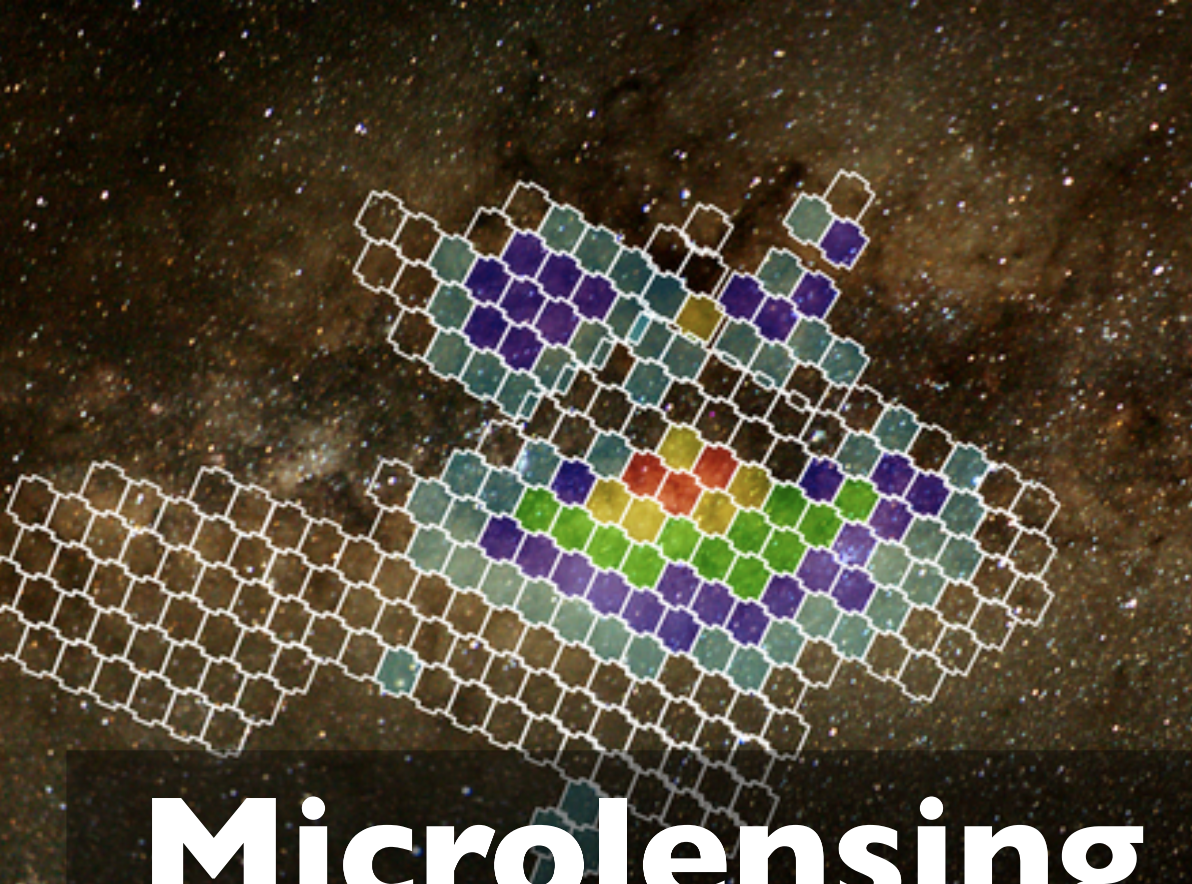
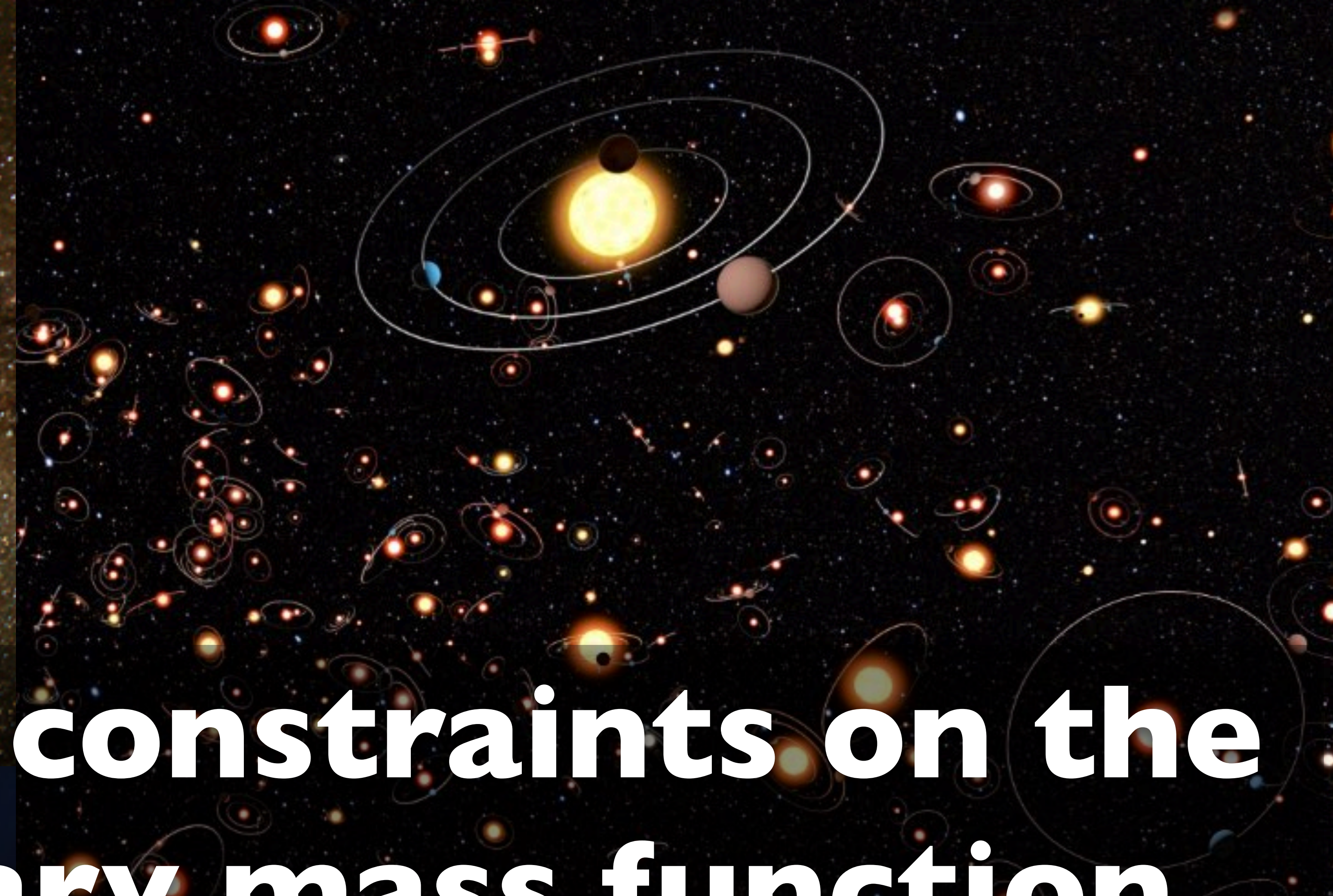
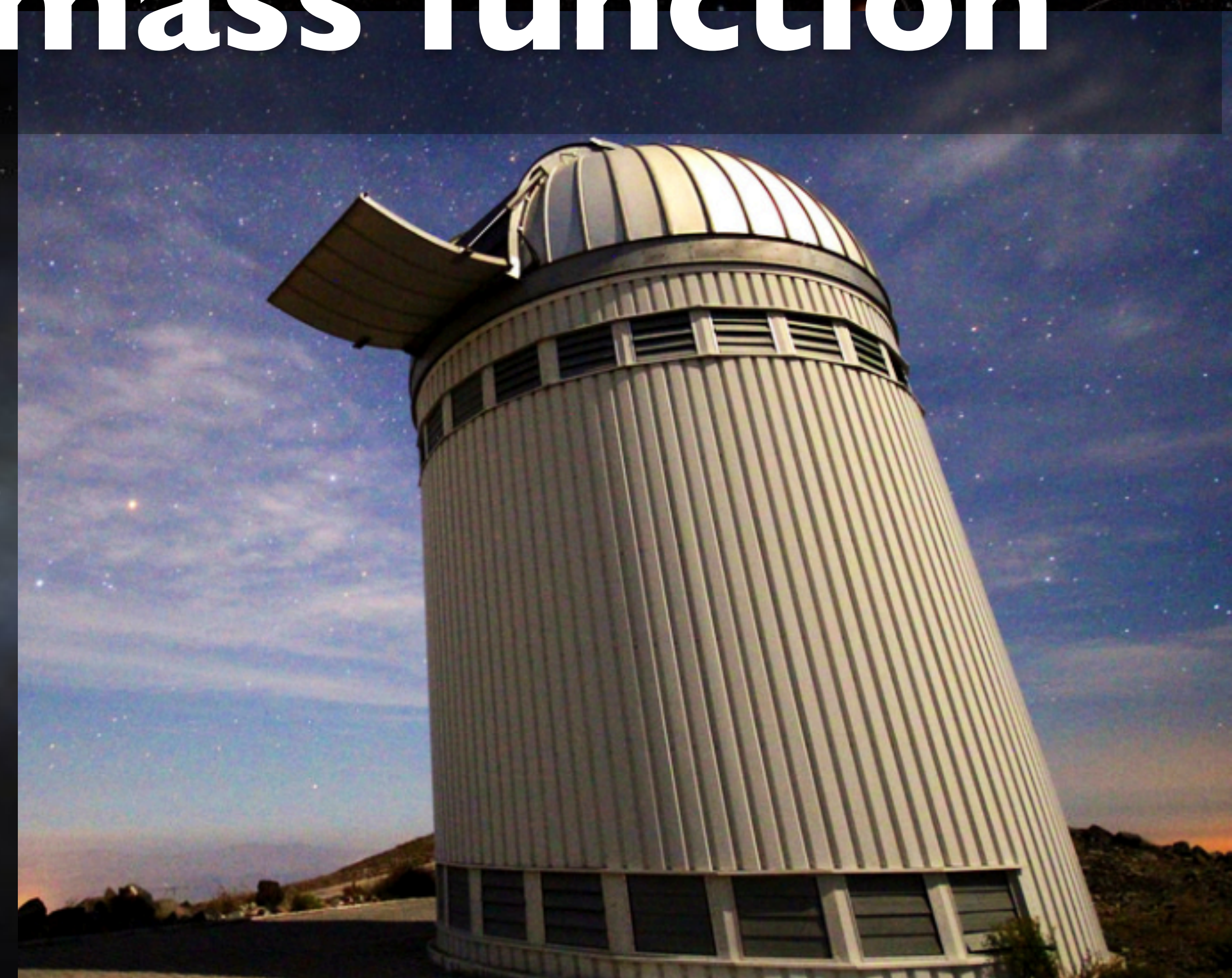


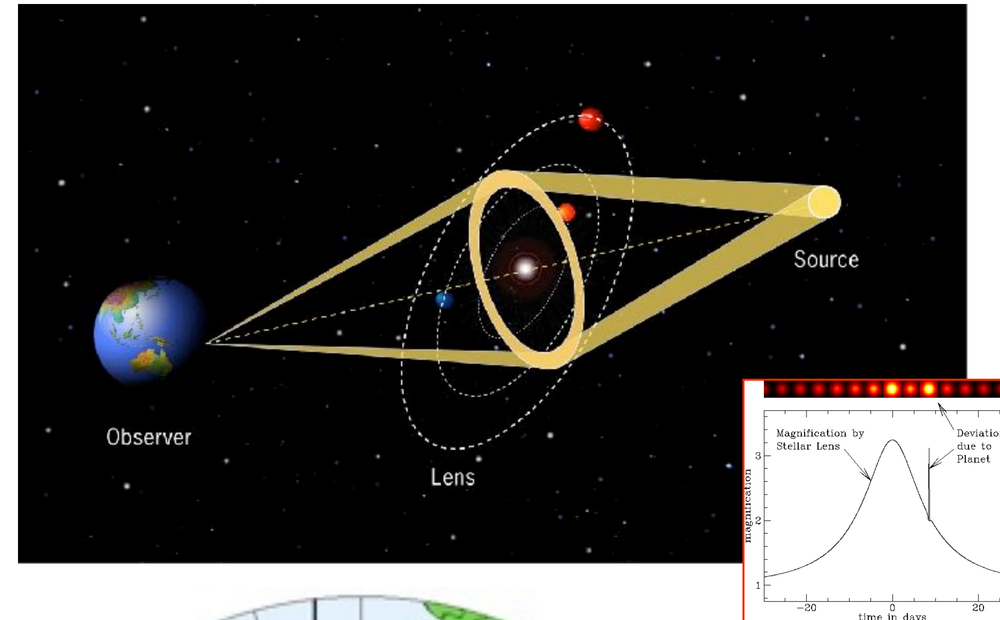


Microlensing constraints on the cool planetary mass function

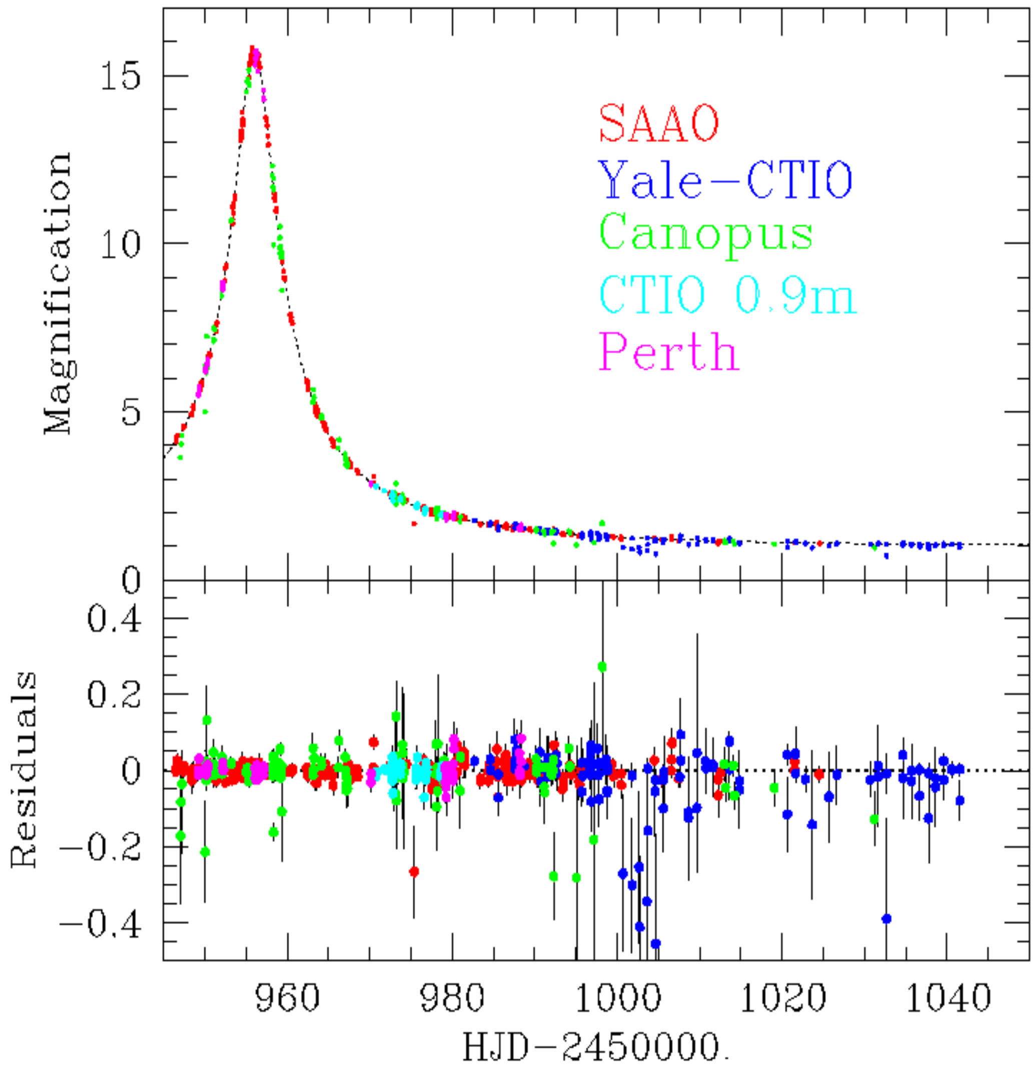


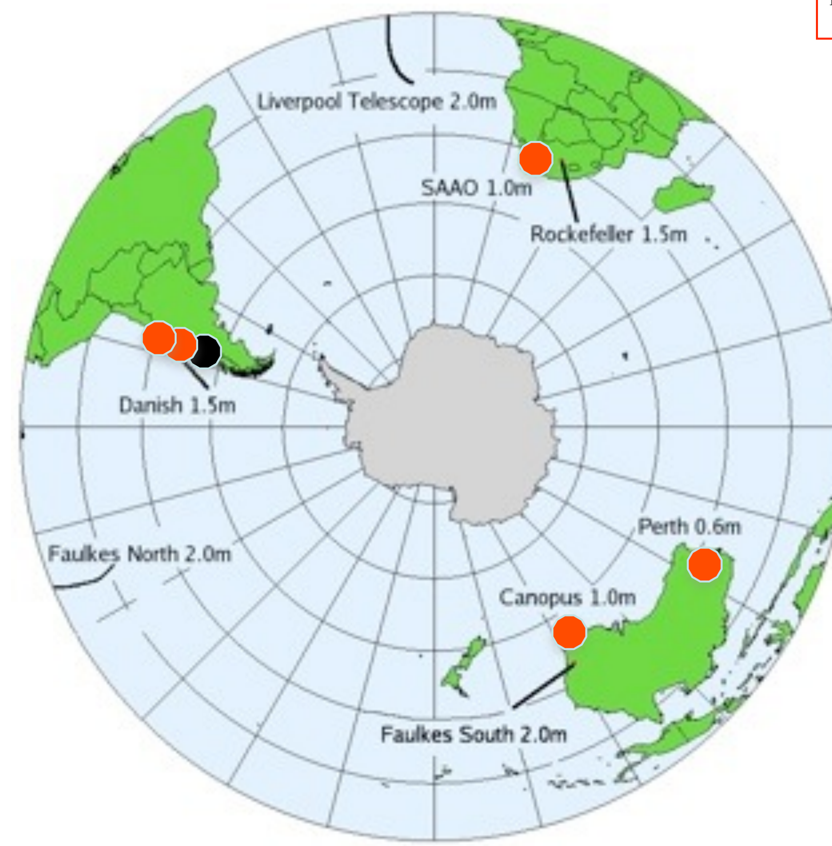
Arnaud Cassan
Institut d'Astrophysique de Paris
Université Pierre et Marie Curie

The “follow-up” strategy



Alert and **follow-up** strategy
(“round-the-clock” monitoring) :



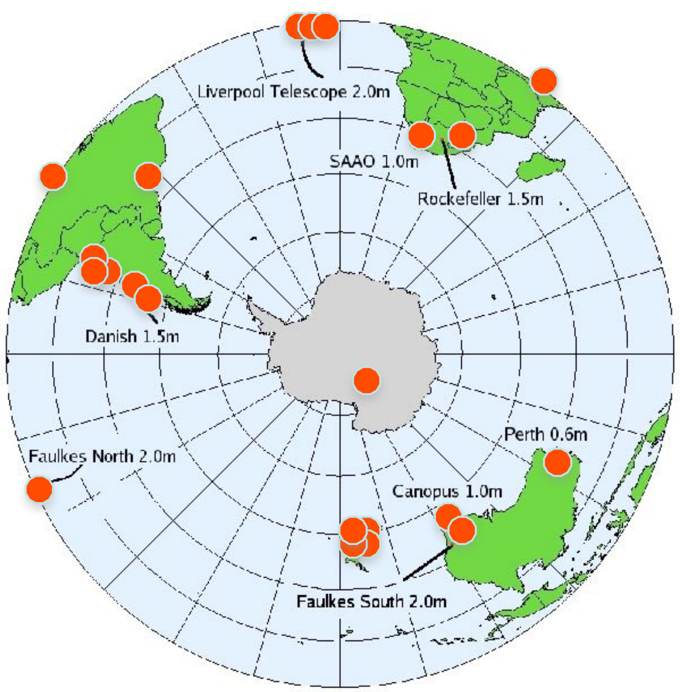


Alerts : OLGE, MOA

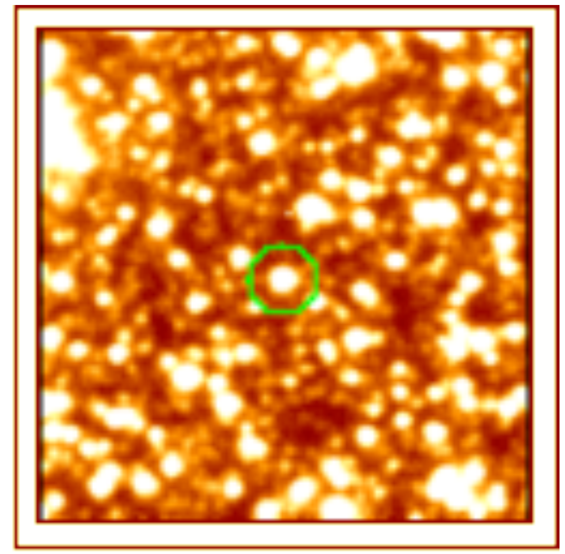
Follow-up : PLANET, μFUN, RoboNET, LCOGT, MiNDSTEp, MONET, amateur telescopes, …

The “follow-up” strategy

Observatories



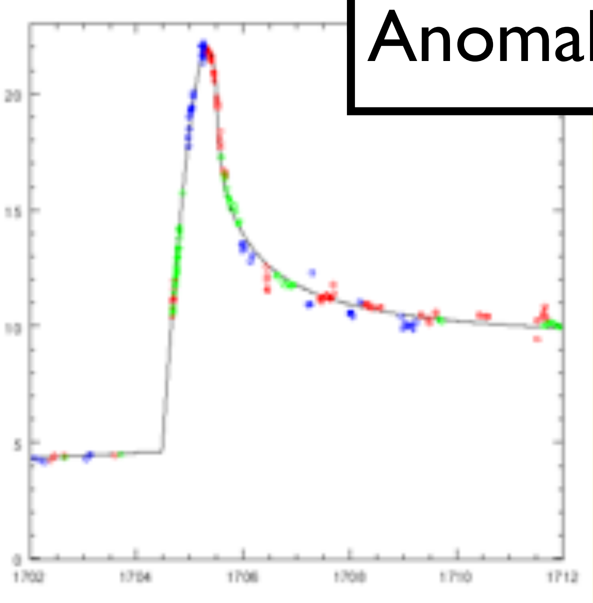
raw data



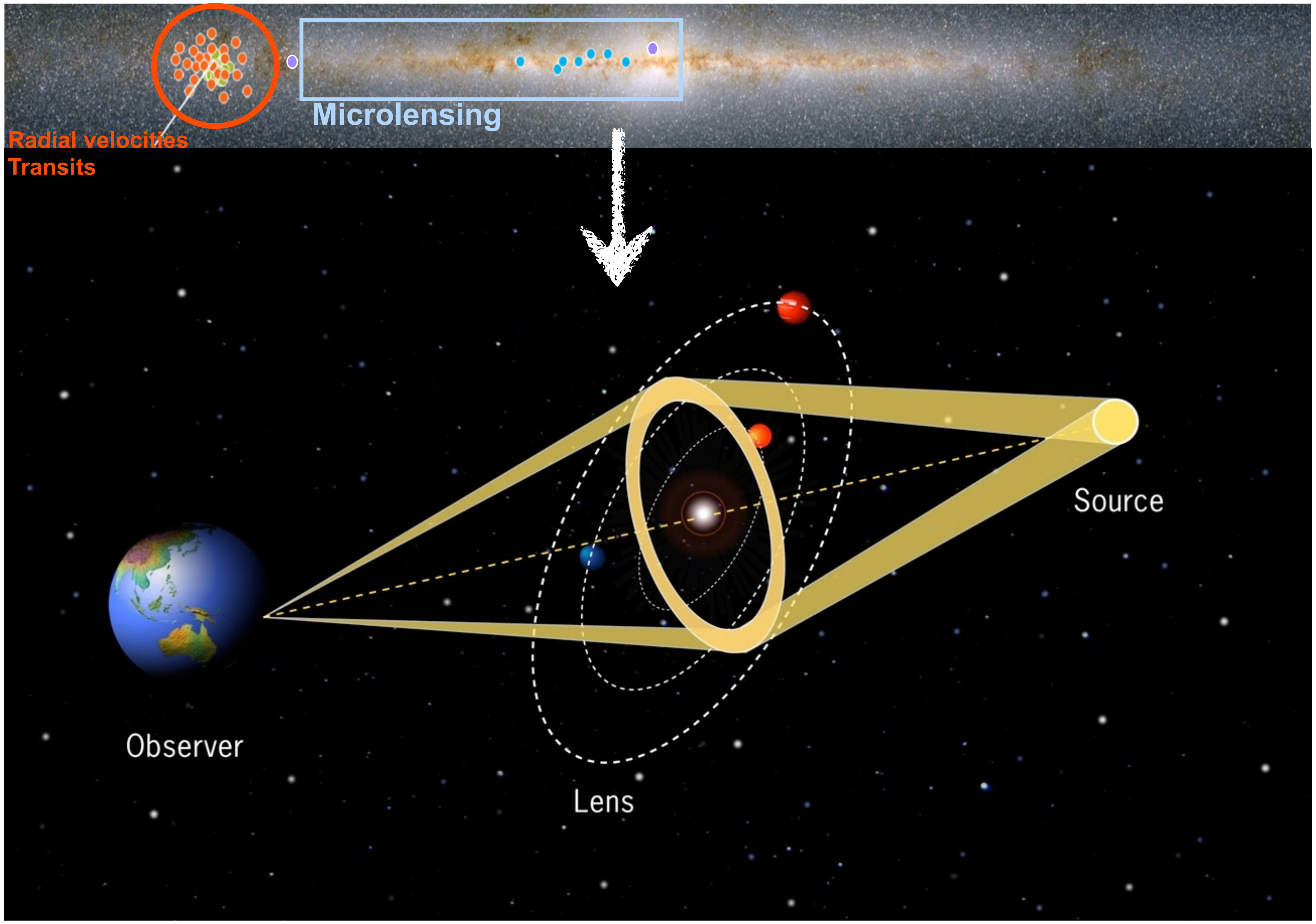
- Online reduction
- Real-time modeling

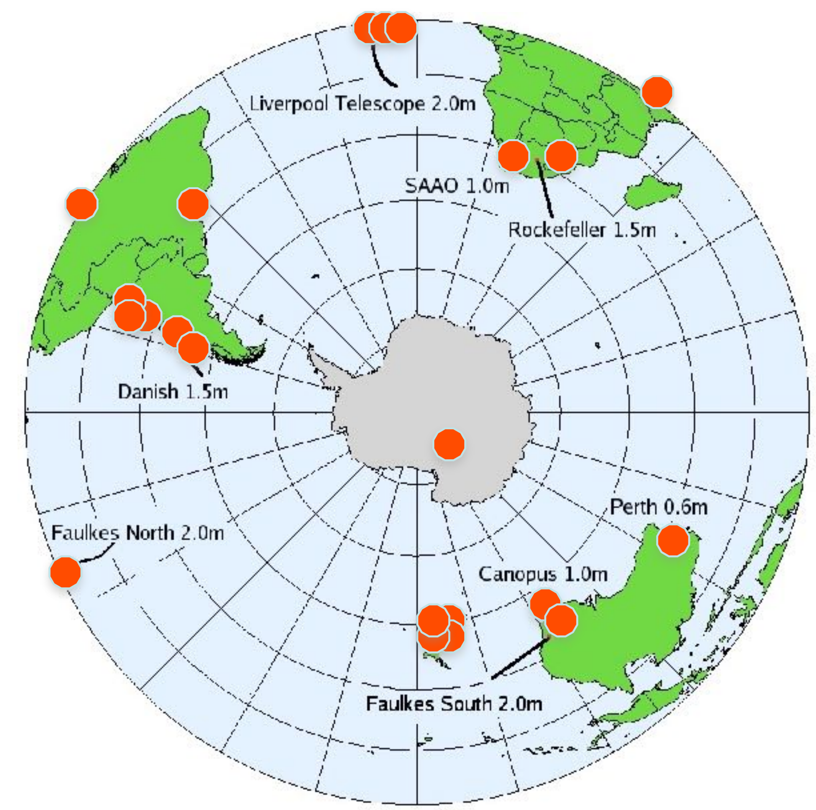
Homebase
- light curves modeling
- observational strategy
- public alerts
- anomaly predictions

Anomalous light curve



The "follow-up" strategy



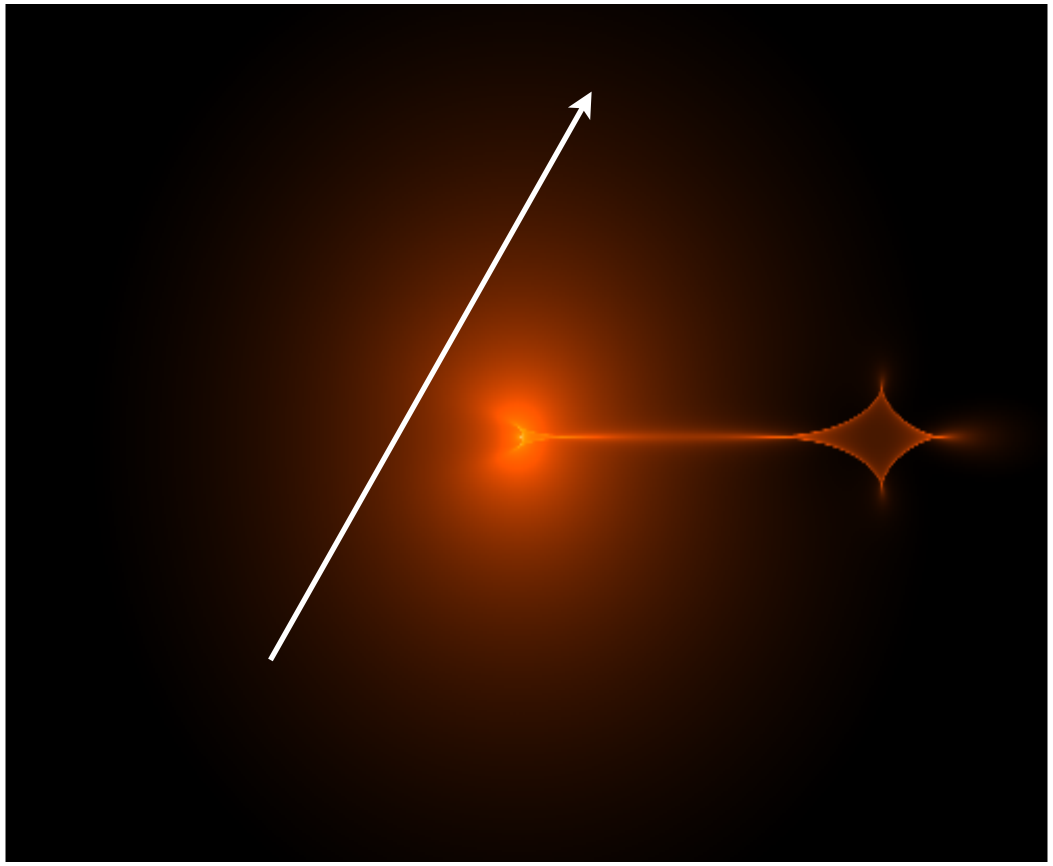


➟ **Large increase of microlensing alerts since season 2002**
- OGLE II (1998-2000): ~50 events/year
- OGLE III (2002-09): ~600 events/year
- OGLE IV (2011+): ~1500 events/year

➟ **Today OGLE+MOA: ~2500+ events/year!**

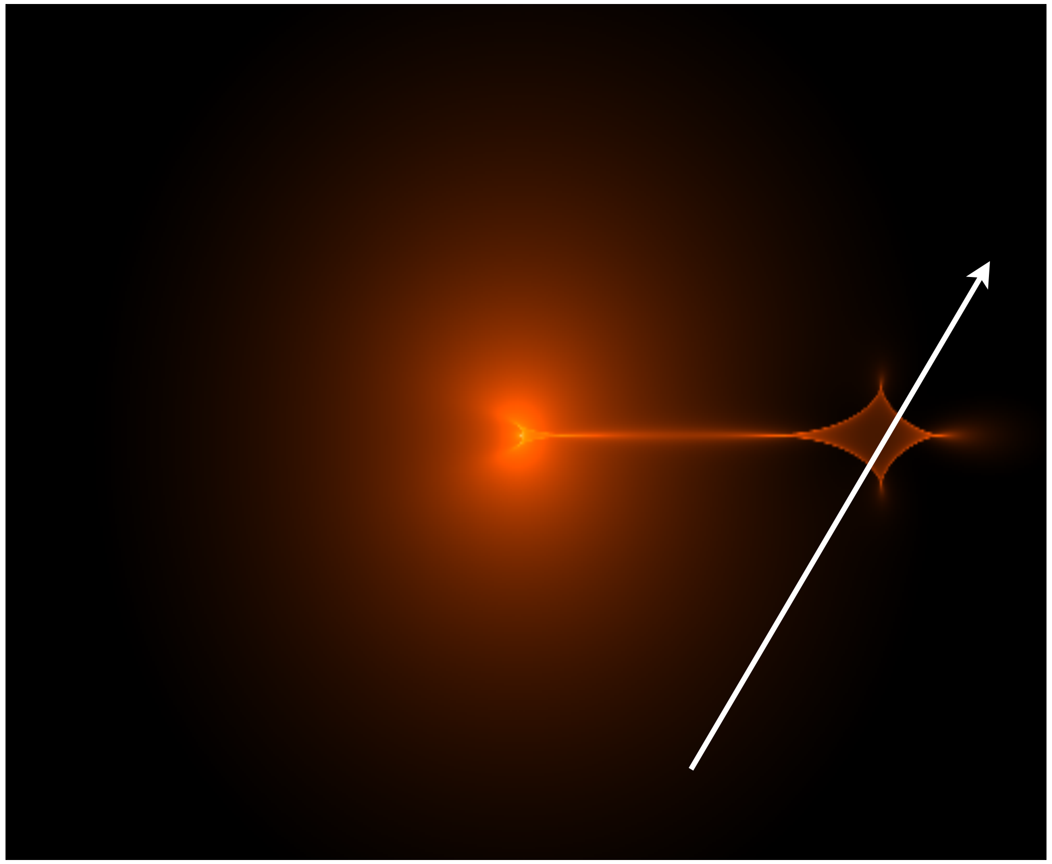
The “follow-up” strategy : Two detection channels

1) The **high-magnification** channel
= central caustic



Griest & Safizadeh (1998)

2) The planetary caustic channel
= secondary caustic



Albrow et al. (1995)

First microlensing constraints on exoplanet frequency

First microlensing campaigns **1995-2002:**
No giant planet detections ?

… if giant planets at 1 AU were frequent (cf. Solar system), microlensing would detect many planets, but no planet was found (until 2003)!

Griest & Safizadeh (1998), Gould & Loeb (1992)

- 1995-2000 sample : less than 1/3 of the lens stars have Jupiter-mass companions, while less than 2/3 of the lenses have Saturn- mass companions in the orbital range 1.5 − 4 AU.

  Gaudi et al. (2002)

- 1998-2000 OGLE data : upper limit of 20% of Jupiter-mass planets

  Tsapras et al. (2003)

- 2002 OGLE data : upper limit of 18% for Jupiters at 4 AU

  Snodgrass et al. (2004)

- 2006 : no giant companion to OGLE 2005-BLG390Lb : cool giants are rare

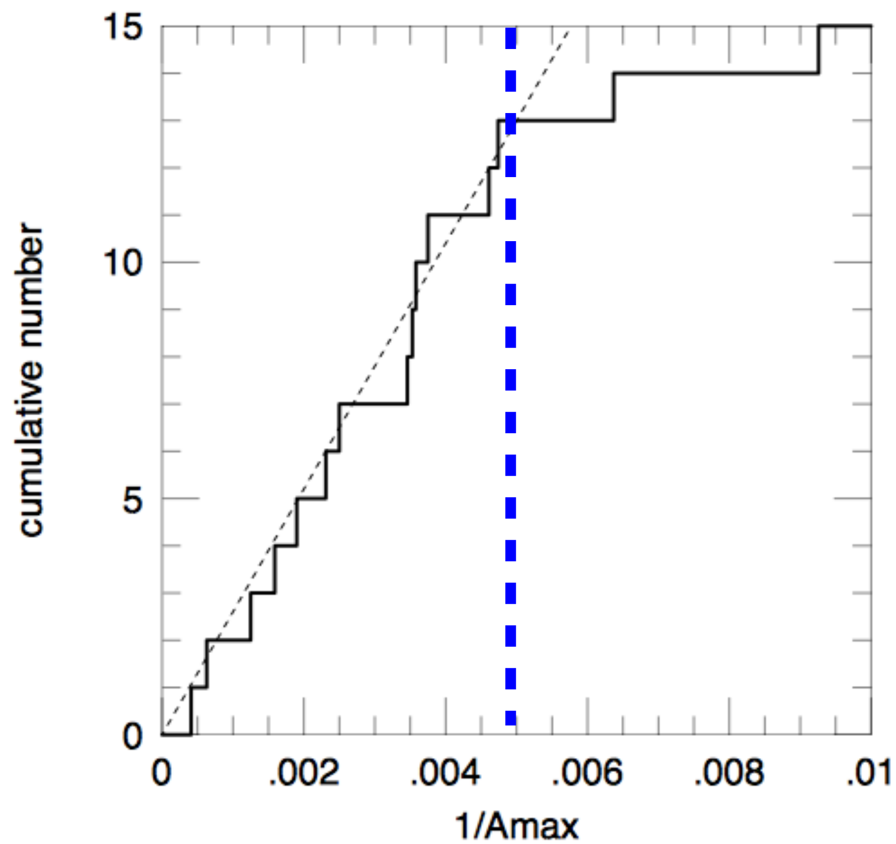
  Kubas, Cassan et al. (2008)

- 2010 and a few more Neptune-mass planets : cool Neptunes are common

  Sumi et al. (2010)

The high-magnification sample, 2005-08

- unbiased sample of 13 high- magnification events with peak magnification greater than 200 :



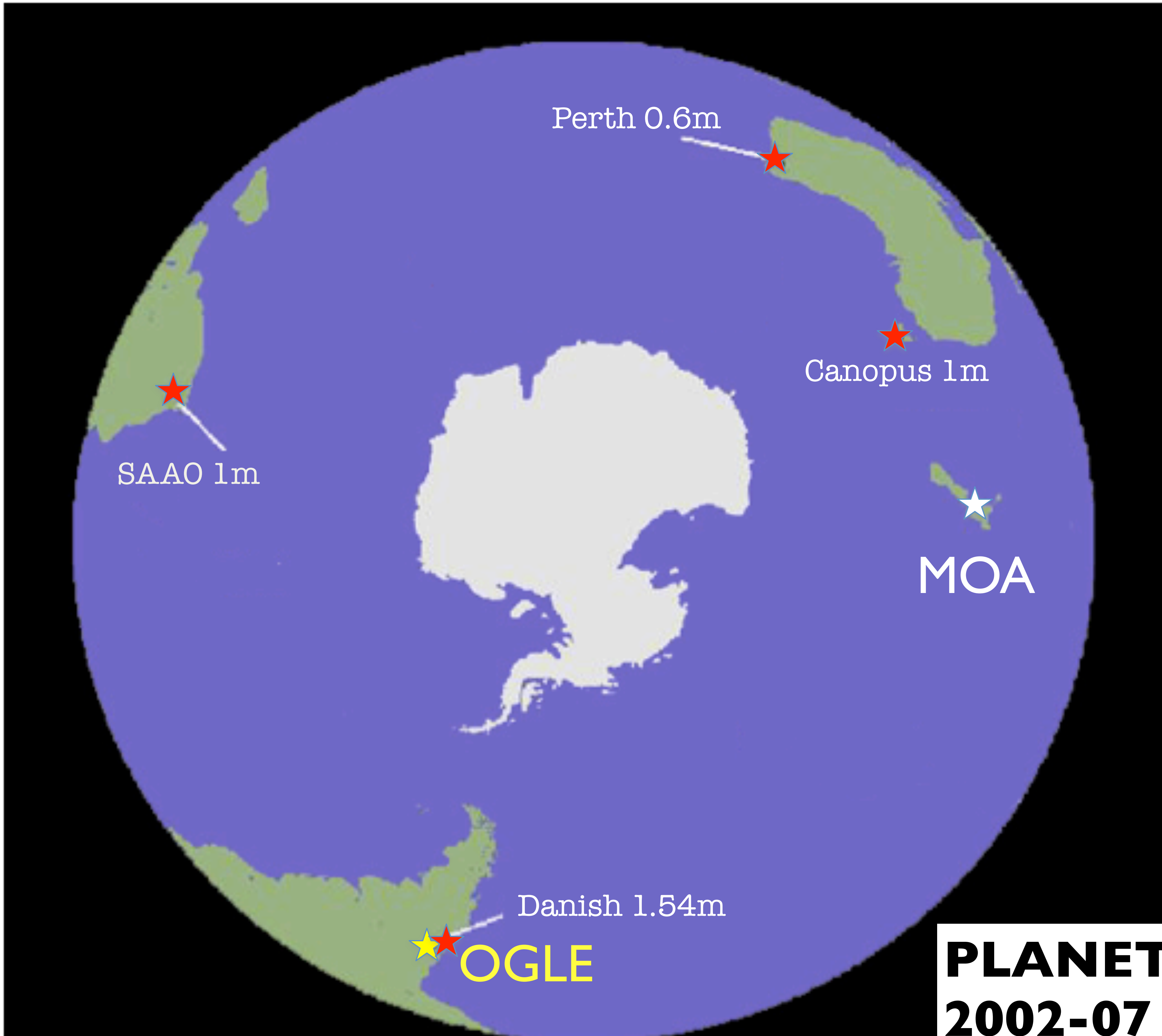
- One point on the planet mass function around q = 5×10^{-4} :

$$\frac{d^2 N_{\rm pl}}{d \log q \, d \log s} = (0.36 \pm 0.15)\, {\rm dex}^{-2}$$

- First estimate of ~1/6 for the frequency of solar-like systems

Gould et al. (2010)

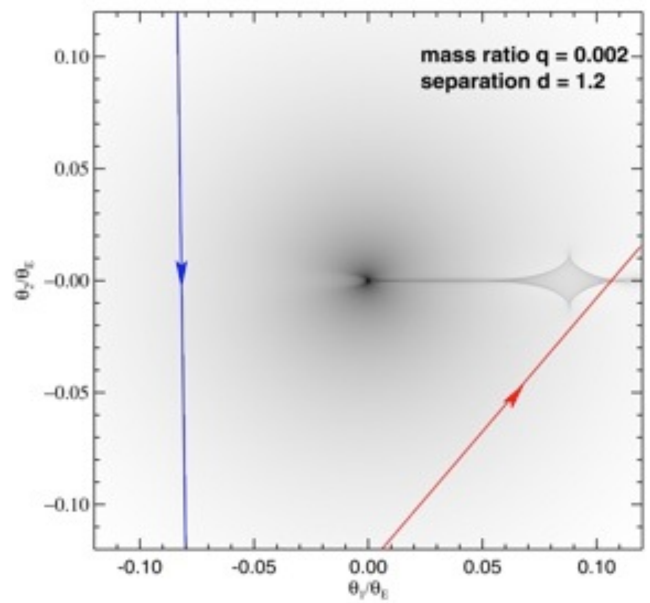
2002-07 PLANET + OGLE microlensing constraints on the cool exoplanet mass function Cassan+ (2012)

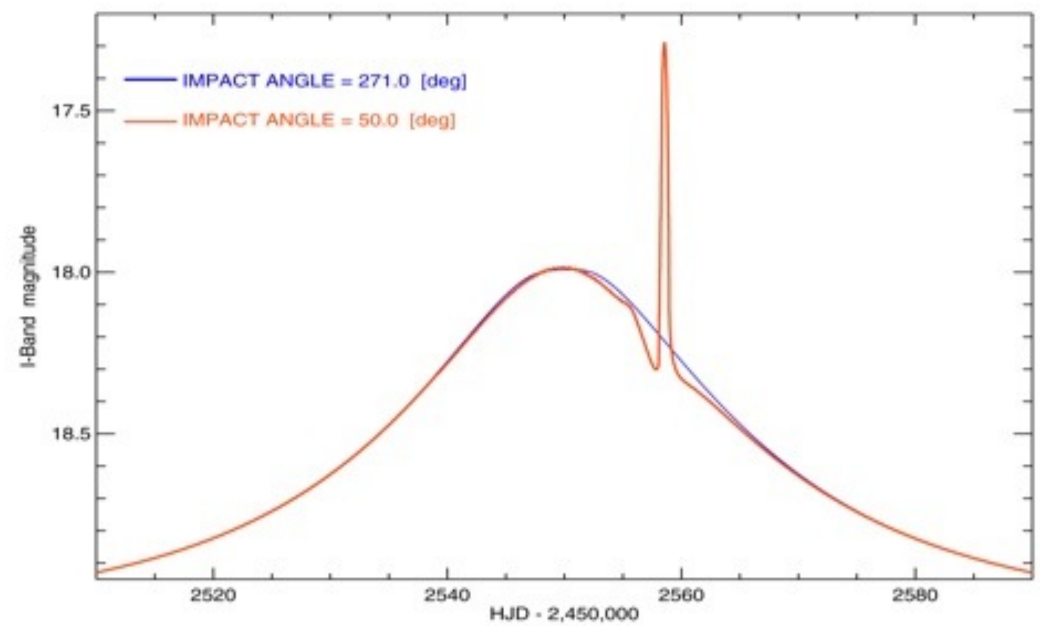


PLANET network 2002-07 + surveys

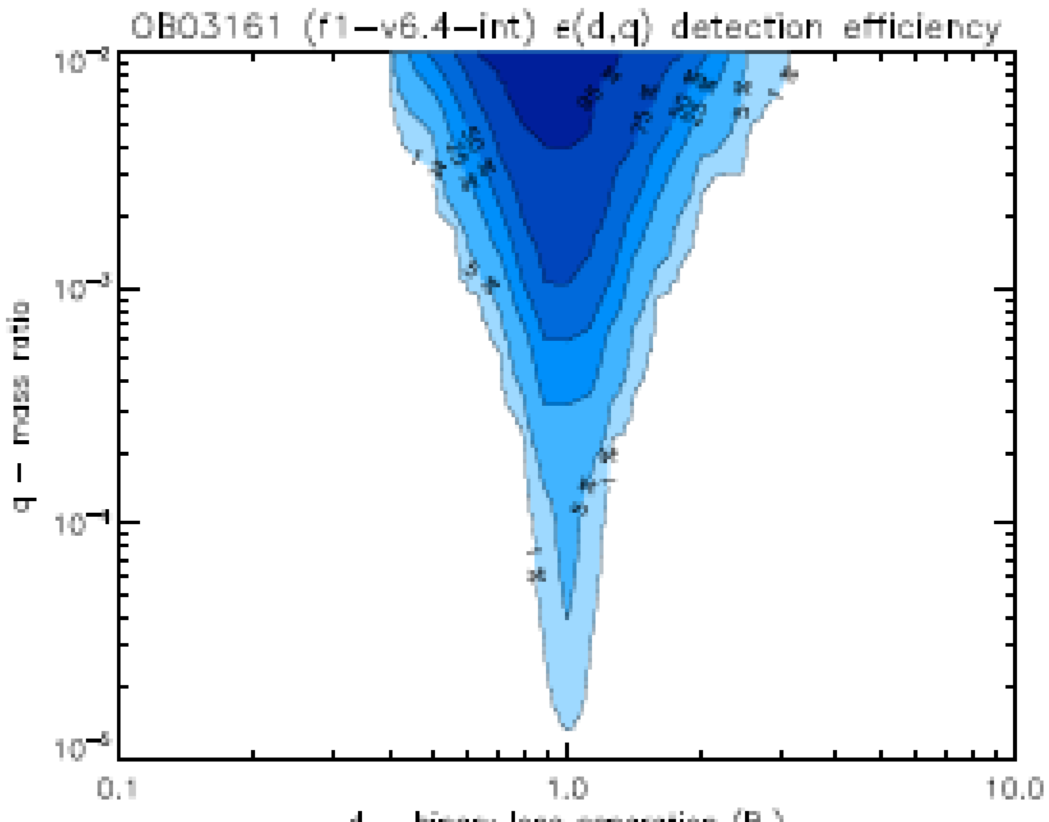
Microlensing planet detection efficiency

- Basic approach to detection efficiency :





- Detection efficiency diagram of an individual event :

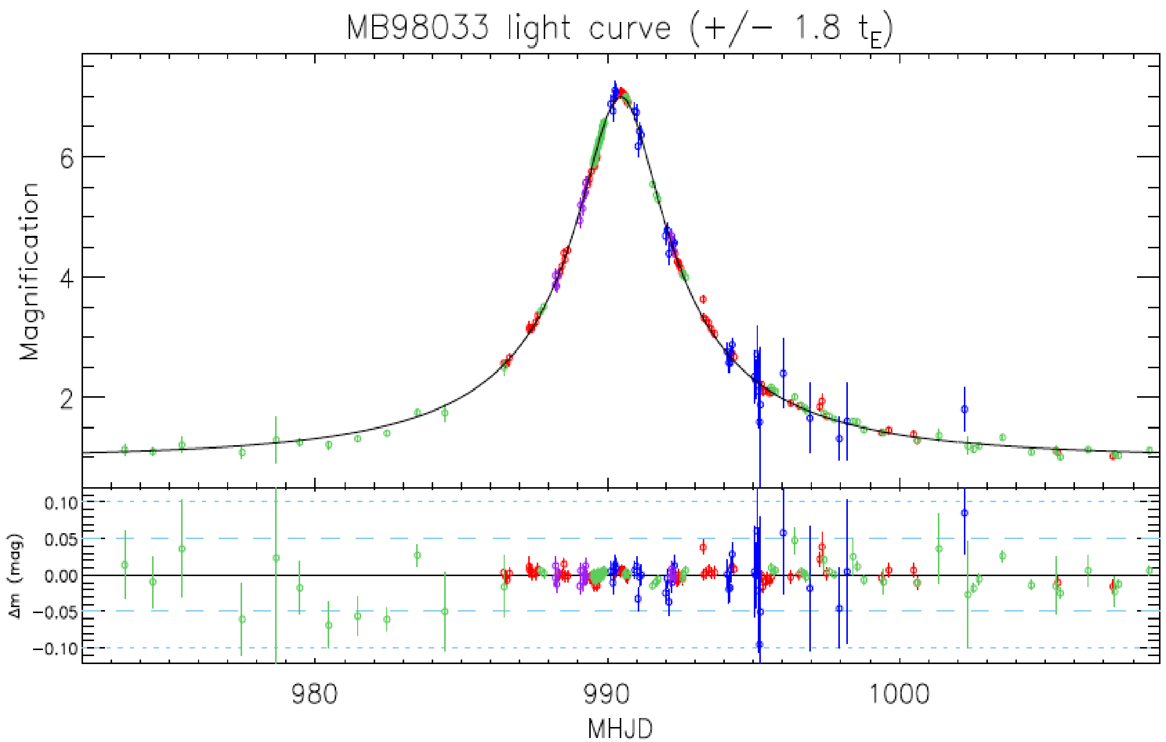


Gaudi & Sackett (1998),
Cassan (2005),
Kubas (2005),
Wambsganss (1997)

The method : Light curve modeling

- For every individual microlensing event, detection efficiency is computed using Gaudi & Sackett (2000)

- Light curves selection criteria :



1. the event does not show any kind of anomaly (including parallax, finite-source effects, source or lens binarity),
2. PLANET has obtained at least 20 data points for at least one site and passband,
3. the fractional uncertainty in the obtained impact parameter u_0 for the adopted model does not exceed 50 % .

\+ *few other technical things...*

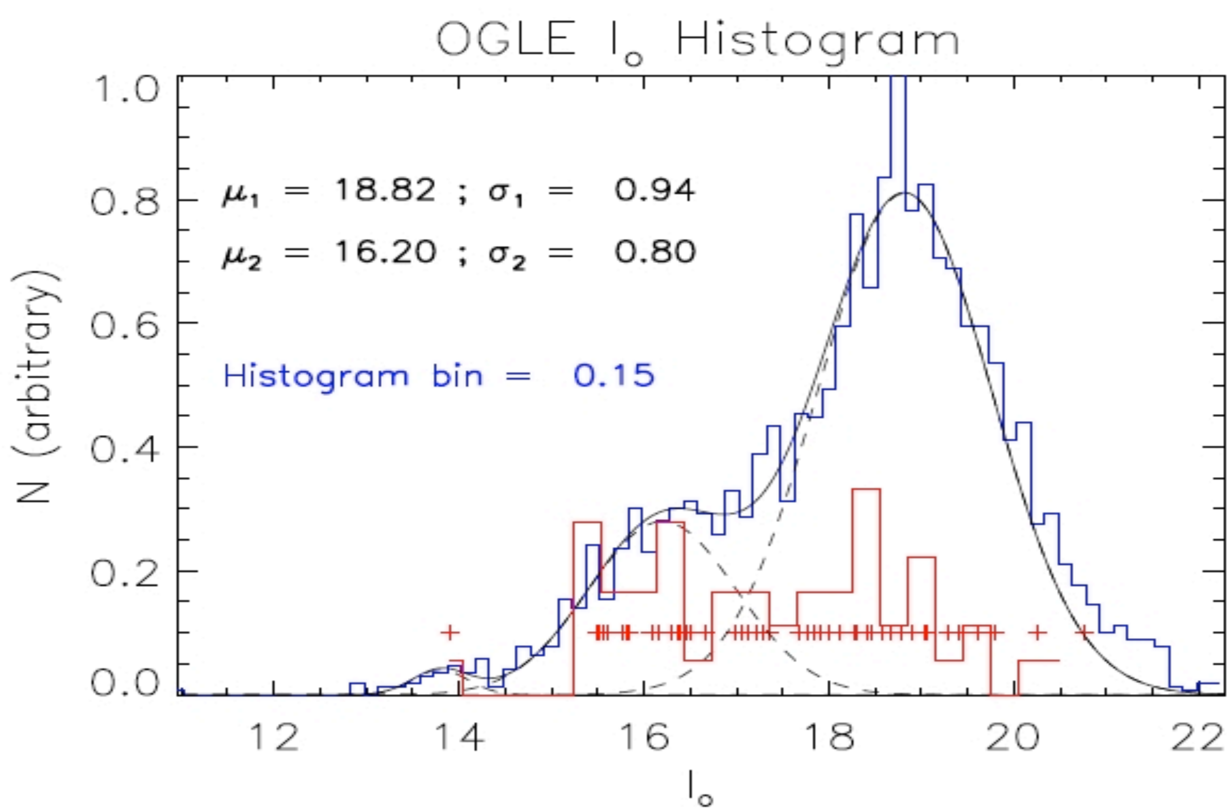
- In 2002-07 :

OGLE alerts: 389, 462, 608, 597, 581, 610

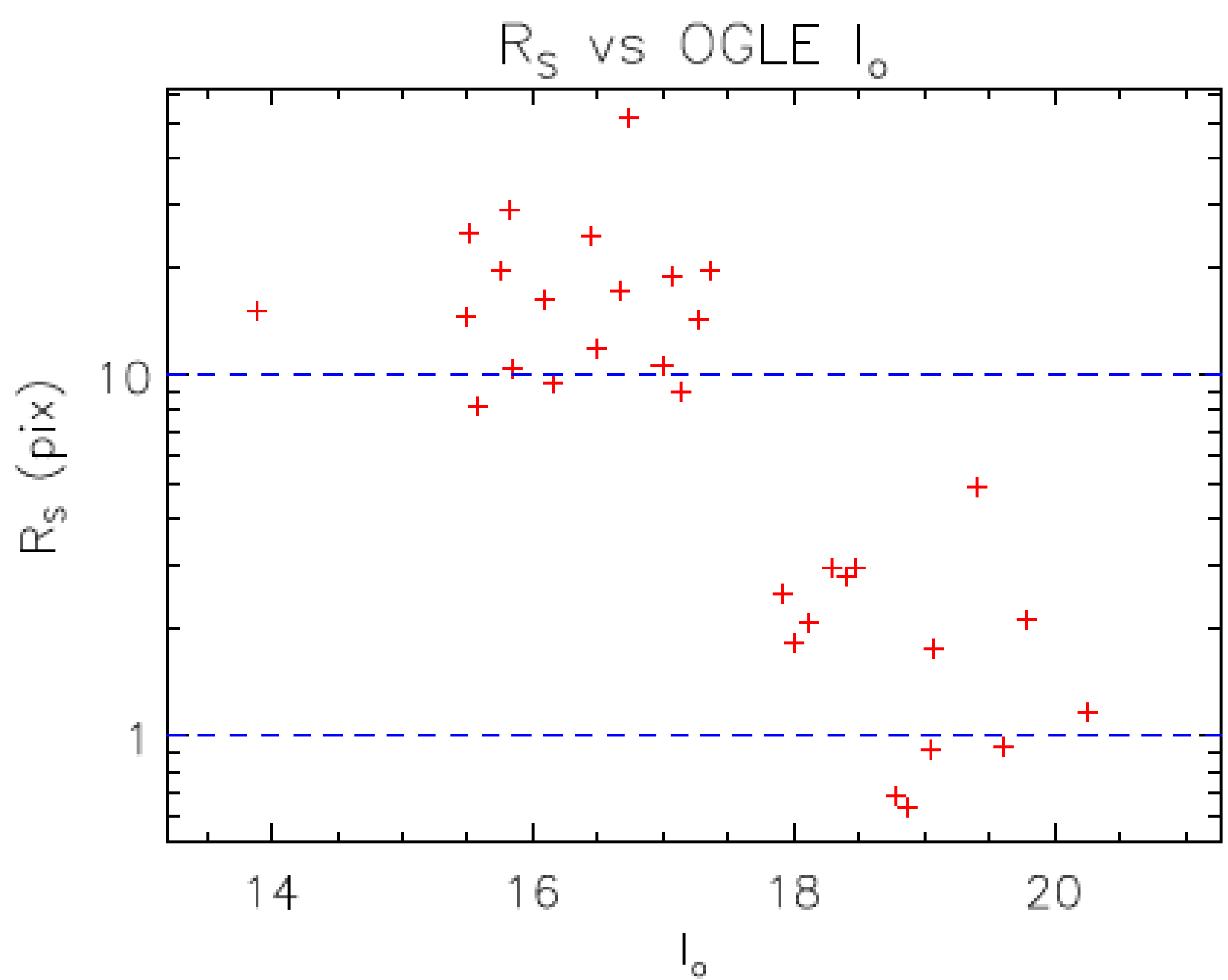
PLANET targets: 40, 51, 98, 83, 96, 72

[ratio PLANET/OGLE : ~10-16%, mean 13%]

Detection efficiency : estimating finite-source effects



OGLE Magnitude I

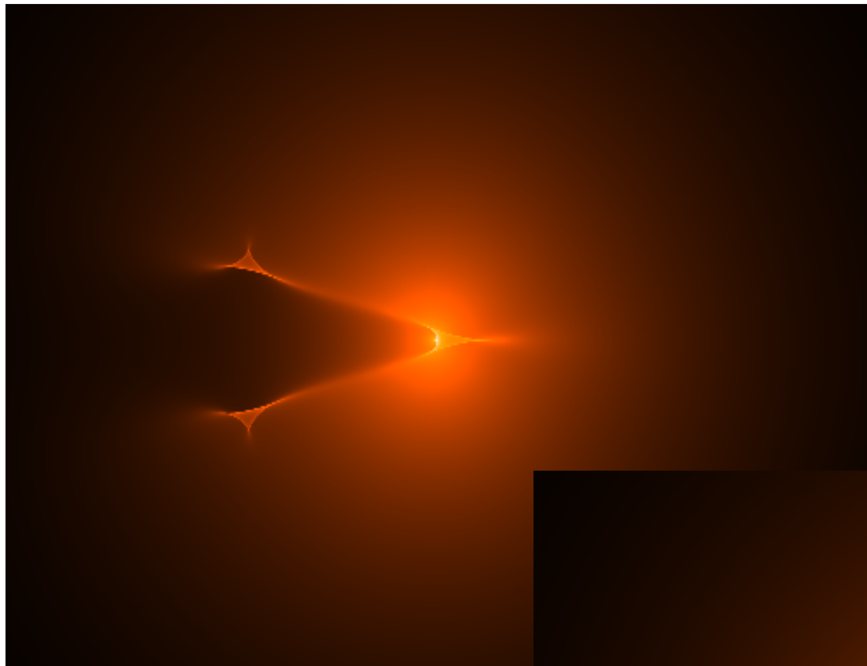


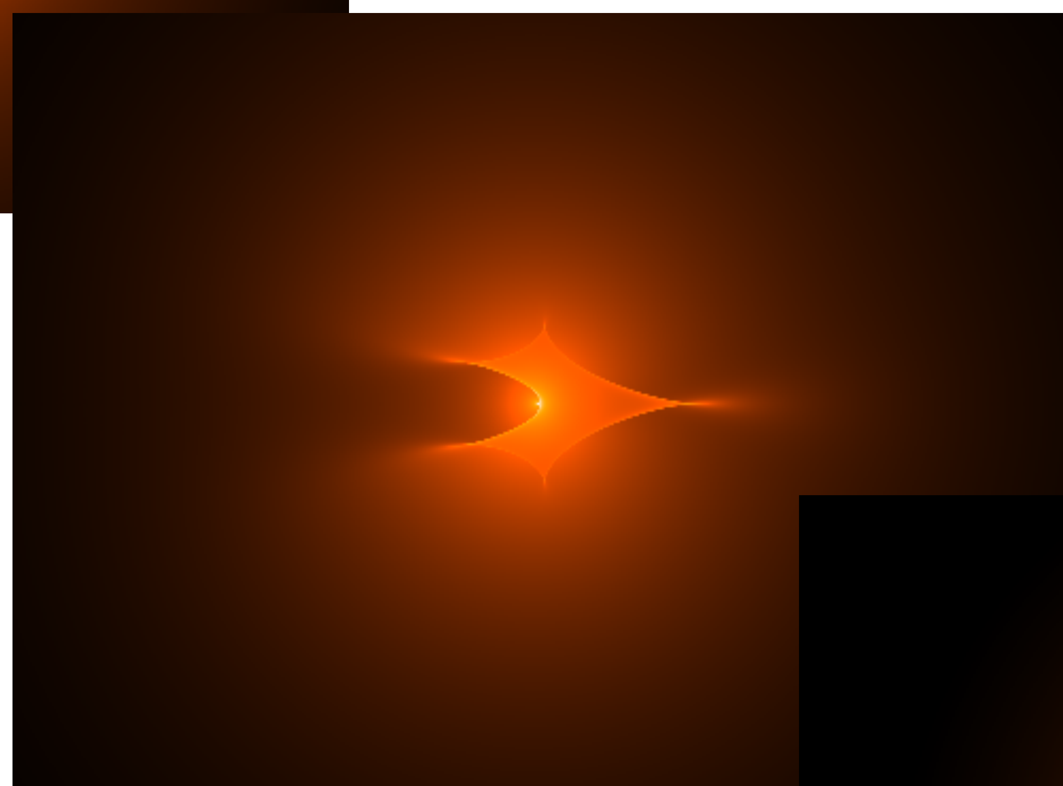
For a couple of events available on 2MASS : check with surface brightness relations the *I* vs. *Rs* estimation

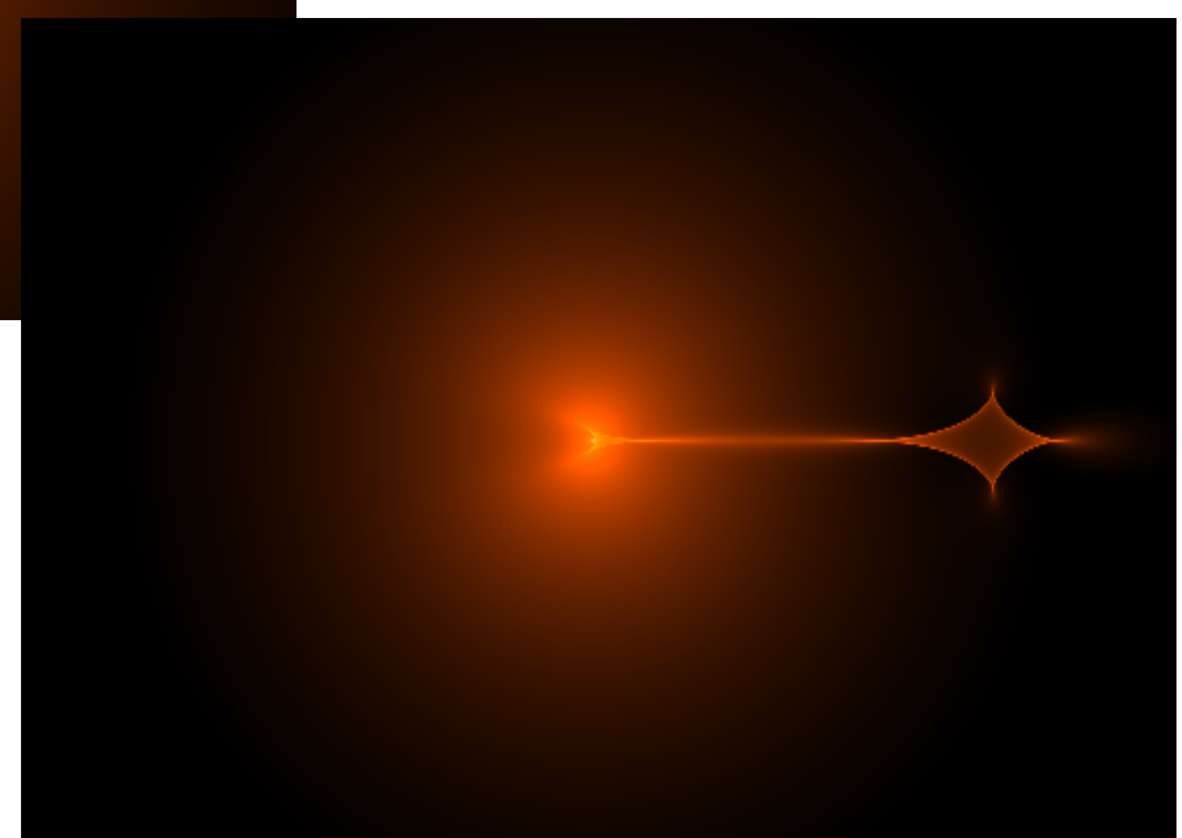
Estimated source radius

Magnification maps

- 230 pre-computed magnification maps
- Convolved with 3 different source radii
- 400 fitted trajectory / map



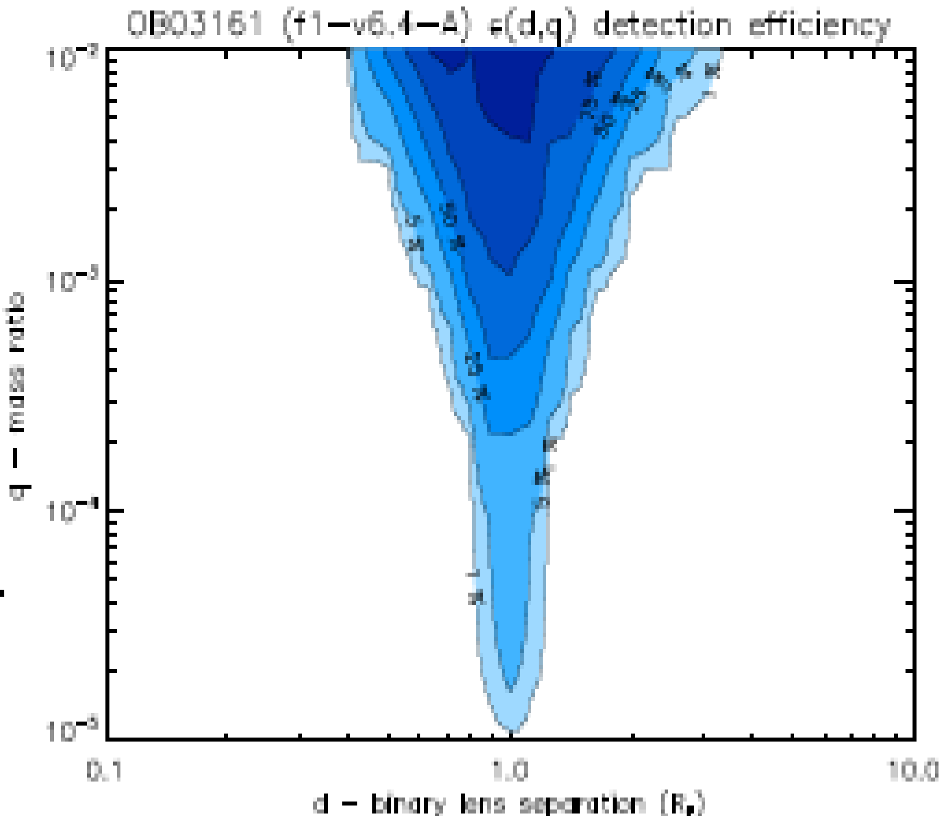




Detection efficiency : modeling finite-source effects

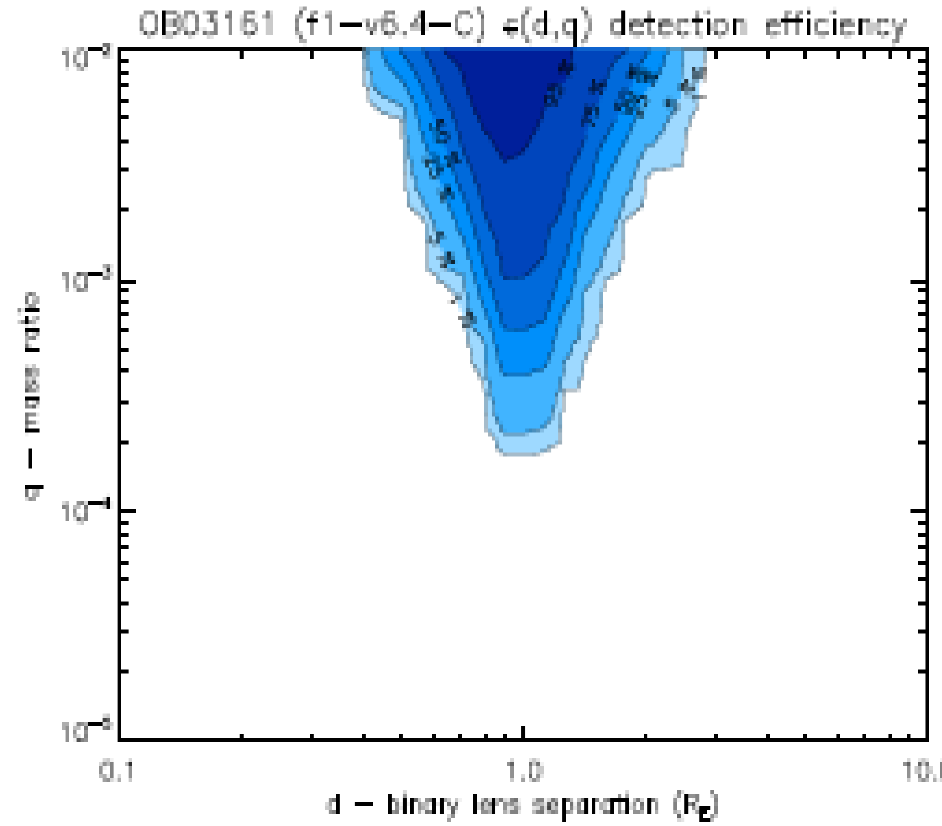
$Rs = 10^{-3}\ R_E$

Star-planet mass ratio

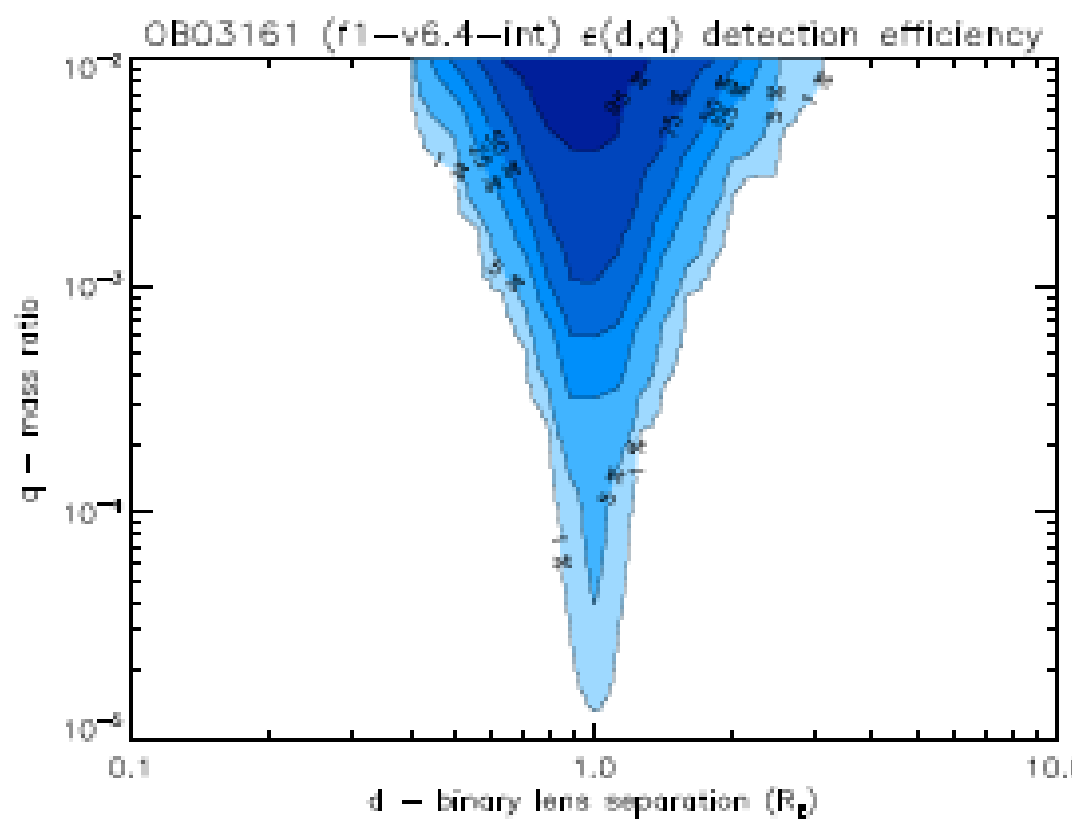


Star-planet separation (R_E)

$Rs = 10^{-2}\ R_E$

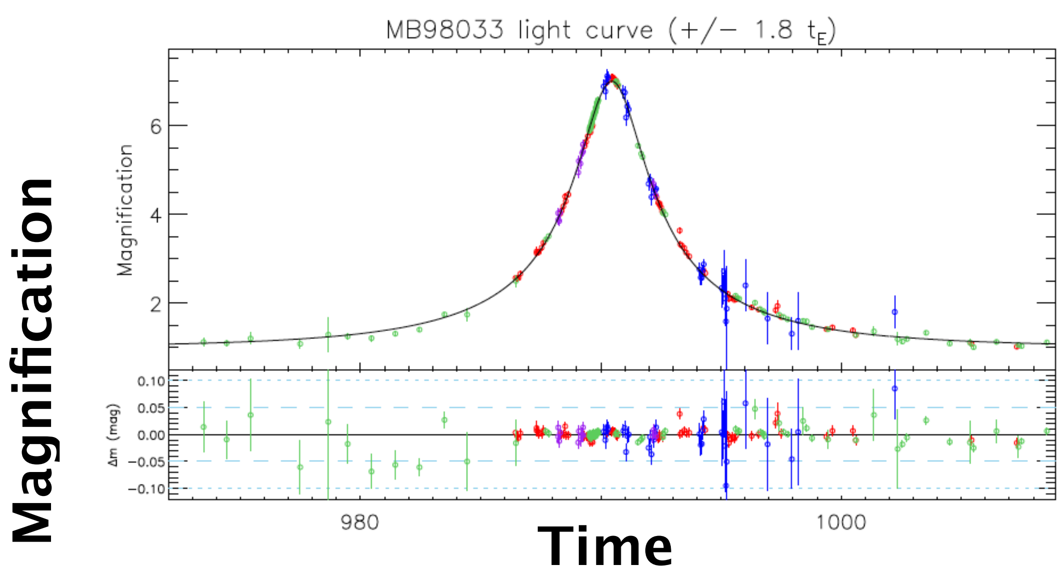


Interpolated efficiency diagram ➜

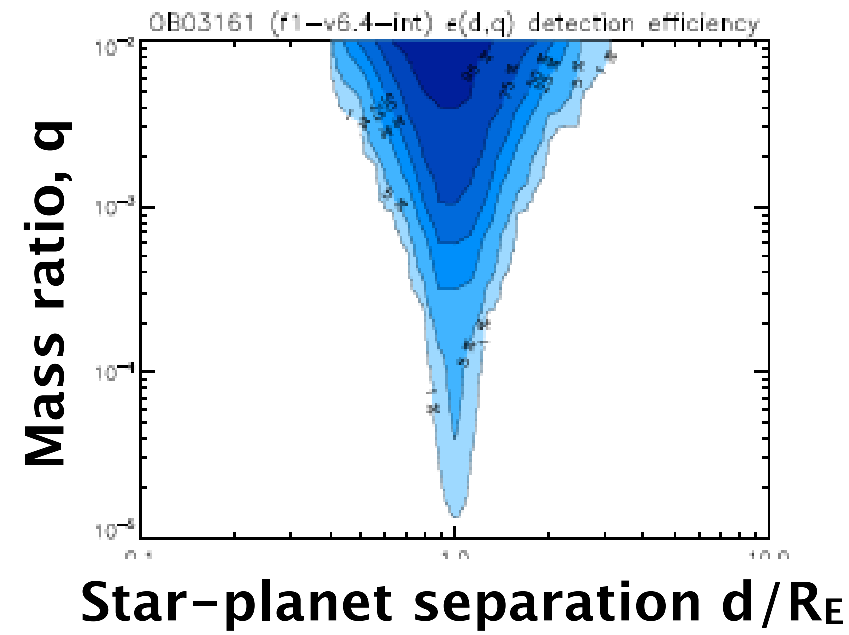


The PLANET+OGLE 2002-07 sample

Individual light-curve modeling

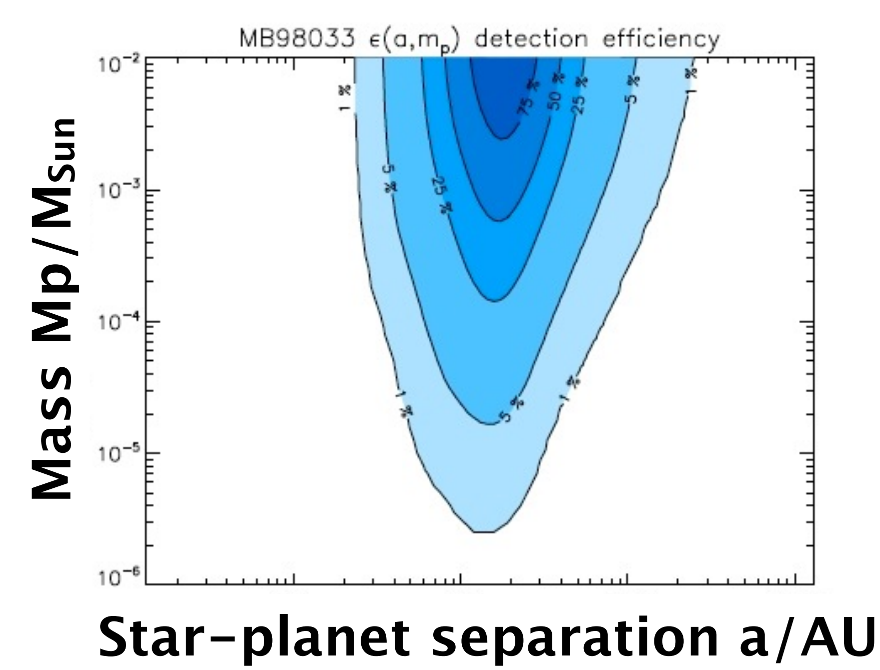


Individual detection efficiency diagram (d, q)



Galactic model

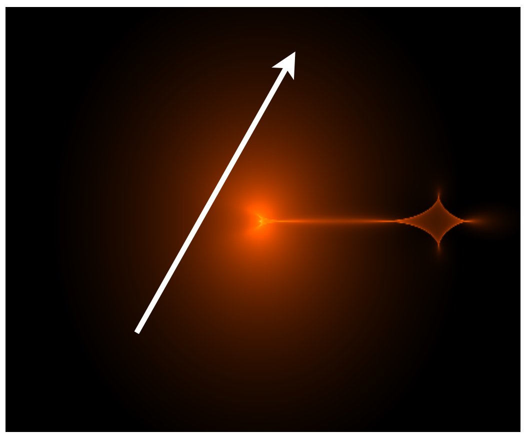
Individual detection efficiency diagram (a, Mp)



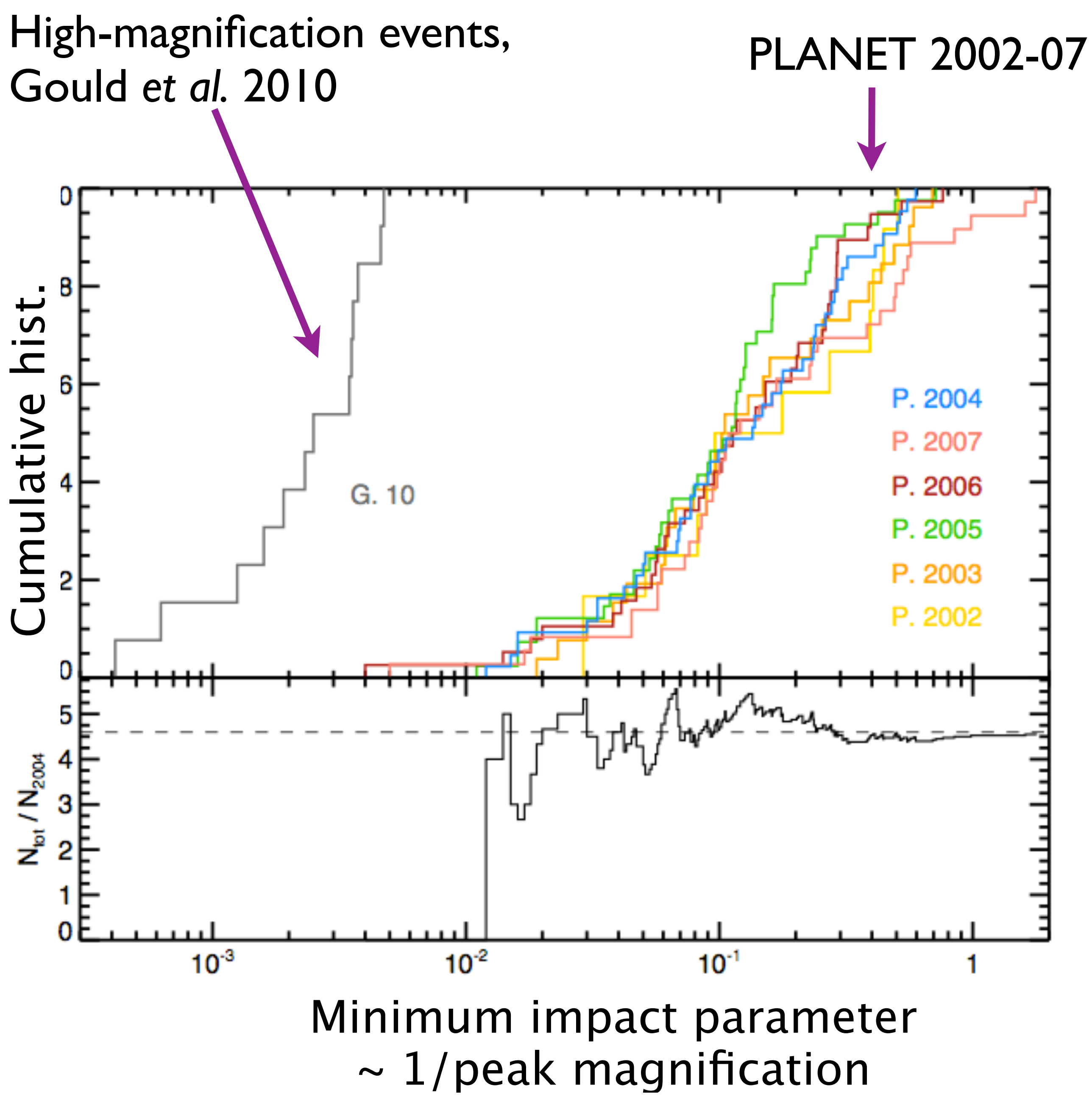
- Light-curve selection criteria based on observation frequency, reliability of the data, errors on fitting parameters
- In 2002-07:
OGLE alerts: 389, 462, 608, 597, 581, 610
PLANET targets: 40, 51, 98, 83, 96, 72

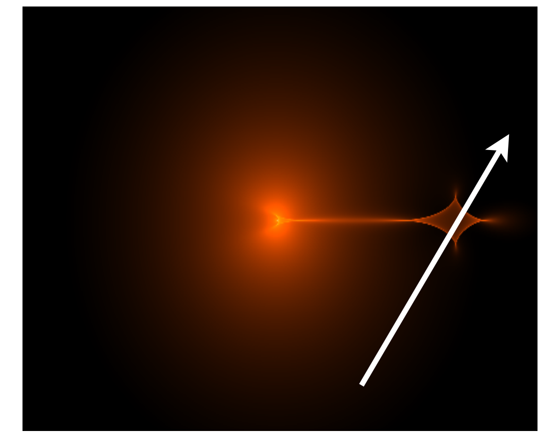
Combine all efficiency diagrams and correct for incompleteness

NB: High-magnification vs. standard magnification



High–magnification
= central caustic





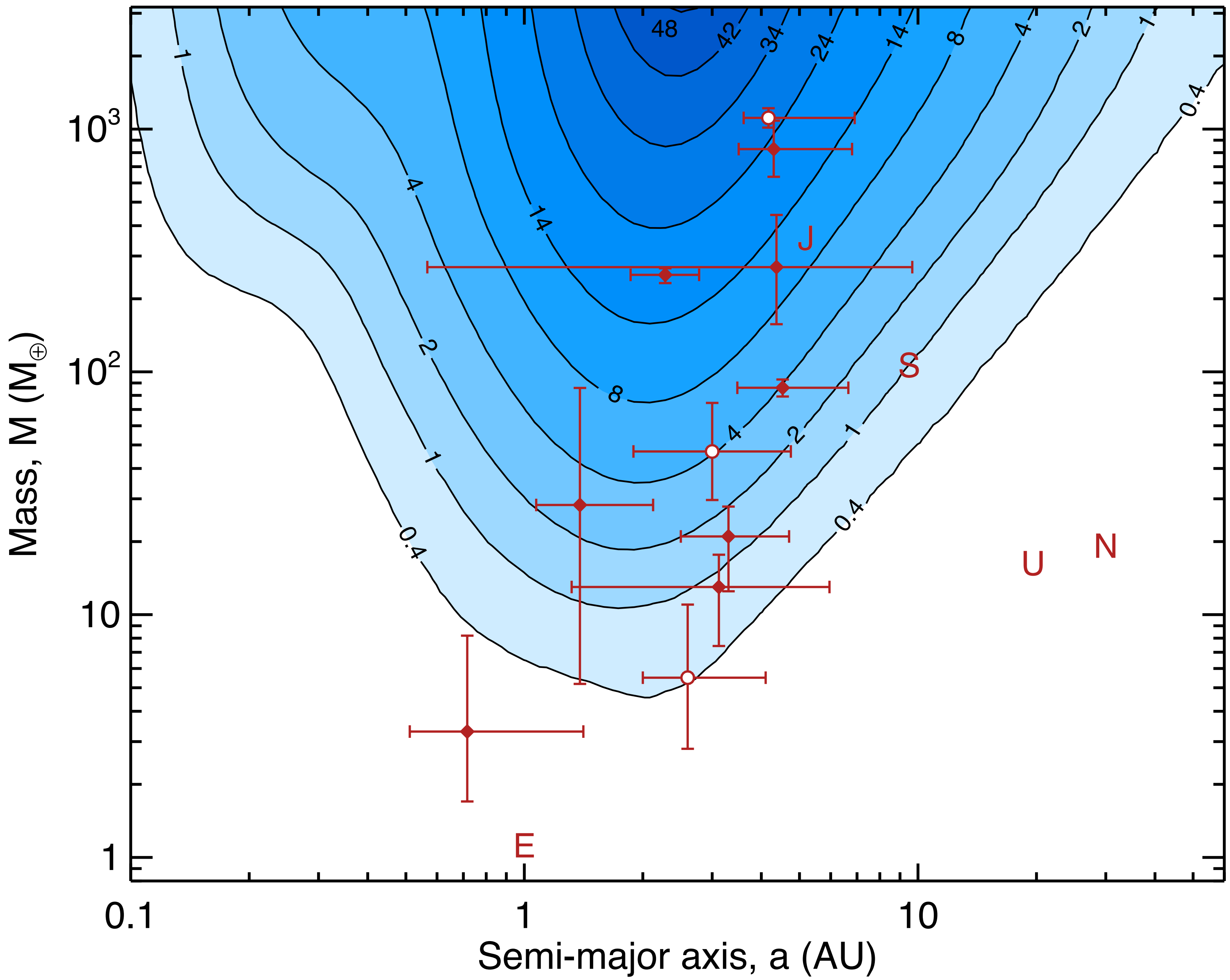
Middle magnification
= planetary caustic

After light-curve modelling: observing strategy is homogeneous in 2002-07. Correction for incompleteness using 2004 season as a reference

Detection sensitivity - PLANET follow-up, OGLE alerts 2002-07

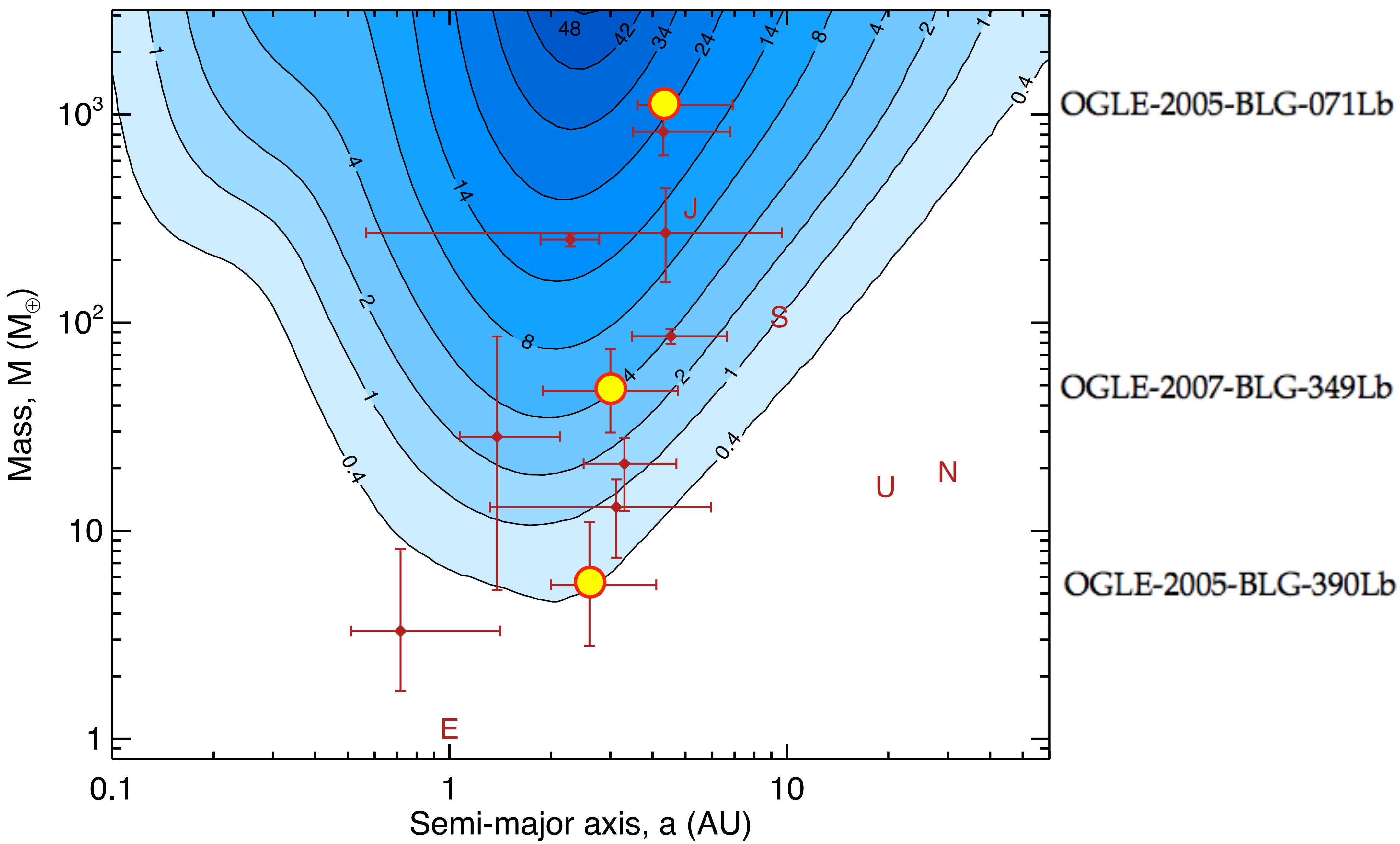
Blue contours are the expected number of detections
if all stars have one planetary companion :

$$S(\log a, \log M) \equiv \sum_{n=1}^{N} \varepsilon(n)$$



Detections - PLANET follow-up, OGLE alerts 2002-07

Red-yellow points are detections which are **compatible** with PLANET observing strategy



The method

Step 1.

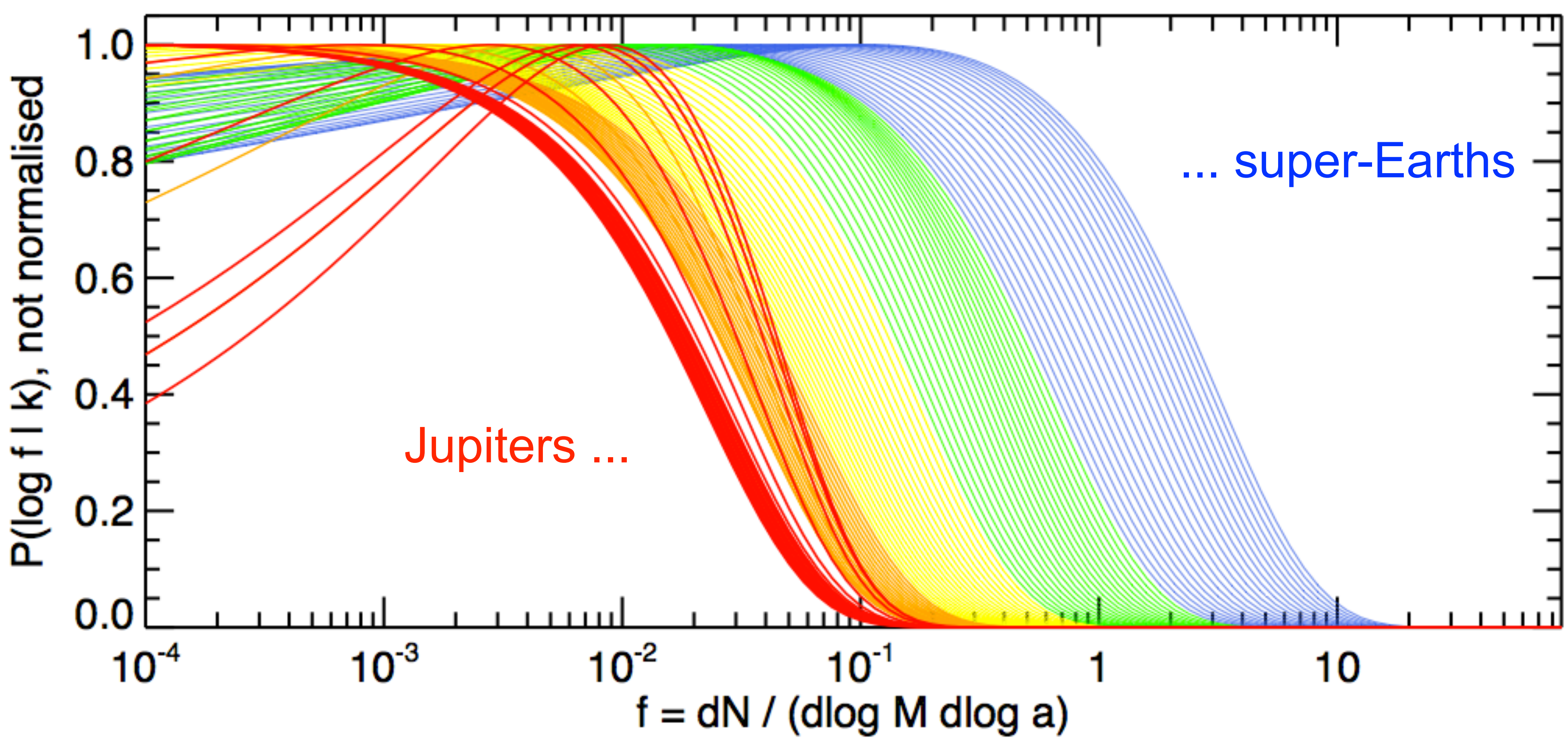
$$f(a\,M) \equiv \frac{\mathrm{d}N_p(a,M)}{\mathrm{d}\log a\,\mathrm{d}\log M}\,.$$

Expected number of planets: $$E = \int S(a,M)\,f(a,M)\,\mathrm{d}\log a\,\mathrm{d}\log M\,,$$

Poisson density of k detection: $$P(k|E) = \frac{E^k \exp(-E)}{k!}\,,\quad P(\log f) = 1.$$

Bayes theorem: $$P(\log f|k) = \frac{P(k|E)\,P(\log f)}{\int P(k|E)\,P(\log f)\,\mathrm{d}\log f}\,.$$

Step 2. Then, sub-divide into a large number of bins (eg. here 200):

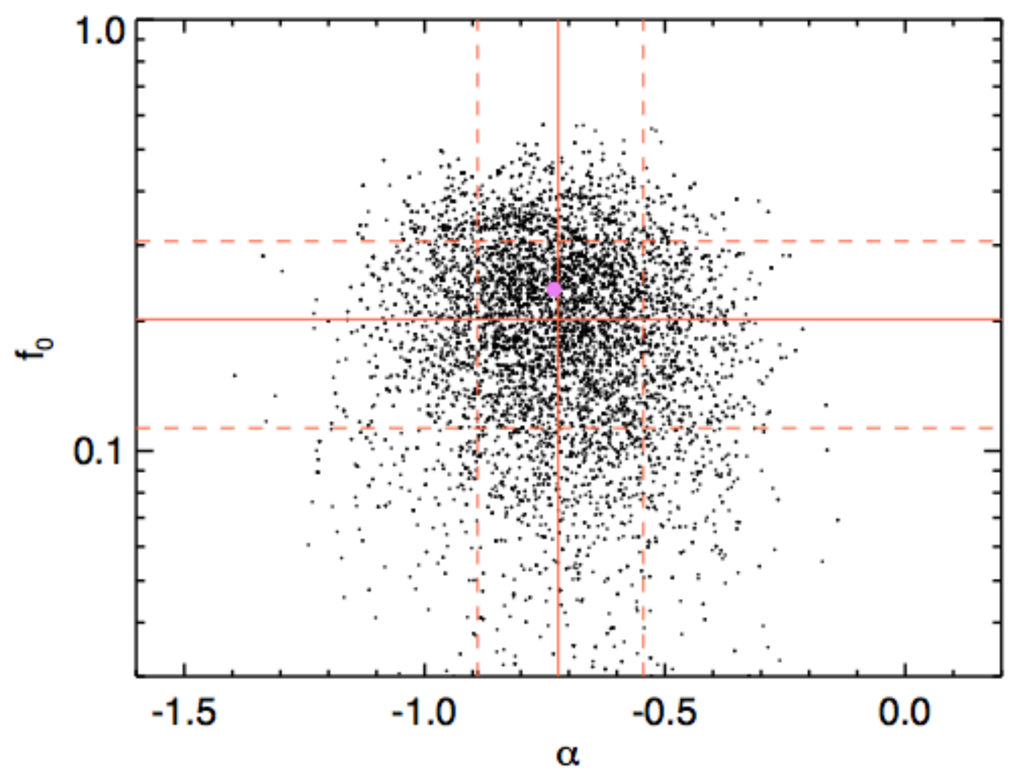


The method

Step 3. We want to constrain the power-law planet mass function:

$$f(a, M) = f_\oplus \, (M/M_\oplus)^{-\alpha}.$$

Perform a MCMC run with a large number of bins in mass....



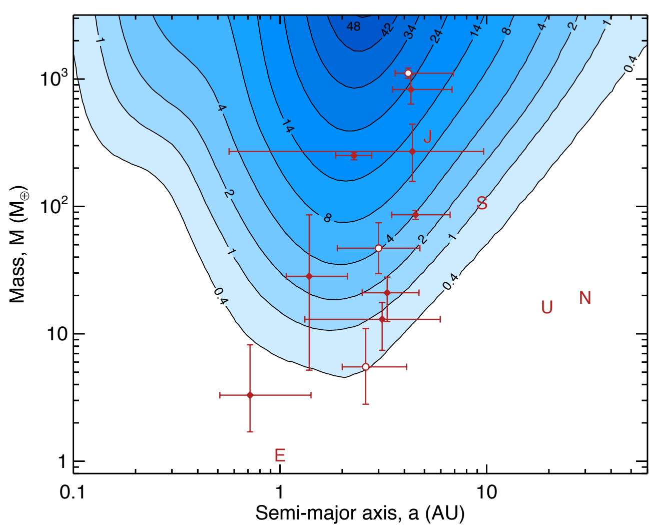
... and determine f_0 and α

Step 4. Include estimates of Gould et al. (2010) and Sumi et al. (2010) as priors.

The PLANET+OGLE 2002-07 sample

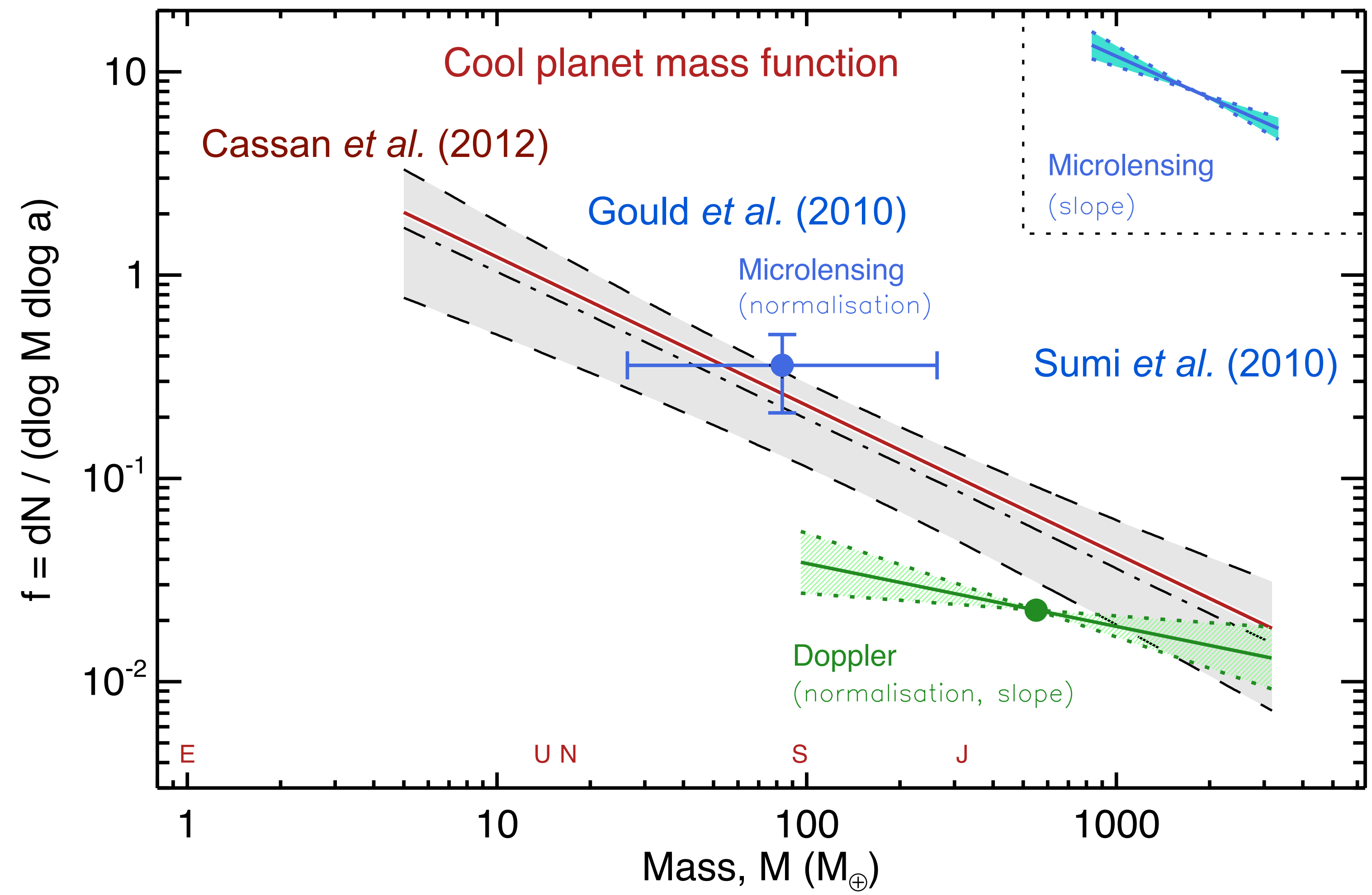
Bayesian analysis, using a power-law planetary mass function: $f(a, M) = f_{\oplus}\,(M/M_{\oplus})^{-\alpha}$.

PLANET+OGLE 2002-07



+
Gould et al. 2010
+
Sumi et al. 2010

Bayesian
priors



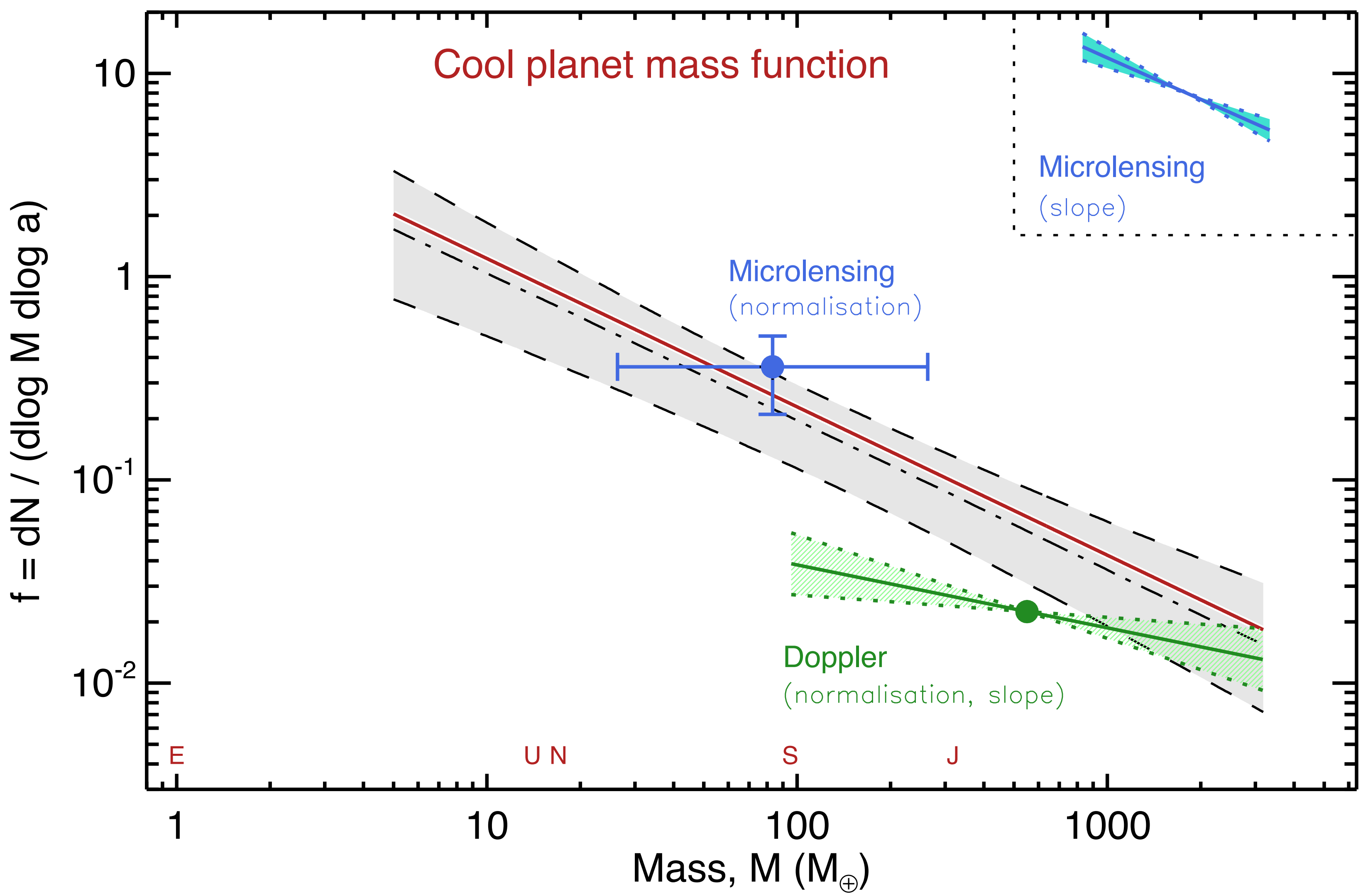
Sensitivity: 0.5-10 AUs and 5 M_{Earth}-10 $M_{Jupiter}$
Accounts for all constraints obtained by microlensing

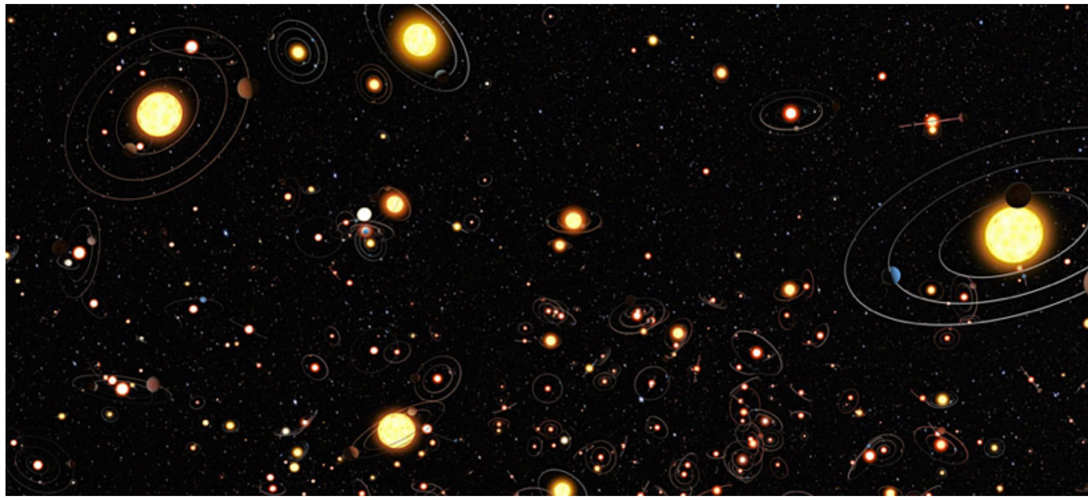
LETTER

doi:10.1038/nature10684

One or more bound planets per Milky Way star from microlensing observations

A. Cassan[1,2,3], D. Kubas[1,2,4], J.-P. Beaulieu[1,2,25], M. Dominik[1,5], K. Horne[1,5], J. Greenhill[1,6], J. Wambsganss[1,3], J. Menzies[1,7], A. Williams[1,8], U. G. Jørgensen[1,9], A. Udalski[10,11], D. P. Bennett[1,12], M. D. Albrow[1,13], V. Batista[1,2], S. Brillant[1,4], J. A. R. Caldwell[1,14], A. Cole[1,6], Ch. Coutures[1,2], K. H. Cook[1,15], S. Dieters[1,6], D. Dominis Prester[1,16], J. Donatowicz[1,17], P. Fouqué[1,18], K. Hill[1,6], N. Kains[1,19], S. Kane[1,20], J.-B. Marquette[1,2], R. Martin[1,8], K. R. Pollard[1,13], K. C. Sahu[1,14], C. Vinter[1,9], D. Warren[1,6], B. Watson[1,6], M. Zub[1,3], T. Sumi[21,22], M. K. Szymański[10,11], M. Kubiak[10,11], R. Poleski[10,11], I. Soszynski[10,11], K. Ulaczyk[10,11], G. Pietrzyński[10,11,23] & Ł. Wyrzykowski[10,11,24]



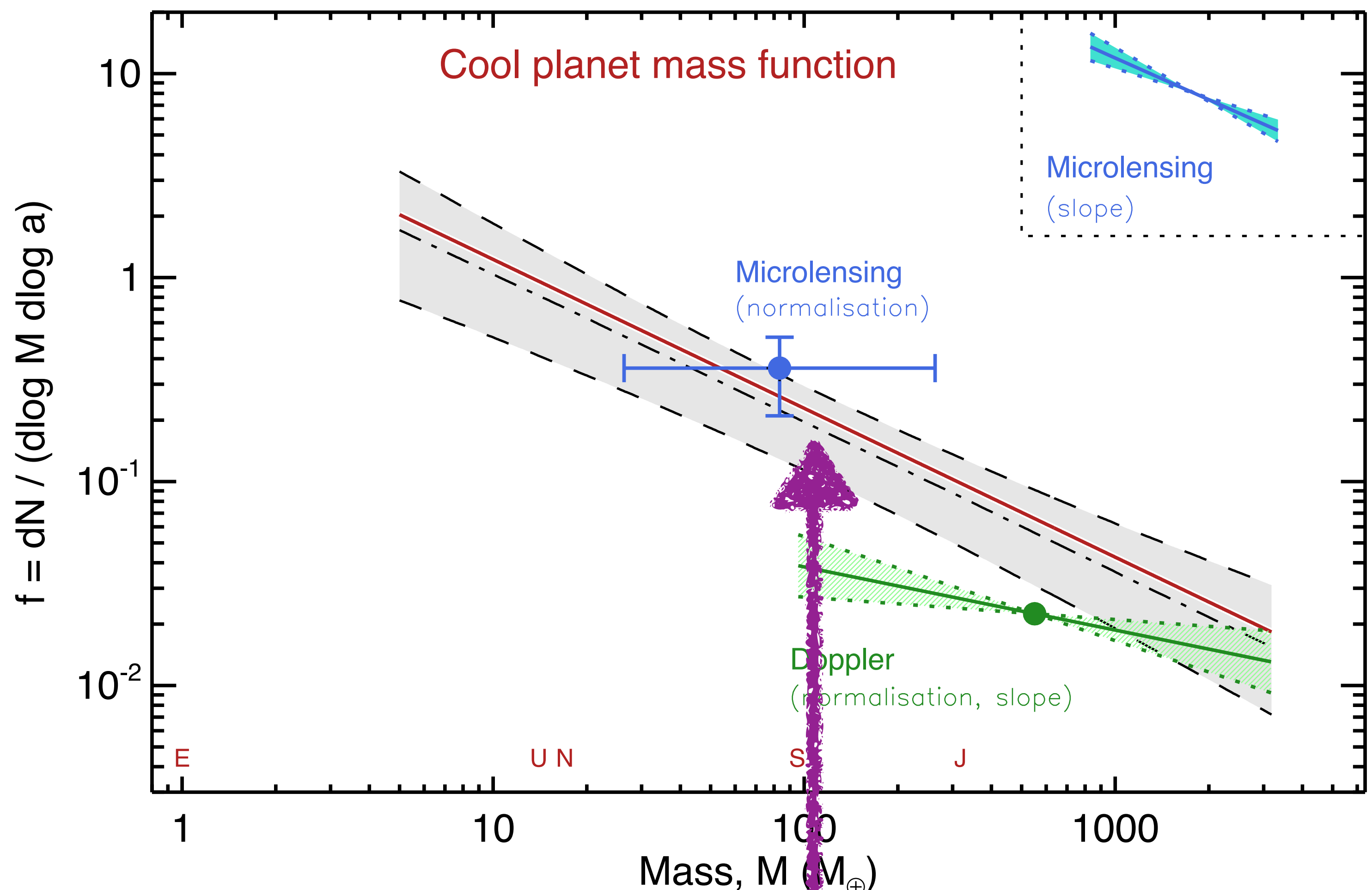


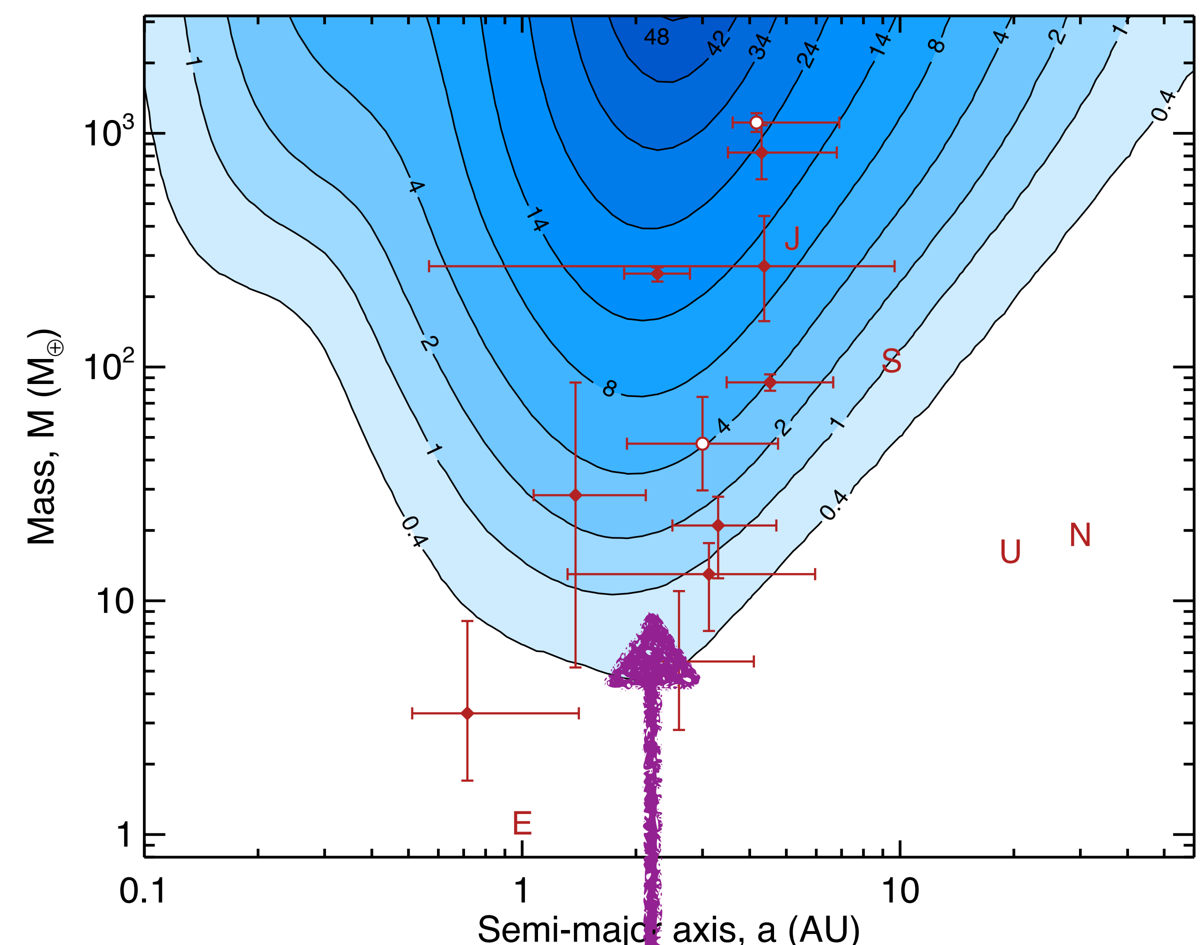
On average :

- → 2/3 of stars have a super-Earth
- → 1/2 of stars have a Neptune
- → 1/6 of stars have a Jupiter

→ One or more planets per star

Note:





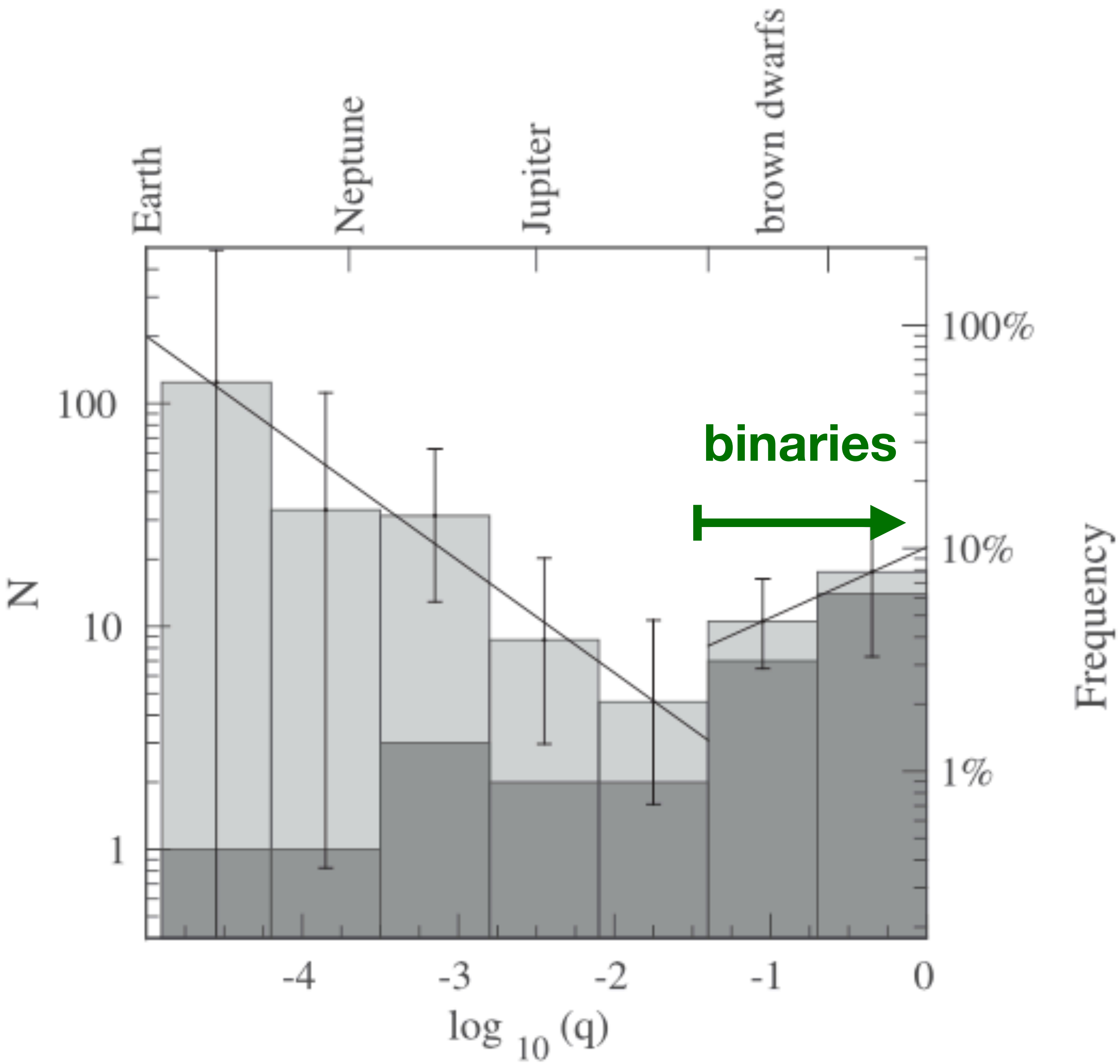
— Pivot point : 100 ME ~ **Saturn's mass**

— Maximum detection efficiency for all masses : **2.6 AU**

... typical of current microlensing surveys

Frequency from 4 seasons of OGLE+MOA+Wise second generation microlensing Shvartzvald+ (2016)

— 224 events from the 4 seasons 2011–2014
— Observed by OGLE *and* MOA *and* Wise
— Data near the peak of the event

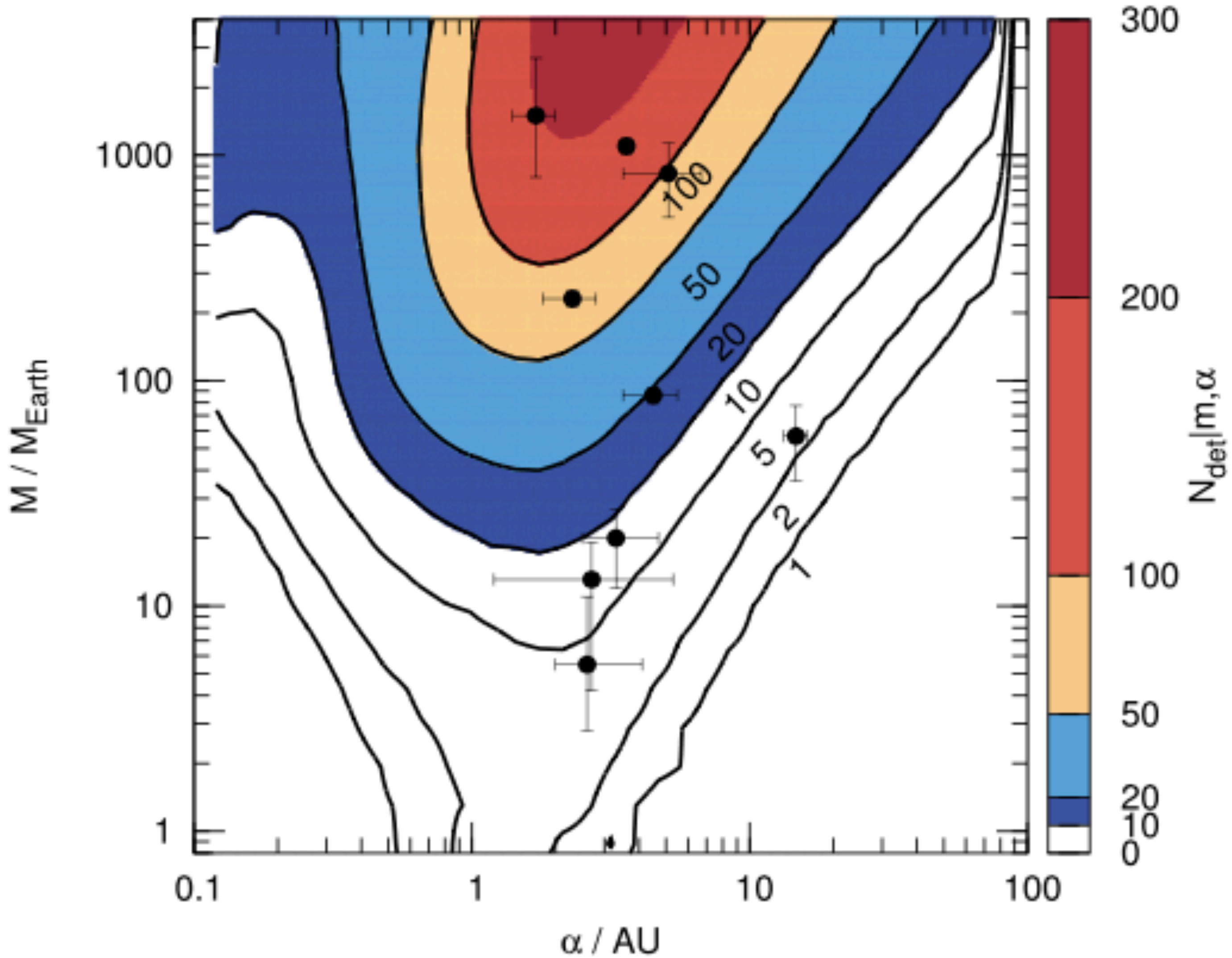


— After correcting from orbital separation ranges, result is consistent with Cassan+ (2012) integrated frequencies, albeit slightly lower

— Also consistent with RV and imaging

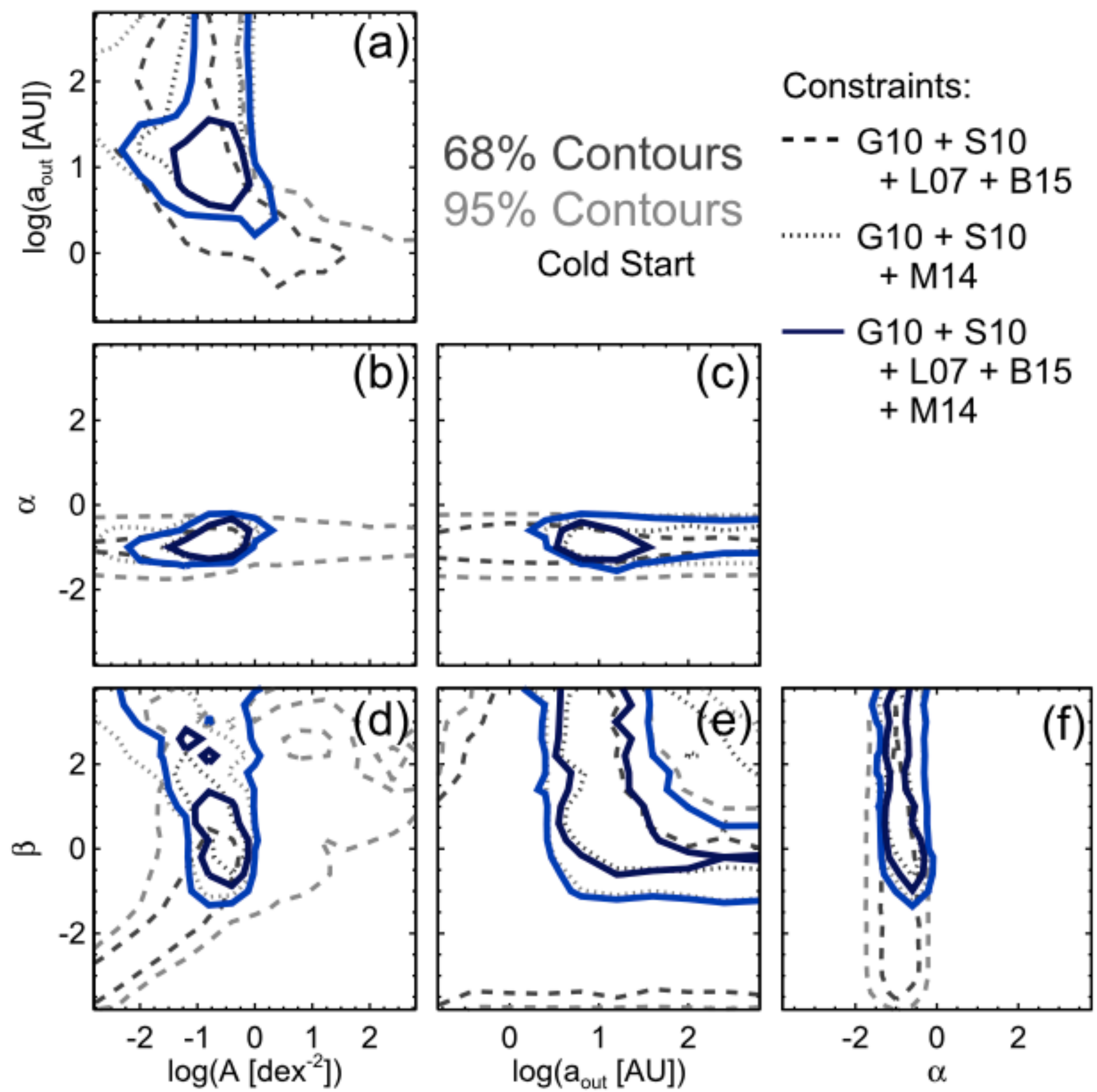
OGLE-III planet detection efficiency from 2003–2008 microlensing observations   Tsapras+ (2016)

— Initial sample of 3084 light curves
— Assess quality of data and remove events parameters too loosely constrained
— Final sample of 2433 light curves



Constraints on the planetary mass function to come

Synthesis of Microlensing, Radial Velocity, and Direct Imaging for long-period M dwarfs Clanton & Gaudi (2016)

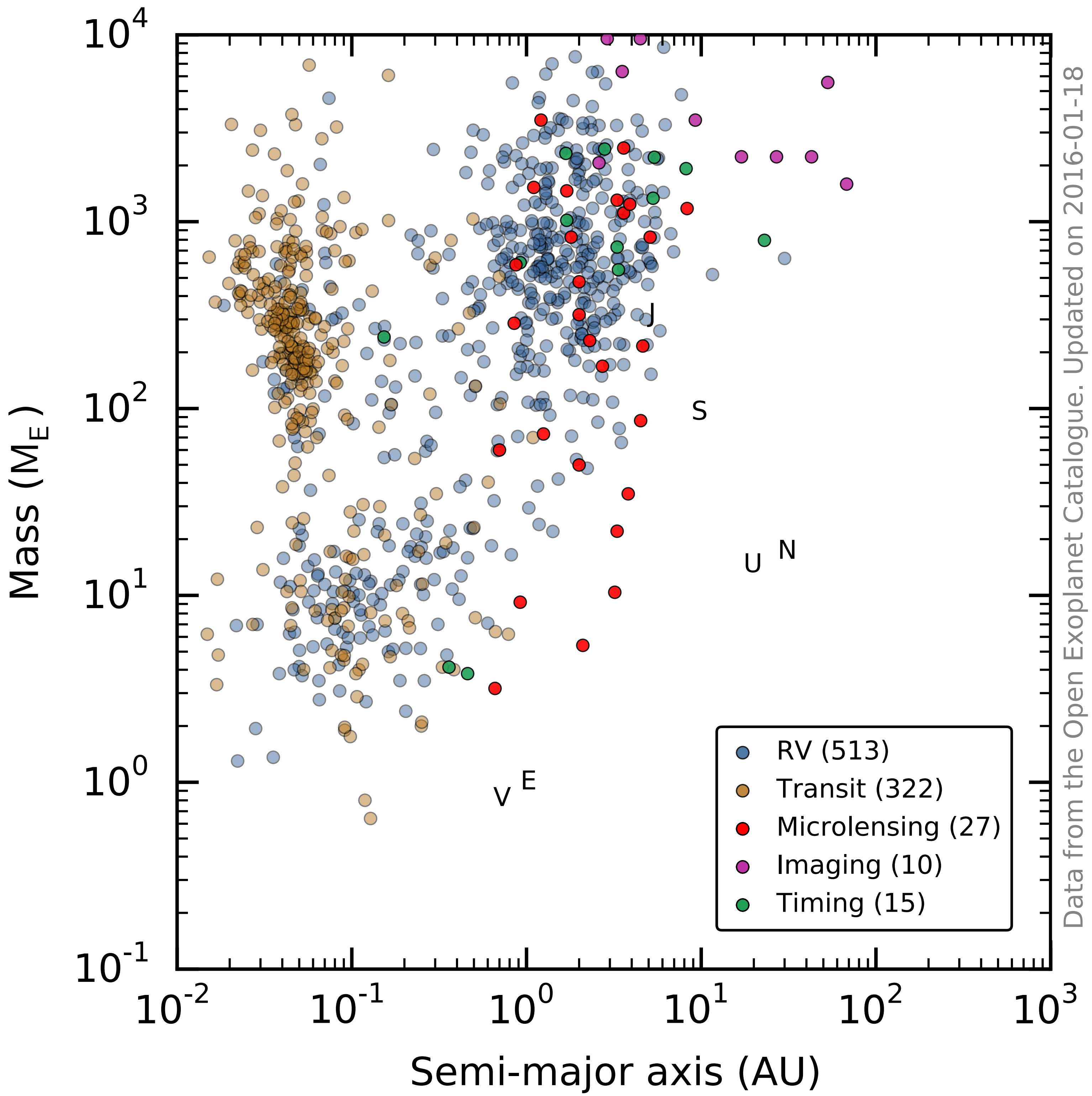


$$\frac{d^2N_{\rm pl}}{d\log m_p\, d\log a} = \mathcal{A}\left(\frac{m_p}{M_{\rm Sat}}\right)^{\alpha}\left(\frac{a}{2.5\ \rm AU}\right)^{\beta}$$

Cassan+ (2012) $0.5 - 10\,\mathrm{AU}\,;\,5\,\mathrm{M}_{\oplus} - 10\,\mathrm{M}_{\mathrm{J}}$ Microlensing only	Clanton & Gaudi (2016) $a \geq 2\,\mathrm{AU}$ Microlensing+RV+Imaging
$\mathcal{A} = 0.24 \pm 0.13$ $\alpha = -0.73 \pm 0.17$ $\beta = ?$	$\mathcal{A} = 0.21 \pm 0.2$ $\alpha = -0.85 \pm 0.2$ $\boxed{\beta = 1.1^{+1.9}_{-1.4}}$

Nota 2017:
Prior slope from Sumi+ (2010): $\alpha = -0.68$
Prior normalization from Gould+ (2010): $A = 0.36$

Removing priors in Cassan+ analysis make the two mass functions even more consistent

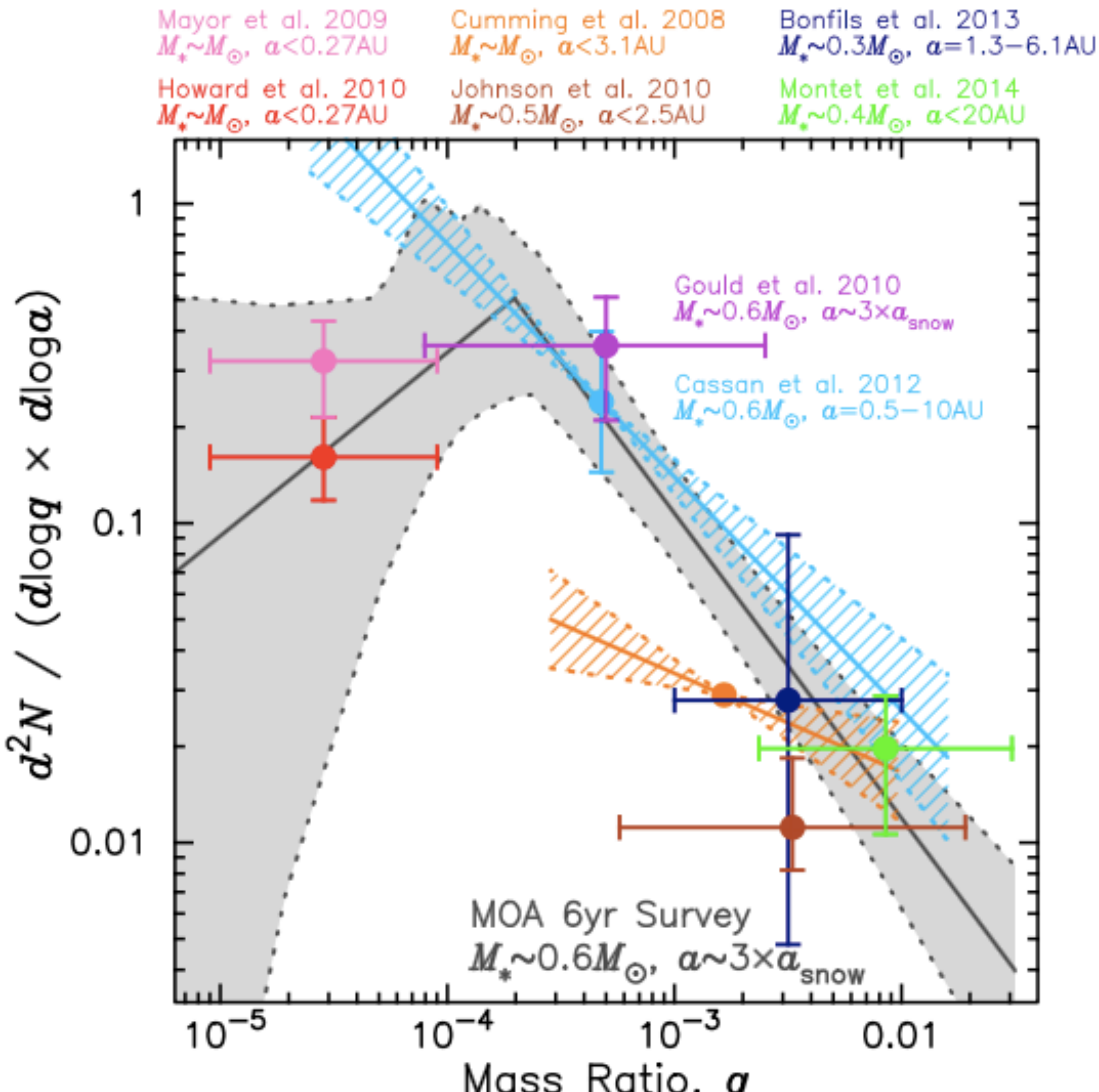


Necessity to include RV / imaging to constraint ß:

— Microlensing alone do span only one order of magnitude in *a*

— Microlensing measures only *projected* separations

A break in the mass function and a frequency peak at Neptune's mass from MOA II survey Suzuki+ (2016)



To conclude

We still do not have the last word
on exoplanet frequency, but:

Microlensing constraints on the frequency
of exoplanets beyond the snow line of low-mass stars
have been steadily improving over the last 20 years, and
up to now, results have kept a certain degree of consistency

This is a firm evidence that microlensing provides over years
high quality data that have been analyzed with great care

Future is never written in advance, and we may expect surprises!

Merci de votre attention