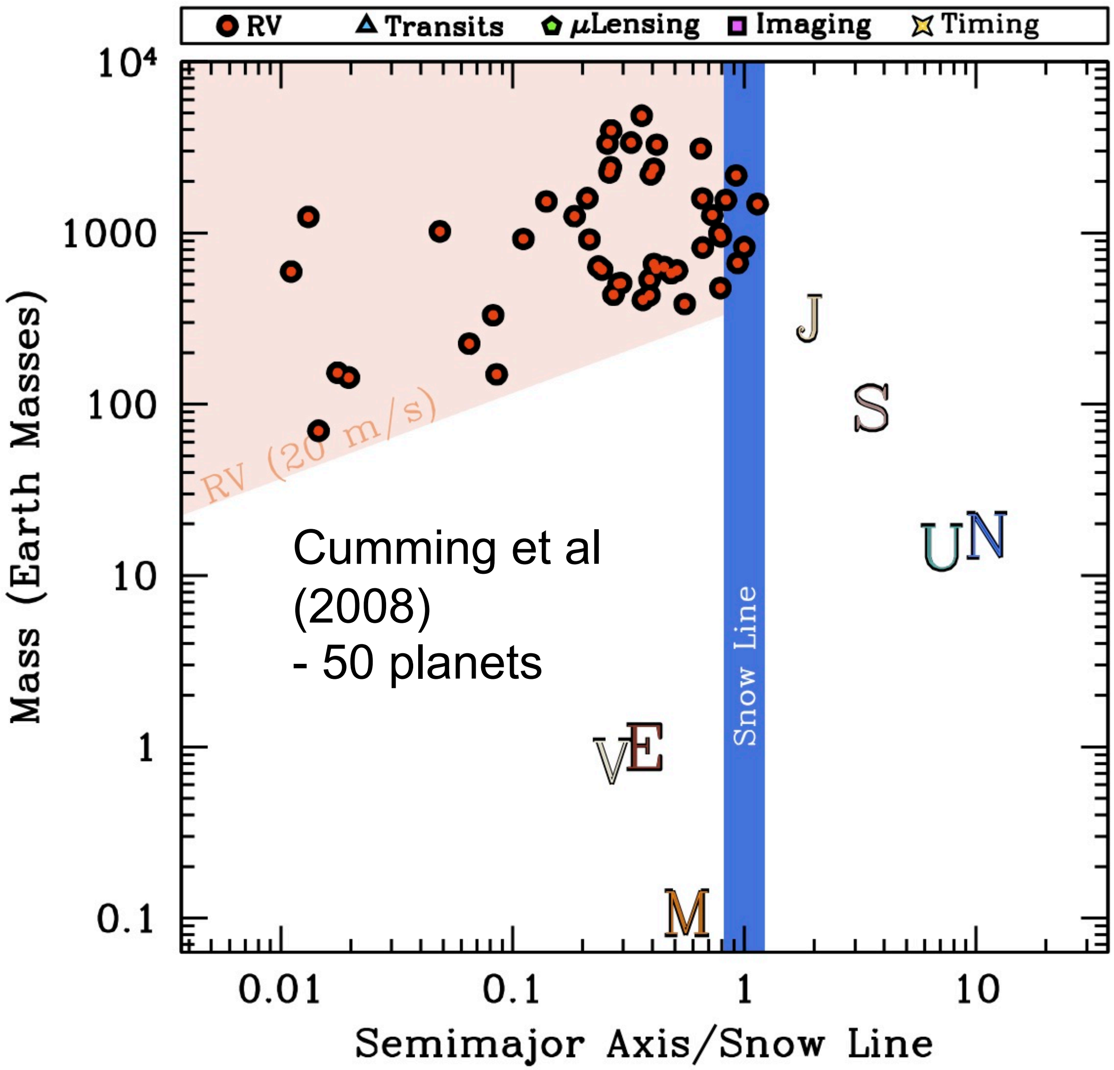
- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered

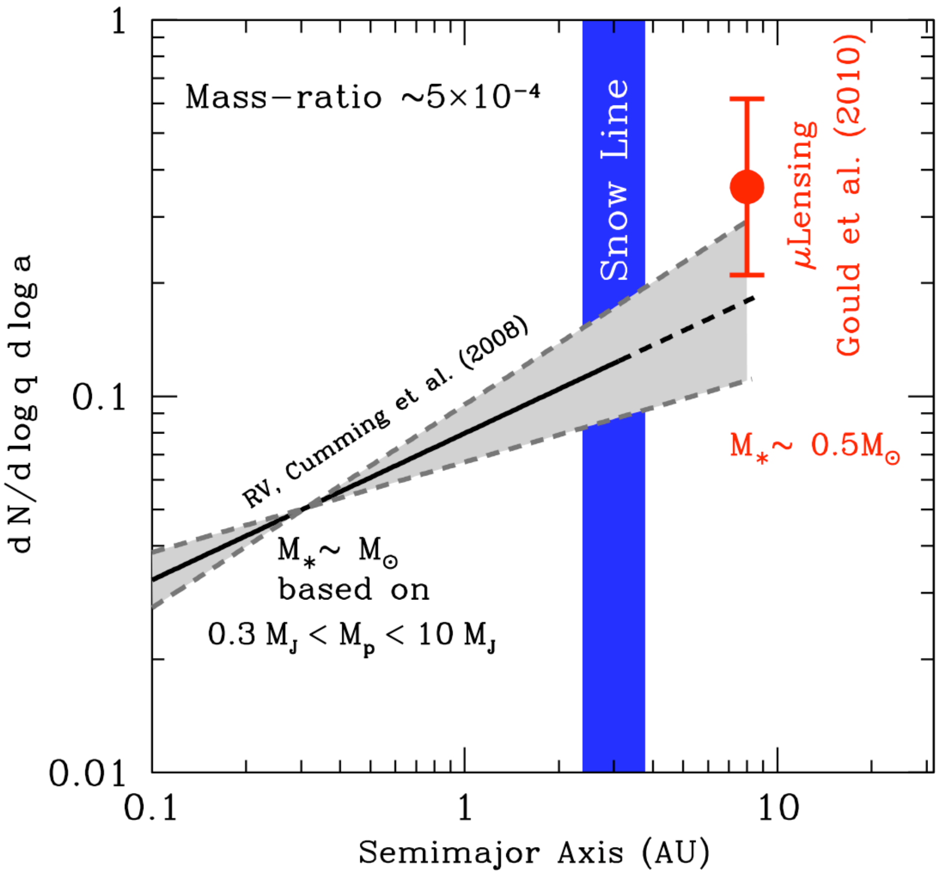


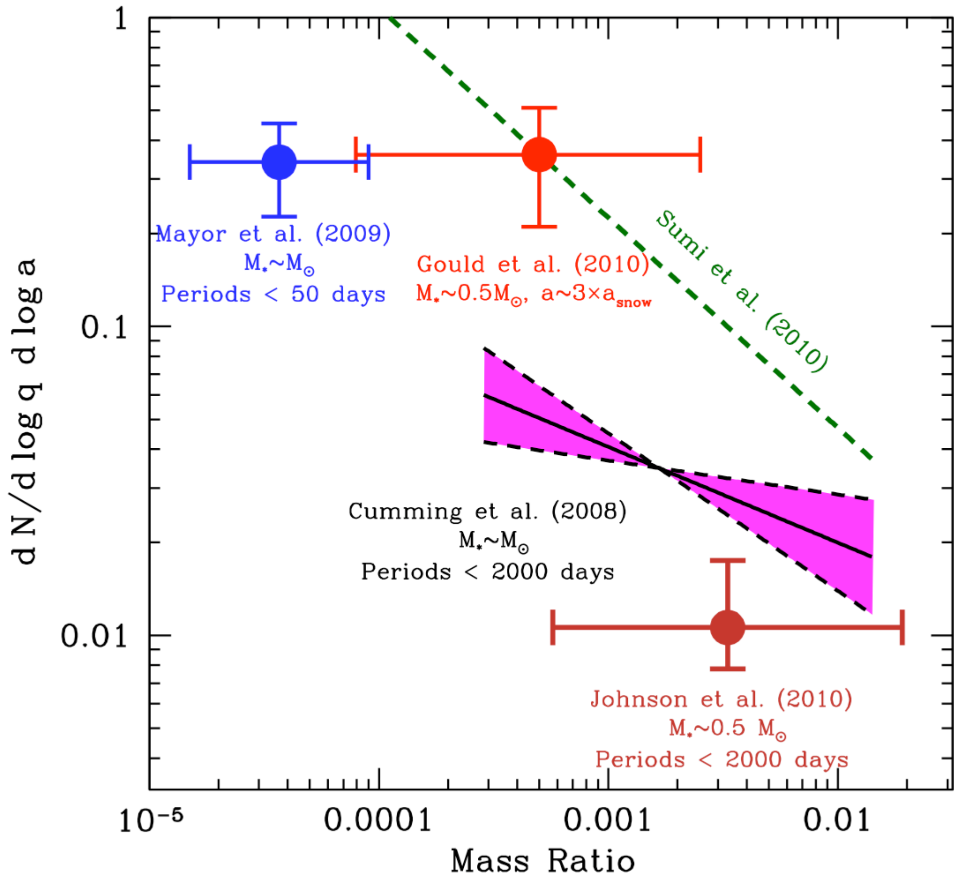
Homogenous RV sample is not so Large

Selection Effects are poorly understood for most RV discoveries



Comparison of Statistical Results





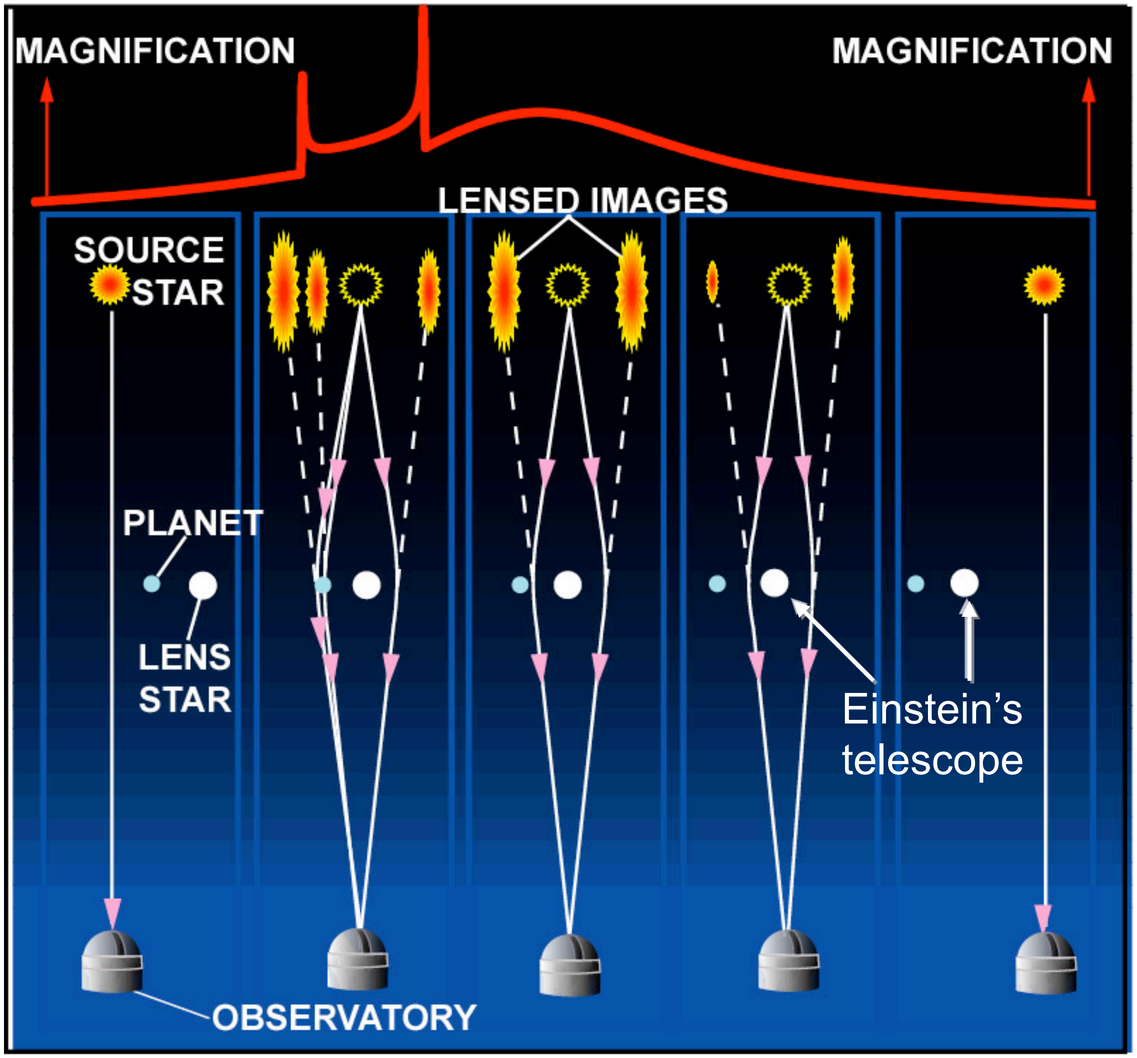
Sumi et al. (2010) : $dN_p/d(\log q) \sim q^{-0.7}$

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

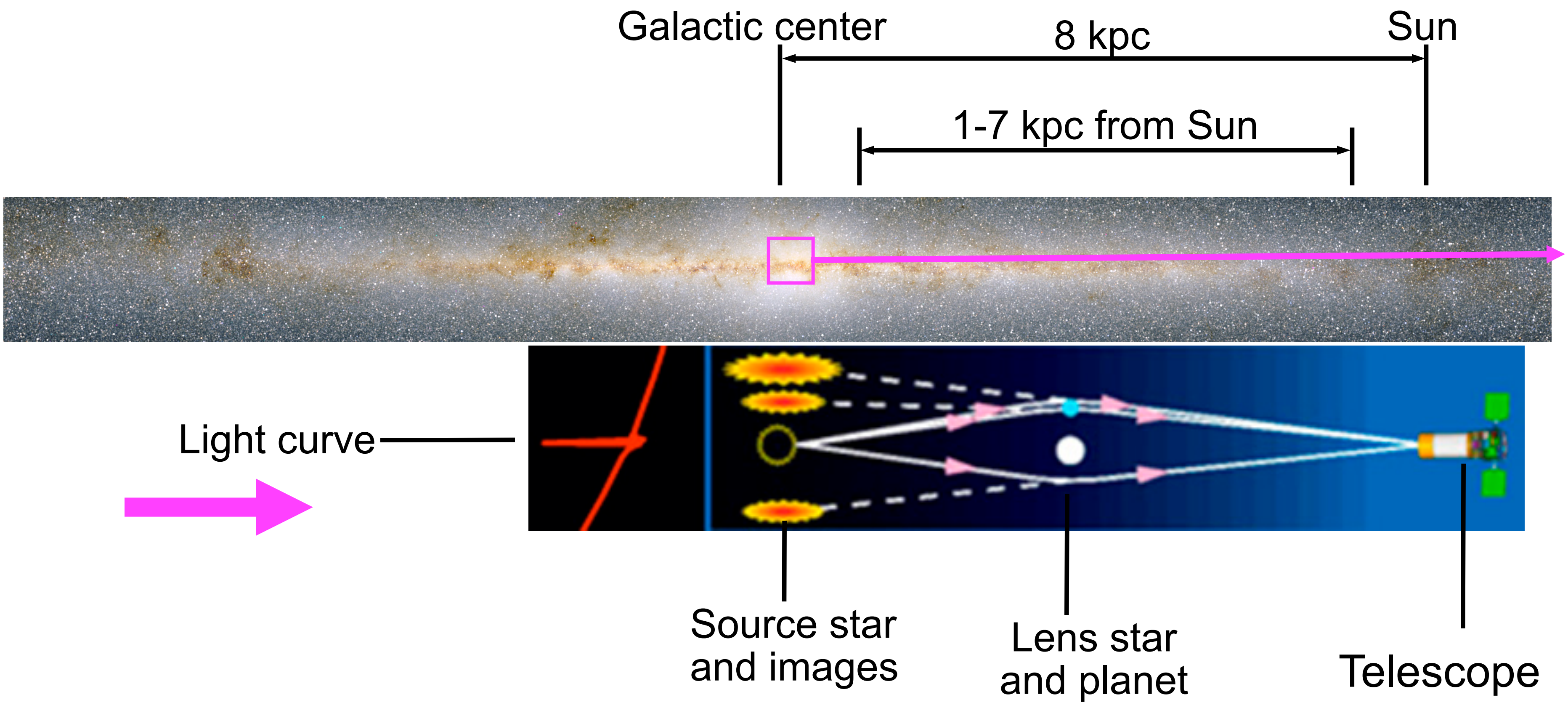
for $M \approx 0.5\ M_\odot$ and $q \approx 5 \times 10^{-4}$

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

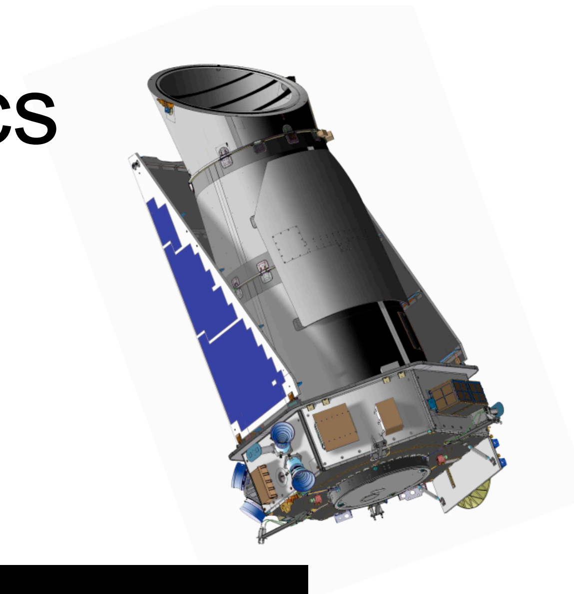


Microlensing Target Fields are in the Galactic Bulge

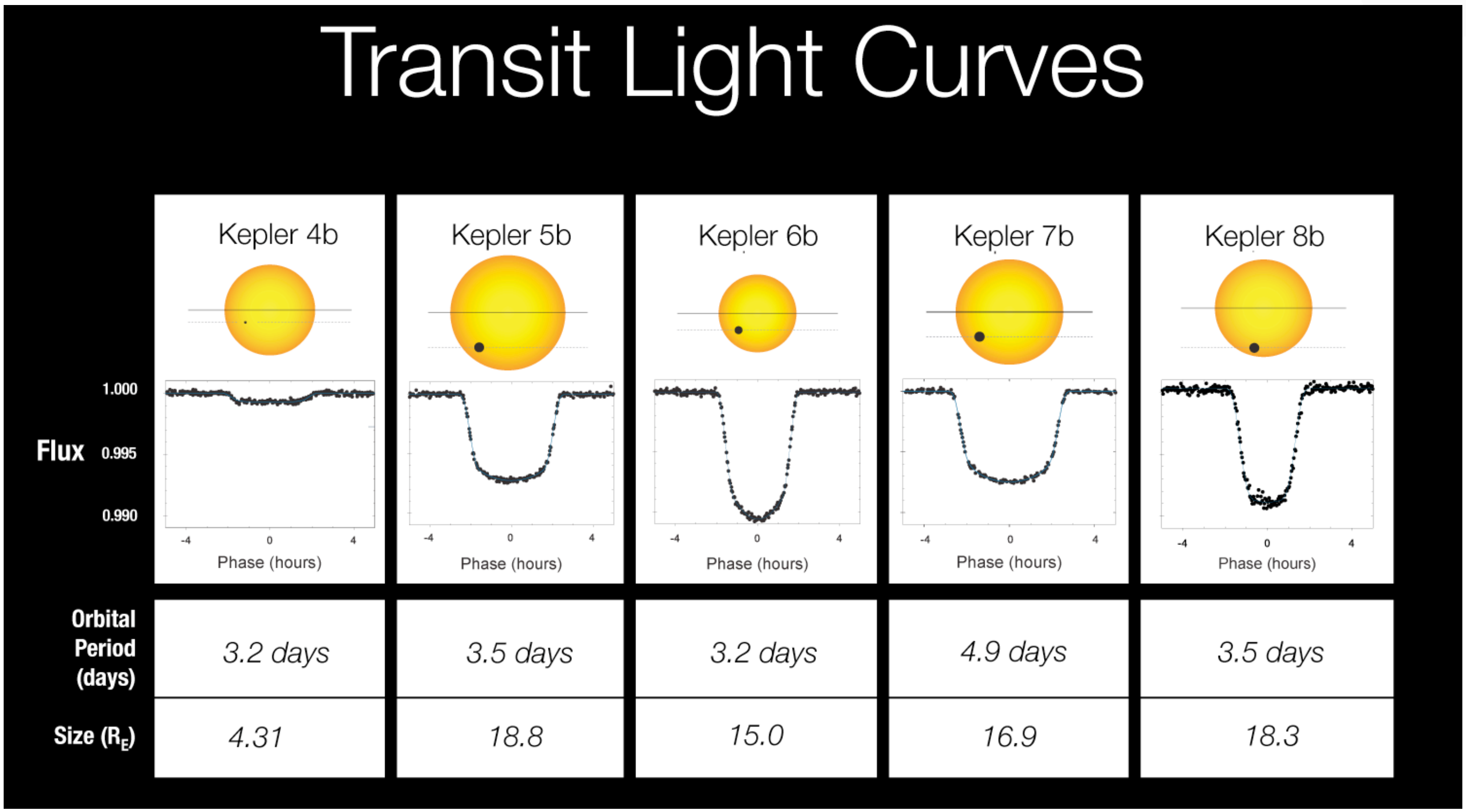


10s of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.

Hot Planet Statistics

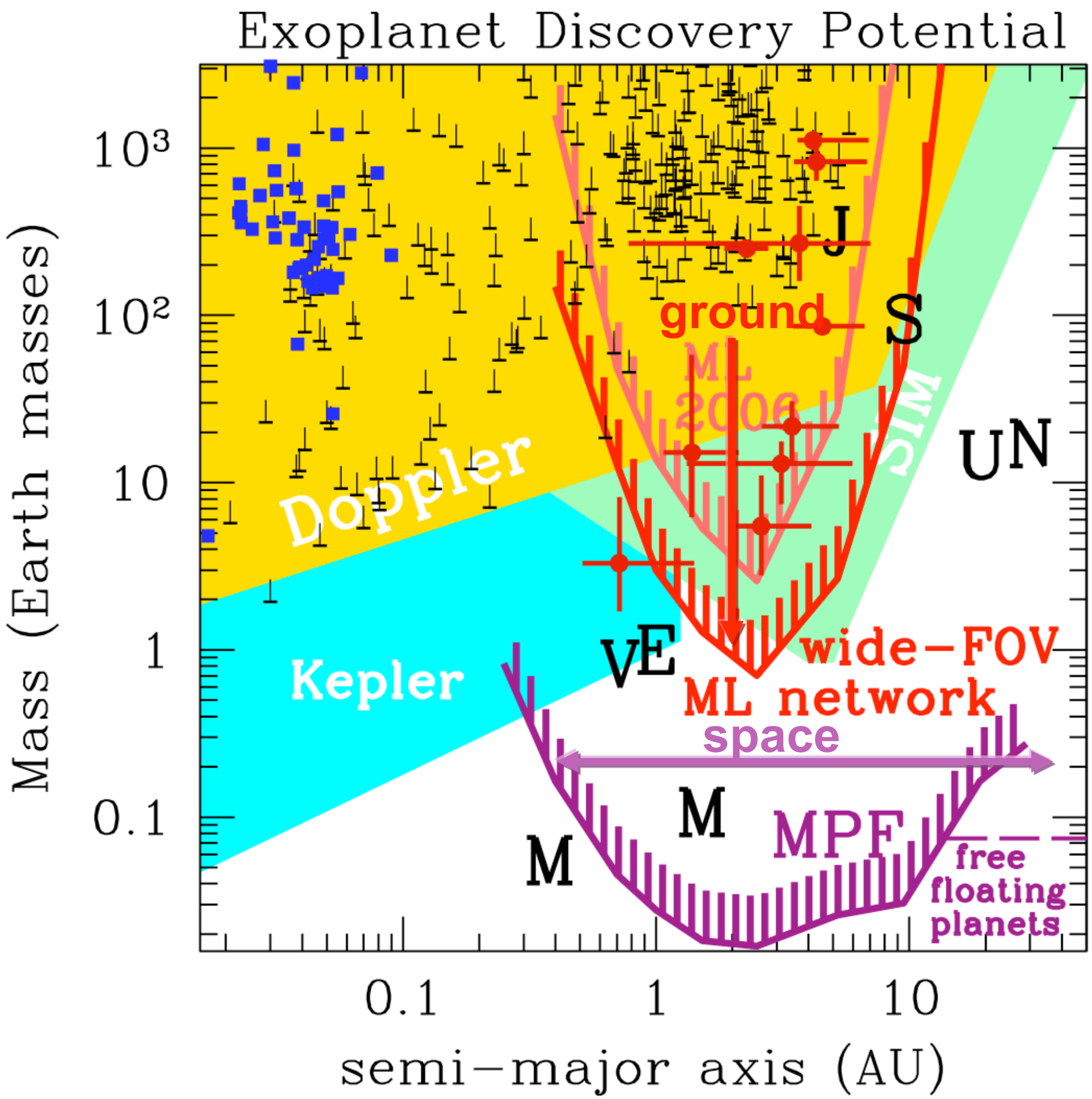


- Should be provided by Kepler down to < 1 R_{earth}
- but only for periods of ≤ 1 year
- masses from RV for super-earths and larger planets



Cold, Low-mass Planets

- microlensing is most sensitive for statistical studies
- space-based astrometry (i.e. SIM) can find nearby cold, low-mass planets
- a very wide FOV microlensing telescope network can find more cold planets, just beyond the snow line, but space is needed to go below an Earth-mass and to the HZ

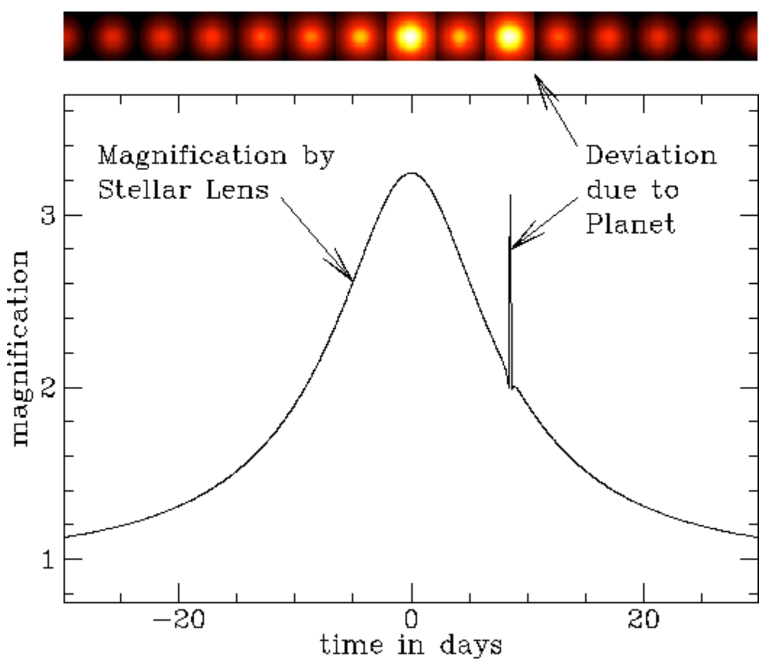


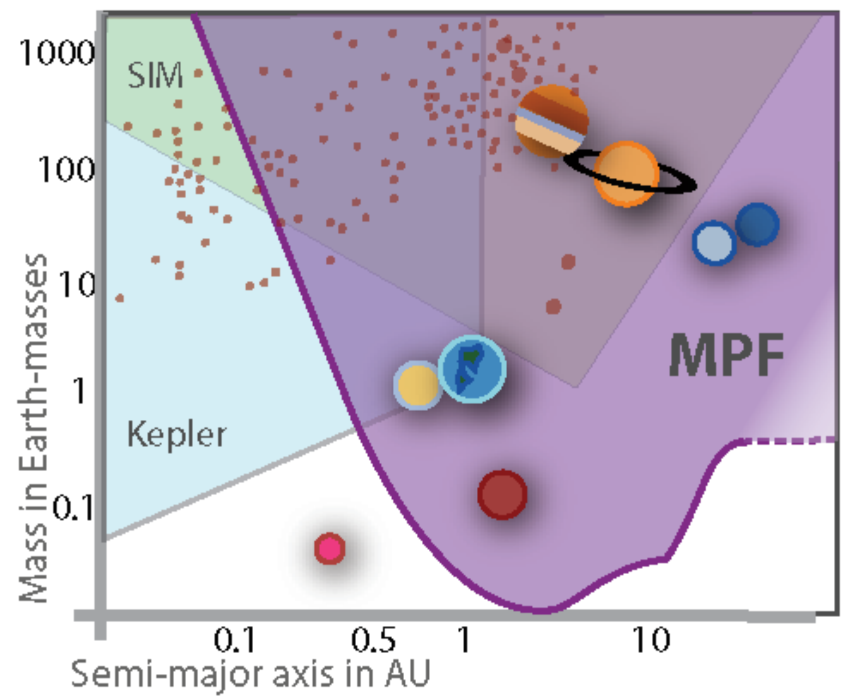
The Microlensing Planet Finder (MPF)

David Bennett, PI

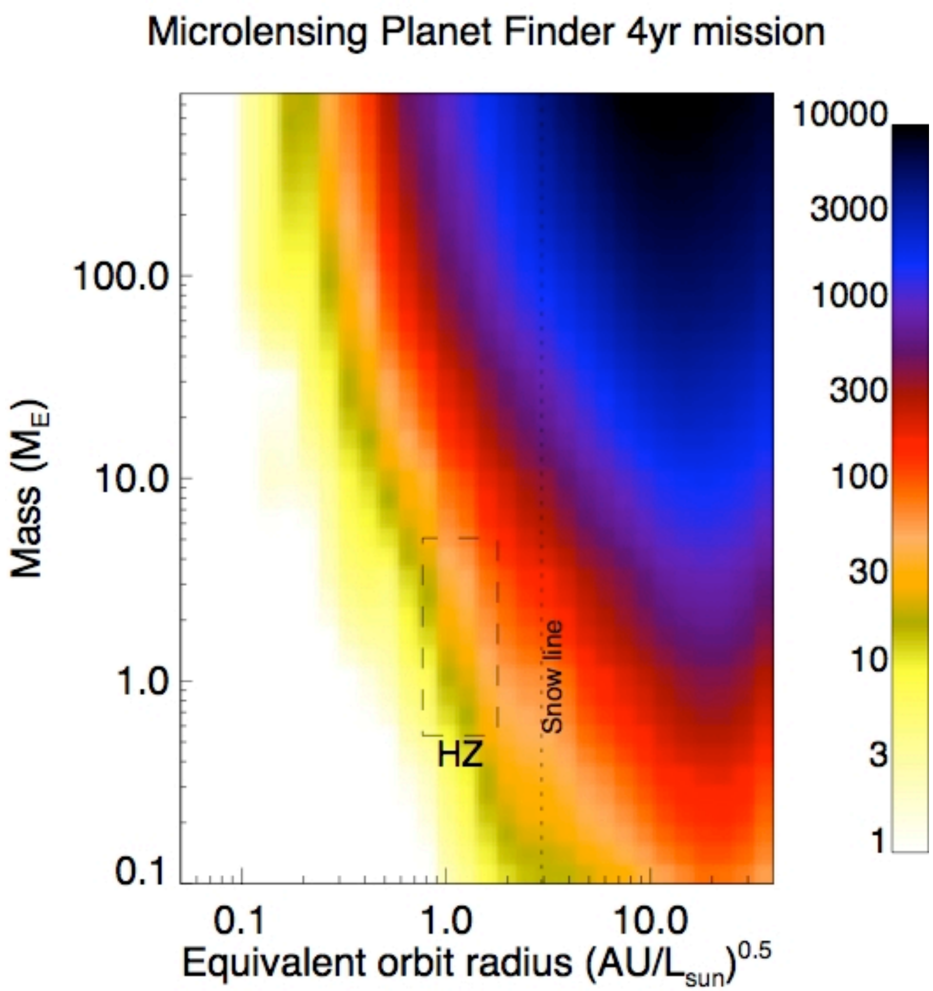
Ed Cheng, Deputy PI

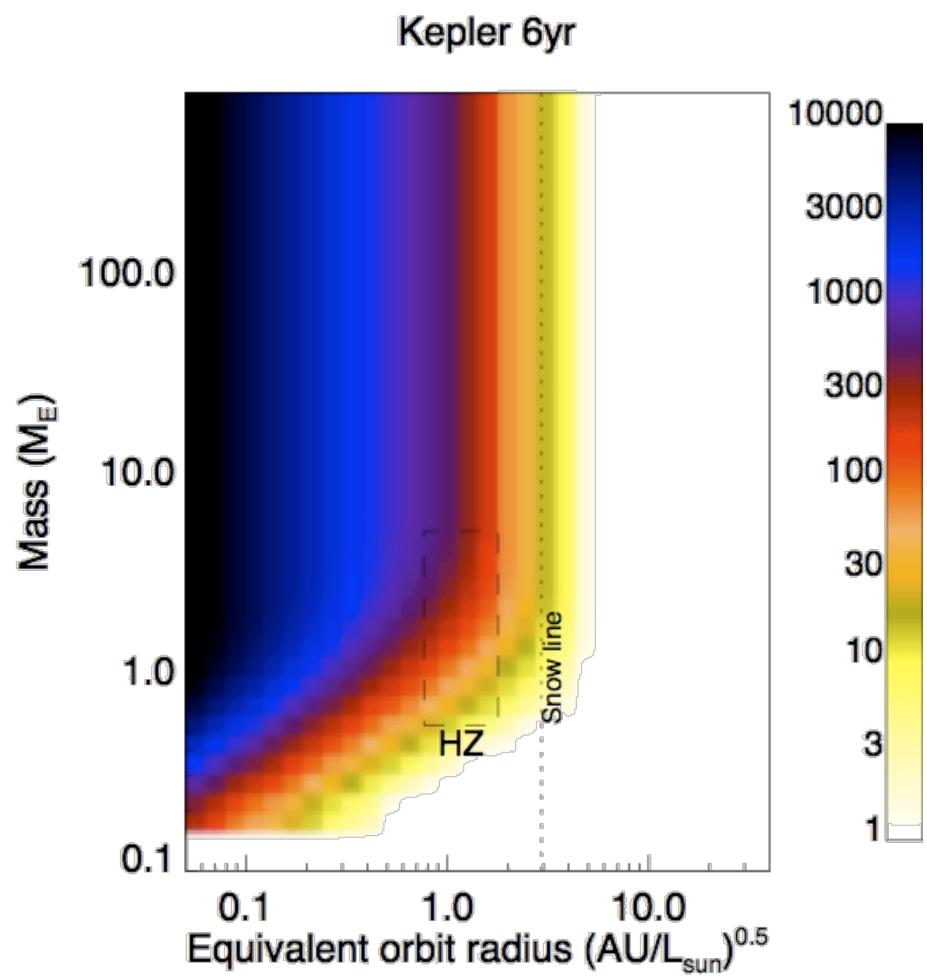
John Mather, GSFC lead





MPF + Kepler = a nearly complete census





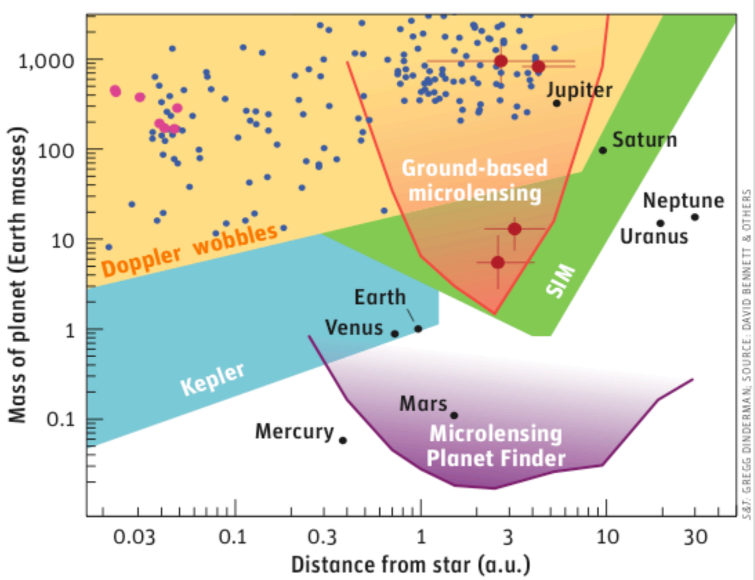
Figures from B. MacIntosh of the ExoPlanet Task Force

From Sky & Telescope, July 2007 issue:

The Best Way to Find Exoplanets

WHAT'S THE BEST WAY to take the census of every kind of planet that orbits every kind of star? It's not by looking for wobbles in stars' radial (line-of-sight) velocities, the method that has turned up nearly all of the 220 giant exoplanets discovered since 1995. Instead, it would be by using a space telescope to search for large numbers of *microlensing events* — temporary brightenings caused by the slight gravitational focusing of starlight when a massive object passes between us and a background star.

David Bennett (University of Notre Dame) and 16 coauthors tell the NASA/NSF Exoplanet Task Force that a $390 million Micro-



Planets that orbit other stars surely come in a wide variety of masses (vertical axis) and distances from their stars (horizontal axis). Different search methods can find different kinds.

"What's the best way to take the census of every kind of planet orbiting every kind of star? It's not by looking for wobbles in stars' radial (line-of-sight) velocities, the method that has turned up nearly all of the 220 giant exoplanets discovered since 1995. Instead, it would be by using a **space telescope to search for large numbers of microlensing events** — temporary brightenings caused by the slight gravitational focusing of starlight when a massive object passes between us and a background star."

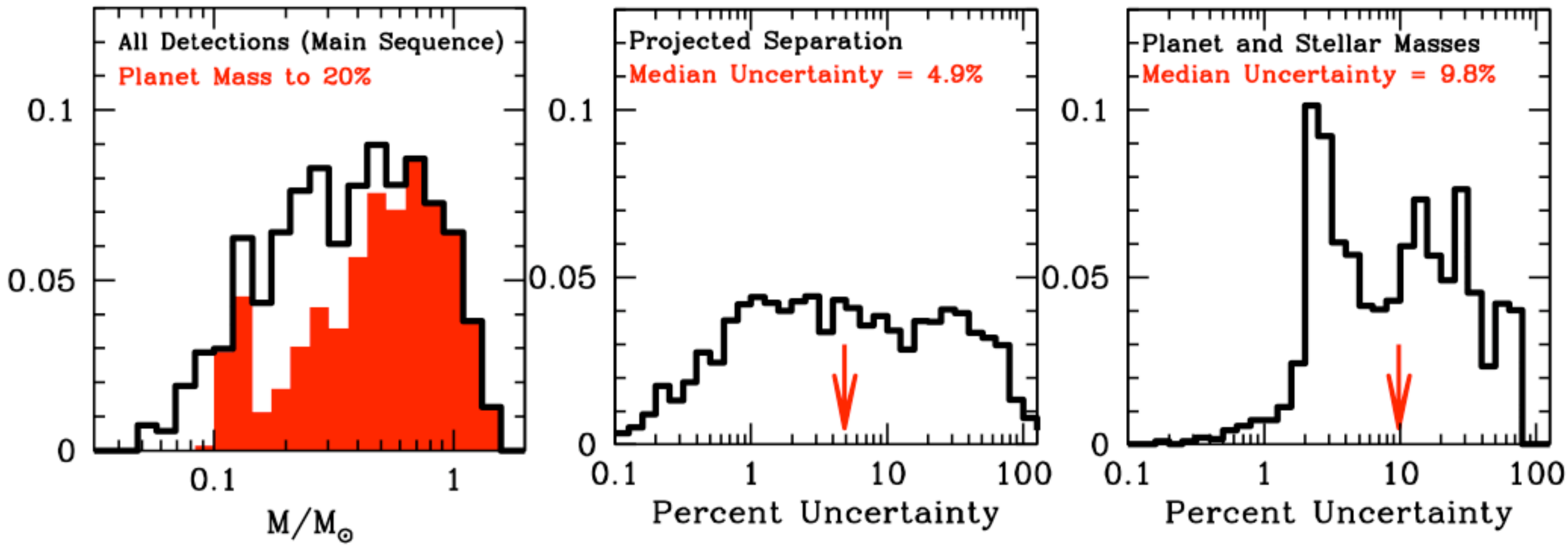
MPF!

and can cover the area of the graph indicated. The Microlensing Planet Finder could do far better. — ALAN MACROBERT

From the ExoPlanet Task Force:

- *"Recommendation B. II. 2 Without impacting the launch schedule of the astrometric mission cited above,* ***launch a Discovery-class space-based microlensing mission*** *to determine the statistics of planetary mass and the separation of planets from their host stars as a function of stellar type and location in the galaxy, and to derive* $\eta_{\oplus}$ *over a very large sample.*

Lens Detection Provides Complete Lens Solution



- The observed brightness of the lens can be combined with a mass-luminosity relation, plus the mass-distance relation that comes from the μ_{rel} measurement, to yield a complete lens solution.
- The resulting uncertainties in the absolute planet and star masses and projected separation are shown above.
- Multiple methods to determine μ_{rel} and masses (such as lens star color and microlensing parallax) imply that complications like source star binarity are not a problem.

Space Microlensing Fight Opportunities

- Discovery Program – no longer considers exoplanet missions
  - Good science review in 2004; good technical review in 2006
  - 2006 cost estimate of $300M plus launch vehicle passed technical review
  - **Discovery Class Microlensing Mission is Recommended by US Exoplanet Task Force!**
- Exoplanet Probe competition (~$600M cost cap)
- Astro-2010 Decadal Survey is considering a joint Exoplanet-Dark Energy mission
  - technical requirements are very similar, but would require a longer mission lifetime

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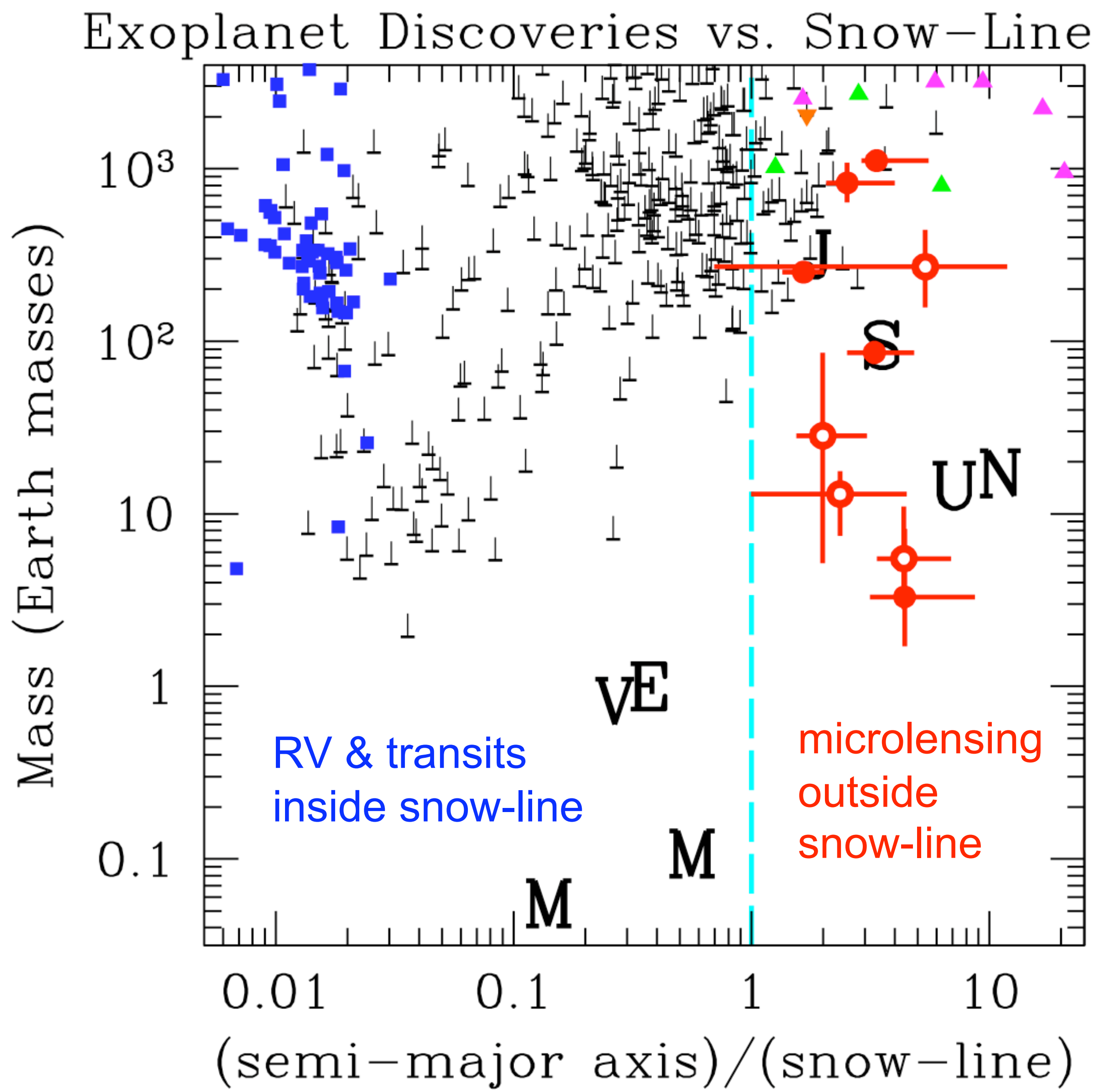
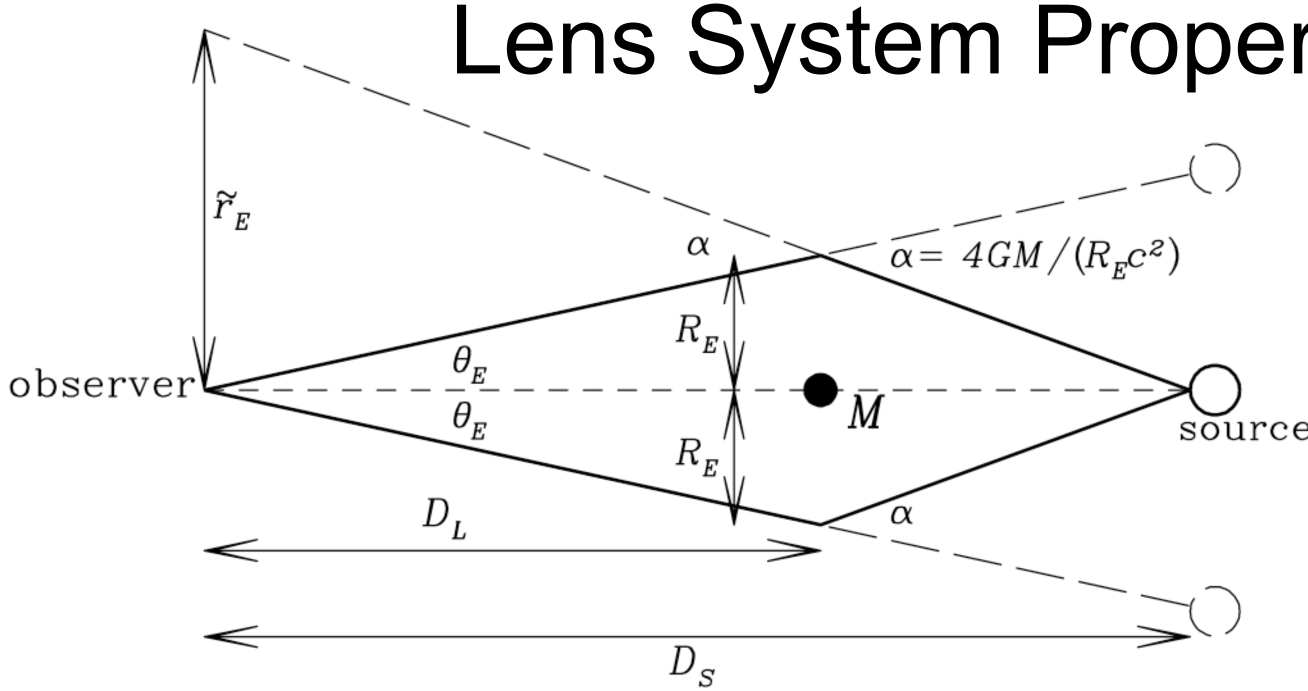


Lens System Properties

- 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 : $\theta_E = \theta_* t_E / t_*$ and projected Einstein radius, $\tilde{r}_E$
  - θ_* = 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:

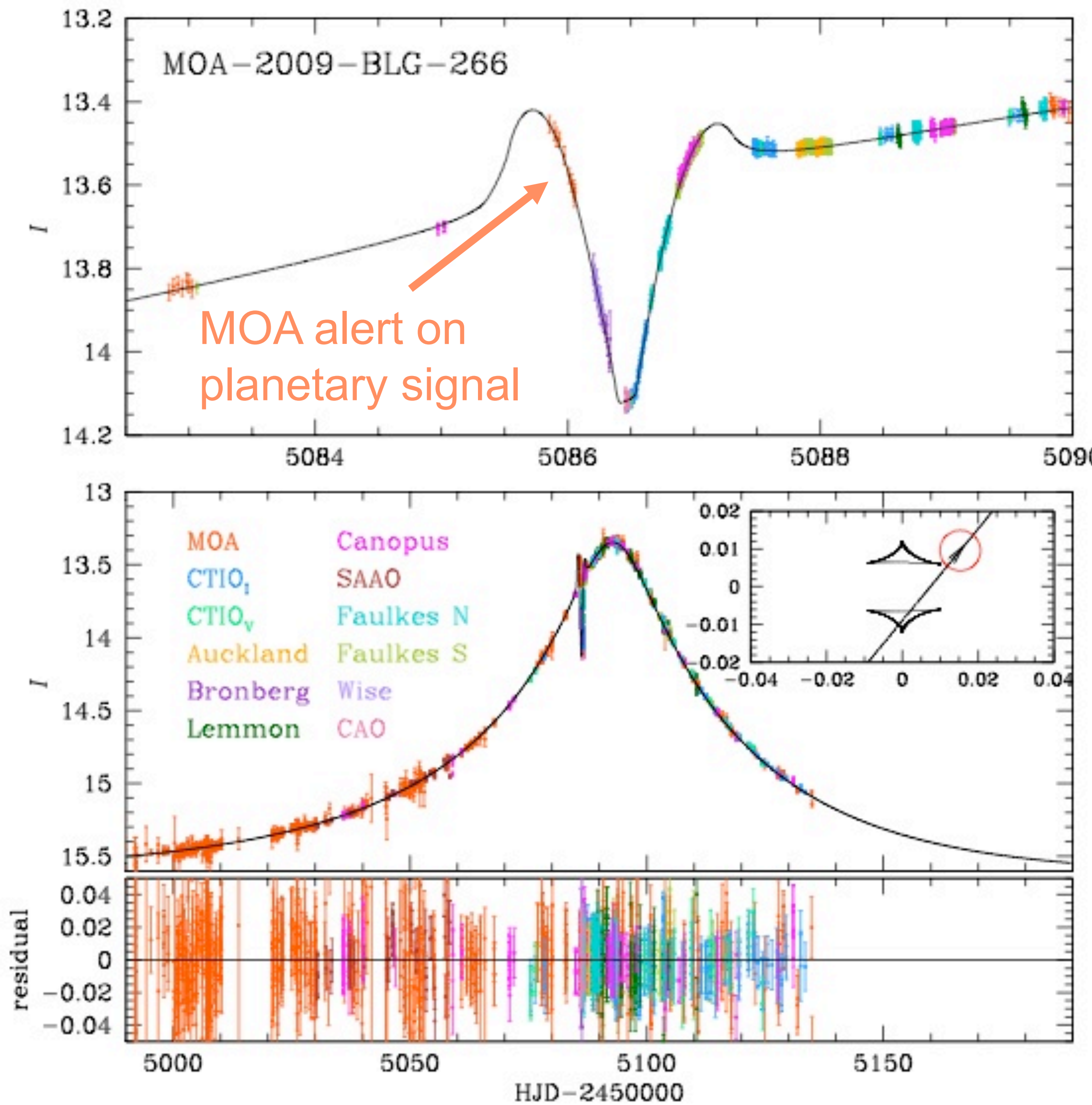
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

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

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

Survey Discovery: MOA-2009-BLG-266

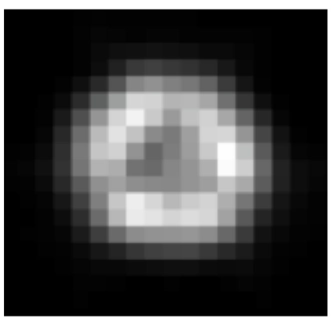
- Planet discovered by MOA on Sept. 11, 2009
- Low-mass planet
  - Probably $\sim 10 M_{\oplus}$
- Mass measurement from Deep Impact (now EPOXI) Spacecraft



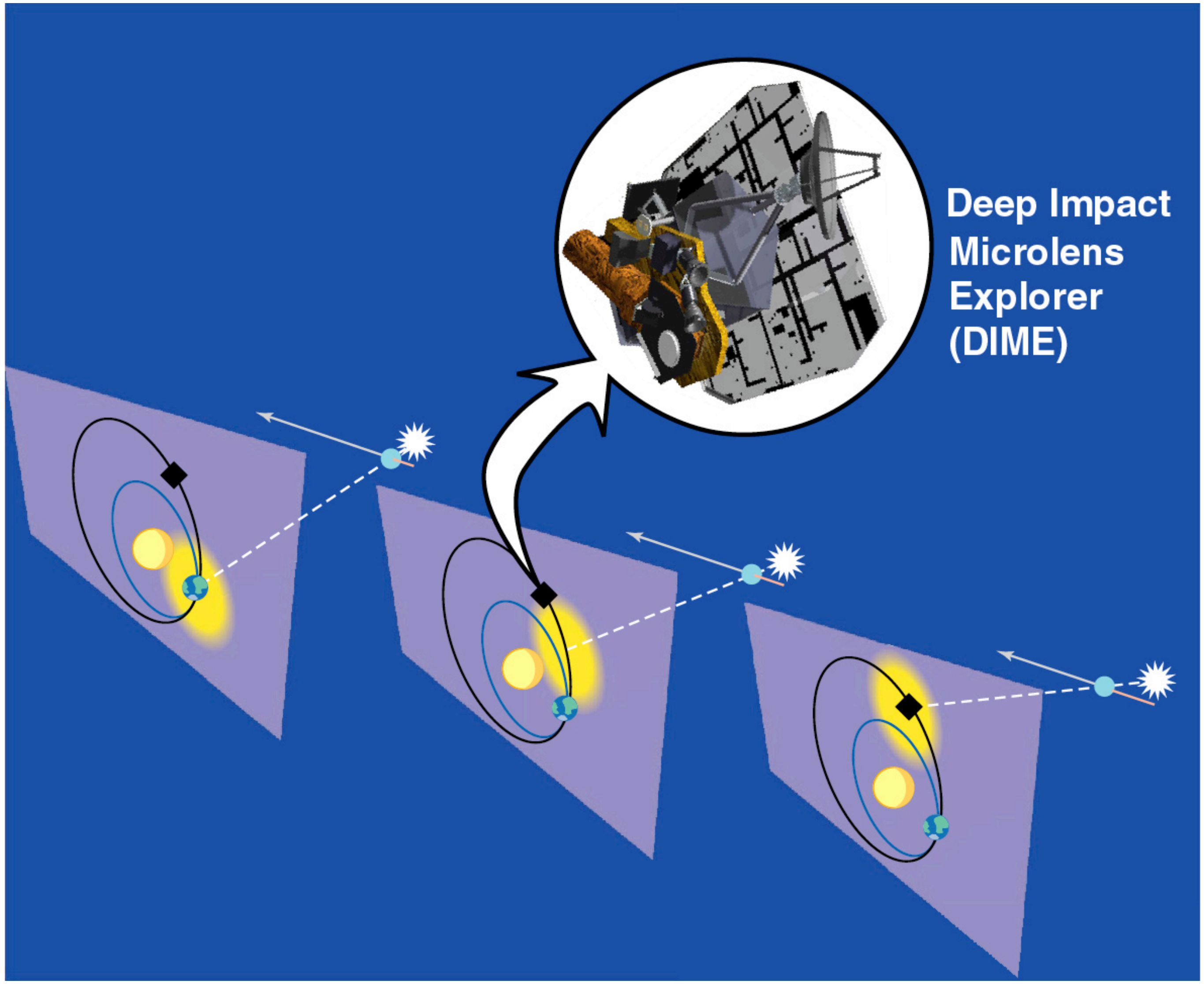
Space-Based Microlensing Parallax

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

2009: Geometric exoplanet and host star mass measurements with DI

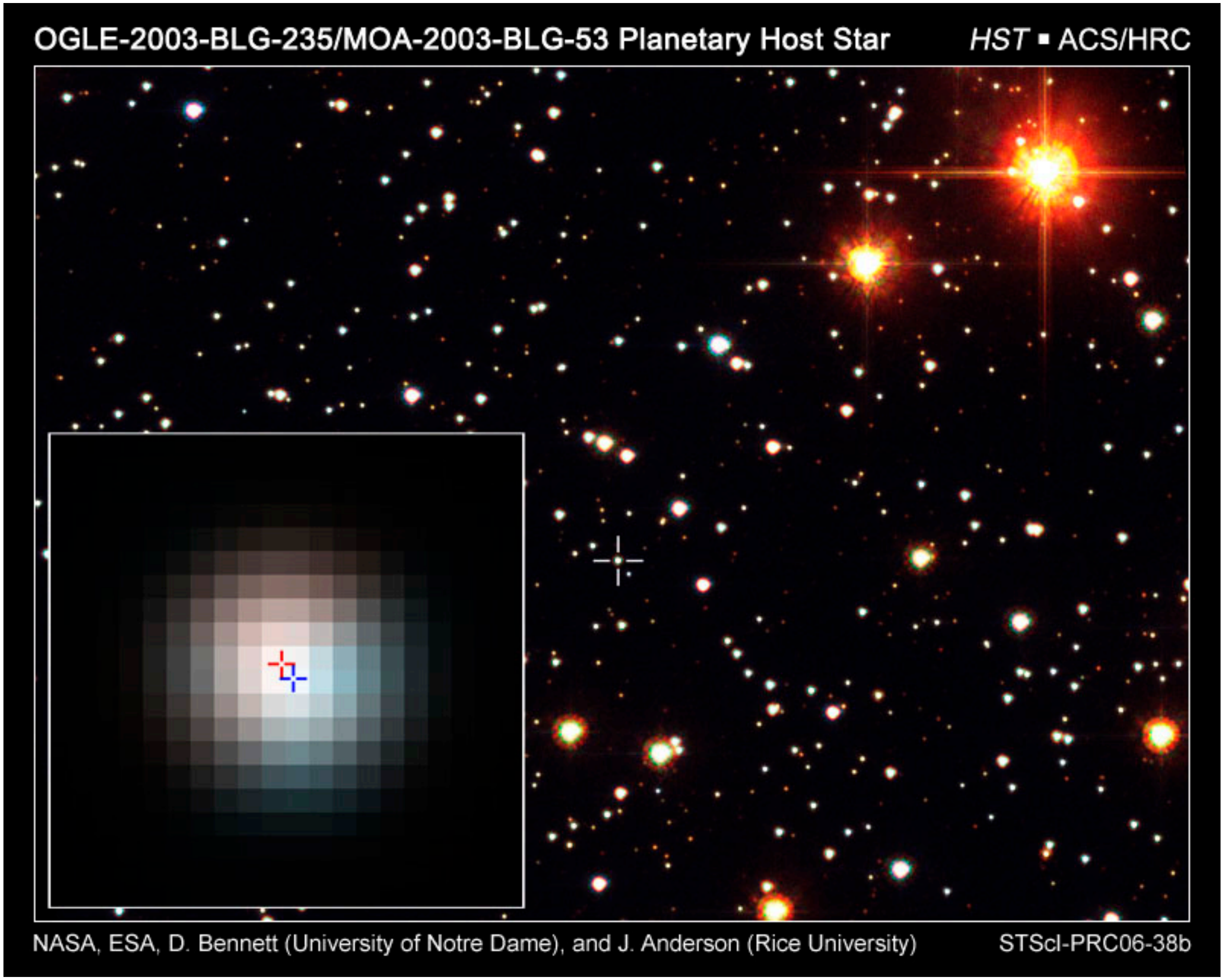


EPOXI PSF!



1st epoch observations in Oct. – awaiting 2nd epoch in March

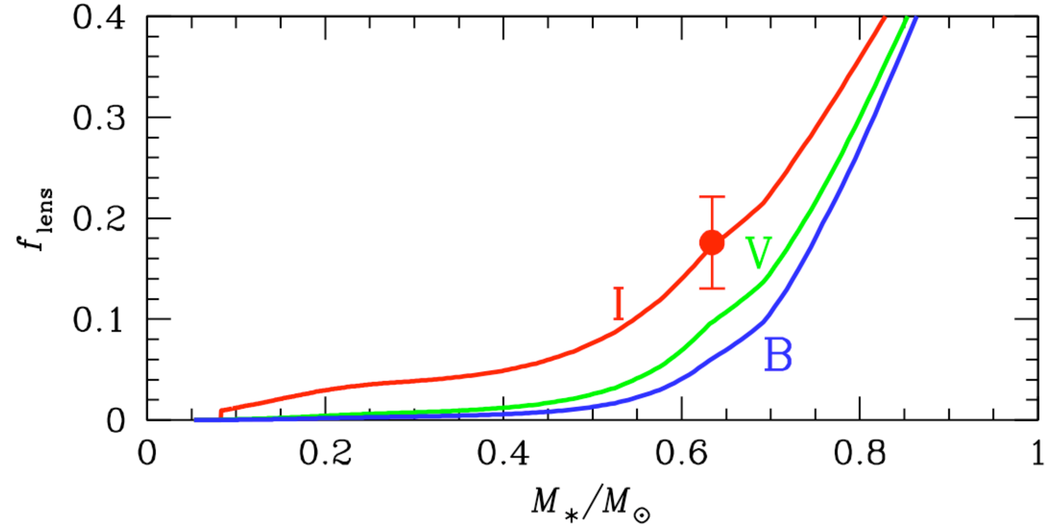
Color Dependent Image Center Shift



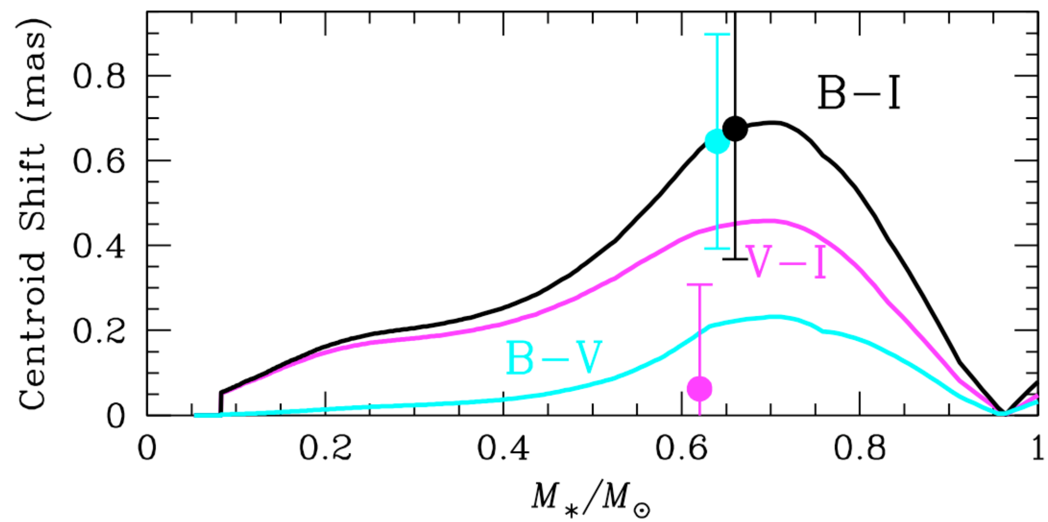
Source & Planetary Host stars usually have different colors, so lens-source separation is revealed by different centroids in different passbands

HST Observation Predictions for OGLE-2003-BLG-235L/MOA-2003-BLG-53L

Fraction of total flux due to lens star.



Centroid Shift between HST-ACS/ HRC passbands for follow-up images. (Units are 25 mas pixels.)



Relative proper motion μ_{rel}= 3.3±0.4 mas/yr from light curve analysis (μ_{rel}= θ_*/t_*)

Lens Star Identification from Space

- Lens-source proper motion gives $\theta_E = \mu_{rel} t_E$
- μ_{rel}= 8.4±0.6 mas/yr for OGLE-2005-BLG-169
- Simulated HST ACS/HRC F814W (*I*-band) single orbit image "stacks" taken 2.4 years after peak magnification
  - 2× native resolution
  - also detectable with HST WFPC2/PC & NICMOS/NIC1
- Stable HST PSF allows clear detection of PSF elongation signal
- A main sequence lens of any mass is easily detected (for this event)

Simulated HST images: