AST 205. Lecture 9. October 13, 2003
Gravitational Microlensing

- Drake Equation context & the need for other planet detection methods
- Basic gravitational lensing theory
- Gravitational microlensing by planets
- Advantages & disadvantages of technique
- The PLANET project
- Early results of the microlensing search

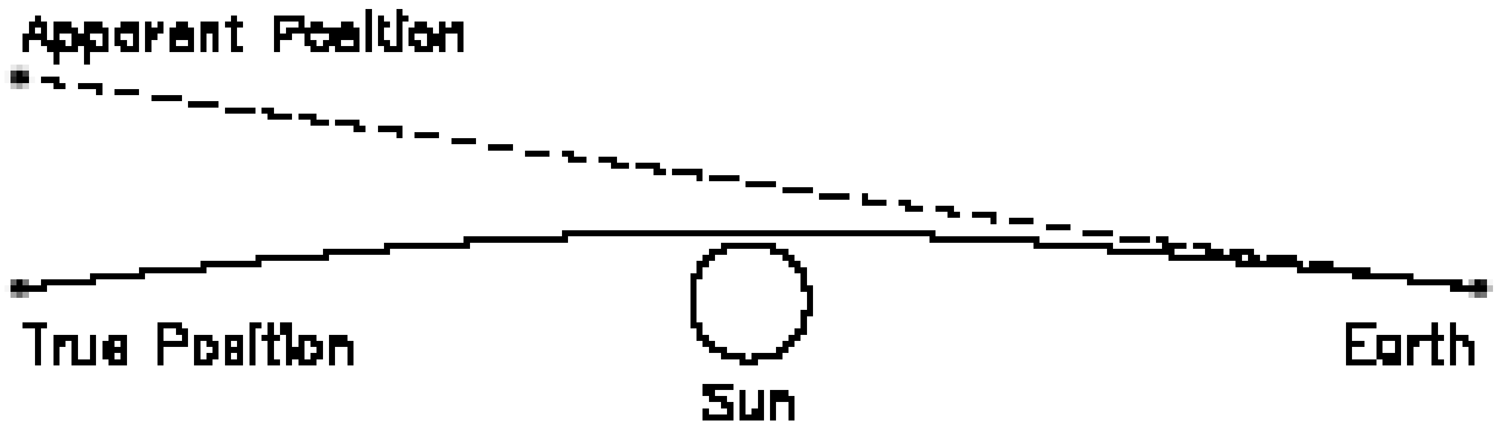
$N = f(p)n(e)f(l)f(i)f(c)R_{*}L$

- Radial velocity techniques have provided first direct clues about f(p), ≥ 5 -10%
- Wealth of data for the study of planetary systems and their formation in general
- *BUT* this information is incomplete and severely biased
- No direct information on n(e) yet
- Radial velocity and astrometric methods are poorly suited to detection of Earth-like planets in Solar System-like environments

Gravitational Lensing History

- Deflection of light/radiation by gravity
- Einstein (1915) = 2 x Newton prediction
- Eddington confirms in 1919 eclipse obsv.
- Chwolson (1924), Einstein (1936), Zwicky (1937), Refsdal (1964) … developed theory
- First observed in 1979 for a distant quasar
- Became a common tool for astronomy in the 1980s and 90s

Gravitaional Deflection of Light



Eddington proves Einstein right in 1919 eclipse!

Gravitational Deflection of Light Formula

Achromatic = wavelength independent!

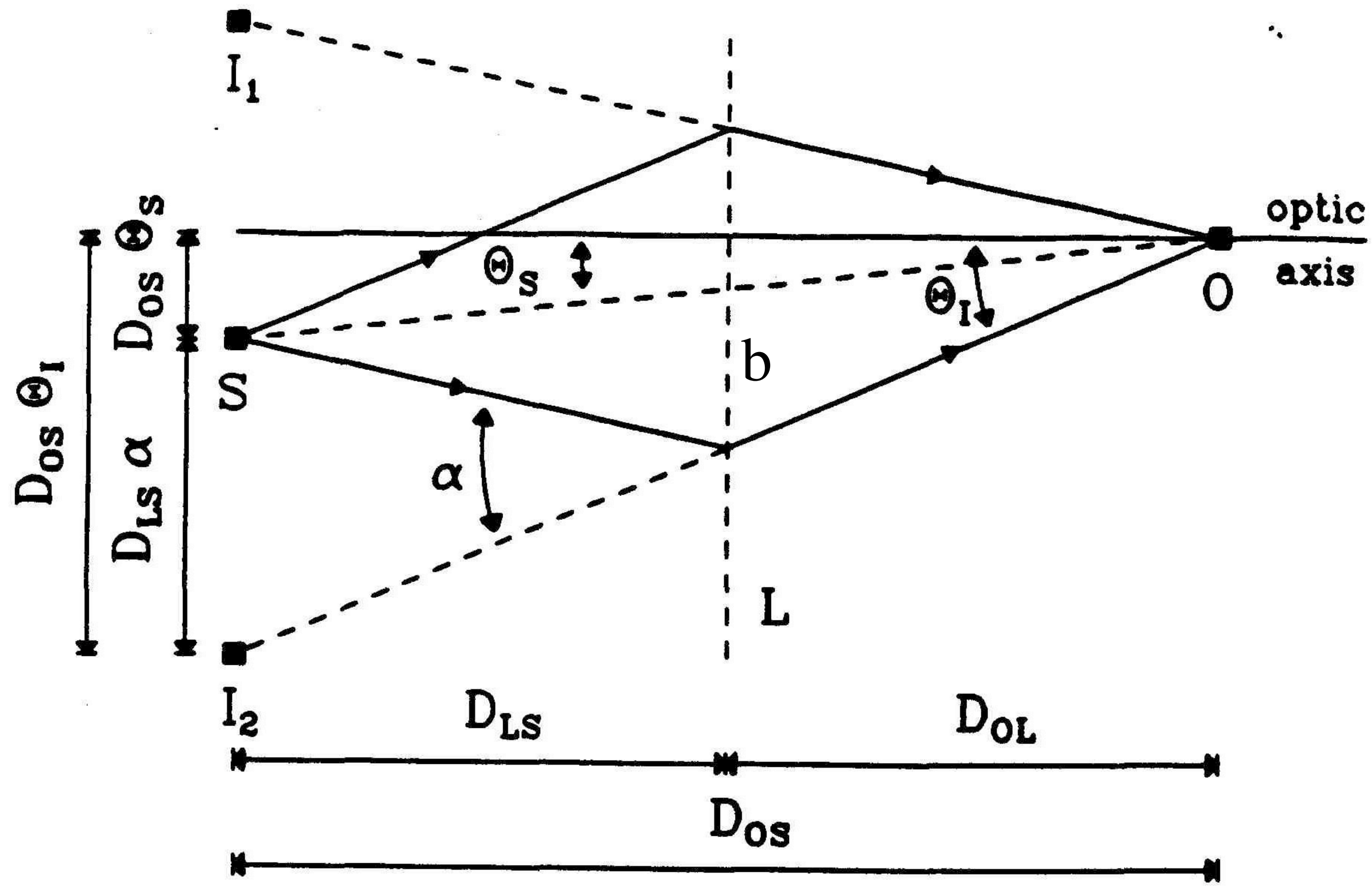
For a circularly symmetric mass distribution

$$\square = 4GM(<b)/bc^2$$

For a point mass (relevant for stars & planets)

$$\square = 4GM/D_{OL}\square_I c^2$$

Gravitational Lensing Geometry

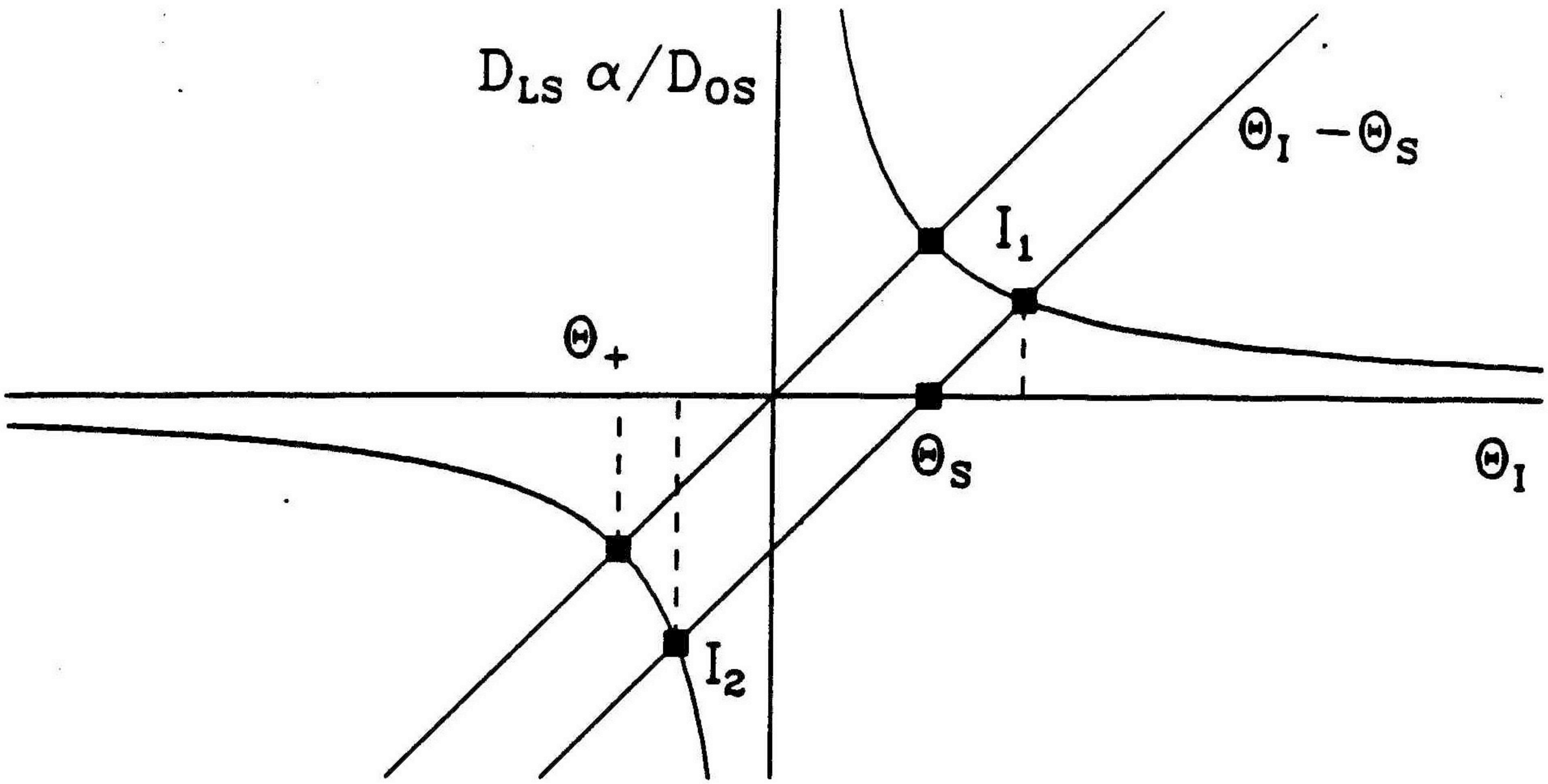


Geometrical Optics - Image Condition

$$D_{OS}\square_{I} = D_{LS}\square + D_{OS}\square_{S}$$

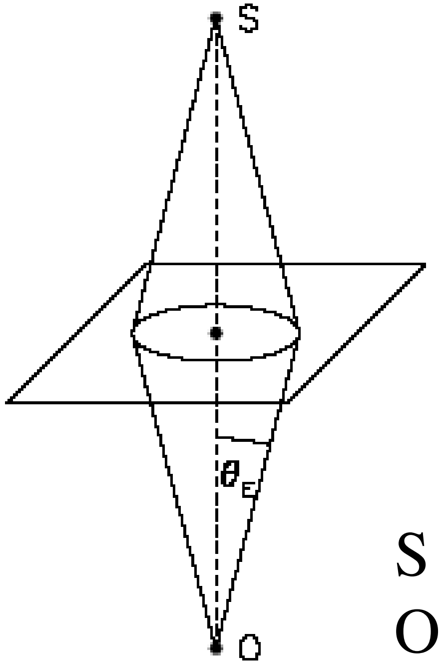
$$\square = D_{OS}(\square_{I} - \square_{S})/D_{LS}$$

Solution of Gravitational Lens Equations

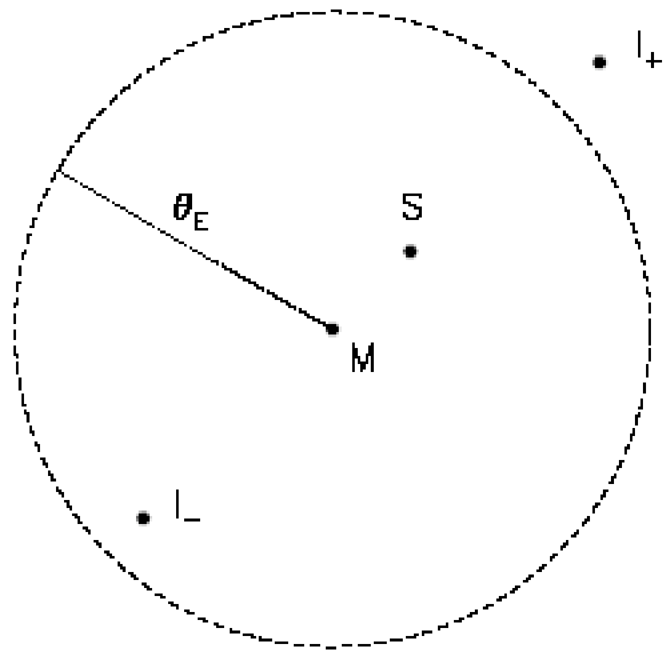


Simultaneous solution of lens & optical equations

The Einstein Ring and Lensed Images



S = source
O = observer
I = images
M = lens/mass

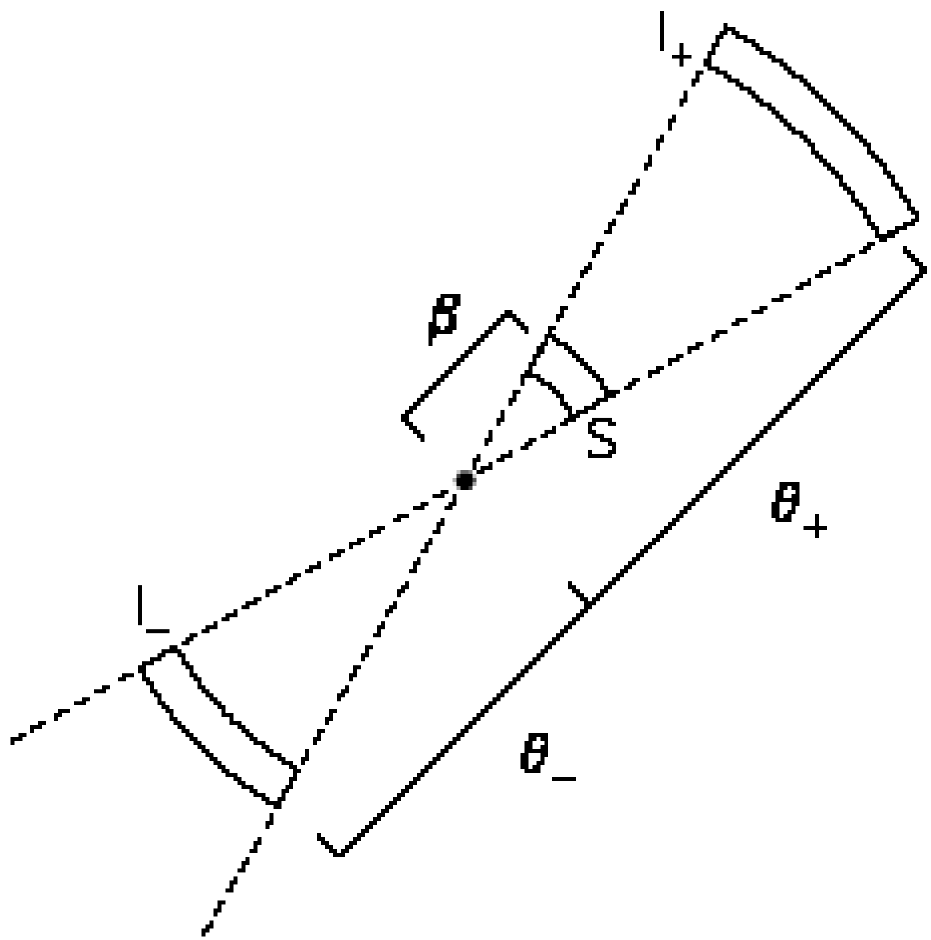


Appearance in the sky

Einstein Ring Radius Formula

$$\theta_E = [4GMD_{LS}/D_{OS}D_{OL}c^2]^{1/2}$$

Gravitational Lens Magnification Image Effect



Gravitational Lens Magnification Formula

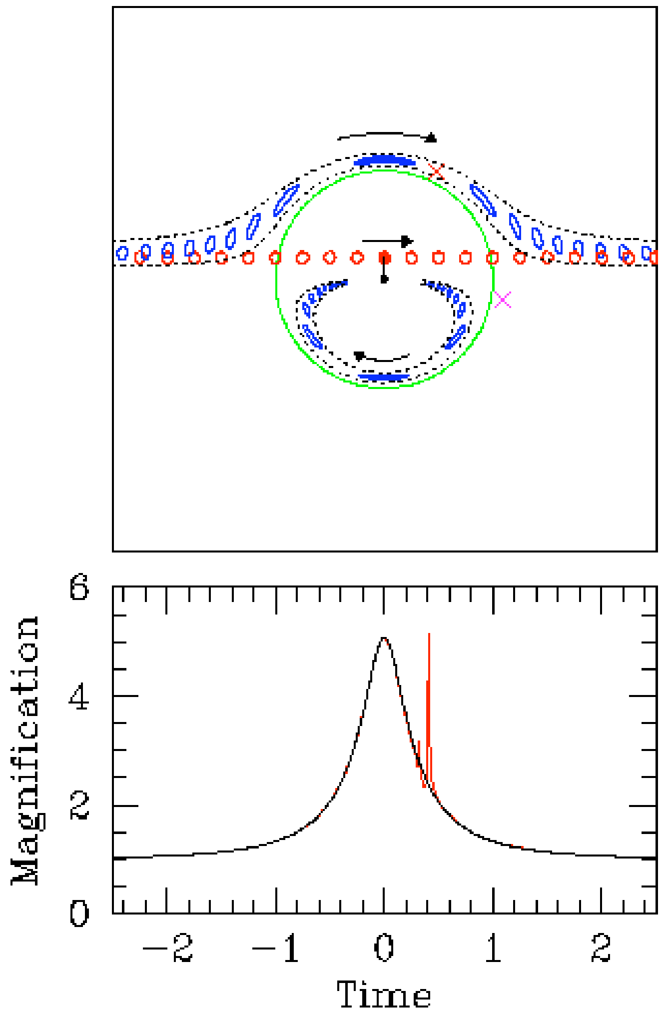
$$\mu_{\pm} = \left[1 - \left(\frac{\theta_E}{\theta_{\pm}}\right)^4\right]^{-1} = \frac{u^2 + 2}{2u\sqrt{u^2 + 4}} \pm \frac{1}{2} ,$$

$$\mu = |\mu_+| + |\mu_-| = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} .$$

where u = $\square_S / \square_E$

A Gravitational Microlensing Event

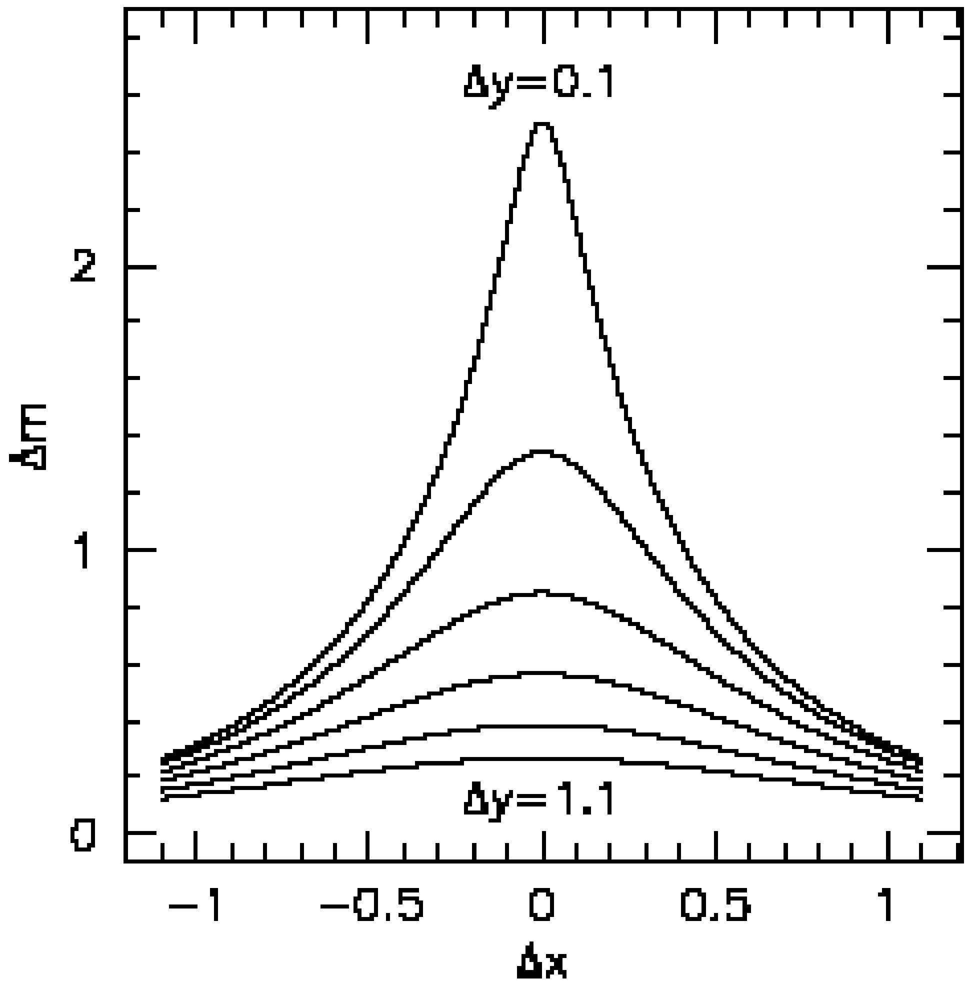
During a micro-lensing event the relative positions of the source and the lens change due to the motions of both through cross the sky.



As a result both the image positions and magnifications change with time.

Planets can make small perturbations in the microlensing event produced by their primary star.

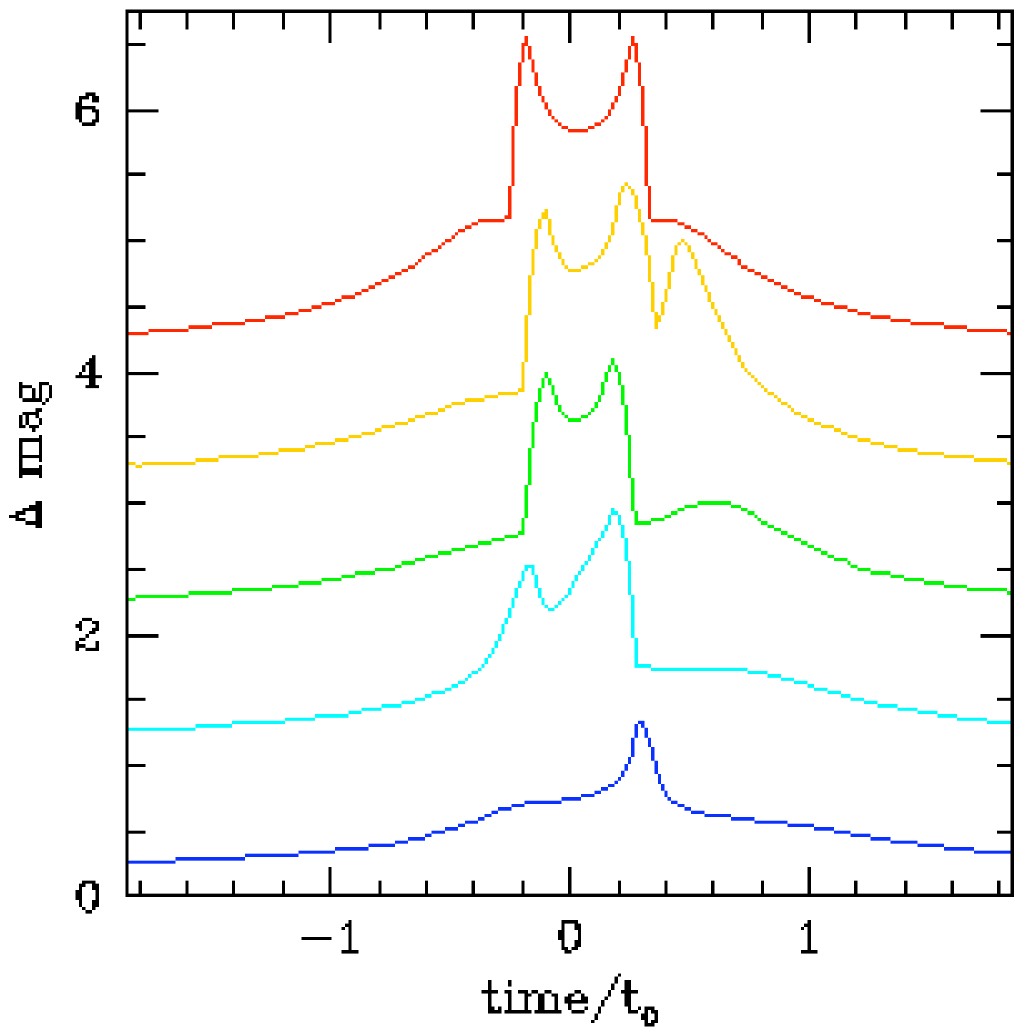
Gravitational Microlensing Light Curves



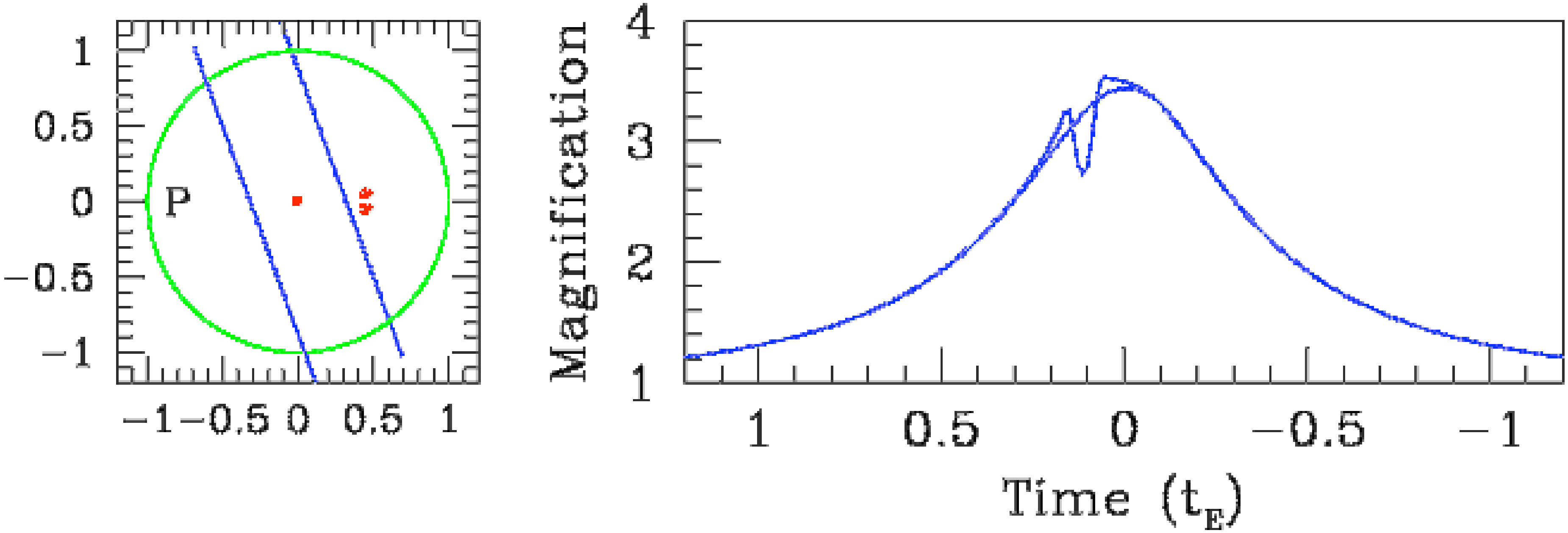
Duration of Gravitational Microlensing Events

$$\text{Duration} = \frac{2\,D_L\,\theta_E}{v_L} = \frac{2\,D_L}{v_L}\sqrt{\frac{4\,G\,M\,[1-\frac{D_L}{D_S}]}{c^2\,D_L}}$$

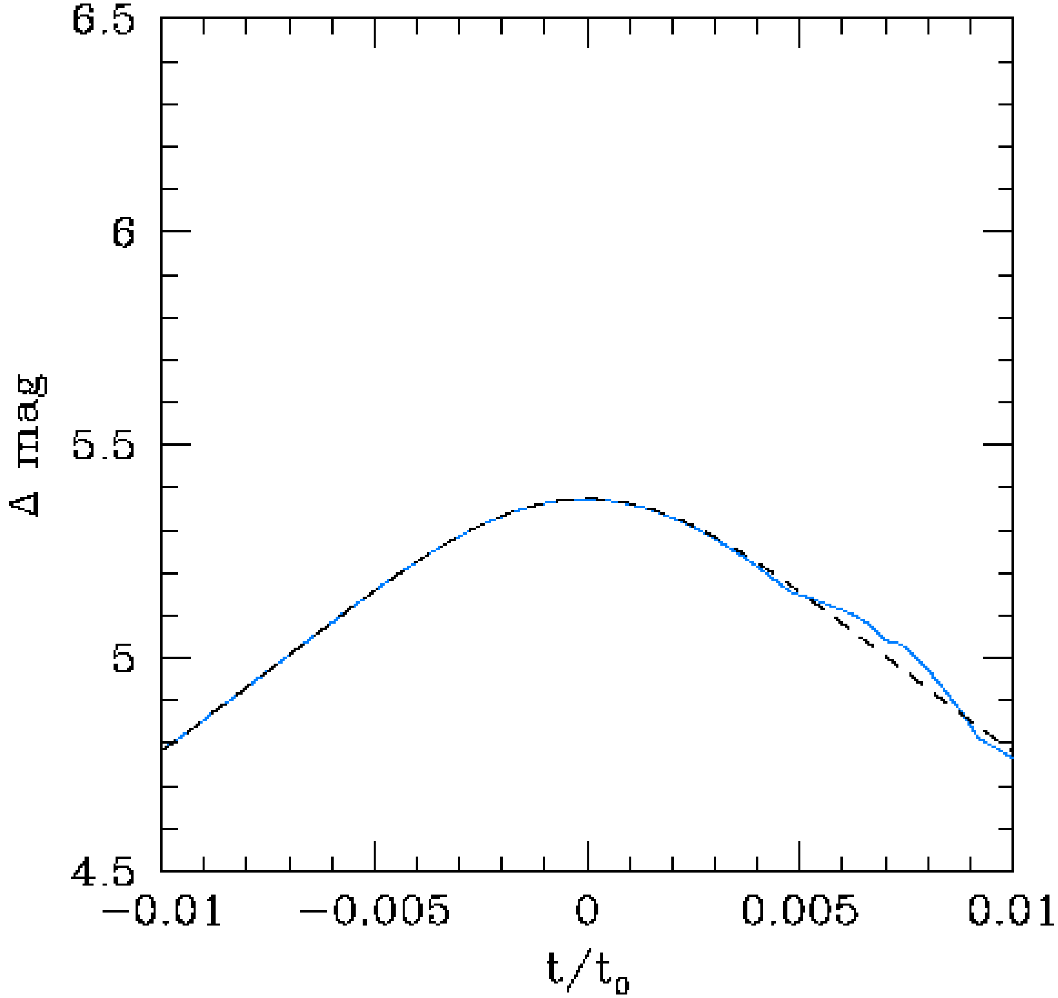
Light Curves from Two Equal Point Masses



Light Curve Produced by a Hypothetical Planetary System Gravitational Lens



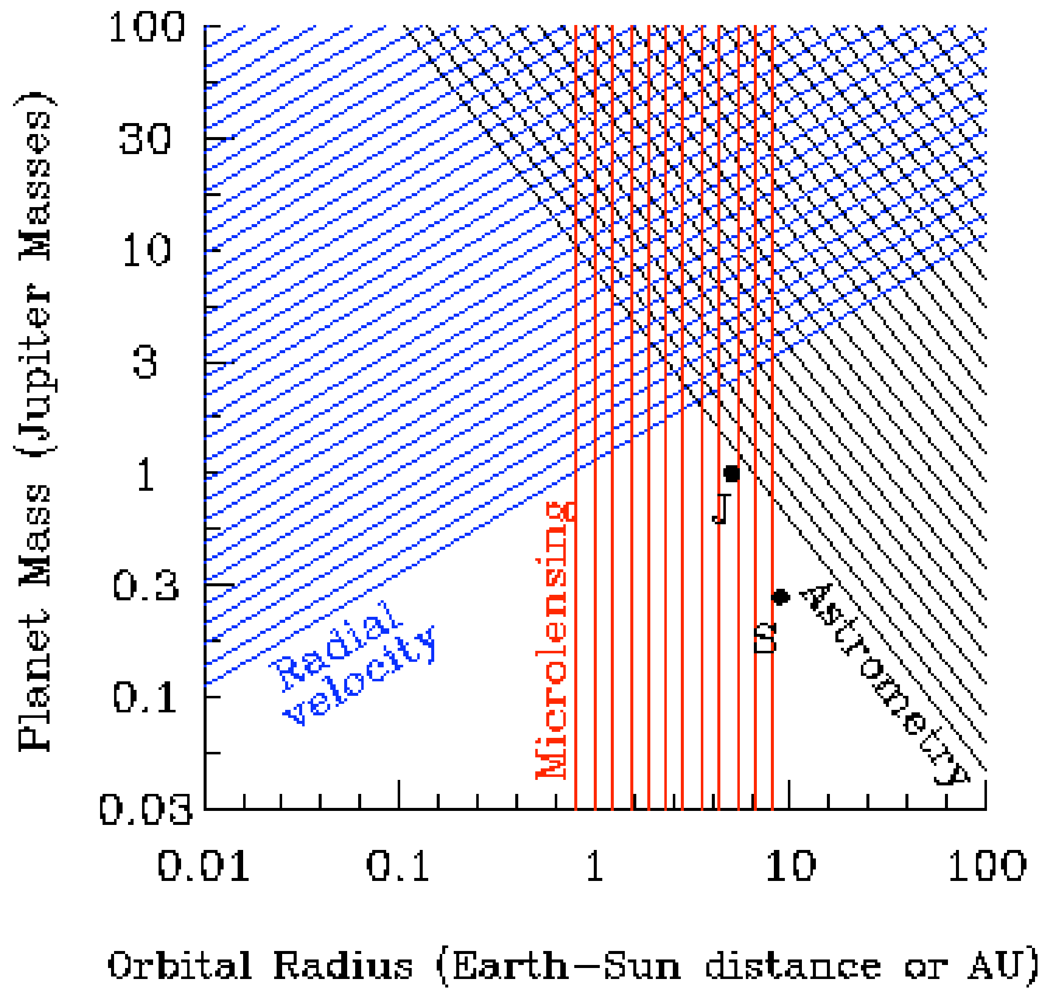
The Earth's Perturbation of a Light Curve Produced by the Sun Acting as a Grav Lens



Advantages of Microlensing Technique

- Jupiter-like planets "always" detectable
- Anomalies last hours to days (not years to decades)
- Earth-like planets "occasionally" detectable
- Can measure mass ratio & projected separations of planet and star
- Based on chance alignments; ideal for statistical characterization of Galactic planetary system population

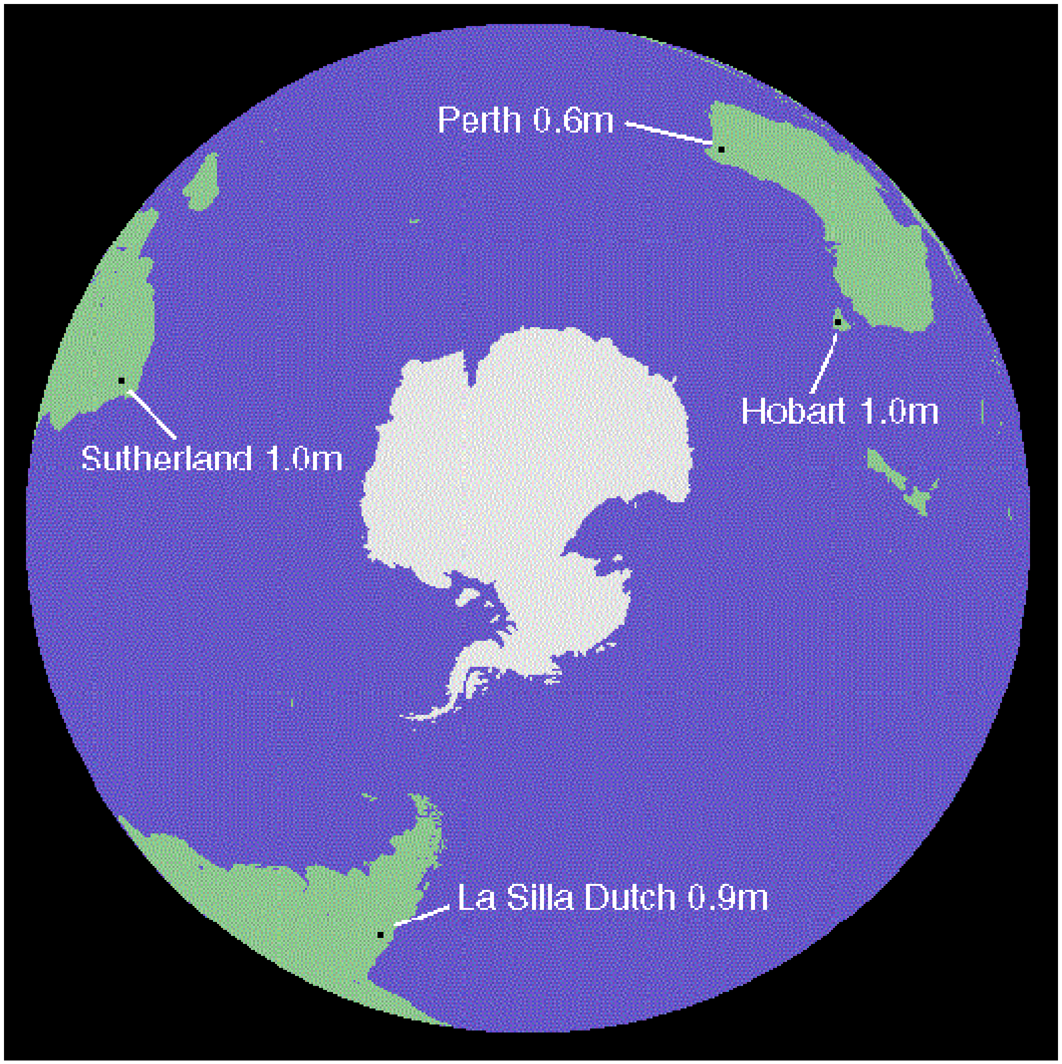
Regions of Sensitivity for Three Planet Detection Techniques



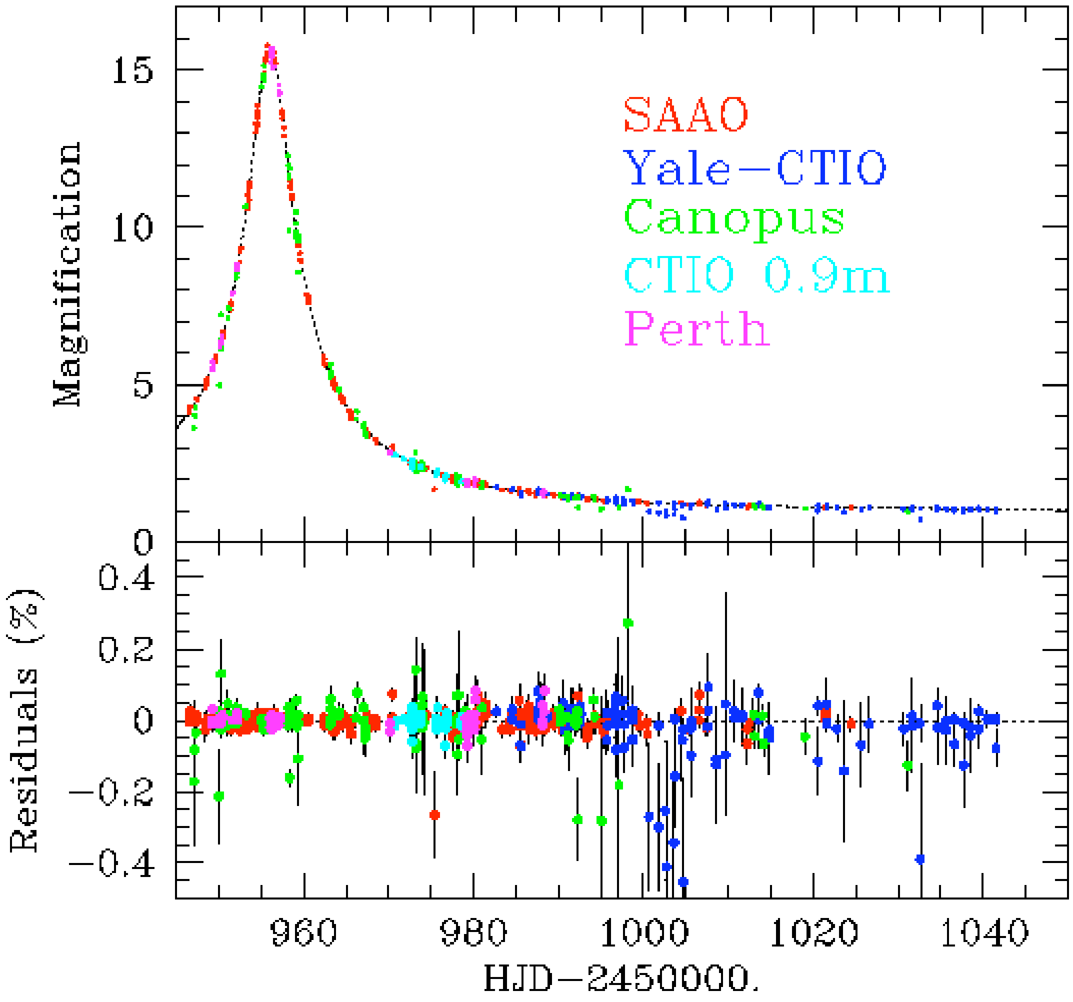
Disadvantages of the Microlensing Technique

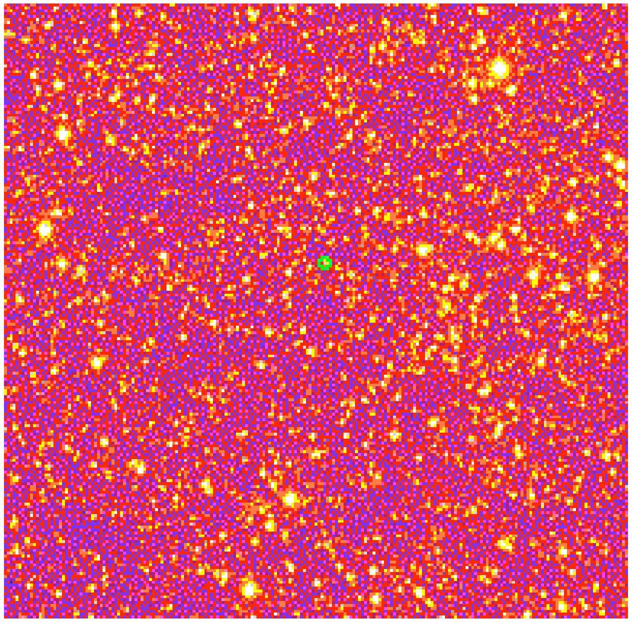
- Requires *very precise* chance alignment of a source and the foreground planetary system
  - Rare and unpredictable
  - Transient and non-repeating
- Planetary systems detected will typically be very distant and impossible to study further
- Event durations are comparable to Earth's diurnal cycle (i.e., 24 hours)

PLANET: Probing Lensing Anomalies NETwork (http://mplanet.anu.edu.au/)



PLANET Light Curve of a Well Studied Microlensing Event

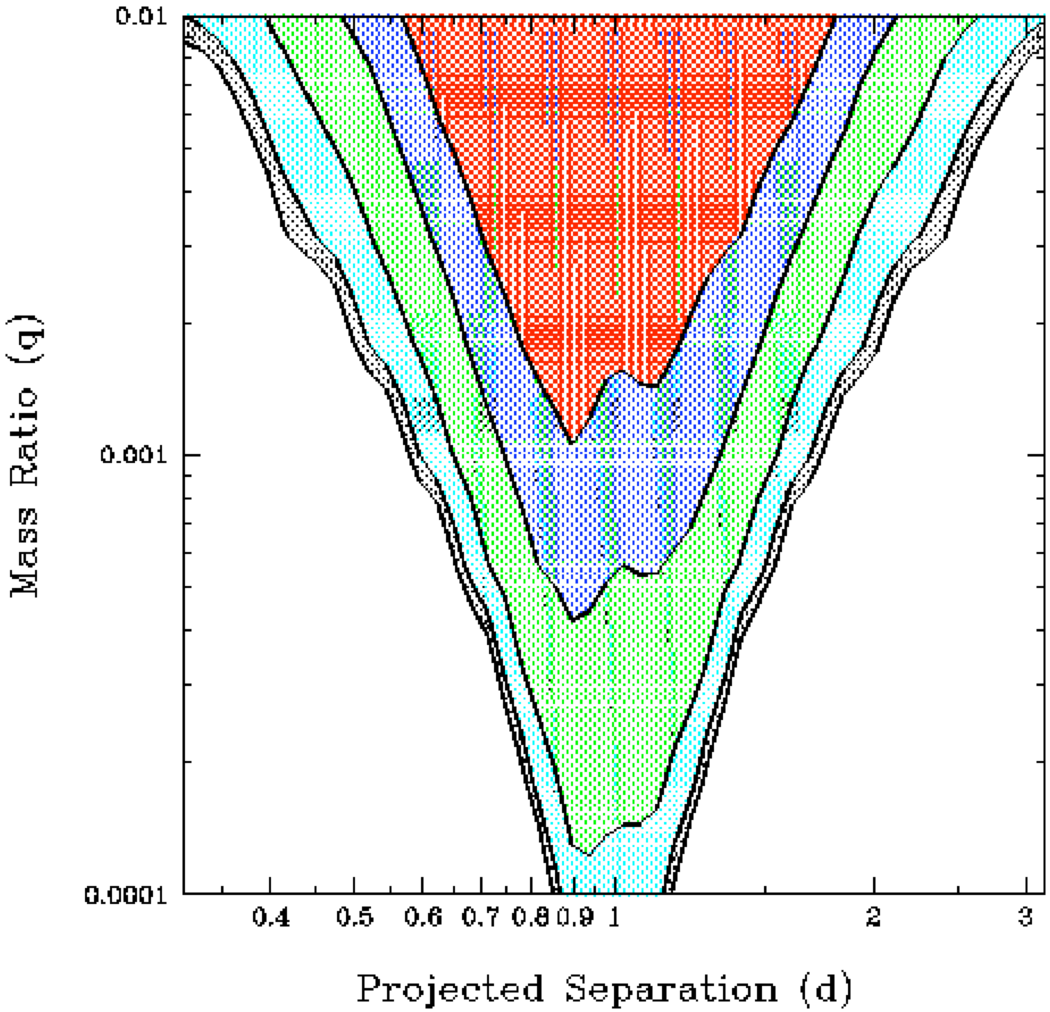




PLANET: Null Results for First Five Years

"Analysis of 43 microlensing events from five years of PLANET team monitoring data has revealed no indication of the short-lived ``wiggles'' that planets orbiting the lens would create on light curves of the background stars. At the level of the observational uncertainties, all light curves were consistent with those due to an isolated stellar lens. The lack of any detected planetary signature in these 43 events implies that less than 1/3 of M-dwarfs have Jupiter-mass companions orbiting at 1.5 to 4 AU. M-dwarfs are cool, low-mass stars that make up the bulk of stars (and microlenses) in the Galaxy."

Summary of PLANET Null Result from Five Years of Data (43 Events)



Assume

25%

33%

50%

67%

100%

of stars to

have planets.