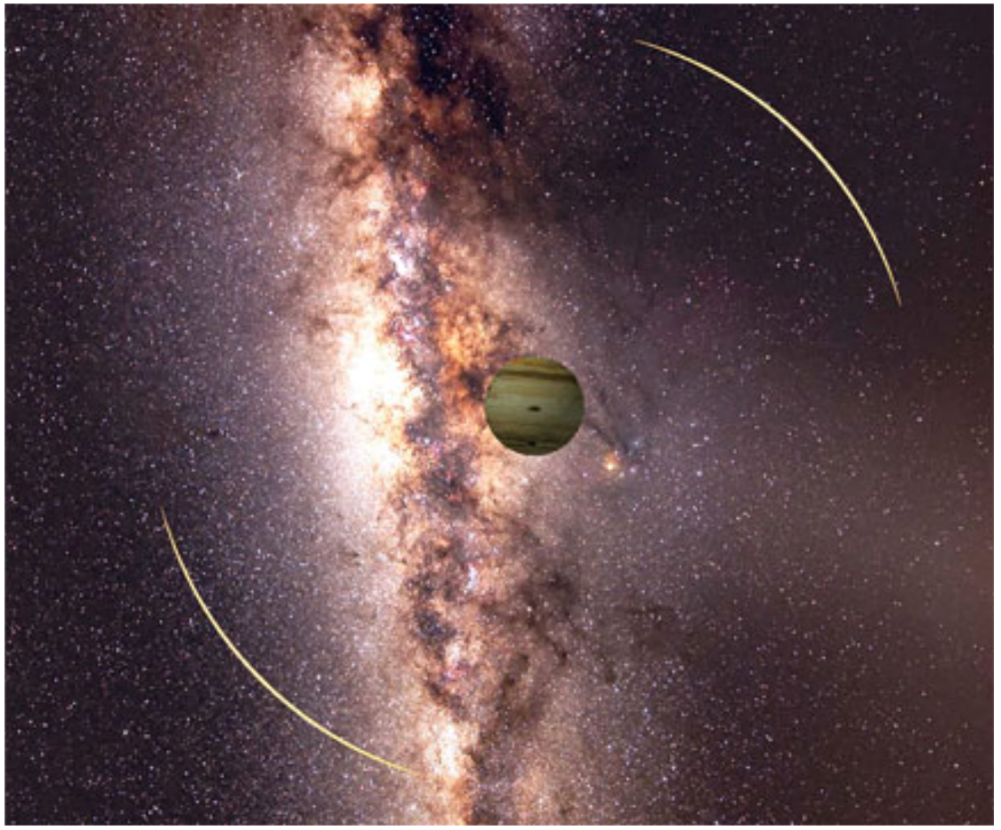
Microlensing Planet Searches & their Selection Effects



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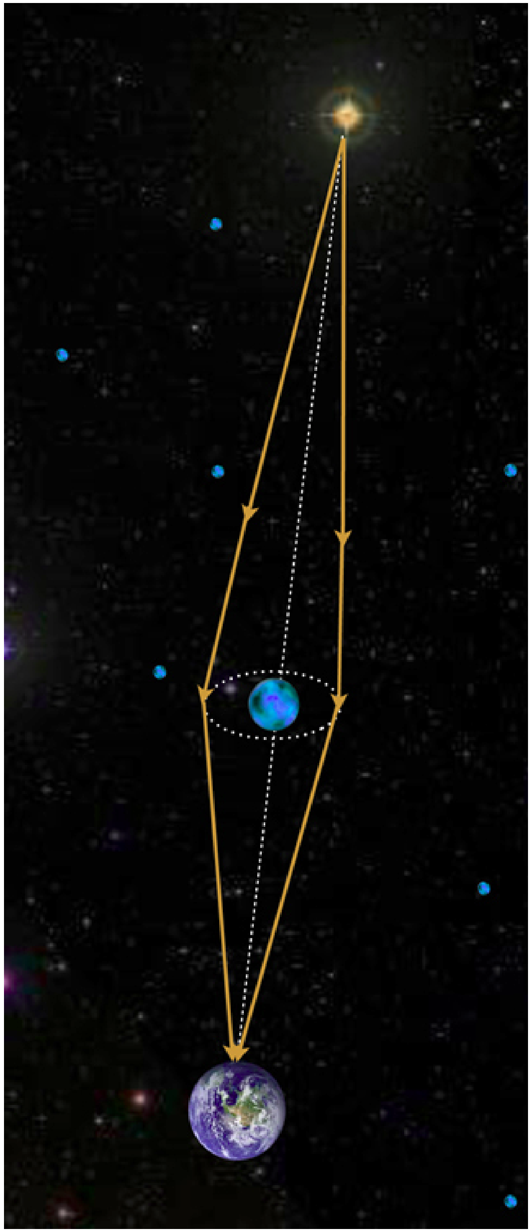
PART 1

Finding Planets with Microlensing

Microlensing Events

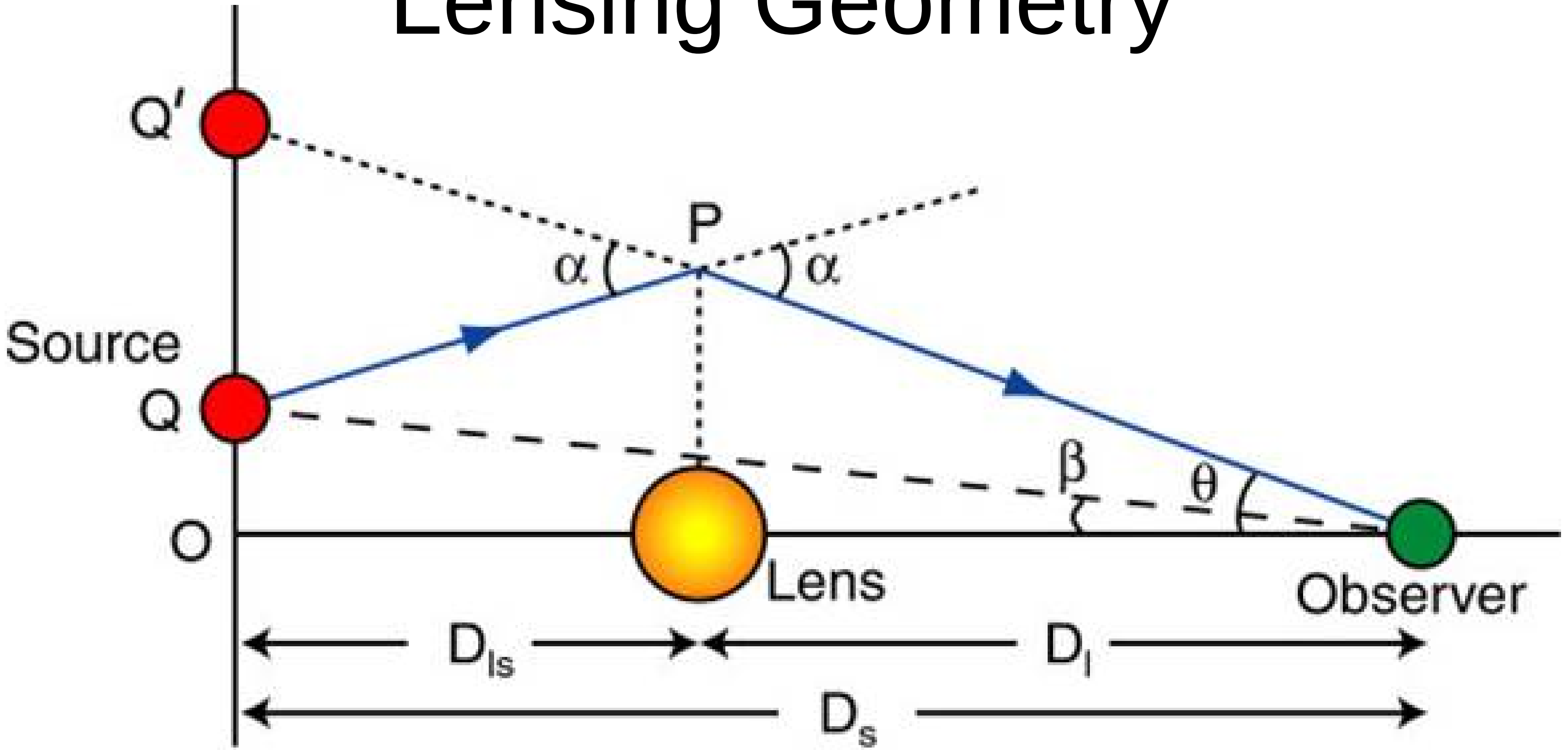


Source

Lens – ***host & its planet(s)***

Observer

Lensing Geometry



Lens equation

$$\beta = \theta - \frac{\theta_E^2}{\theta}$$

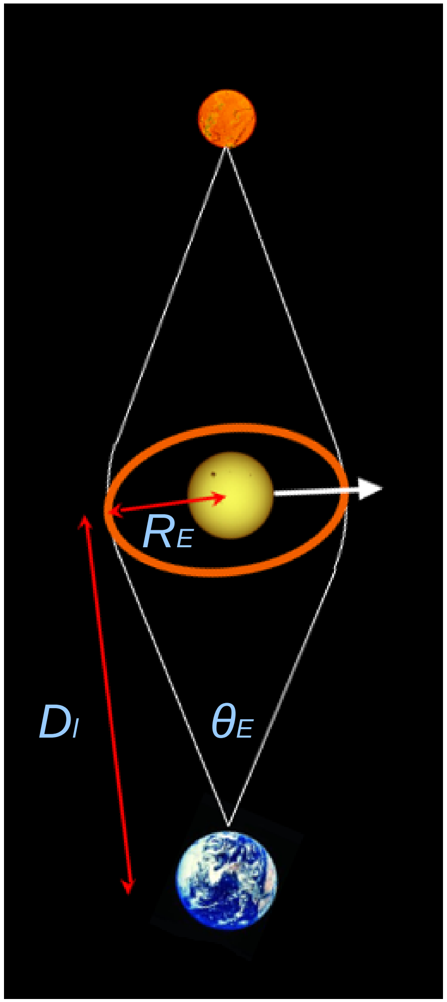
Angular Einstein ring

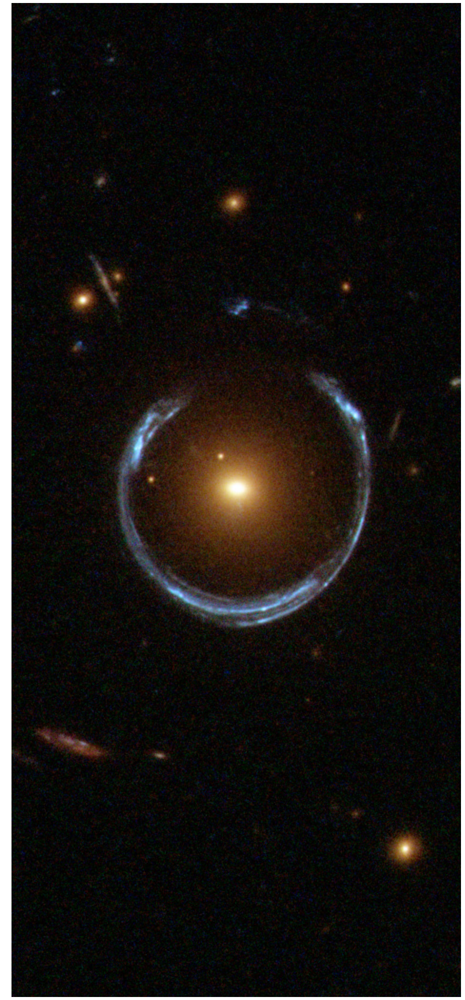
$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{ls}}{D_l D_s}}$$

Physical Einstein ring

$$r_E = D_l \theta_E$$

Gravitational Lensing Regimes





	Micro = stars	Galaxy	Cluster
Distance:	~kpc	~Gpc	~Gpc
R_E:	~AU	~10 kpc	~Mpc
θ_E:	~mas	~arcsec	~arcmin
Probability:	~10^{-6}	~10^{-2}	~1

Stars as Lenses

Looking towards Galactic bulge:

Mass ~ 0.5 M_{sun}

Distances: lens~6 kpc source~8 kpc

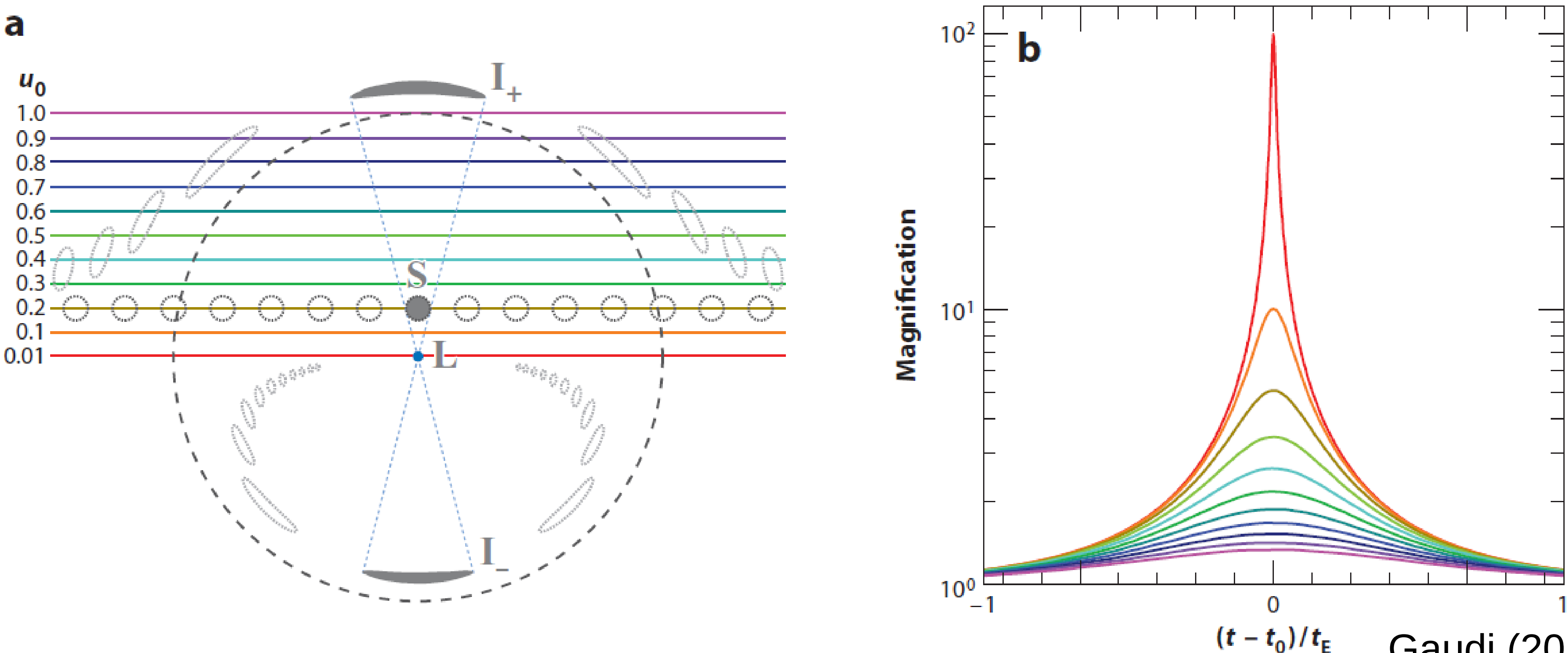
R_E ~ 2.5 AU θ_E ~ 0.4 milli-arcsec

Bulge stars have proper motions μ ~ 6 mas/yr

Microlensing is transient.

Event Timescale $t_E \equiv \theta_E/\mu_{rel}$ ~ 25 days

Microlensing Events I



Gaudi (2012)

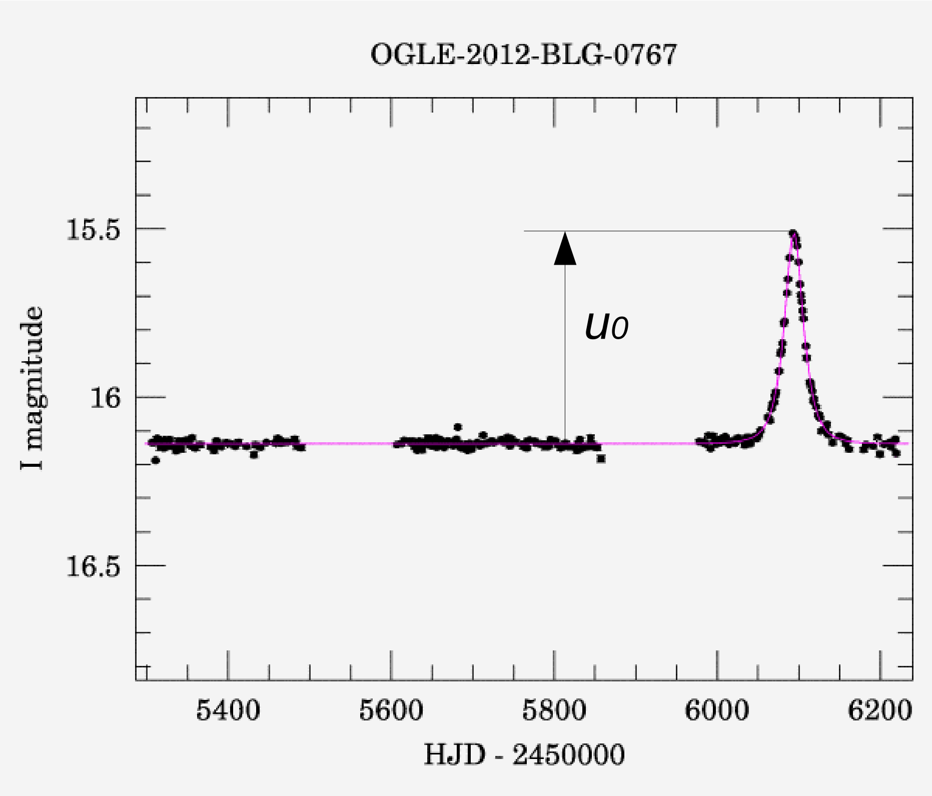
Parameters:

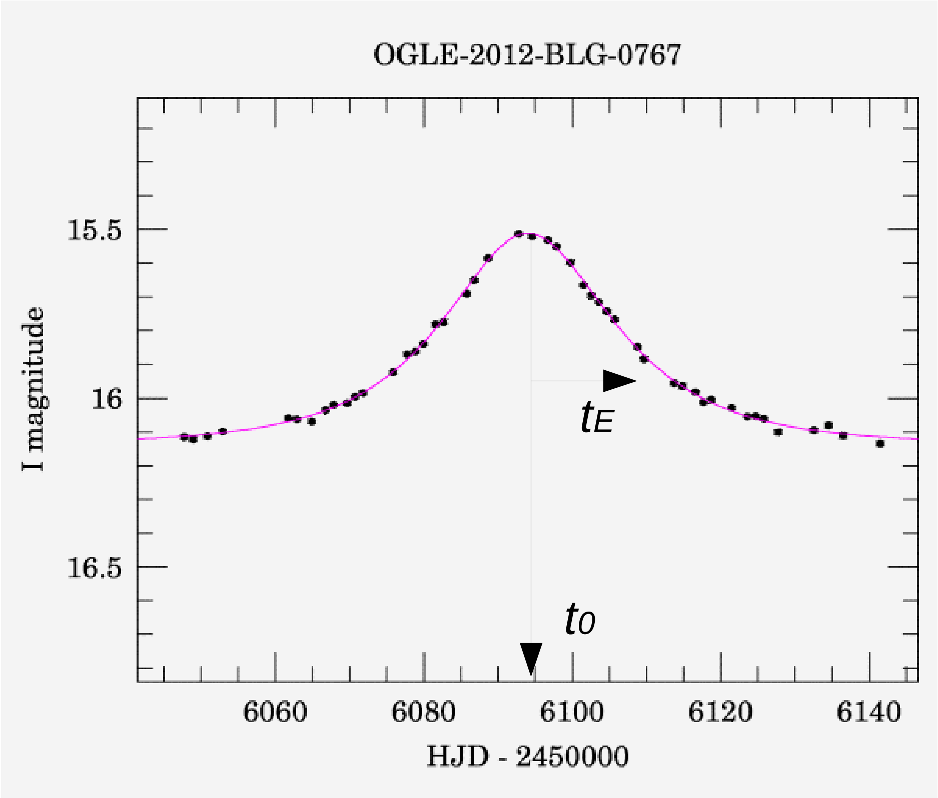
1. Impact parameter u_0
2. Peak time t_0
3. Event timescale t_E

$$u(t) = \sqrt{u_0^2 + \left(\frac{t - t_0}{t_E}\right)^2}$$

$$\text{Magnification} = \frac{u(t)^2 + 2}{u(t)\sqrt{u(t)^2 + 4}}$$

Microlensing Events II

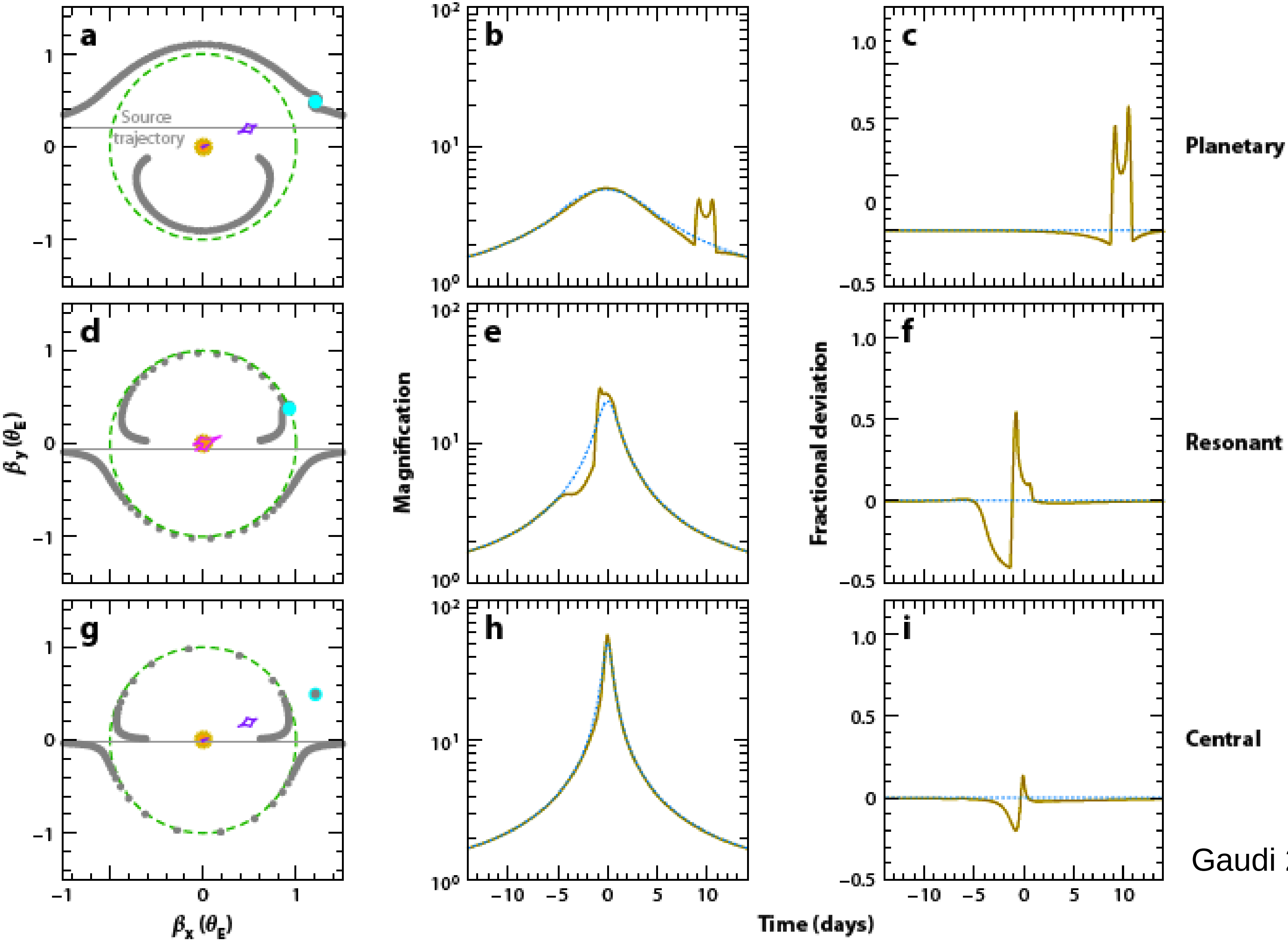




Only the timescale contains physical information about the lens:

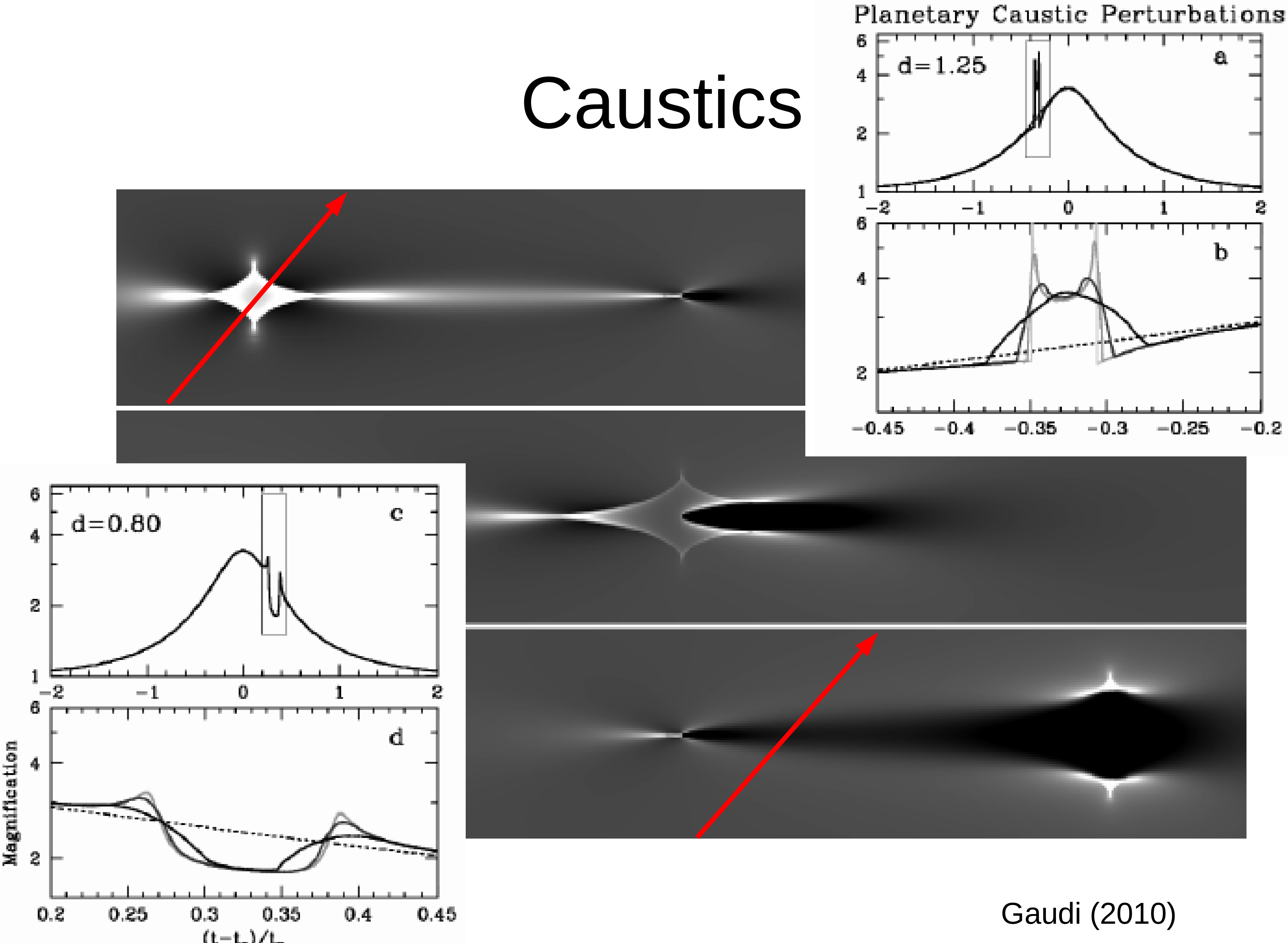
$$t_{\rm E} \equiv \frac{\theta_{\rm E}}{\mu_{\rm rel}} = \frac{1}{\mu_{\rm rel}} \sqrt{\frac{4GM}{c^2} \frac{D_{\rm ls}}{D_{\rm l} D_{\rm s}}}$$

Planetary microlensing



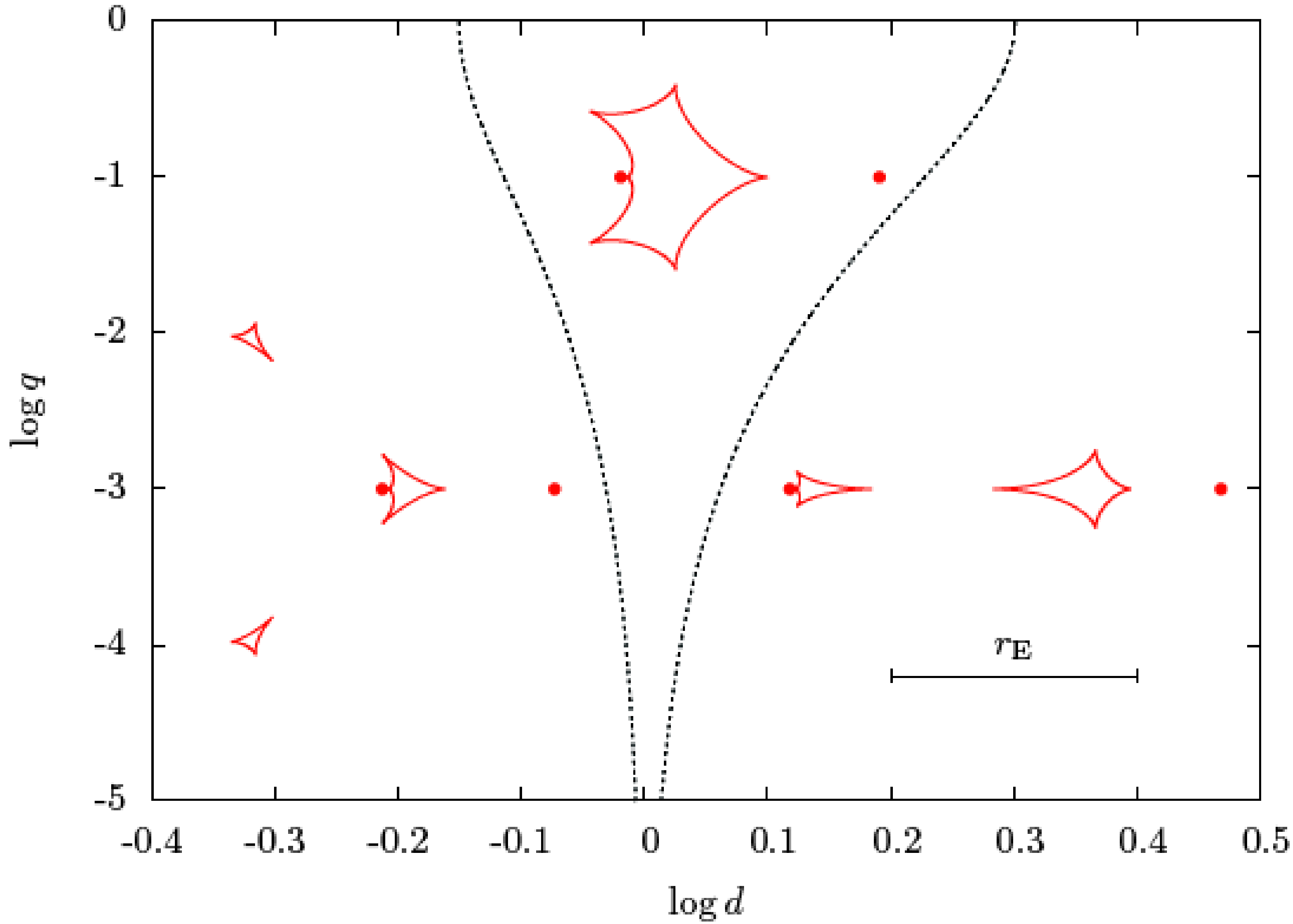
Gaudi 2012

Caustics

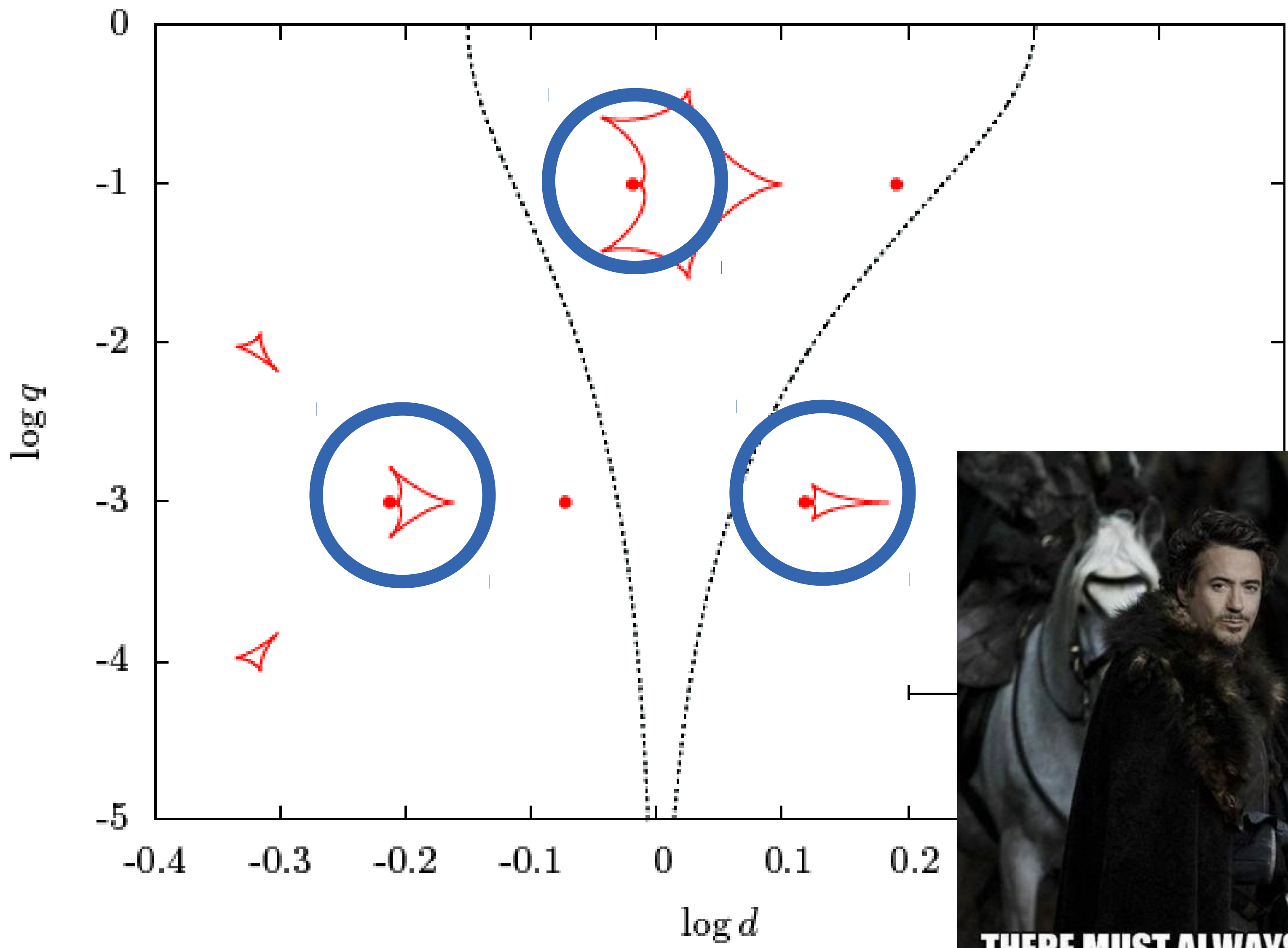


Gaudi (2010)

Three regimes of caustics

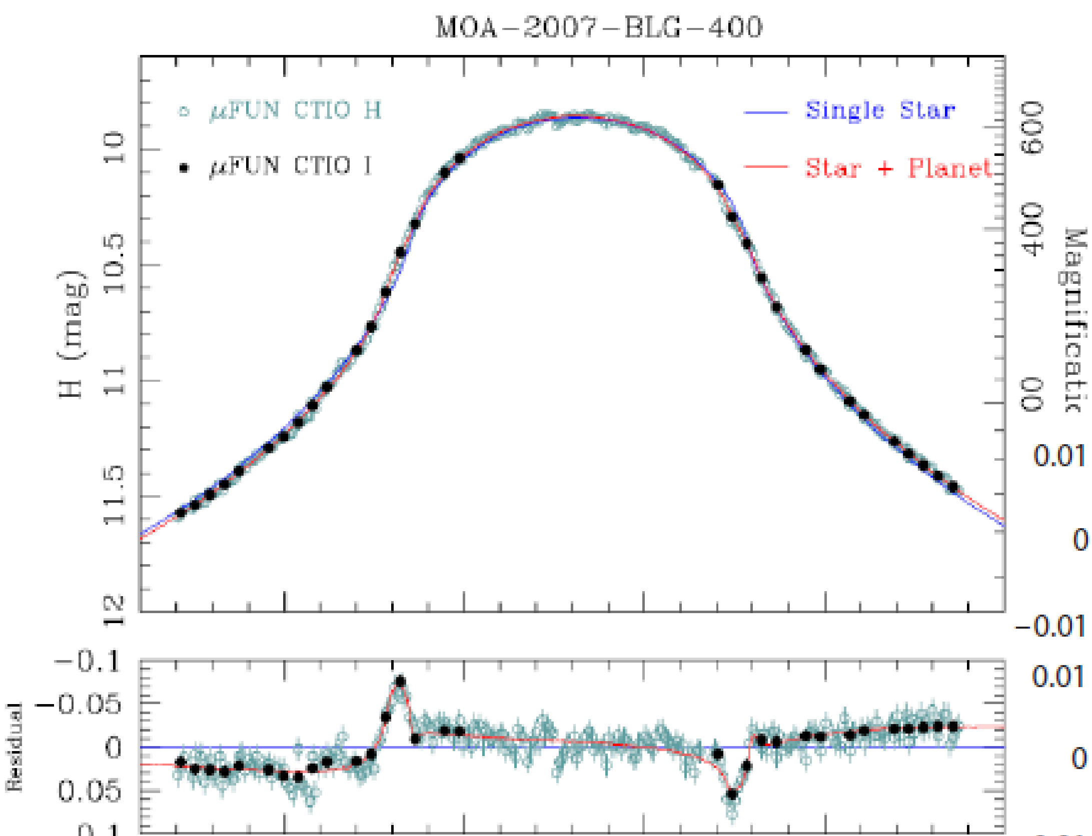


Three regimes of caustics

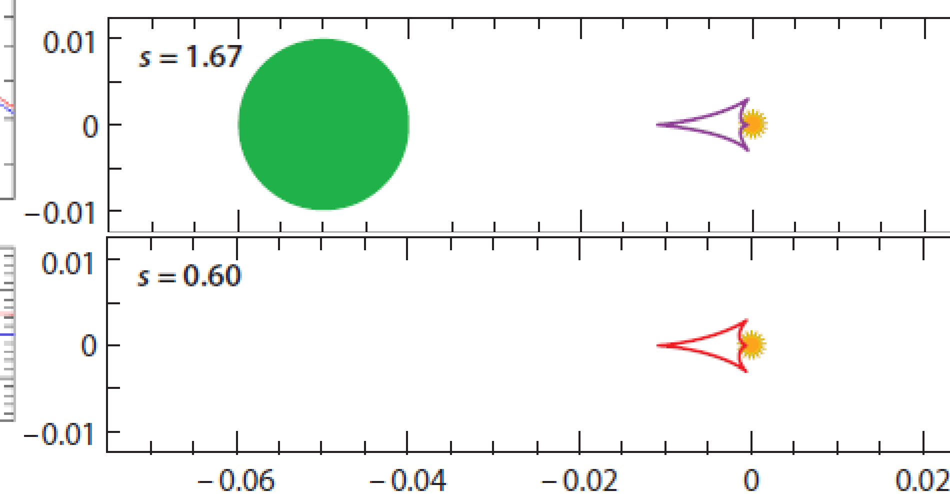


High-magnification events

- Implies the source will pass close to the lens
- Virtually 100% planet detection efficiency

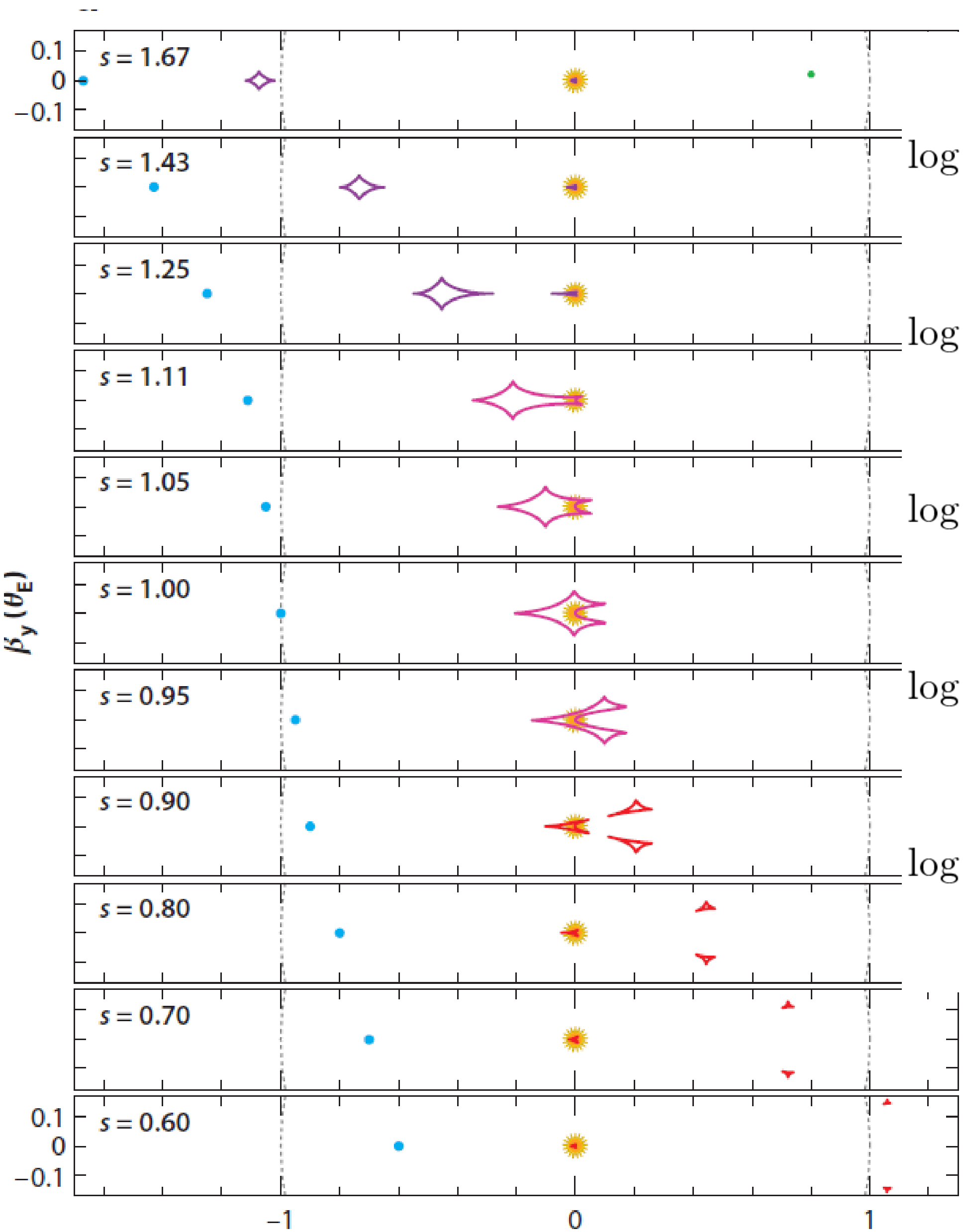


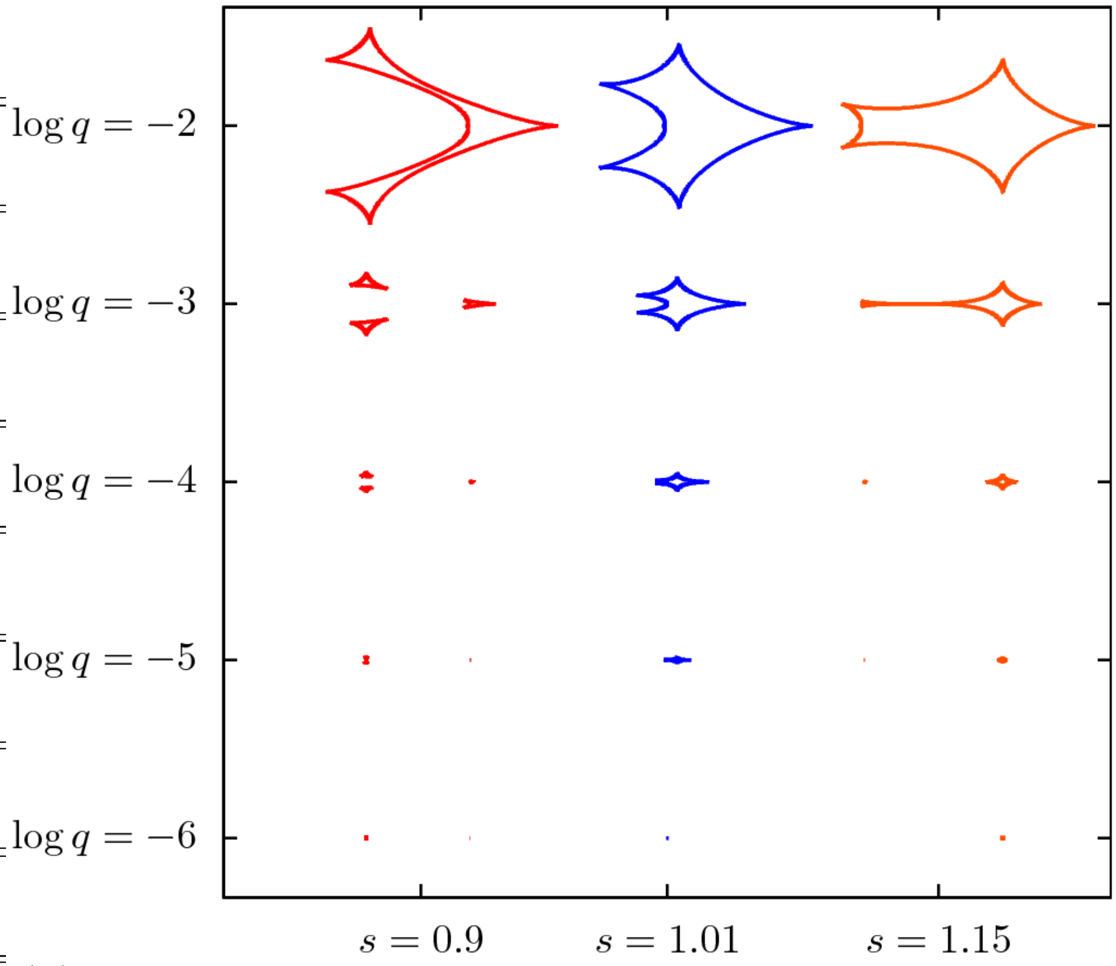
- But rare, and close and wide separation planets v. degenerate



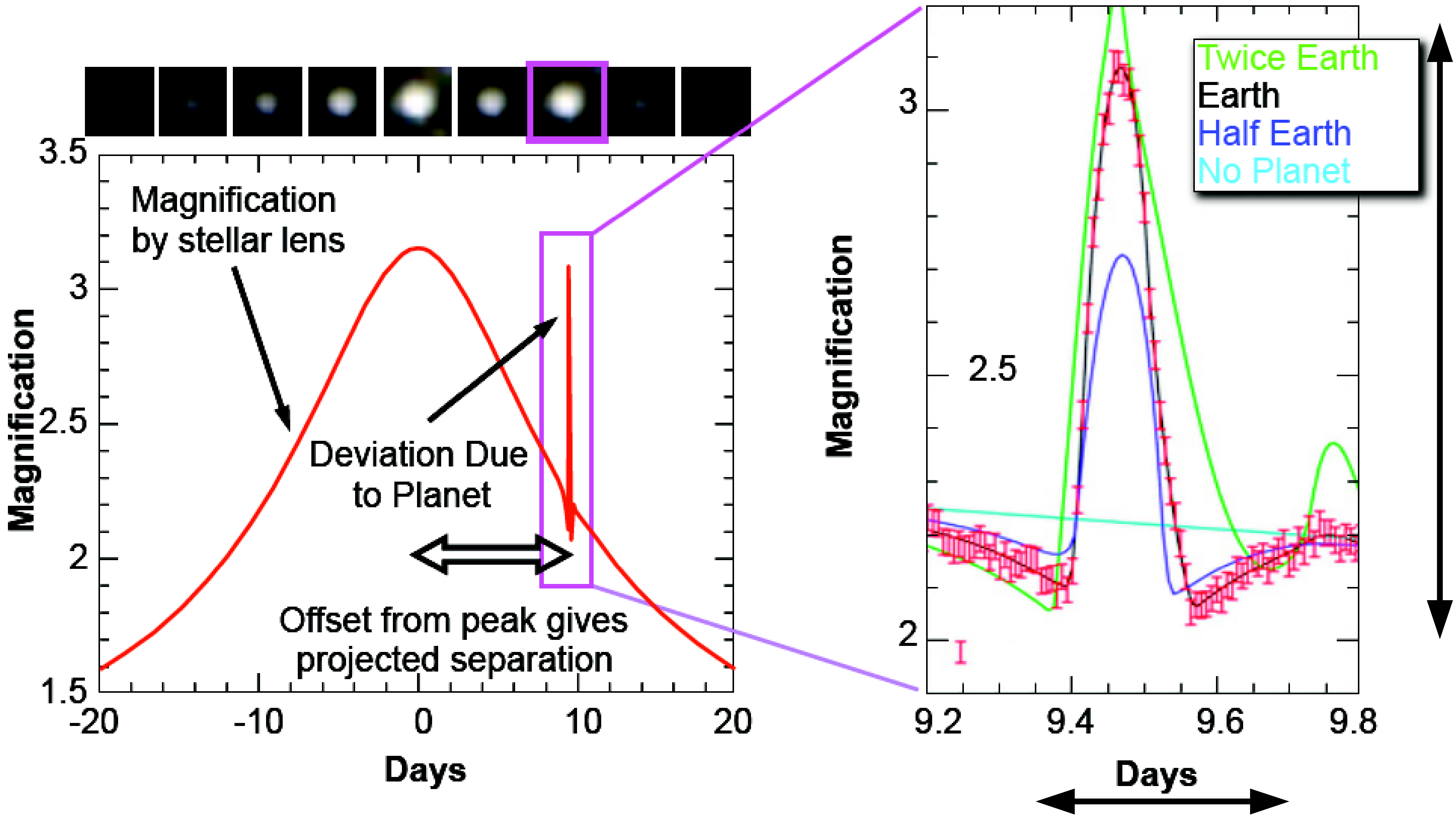
Projected separation (s)

Mass ratio (q)





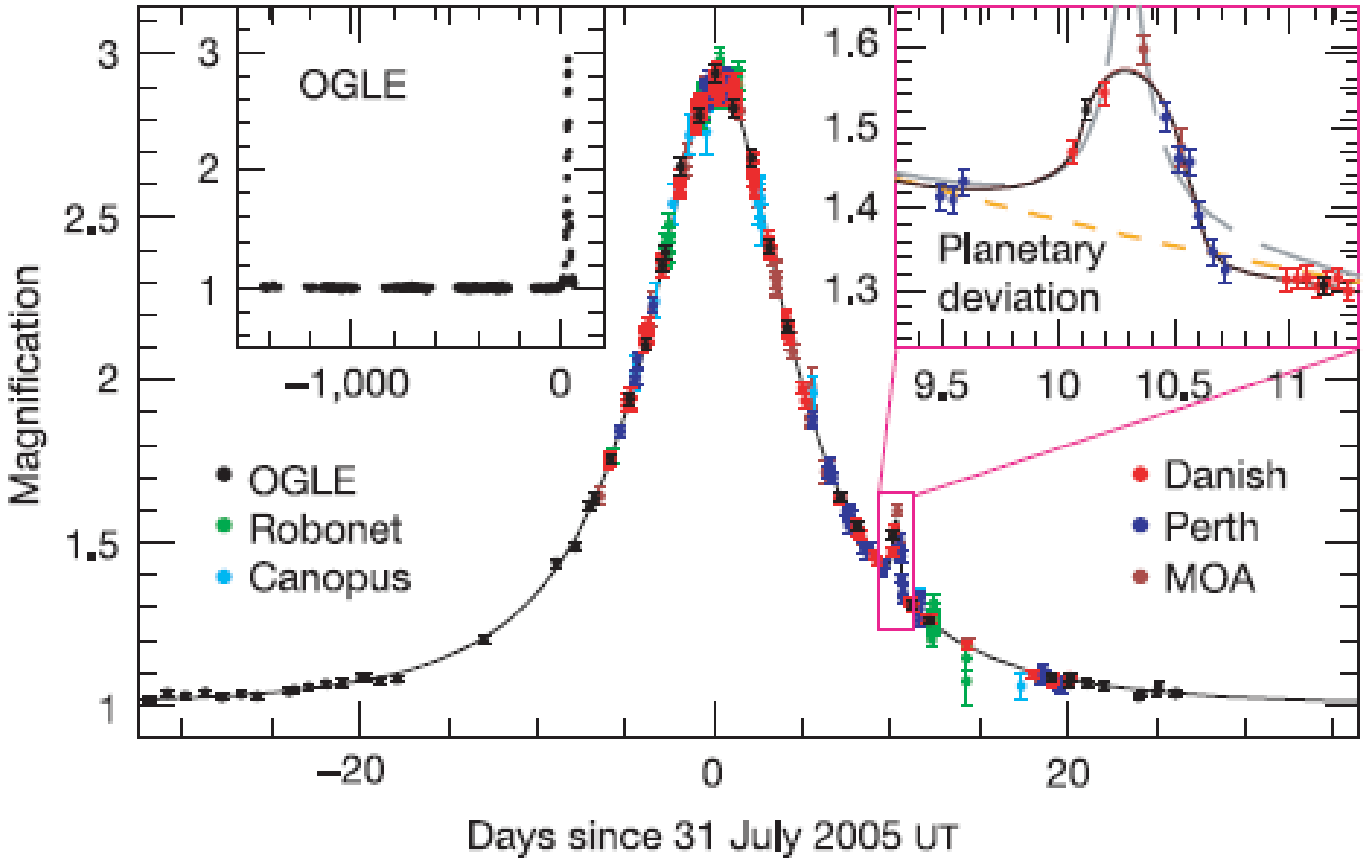
Inferring planet parameters



Duration and amplitude of deviation determined by planet mass

Figure by D Bennett

Planetary systems - perturbations



q = (ratio of durations)^2

~ $(0.5/40)^2$

~10^{-4}; x$0.3M_{sun}$=$15M_{Earth}$

s = time of deviation/t_E

~ 10/10 ~ 1

~ x r_E ~ 2 AU

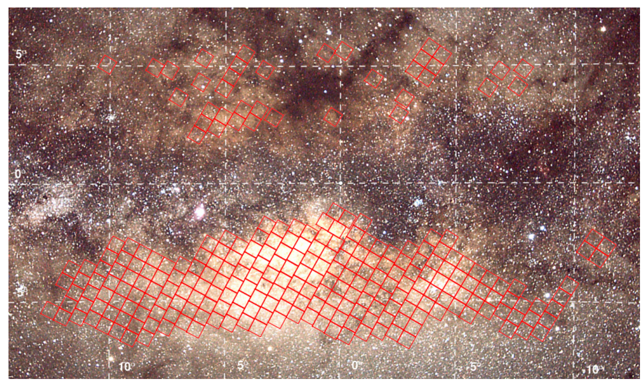
Searching for Planets - Requirements

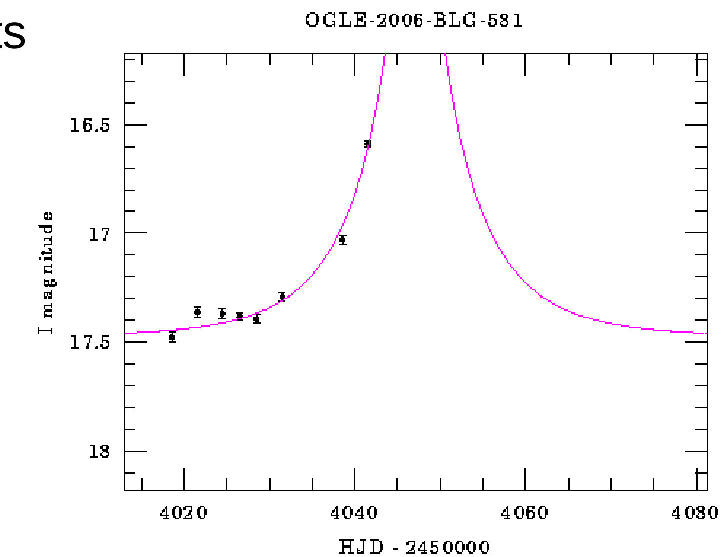
- Goal: Find 10 planets/year

	Jupiters		Earths	
Find 10/year		10 planets		10 planets
Detection efficiency	~10%	100 events	~1%	1000 events
Event rate (star^{-1} year^{-1})	~10^{-5}	10^{7} stars	~10^{-5}	10^{8} stars
Stellar density (star deg^{-2})		~10^{7} (ground)		10^{8} (space)
Image Resolution (arcsec)		~1.1		~0.36
Survey Duration	>2 t_E	>2 months	>2xt_E	>2 months
Survey Cadence	>3/$t_{E,\mathrm{Jup}}$	>4/day	>3/$t_{E,\mathrm{Earth}}$	>3/hour
Survey Area		>deg^2		>deg^2

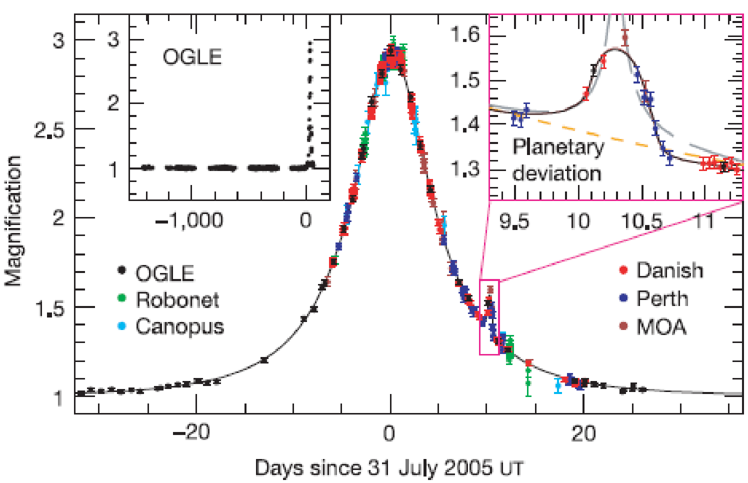
Microlensing planet search v1.0

Survey telescopes find uL events @ low cadence over a wide area and issue alerts



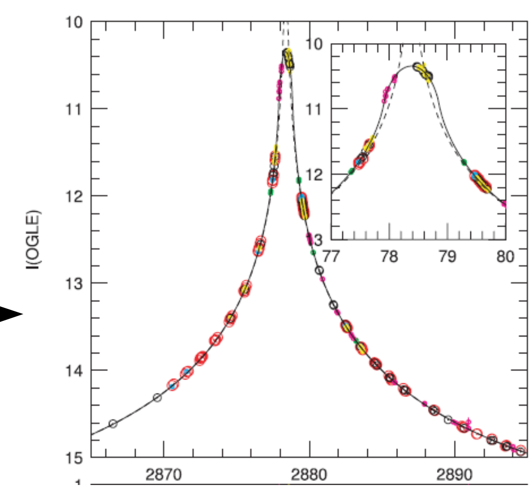


Follow-up networks obtain high-cadence coverage of a few events at a time



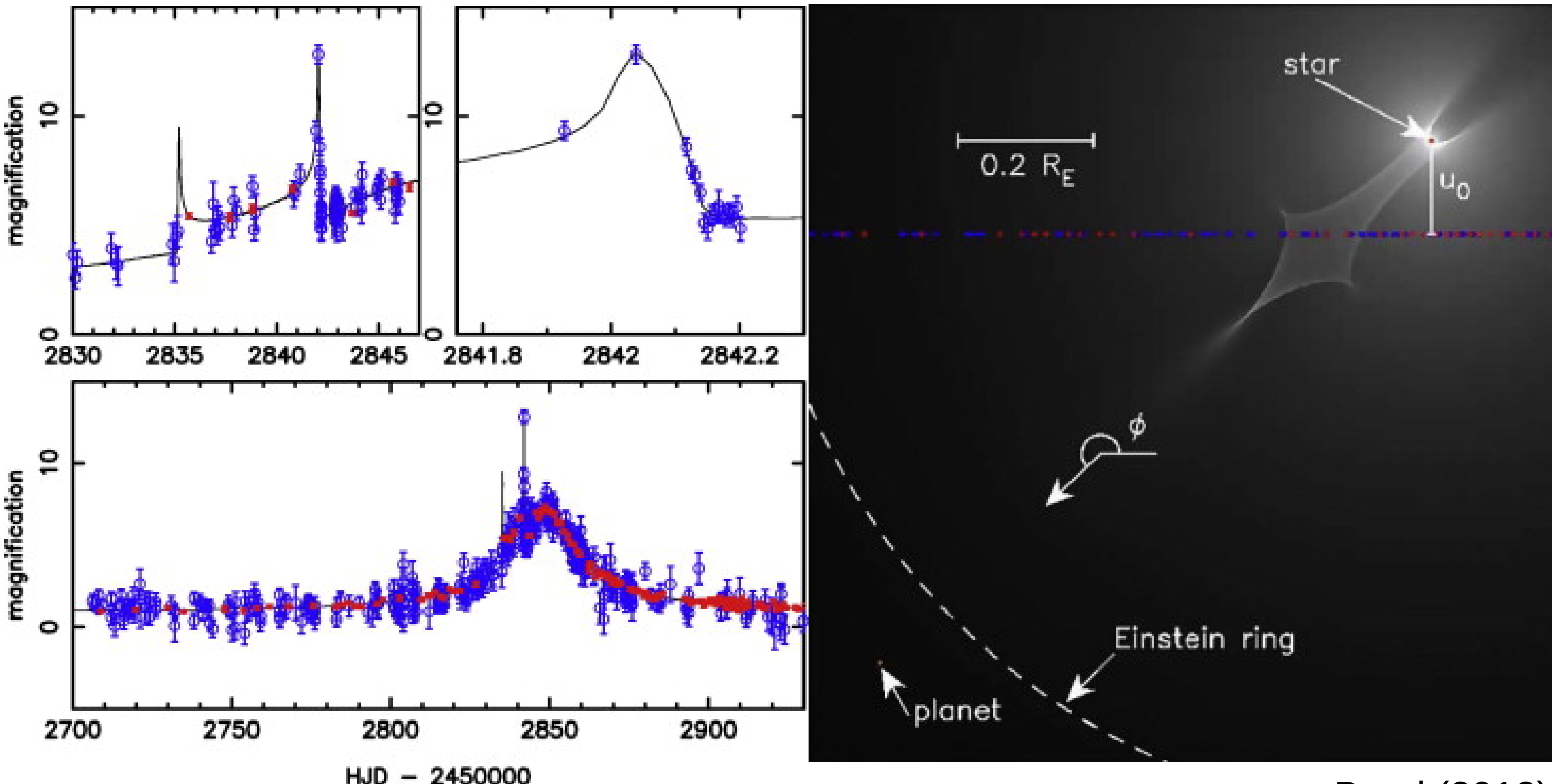
e.g., PLANET used 1-m telescopes to follow

microFUN uses smaller telescopes to target rare, bright, high-magnification events



1st Microlensing planet

OGLE-2003-BLG-235/MOA 2003-BLG-53

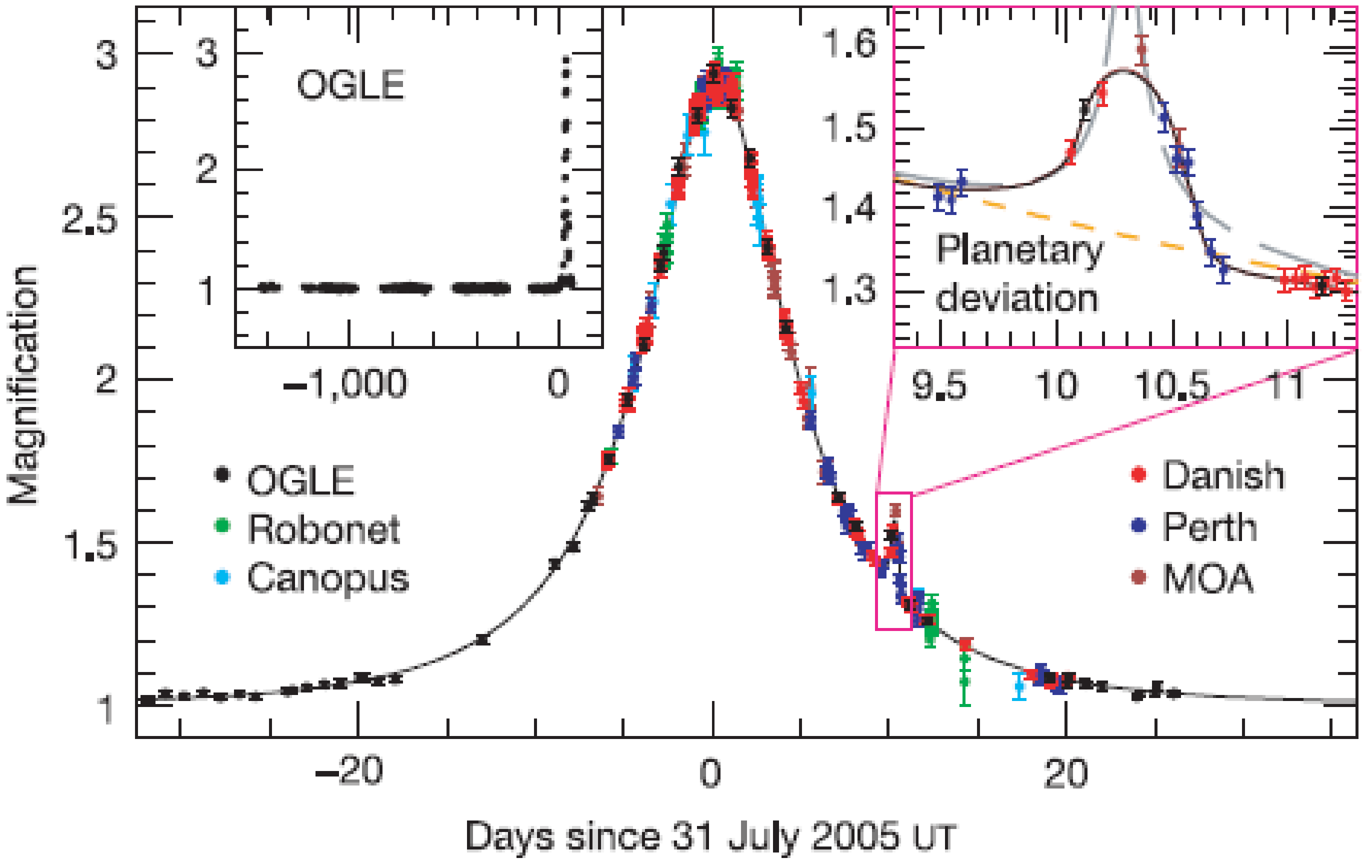


Bond (2012)

2.6 M_{jup} planet orbiting 0.6 M_{sun} K-dwarf at >4.6 AU

Low mass Planets

OGLE-2005-BLG-390

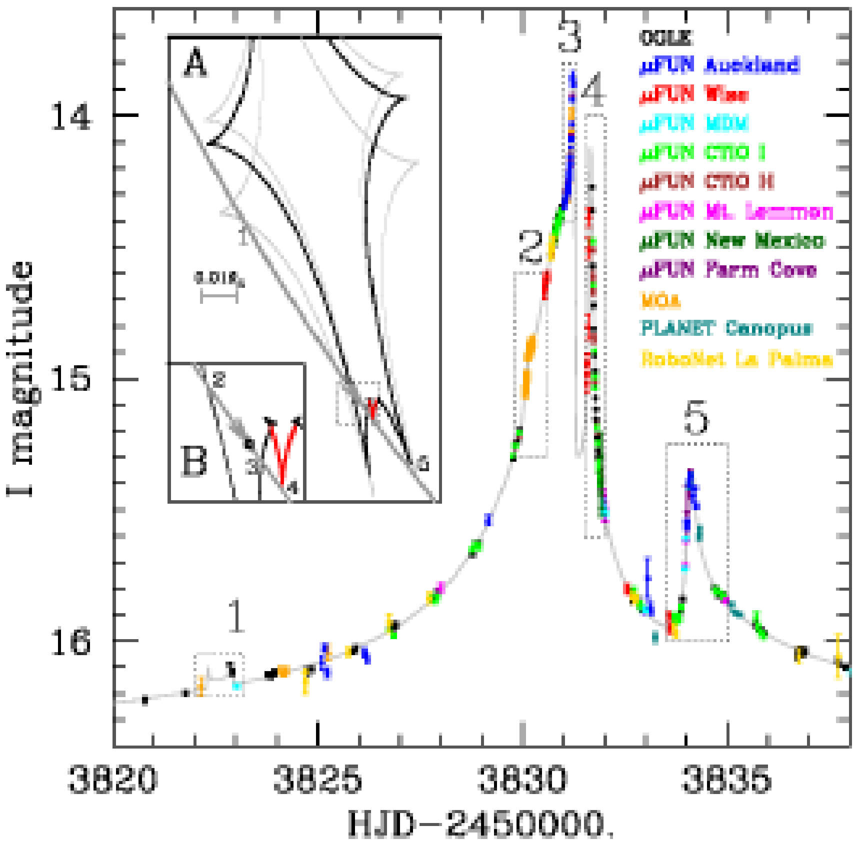


Beaulieu et al. (2006)

5.5 M_{Earth} planet orbiting a 0.2 M_{Sun} star at >2.6 AU

Multiple planet systems I

OGLE-2006-BLG-109



0.5 M_{sun} star

Planet b:

0.71 M_{jup} @ 2.3 AU

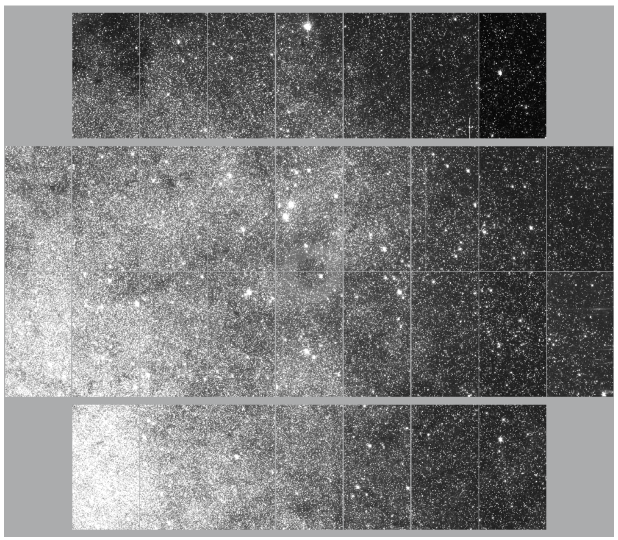
Planet c:

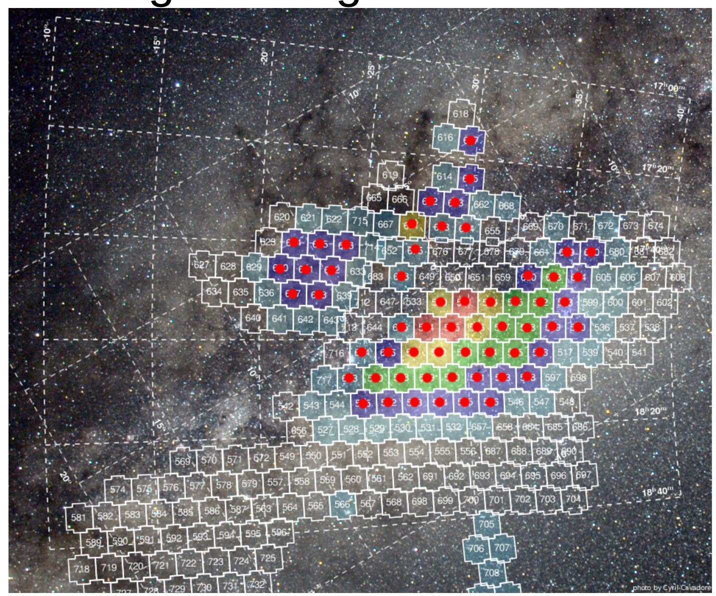
0.27 M_{jup} @ 4.5 AU

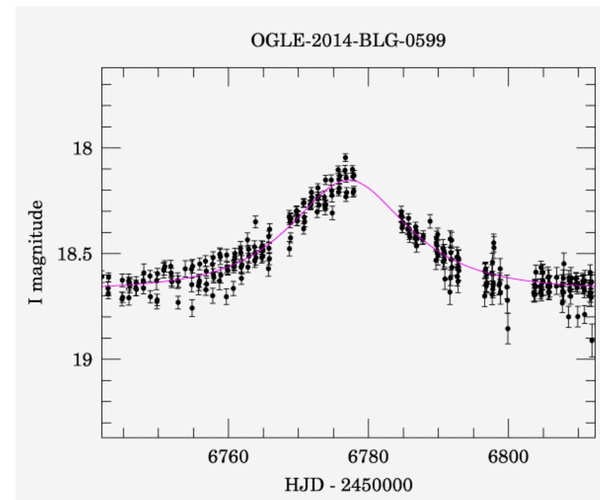
Gaudi et al. (2008), Bennett et al. (2010)

Microlensing planet search v2.0

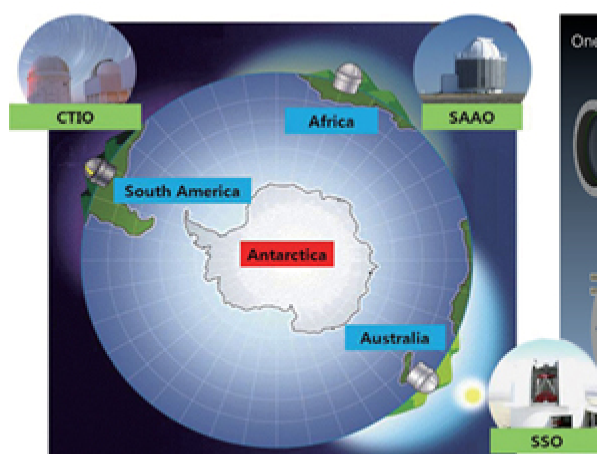
Larger format cameras enable high-cadence observations over a small number of fields covering ~10 deg^2

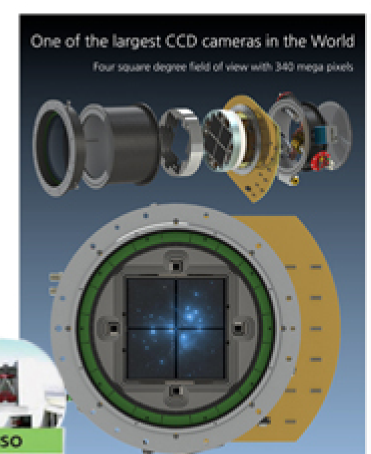


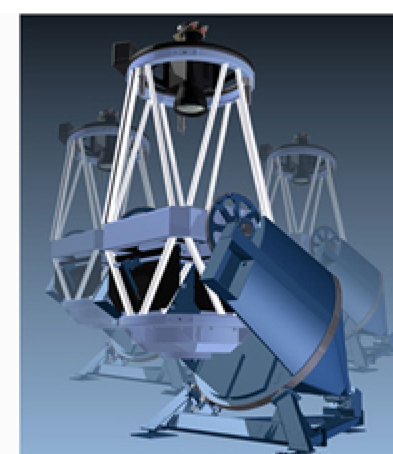




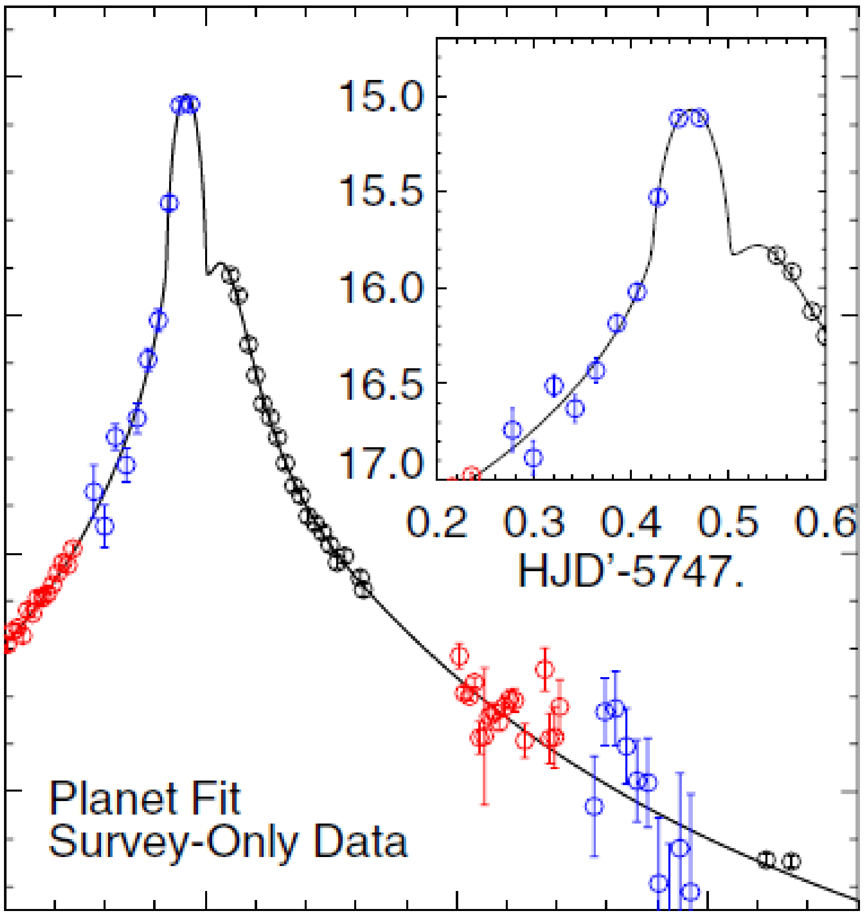
MOA-II	2.2 deg^2	2006-
OGLE-IV	1.4 deg^2	2011-
KMTNet	4.2 deg^2	2015-



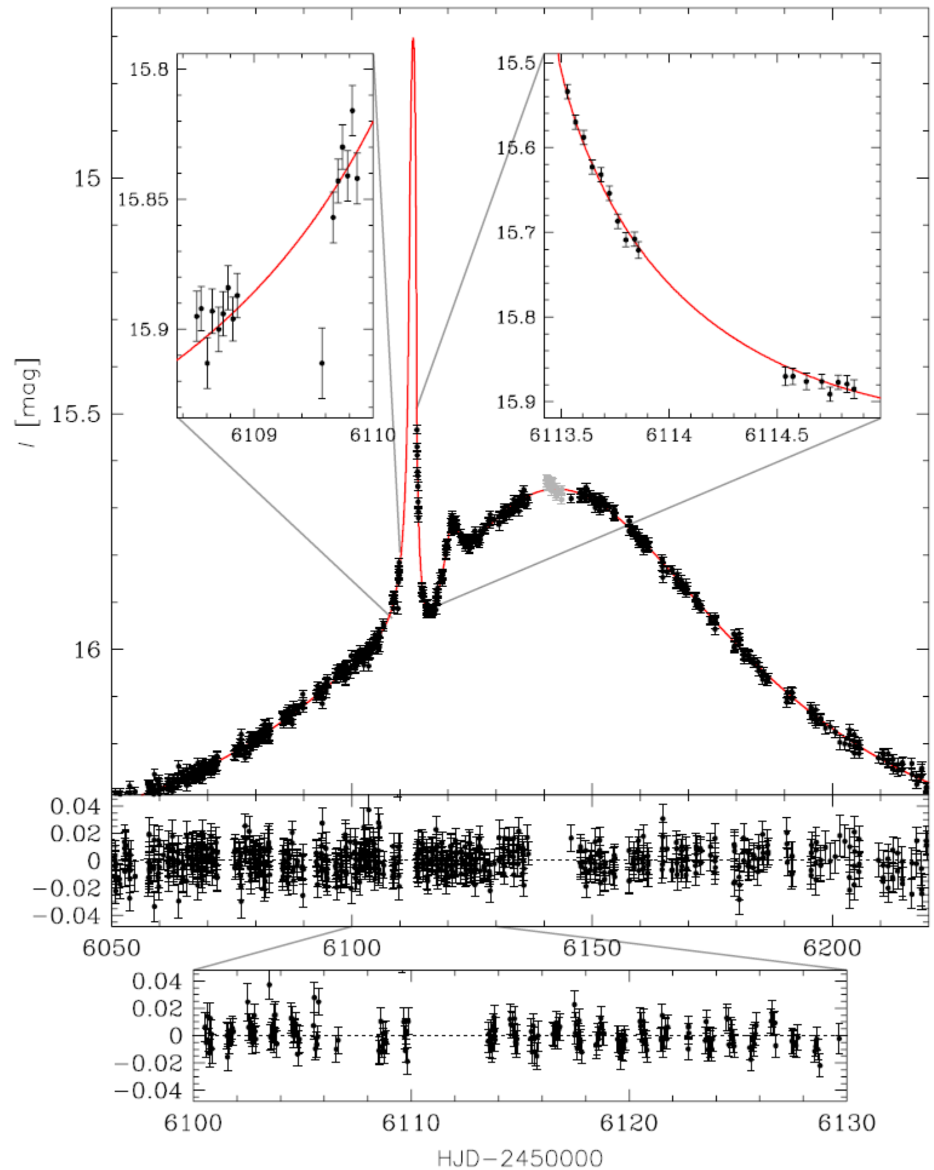




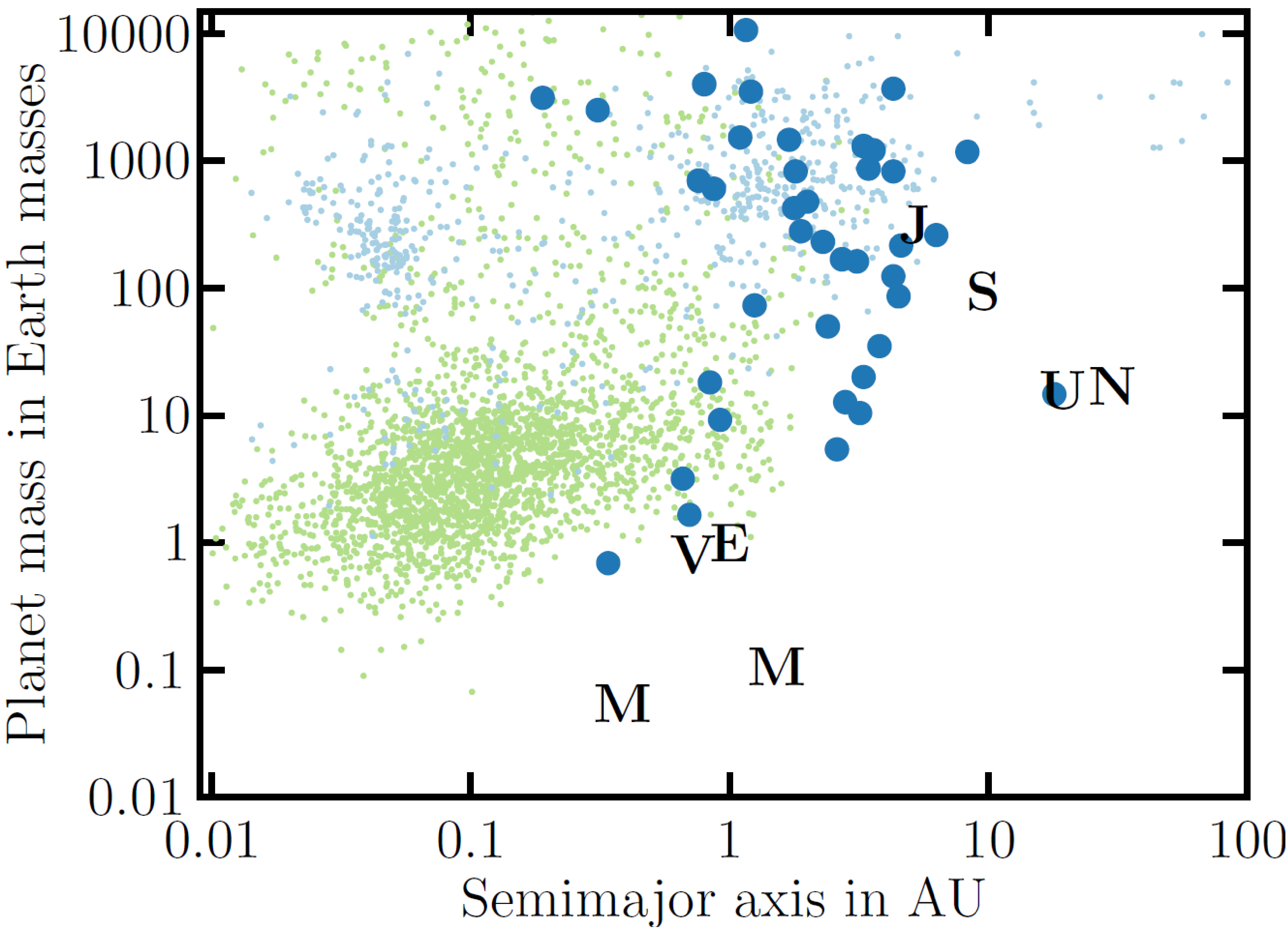
Survey-only planets



MOA-2011-BLG-293 Yee+2013



OGLE-2012-BLG-0406 Poleski+2014



Planet mass in Earth masses
10000
1000
100
10
1
0.1
0.01
Semimajor axis in AU
0.01
0.1
1
10
100
J
S
U
N
V
E
M
M

PART 2

Selection Effects

Selection effects

- Can divide into two groups
  - Host star selection effects
  - Planet selection effects

Event rate – how often will a star act as a lens

- Each star contributes: cross section (θ_E) x speed (μ_{rel})
  - Proportional to sqrt(Mass), f(distances), relative proper motions
- Sum over all stars
  - Integrate over galactic density and kinematic distribution, and mass function
    - ~60/40 split of bulge and disk lenses
    - Distance affects Einstein ring radius (→probe a different region of systems at different distances)

Microlensing effectively probes all main sequence masses ($<1\ M_{sun}$)

- ~Kroupa IMF ($M>0.5M_{sun}$, $\alpha=-1.3$; $M>0.5M_{sun}$, $\alpha=-2.3$)

Mass range (M_{sun})	Microlensing rate
1 → 0.5	24%
0.5 → 0.25	29%
0.25 → 0.125	25%
0.125 → 0.0625	22%

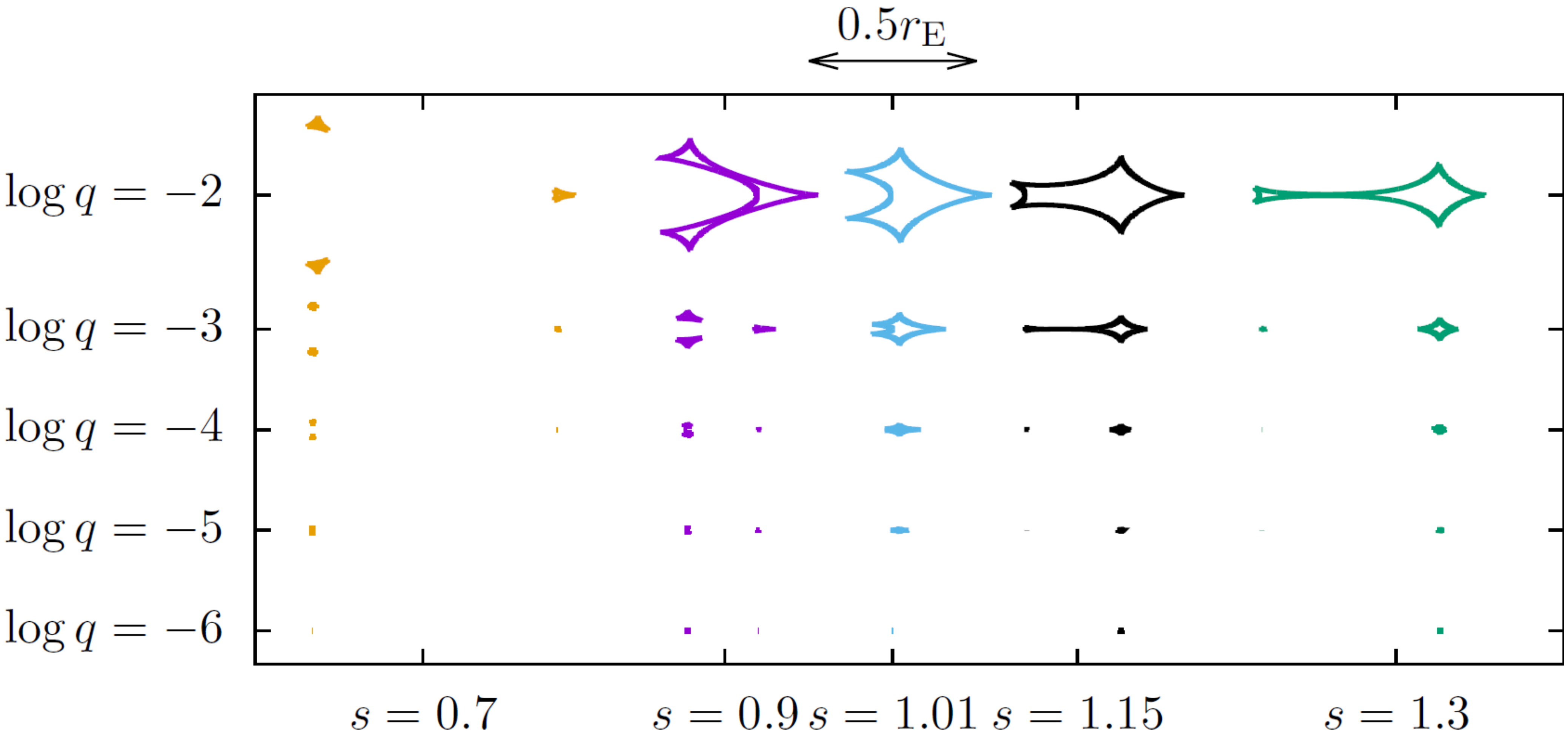
Unfortunately, the host masses are not measured most of the time

But host mass is usually not measured

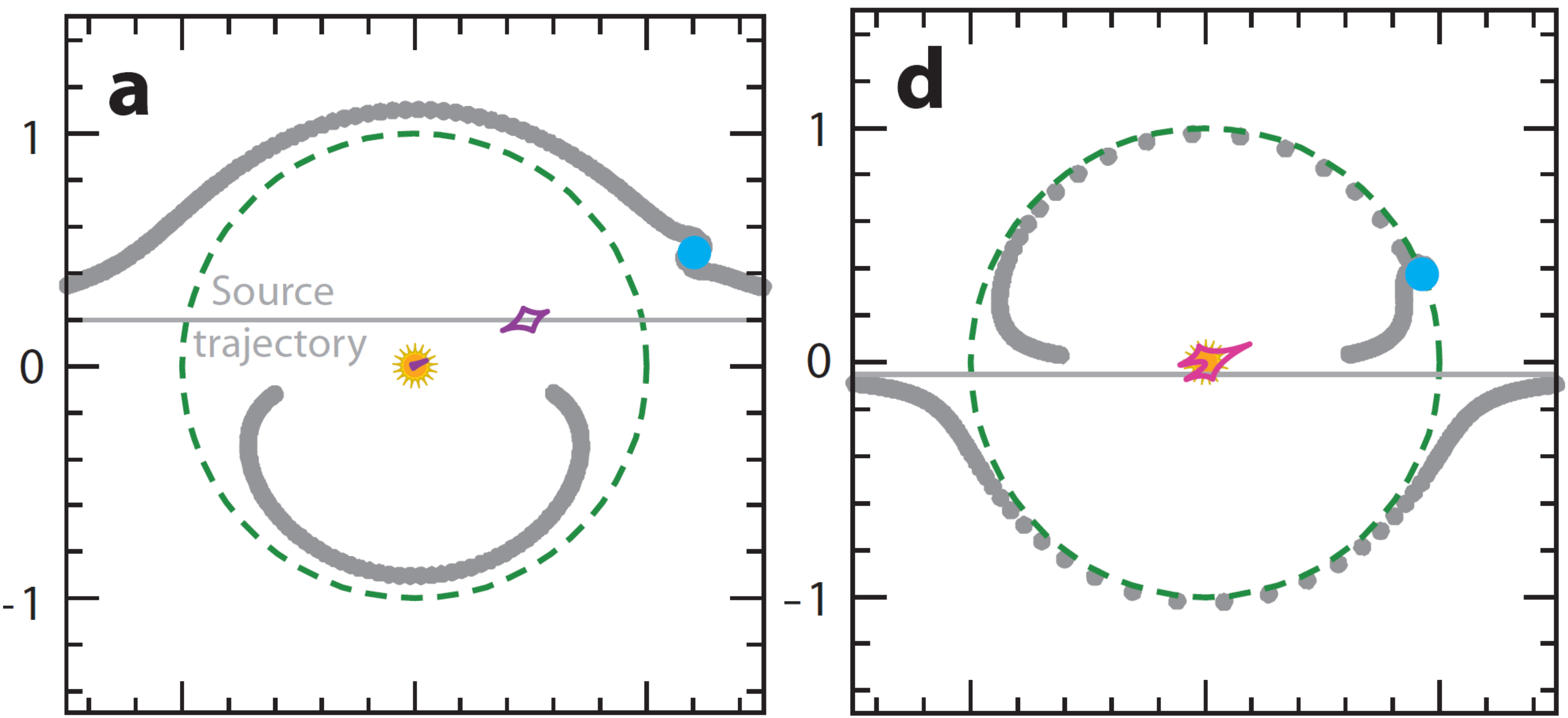
- Parallax measurement is needed for planetary events (and also rare finite source effects for the control sample)
- Some events are long enough for Earth's orbital motion to cause measurable parallax effects
- Spitzer and K2 are for the first time making systematic parallax measurements from space

Selecting the planet

- Essentially: What is the probability of encountering a caustic?

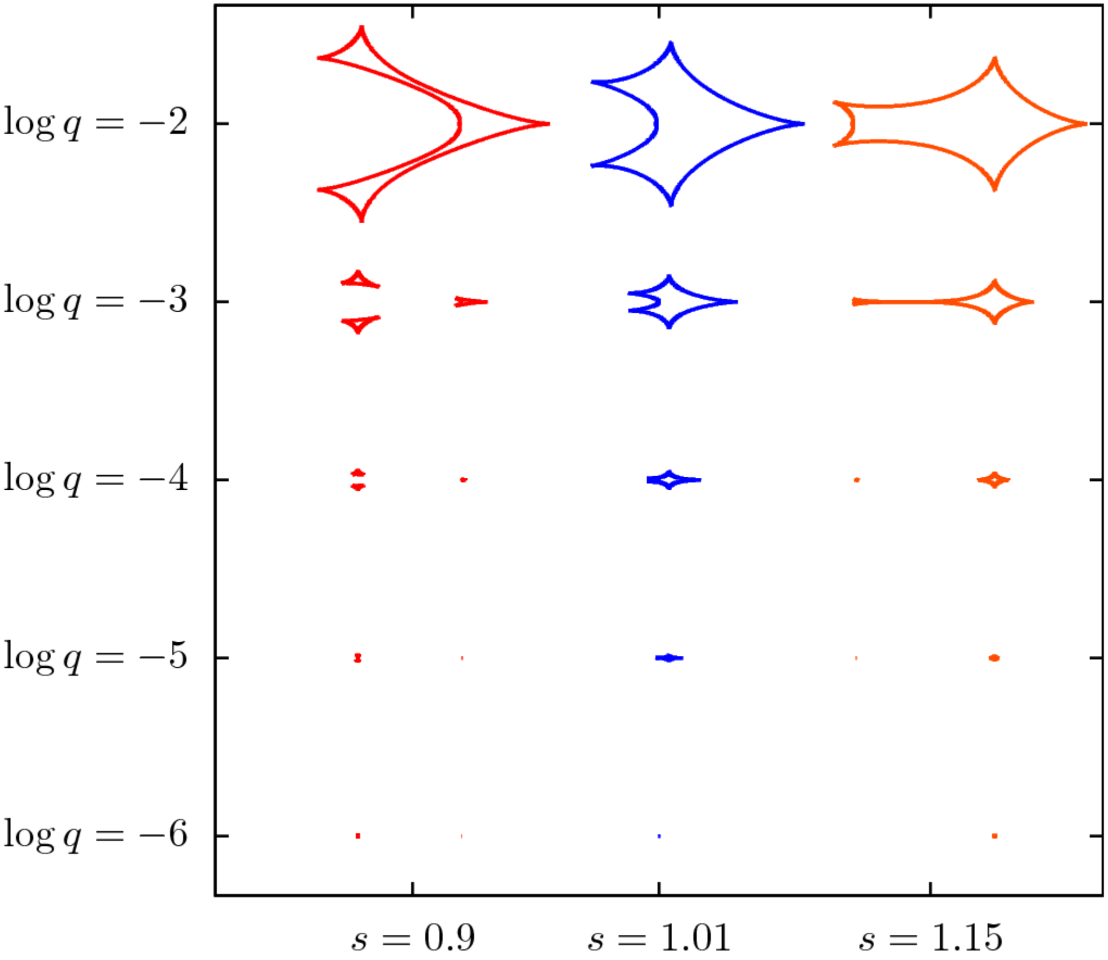


Caustics ~ Detection

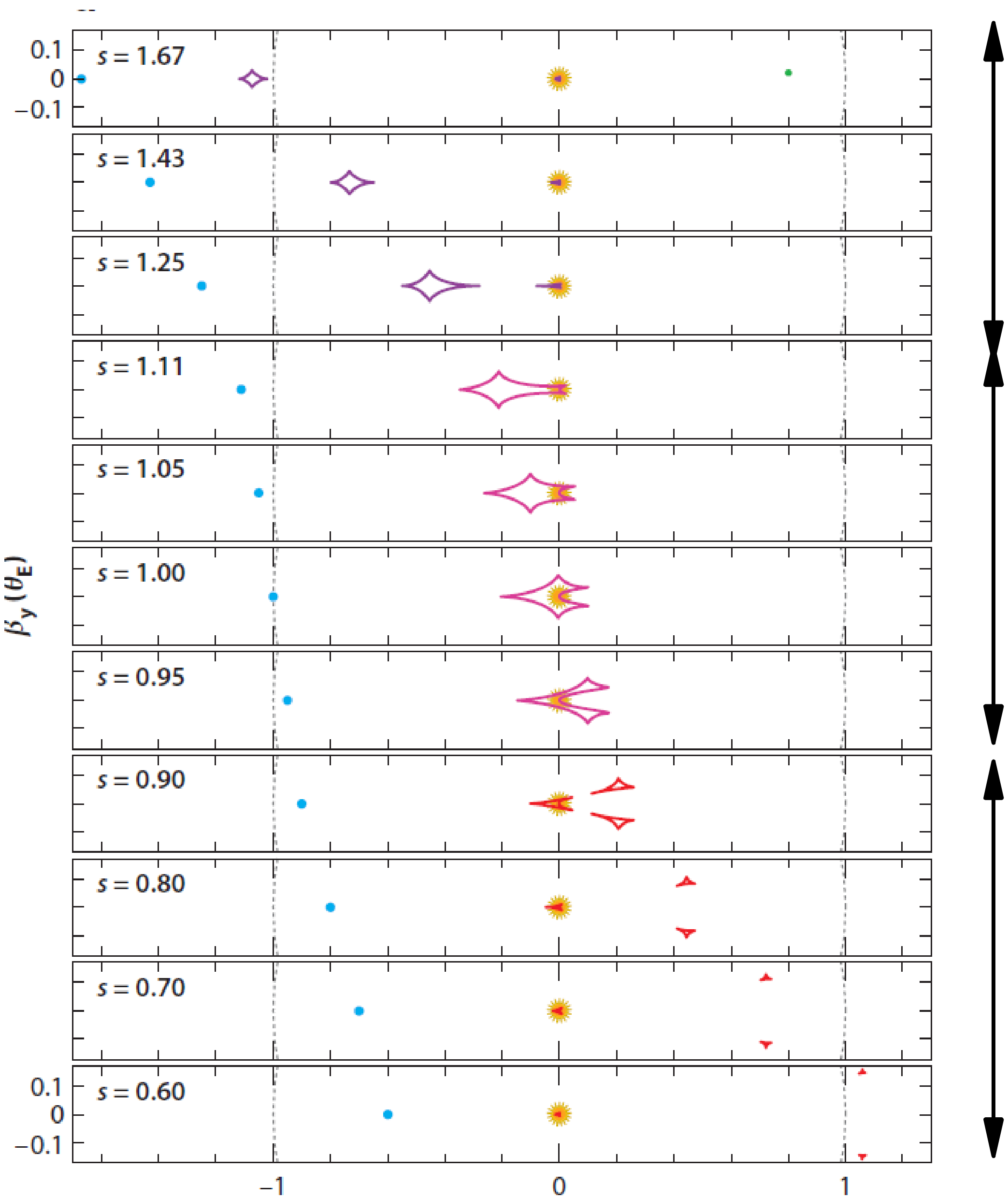


Mass ratio (q)

- Caustic size
  - ~$q^{1/2}$ (planetary)
  - ~q (central)
  - ~$q^{1/3}$ (resonant)
- Implies:
  - Planetary caustics sensitive to low mass planets
  - High-mag events only sensitive to more massive planets (i.e ~Neptune+)

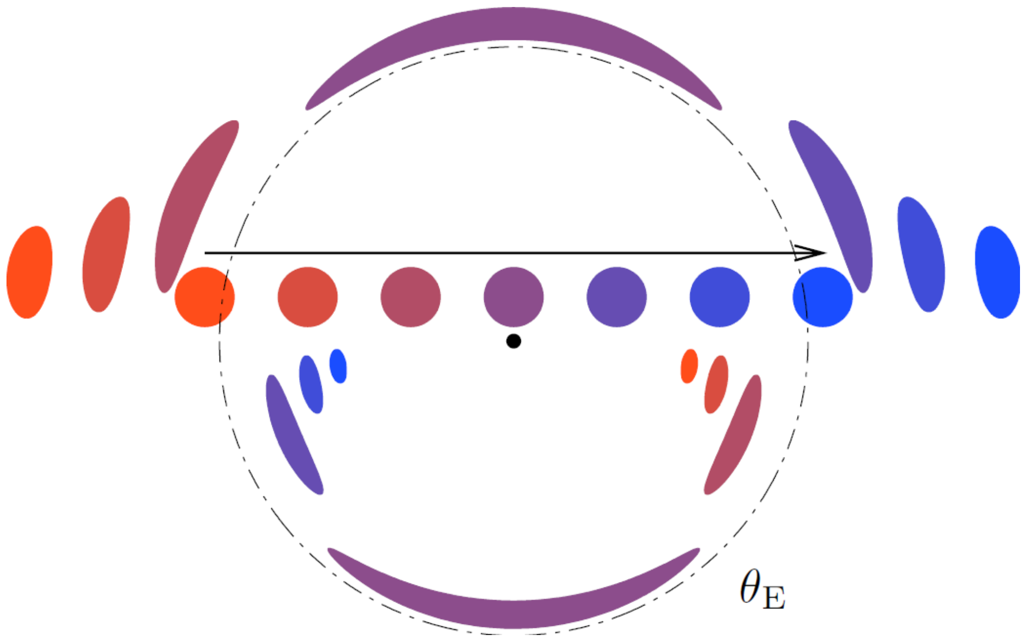


Projected separation (s)



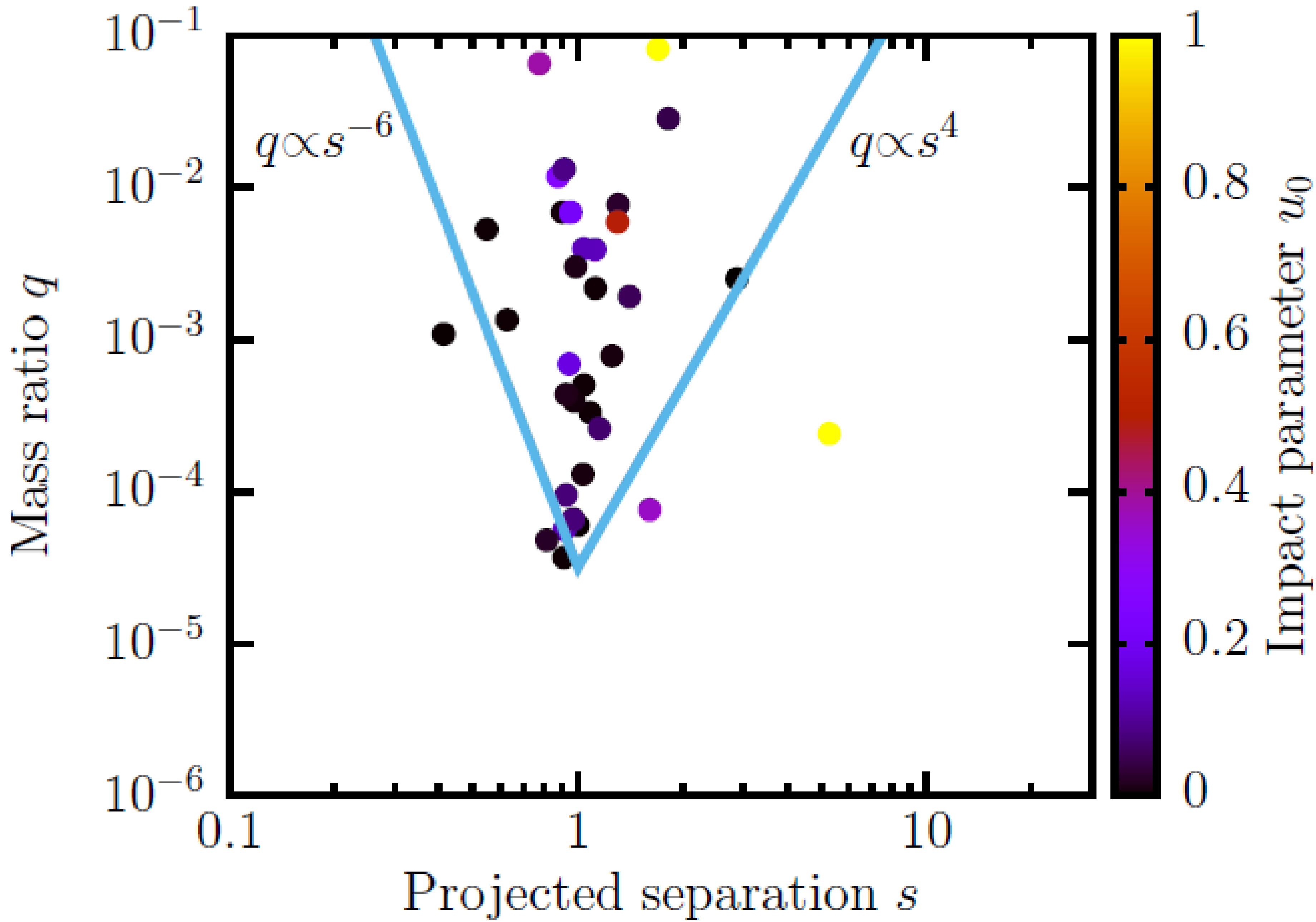
- Planetary caustic located at:
    - s – 1/s
- Caustic size:
    - $\sim s^{-2}$ (wide)
    - $\sim s^{3}$ (close, planetary)
    - $\sim s^{2}$ (close, central)

Also depends on image perturbation

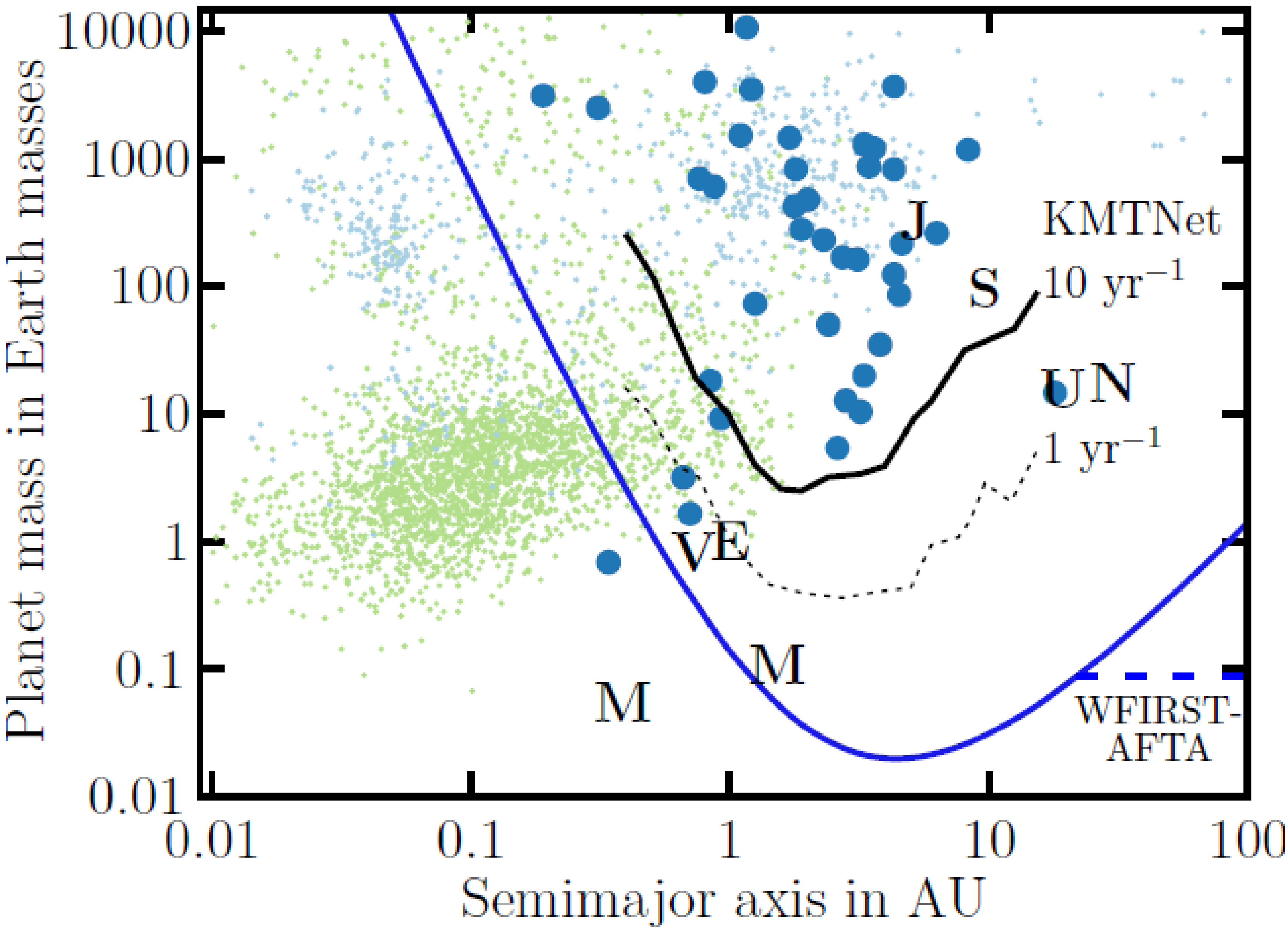


- Major image magnification → 1 as u → ∞
- Minor image magnification → 0 as u → ∞
- => Wide planets can be found at any distance (though probability drops if primary event required)

Putting it together



Putting it together



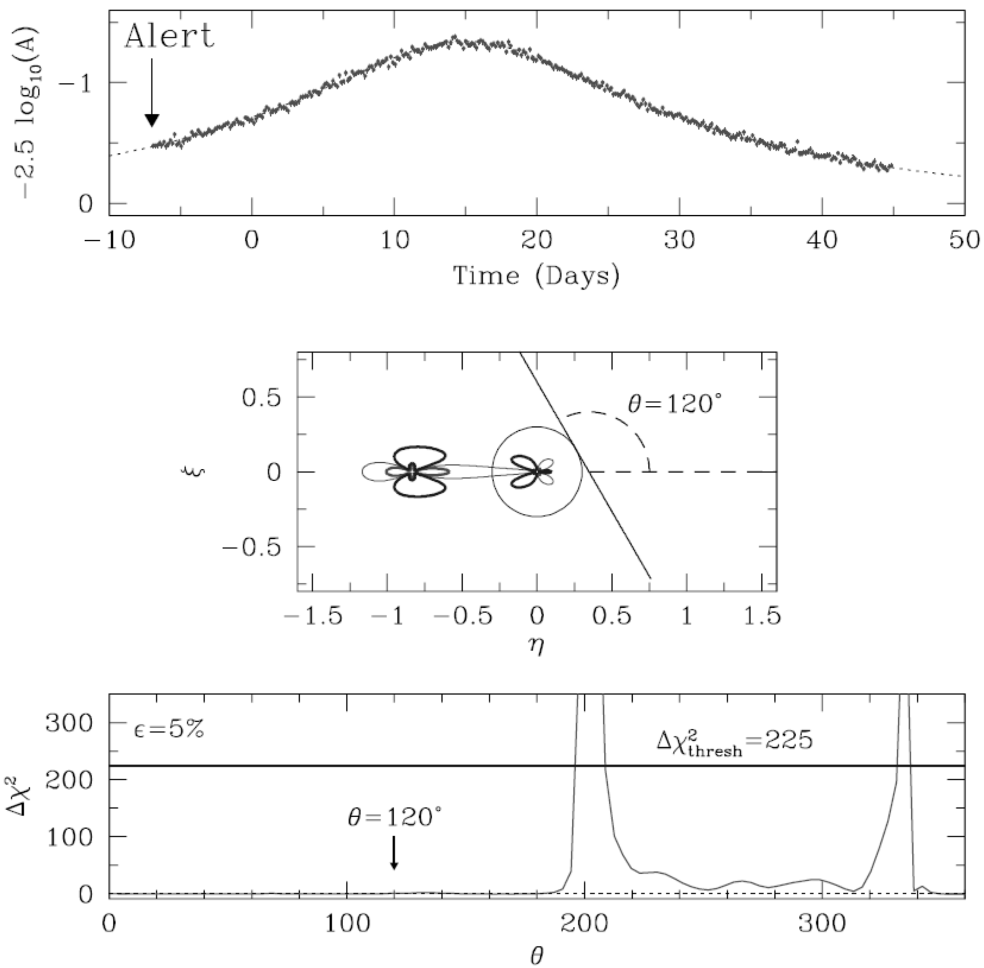
PART 3

From Detections to Abundances

Calculating detection efficiency

- Basically a brute-force injection-recovery tests
- Need to marginalize over 5(6) nuisance parameters
  - t_0, t_E, u_0, α, ρ, (also blending)
  - when, duration, peak mag, direction, source size
- Result: Map of detection efficiency as a function of s,q
- Do on event-by-event basis

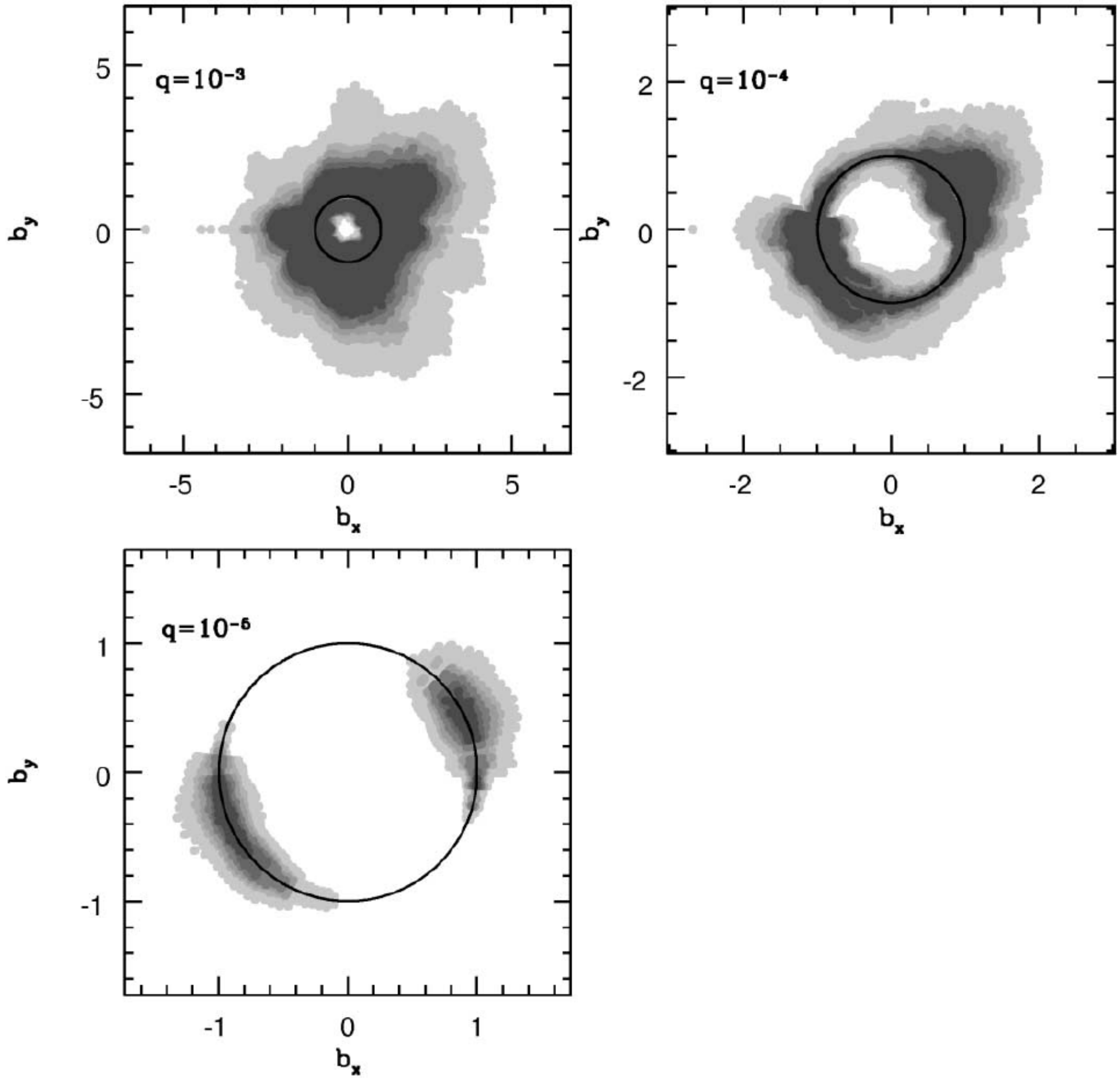
Calculating detection efficiency



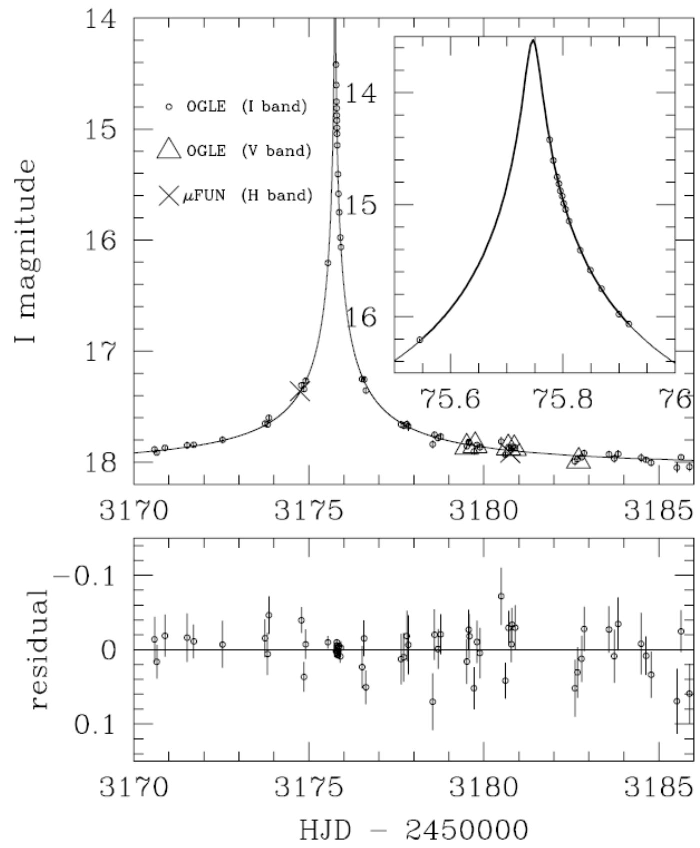
- In practice
  - t_0 known
  - t_E, u_0, blending, known or well constrained
  - ρ can be guessed
  - Leaves α to explore

Gaudi & Sackett (2000)

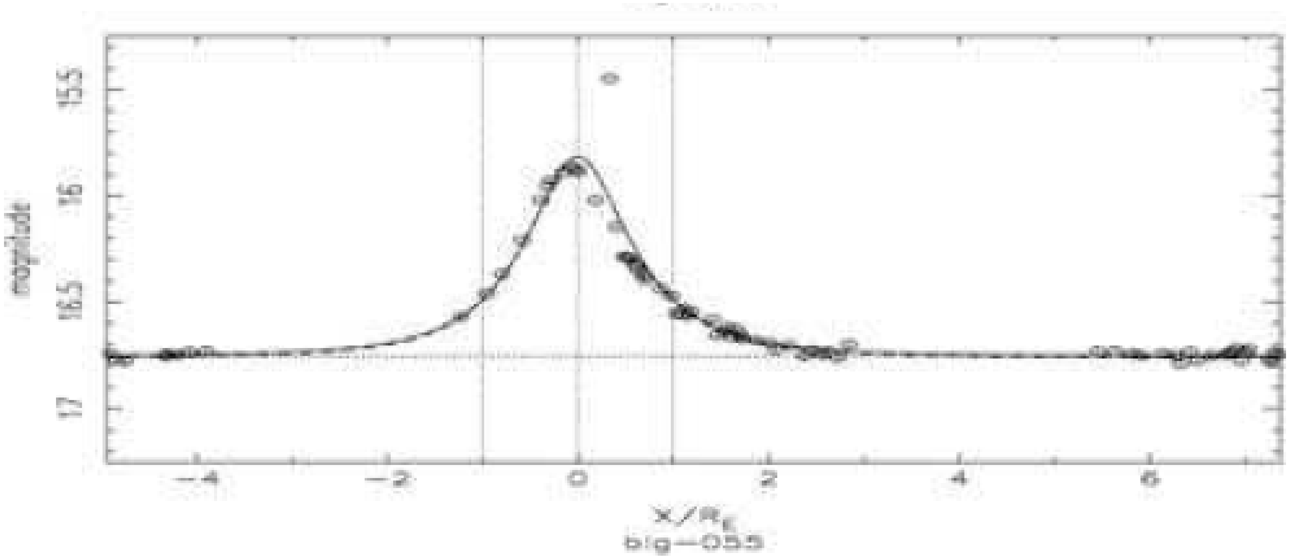
Planet exclusion plots – high-mag



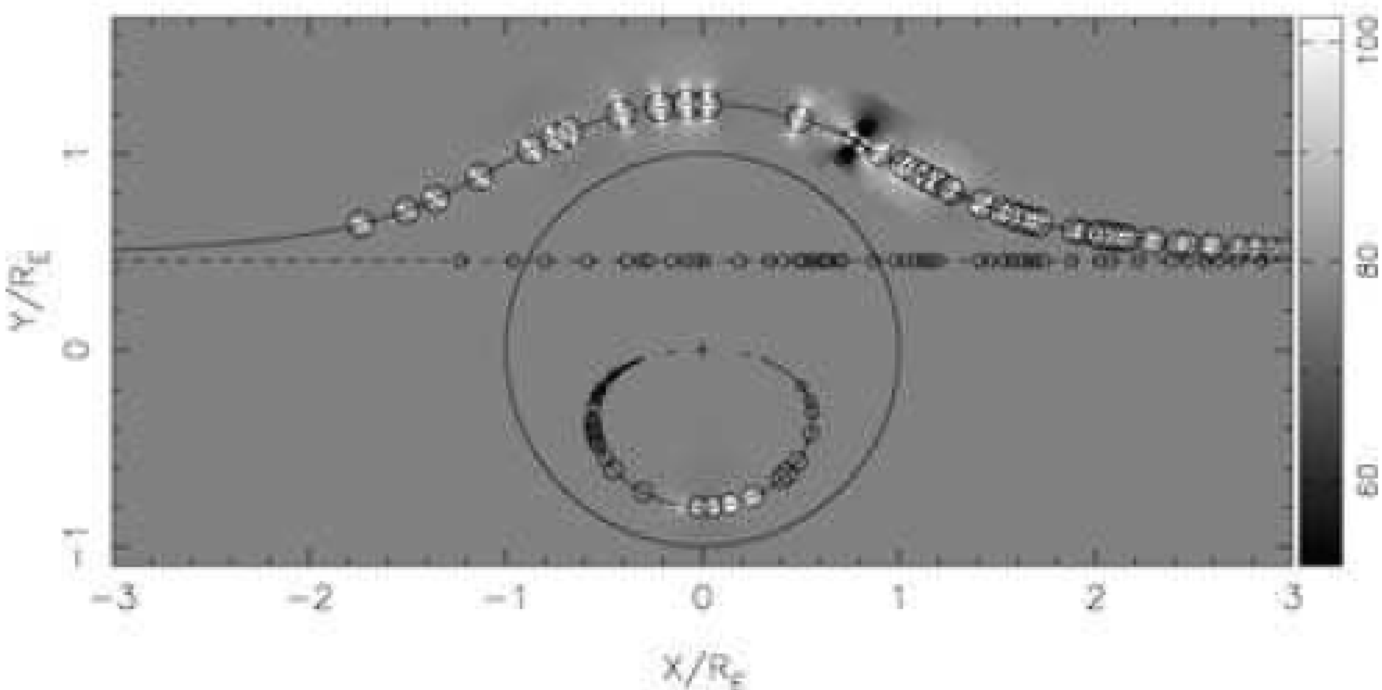
Dong+2006



Planet exclusion plots – low-mag

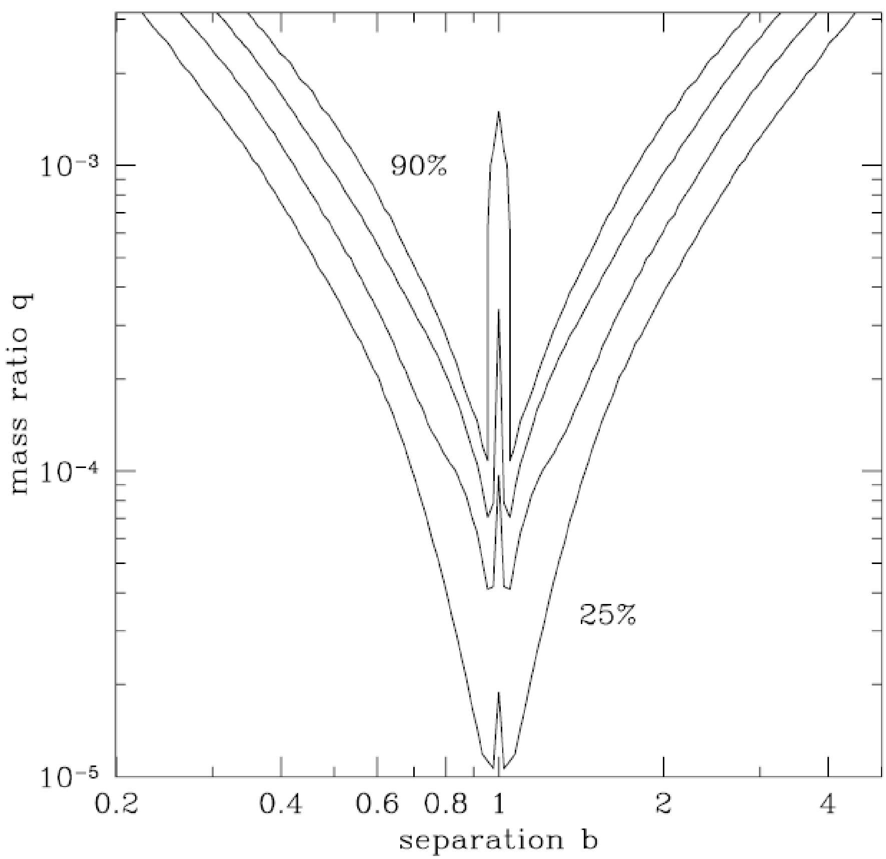


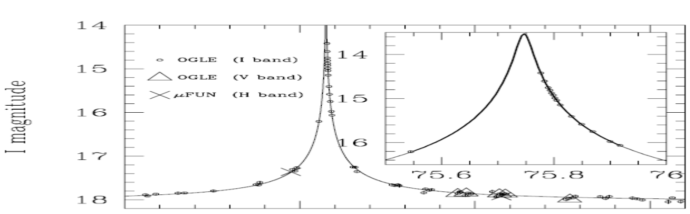
Snodgrass+2004



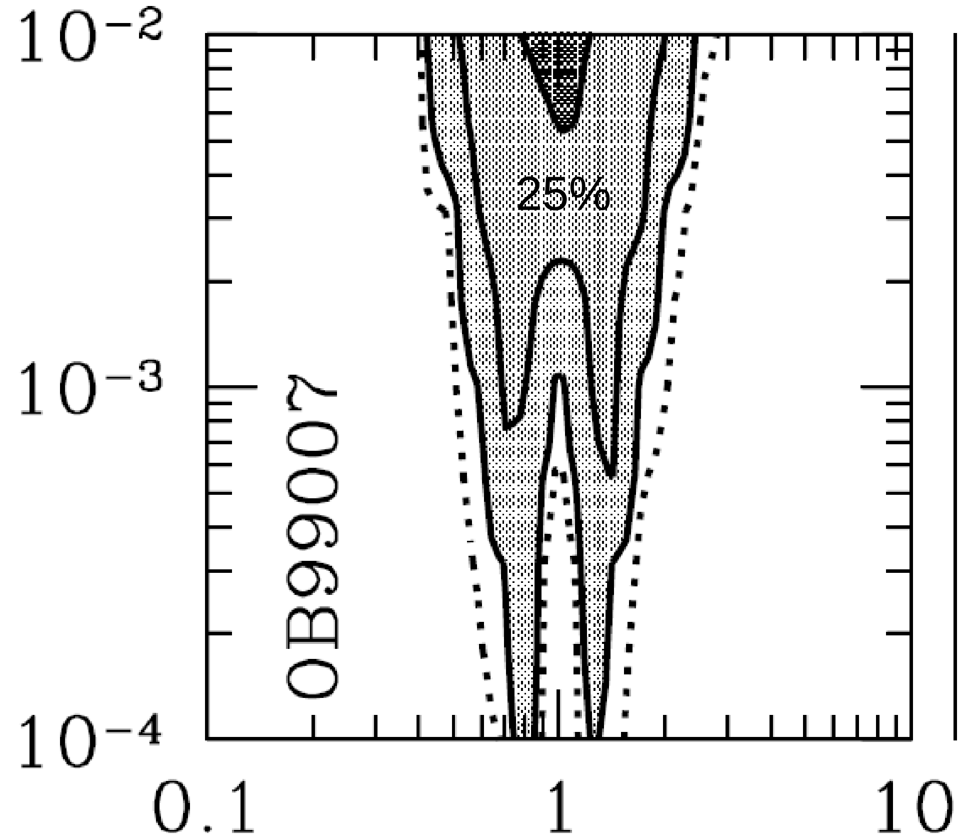
Detection efficiency maps

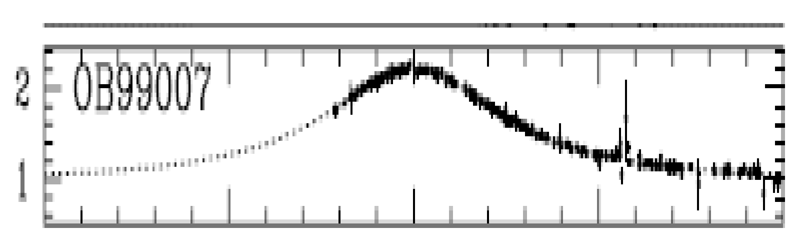
High-magnification (Dong+2006)





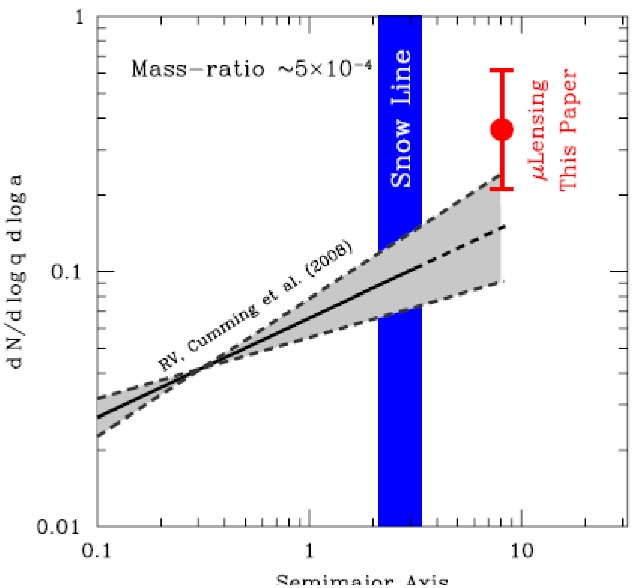
Low-magnification (Gaudi+2002)

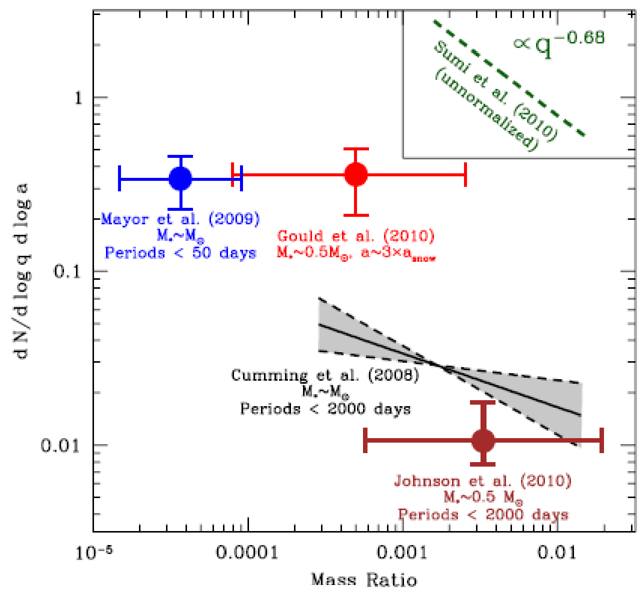




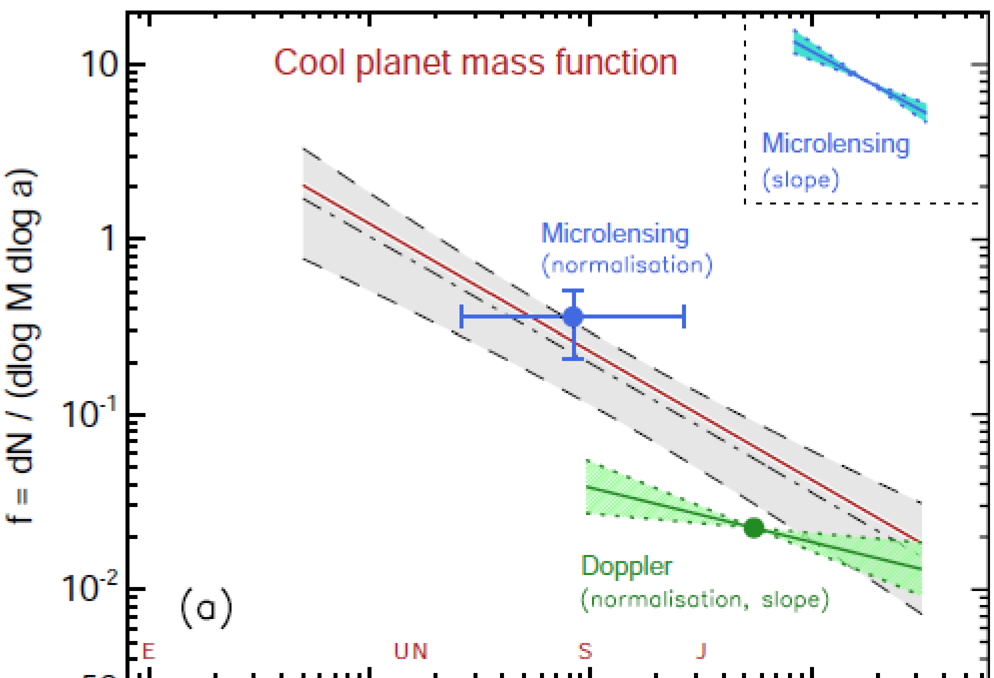
Gould+2010
Sumi+2011
Cassan+2012

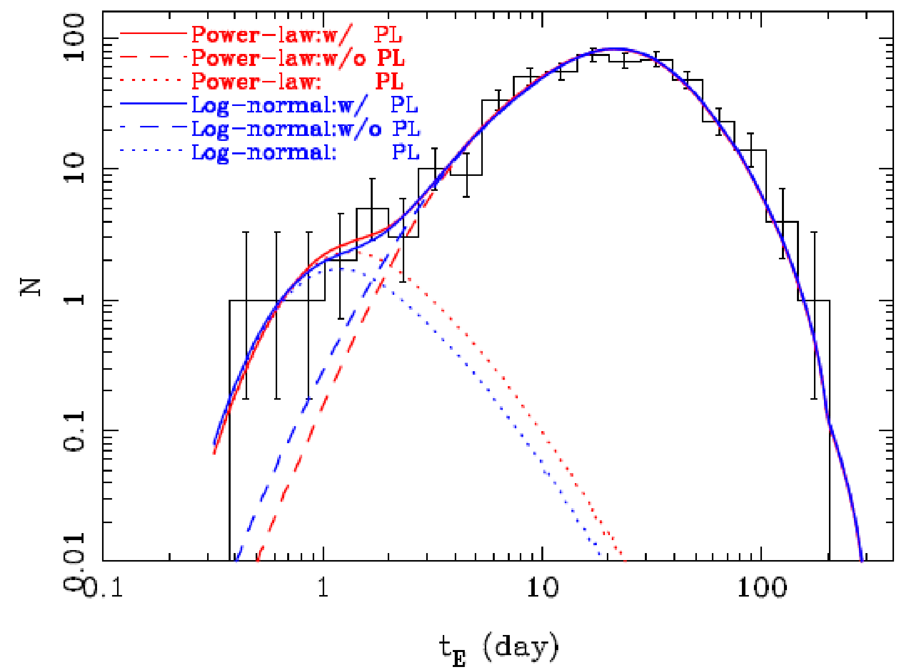
Results so far





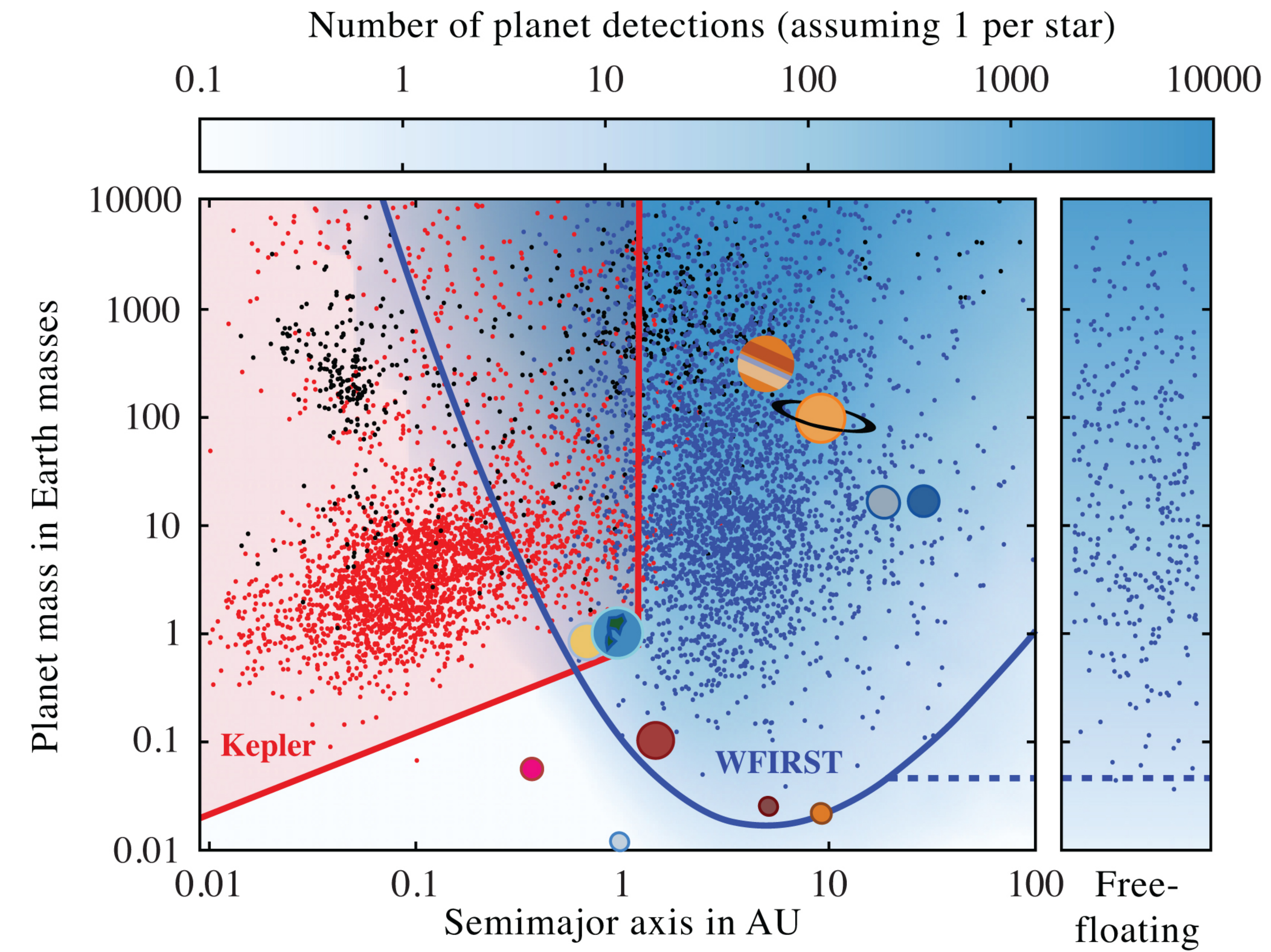
- Cool planets
  - $N \sim M^{-0.7}$
  - N~0.3 giants/star
  - ~2 FFPs/star





New experiments will make robust demographics possible

- OGLE, MOA and KMTNet are conducting blind, high-cadence observations over ~10 sq degrees and will find 10s of planets per year
- Spitzer and K2 Campaign 9 are and will revolutionize mass and distance measurements for large samples of microlensing planets
- WFIRST-AFTA and EUCLID will measure the demographics of Earth- and Mars-mass planets from 1 AU outwards



Number of planet detections (assuming 1 per star)
0.1
1
10
100
1000
10000
Planet mass in Earth masses
10000
1000
100
10
1
0.1
0.01
Kepler
WFIRST
0.01
0.1
1
10
100
Semimajor axis in AU
Free-
floating

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