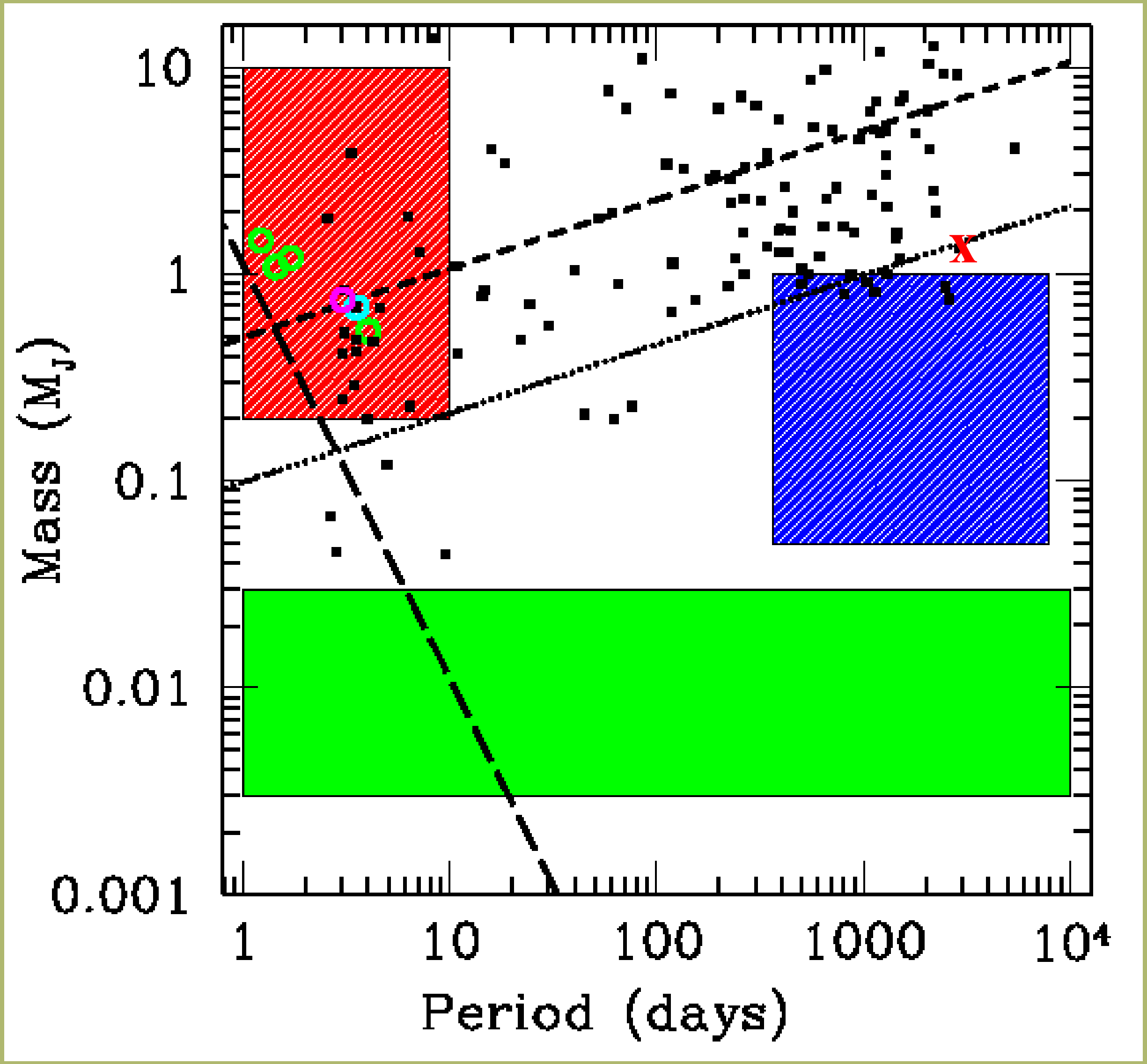
Hot Jupiters Cool Neptunes & Extrasolar Earths

Topics in the Search for Extrasolar Planets

Korean Astronomical Society Meeting, April 22, 2005
Scott Gaudi
Harvard-Smithsonian Center for Astrophysics

Extrasolar Planet Surveys



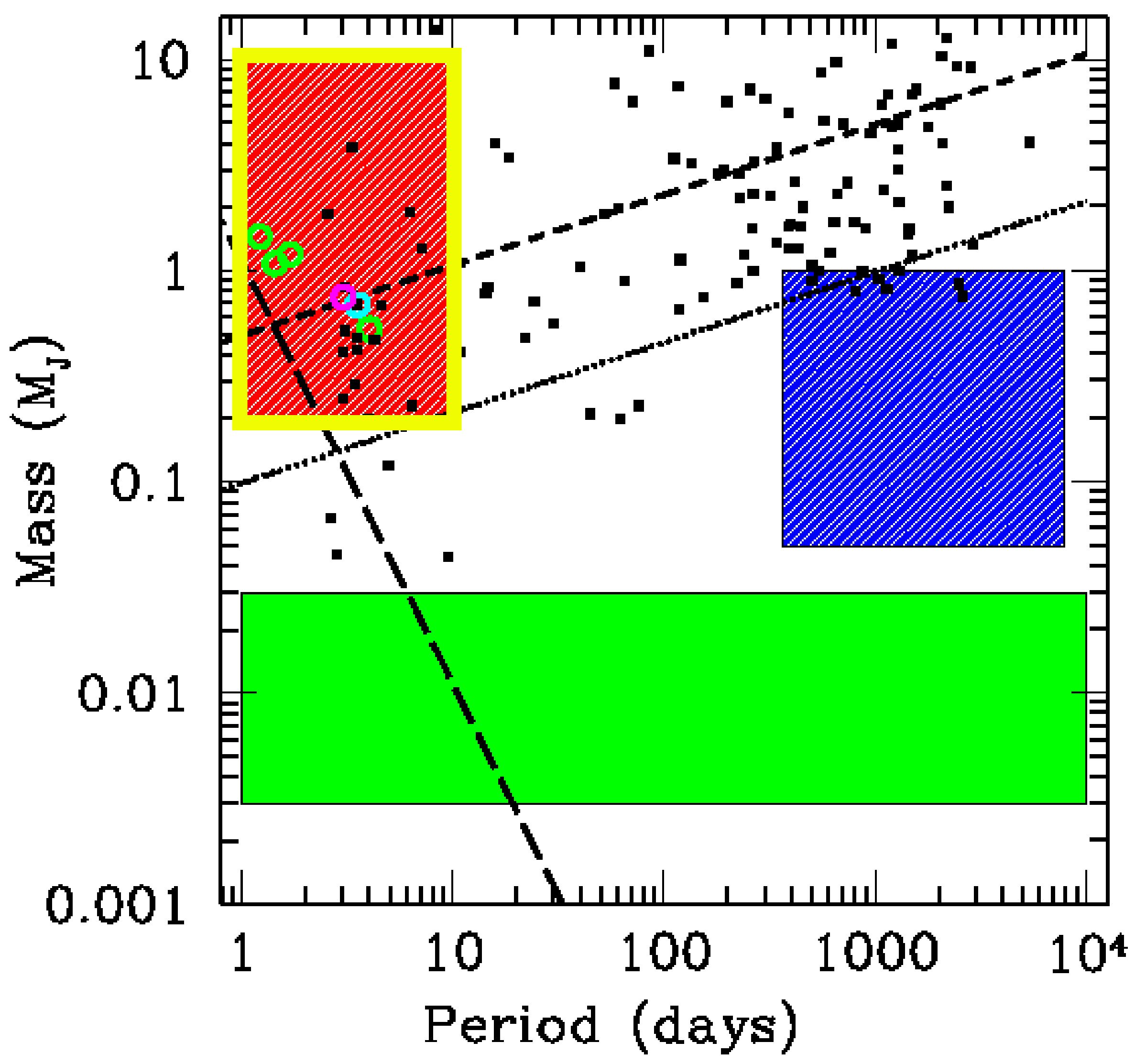
~150 Planets Found

Radial Velocity, Transits, and Microlensing

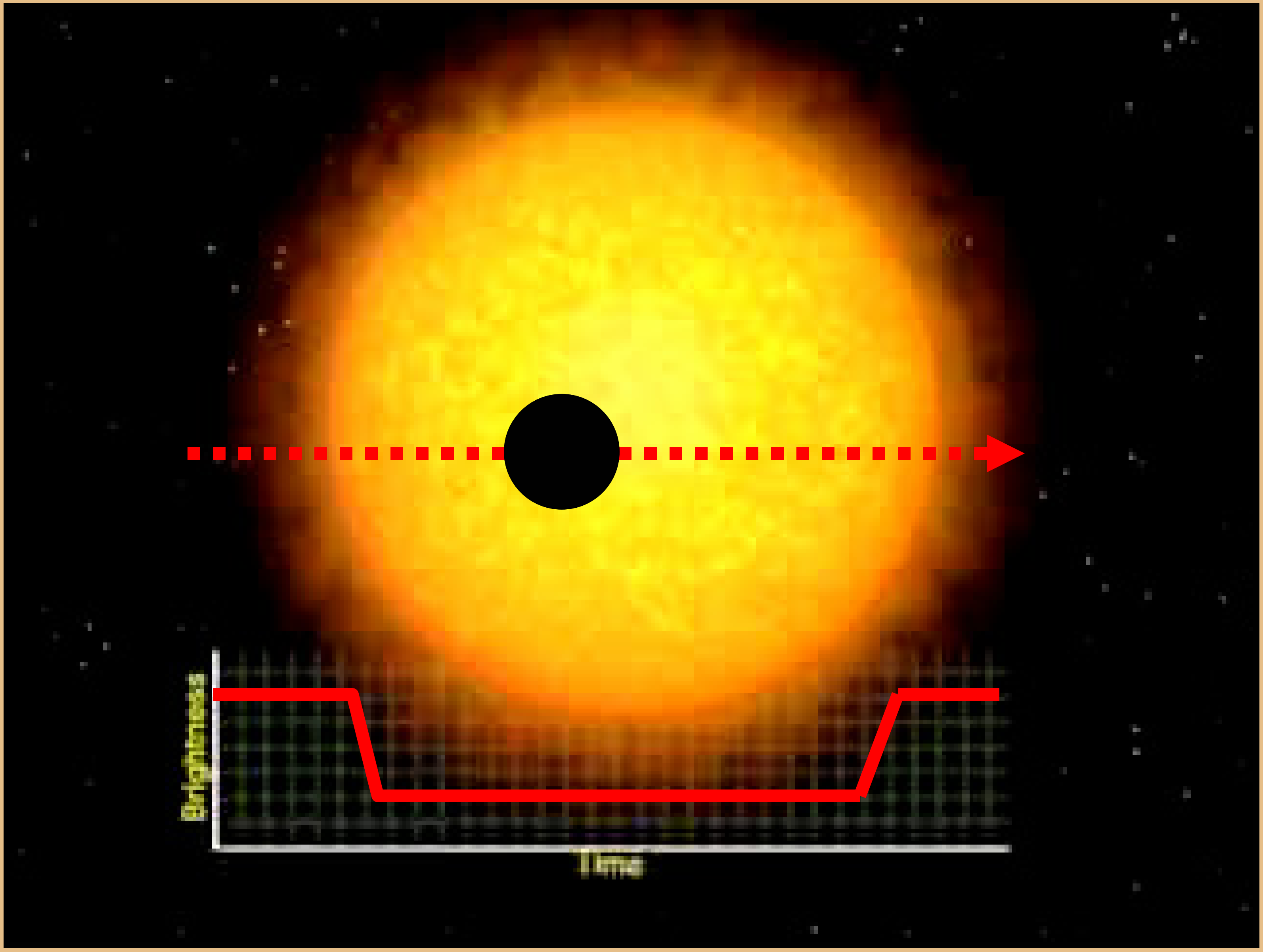
Hot Jupiters

(and Very Hot Jupiters)

Sara Seager (DTM), Gabriela Mallen-Ornelas (CfA)



10
1
0.1
0.01
0.001
Mass (M_J)
1
10
100
1000
10^4
Period (days)


Brightness
Time

Transits – Requirements

- Detection
  - Many Stars
    - Frequency ~1%, Transit Probability ~10%
  - Accurate Photometry
    - Depth < 1%
  - Lots of Observing Time
    - Strong aliasing effects
- Confirmation and Parameter Estimation
  - Accurate Light Curves
    - Precision ~ 0.1%
  - Follow-up
    - Spectroscopic
    - Radial Velocity

Transits – Flavors

Bright Targets

- RV Follow-up
- All-Sky/Large FOV

$$V \leq 14$$

Amenable to Follow-up

(RV, Oblateness, Atmospheres, Rings, Moons, etc.)

Faint Targets

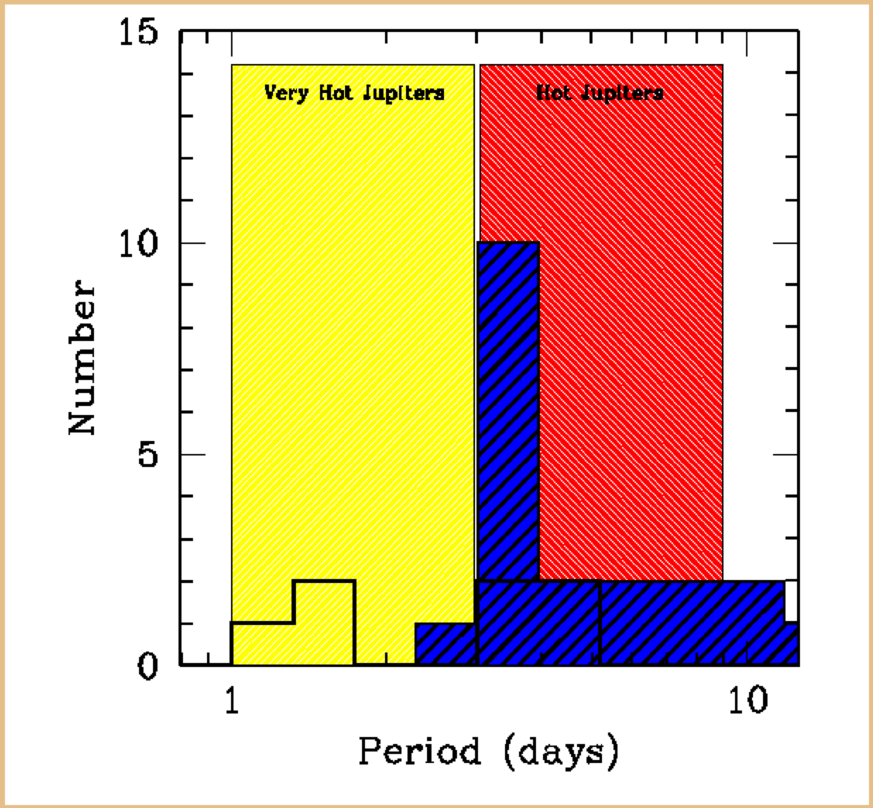
- Field Stars (Galactic Disk)
- Clusters

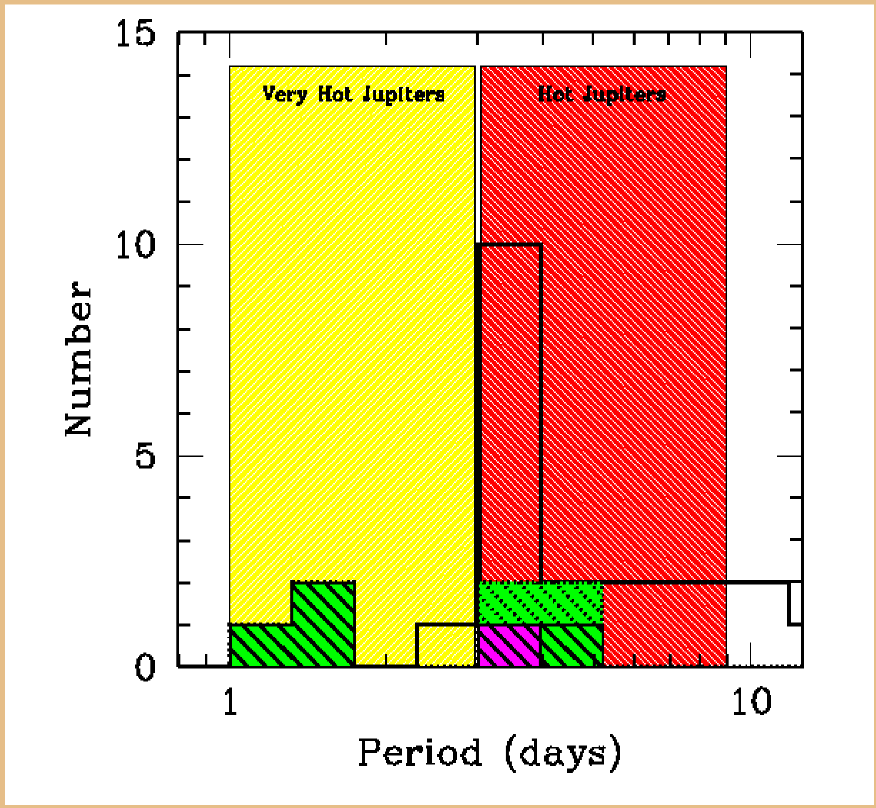
$$V \geq 14$$

Not Amenable to Follow-up

Primaries *too faint* for detailed study ⟹ Masses, Radii, Periods only.

→ Statistics





Radial Velocity Surveys

Transit Surveys

~150 Planets Found
Pile-up at P ~ 3 days
Shortest Period P = 2.55 days
VHJ:1, HJ:15

6 Planets Found (OGLE and TrES)
Discovered Very Hot Jupiters
P ~ 1 day
VHJ:3, HJ:2

Radial Velocity Surveys vs. Transit Surveys

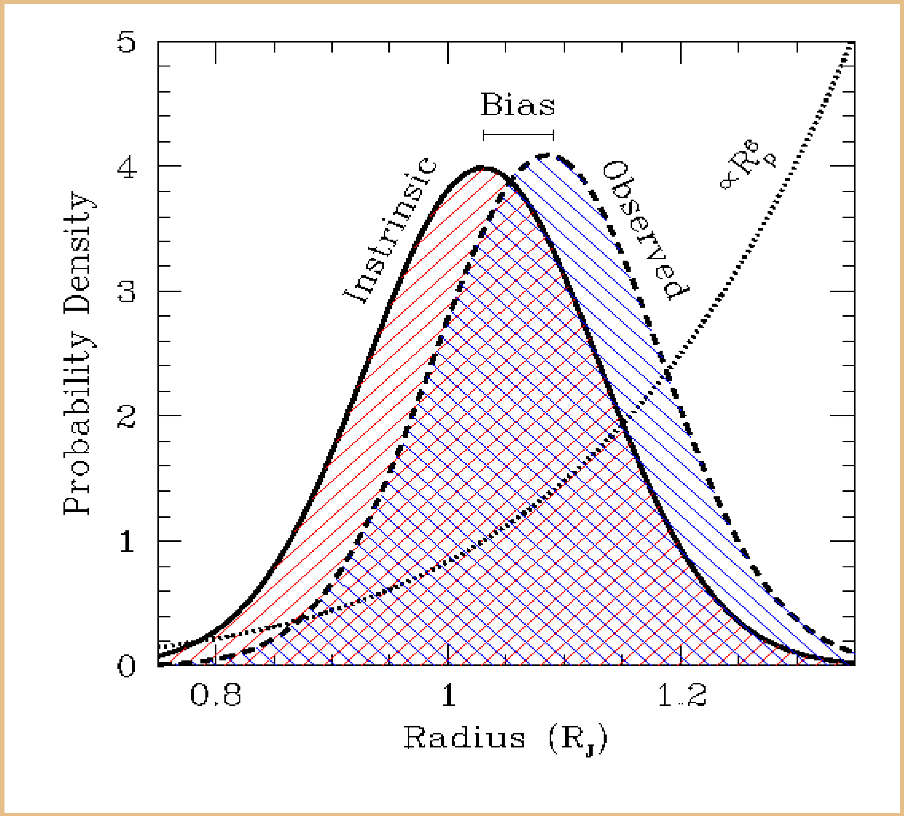
- Inconsistent?
  - Selection effects:

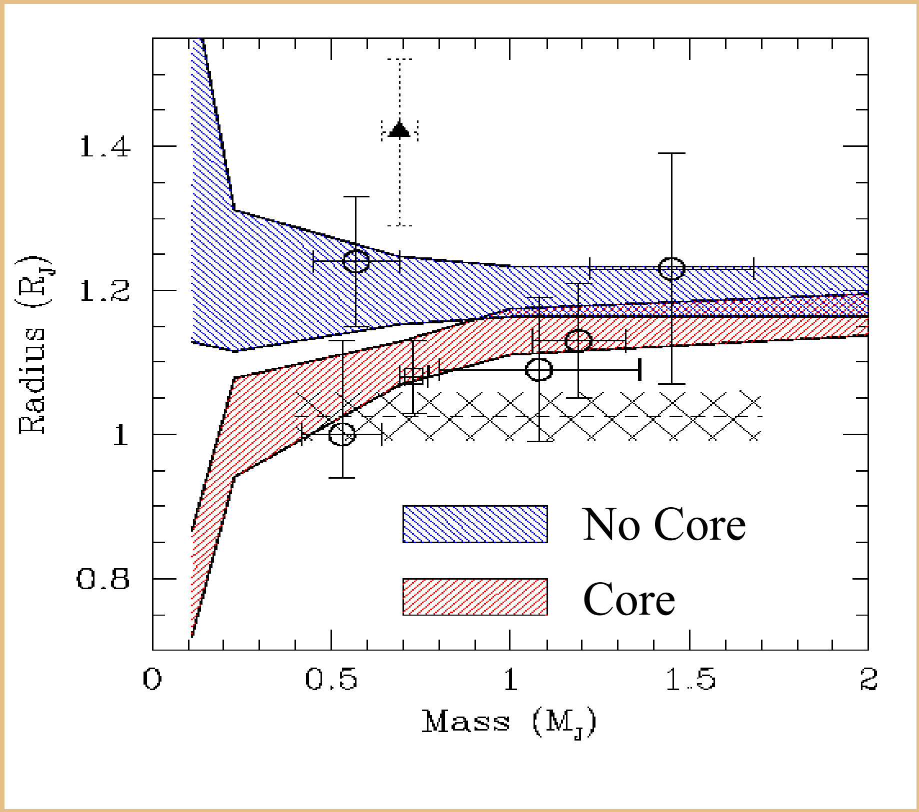
$$N \propto R_p^6 P^{-5/3}$$

  - RV: $\mathrm{VHJ/HJ} = 0.07^{+0.09}_{-0.04}$
  - TR: $\mathrm{VHJ/HJ} = 0.25^{+0.55}_{-0.12}$

- RV and TR surveys consistent at ~ 1 sigma
- Relative Frequency of VHJ to HJ is ~10-20%

Planetary Radii





$$\left\langle R_p \right\rangle \approx (1.03 \pm 0.03) R_J$$

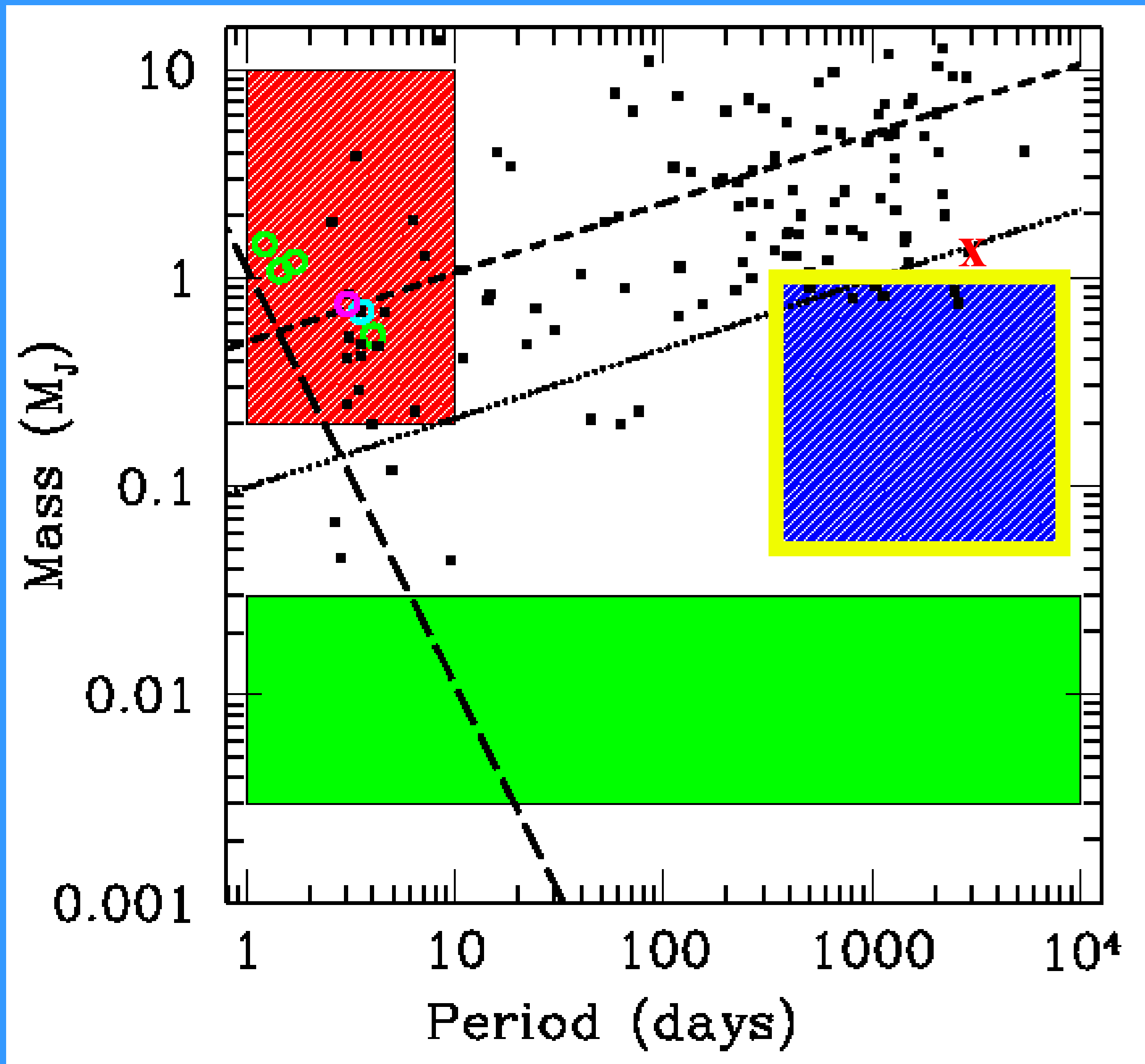
What do we know about Hot Jupiters?

- One in ~100 FGK Stars has a HJ
- One in ~500-2000 FGK Stars has a VHJ
- Pile up at ~3 days?
- Typical radii ~ Jupiter radius
- HD209458b anomalously large
- Most HJ have massive cores?

Cool Neptunes

(or, How to Find Planets with Microlensing)

μFUN Collaboration



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0.01
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Mass (M_J)
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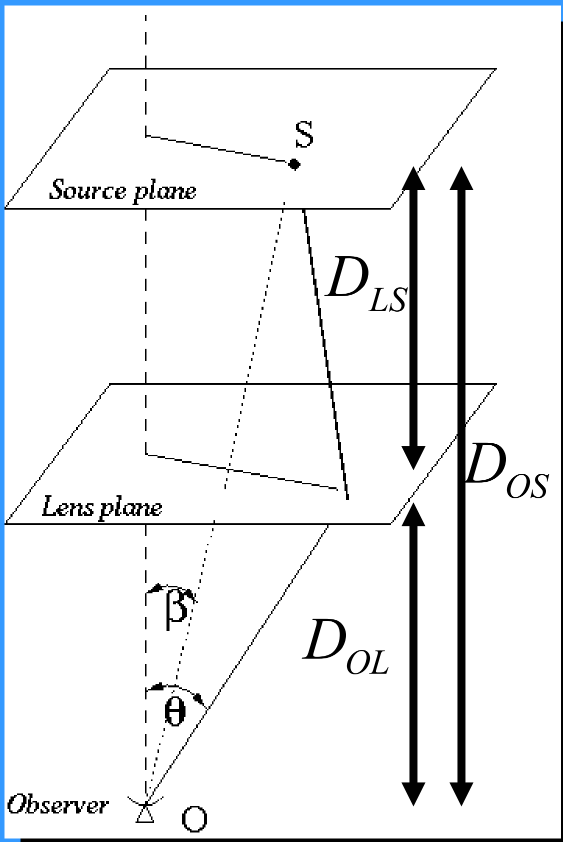
10^4
Period (days)
x

Microlensing and Planets



$$\vec{\beta} = \vec{\theta} - \vec{\nabla}\psi$$

(Lens Equation)

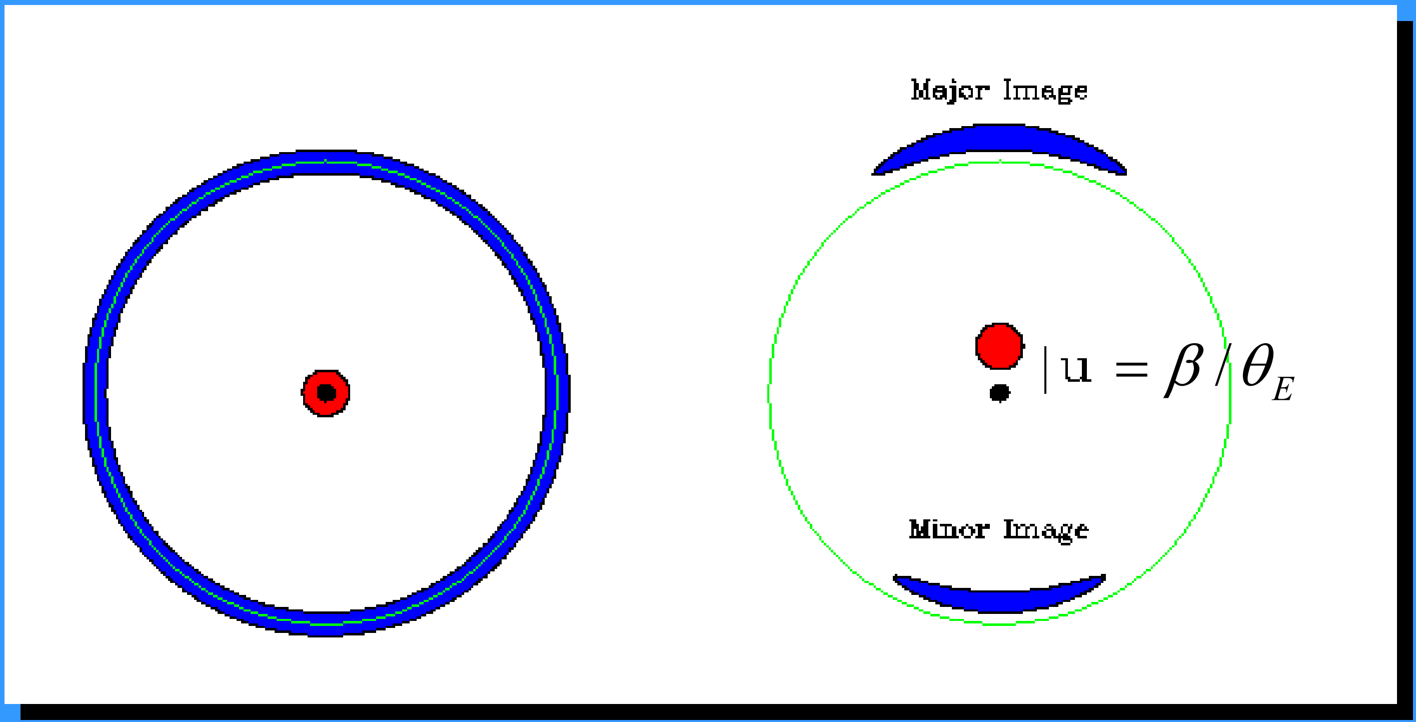
$$\beta = \theta - \theta_E^2 / \theta$$

(Point Lens)

$$\theta_E^2 = \frac{4GM}{c^2} \frac{D_{LS}}{D_{OL} D_{OS}}$$

(Einstein Ring Radius)

Microlensing and Planets



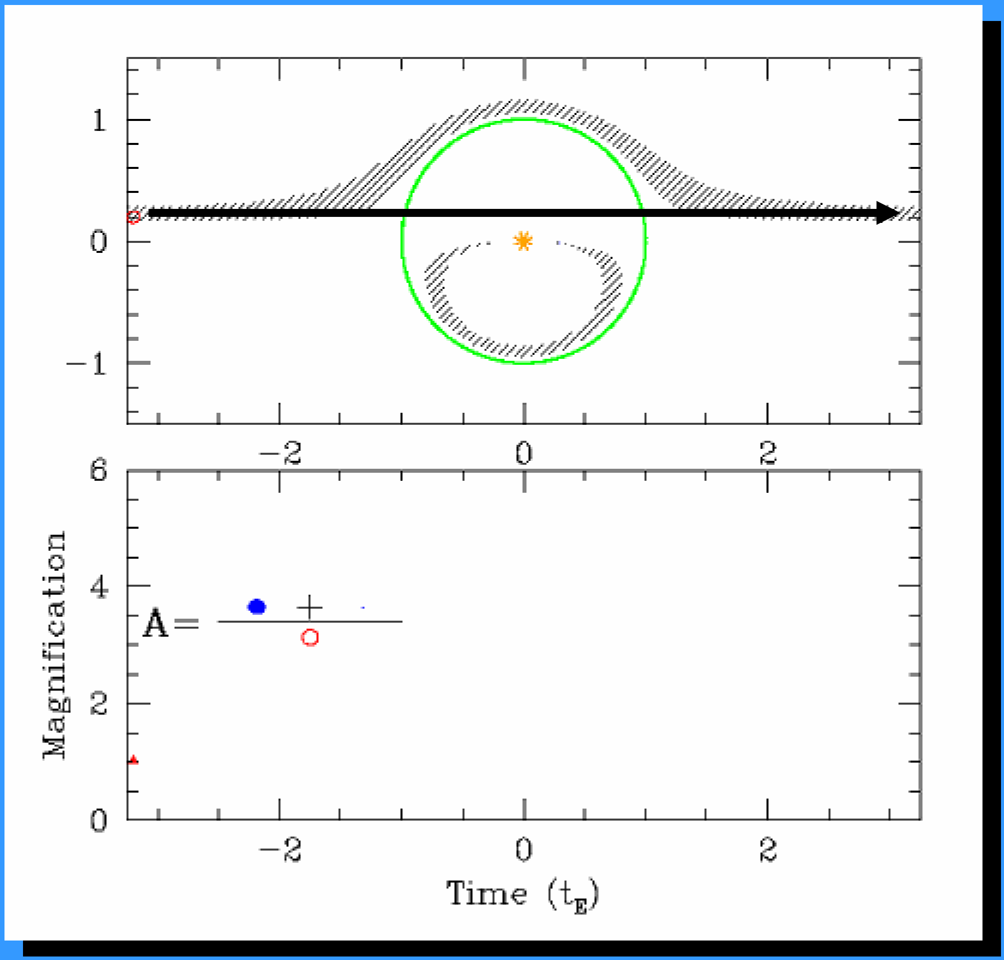
$$\beta = \theta - \theta_E^2 / \theta$$

If: $\beta = 0$ **Then:**

$$\theta = \theta_E = 0.3\text{mas}\left(\frac{M}{0.3M_{Sun}}\right)^{1/2}$$

If: $\beta \neq 0$ **Then:**
two images.

Microlensing and Planets



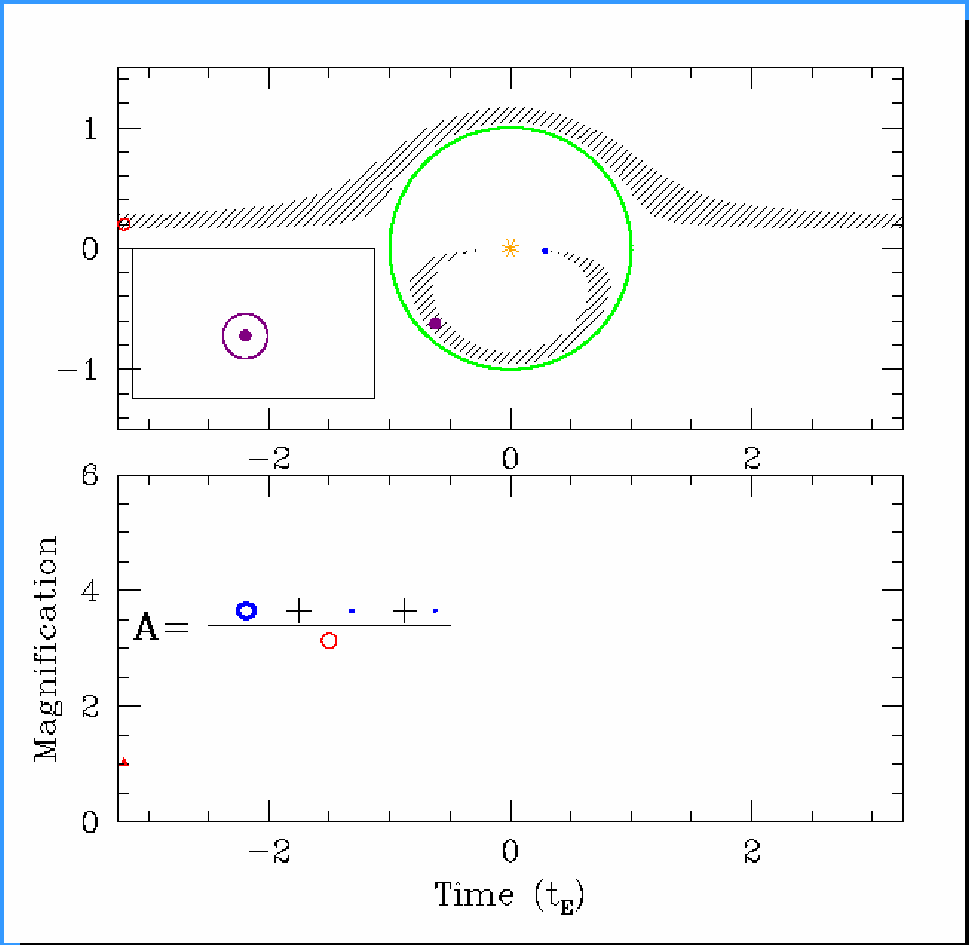
Single Lens Parameters:

- Impact parameter
- Time of Maximum Mag.
- Timescale

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

Idea: Paczynski 1986,
LMC: Alcock et al 1993,
Aubourg et al 1993,
Bulge: Udalski et al 1993

Microlensing and Planets



Single Lens Parameters:

- •Impact parameter
- •Time of Maximum Mag.
- •Timescale

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

Planet Parameters:

- •Angle wrt Binary Axis
- •Angular Separation θ_p
- •Mass Ratio - q

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

Maximized at $\theta_p \approx \theta_E$

Microlensing and Planets

Advantages:

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

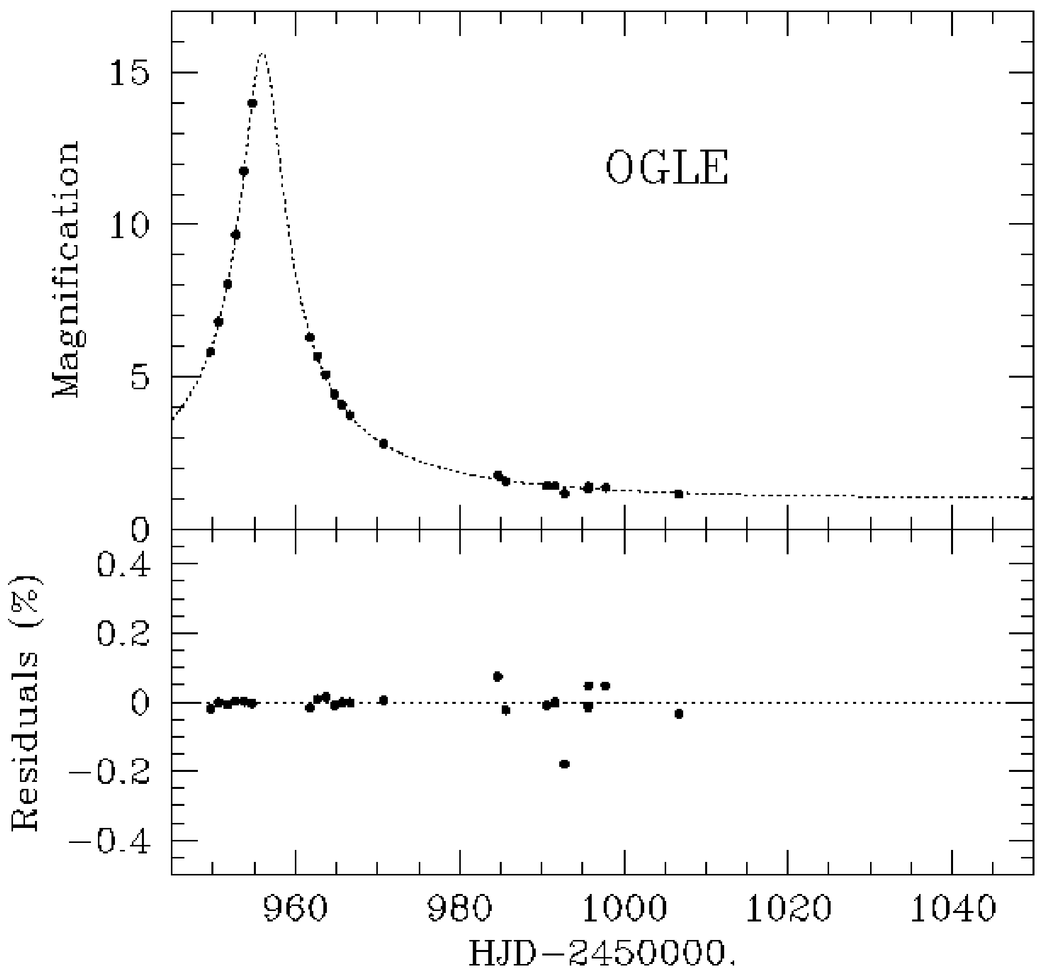
Disadvantages:

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

Basic Requirements:

- Nearly Continuous Sampling.
- Good Photometry for Detection.

Alerts and Follow-up



Optical Depth to μlensing

$$\tau \approx (\sigma / c)^2 \approx 10^{-6}$$

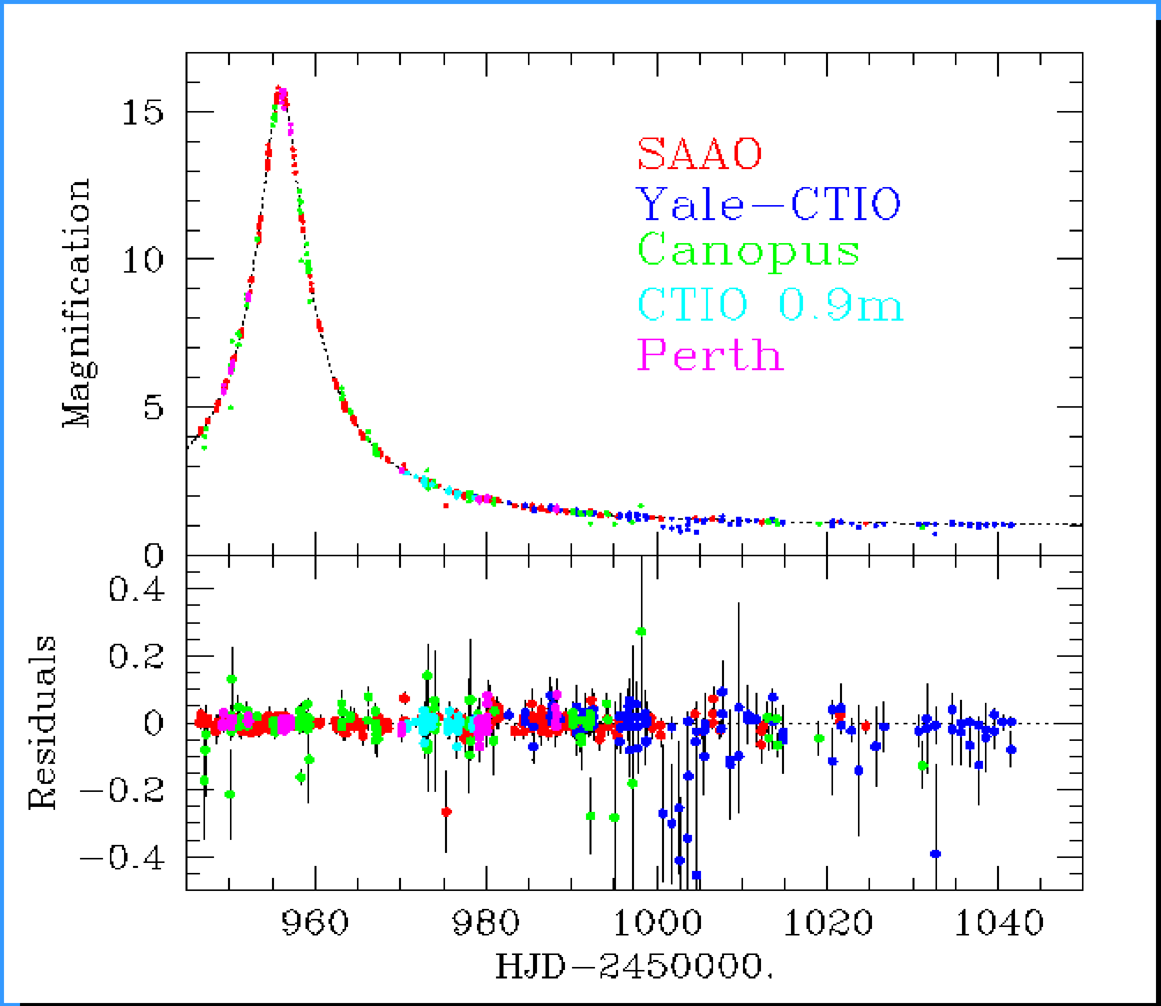
"Survey" Collaborations

- Insufficient Sampling
- Real-time Alerts

Current Alerts

- MOA (~75 per year)
- OGLE III (~500 per year)

Alerts and Follow-up



Follow-up Collaborations

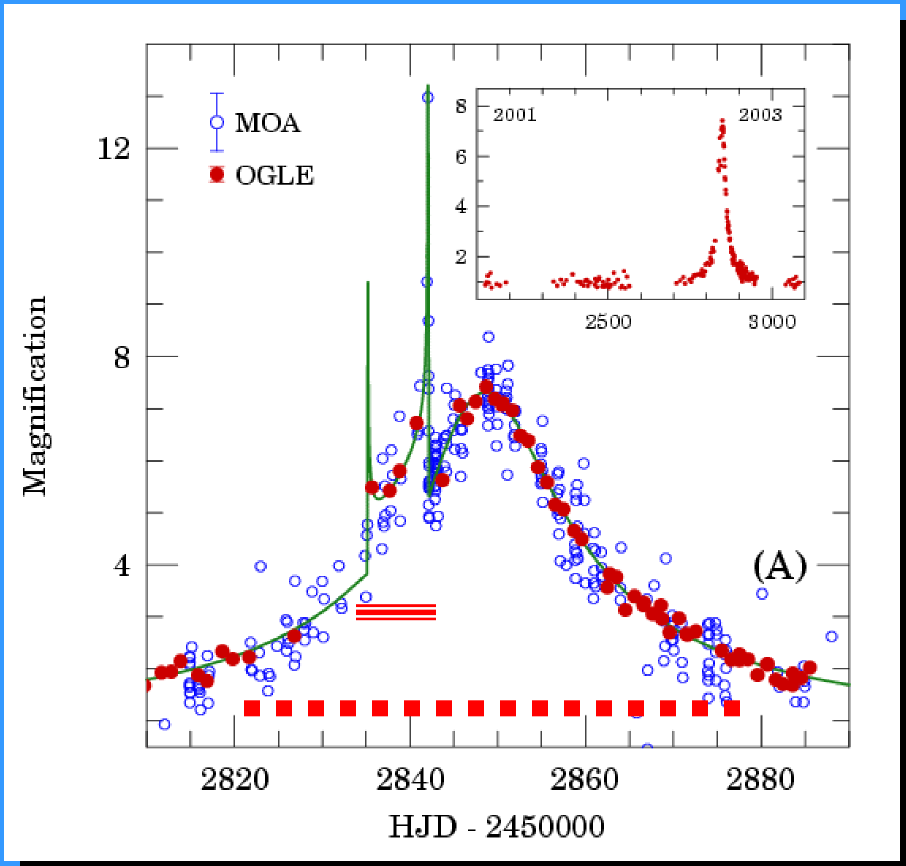
- High Temporal Sampling
- Good Photometry

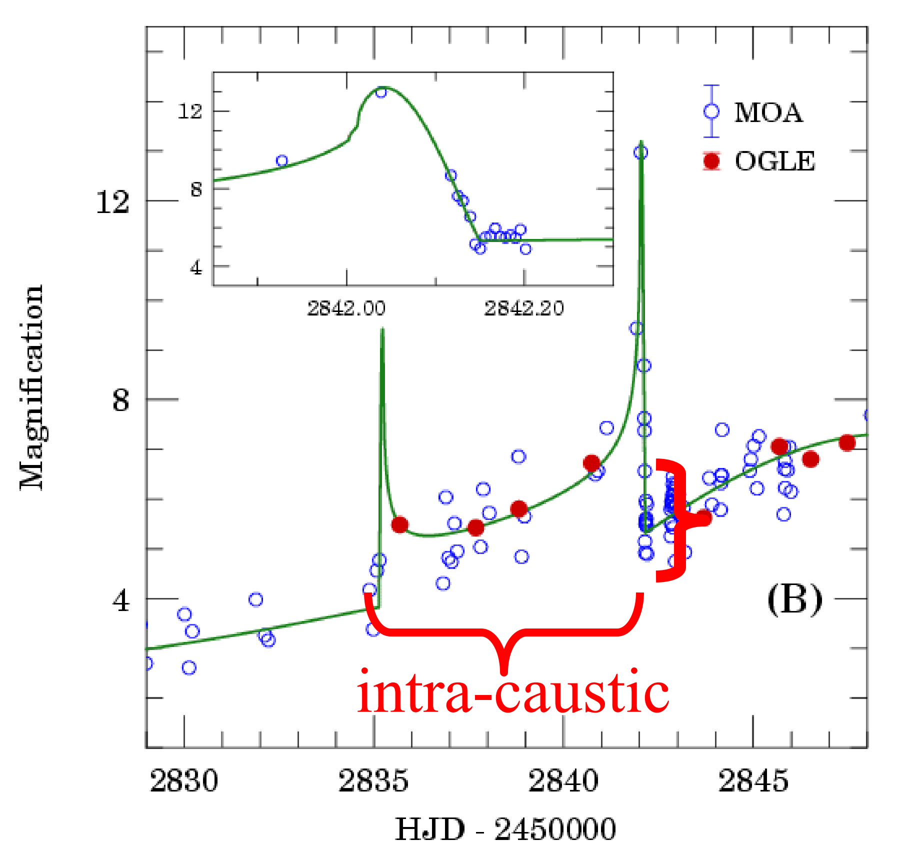
Current Collaborations

- EXPORT (12 events) (Tsapras et al. 2002)
- MOA (30 events) (Bond et al 2002)
- MPS (50 events) (Rhie et al. 2000)
- PLANET (100+ events) (Albrow et al. 1998)
- µFUN (50 events) (Yoo et al. 2003)

OGLE-2004-BLG-235/MOA-2004-BLG-53

(Bond et al. 2004, ApJ, 606, L155)





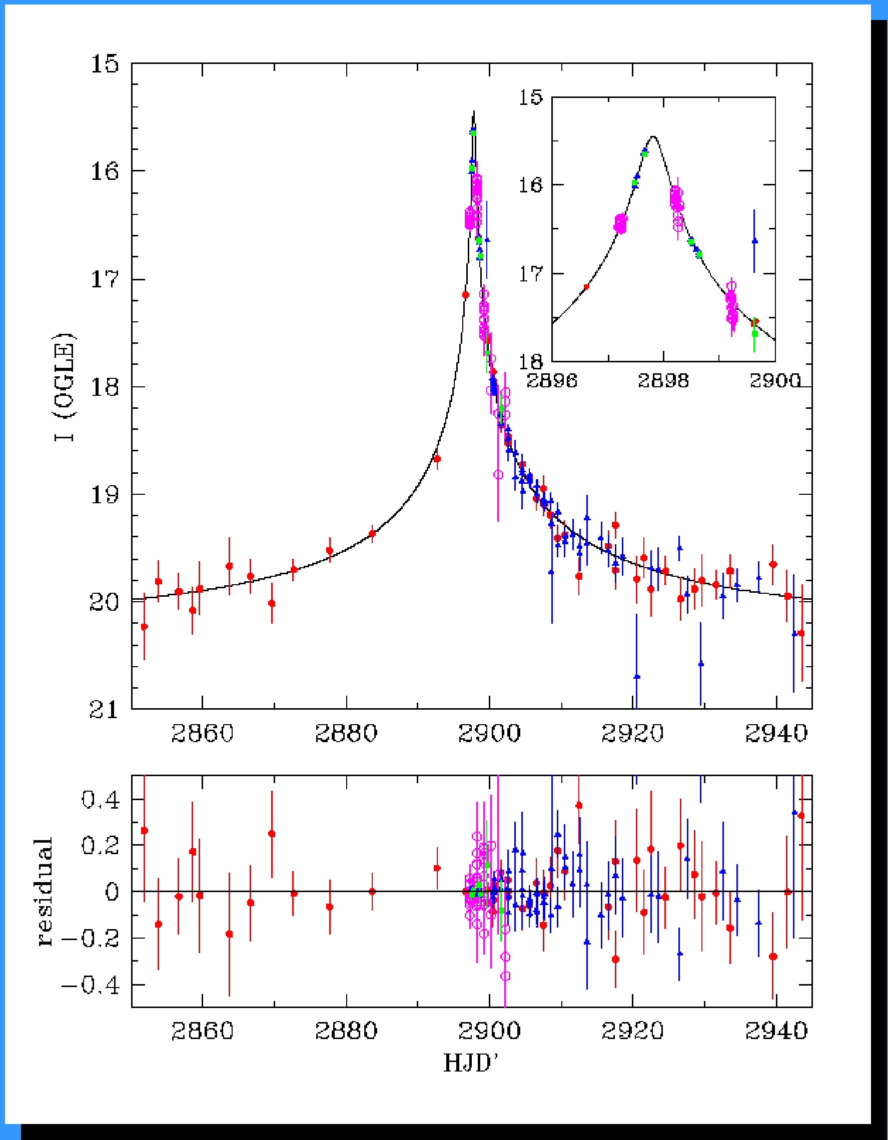
MOA + OGLE Collaborations

$$q \approx 4\times10^{-3}, \theta_p \approx \theta_E \;\rightarrow\; M \approx 1.5 M_J, a \approx 3\text{AU}$$

$$f \approx (1-10)\%$$

OGLE III and μFUN

(Yoo et al. 2004)



Microlensing Follow-Up Network (μFUN)

Telescopes:

CTIO 1.3m (ex-2MASS)

Wise 1m

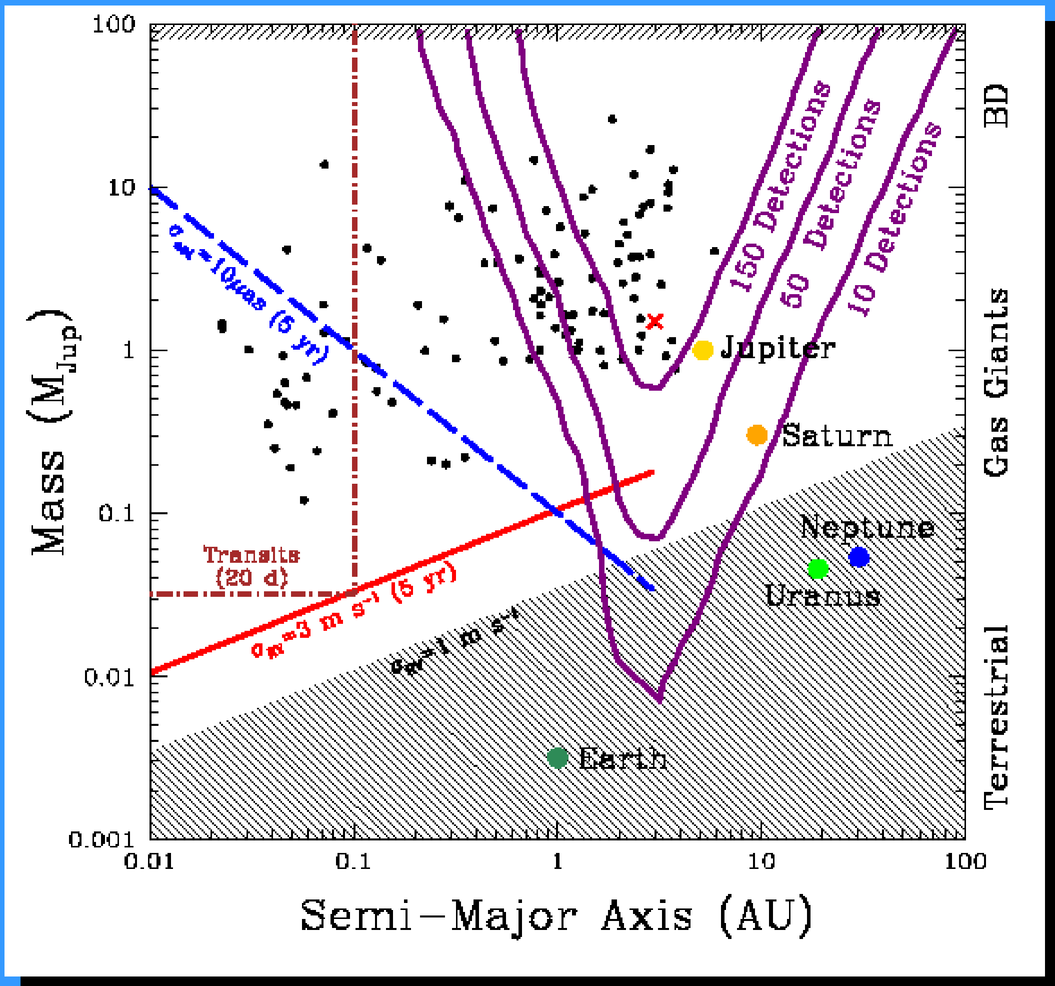
OGLE III

Example lightcurve:

OGLE-2003-BLG-423

•Magnification ~ 250!

OGLE III and μFUN



Microlensing Follow-Up Network (μFUN)

Telescopes:

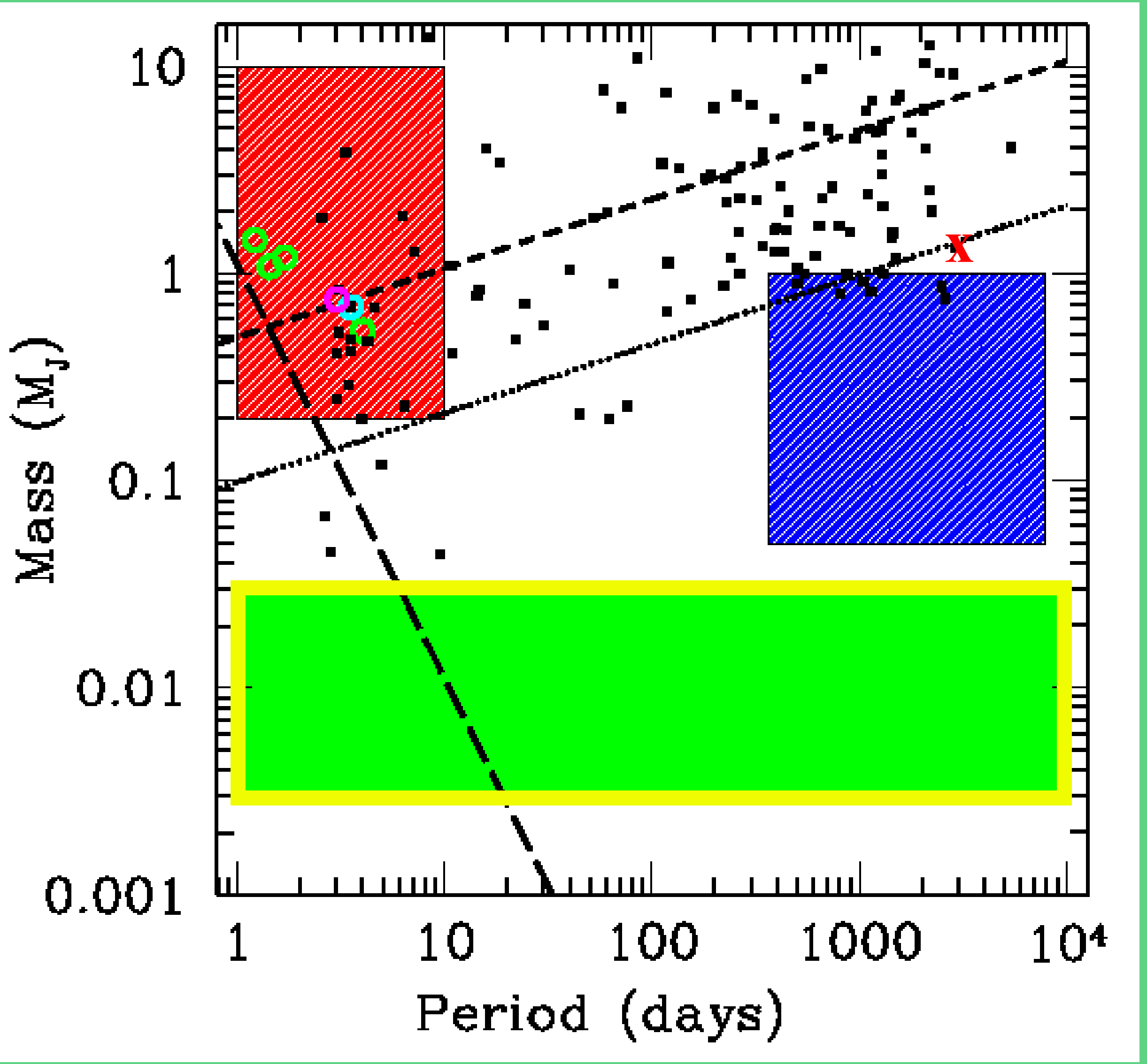
CTIO 1.3m (ex-2MASS)

Expected Results:

- 96 magnification >10 events per year
- Each for 8 hours, over 6 nights near peak from CTIO
- 3 year campaign

Extrasolar Earths

Andrew Gould (OSU), Cheongho Han (Chungbuk)



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Period (days)
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Earth-mass Planets and Future Experiments

Radial Velocity: *Next Generation Survey?*

• 1 m/s limit?

- hard

+ ground based, flexible,cheap, unlimited observing time, nearby stars (TPF)

Astrometry: *SIM*

• 1 μas limit

- space-based, very expensive, hard to confirm

+ flexible, nearby stars (TPF)

Transits: *Kepler*

- spaced-based, expensive, distant stars, very difficult to confirm

+habitable, simple

Microlensing: *MPF, Ground Based?*

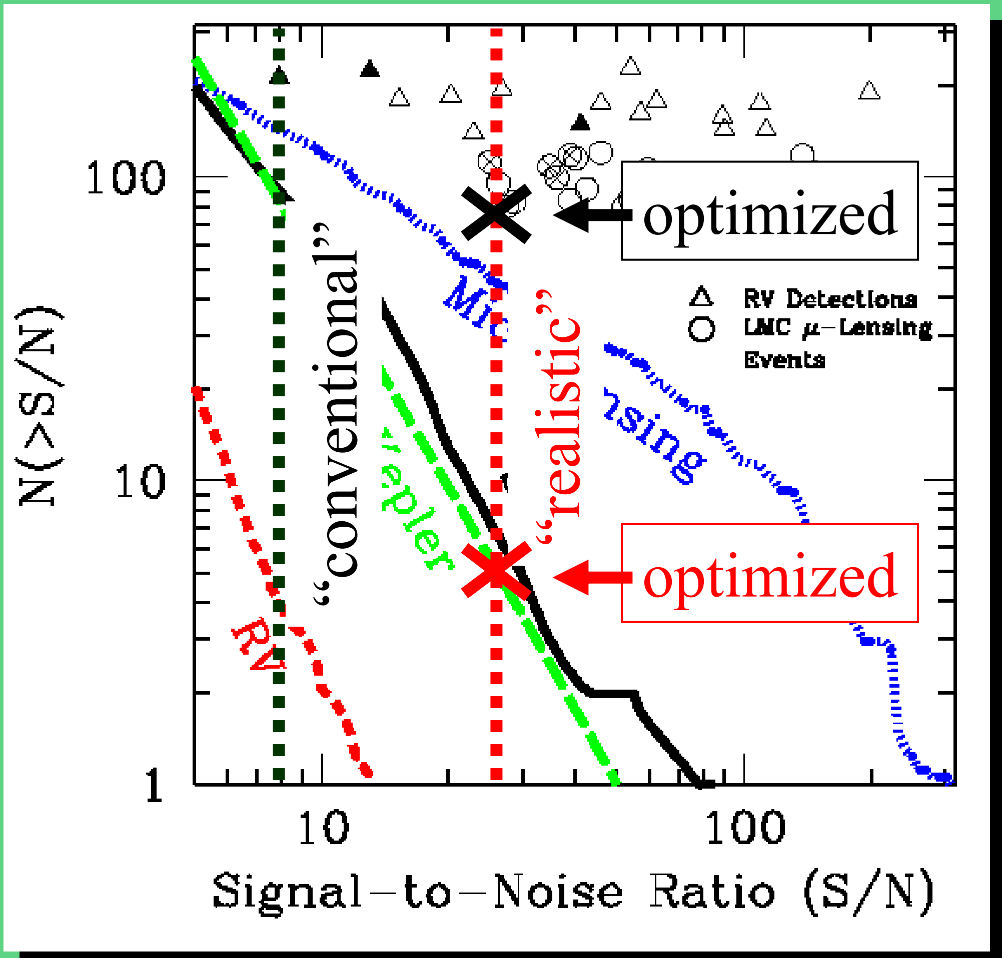
-expensive, distant stars, impossible(?) to confirm

+very low mass planets, robust statistics, many detections

Direct: *TPF, Darwin*

Earth-mass Planets and Future Experiments

Earth-mass planet sensitivities



(Gould, Gaudi, & Han 2004)

Comparison with other methods

- ***SIM:*** P=3yr, 2000 hours over 5 years, σ=1μas.
- ***Kepler:*** Habitable zone, Kepler parameters
- ***RV:*** P=0.5yr, four dedicated 2m telescopes, 60,000 hrs, σ=1m/s
- ***Microlensing:*** a=2.5AU

What S/N threshold?

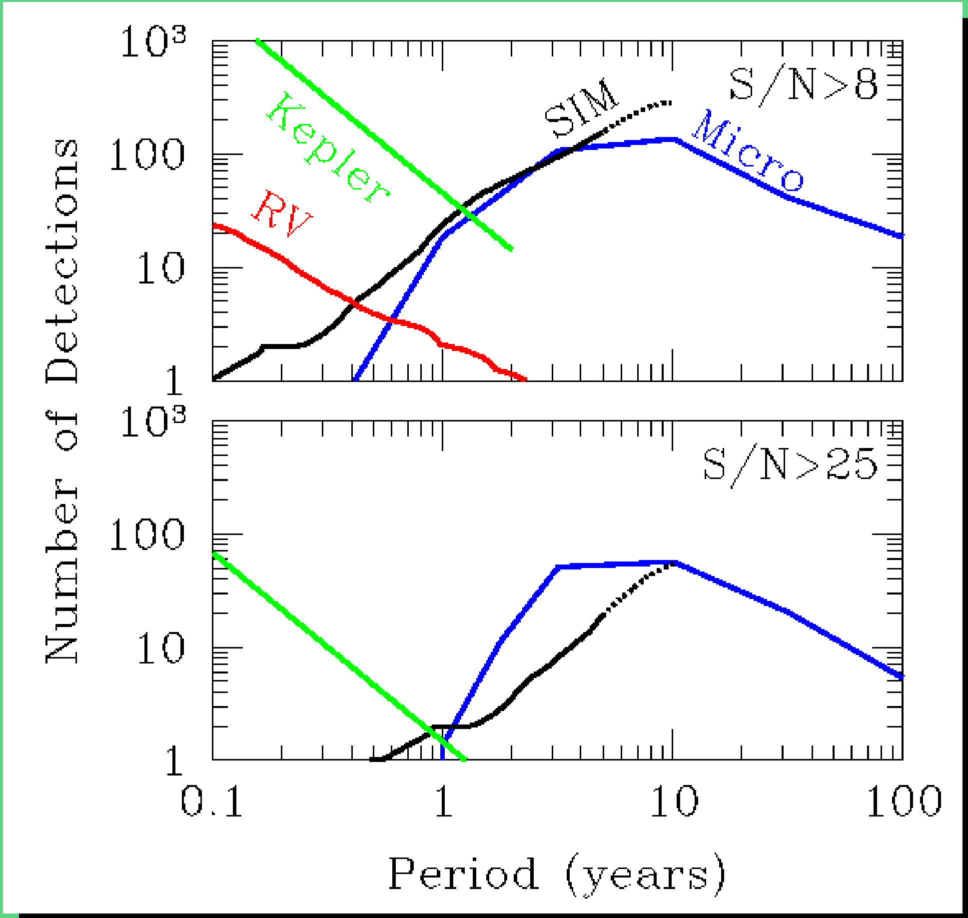
Conventionally: S/N ~ 8

Realistic: S/N ~25

Optimization

Earth-mass Planets and Future Experiments

Earth-mass planet sensitivities



(Gould, Gaudi, & Han 2004)

Comparison with other methods, cont.

•Every star has a Earth-mass planet with period P
•Each technique is confronted with the same ensemble of planetary systems.

Even under *optimistic* assumptions, only ~5 Earth-mass planets with P=1 year detected with S/N > 25!

Efforts can and should be made to ensure and improve these statistics.

Summary

1. RV & TR Surveys consistent

2. VHJ/HJ ~ 10-20%

3. HJ require massive cores?

4. µLensing – sensitive to wide, small mass planets

5. Constrain frequency of "Cool Neptunes" to 10%

6. Strong dependence on S/N threshold

7. Statistics on Earth-Mass planets may be meager