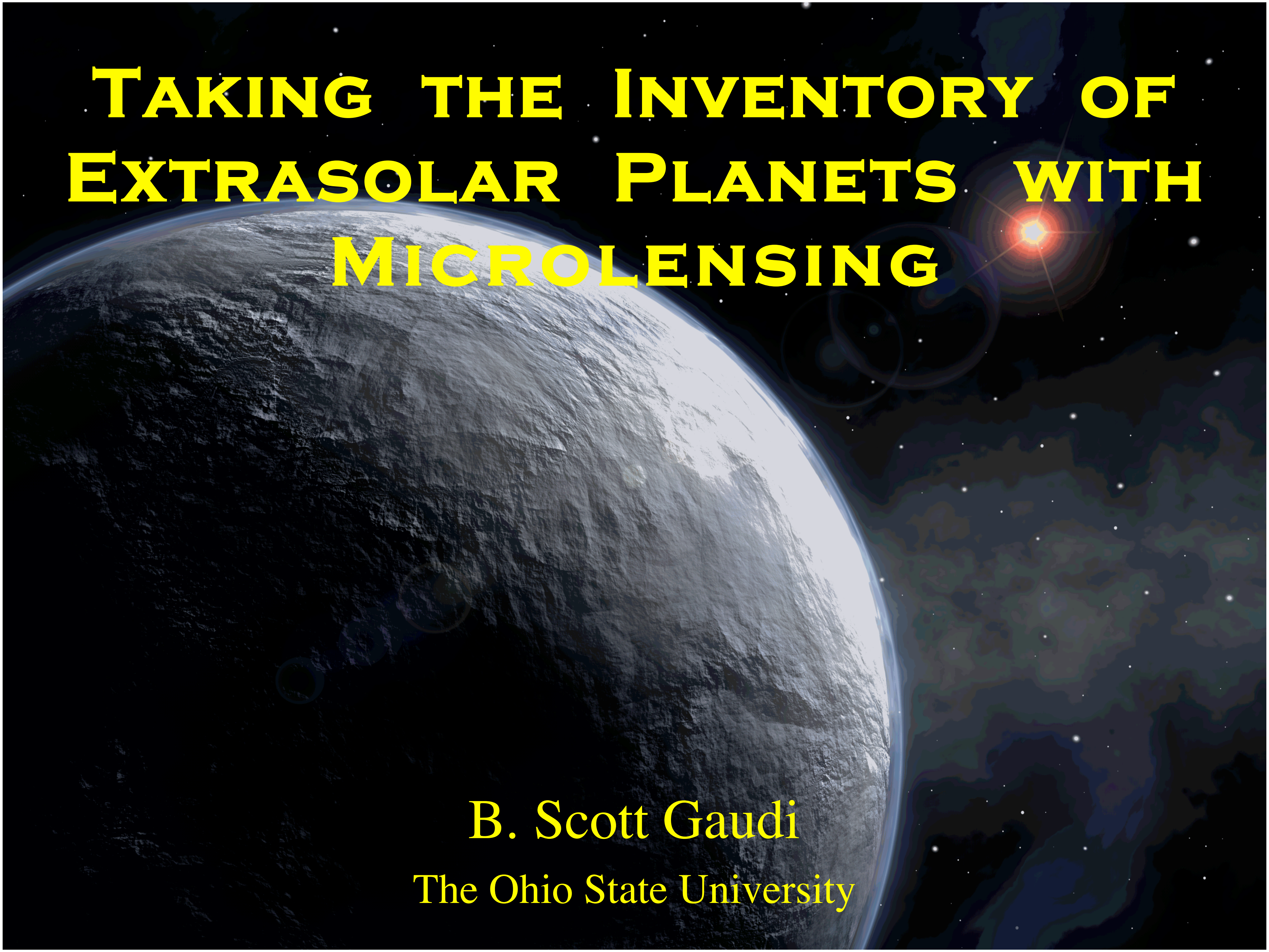


Taking the Inventory of Extrasolar Planets with Microlensing

B. Scott Gaudi

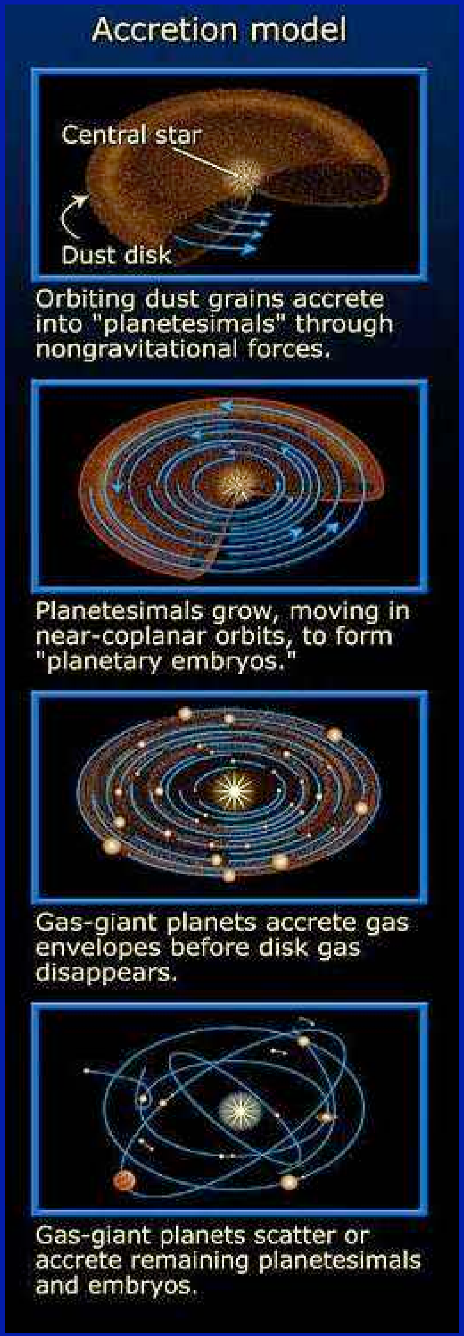
The Ohio State University

"I don't understand. You are looking for planets you can't see around stars you can't see."

-Debra Fischer

"Microlensing is a cult."

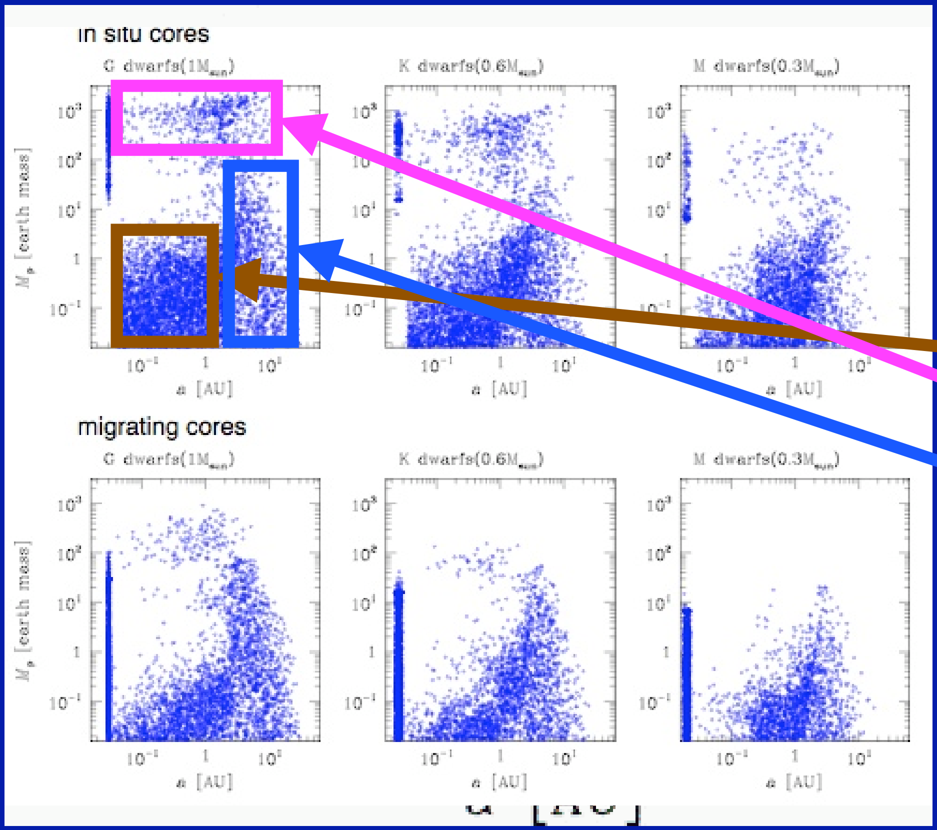
-Dave Koerner



Planet Formation

- Core-accretion Model
- Dust → Planetesimals (non G)
- Planetesimals → Protoplanets
- Protoplanets → Gas Giants (Outer Solar System)
- Protoplanets → Terrestrial Planets (Inner Solar System

Planet Formation

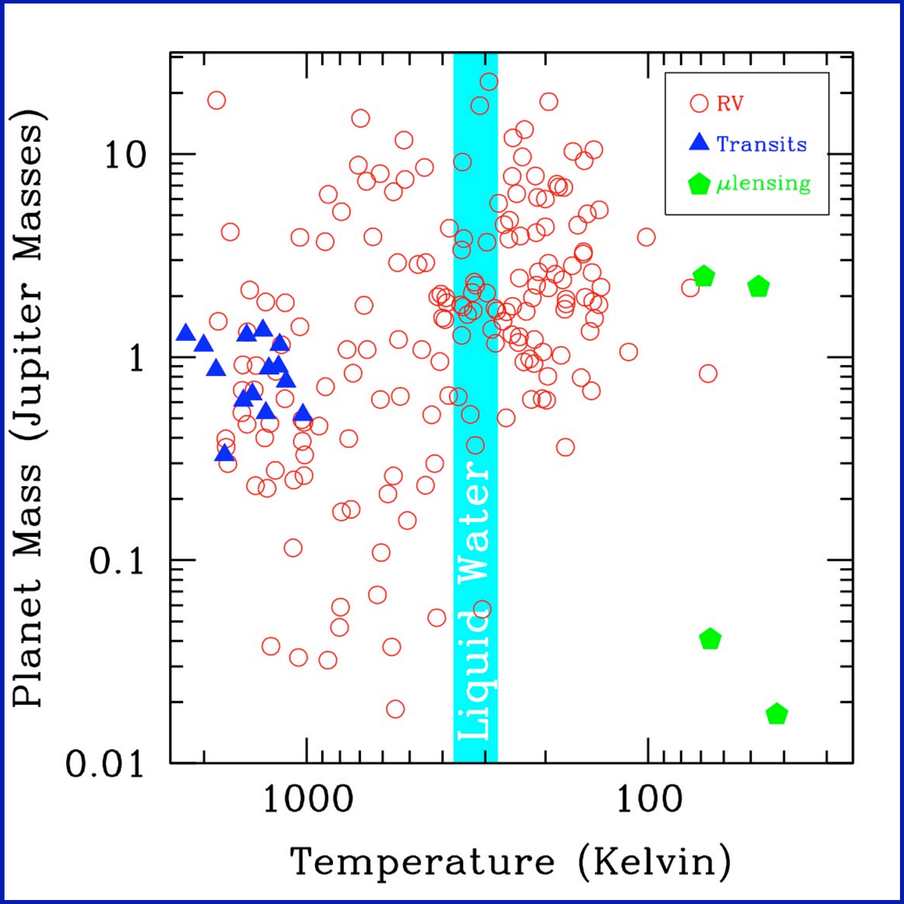


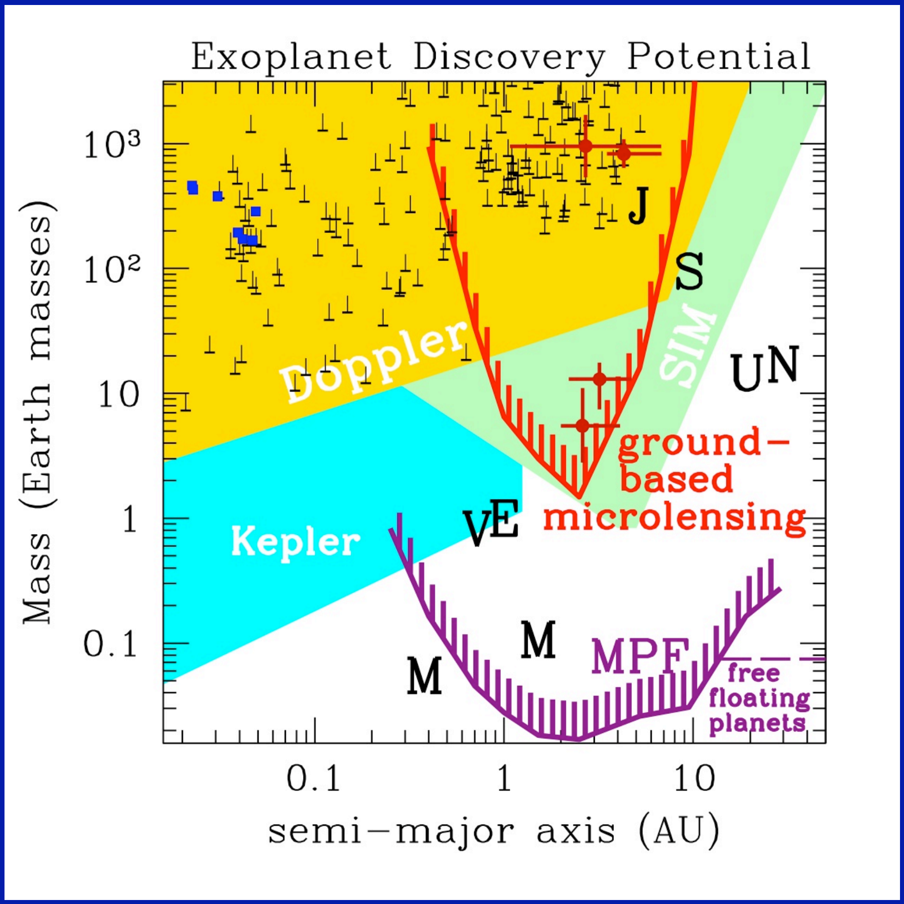
(D. Lin)

- "Semi-analytic" Planet Formation
- Three classes of planets
  - Terrestrial Planets
  - Gas Giants
  - Ice Planets
- Segregation in Mass/Separation
- Frequency versus M_* and M_p

Assertions:

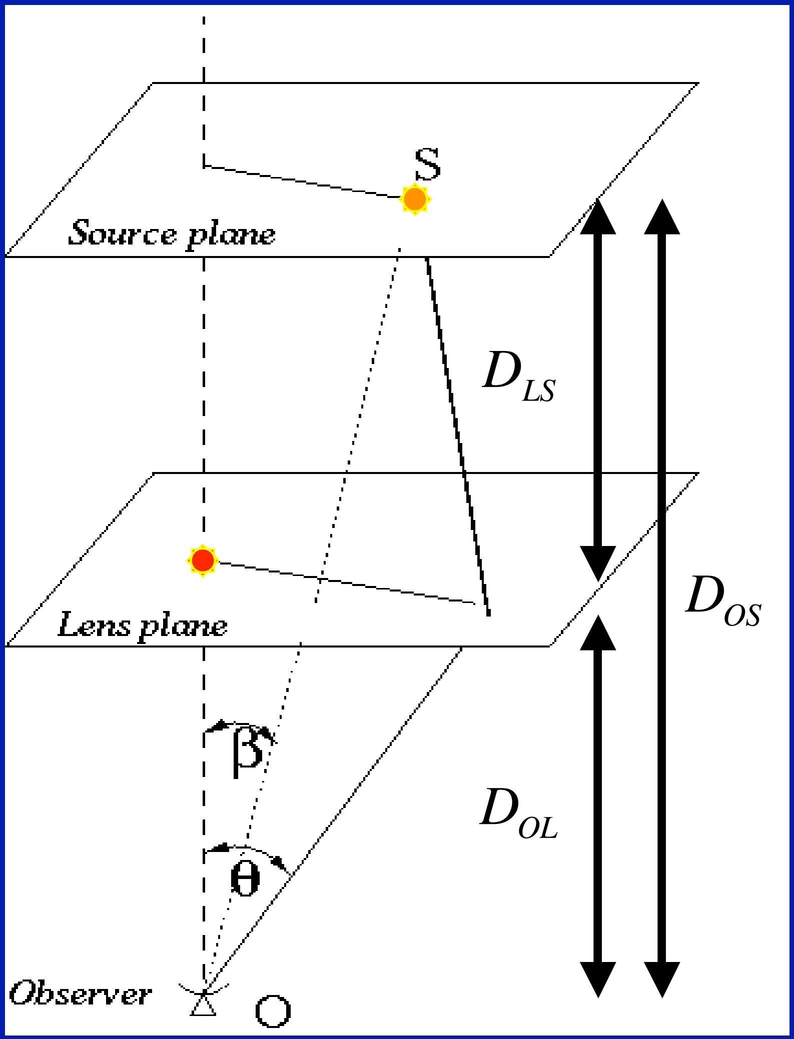
- This field is observationally driven.
- Understanding planet formation requires a complete census of planets
- Issues of habitability are inexorably tied up with planet formation, and in particular processes beyond the snow line.





- Ground-based μlensing surveys probe low-mass planets at or beyond the snow-line.
- A space-based survey will provide a complete picture of the diversity of planetary systems for a > 0.5 AU (from 0 to ∞ with Kepler)
- Without μlensing, we will remain ignorant of many of the details of planetary systems

Gravitational Lensing



- Point Lens Equation

$$\beta = \theta - \theta_{\mathrm{E}}^{2} / \theta$$

- Einstein Ring Radius

$$\theta_{\mathrm{E}} = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_{OL} D_{OS}}}$$

$$\approx 300\mu\mathrm{as} \left(\frac{M}{0.3 M_{\odot}} \right)^{1/2}$$

Microlensing

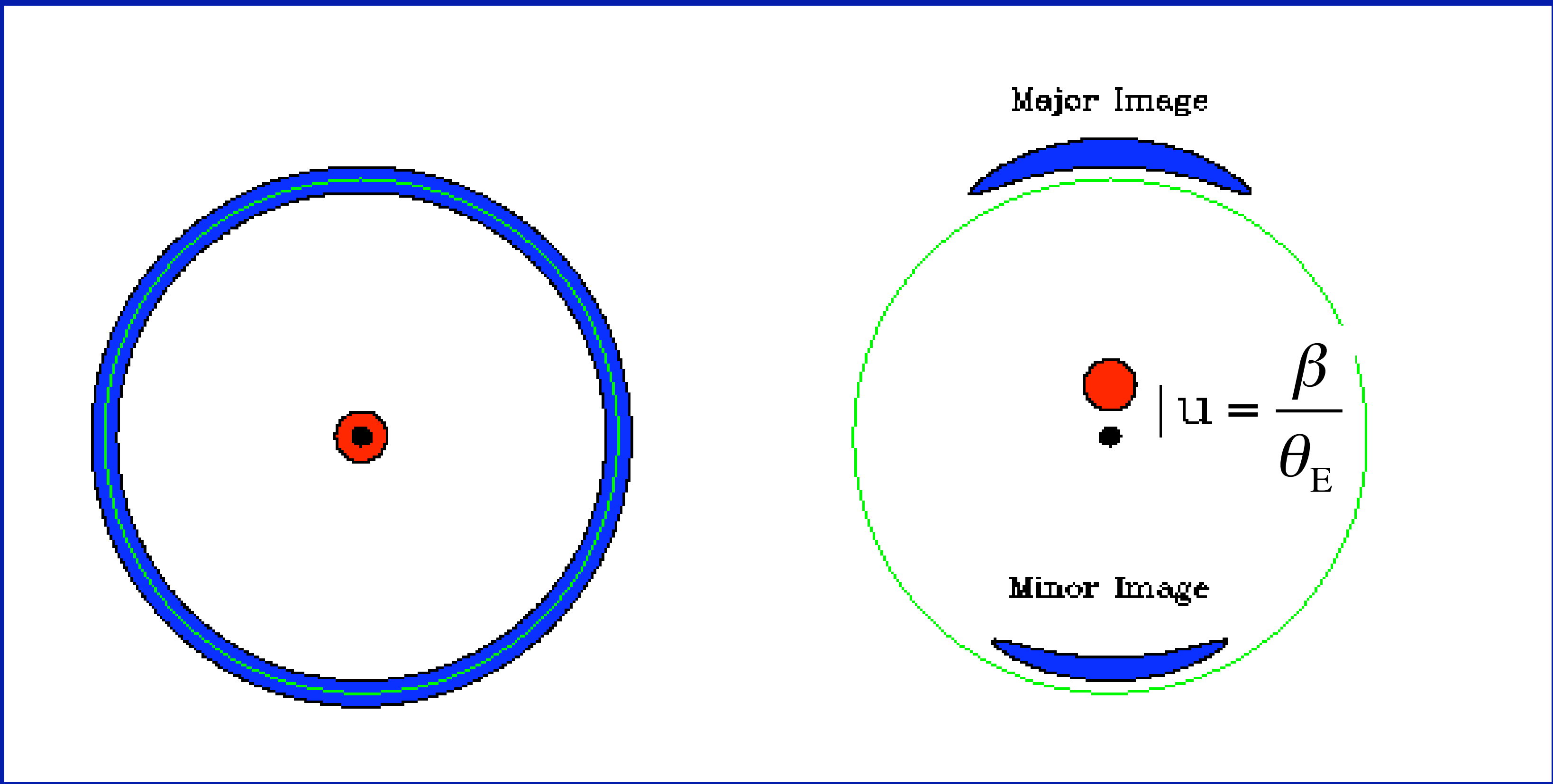
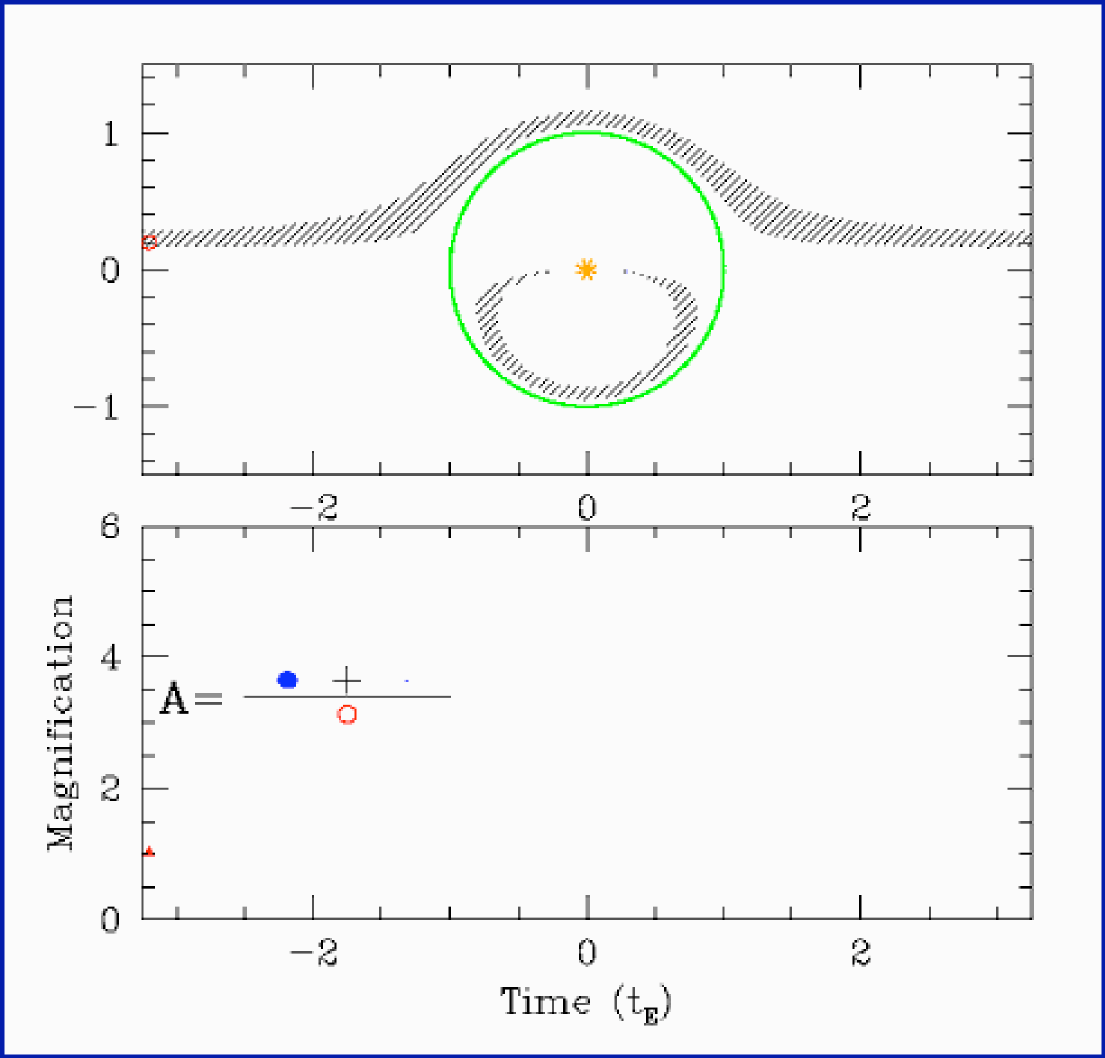


Image Separation $\approx 2\theta_E$ Magnification $= \frac{\text{Area of Image}}{\text{Area of Source}}$

Microlensing Events

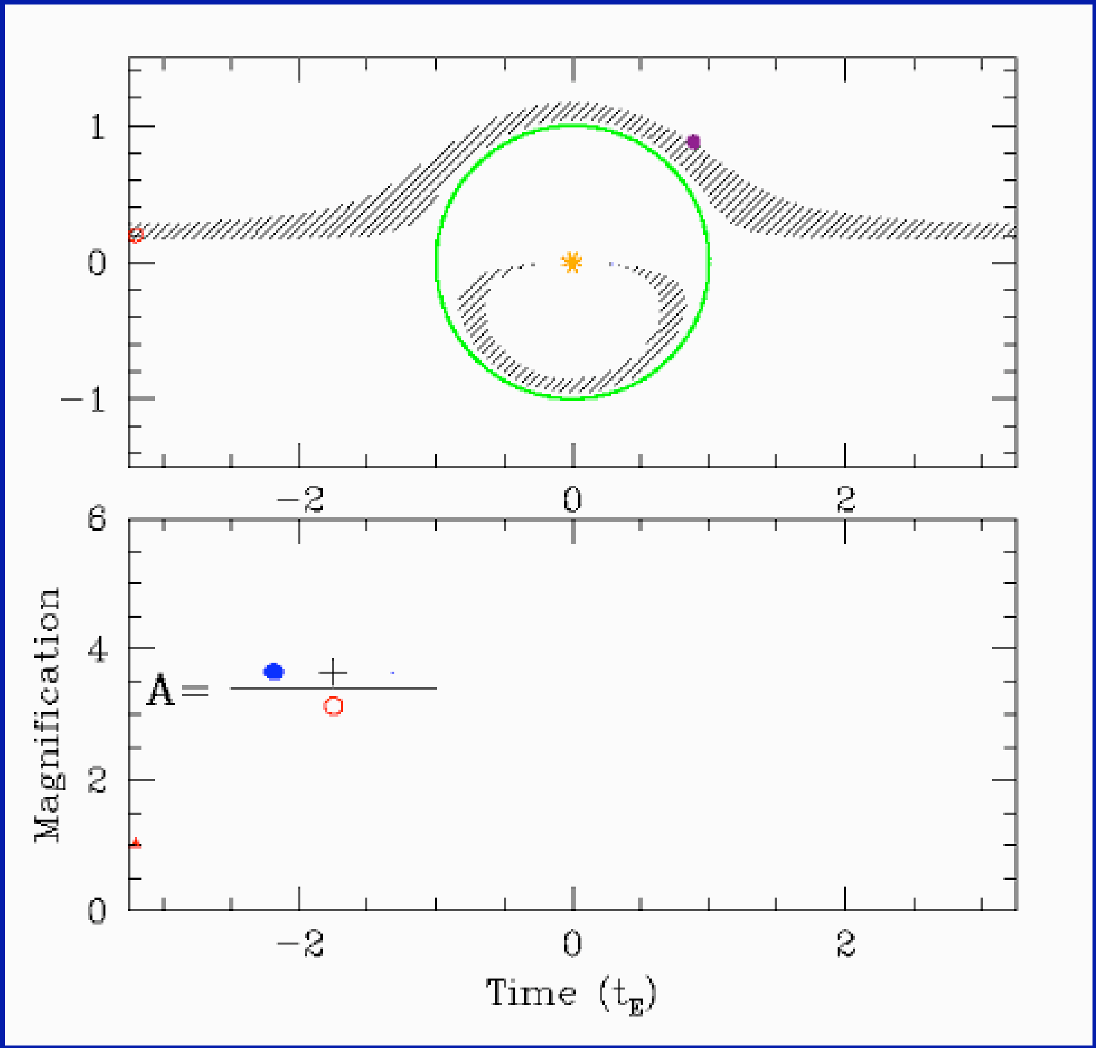


Single Lens Parameters

- Impact Parameter
- Time of Maximum
- Timescale

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

Detecting Planets



Single Lens Parameters

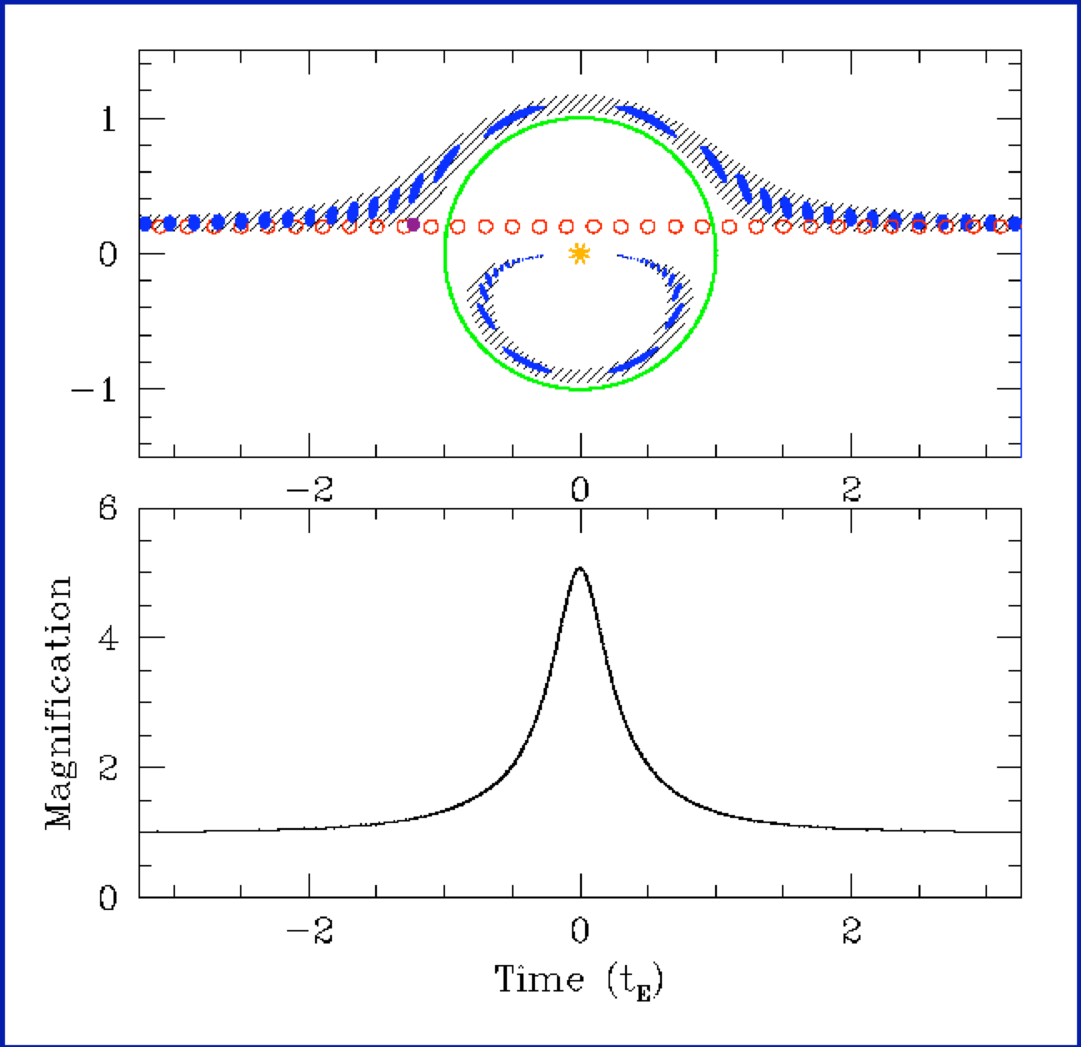
- Impact Parameter
- Time of Maximum
- Timescale

Planet Parameters

- Angle wrt Binary Axis
- Projected Separation
- Mass Ratio

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

Detection Probability



Detection Probability

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

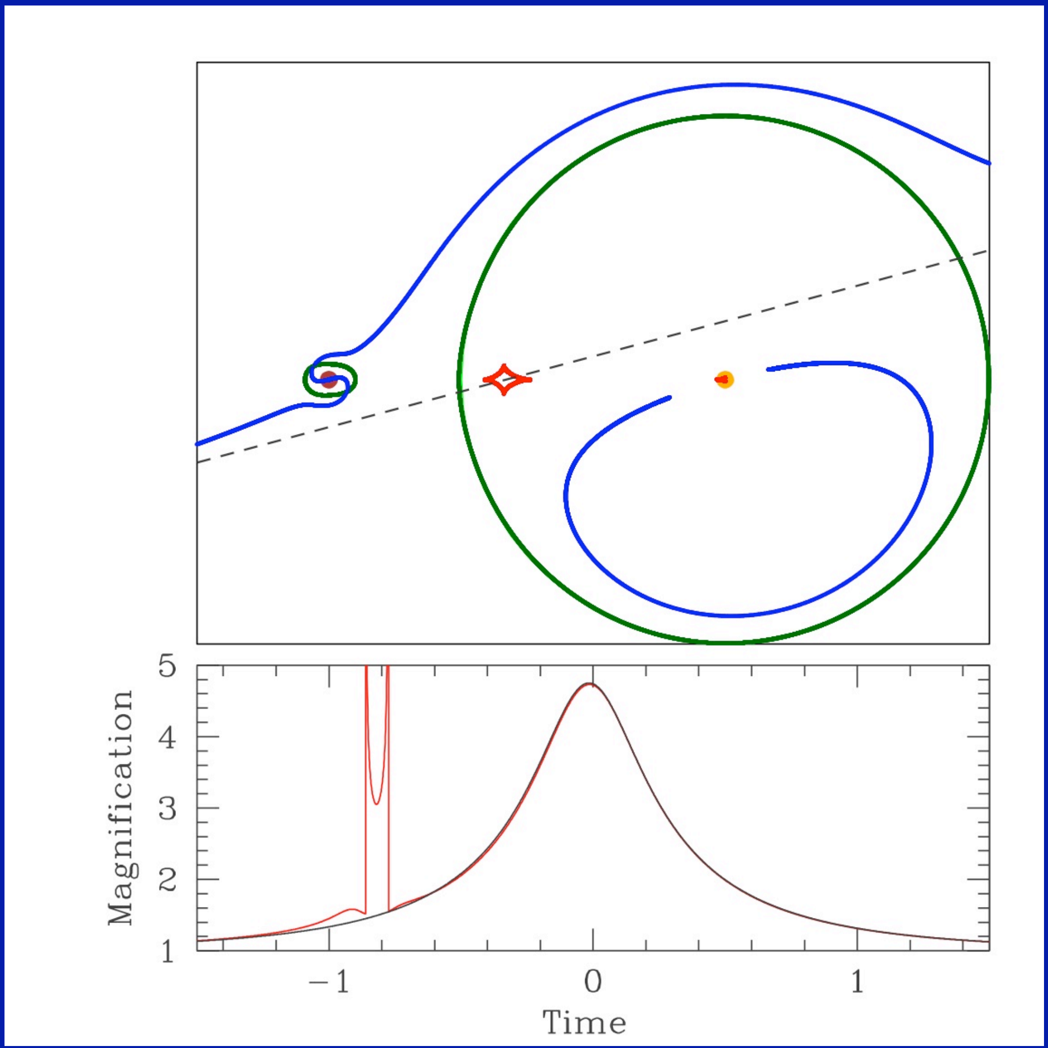
High-Magnification →

High Efficiency

Maximized when

$$a \approx R_E = D_{OL}\theta_E \approx 3\text{AU}$$

High Magnification Events



Why high-mag events rule:

Nearly 100% efficiency.

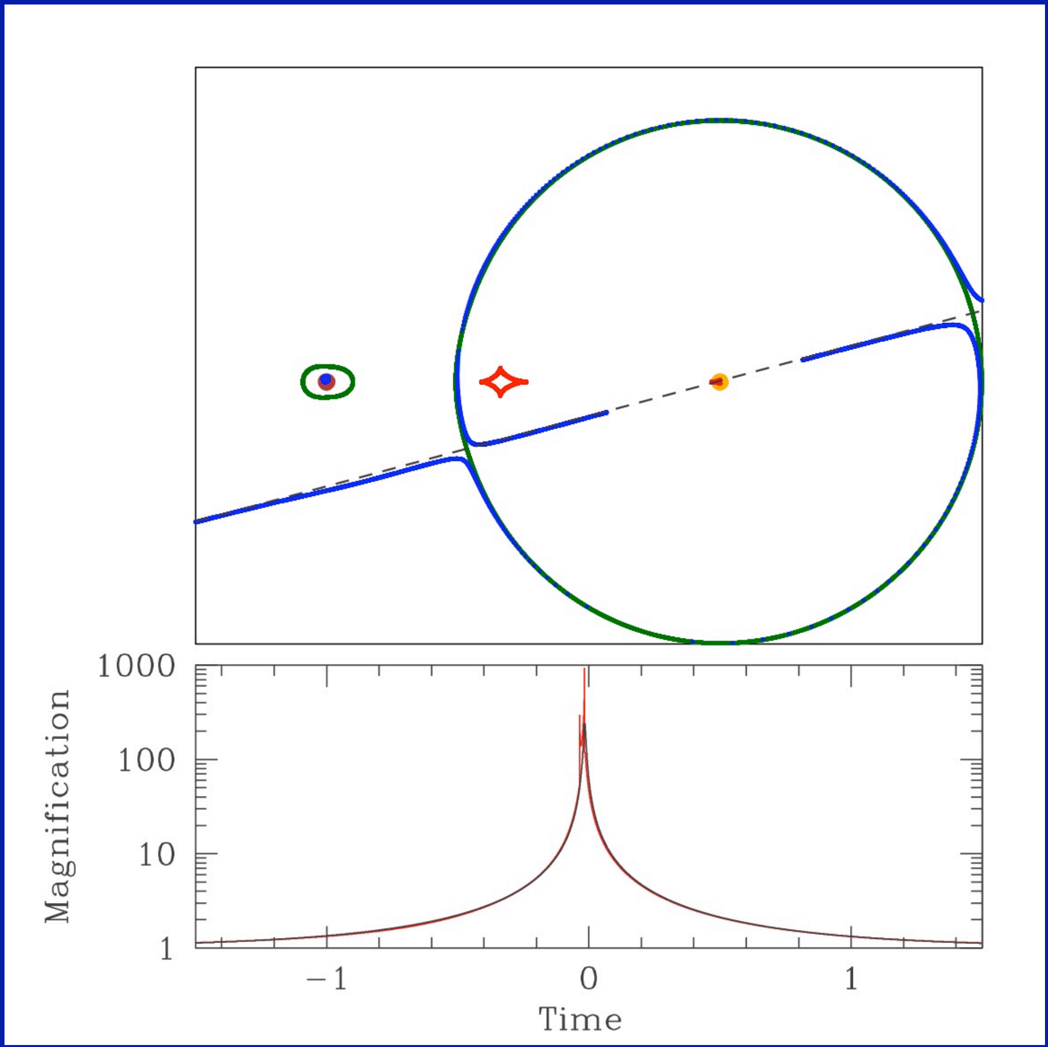
(Griest & Safizadeh 1998)

Localized perturbations.

Predictable.

Multiple planets! (Gaudi et al. 1998)
(planets in binaries including
circumbinary planets)

High Magnification Events



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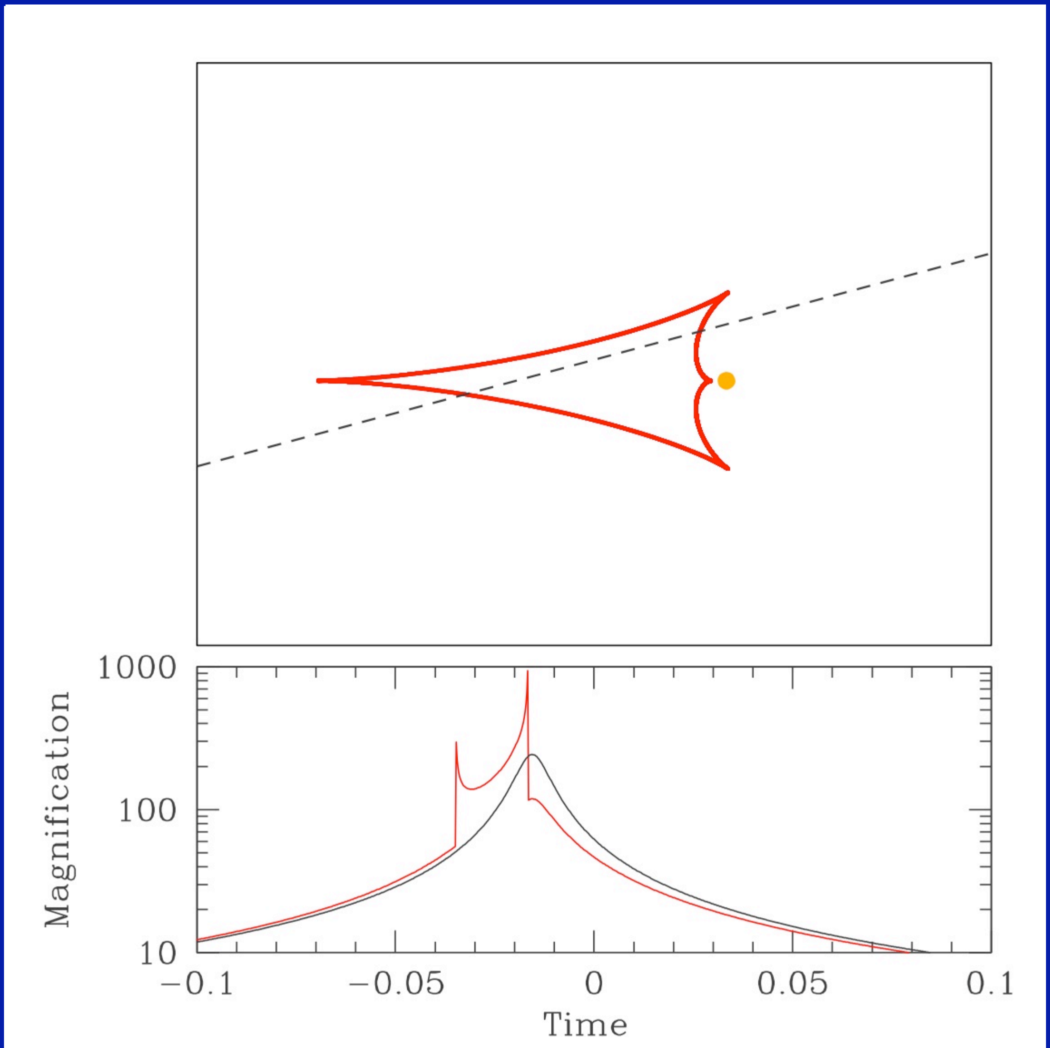

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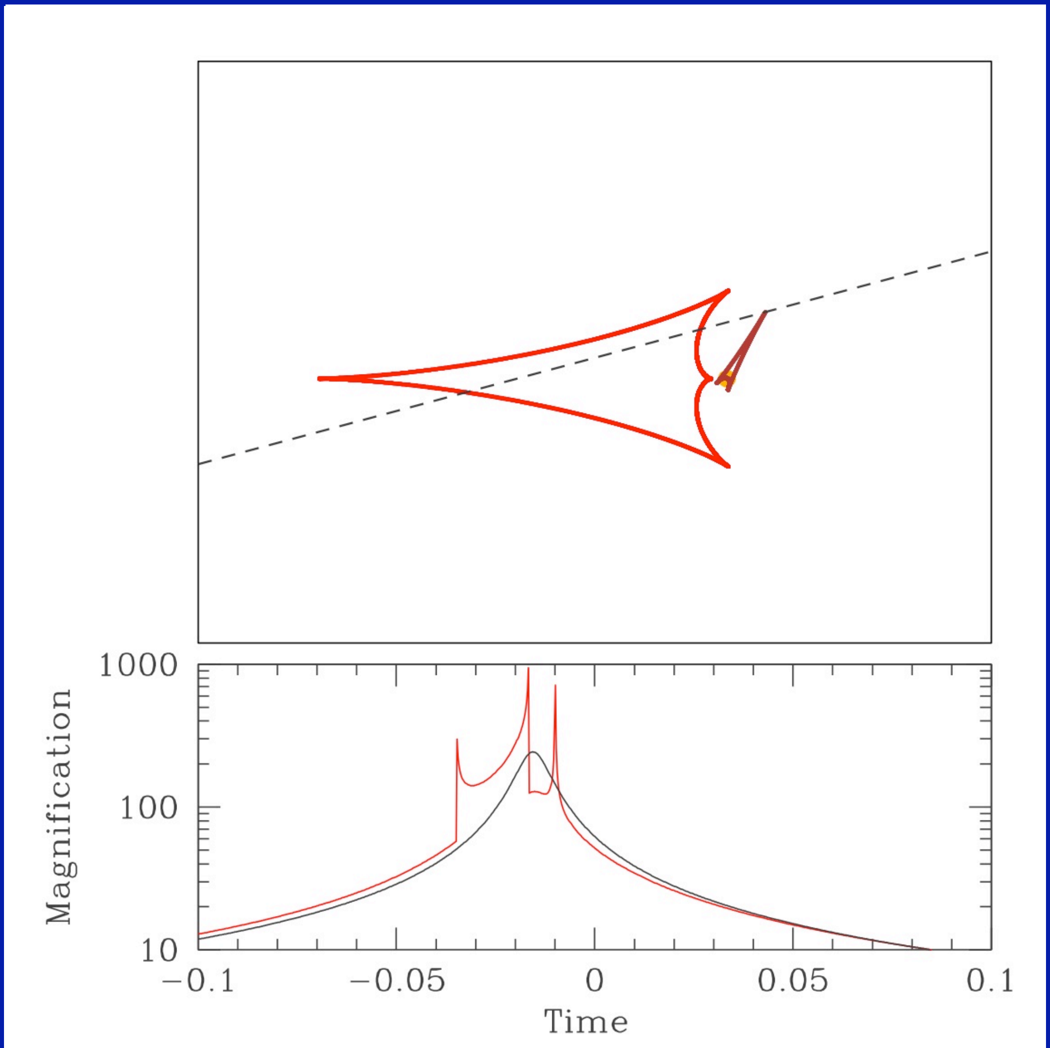

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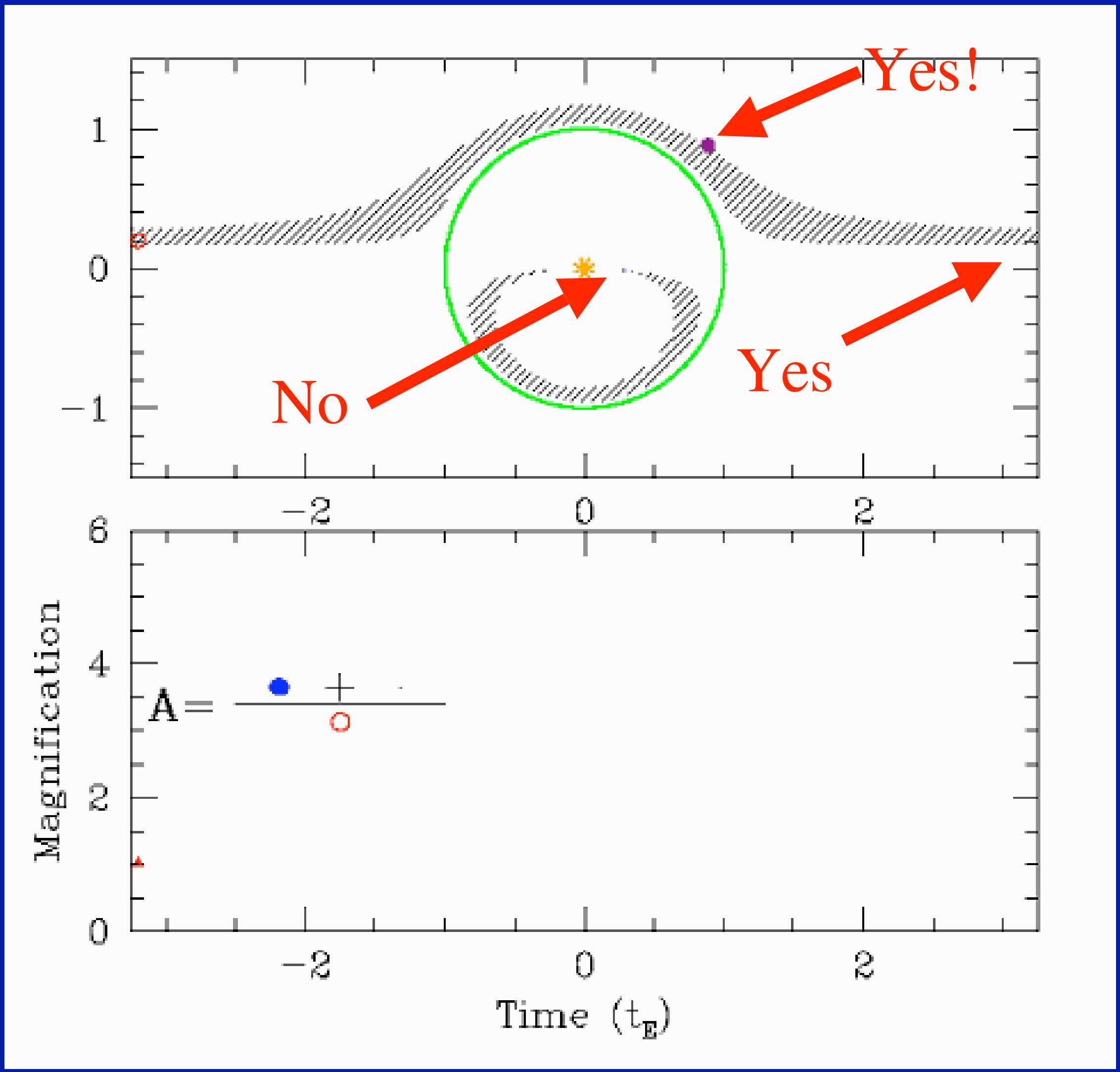
Predictable.

Multiple planets! (Gaudi et al. 1998)

(planets in binaries including circumbinary planets)

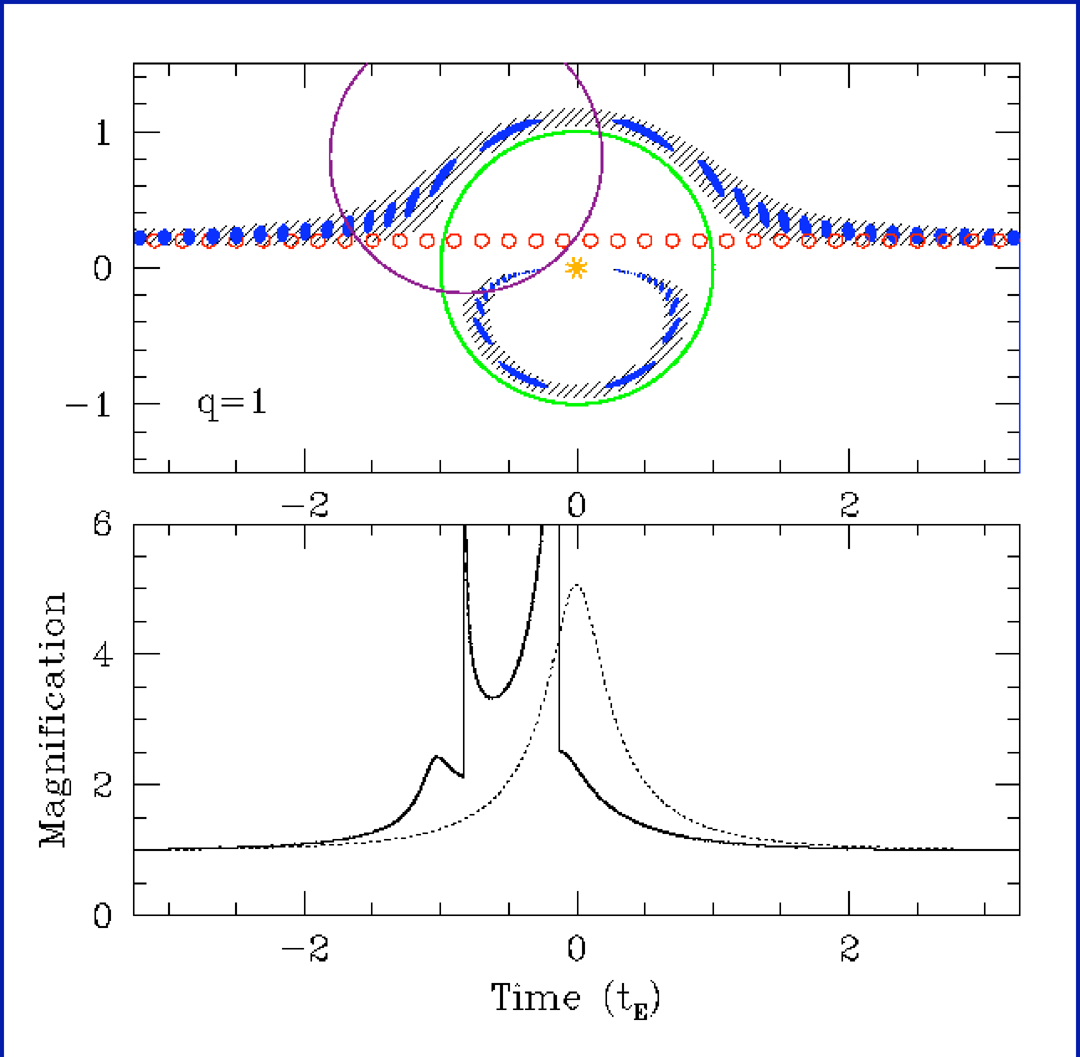
Microlensing is directly sensitive to planet mass



- Works by perturbing images
- Does not require light from the lens or planet.
- Sensitive to planets in the disk and bulge with D_{OL}=1-8 kpc
- Sensitive to wide or free-floating planets
- Not sensitive to very close planets

Very Low Mass Planets

Signal magnitude is *independent* of planet mass.

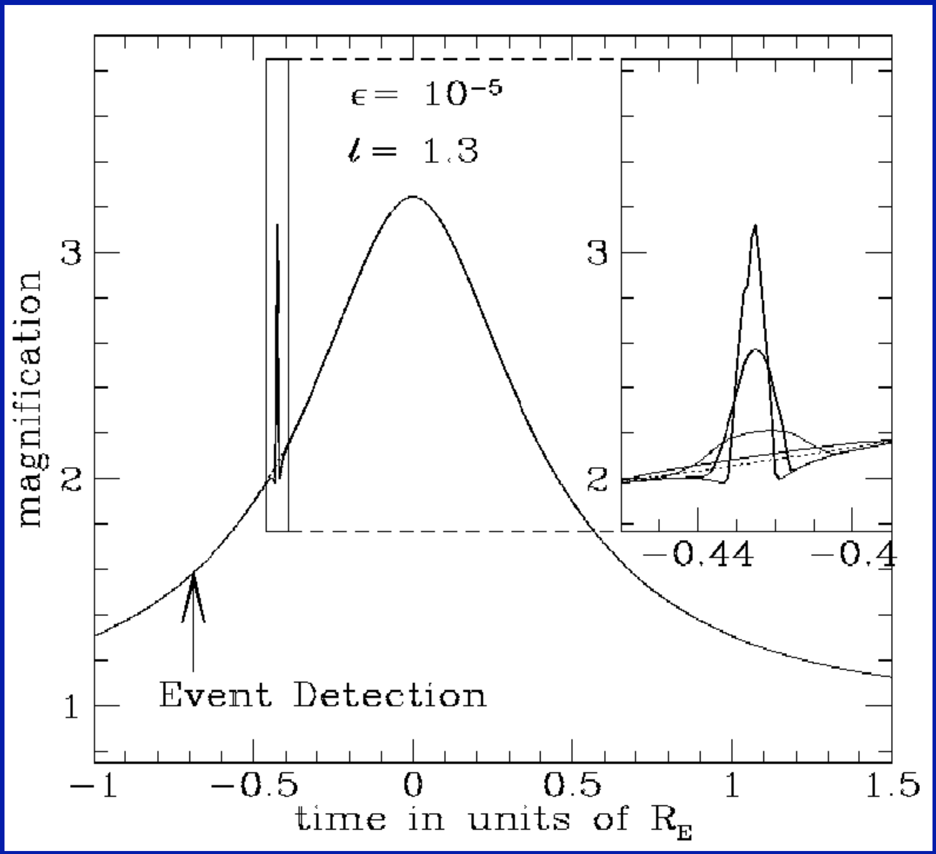


- Magnitude depends on separation of planet from image.
- Duration depends on mass.

$$t_p = q^{1/2} t_E \approx 2 \text{ hrs} \left(\frac{M_p}{M_\oplus} \right)^{1/2}$$

- Signals get rarer and briefer.
- Detection Probability
  ~ few %

How Low Can We Go?



(Bennett & Rhie 1996)

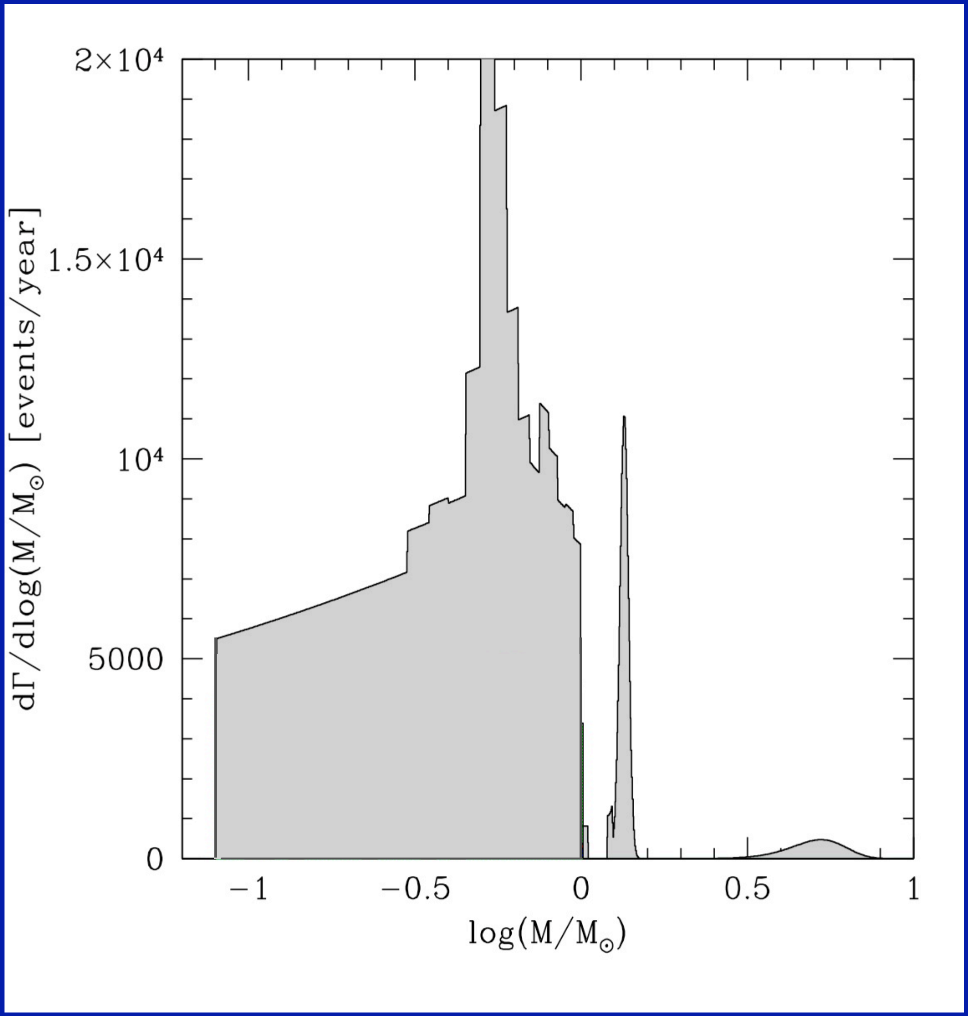
- Limited by Source Size

$$\rho_* = \frac{\theta_*}{\theta_E} \approx 1$$

$$\theta_E \approx \mu\text{as}\left(\frac{M_p}{M_\oplus}\right)^{1/2} \quad \Longleftrightarrow \quad \theta_* \approx \mu\text{as}\left(\frac{R_*}{R_\odot}\right)$$

Mars-mass planets detectable ***if solar-type sources can be monitored!***

Sensitivity Depends Weakly on Host Mass

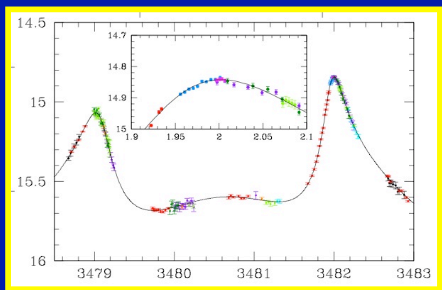


Sensitive to planets around:

- Main-sequence stars with $M < M_\odot$
- Brown dwarfs
- Remnants

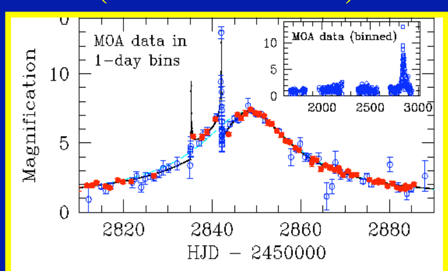
Four Detections

OGLE-2005-BLG-071
(Udalski et al 2005)

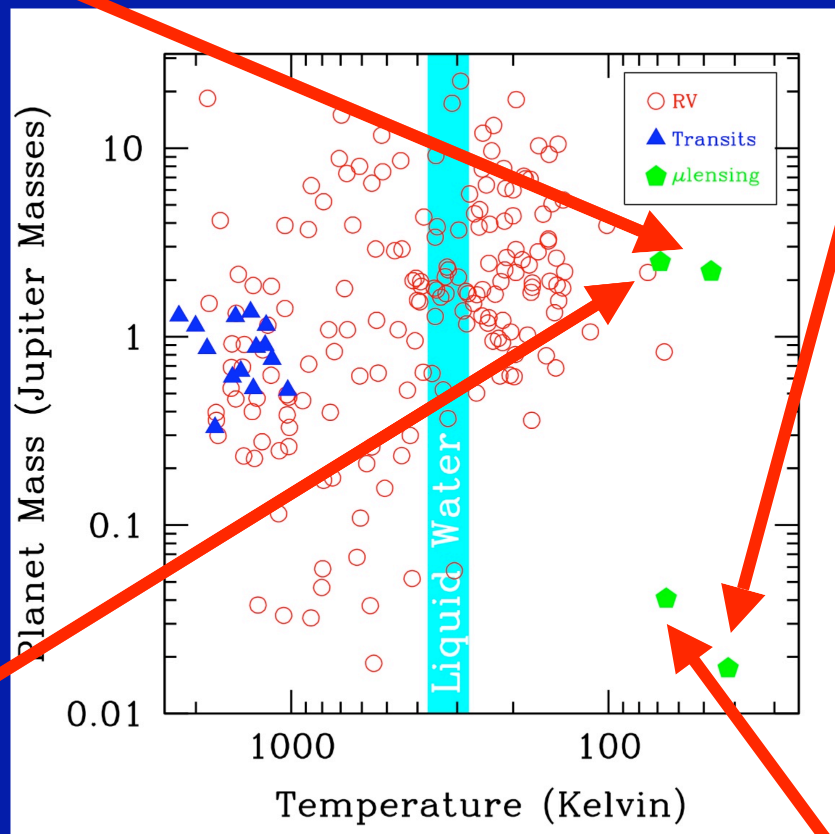


$M_p \sim 2.2 M_J, \;\; r \sim 3.7\text{AU}$

OGLE-2004-BLG-235
MOA-2004-BLG-53
(Bond et al 2004)

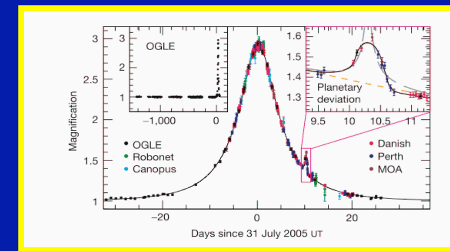


$M_p \approx 2.5 M_J, \;\; r \approx 4.3\text{AU}$



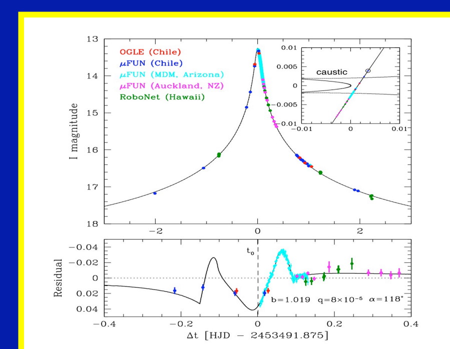
Two Jovian-mass planets
Two Neptune-mass planets

OGLE-2005-BLG-390
(Beaulieu et al 2006)



$M_p \sim 5.5 M_{\oplus}, \;\; r \sim 2.6\text{AU}$

OGLE-2005-BLG-169
(Gould et al 2006)



$M_p \sim 13 M_{\oplus}, \;\; r \sim 3.5\text{AU}$

Cool Neptunes Are Common

Two high-mass detections imply:

Jupiter-mass planets are uncommon but not rare.

Two low-mass detections imply:

~37% of stars have Neptunes between 1.6-4.3 AU

Also:

Cool Neptunes are more common than cool Jupiters

A Confession:

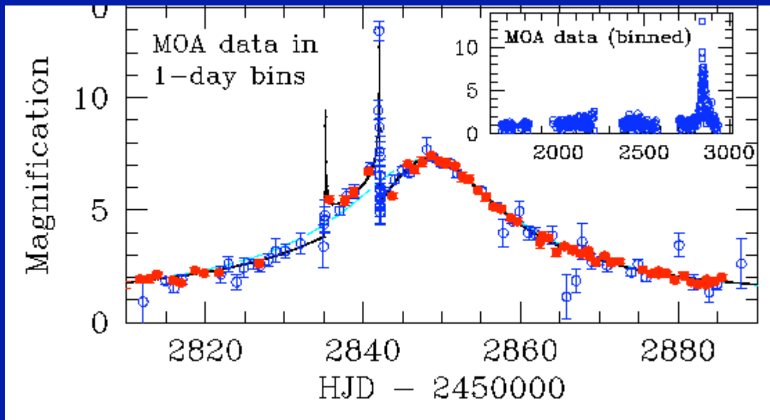
We've been lying to you.

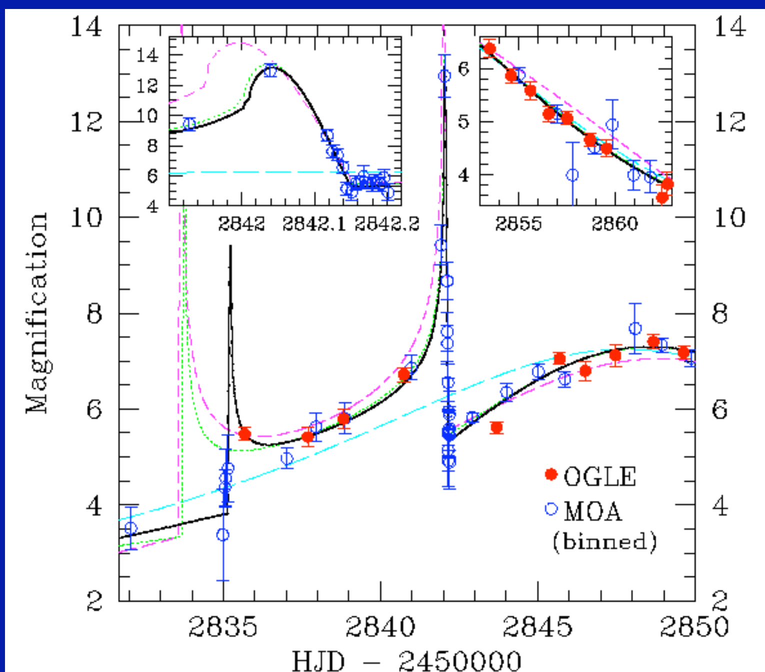
Lie #1: Only measure mass ratio and timescale.

Lie #2: No information about host.

Constraints on Host

(Bond et al 2004, Bennett et al 2006)





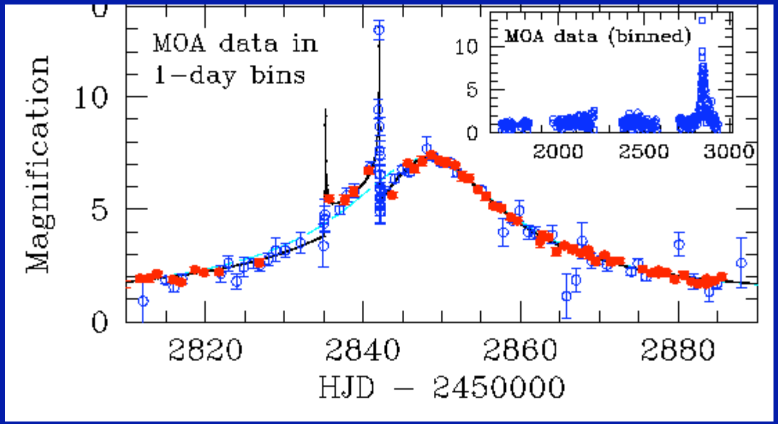
Information from lightcurves:

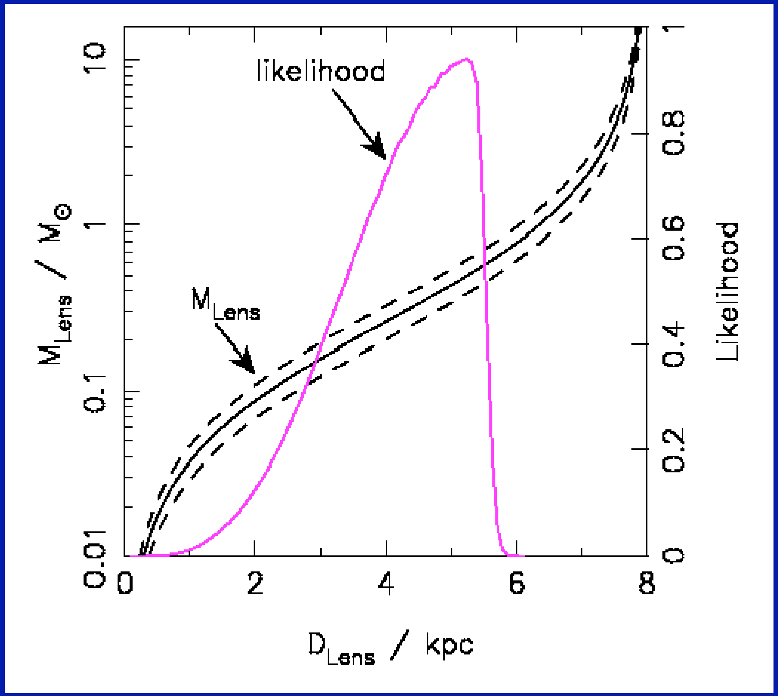
- Measure q, b, t_E from lightcuve
- Detect influence of the source size
- Can determine ρ_* and so θ_E

$$\rho_* = \frac{\theta_*}{\theta_E} \rightarrow \theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_{OL}D_{OS}}}$$

- Lens light yields lens mass
- Lens light can be detected by:
  - Resolving unrelated blended light
  - Waiting until lens and source separate
  - Measuring PSF elongation or centroid shift
- Measurement of host star mass

Constraints on Host





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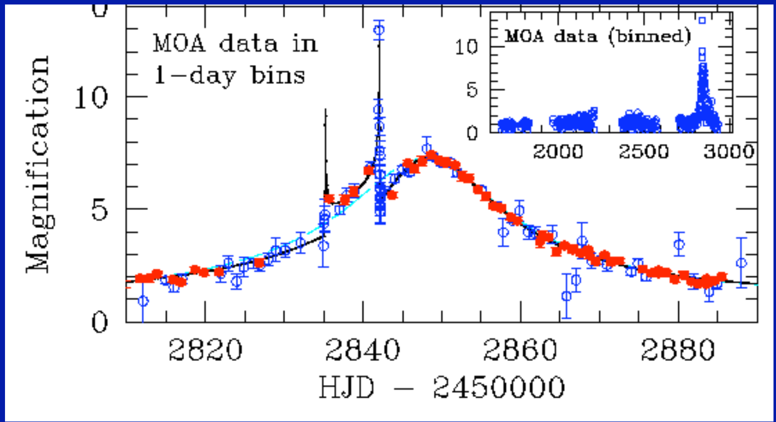

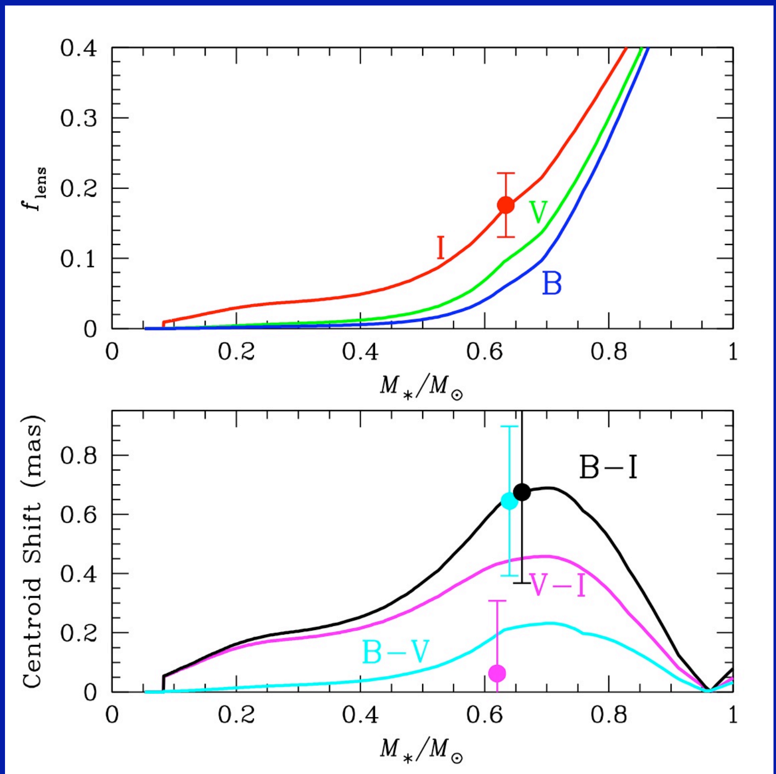

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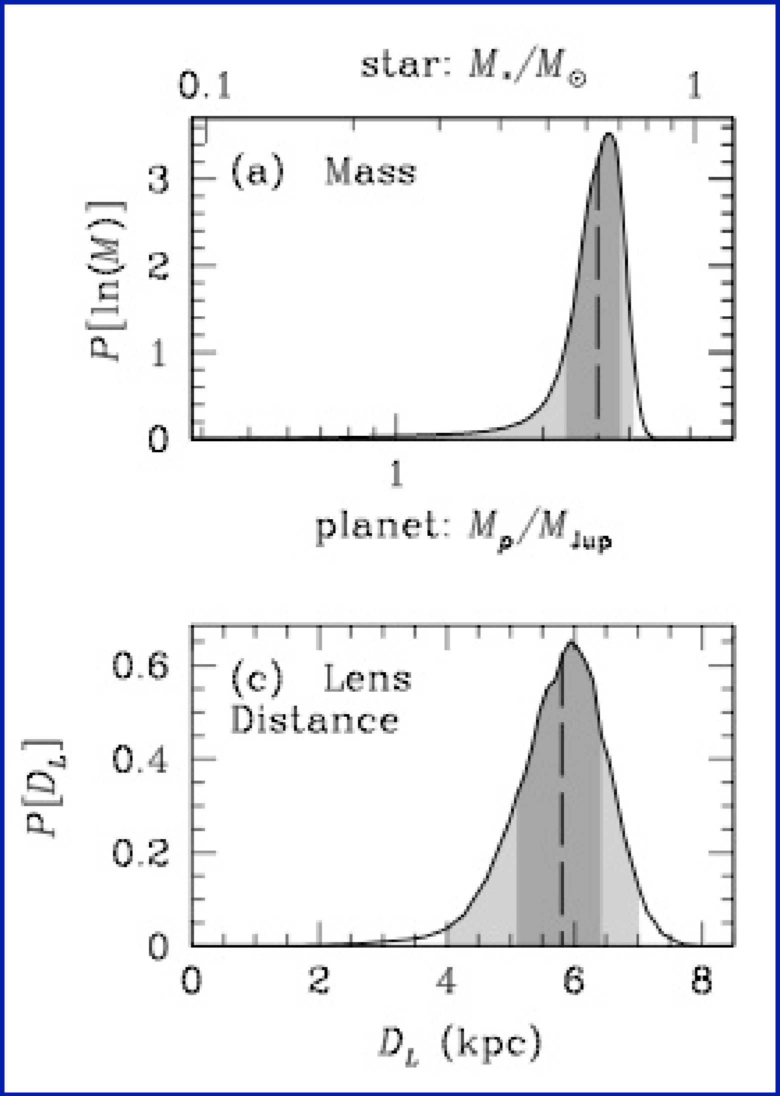

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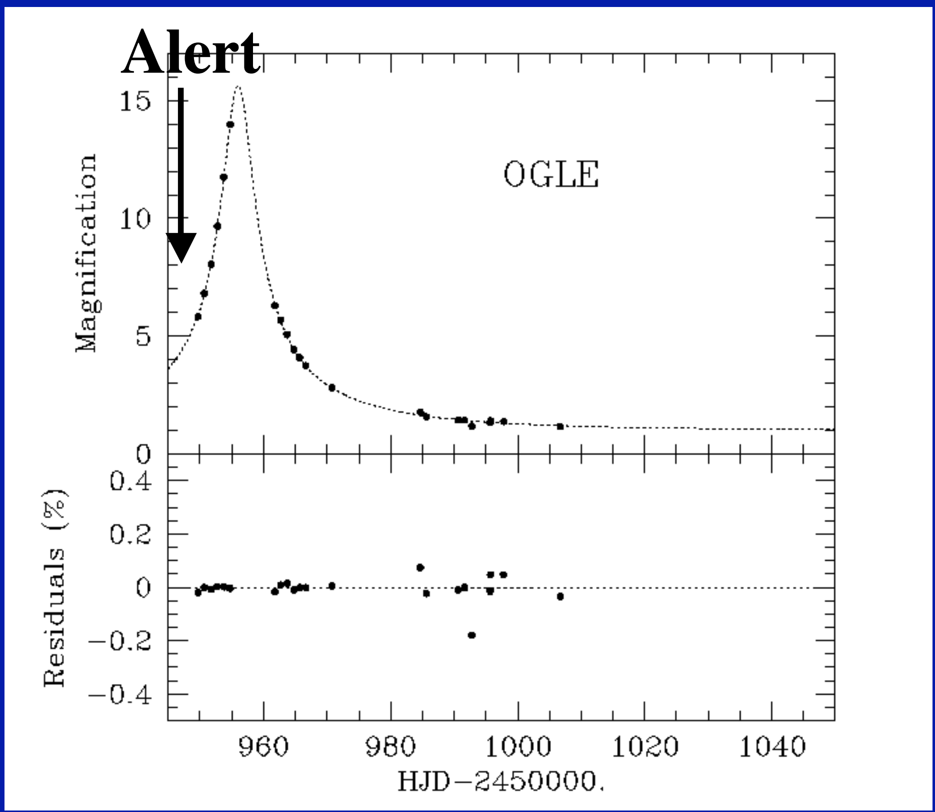
How It Is Done : Alerts



"Survey Collaborations"

- Monitor the bulge
- Insufficient sampling
- Real-time Alerts

MACHO, EROS, OGLE, MOA

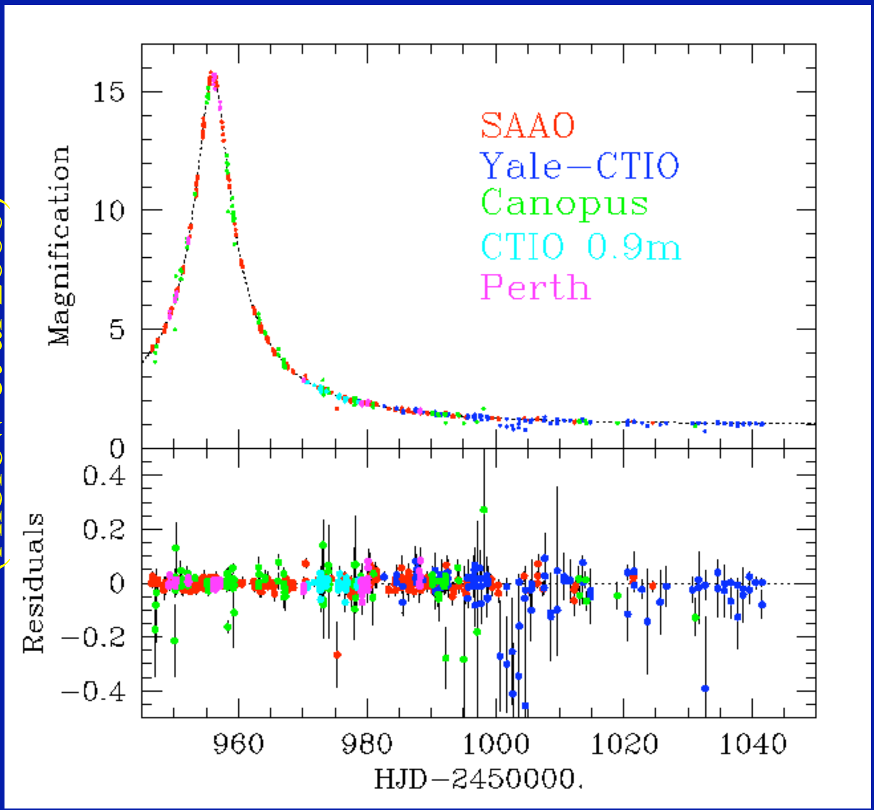
"Follow-Up Collaborations"

- Monitor microlensing events
- High cadence and optimized photometry

GMAN, MPS, EXPORT, PLANET, μFUN

How It Is Done : Follow-Up

(Albrow et al 2000)



Median Sampling ~ 1 hour
RMS scatter over peak ~1.5%

"Survey Collaborations"

- Monitor the bulge
- Insufficient sampling
- Real-time Alerts

MACHO, EROS, OGLE, MOA

"Follow-Up Collaborations"

- Monitor microlensing events
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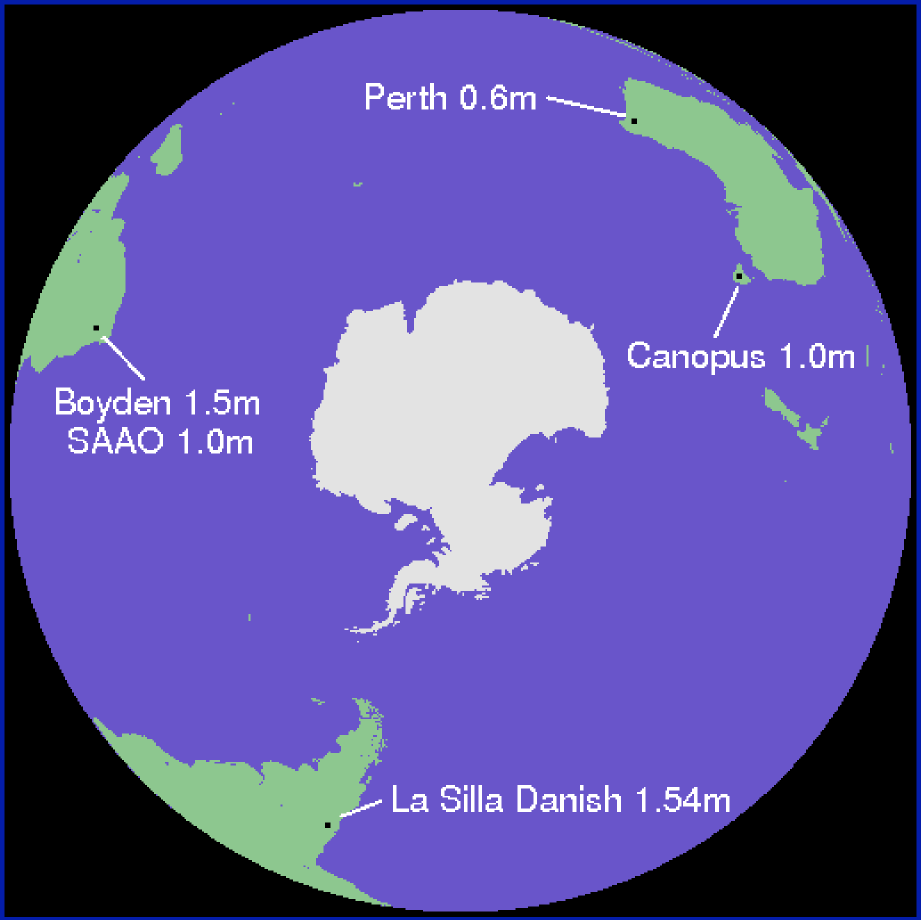
GMAN, MPS, EXPORT, PLANET, μFUN

PLANET: Follow Everything you can



Distributed network:

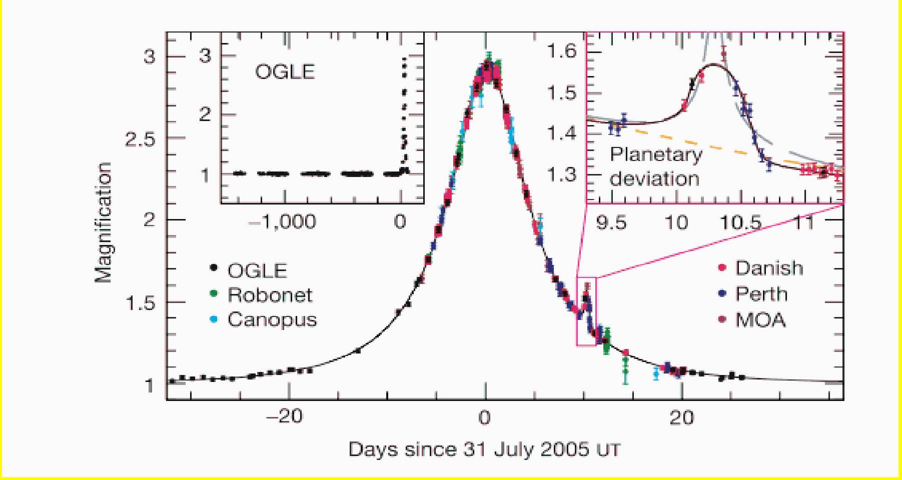
- Cover as many events as possible
- Dense coverage of many events

Led to detection of the lowest mass exoplanet

- Individual probability very low
- Only possible because of the PLANET approach
- Took 10 years!

PLANET: Follow Everything you can

OGLE-2005-BLG-390
(Beaulieu et al 2006)



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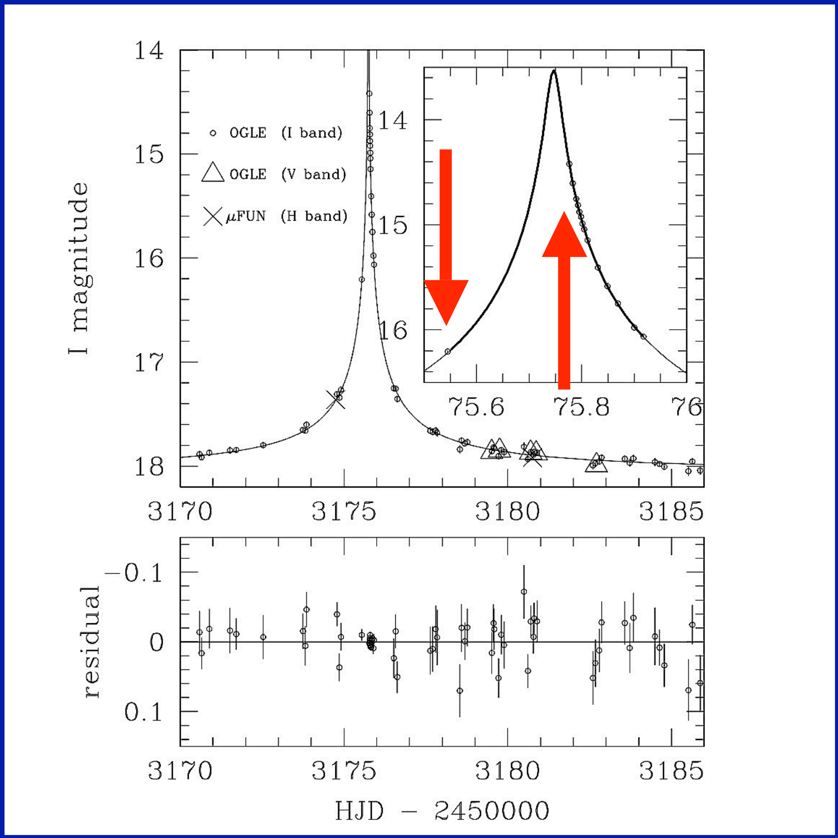
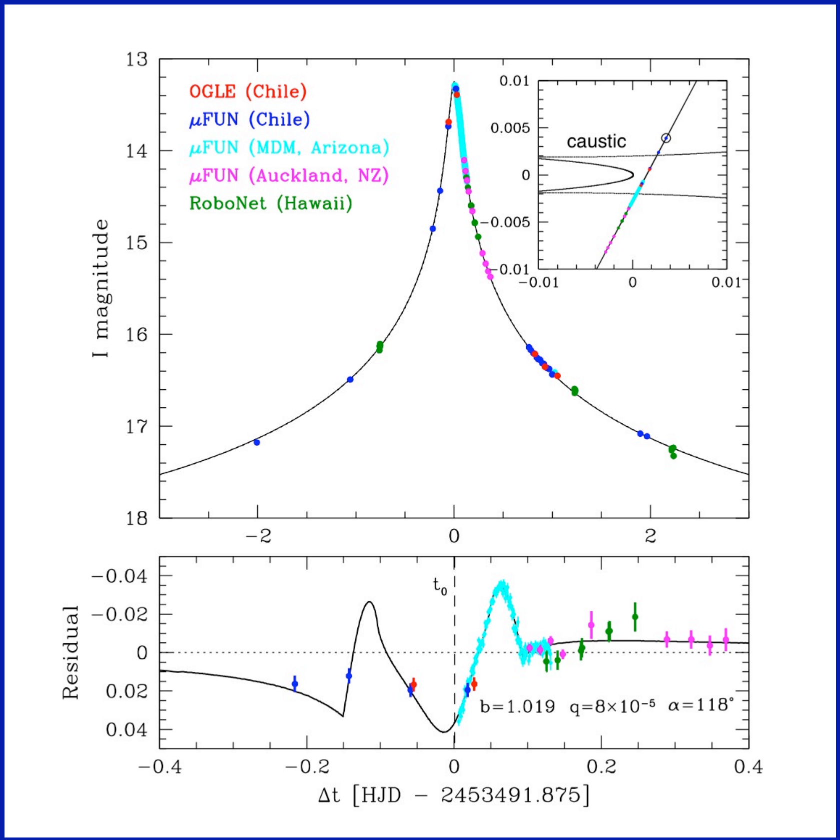
Current Shoe-String, Slipshod μFUN Approach

- Focus on high-magnification events
- Struggle to identify events real time
- Save money by employing enthusiastic amateurs
- Wait…. wait… wait…. PANIC!

The Elusive High-magnification Event

The one that got away… …and the one that didn't



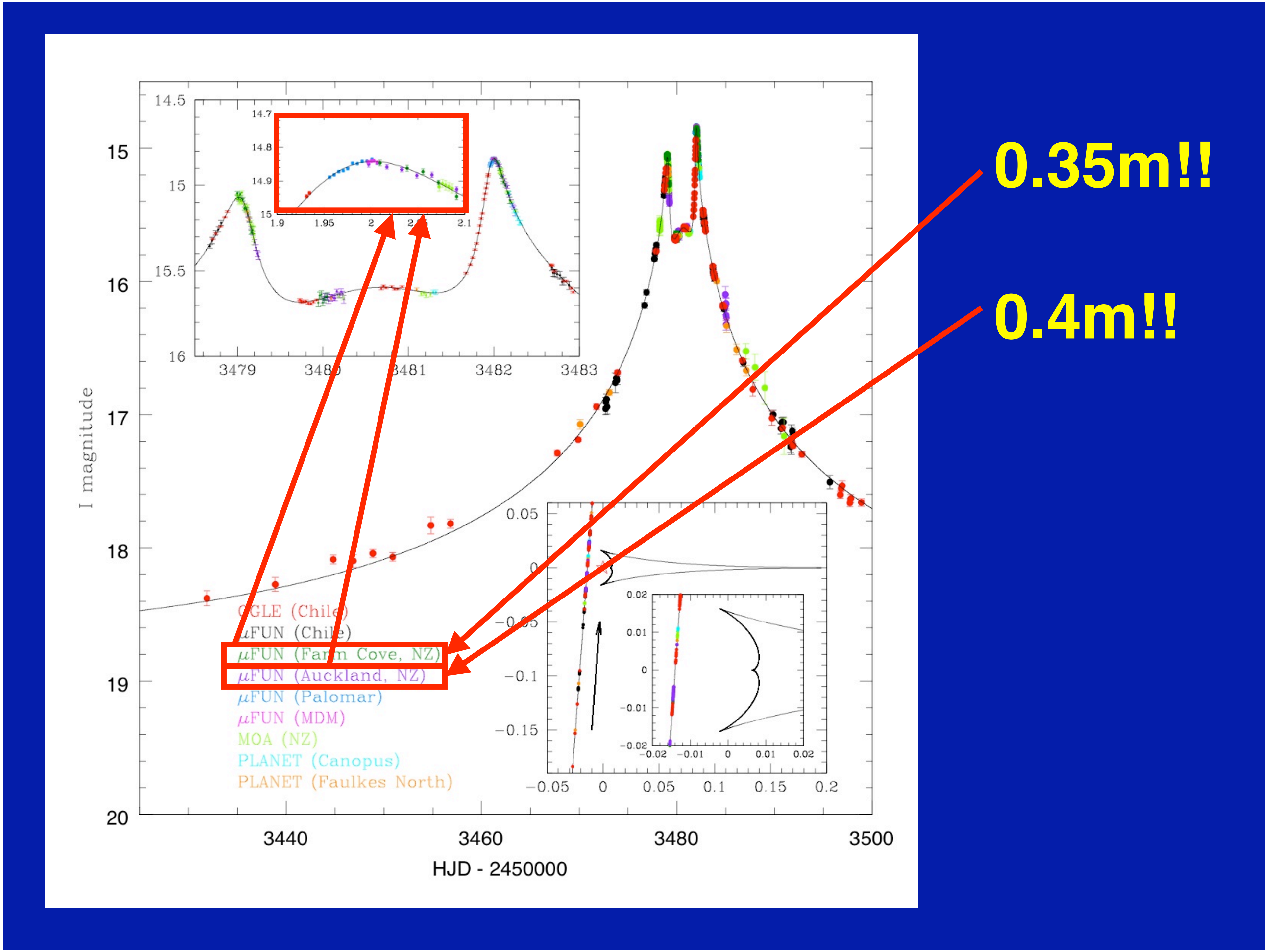


(would have had sensitivity to Earth-mass planets)

Amazing Amateurs

- **Auckland Observatory** (0.4-meter)
- **Bronberg Observatory** (0.4-meter)
- **Catino Austral Observatory** (0.4-meter)
- **CTIO** (1.3-meter)
- **Farm Cove Observatory** (0.4-meter)
- **Hunters Hill Observatory** (0.4-meter)
- **MDM Observatory**, (2.4-meter)
- **Mt Lemmon Observatory** (1.0-meter)
- **Palomar Observatory** (60-inch)
- **Perth** (0.3-meter)
- **Southern Stars Observatory** (0.3-meter)
- **Vintage Lane Observatory** (0.4-meter)
- **Wise Observatory** (1.0-meter)


•12” Meade LX200R
MEADE



0.35m!!
0.4m!!
I magnitude
HJD - 2450000
OGLE (Chile)
μFUN (Chile)
μFUN (Farm Cove, NZ)
μFUN (Auckland, NZ)
μFUN (Palomar)
μFUN (MDM)
MOA (NZ)
PLANET (Canopus)
PLANET (Faulkes North)

"It just shows that you can be a mother, you can work full-time, and you can still go out there and find planets."

-Jenny McCormick
Farm Cove Observatory

What's Next?

- **Current setup (alert/follow-up) saturated**
  - Nearly all of the useable bulge monitored
  - Many events cannot be monitored
  - Monitoring one event at a time too inefficient
- **A new strategy**
  - Dispense with alert/follow-up
  - Simultaneously detect and monitor microlensing events

What is Required?

Detecting the Perturbations from Earth-mass Planets

- Sampling rate ~ 10 minutes

$$t_{E,p} = 2\text{hrs}\left(\frac{M_p}{M_E}\right)^{1/2}$$

- Photometric Accuracy ~ 1% at I~21
  - Signal Magnitude

$$\frac{\Delta F}{F} \approx 1\% \left(\frac{M_p}{M_{♂}}\right)\left(\frac{R_*}{R_\odot}\right)^{-2}$$

  - Photometric Uncertainty

$$\sigma = 1\% \left(\frac{D}{2\text{m}}\right)^{-1}\left(\frac{t_{\exp}}{120\text{s}}\right)^{-1/2} 10^{0.2(I-21)}$$

What is Required?

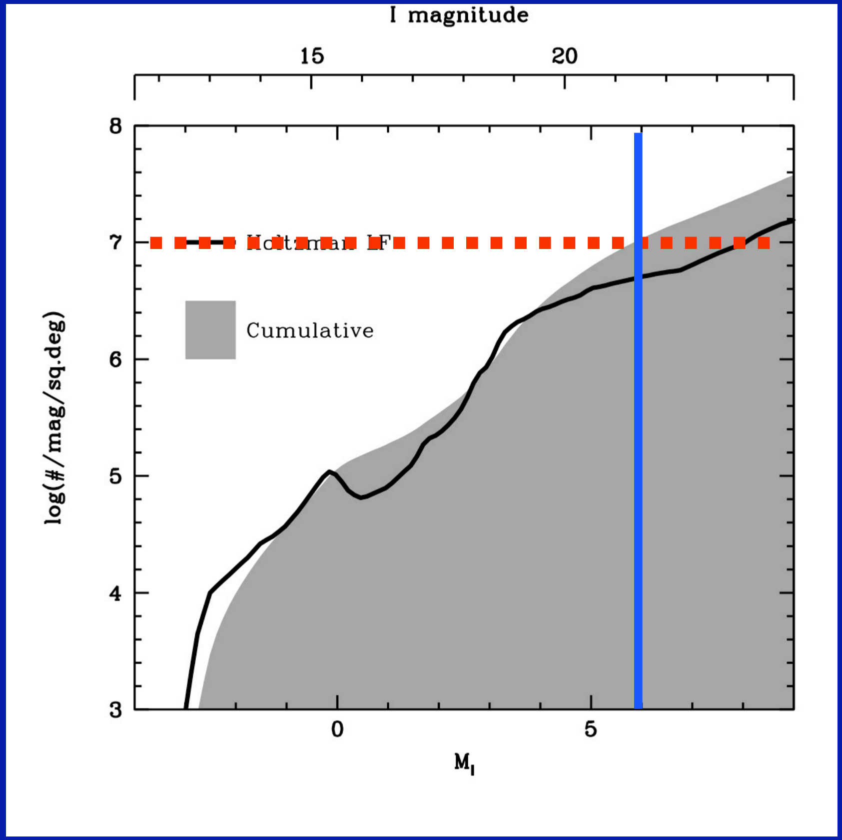
- Event Rate
  - Primary Event Rate

$$\Gamma \approx 10^{-5}\,\mathrm{yr}^{-1}$$

  - Detection Probability

$$P \approx A_0\theta_p \approx 1\%\left(\frac{M_p}{M_{Earth}}\right)^{1/2}$$

  - Detections Per Year



$$N \approx n_F \Omega \Phi \Gamma P \approx 10\ \mathrm{yr}^{-1}\left(\frac{\Omega}{10\square^\circ}\right)\left(\frac{\Phi}{10^7\ /\square^\circ}\right)\left(\frac{\Gamma}{10^{-5}\,\mathrm{yr}^{-1}}\right)\left(\frac{P}{1\%}\right)$$

NextGen μLensing Survey

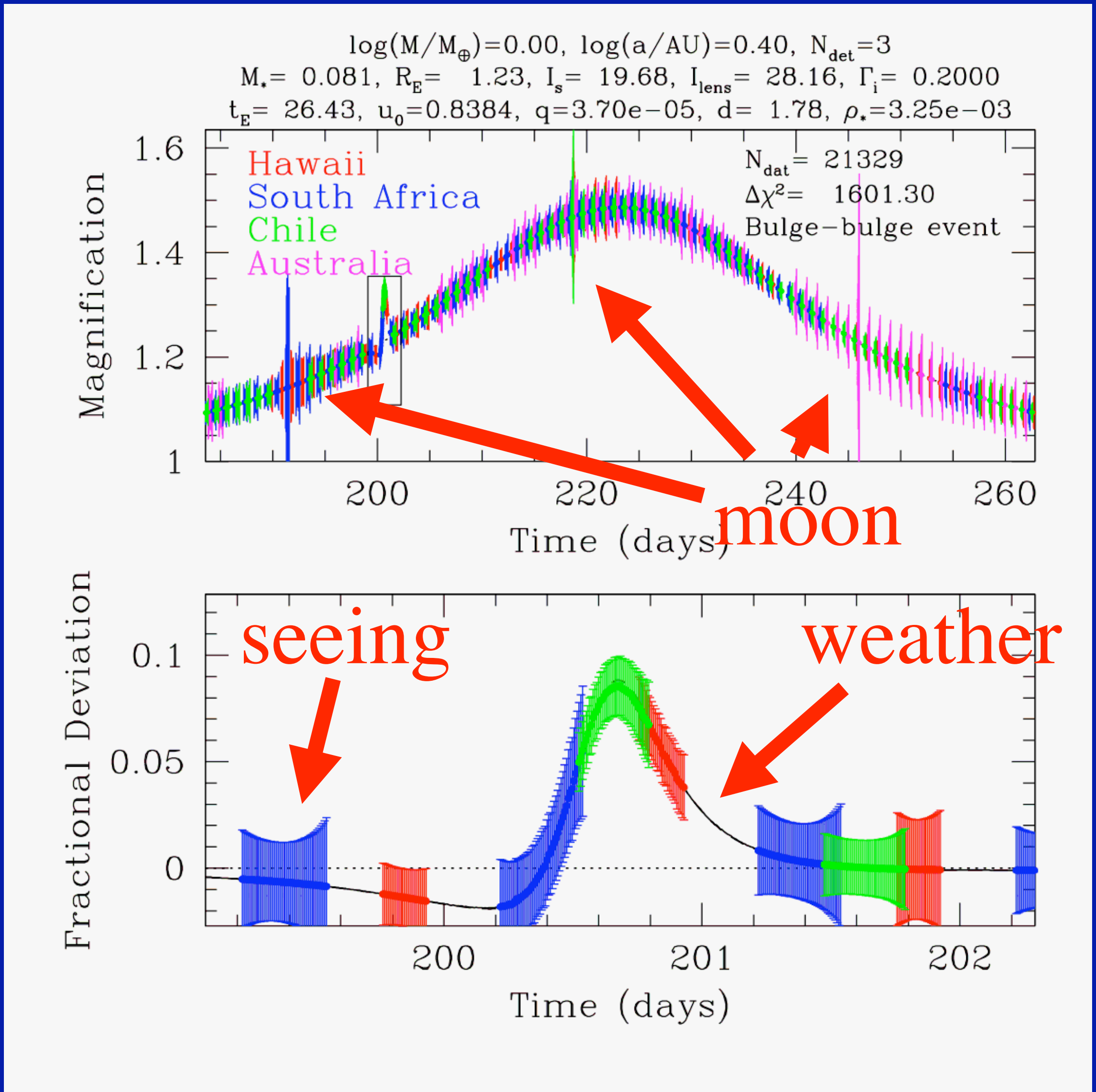
- Requirements to detect ~10 Earth-mass planets per year
  - Monitor ~10 square degrees of the Galactic bulge continuously with ~10 minute sampling using 1-2m class telescopes

- Monte Carlo simulation
  - Survey specifications
    - Four 2m telescopes in Hawaii, Chile, South Africa and Australia
    - 4 square degree cameras
    - 4 fields in the bulge (16 square degrees, 7000 events per year)

Simulation Ingredients

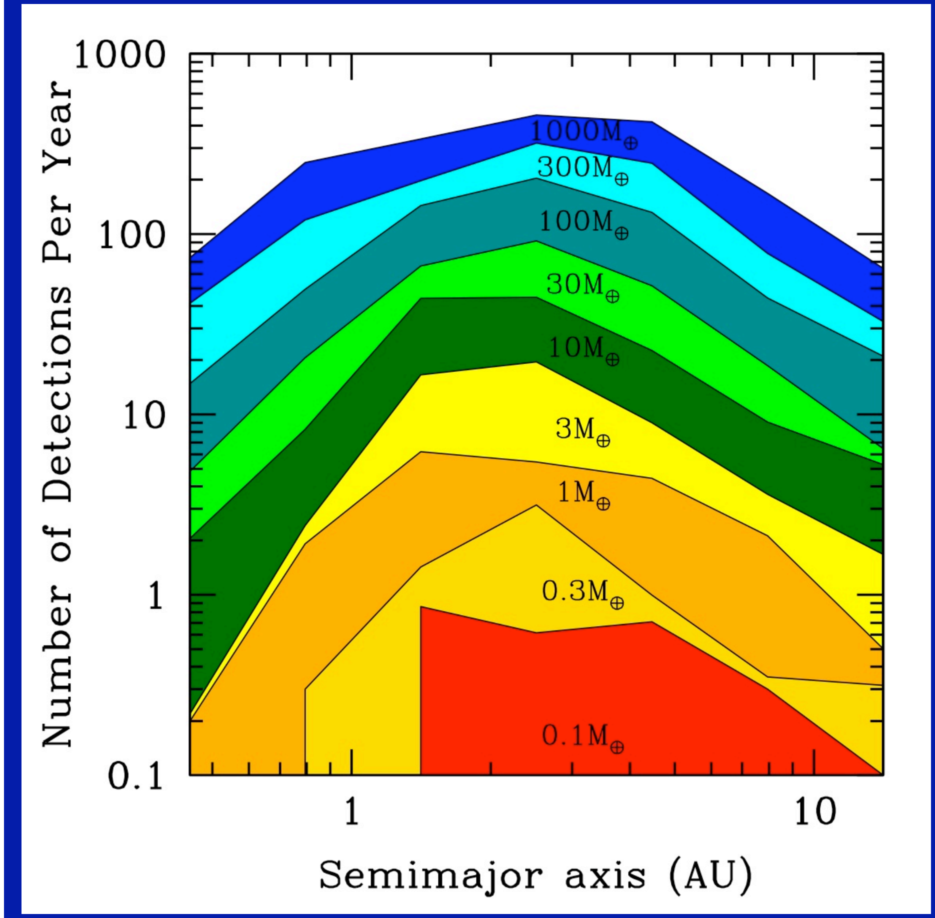
Monte Carlo Simulation

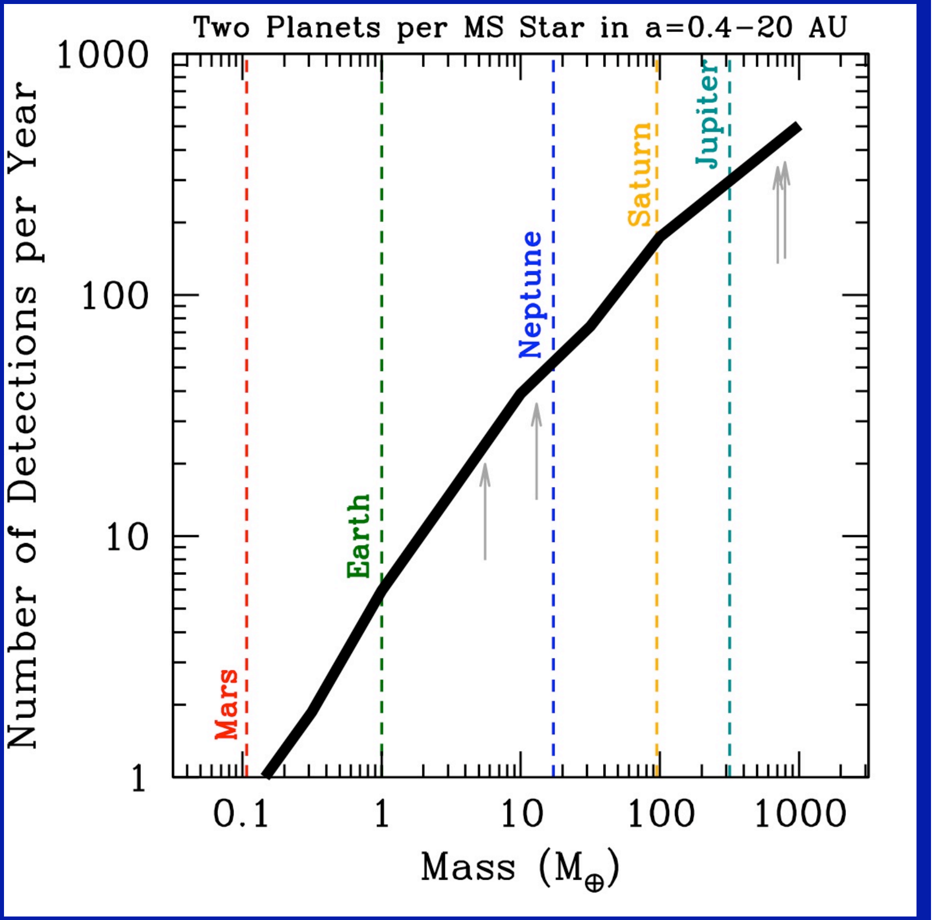
- µLensing Event Model
- Blending Model
- Moon + Sky
- Weather
- Seeing



(Gaudi, Han, & Gould, in prep)

Detecting planets...





13σ!!

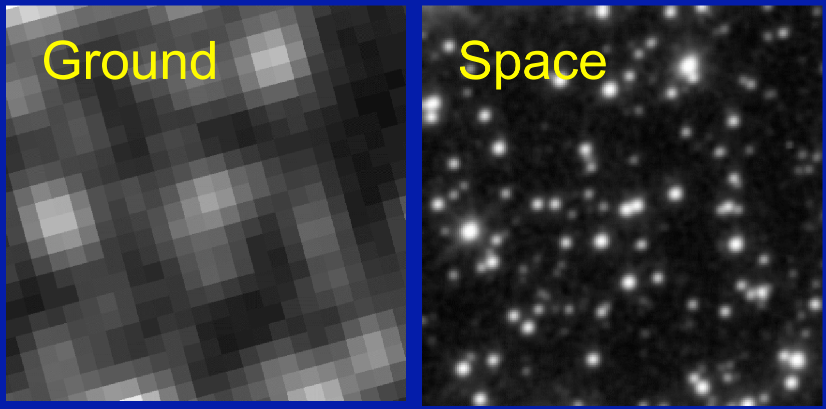
With or Without Us…

- MOA-II
  - 1.8m telescope, 2.18 sq. degree camera, NZ
- OGLE -IV
  - 1.3m telescope, funding for upgrade to camera, Chile
- Proposed Initiatives
  - Korean, German, Chinese
- Pan-STARSS?
- Other Initiatives?
  - Camera for $2 million
  - Telescope for $5 million
- Pilot campaign this summer
  - OGLE, MOA, Wise

Why Ground Isn’t Good enough

Cannot yield the true potential

- MS sources severely blended
- Getting constraints on hosts is expensive
- Perturbations can be poorly sampled



The field of microlensing event MACHO 96-BLG-5

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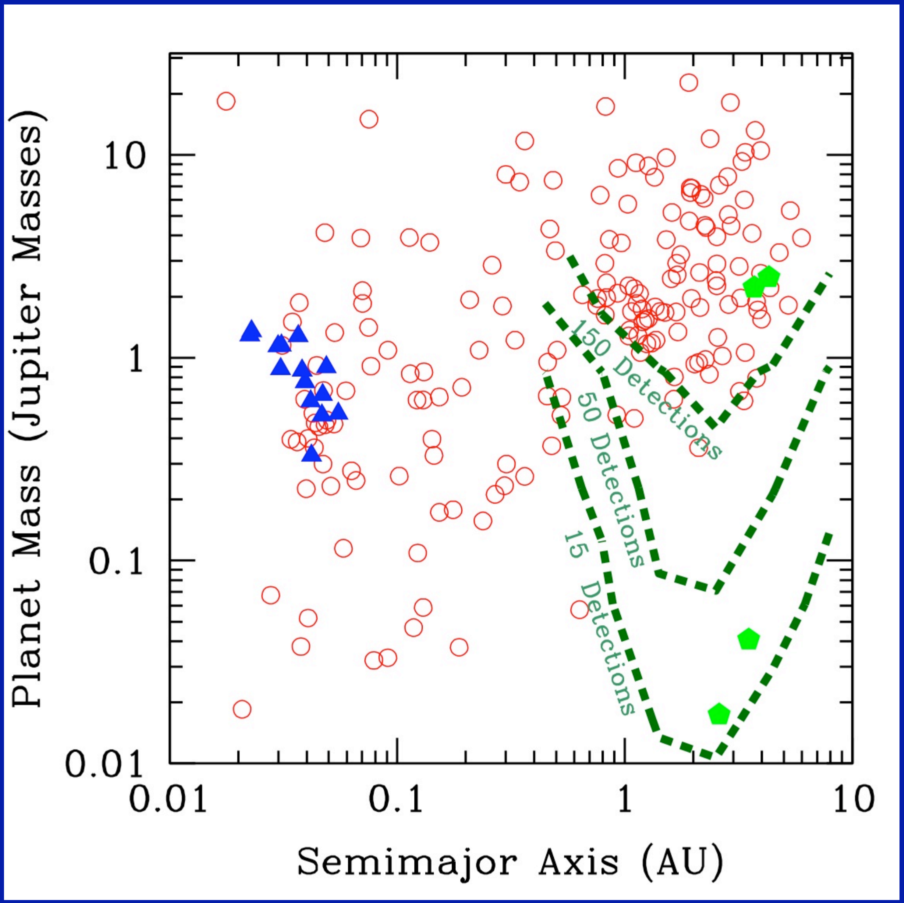

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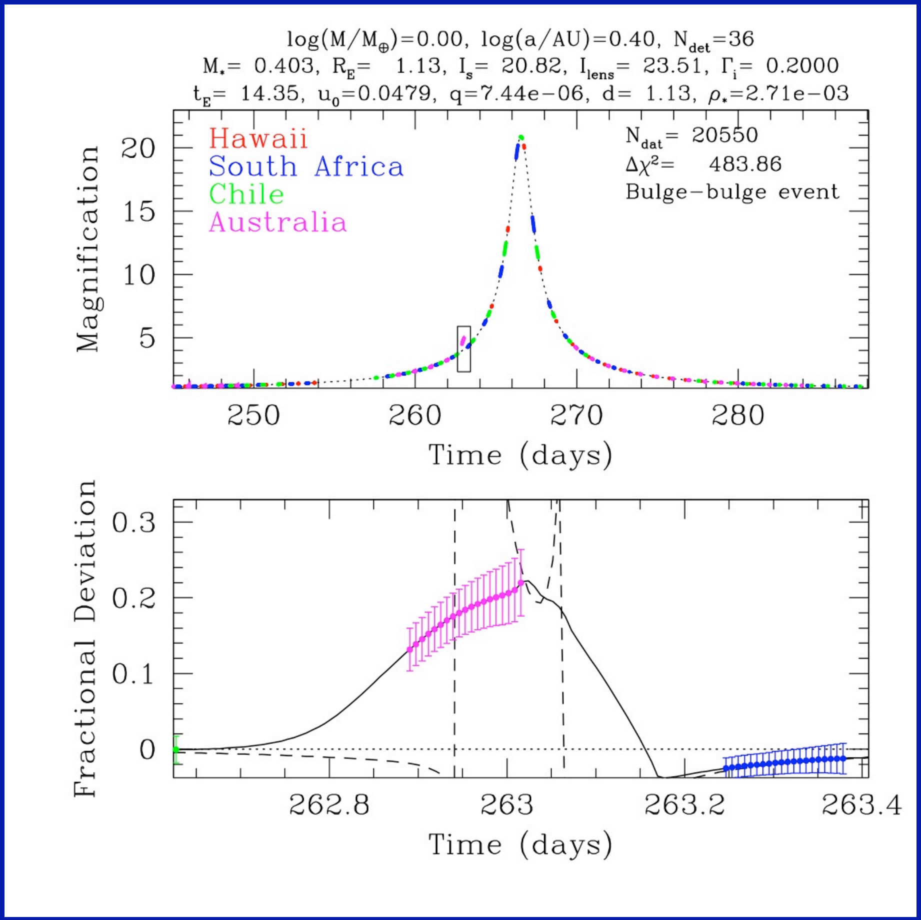


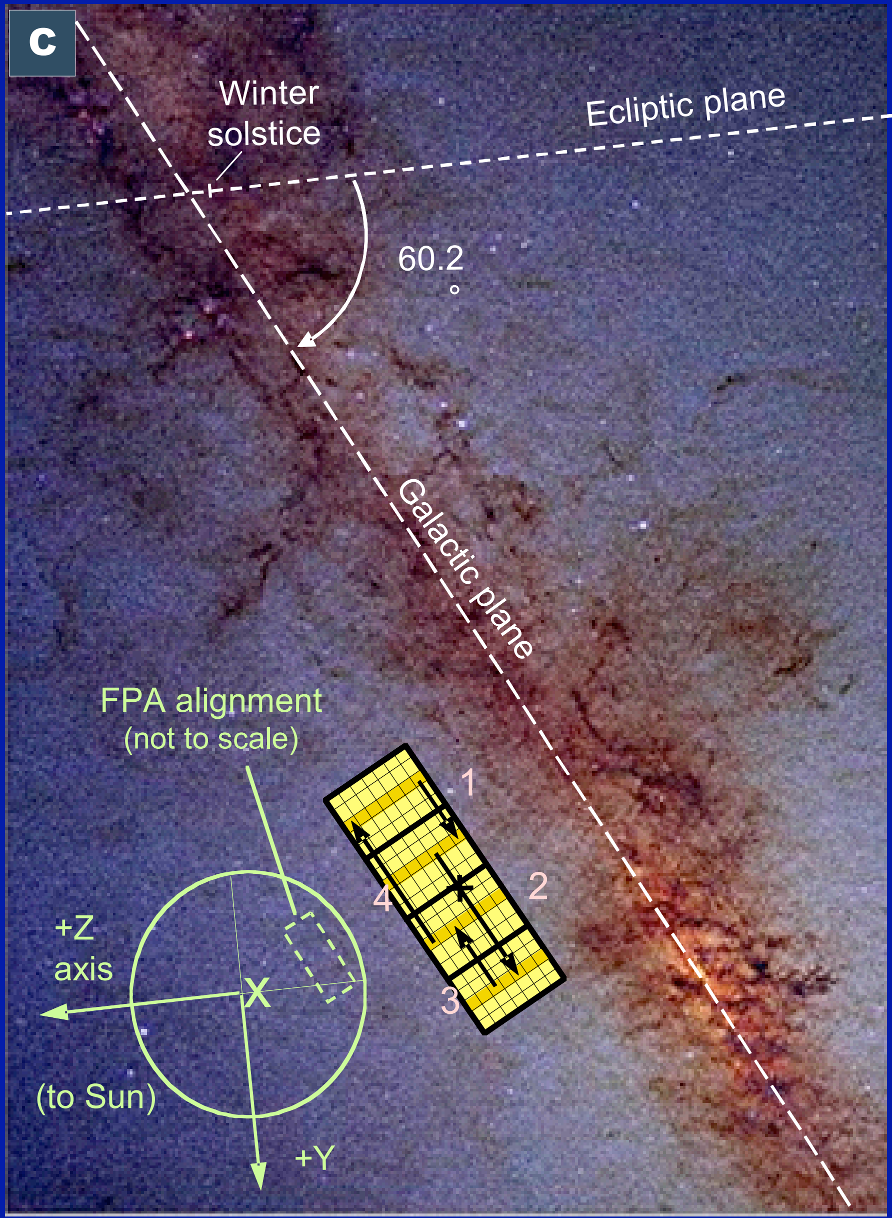
What can we expect from Space?

A worked example: Microlensing Planet Finder (Bennett PI)

- Simulations from Bennett & Rhie (2002) ApJ 574, 985
- Basic results confirmed by independent simulations by me
- Continuous observations of 4×0.66 sq. deg. central Galactic bulge fields: $\sim 2 \times 10^8$ stars
- Observations in near IR to increase sensitivity
- Simulated images based on HST luminosity function from Holtzman et al (1998)
- ~15,000 events in 4 seasons

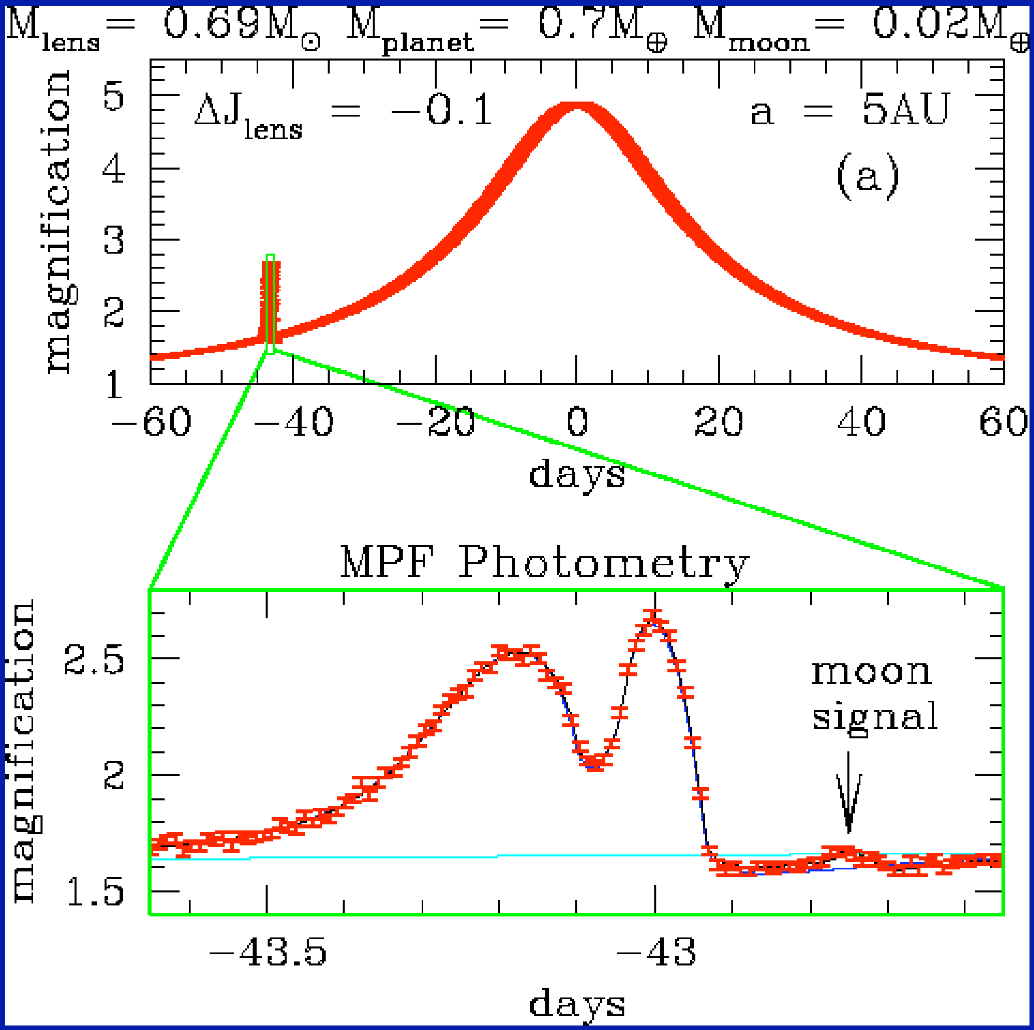
MPF Fields

Four fields oriented parallel to the Galactic plane to maximize the microlensing rate.



Simulated Planetary Light Curves

- Planetary signals can be very strong
- Light curve features unambiguously yield planetary mass ratio and separation
- Exposures every 10-15 minutes
- The small deviation at day –42.75 is due to a moon of 1.6 lunar masses.



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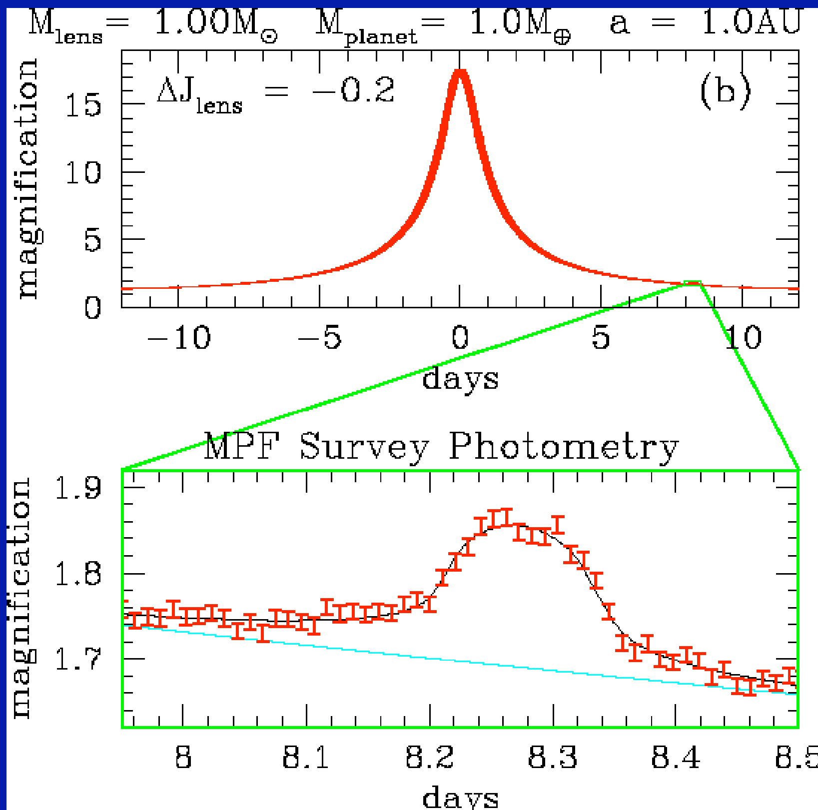
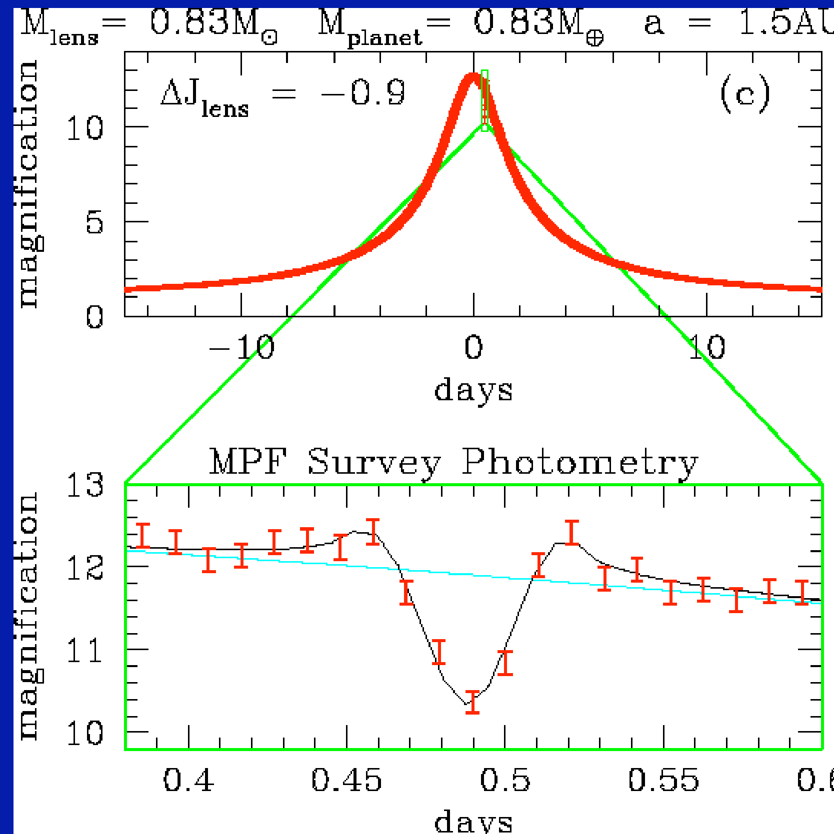


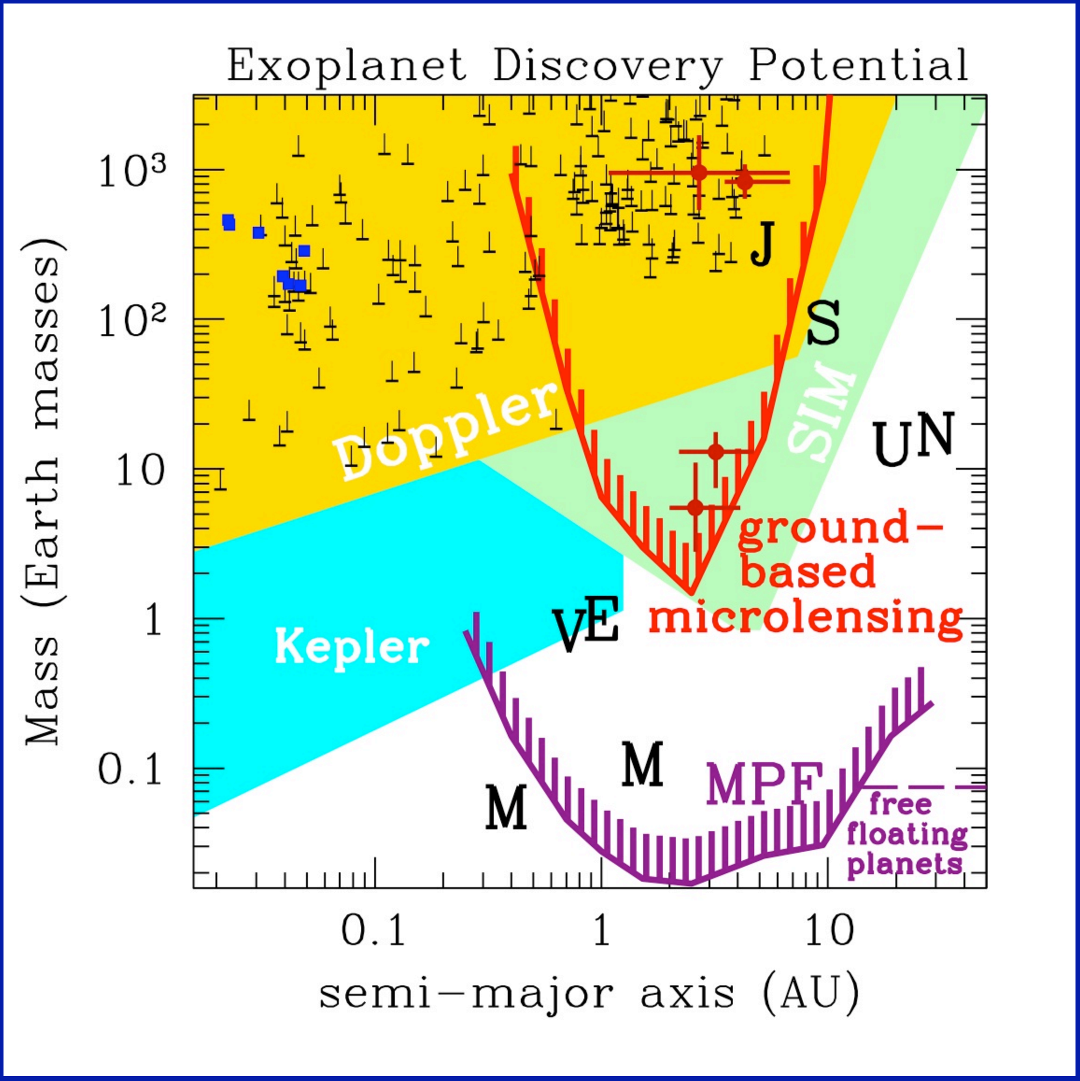


The light curves of simulated planetary microlensing events.

The lens star is brighter for each of these events.

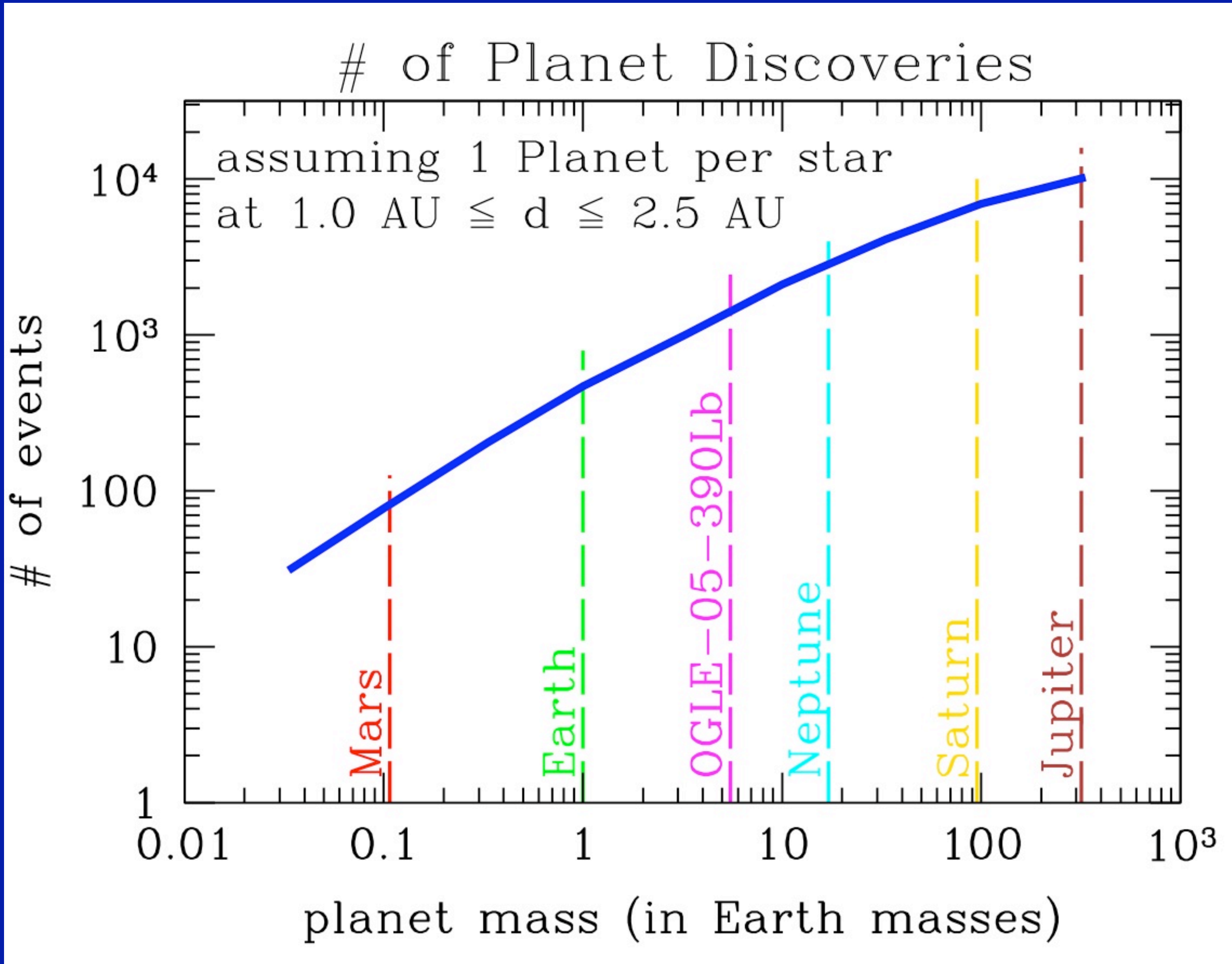
Planet Detection Sensitivity

- Sensitivity to all Solar System-analogs except Mercury
- most sensitive technique for a ≥ 0.5 AU
- Good sensitivity to "outer" habitable zone (Mars-like orbits) where detection by TPF is easiest
- Assumes $\Delta\chi^2 \geq 80$ detection threshold
- Can find moons and free floating planets

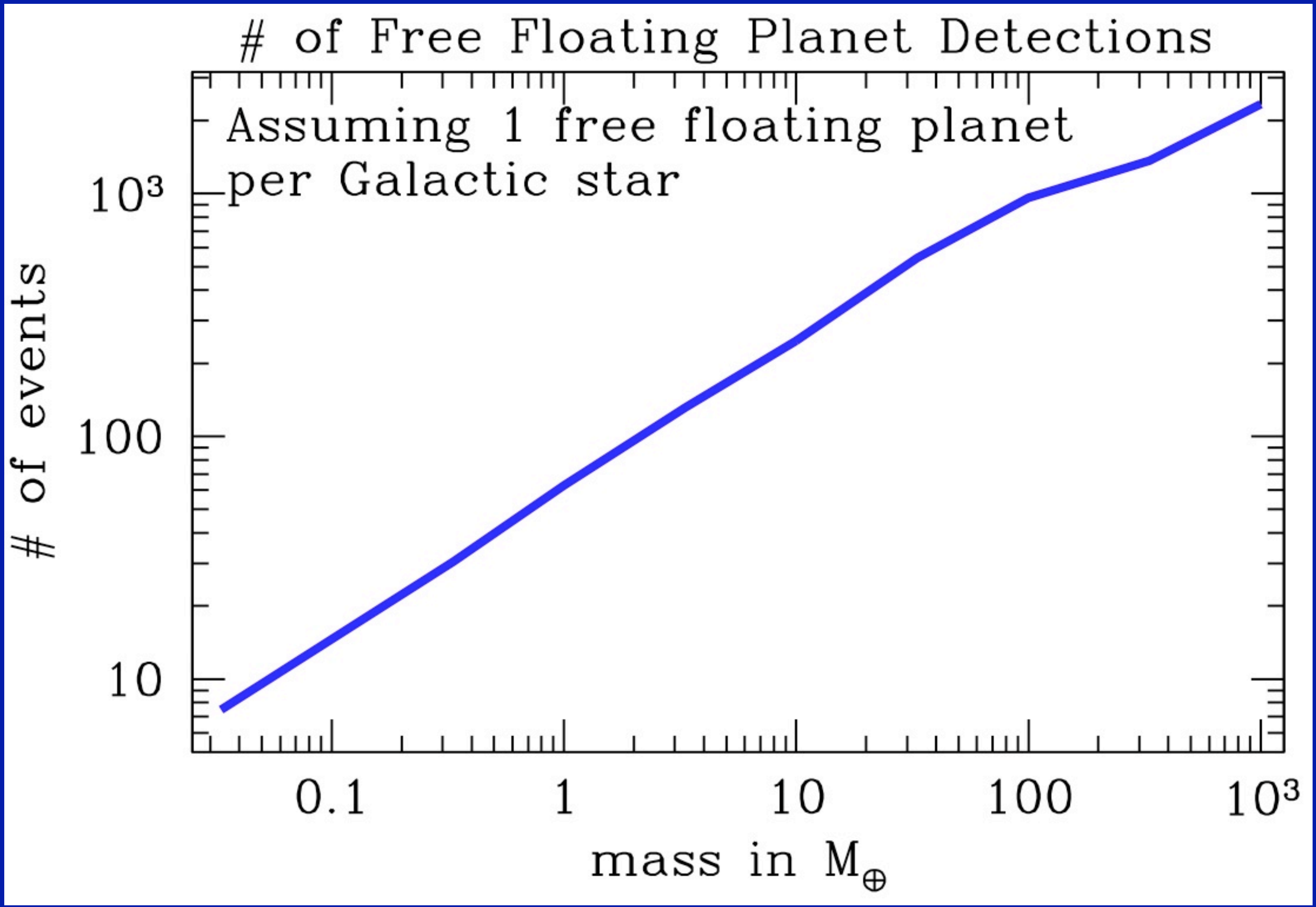


Updated from Bennett & Rhie (2002) ApJ 574, 985

MPF Discoveries

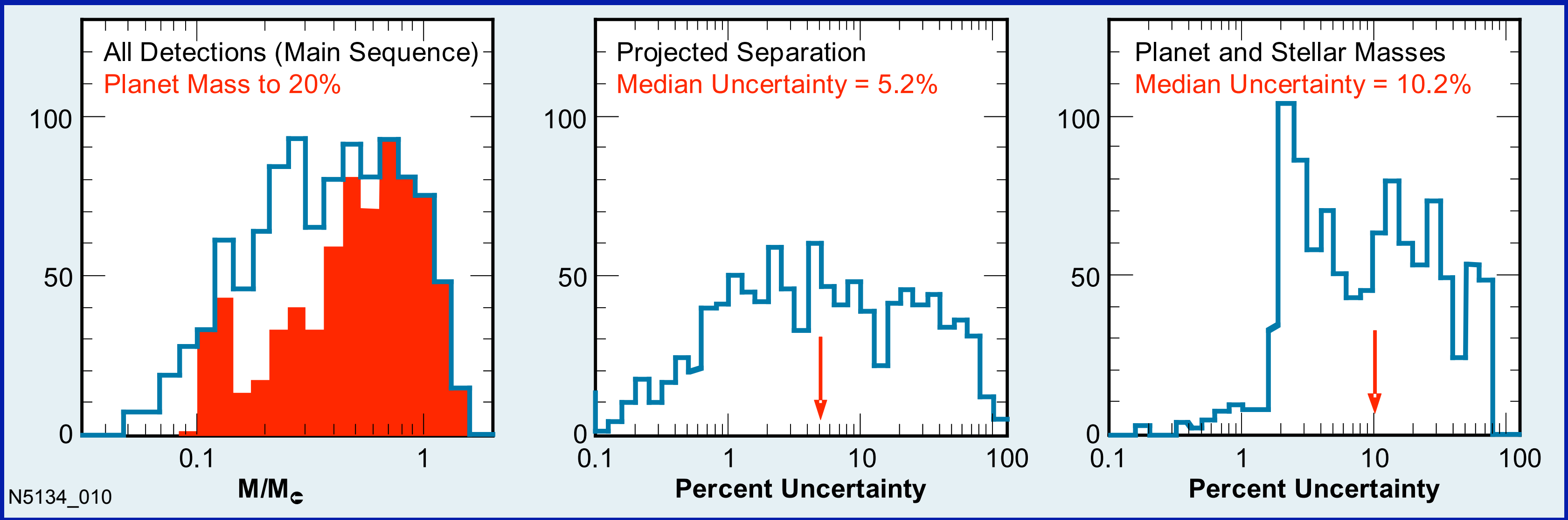


Free Floating Planets



Planet formation theories generically predict many free-floating planets
(Goldreich et al. 2004, Juric & Tremaine 2007, Ford & Rasio 2007)

Lens Detection Provides Accurate Mass Estimate



- Lens will be detected for the majority of main-sequence lenses.
- Host star masses will be measured to 10% for half of the event.
- Projected separations will be measured to 5% for half of the events.

MPF will tell us..

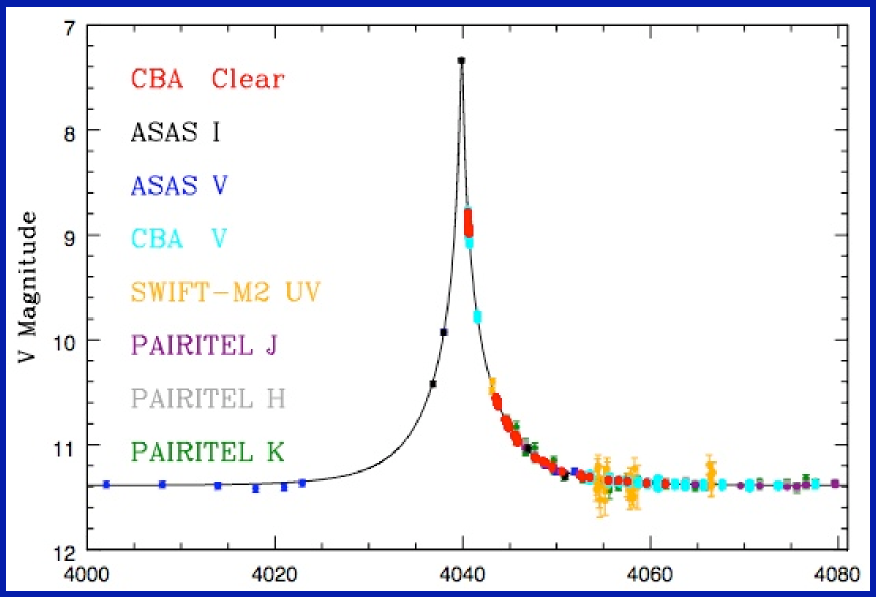
- Frequency of planets as a function of
  - –mass down to $M_{mars} = 0.1M_{\oplus}$
  - –separation from ~0.5 AU to ∞
  - –host star mass from $0.1M_{sun}$ to 1 M_{sun}
  - –Galactocentric distance from ~1-8 kpc (disk & bulge)
- Frequency of free-floating planets down to M_{mars}
- In other words,

MPF will tell us the frequency of almost every kind of planet that has been detected or predicted.

Future Directions

Domestic μLensing Events

- First event detected accidentally
- Should be 8/year within 4kpc
- Could be found with a fly's eye setup ~$5M



(Gaudi et al 2007)

Extragalactic Planets?

- Could be detected in M31
- Relatively minor modifications to current strategy

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Cost to the Community

- Next generation ground-based survey
  - One telescope in South Africa would get things started
  - Cost ~$4 M (hardware, site costs, labor)

- MPF fits comfortably under the Discovery cost cap ~$400M

A Census of Planetary Systems

Understand planet formation and habitability requires a census of planets of all masses and Separations, orbiting stars of all masses.

•Kepler will provide such a census for a <0.5AU

•Microlensing is the only method that can do this for larger separations.