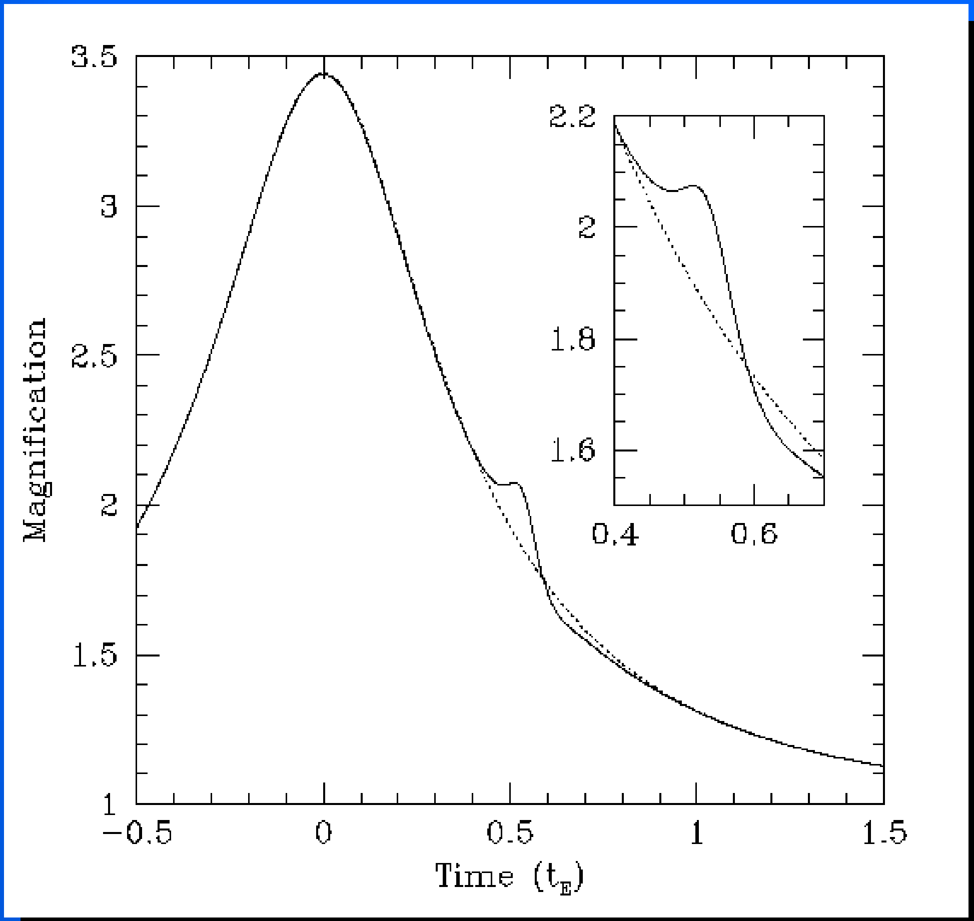
Microlensing Searches for Extrasolar Planets



I. The Search for Planets.
II. Microlensing and Planets
III. Alerts and Follow-up.
IV. Detection and Efficiency.
V. 5 Years of PLANET Data.
VI. Future Prospects
VII. Conclusions.

The Search for Extrasolar Planets

Why Search for Extrasolar Planets ?

- Frequency of Life
- Clues to Star Formation
- Low End of the Compact Object Mass Function

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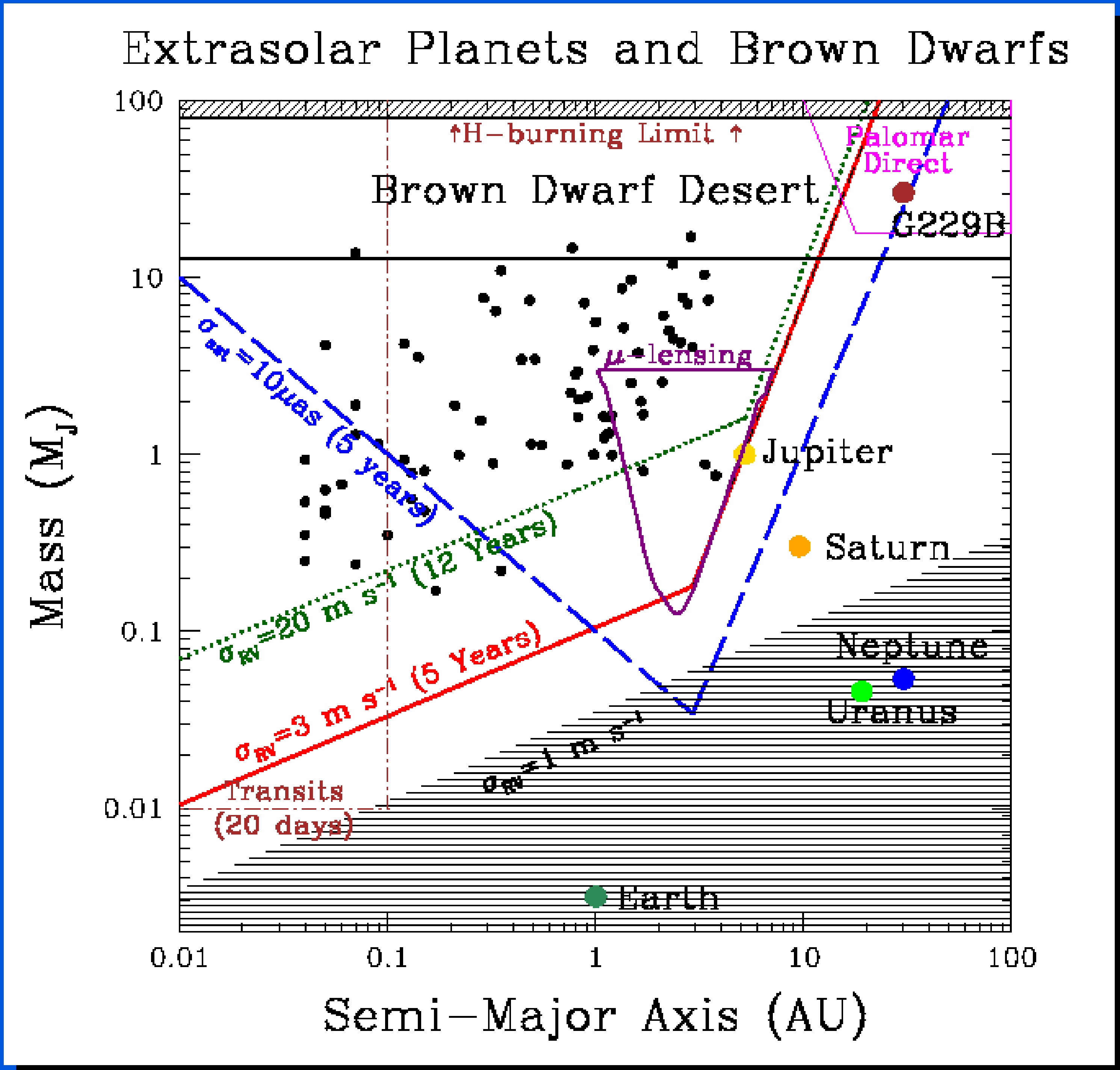
“Classical” Detection Methods:

- Radial Velocities
- Astrometry
- Transits
- Direct Detection



"Classical" Detection Methods

Radial Velocities

Astrometry

Transits

Direct Imaging

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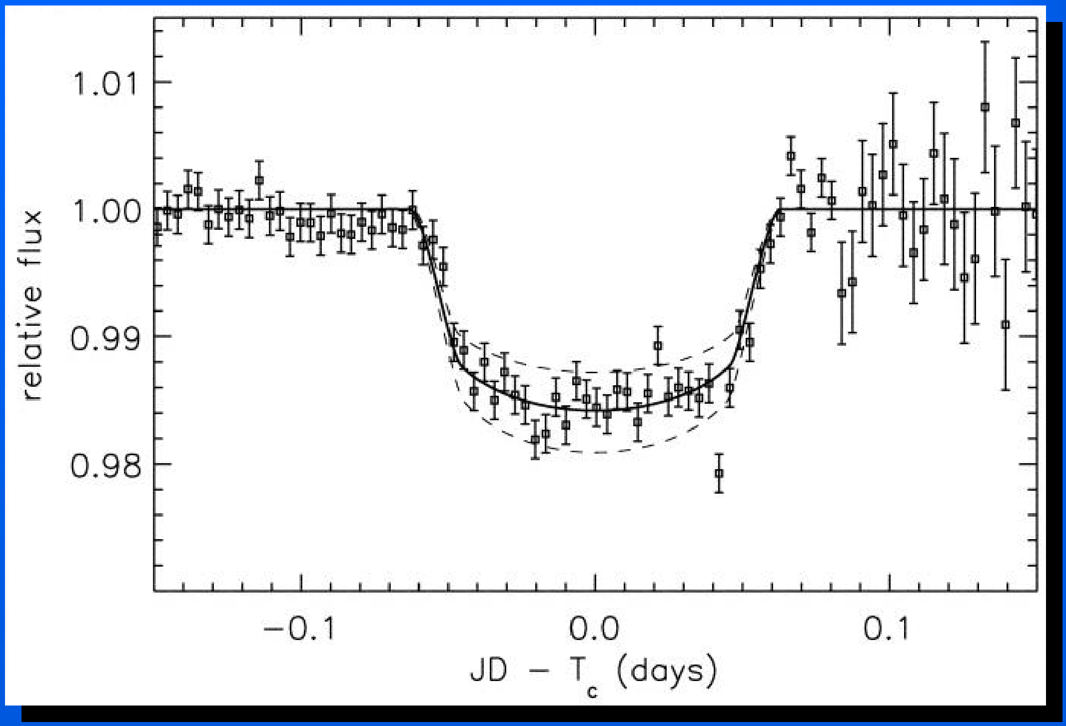
Various Methods are Complimentary:

- Parameters Measured
- Separations Probed



Charbonneau et al. 2000

The Search for Extrasolar Planets

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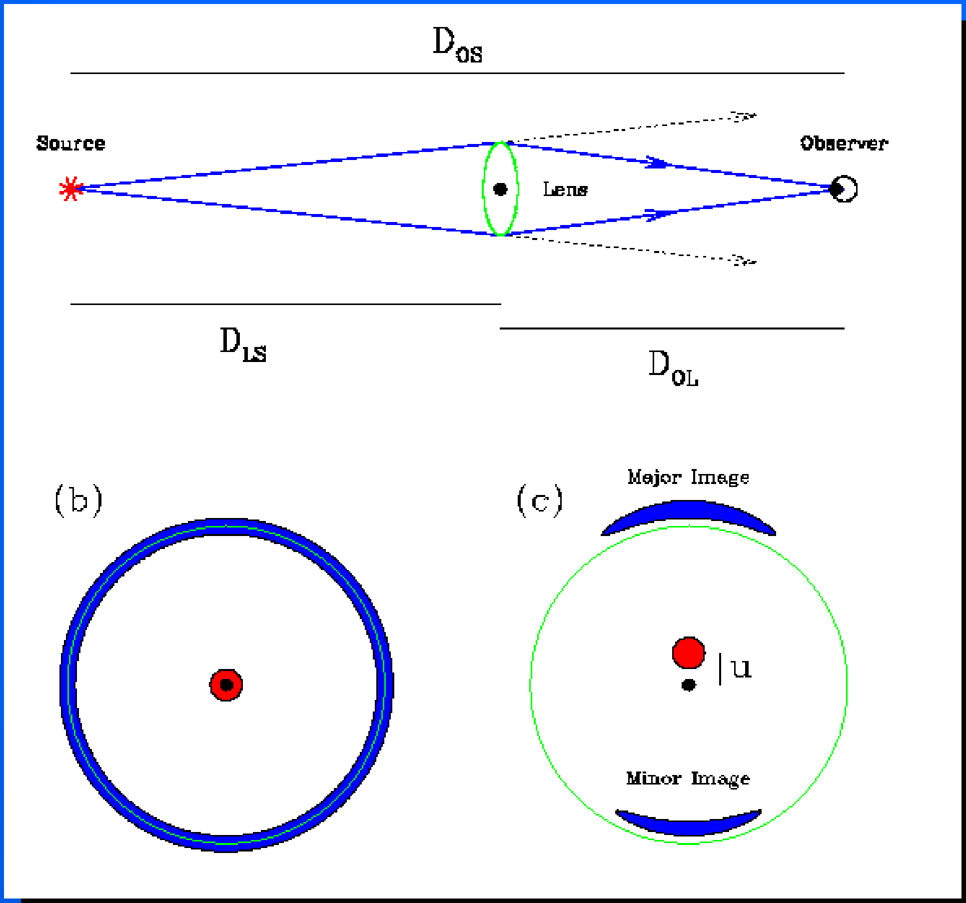
Various Methods are Complementary:

- Parameters Measured
- Separations Probed

Drawbacks:

- Not sensitive to small mass planets.
- Limited to nearby systems.
- Period must be less than duration of observations.

Microlensing and Planets



Time Delay

$$\tau = \frac{1}{2}(\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta})$$

$$\psi(\vec{\theta}) = \frac{1}{\pi}\int \kappa(\vec{\theta'}) \ln|\vec{\theta} - \vec{\theta'}| d^2\vec{\theta'}$$

$$= \theta_E^2 \ln \theta$$

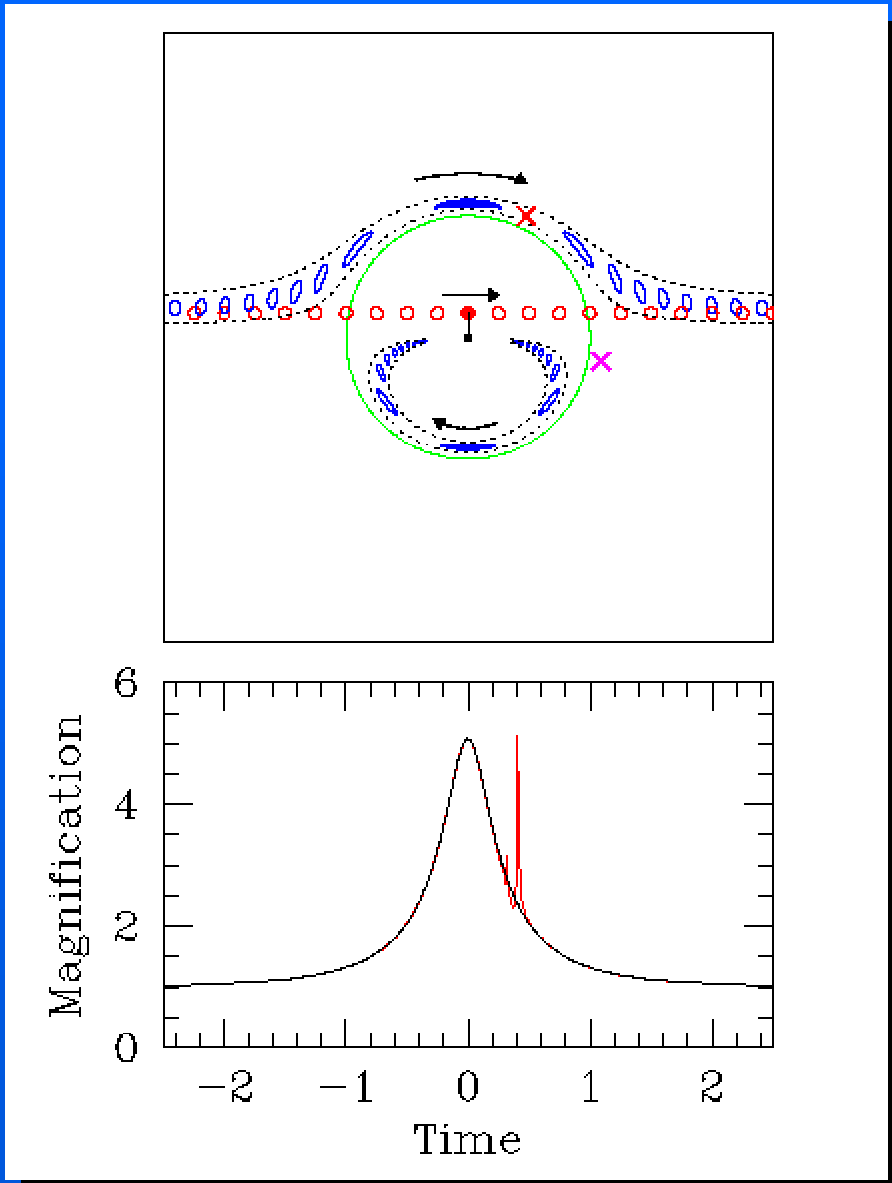
Lens Equation

$$\beta = \theta - \theta_E^2/\theta$$

Angular Einstein Ring Radius

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_{OL}D_{OS}}} \simeq 300\mu as \left(\frac{M}{0.3M_\odot}\right)^{1/2}$$

Microlensing and Planets

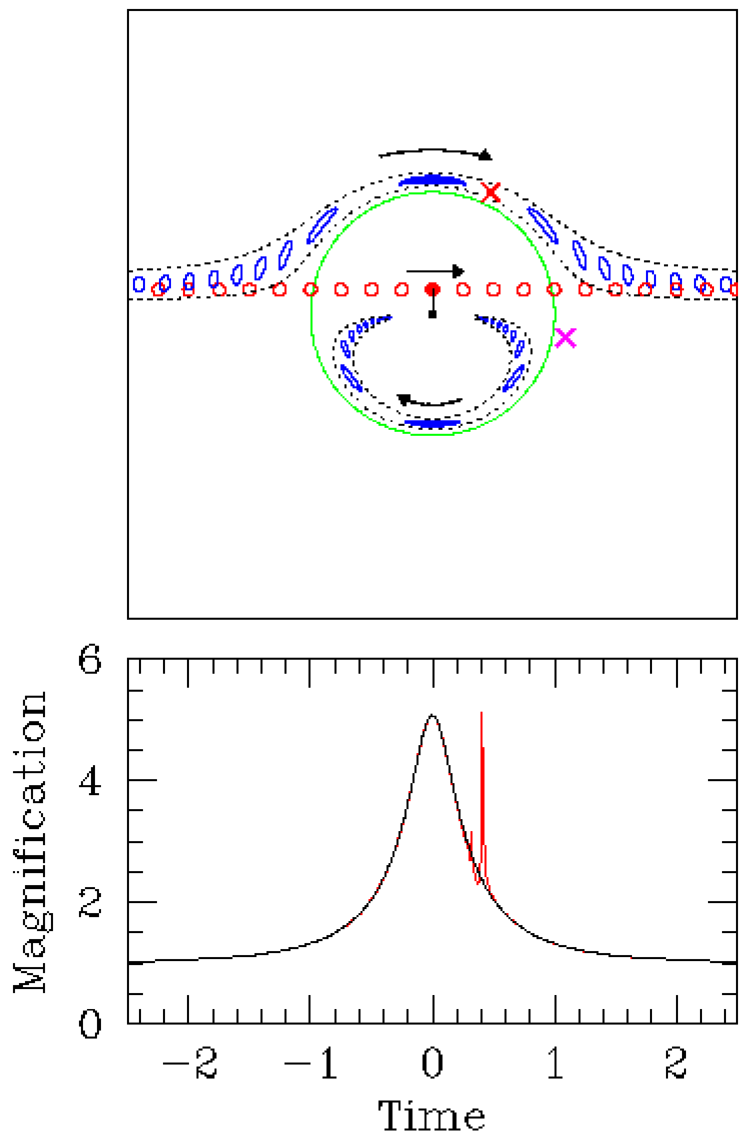


Single Lens Parameters:

- Impact parameter
- Time of Maximum Mag.
- Timescale

$$t_E = \frac{\theta_E}{\mu} \simeq 20\text{days}\left(\frac{M}{0.3M_\odot}\right)^{1/2}$$

Microlensing and Planets



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- Impact parameter
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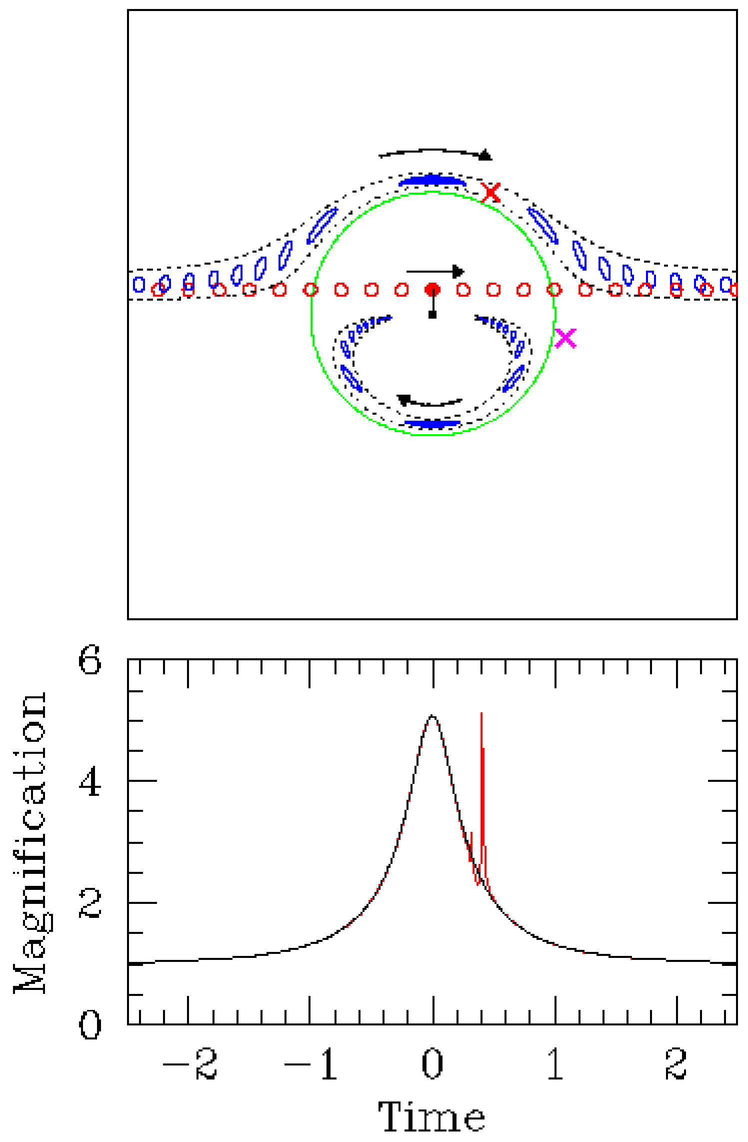
$$t_E = \frac{\theta_E}{\mu} \simeq 20\text{days}\left(\frac{M}{0.3M_\odot}\right)^{1/2}$$

Planet Parameters:

- Angle wrt Binary Axis
- Projected Separation
- Mass Ratio - q

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

Microlensing and Planets



Detection Efficiency:

Naïve Estimate:

$$\sim \frac{\theta_p}{\theta_E} \simeq 3\% \left(\frac{q}{10^{-3}}\right)^{1/2}$$

Enhanced Probability:

$$\sim A\frac{\theta_p}{\theta_E} \simeq 15\% \left(\frac{q}{10^{-3}}\right)^{1/2}$$

High-Magnification Events

➡ Higher Efficiencies

Maximized at $a \sim \theta_E$

Mao & Paczynski 1991,
Gould & Loeb 1992,
Griest & Safizadeh 1998

Microlensing and Planets

Advantages:

- Sensitive to Jupiters at 1-10 AU.
- No Flux Needed.
- Extend Sensitivity to Lower Masses.

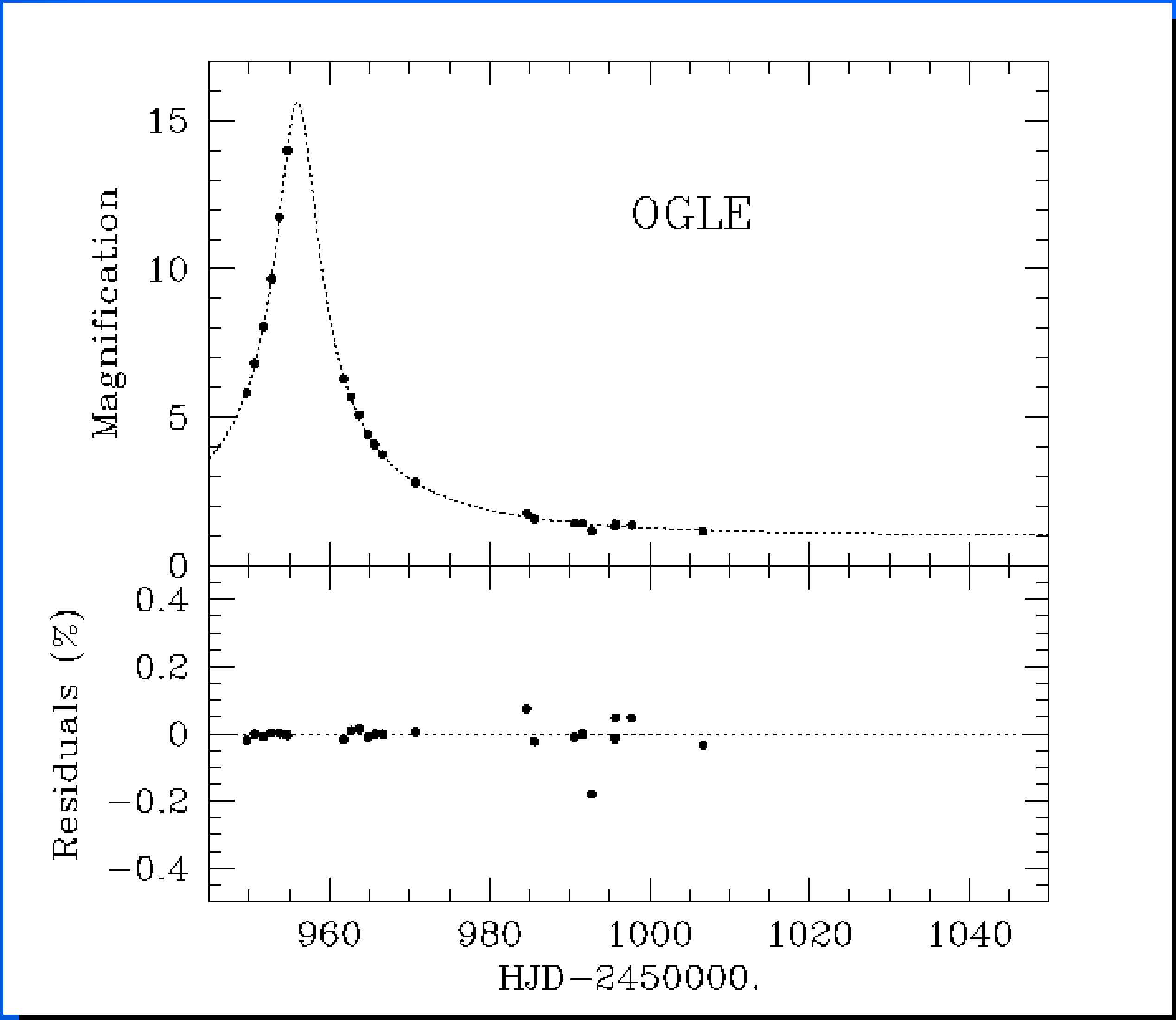
Disadvantages:

- Follow-up Difficult.
- Non-repeatable.
- Short Timescale Perturbations.

Basic Requirements:

- Nearly Continuous Sampling.
- Good Photometry for Detection.

Alerts and Follow-up



“Survey” Collaborations

- Insufficient Sampling
- Real-time Alerts

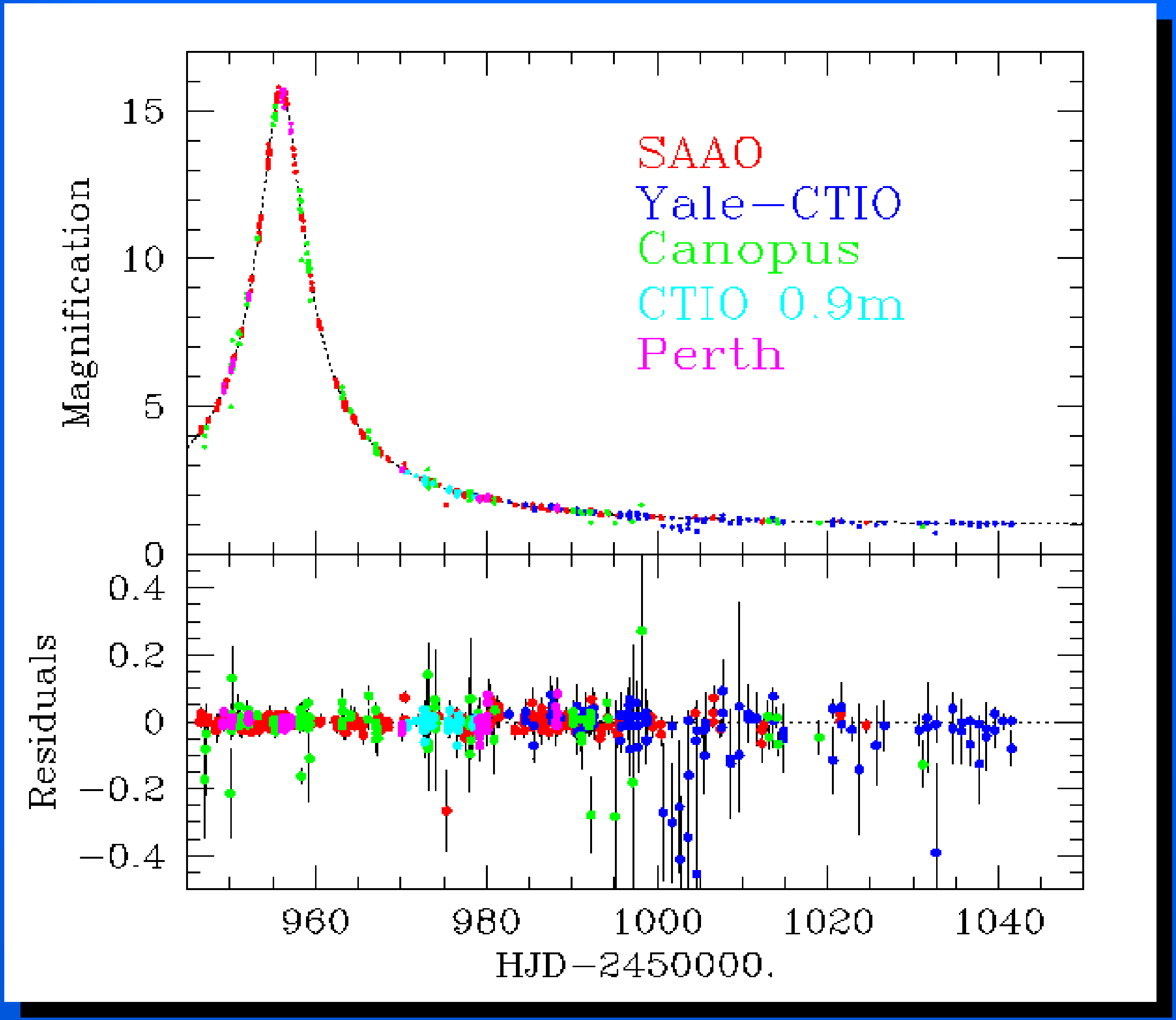
Current and Past Alerts

- EROS (5 per year)
- MACHO* (50 per year)
- MOA (50 per year)
- OGLE II* (75 per year)

Future Alerts

- OGLE III (500 per year?)

Alerts and Follow-up



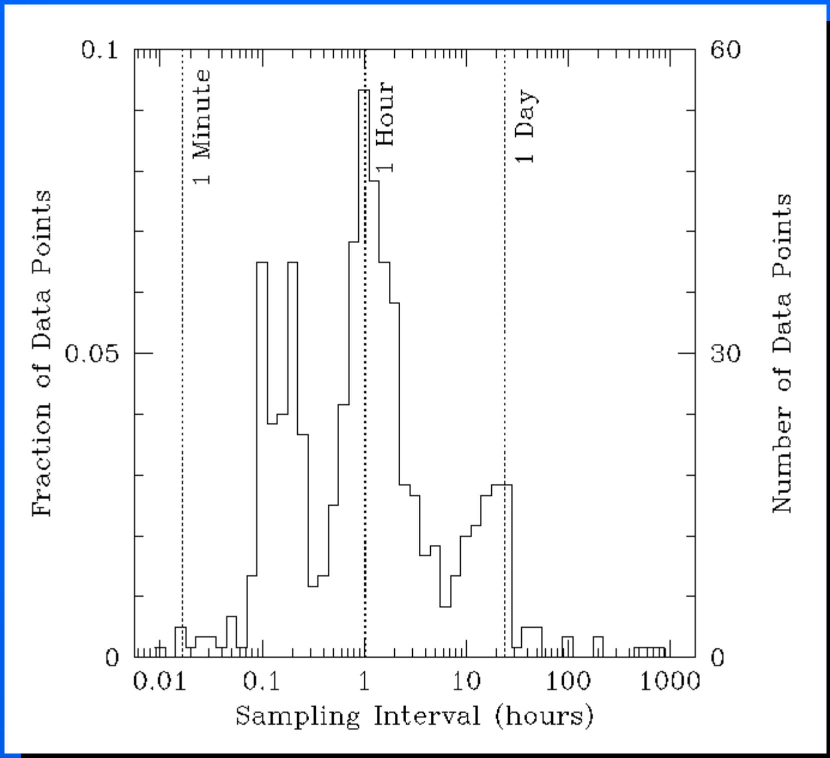
Follow-up Collaborations

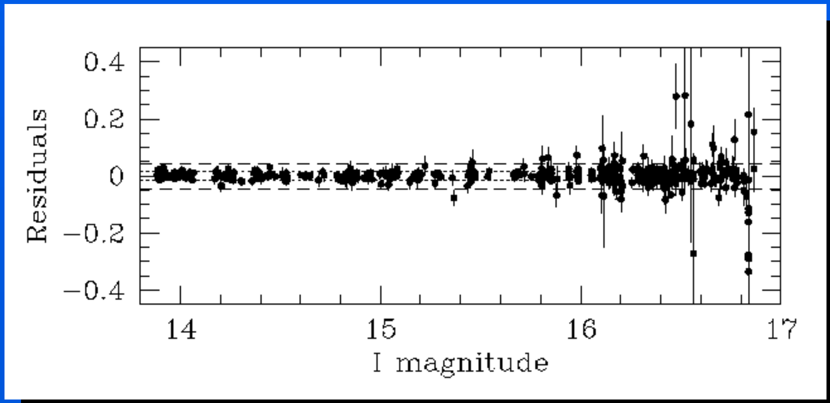
- High Temporal Sampling
- Good Photometry

Current Collaborations

- EXPORT (12 events) (Tsapras et al. 2001)
- MOA (30 events) (Bond et al 2002
- MPS (50 events) (Rhie et al. 2000)
- PLANET (100+ events) (Albrow et al. 1998)

Alerts and Follow-up





OGLE-1998-BUL-14

Total # of Points

- 461 I-band
- 139 V-band

Median Sampling:

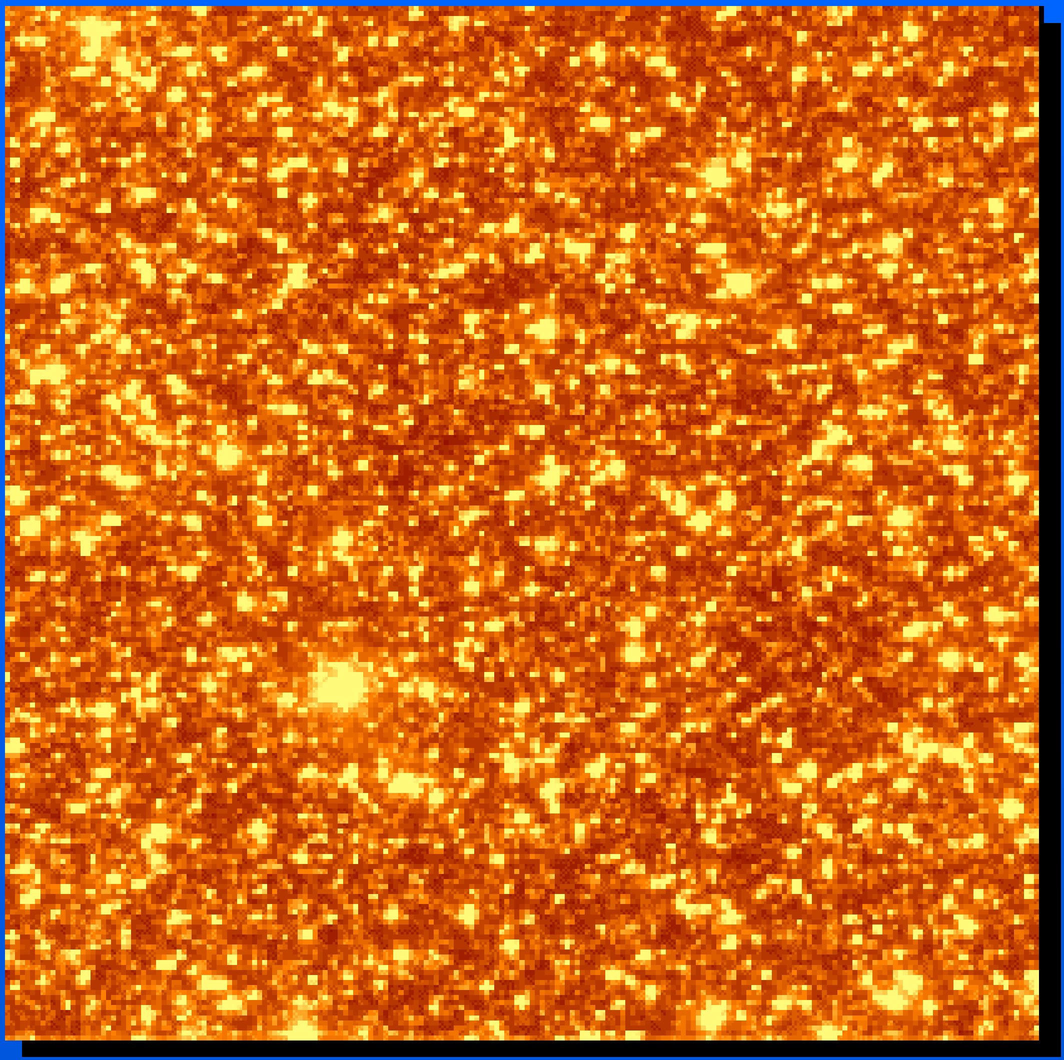
- 1 hour

I-band Scatter

- Entire event ~ 4%
- Over the peak ~ 1.5%

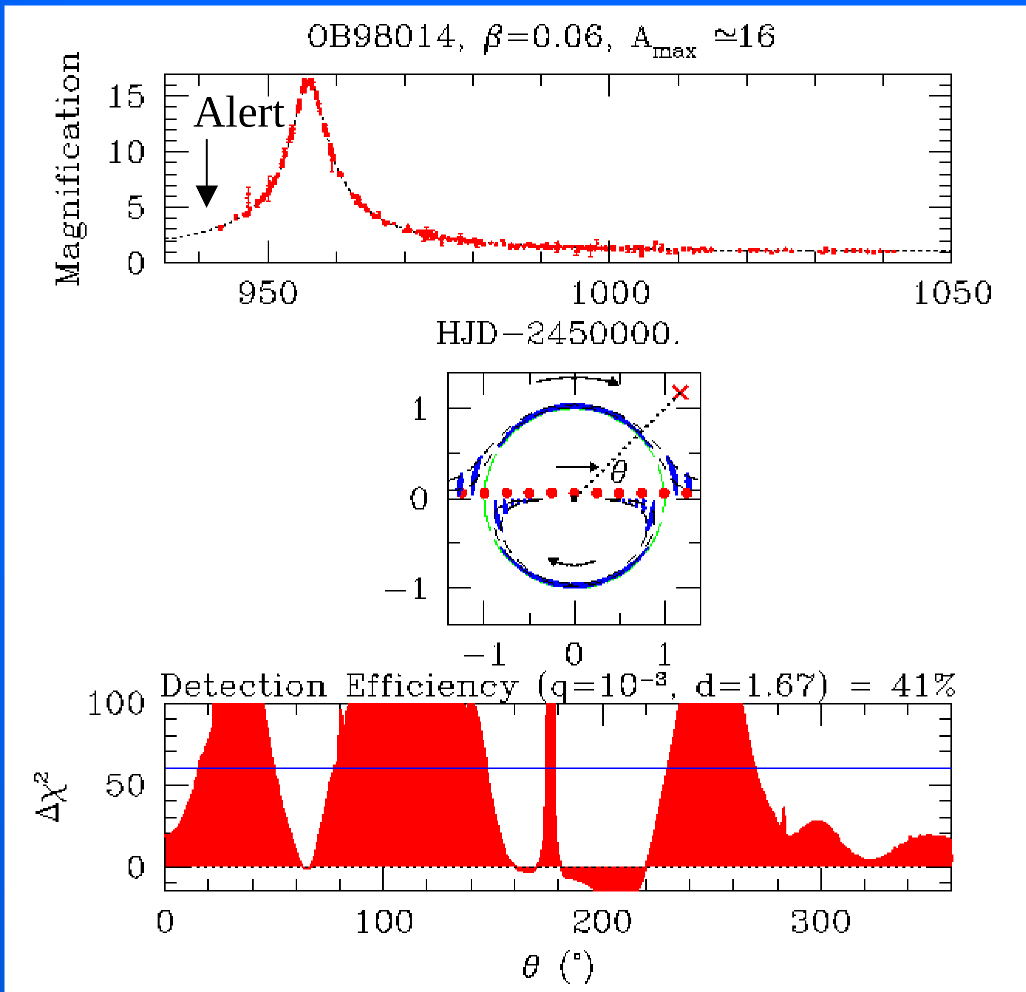
Albrow et al. 2000

Alerts and Follow-up



Extremely Crowded Fields

Detection and Efficiency



$$\epsilon(d,q) = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{d}\theta\,\Theta(\Delta\chi^2 - \Delta\chi^2_{th})$$

Fix Parameters: (q, d, θ)

$\Delta\chi^2 > \Delta\chi^2_{th}$

➡ Excluded

$\Delta\chi^2 < -\Delta\chi^2_{th}$

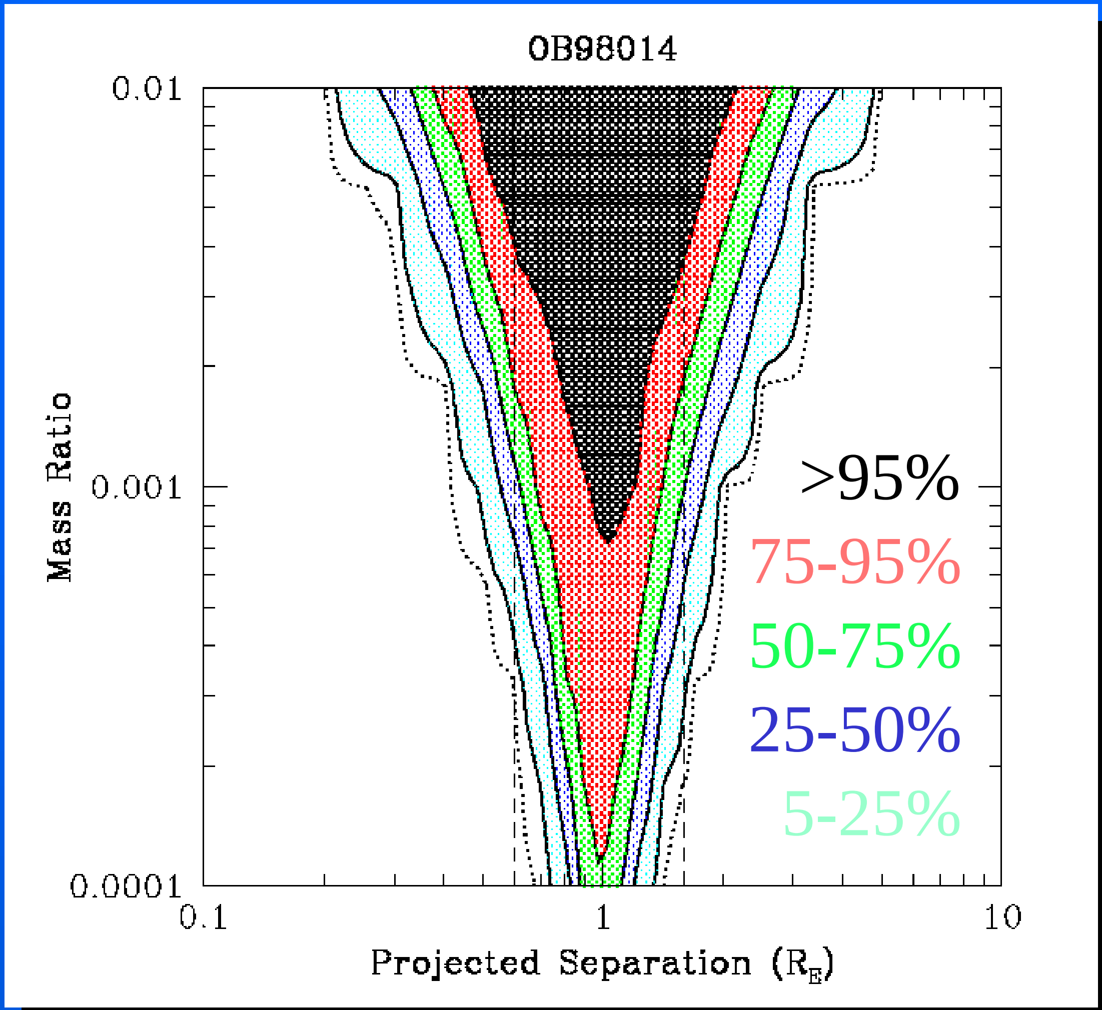
➡ Detection

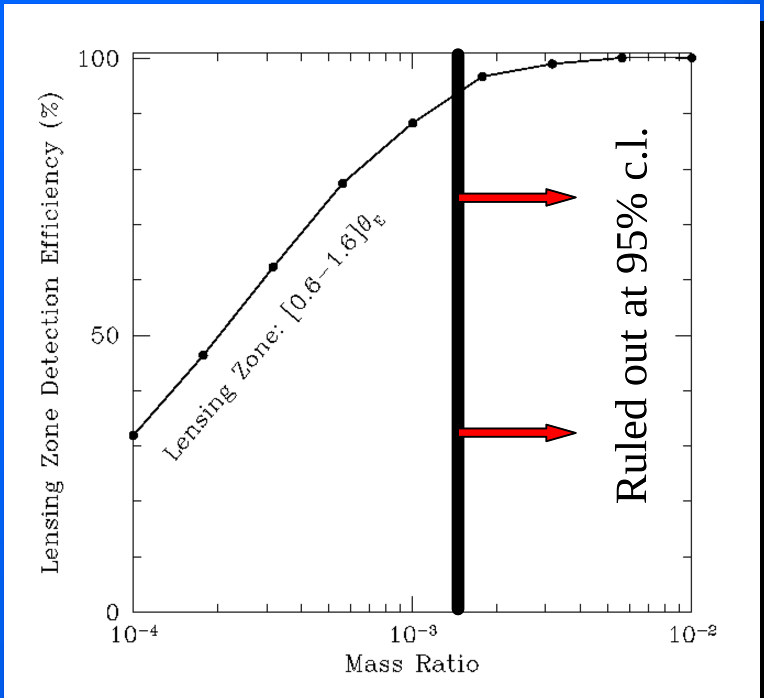
OGLE-1998-BUL-14:

$\epsilon(q = 10^{-3}, d = 1.67) = 41\%$

Gaudi & Sackett 2000

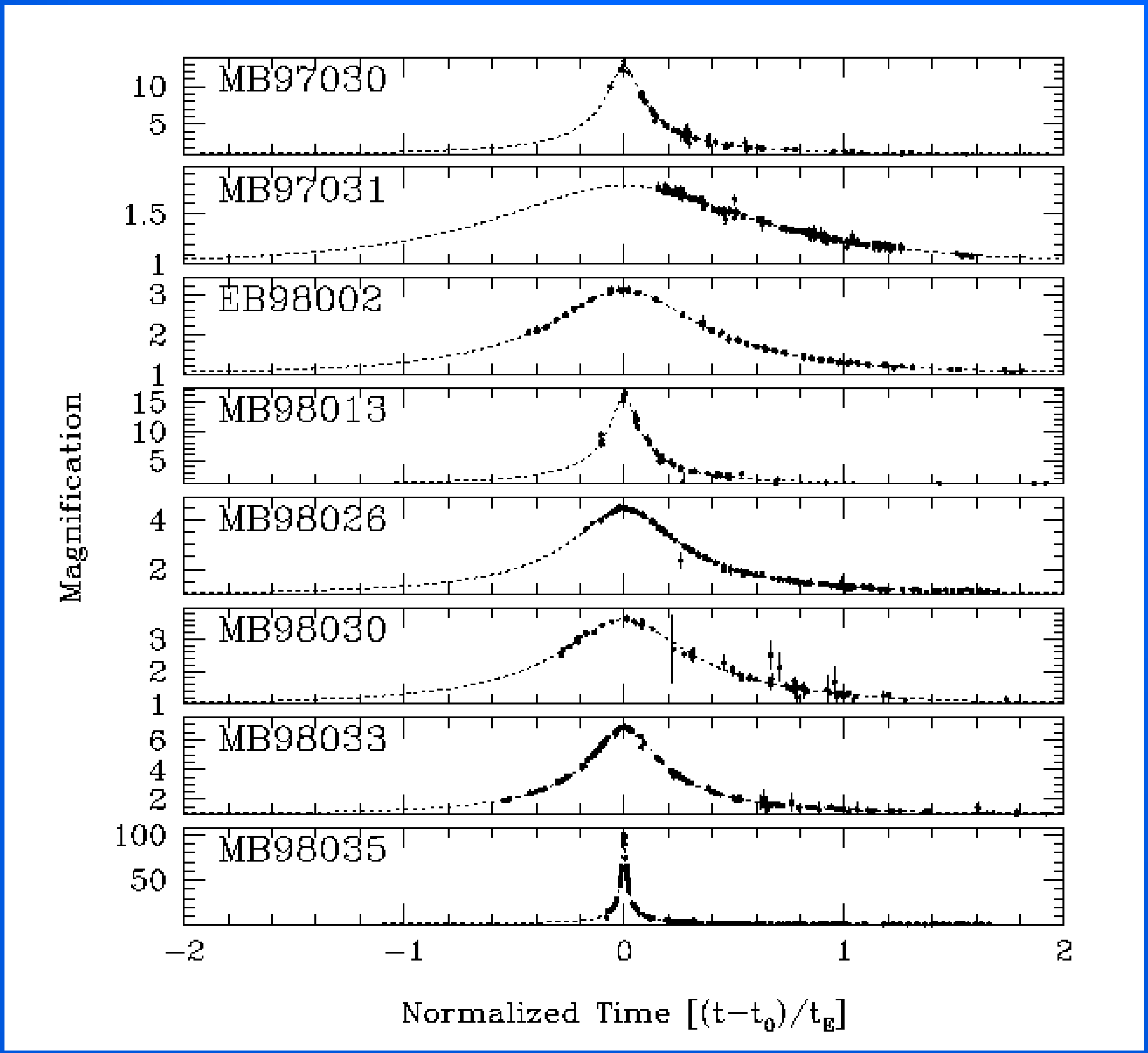
Detection and Efficiency





Albrow et al. 2000
Gaudi et al. 2002

Five Years of PLANET Data



95-99 PLANET Dataset

•126 Events Monitored

Exclude

- Equal-Mass Binaries
- Poorly Sampled Events
- Poorly-Constrained Parameters

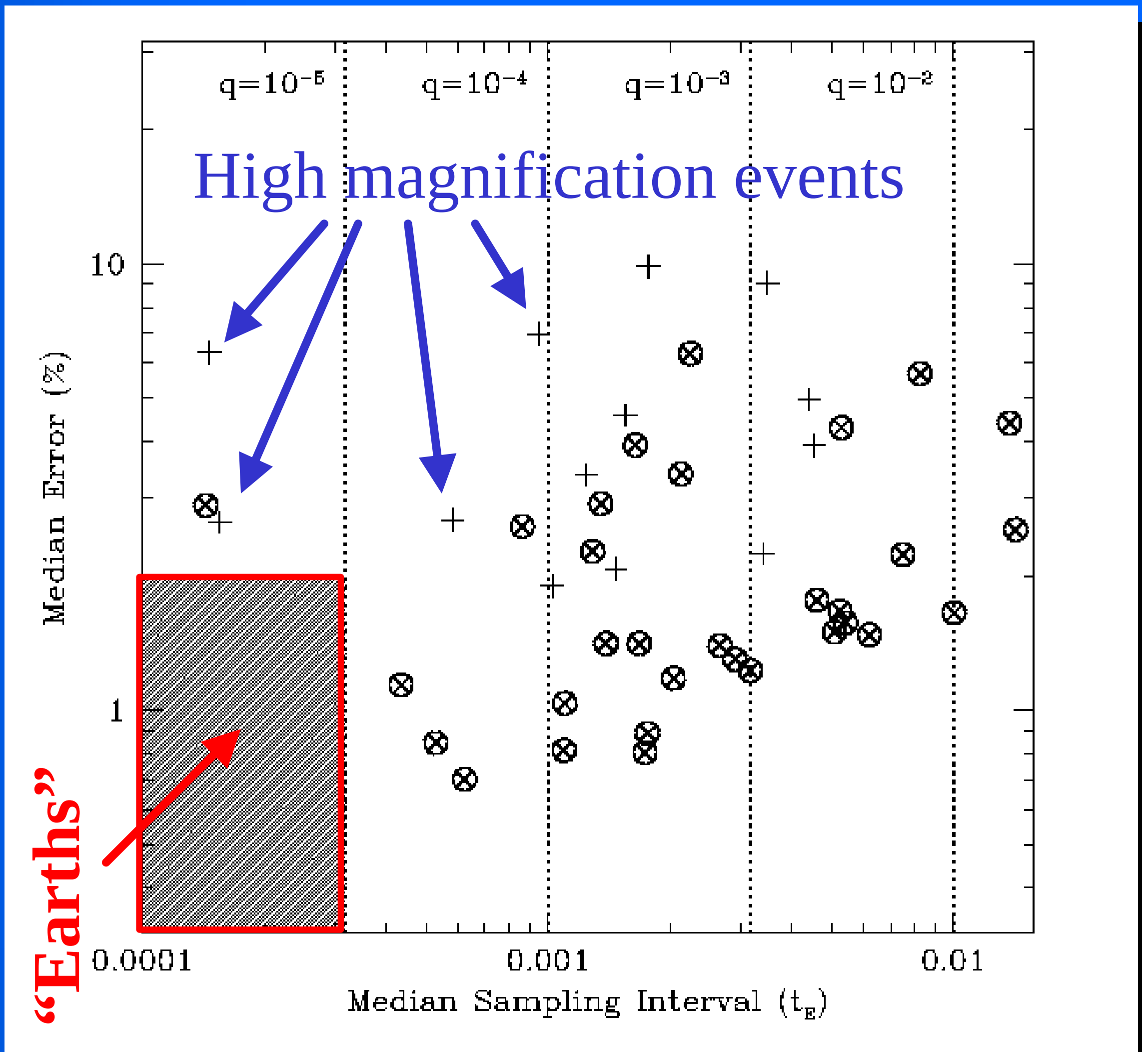
Final Sample

•43 Events

Albrow et al. 2001

Gaudi et al. 2002

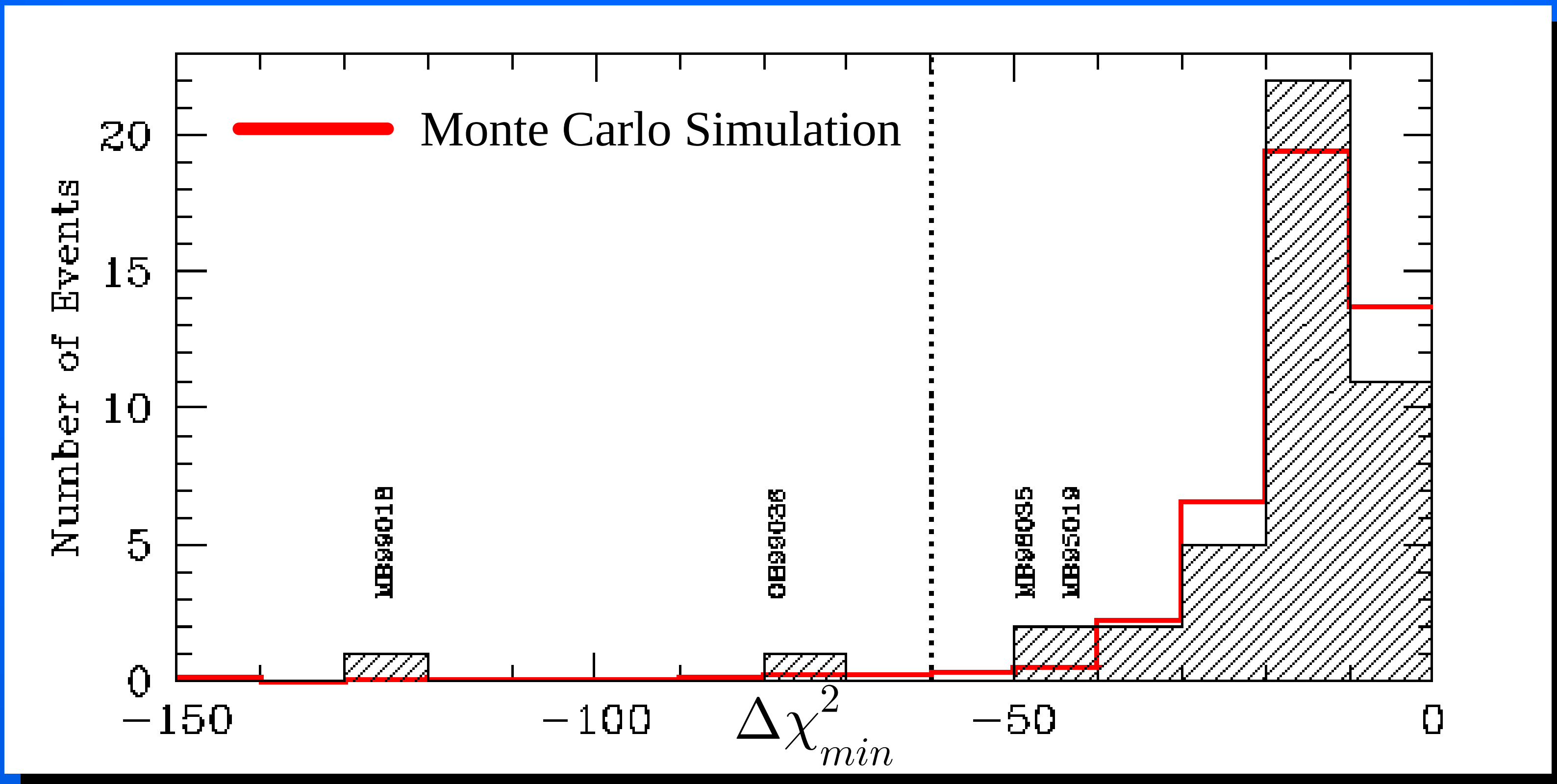
Five Years of PLANET Data



43 Event Sample

- Most Events Sensitive to q>0.001 Companions
- Thirteen A>10 Events
- Not Sensitive to "Earths"

Five Years of PLANET Data



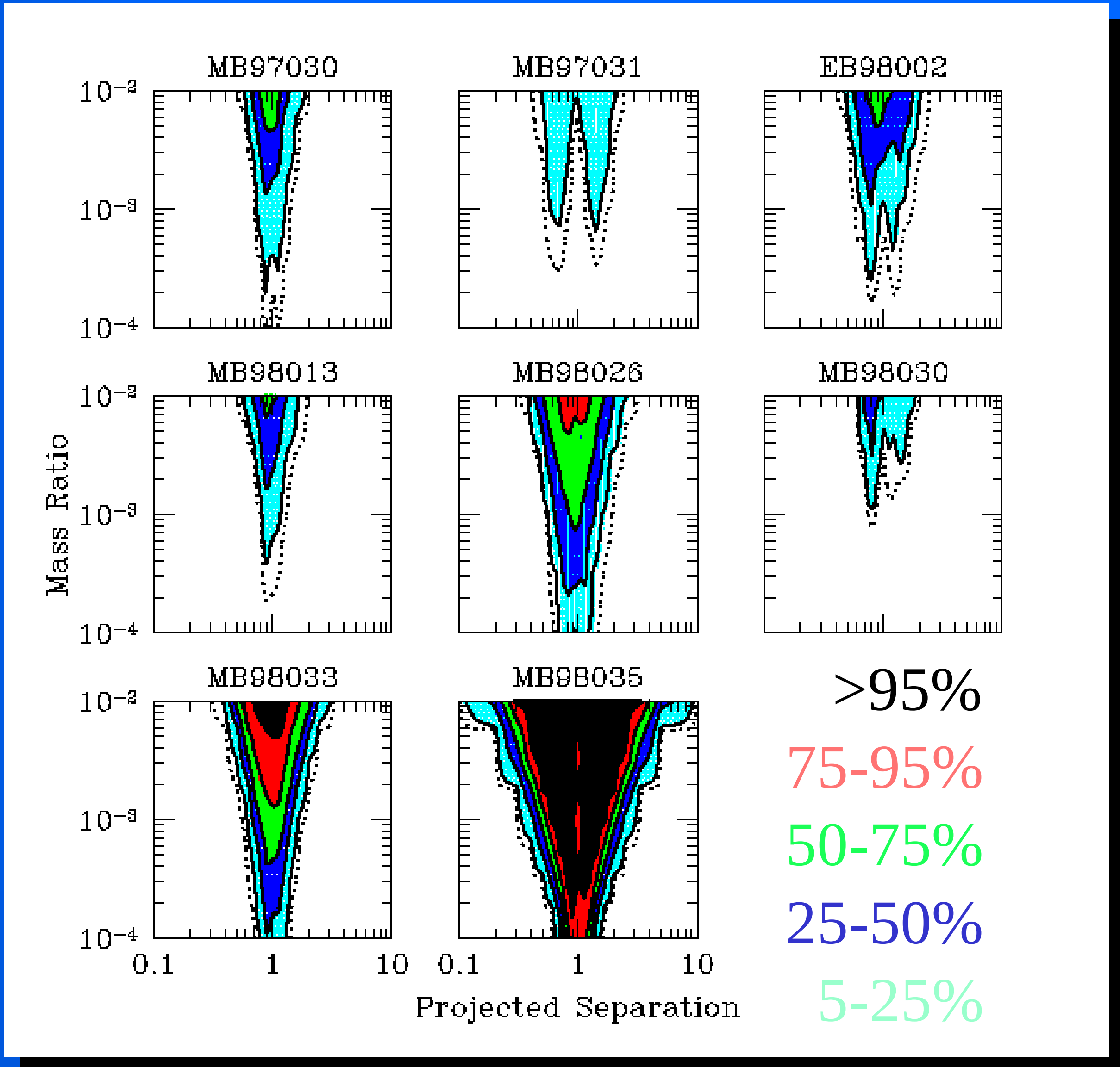
Detection Threshold of $\Delta\chi^2_{th} = -60$

➡ Two Candidate "Detections"

➡ Better Explained by Other Models

➡ No Viable Detections out of 43 Events

Five Years of PLANET Data



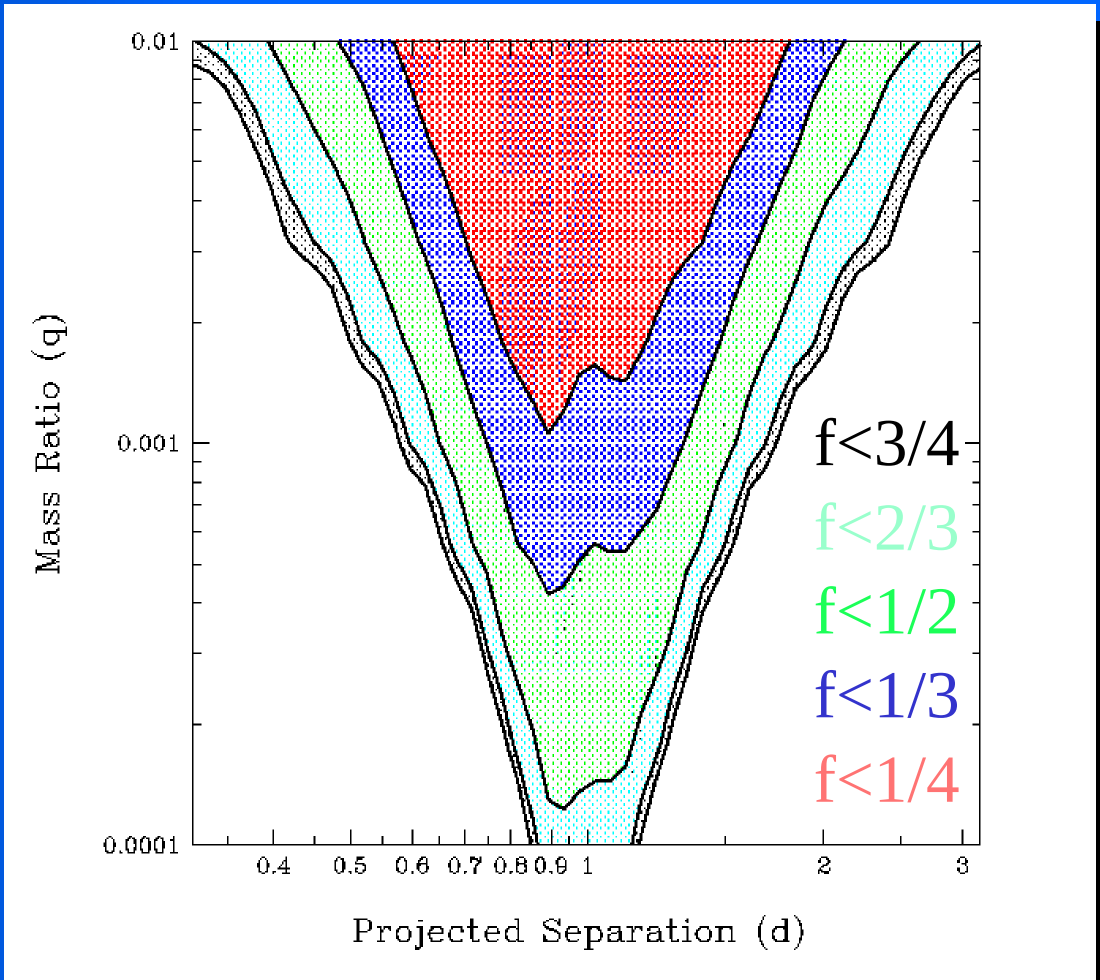
Search for Planets

- -4 < log(q) < -2
- -1 < log(d) < 1

No Viable Detections

What does this mean?

Five Years of PLANET Data



Expected # of Events

$$N_{exp}(d,q) = f(d,q)\sum_i \epsilon_i(d,q)$$

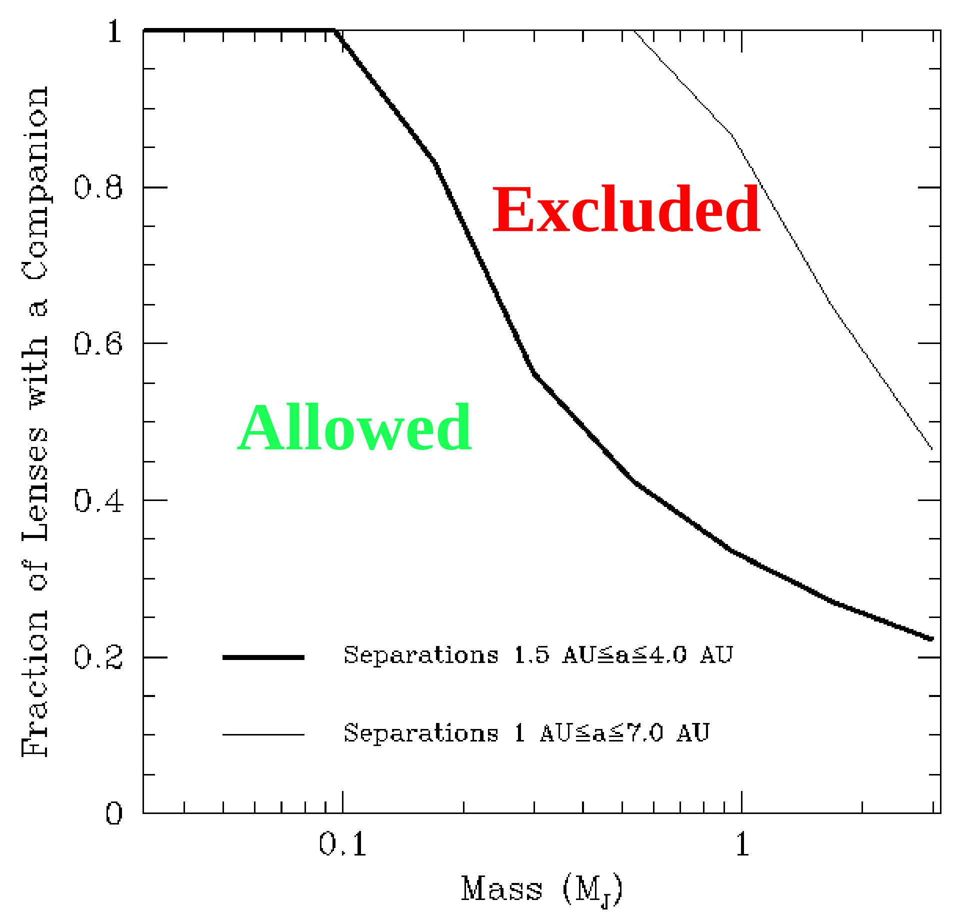
Probability of a Detection

$$P(d,q) = 1 - \exp[-N_{exp}(d,q)]$$

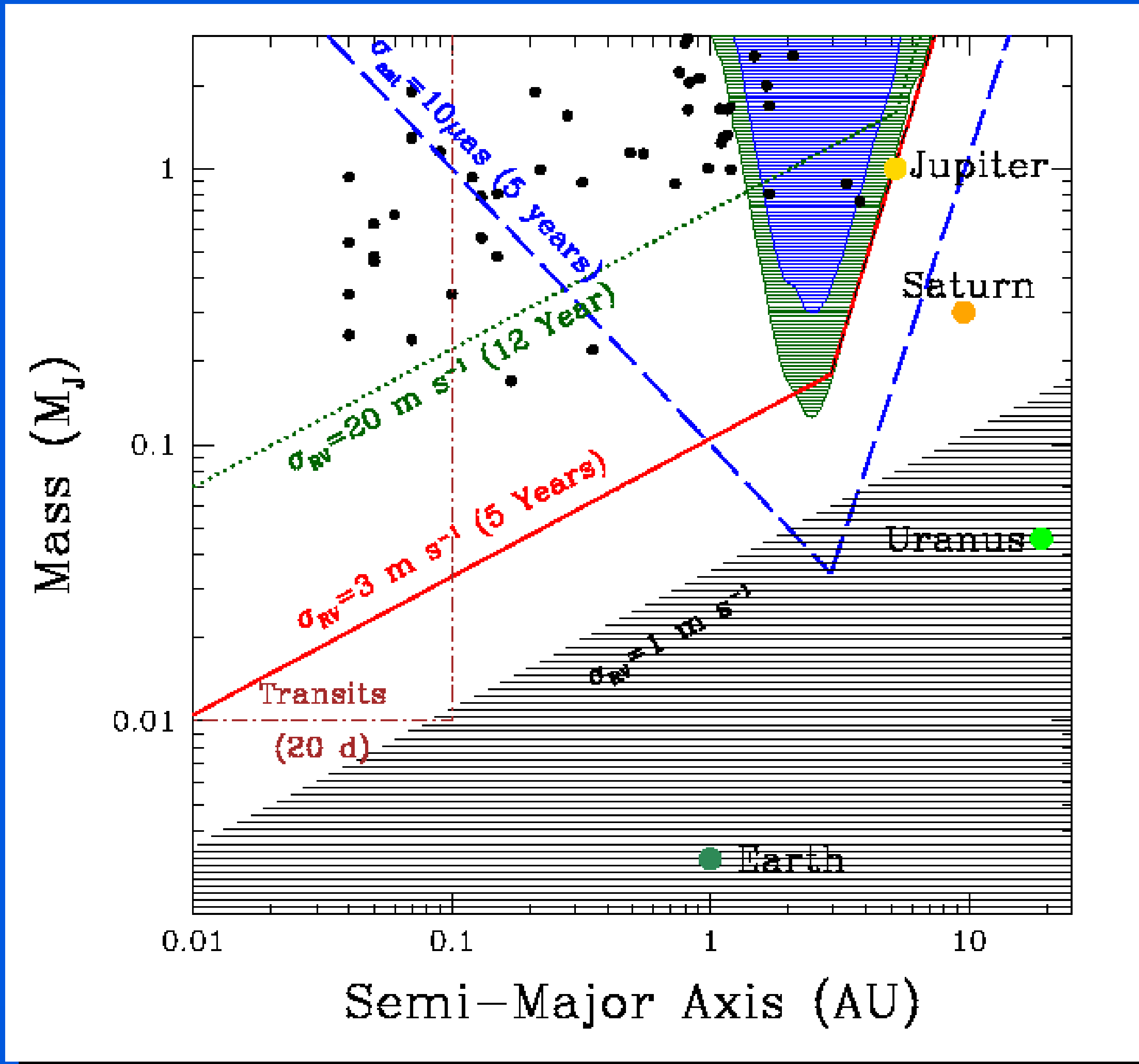
95% c.l. Upper Limit

$f(d,q)$ for which $P(d,q) = 5\%$

Five Years of PLANET Data



<33% Have Jupiter-mass companions between 1.5-4 AU
<45% Have 3 x Jupiter-mass companions between 1-7 AU



Microlensing Searches for Extrasolar Planets

Future Prospects - Ground

Pushing to Lower Fractions

- More Efficient Monitoring
- Image Subtraction Processing

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} Factor of 3 improvement

Future Prospects - Ground

Pushing to Lower Fractions

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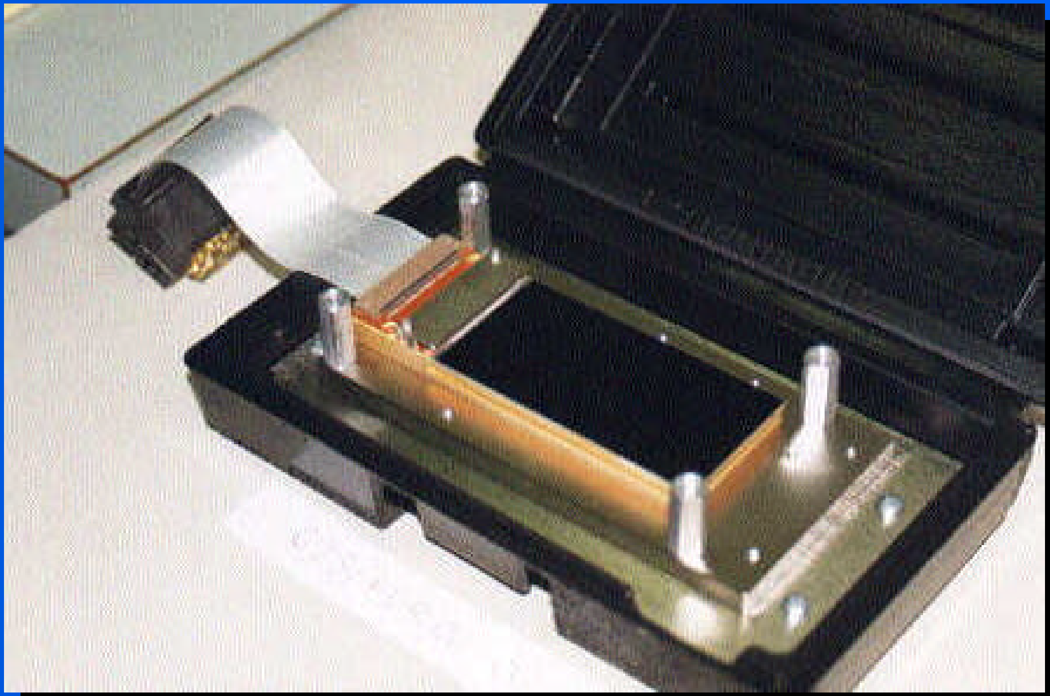
} Factor of 3 improvement

- Increasing the Number of Alerts (OGLE III)



OGLE-III Camera

- 8 2045x4096 CCDs
- 35’ x 35’ field-of-view
- > 300 alerts per year

$$\mathcal{R}_{exp} \sim 0.1 f \mathcal{R}_{alert}$$
$$\sim 1\mathrm{yr}^{-1} \left(\frac{f}{5\%}\right)\left(\frac{\mathcal{R}_{alert}}{200\mathrm{yr}^{-1}}\right)$$

Future Prospects - Ground

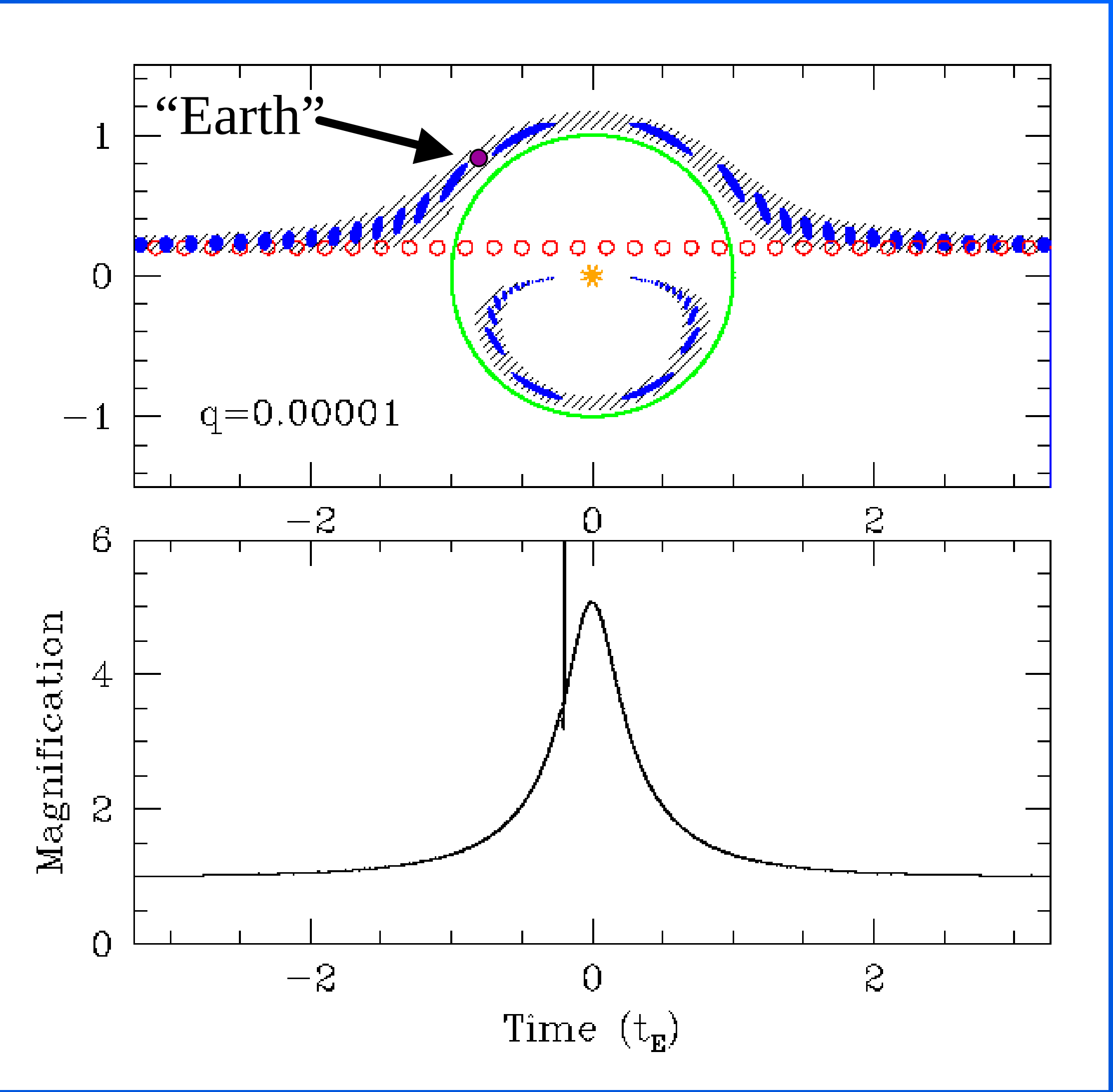
Pushing to Lower Fractions

- More Efficient Monitoring
- Image Subtraction Processing
- Increasing the Number of Alerts (OGLE III)

Pushing to Lower Masses

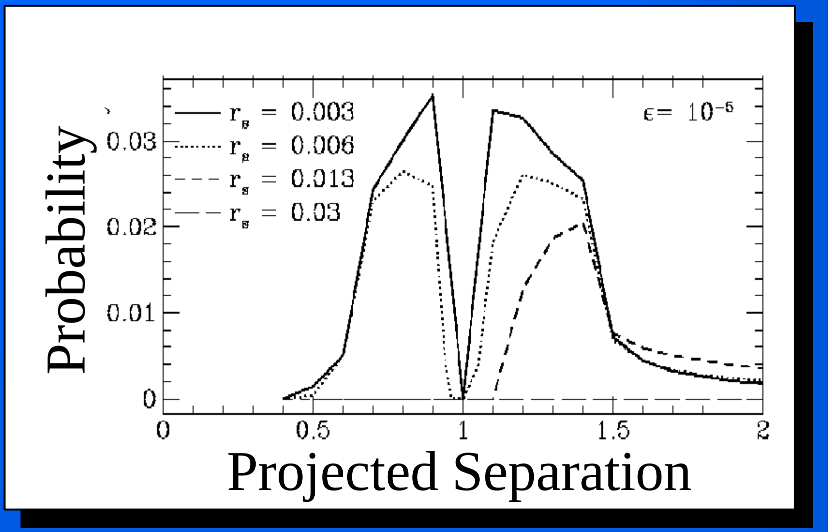
- More Alerts
- Main Sequence Alerts
- Larger Apertures?

Future Prospects - Ground



Earth-mass Planets

$$q \simeq 10^{-5} \left(\frac{M_p}{M_\oplus}\right)$$



Bennett & Rhie 1996

Detection Probability ~ few %

Future Prospects - Ground

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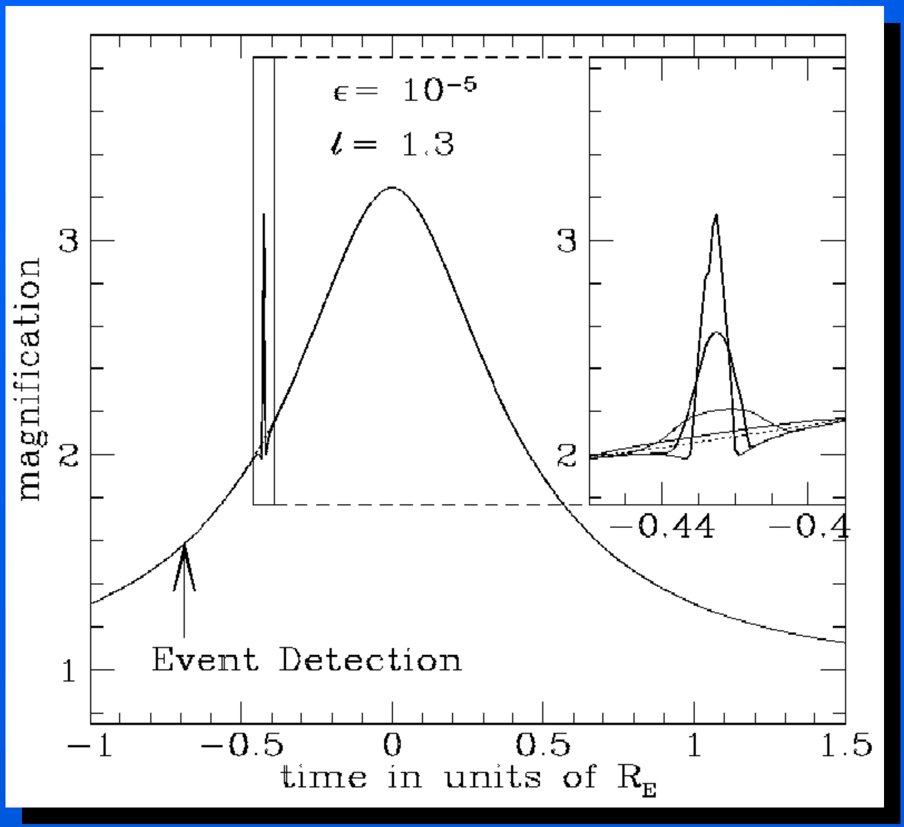

Bennett & Rhie 1996

Require Main Sequence Sources

Future Prospects - Ground

Pushing to Lower Fractions

- Increasing the Number of Alerts (OGLE III)
- More Efficient Monitoring
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Pushing to Lower Masses

- More Alerts
- Main Sequence Alerts
- Larger Apertures?

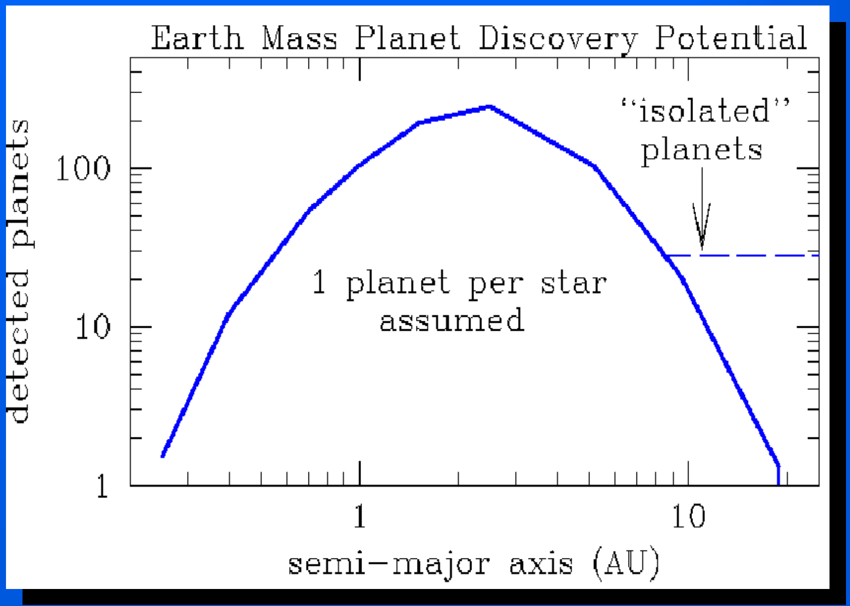
Pushing to Larger Separations

- Longer Duration Monitoring
- Free Floating Planets?

Future Prospects - Space

Galactic Exoplanet Survey Telescope (GEST)

- 1.5m aperture
- 2.1 square degree field-of-view
- Monitor 0.1 billion main sequence stars
- 100f Earth-mass planets at 1 AU



Bennett & Rhie 2002

Future Prospects - Space

Galactic Exoplanet Survey Telescope (GEST)

- 1.5m aperture
- 2.1 square degree field-of-view
- Monitor 0.1 billion main sequence stars
- 100f Earth-mass planets at 1 AU

Space Interferometry Mission (SIM)

- Measure Masses of Planets to 5% accuracy

Conclusions

Microlensing offers a complementary way of searching for extrasolar planets.

Four collaborations obtaining useful data

- EXPORT, PLANET, MOA, MPS

Analysis of 95-99 PLANET database:

- No viable detections.
- <33% of M-dwafs in the Bulge have Jupiter-Mass Companions between 1.5-4 AU
- <45% have 3-Jupiter mass Companions between 1-7AU

Future Prospects

- Probe fractions of 1% in 5 Years with OGLE-III Alerts.
- Possible to push sensitivity to Earth-mass planets, but requires
  - Monitoring of many events.
  - Main-sequence sources.
- A space-based survey might be optimal for detecting Earths.