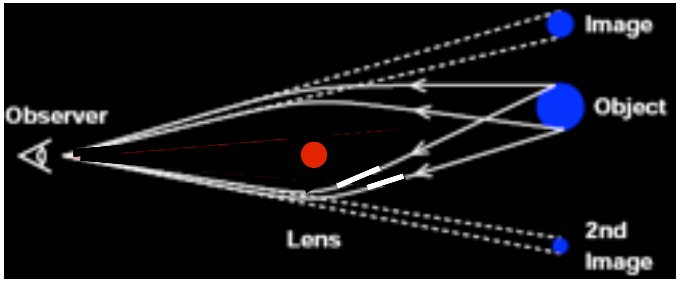
Patrick Tisserand & Jean-Philippe Beaulieu

Microlensing today and tomorrow

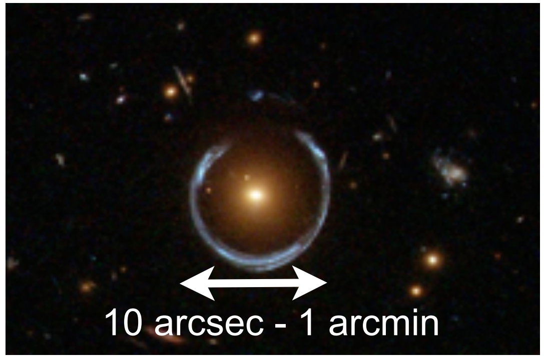
2020+ : EUCLID + LSST

Institut d'Astrophysique de Paris

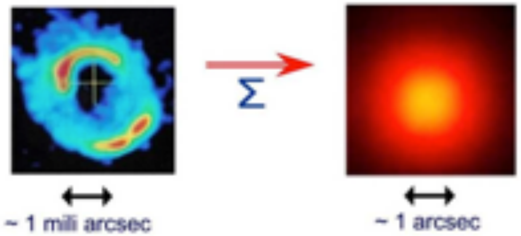
Microlensing

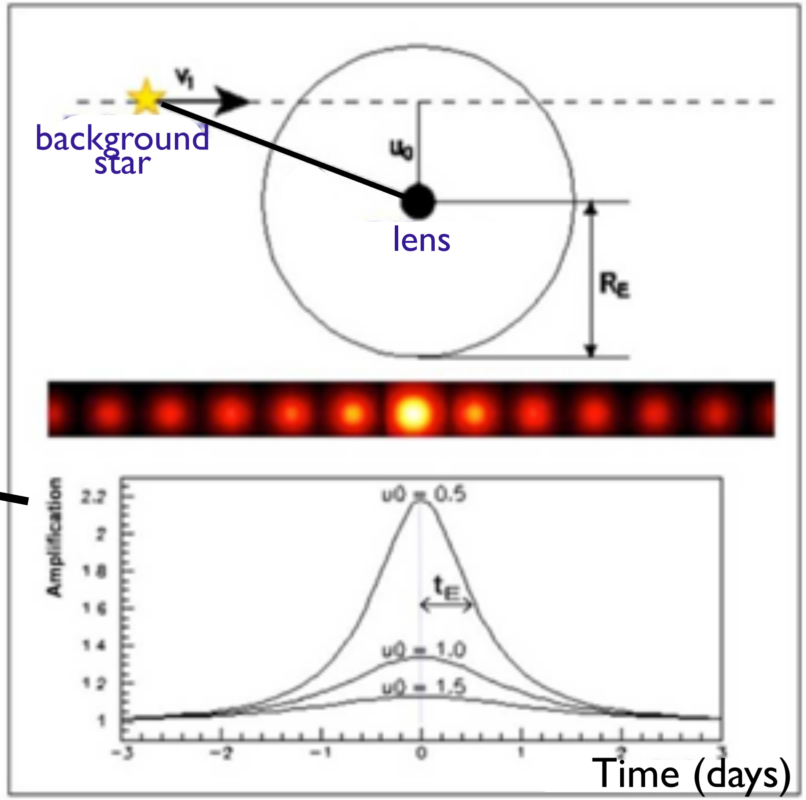


lens of ~10^{11} -10^{12} solar mass :



For a lens of ~1 solar mass :

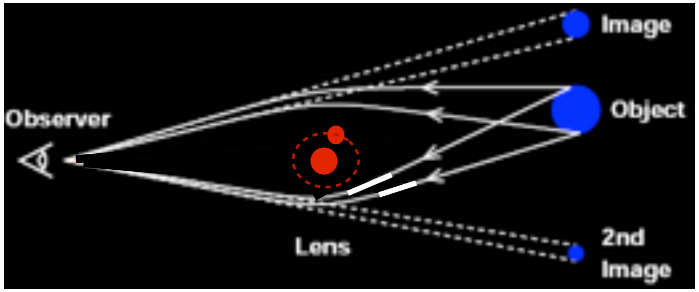




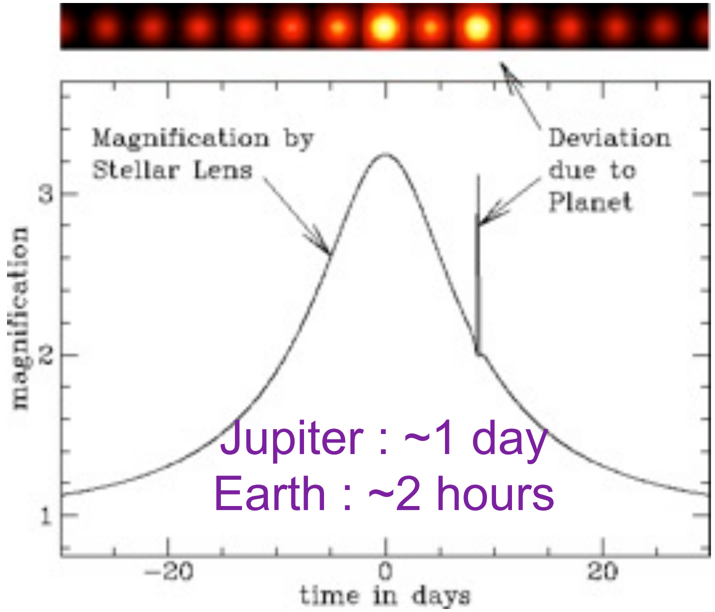
Microlensing effect signature

$$t_E = 30\sqrt{M / Mo}\ \ days$$

Microlensing



We can probe the surrounding of the lenses to search for planets orbiting them.



Monitor ~10^8 stars located in the Bulge

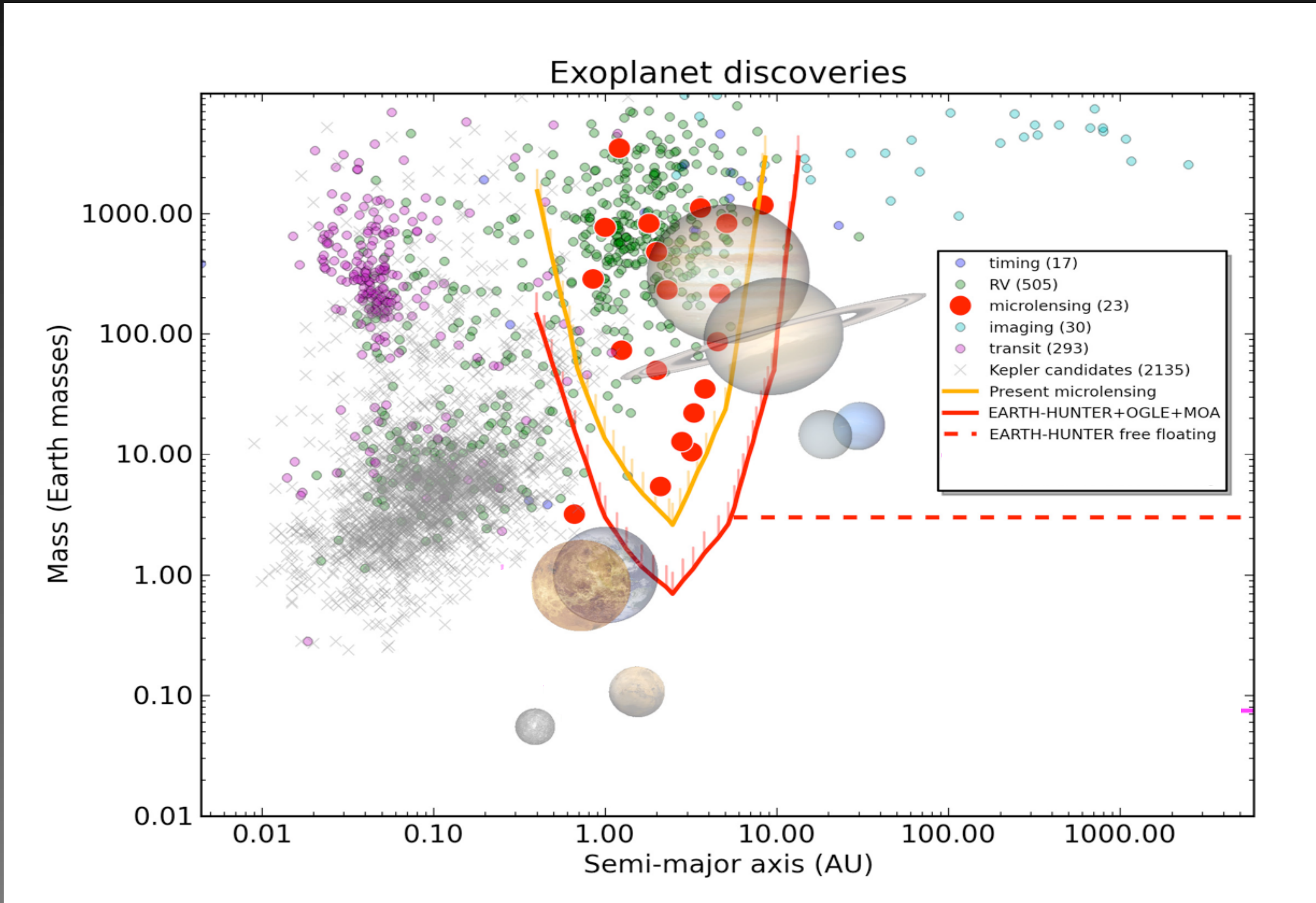
Detection efficiency depends directely to our observational sampling

Lenses are randomly passing. There are not choosen subjectively.

We can reconstruct the number of planets existing in our galaxy in function of their masses, distance to host star and host star type !

Since microlensing can instantaneously detect planets without waiting for a full orbital period, it is immediately sensitive to planets with very long periods… therefore far away from its host star.

Microlensing complements parameter space probed by RV surveys and KEPLER

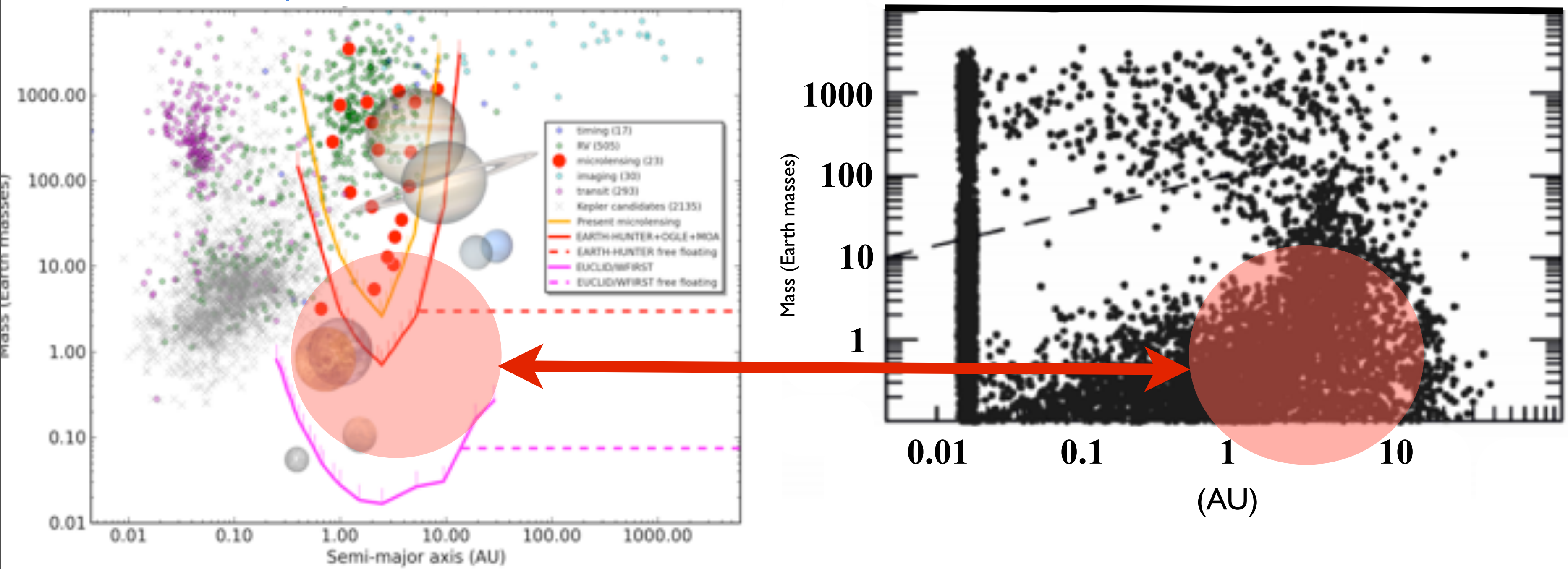


Extending the exoplanet discovery space

Find low-mass planets beyond ~1 AU is presently inaccessible
to any other planet detection technique !

Go to space !

Exoplanets discoveries (~1800) *Core-accretion model*



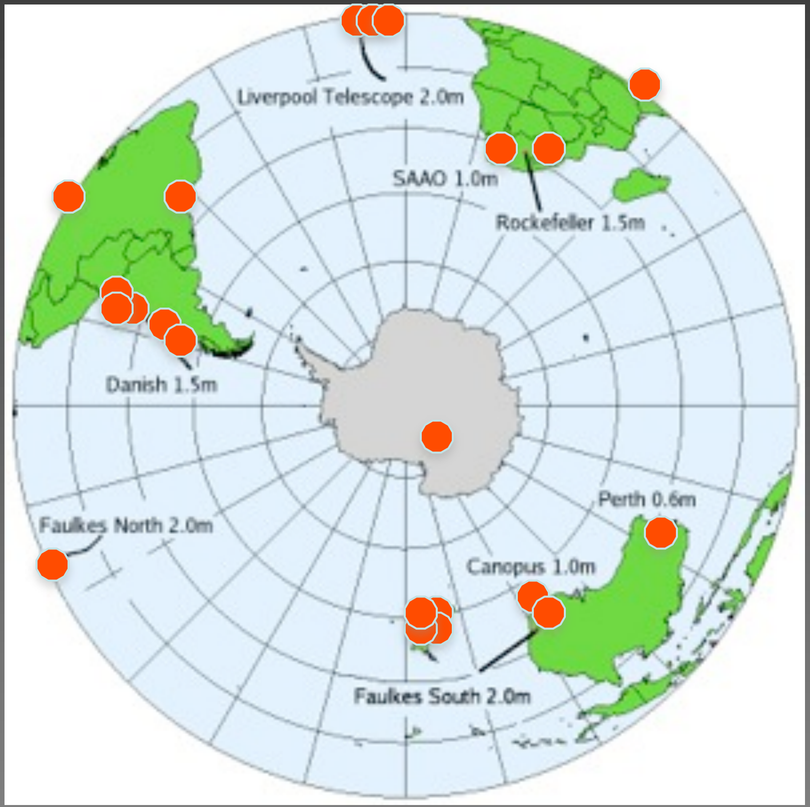
Excellent method for a statistical census of galactic exoplanets

➡ Test planetary system formation

What we are doing these days…
PLANET/uFUN, RoboNET, MOA, OGLE

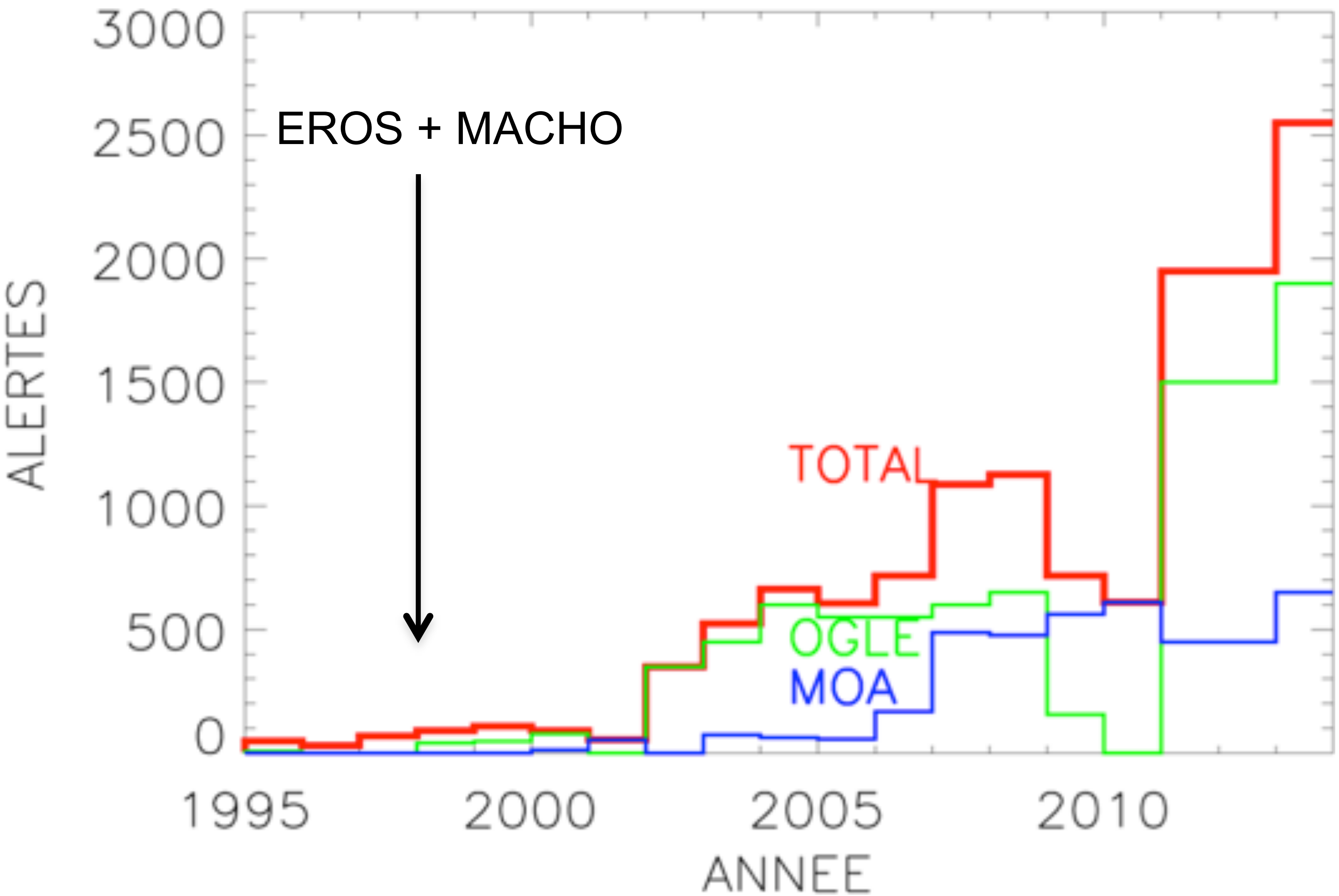
- Network of telescopes, round the clock observations, online analysis.

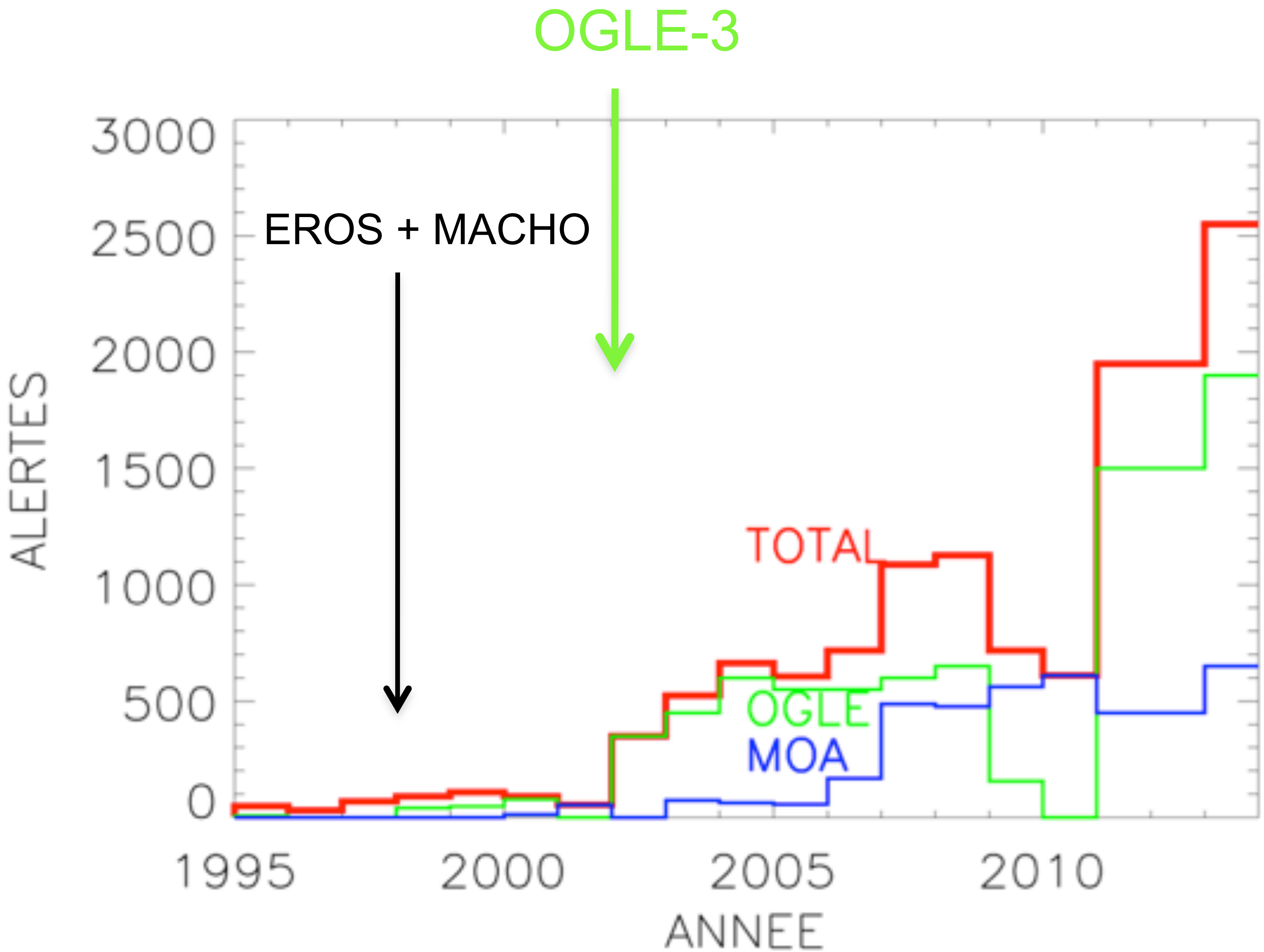
The sun never rises on microlensers !



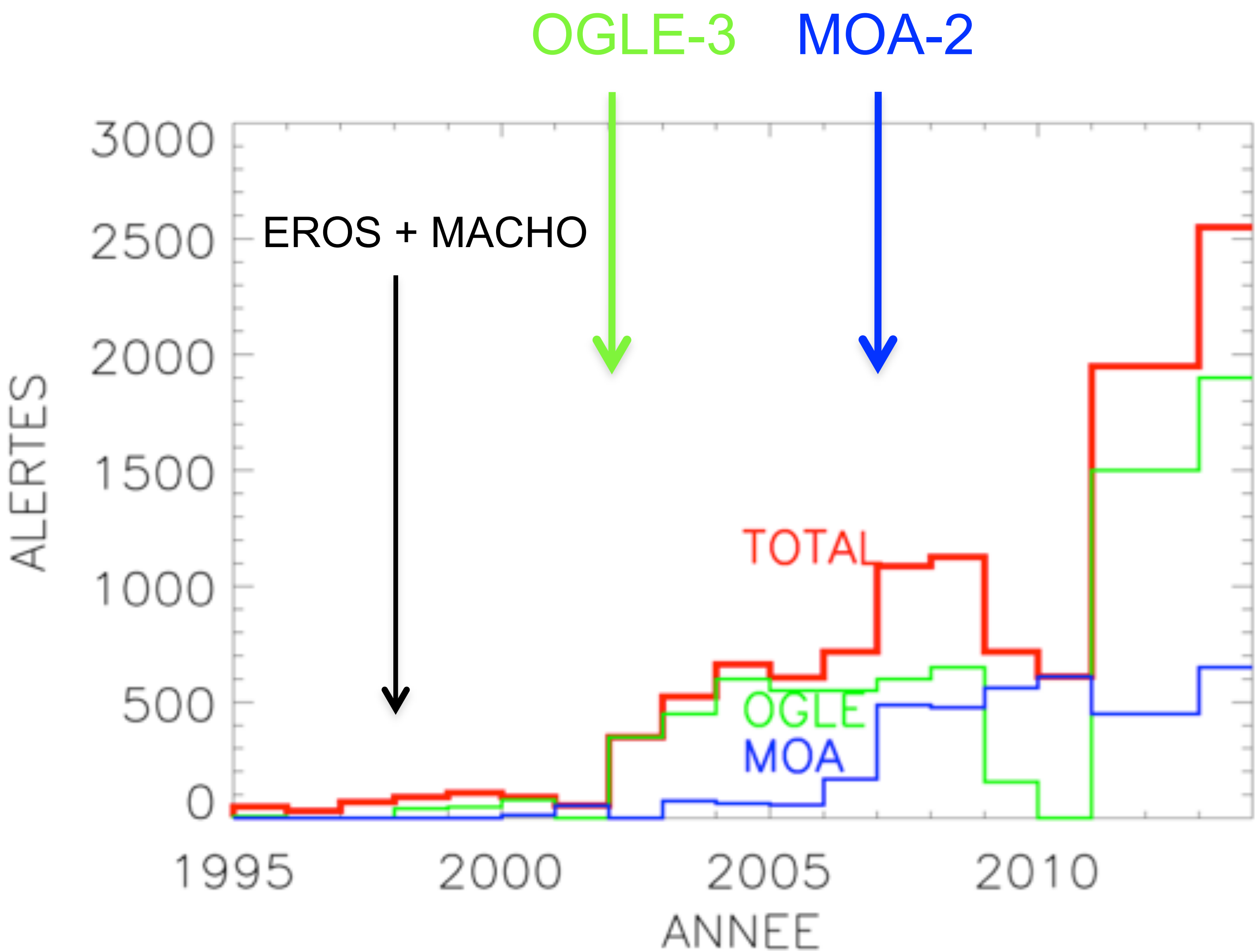
From 4 telescopes, to a fleet of 45+ telescopes on alert

2007-2011: 4-7 planets/Yr
2012 = 22 planets
2013 = 15 planets


EROS + MACHO
TOTAL
OGLE
MOA
ALERTES
ANNEE
0
500
1000
1500
2000
2500
3000
1995
2000
2005
2010



OGLE-3
EROS + MACHO
3000
2500
2000
1500
1000
500
0
ALERTES
TOTAL
OGLE
MOA
1995
2000
2005
2010
ANNEE


OGLE-3
MOA-2
EROS + MACHO
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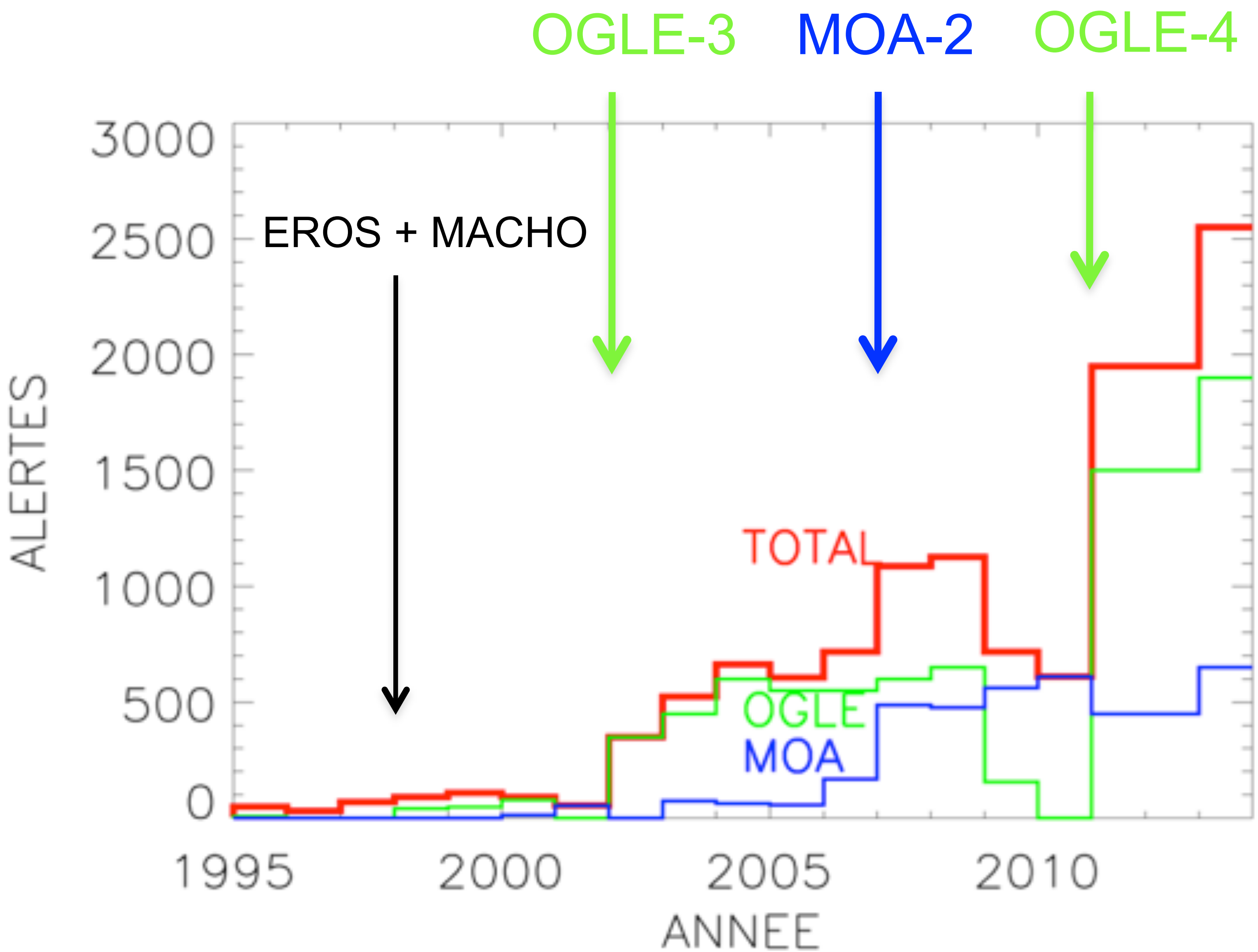
ALERTES
TOTAL
OGLE
MOA
1995
2000
2005
2010
ANNEE


OGLE-3
MOA-2
OGLE-4
EROS + MACHO
TOTAL
OGLE
MOA
ALERTES
ANNEE
3000
2500
2000
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1995
2000
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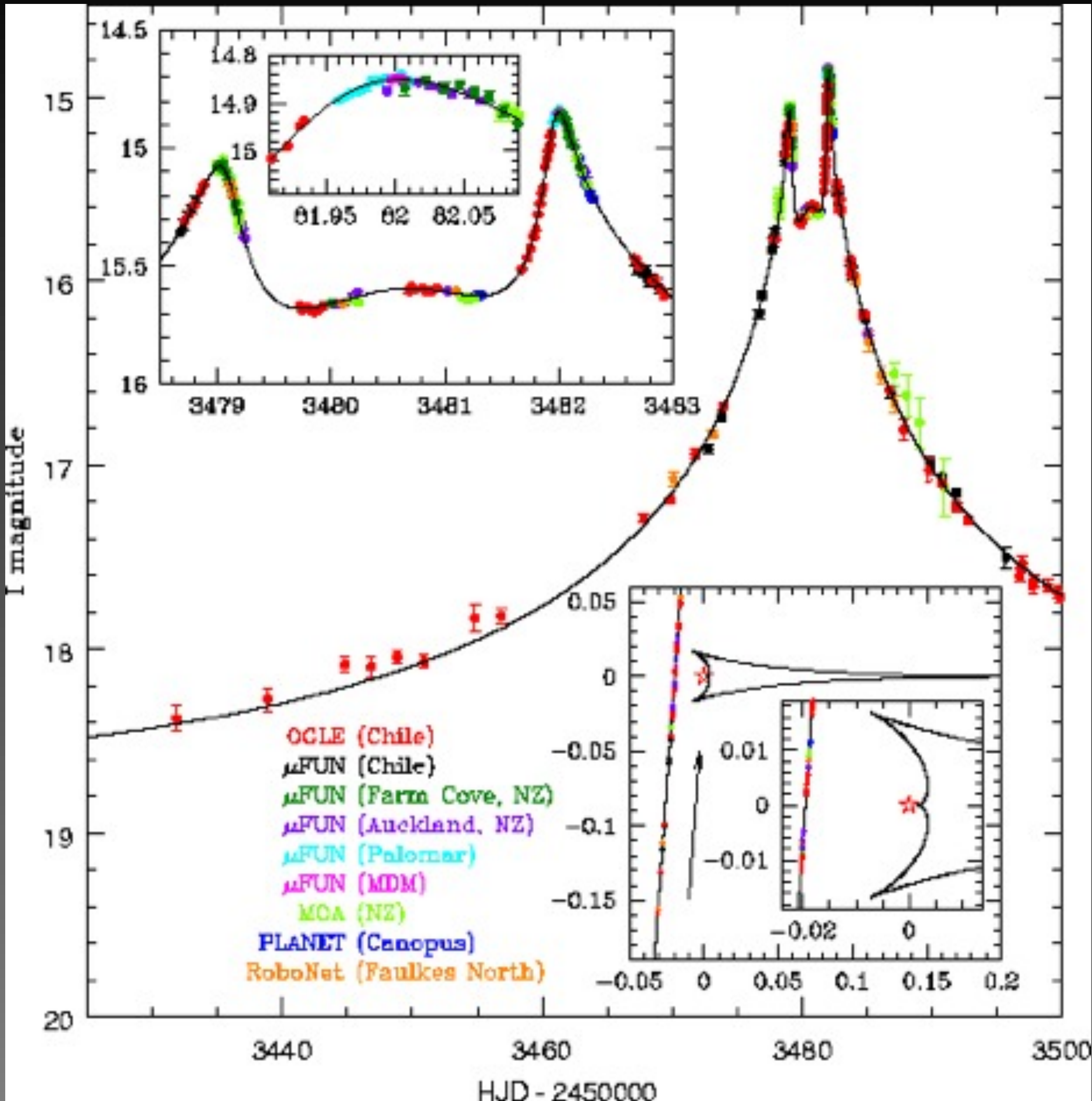
2010

Examples of exoplanets detected by microlensing

OGLE-2005-BLG-071

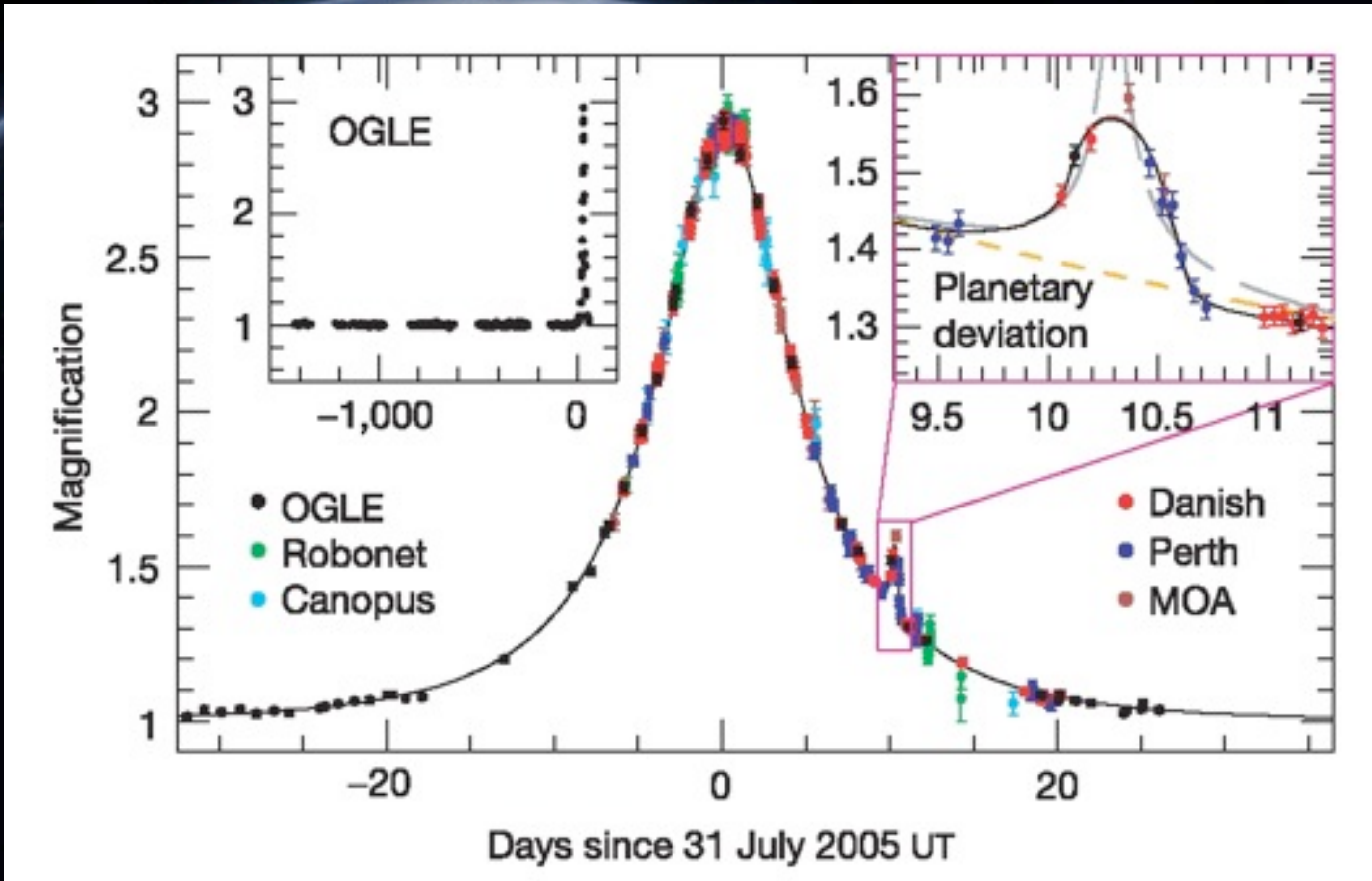


Close binary :
d=0.758
q=6.7 10^{-3}

Wide binary :
d=1.294
q=7.1 10^{-3}

M* ~ 0.45 M_{sun}
5.2 ± 1.8 kpc
2.7 $M_{Jupiter}$
a ~ 2.2 AU or 3.7 AU

A first frozen super Earth



$M_* = 0.22^{+0.21}_{-0.11}\ M_{SUN}$

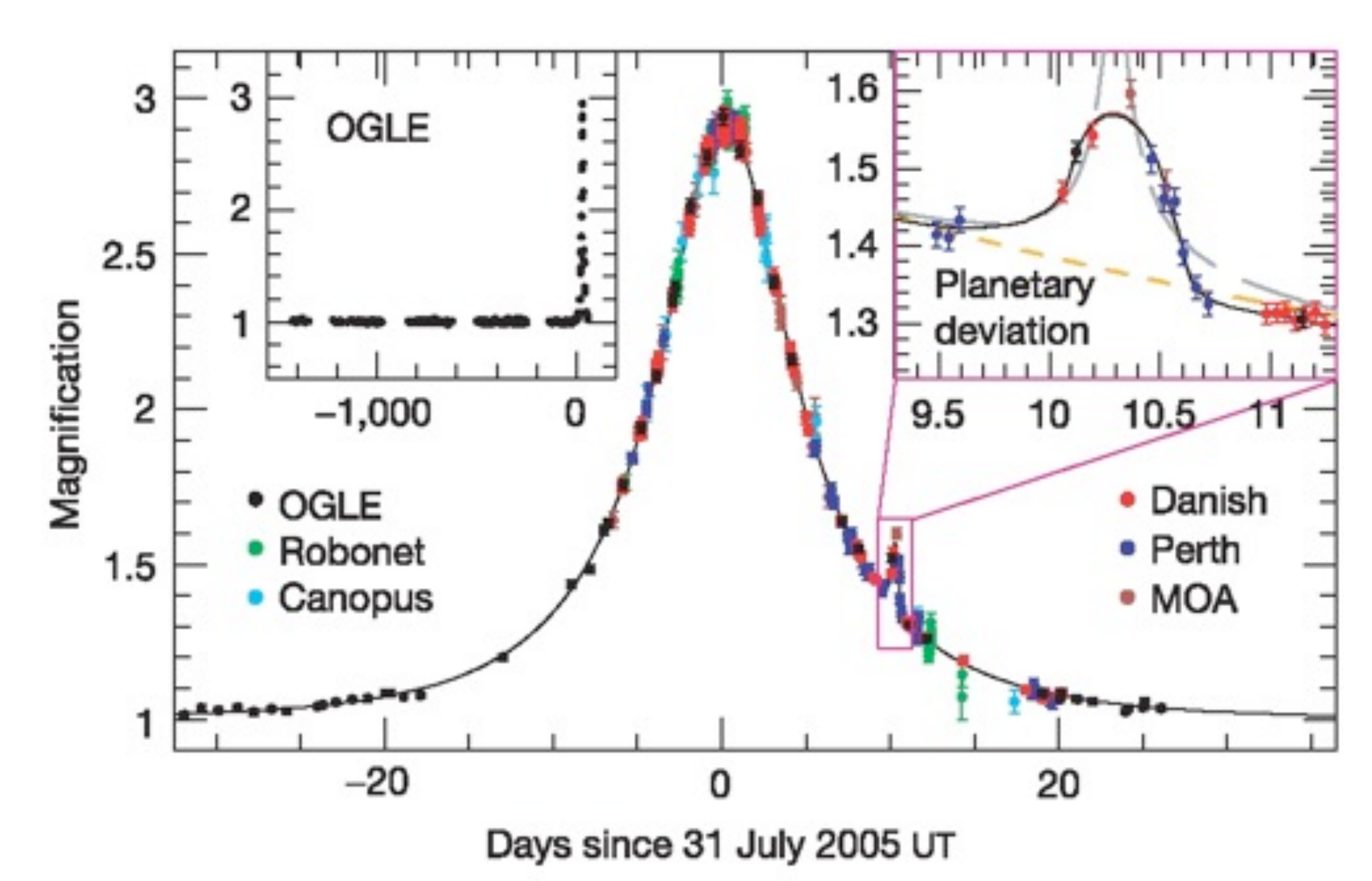
$M_p = 5.5^{+5.5}_{-2.7}\ M_{EARTH}$

$a = 2.6^{+1.5}_{-0.6}$ AU

Beaulieu et al., 2006, Nature (PLANET, OGLE, MOA)

A first frozen super Earth

Gas giants, super Earth-Neptunes are common
Same direction as the core accretion model predictions



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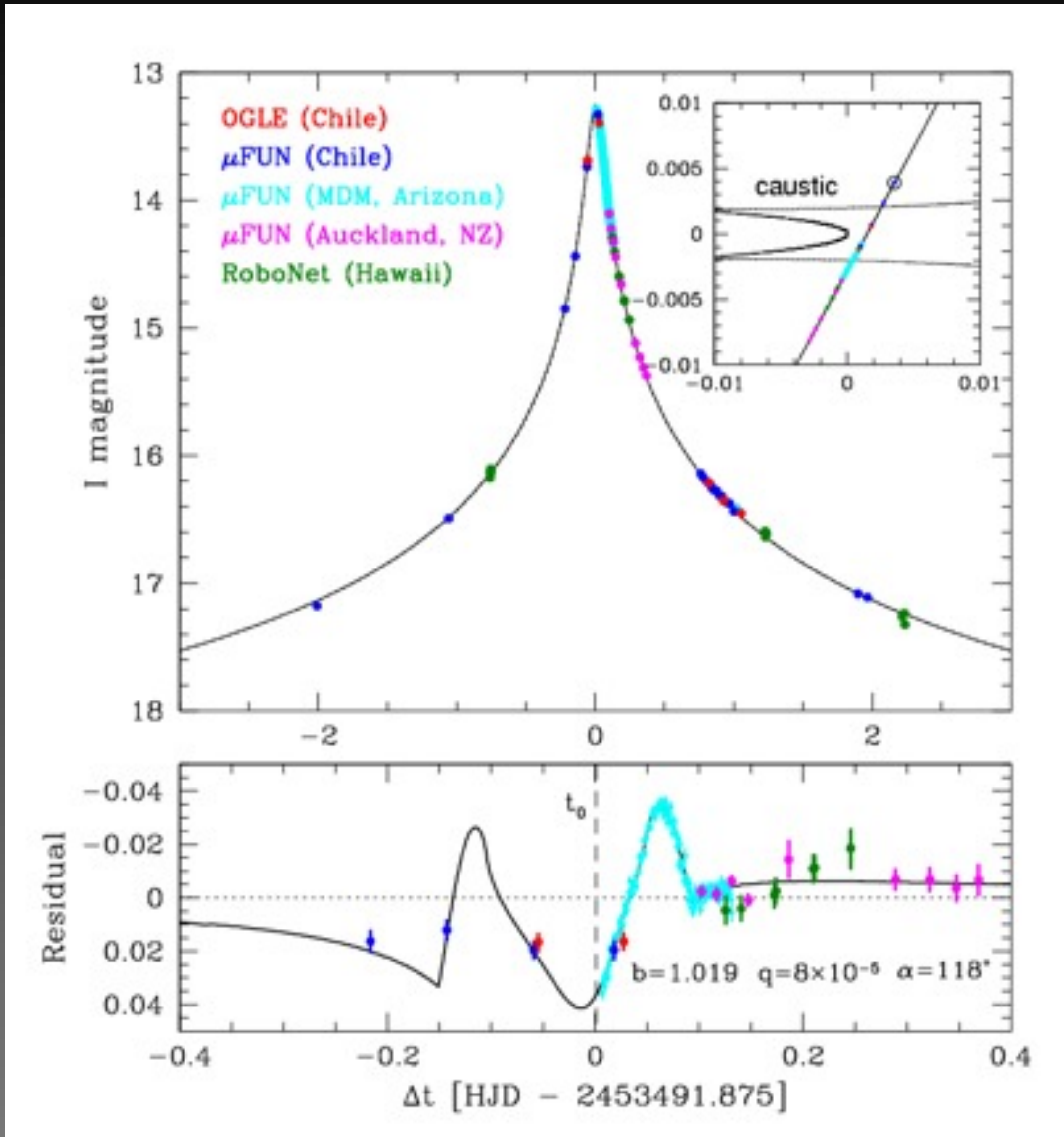
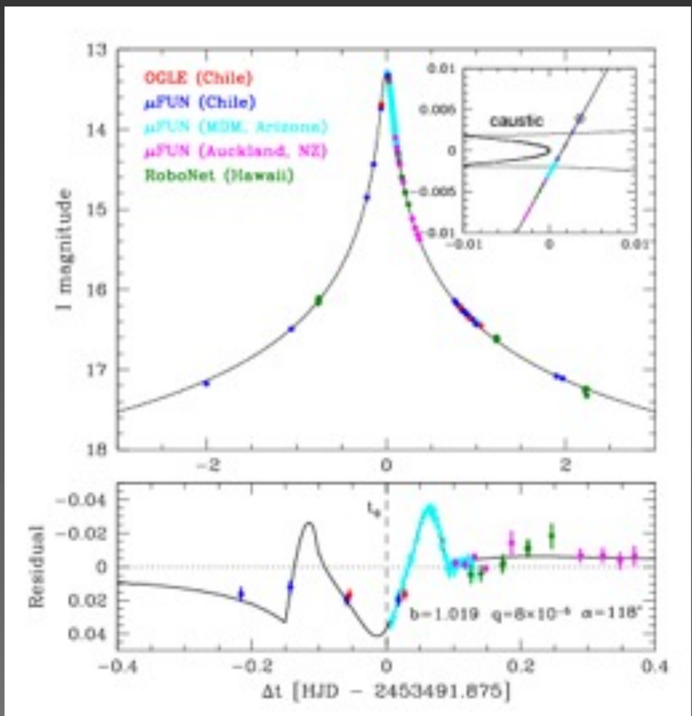
OGLE-2005-BLG-169Lb : a ~ 13 $M_\oplus$ planet

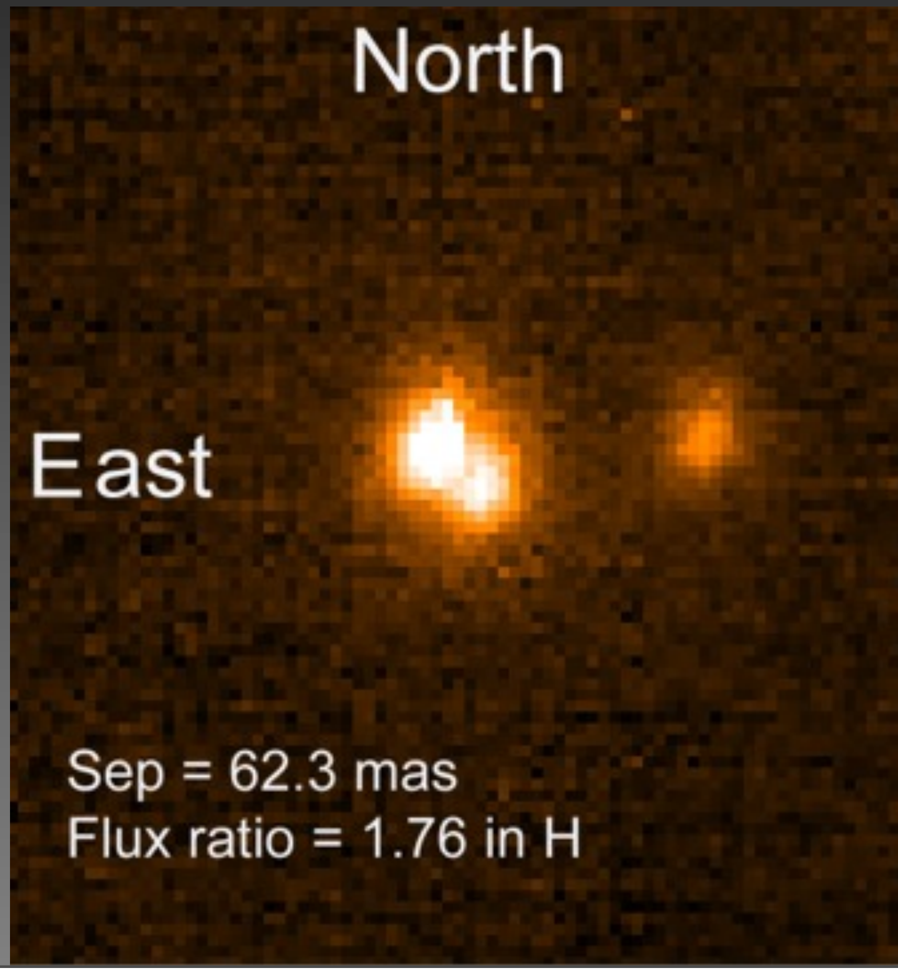


Gould et al. 2006, MicroFUN, OGLE, RoboNet

OGLE-2005-BLG-169Lb : a ~13 $M_\oplus$ planet

With KECK, detecting the lens in 2013
Measuring proper motion

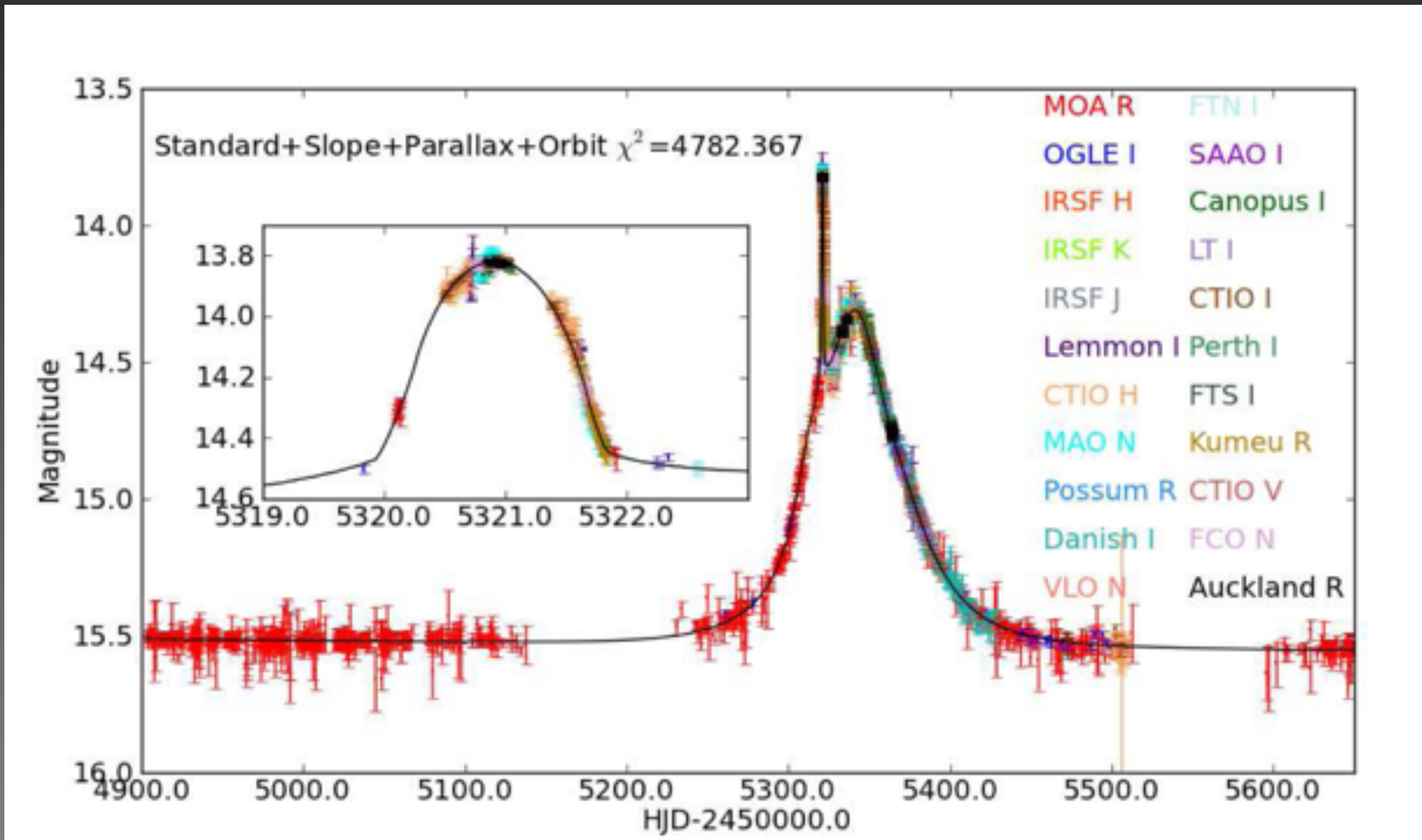




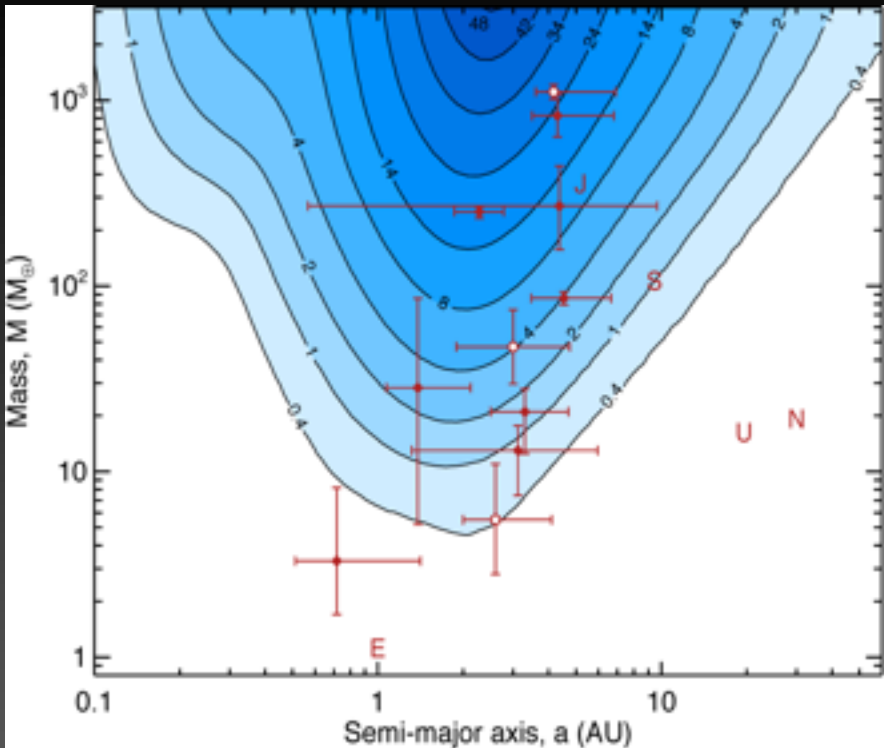
Planet in the brown dwarf desert

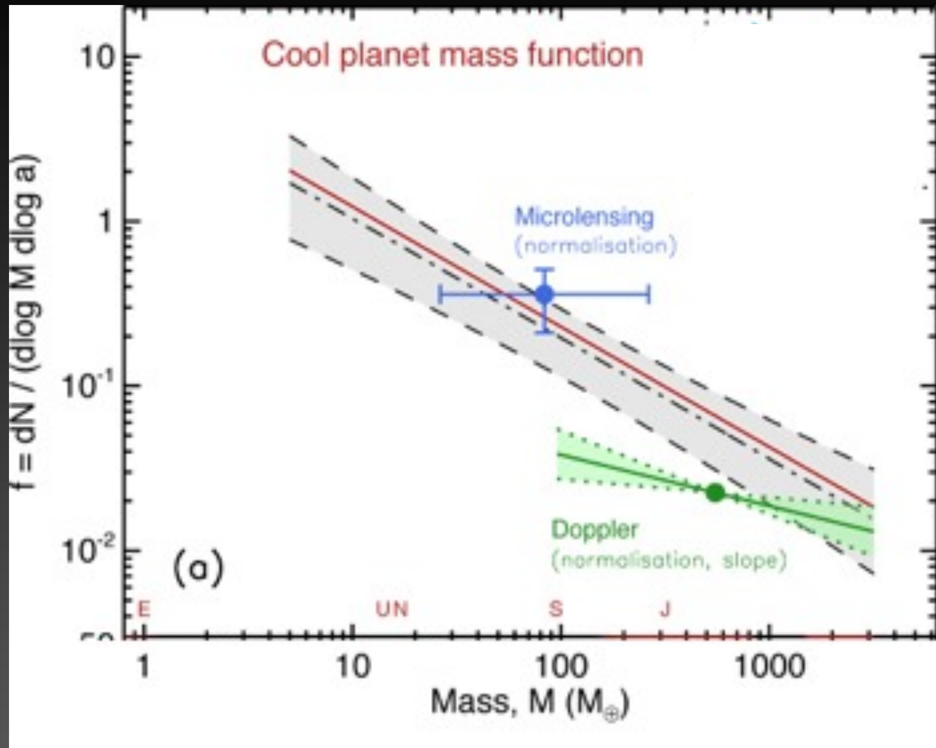
Street et al., 2013

A 0.16 ± 0.03 M_{sun} M dwarf orbited by a 11±2 M_{jup} planet



Results 2002-2007 (over orbits 0.5-10 AU)





- About 17^{+6}_{-9} per cent of stars host Jupiter-mass planets (0.3-10 M_{Jup}).
- However Cool Neptunes (10-30 $M_\oplus$) and super-Earths (5-10 $M_\oplus$), are even more common: Their respective abundances per star are 52^{+22}_{-37}% and 62^{+35}_{-29} % per cent.

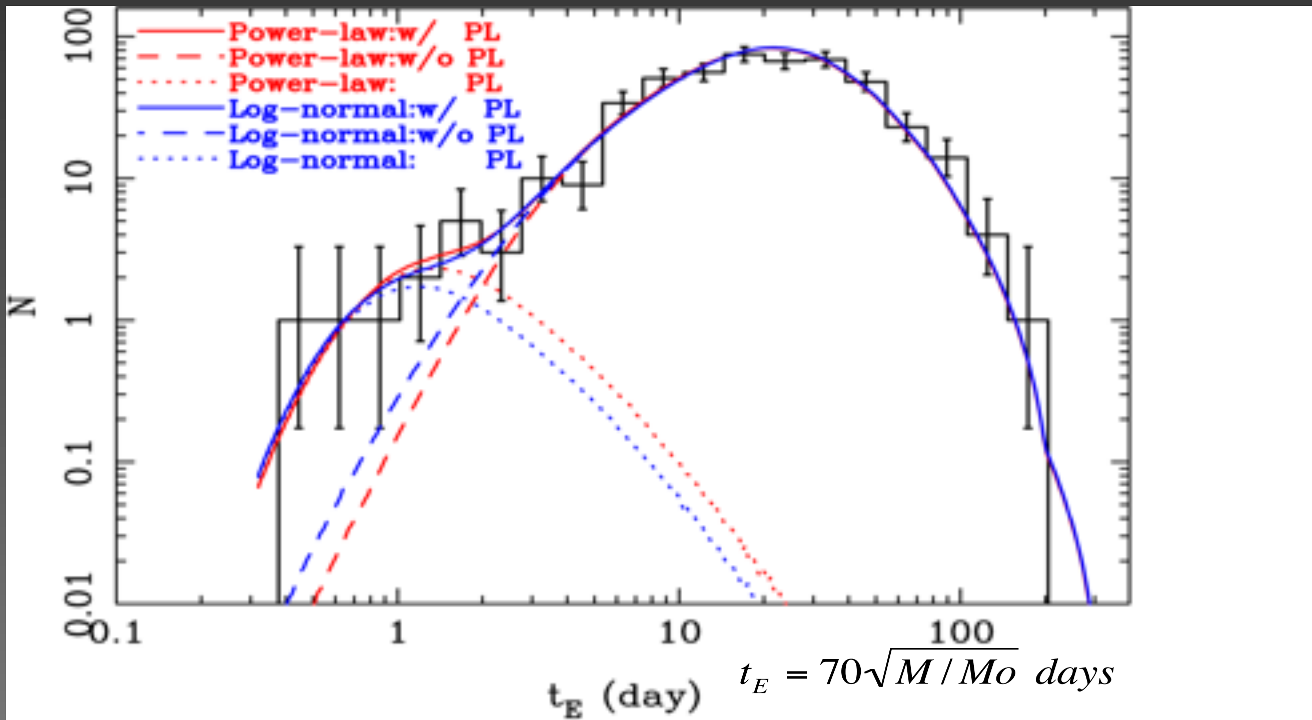
Having a planet is the rule for stars in our galaxy.

Cassan A., et al., 2012, Nature

A large population of free floating Jupiters

Sumi et al., 2010, Nature

- Short duration microlensing events t_E < 2 days
- No companion star at less than 10 AU for all
- Constraints on mass functions



$t_E = 70\sqrt{M/Mo}\ days$

A large population of free floating Jupiters

Sumi et al., 2010, Nature

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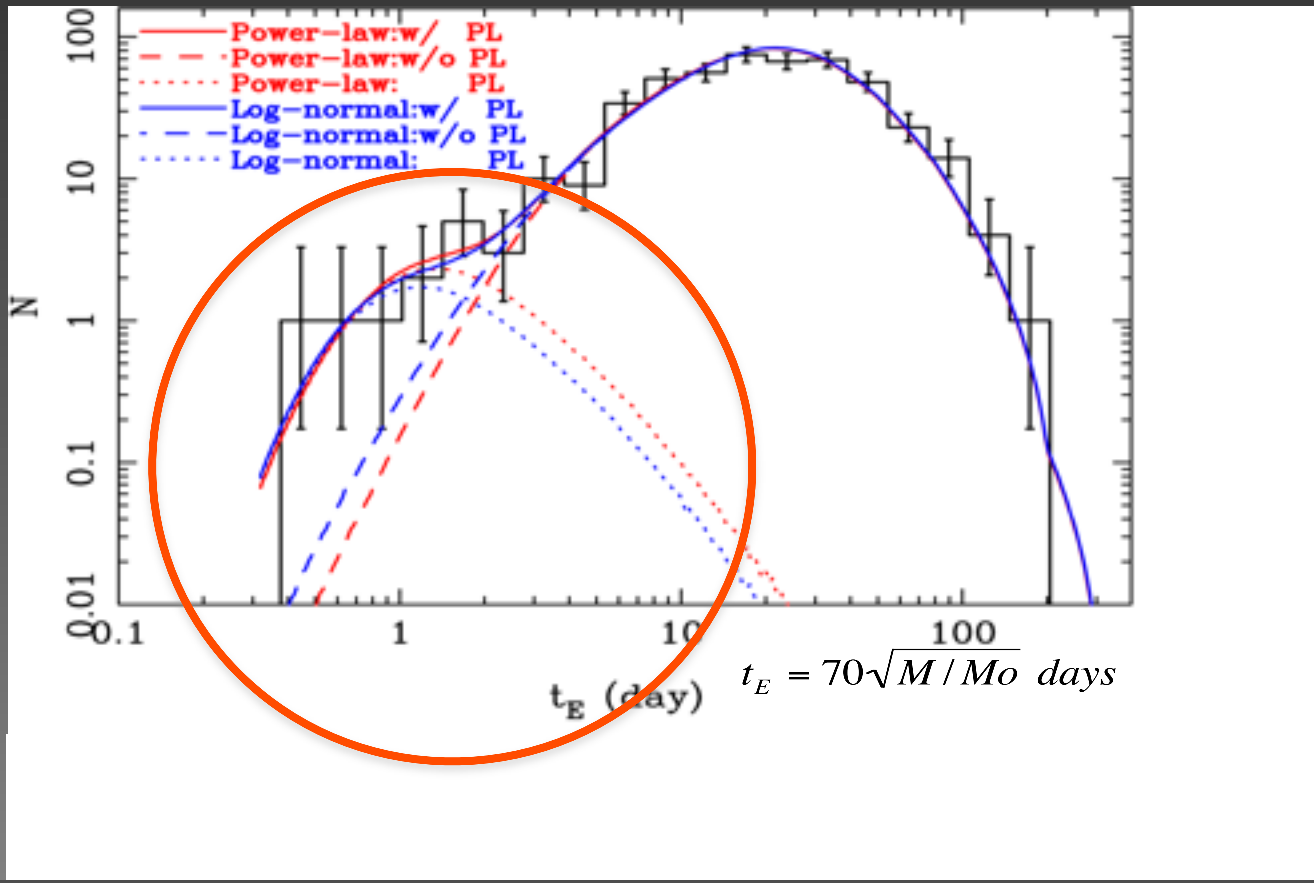


Some recent results

- 27 planets published to date (more in stock)
- Saturns orbiting M-dwarfs beyond the snow line are substantially more common than Jupiters orbiting G-dwarfs
- Cold Neptunes and super-earths are even more common
- Super Jupiters orbiting M dwarfs
- Multi planet systems
- Mass measurements can be accurate 10 %
- Detection and measurement of the mass of brown dwarf
- An important population of free floating planets
- Mass function steeper for planets than brown dwarfs

What is microlensing good for?

- Extending the exoplanet discovery space: capable of finding low-mass planets beyond the snow line

- Understanding exoplanet architecture: microlensing is able to characterise multiple-planet analogues of our solar system

- Putting planet formation theories to the test: microlensing sensitivity is right where core-accretion models predict the bulk of planet formation takes place

Mid-term : 2014-2019

Using existing facilities, automatic feedback of alerts to telescopes, and network of wide-field imagers (OGLE-IV, MOA-2, KMT) :

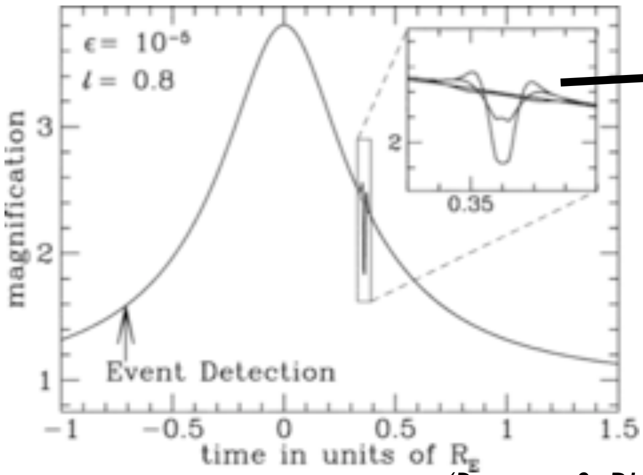
Aim:

- Measure the frequency of Giant planets beyond the snow line as a function of 3 variables: planet-host mass ratio, host mass, planet-host separation's.
- Multi-giant-planet system
- Detection of some Earth-mass planets beyond the snow line
- Free-floating (i.e., ejected) giant planets.
- Firsts Exomoons

Long-term : 2020+ EUCLID, LSST..

- Mass function of bound planets (down to Earth mass and below)
- Free floating planets (down to Super-Earth)
- Simultaneous LSST – EUCLID, Ground space parallax for mass measurements !

Microlensing need and aim to go in space



(Bennett & Rhie 1996)

The amplitude of the maximum light curve deviation decreases with increasing stellar radius.

Earth mass planet signal is washed out for giant source stars !!

For a bulge giant source star, the limiting mass is ~10 $M_\oplus$

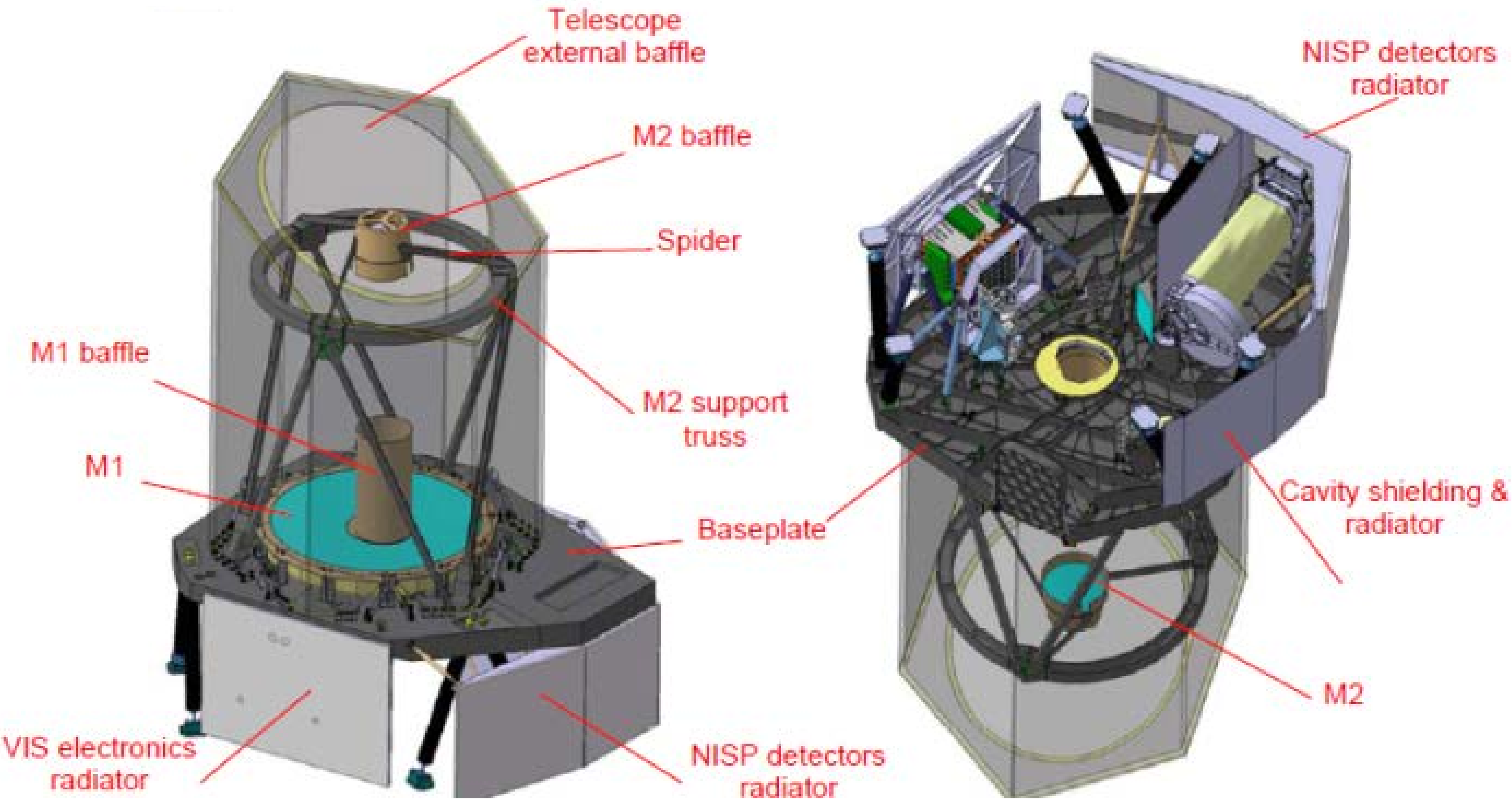
For a main sequence star, the limiting mass is ~ 0.1 $M_\oplus$

To get small mass planets :

- Wide field camera — to monitor as much star time possible
- High resolution — to discriminate stars / field crowded / small stars
- Large mirror — to decrease exposure time / to increase sampling
- Near IR — to observe through interstellar dust
- Space mission — 24 Hr cycle duty == optimal for detection efficiency

Euclid esa

PLM design



Exoplanet Euclid Legacy Survey

(ExELS)

Full science study presented in
Penny et al (2013): arXiv:1206.5296

Primary survey objectives	**Yield**	**Science**
Measure the abundance of cool exoplanets down to Earth mass with host separation > 1 AU to at least 3-sigma precision	Around 35 cool planets per month, including 4.5 Earths and 14 Neptunes per month.	Cool exoplanet regime is crucial for testing planet formation theories and constraining abundance of planets in outer Habitable zone.
Measure the abundance of free-floating planets	Around 15 free-floating Jupiters per month if there is one per Galactic star.	Unbound planets are predicted by planet formation theories. Young counterparts have been observed in clusters. Older population tentatively observed with ground-based microlensing

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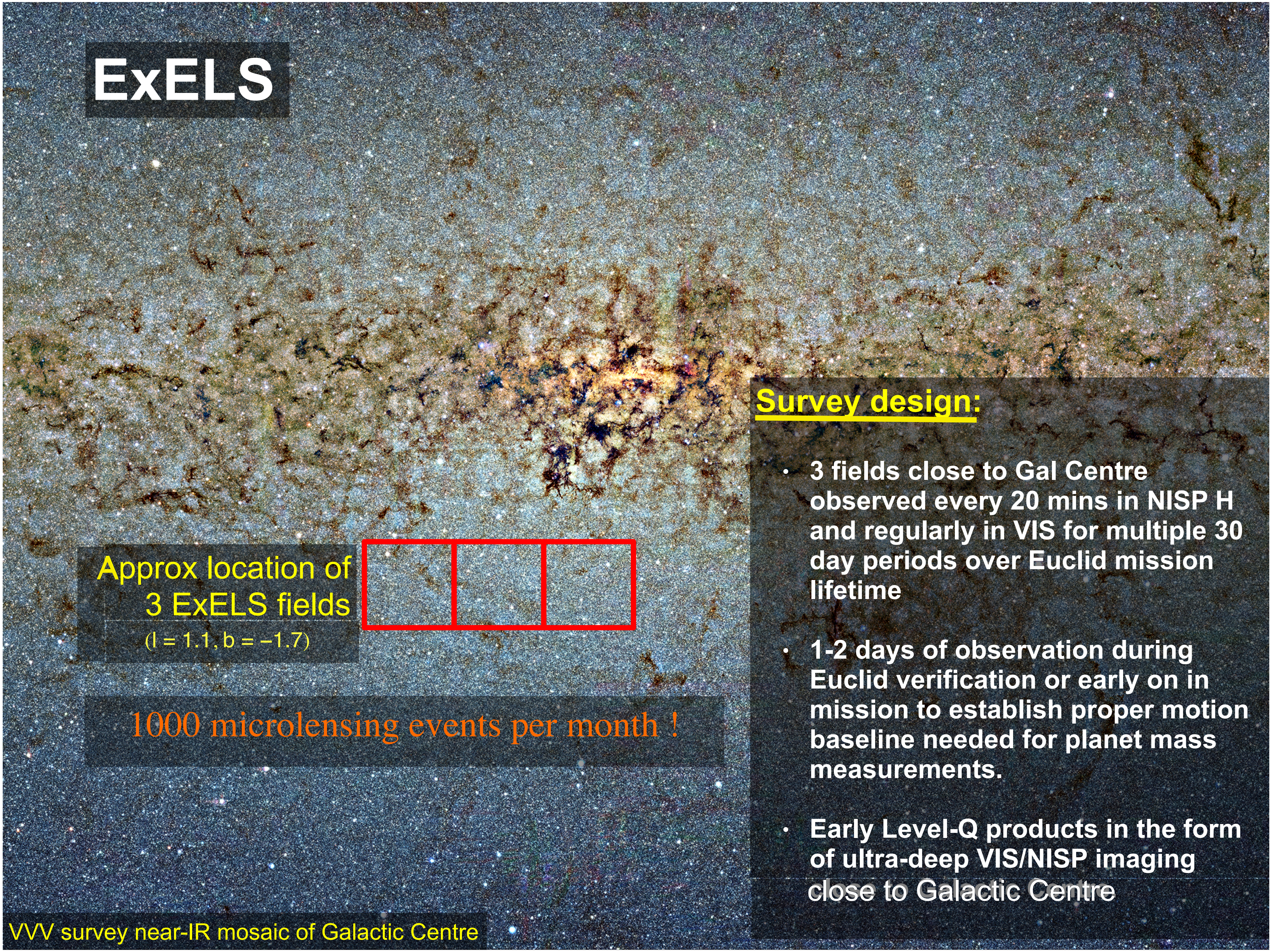
- **Microlensing is the only method able to explore cool exoplanet regime down to Earth mass**
- Poor sensitivity to cool Earths from the ground due to atmosphere. ExELS would provide a step change in microlensing exoplanet discovery efficiency.
- ExELS + Kepler datasets would provide a full statistical census of Earth-mass planets over **all** host separations.

No other ESA mission will explore cool exoplanets. Science goals complement but do not impact on other ESA proposals

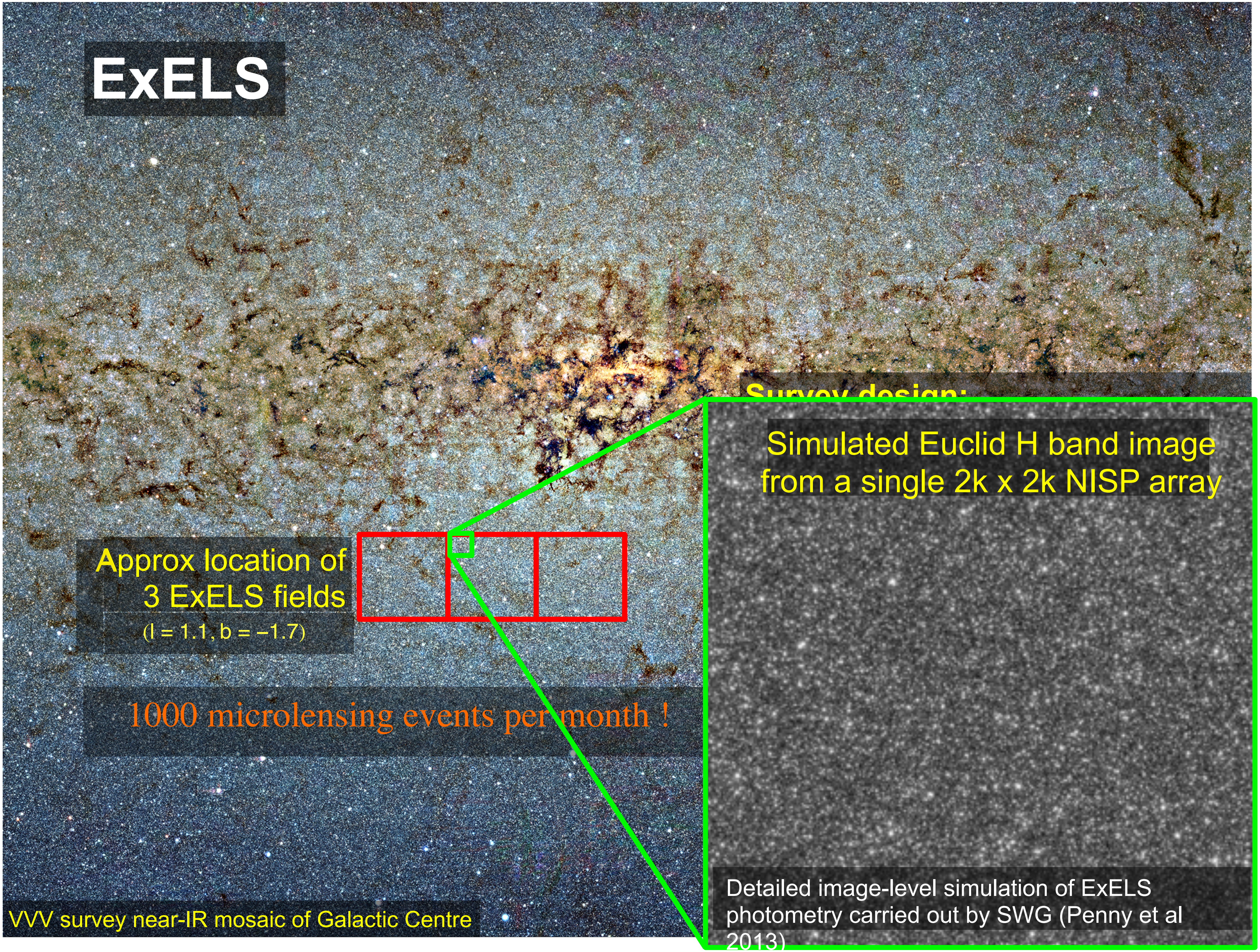
ExELS



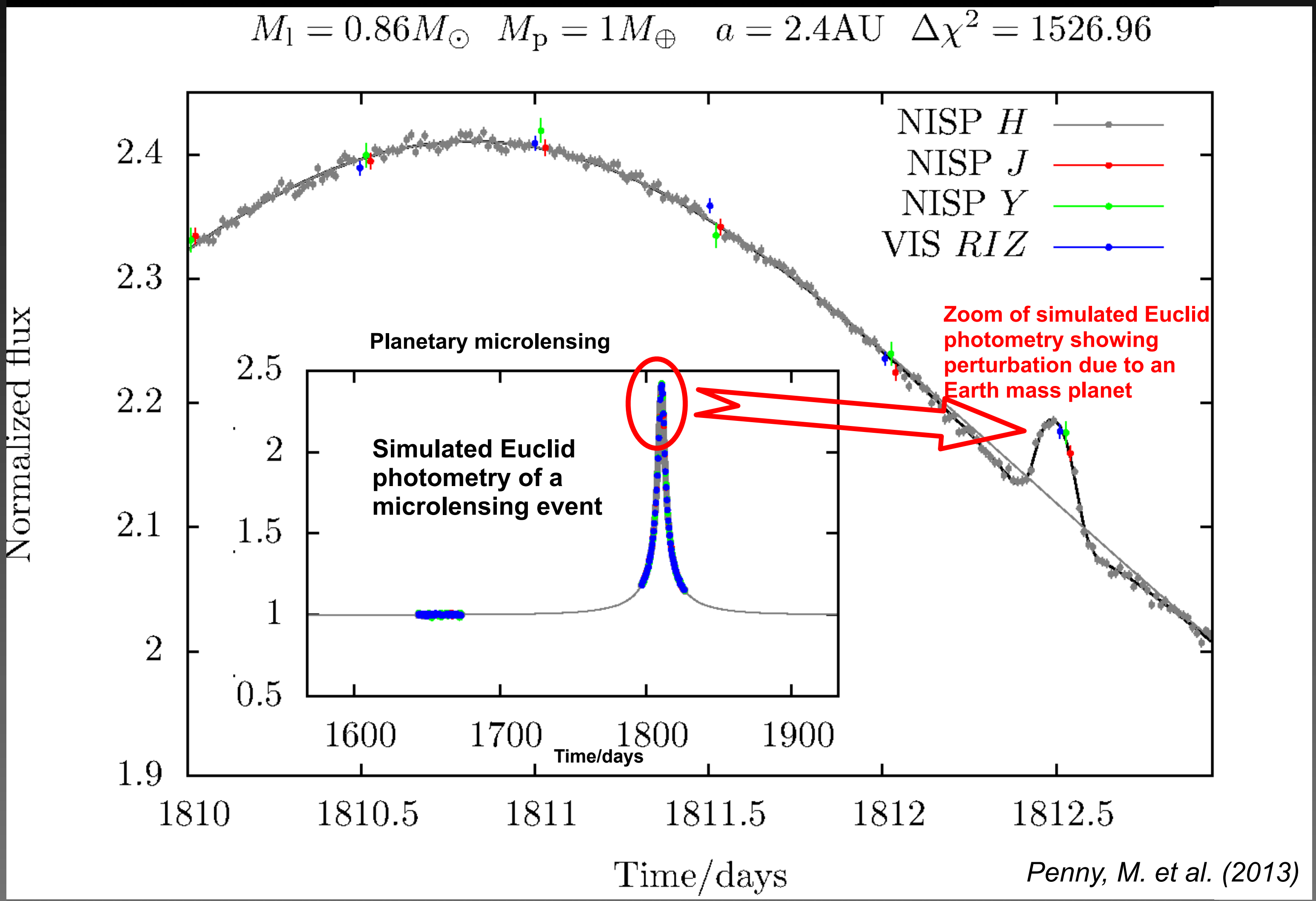
VVV survey near-IR mosaic of Galactic Centre

Survey design:

- 3 fields close to Gal Centre observed every 20 mins in NISP H and regularly in VIS for multiple 30 day periods over Euclid mission lifetime
- 1-2 days of observation during Euclid verification or early on in mission to establish proper motion baseline needed for planet mass measurements.
- Early Level-Q products in the form of ultra-deep VIS/NISP imaging close to Galactic Centre

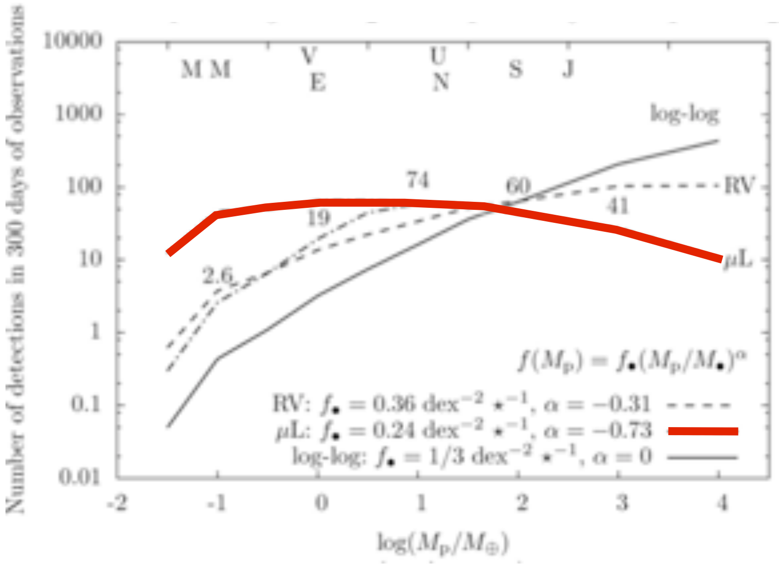


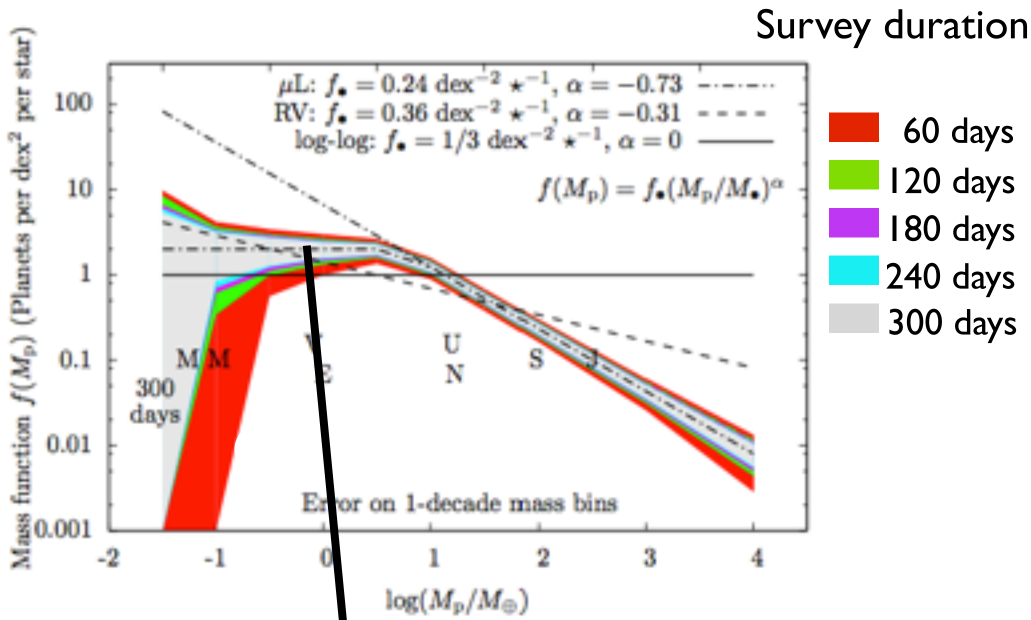
ExELS
Survey design:
Simulated Euclid H band image
from a single 2k x 2k NISP array
Approx location of
3 ExELS fields
(l = 1.1, b = −1.7)
1000 microlensing events per month !
Detailed image-level simulation of ExELS
photometry carried out by SWG (Penny et al
2013)
VVV survey near-IR mosaic of Galactic Centre



$M_l = 0.86 M_\odot$ $M_p = 1 M_\oplus$ $a = 2.4$AU $\Delta\chi^2 = 1526.96$
NISP H
NISP J
NISP Y
VIS RIZ
Normalized flux
Time/days
Zoom of simulated Euclid photometry showing perturbation due to an Earth mass planet
Planetary microlensing
Simulated Euclid photometry of a microlensing event
Time/days
Penny, M. et al. (2013)

Measuring the planet mass function





Measure of the abundance of
Earth mass planets
at ~5 sigma in 300 days.

Range of semi-major axis probed by EUCLID:

- Jupiter mass : ~0.2 - 20 AU
- Earth mass : ~1.0 - 14 AU
- Mars mass : ~1.5 - 5 AU

LSST and EUCLID: ground-space parallax

break degeneracies and allow precise mass measurement of the lens

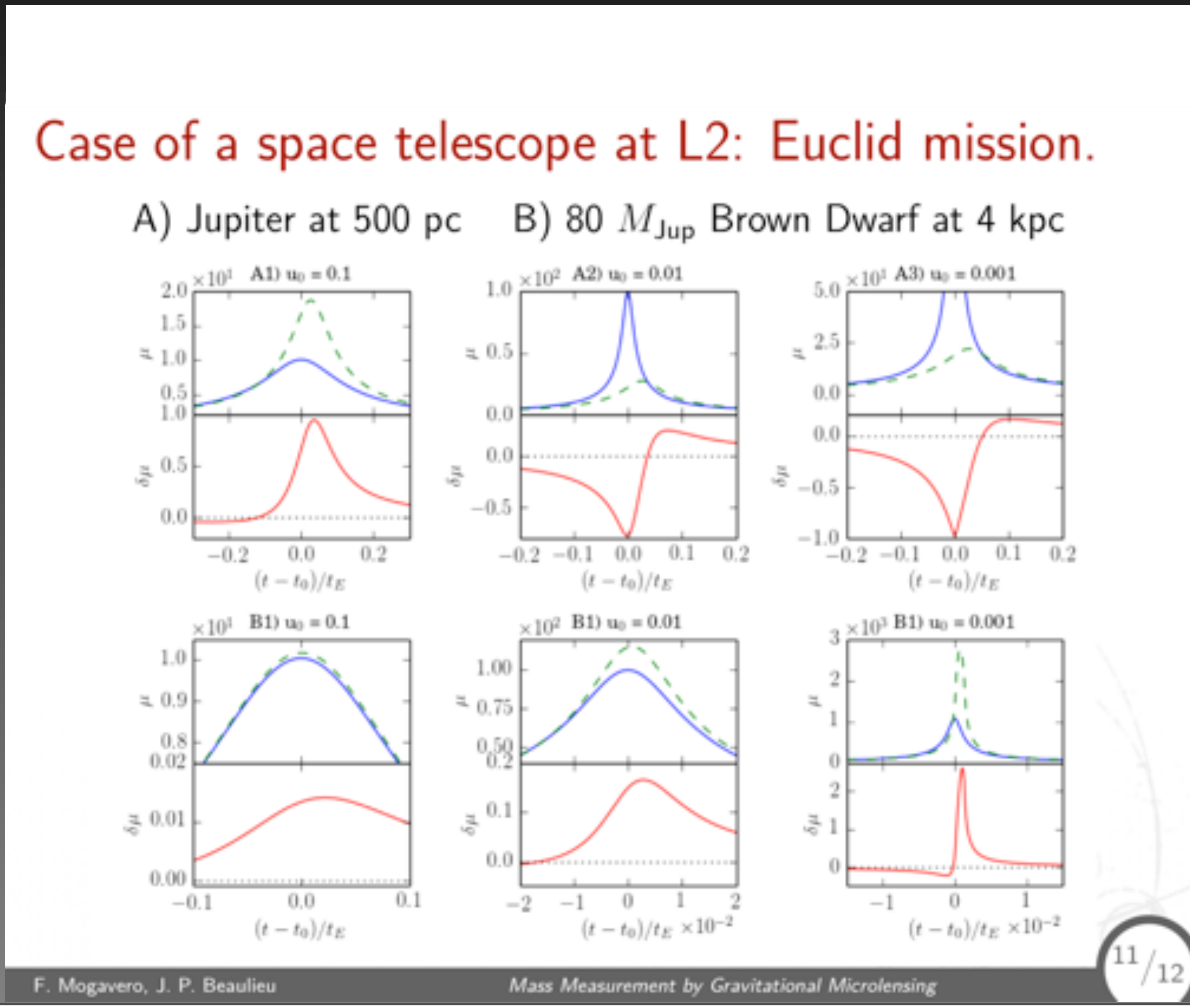


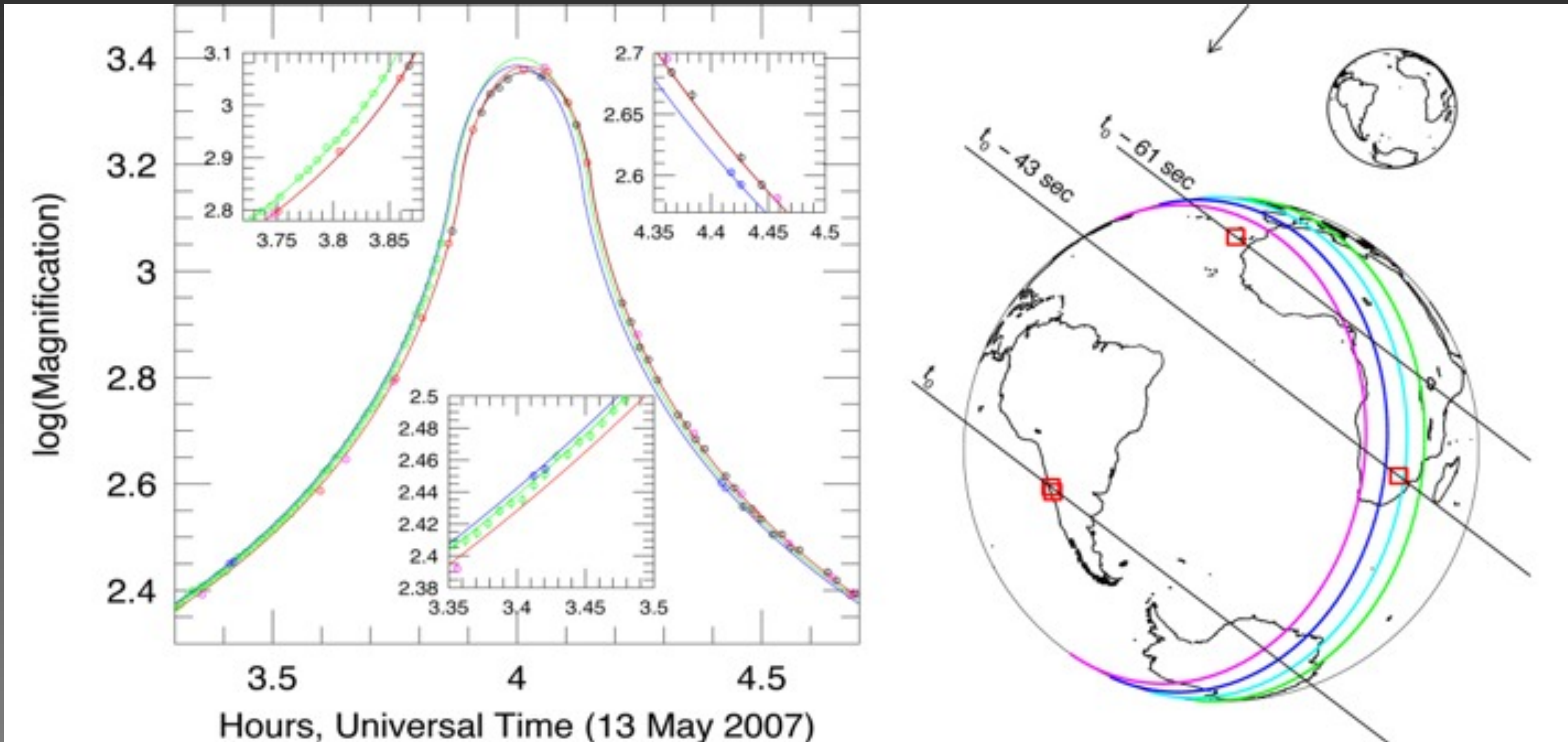
Illustration Parallax

Population of Brown dwarfs

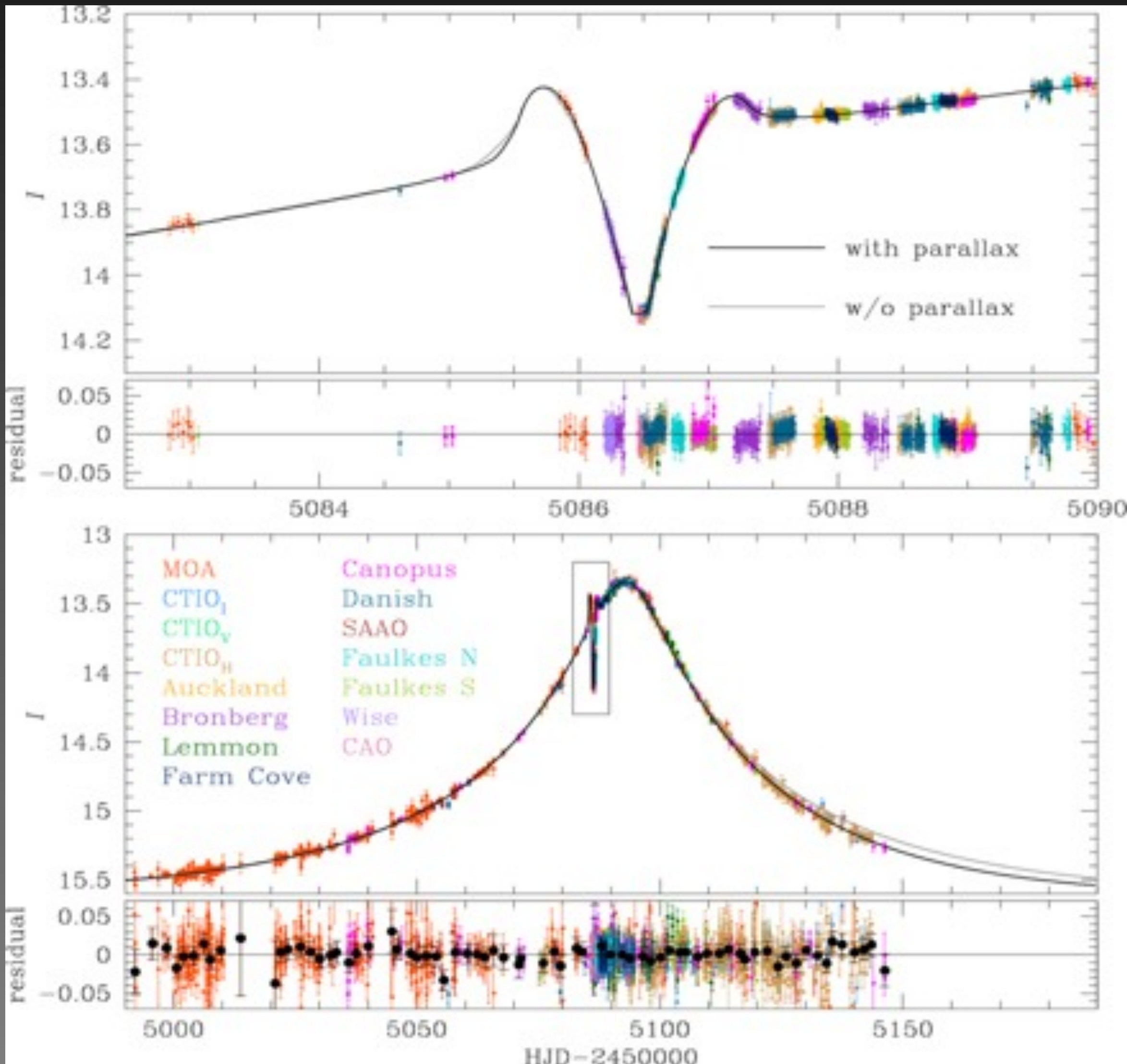
A thick disk brown dwarf of 0.056±0.005 M_{sun}

Gould et al., 2010

Amplification 2500, terrestrial parallax and YES, we measured its mass ☺



A 9.8 ±1.1 $M_\oplus$ planet at 3.42 ±0.34 AU of a 0.56±0.06 M_{sun} star



October 2009

Detected with 40 cm tel

Follow up:
- KECK
- EPOXI (DEEP IMPACT)

Muraki et al., 2011

Unique niche for LSST

Probing different line of sights than the Bulge, i.e. spiral arms etc..
(regular survey : sampling 1 point / 4 nights per Field, multi-band epoch)
=> optical depth / structure of galaxy
=> **detection of planets in multiple direction (x10 / now)**
=> **Need of an alert system of microlensing event**

Bulge fields :
- **Simultaneous LSST – EUCLID,**
ground space parallax for mass measurements
=> **Need LSST light curve of interesting events (~10000)**

Dedicated survey. 1+ month continuous observations of 20 sq degrees with sampling rate of 10 minutes
=> Statistics of low mass free-floating planets (down to Super-Mars)

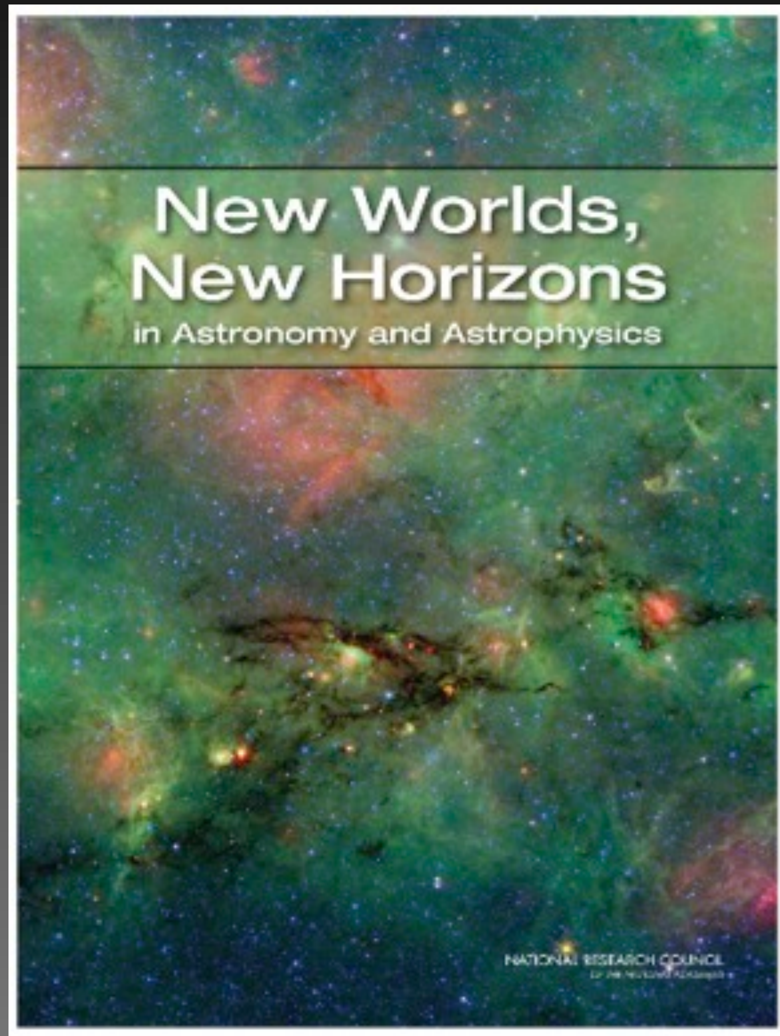
Astro-2010 Decadal Survey

“the Kepler satellite ... should be capable of detecting Earth-size planets out to almost Earth-like orbits.”

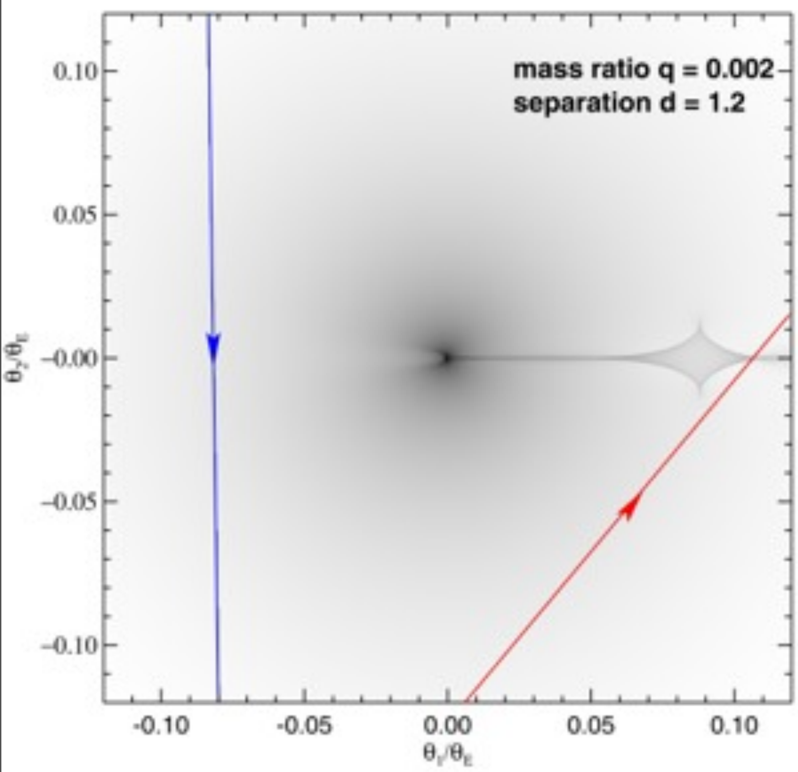
“As microlensing is sensitive to planets of all masses having orbits larger than about half of Earth’s, WFIRST would be able to complement and complete the statistical task underway with Kepler, resulting in an unbiased survey of the properties of distant planetary systems.”

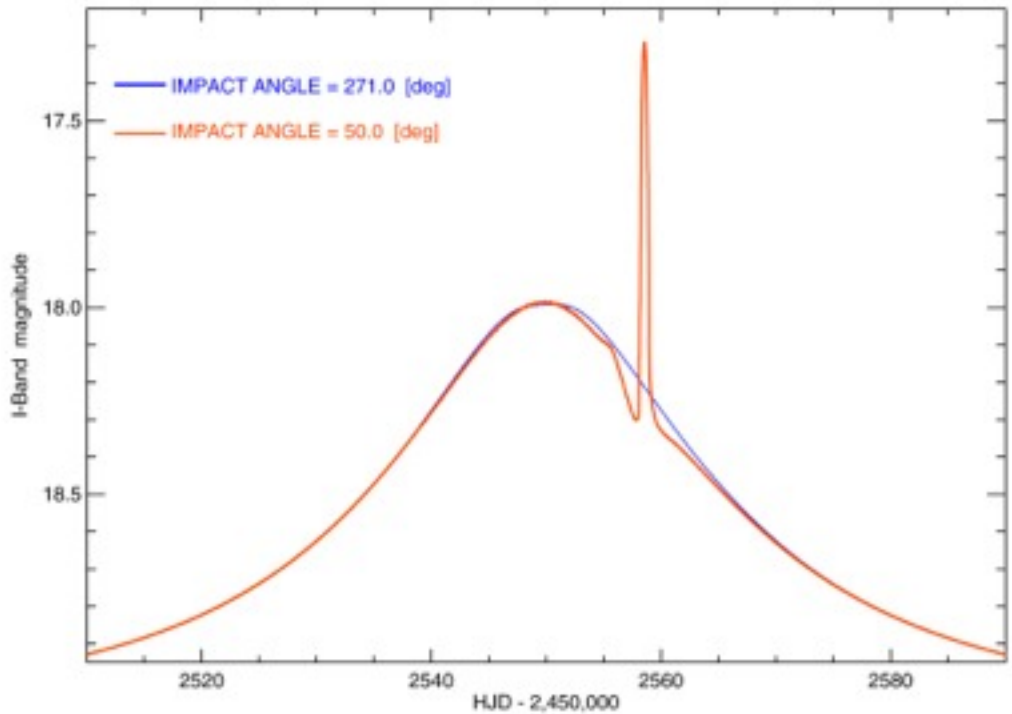
EUCLID 2020

WFIRST 2025



A planetary companion





$$t_{\mathrm{E}} = 20\,\mathrm{d},\, M = 0.3\, M_{\mathrm{sun}}:$$

$$t_{\mathrm{p}} = \sqrt{q}\; t_{\mathrm{E}}$$

$$\text{Jupiter}:\; q = 3\;10^{-3} \Rightarrow t_{\mathrm{p}} = 1\ \mathrm{d}$$

$$\text{Earth}:\; q = 10^{-5} \Rightarrow t_{\mathrm{p}} = 2\ \mathrm{h}$$

A large population of free floating Jupiters

- Short duration microlensing events $t_E < 2$ days
- No companion star at less than 10 AU for all
- Constraints on mass functions

- MF1: $dN/dM = M^{-\alpha}$ $\alpha 1 = 2.0$ $0.7 < M/M_o < 1.0$

  $\alpha 2 = 1.3$ $0.08 < M/M_o < 0.7$

  $\alpha 3 =$ fitted $0.01 < M/M_o < 0.08$

- MF2: $dN/d\log M = \exp((\log M - \log M_c)^2/(2\sigma_c^2))$

Sumi et al., 2010, Nature

Power law in the BD regime

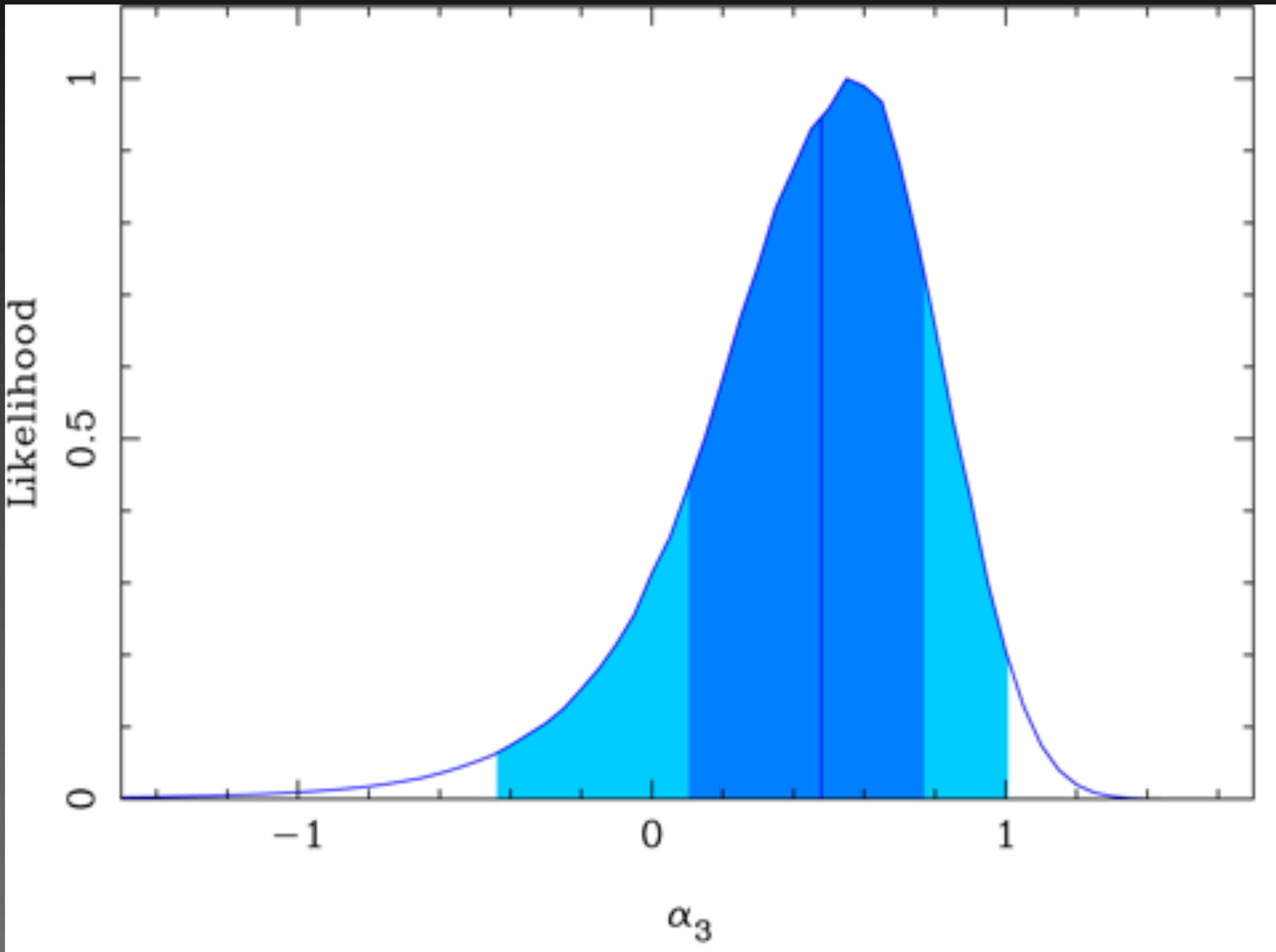


Figure 6.— Likelihood distribution for the Power-law index α_3 in brown dwarf regime without the planetary mass population, including only the events with $t_E > 2$ days. The vertical lines and colored regions indicate the median ($\alpha_3 = 0.48$) and 68% ($\alpha_3 = 0.10$ and 0.77) and 95% ($\alpha_3 = -0.44$ and 1.01) confidence intervals.

For $0.01\,M_{sun} < M$,
$dN/d\log M = \exp[(\log M - \log M_c)^2/(2\sigma_c^2)]$

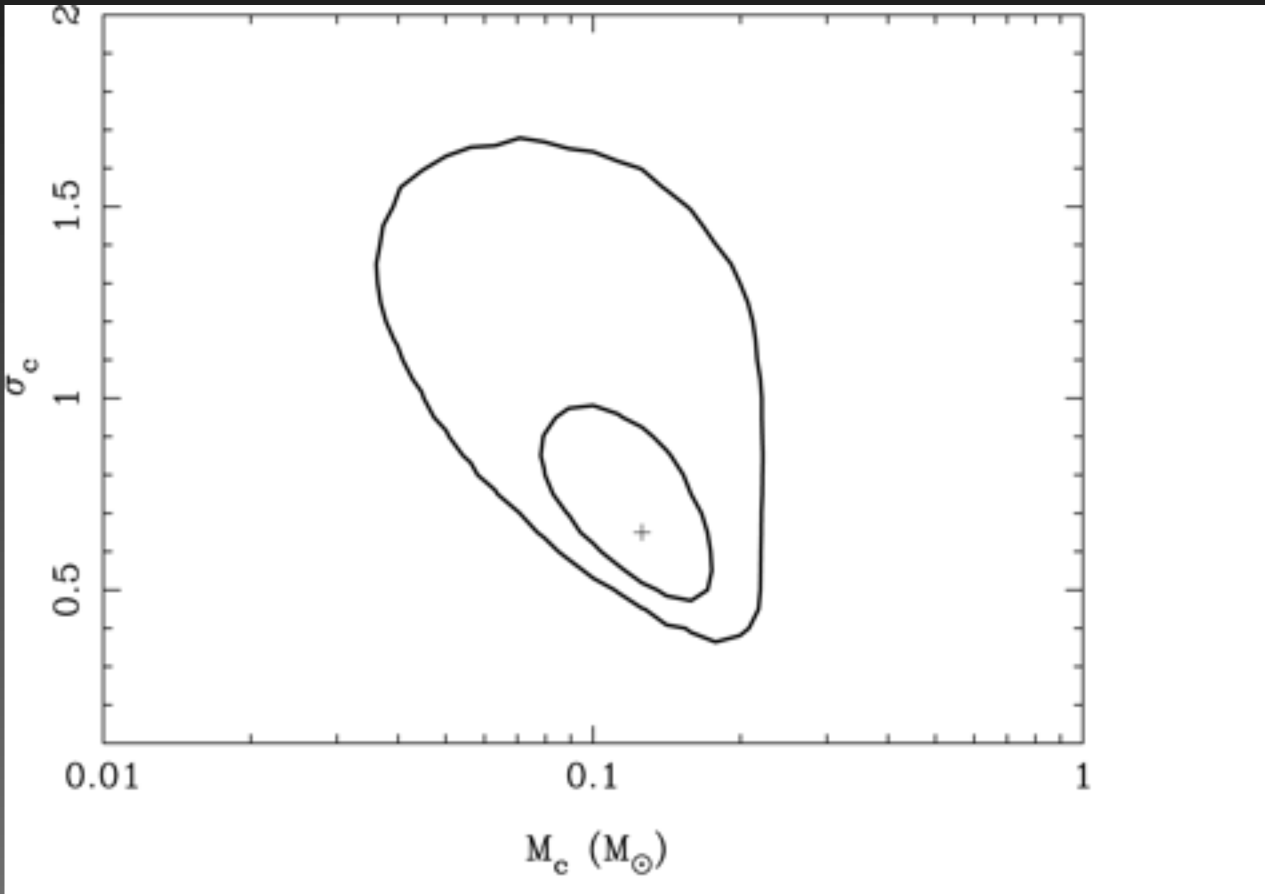


Figure 7.— Likelihood contours for the mean mass, M_c, and variance, σ_c of log-normal mass functions without the planetary mass population, including only the events with $t_E > 2$ days. Two contours indicate the 68% and 95% confidence intervals. "+" indicate the maximum likelihood point. The median and 68% confidence intervals are $M_c = 0.12^{+0.03}_{-0.03}$ and $\sigma_c = 0.76^{+0.27}_{-0.16}$ and these are consistent with previous work[22].

MF steeper for planets than BD

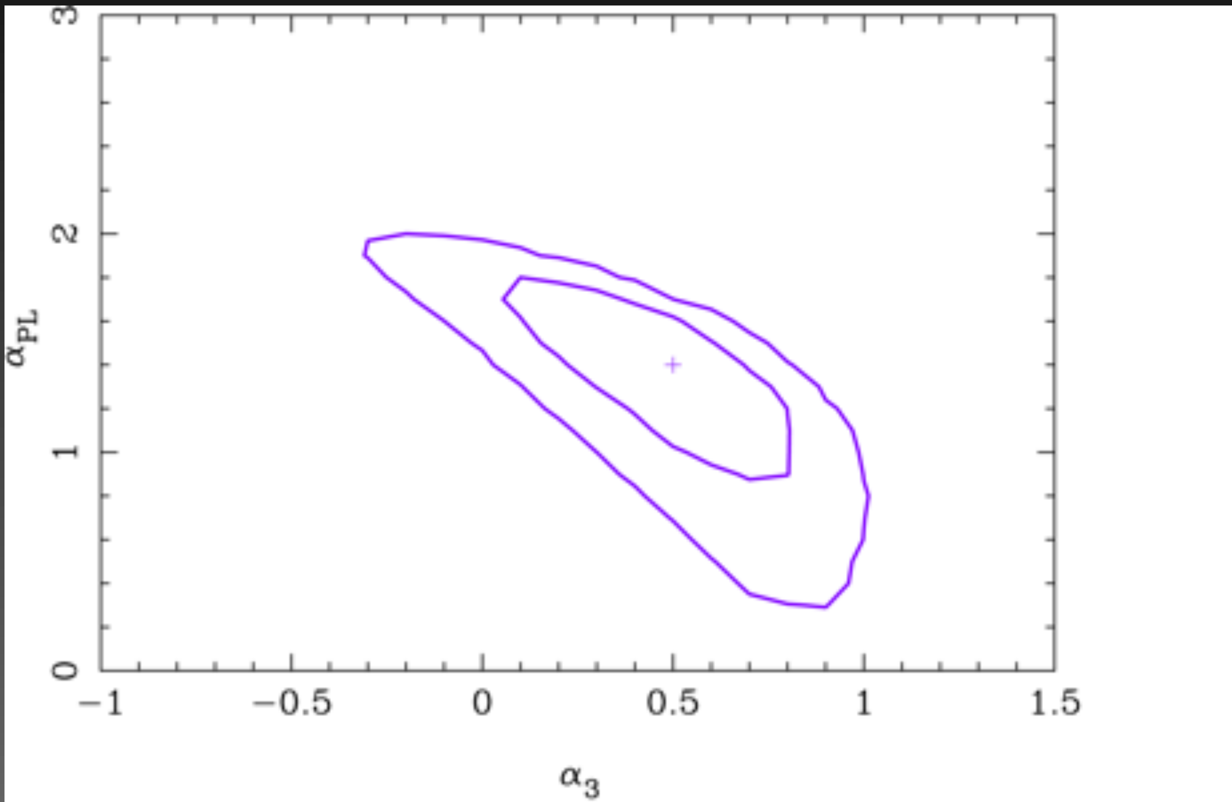


Figure 10.— Likelihood contours for the Power-law indices α_3 in the brown dwarf regime, and α_{PL} in the planetary-mass regime. These brown dwarf and planetary mas regimes span the mass ranges $0.01 \leq M/M_\odot \leq 0.08$ and $10^{-5} < M/M_\odot < 0.01$, respectively. The two contours indicate the 68% and 95% confidence levels, and "+" indicate the maximum likelihood point. These results do not depend on the lower mass limit of $10^{-5}M_\odot$ as the sensitivity to masses lower than $10^{-4}M_\odot$ is poor due to the small detection efficiencies at low t_E. The α_3 distribution is consistent with the α_3 distribution for model (1) with and without the δ-function planetary mass function (see Table 3). The value α_{PL} is much steeper than α_3, indicating that this planetary mass objects are separate population from brown dwarfs.