30 years of planet hunting via microlensing, entering the era of Roman and Euclid

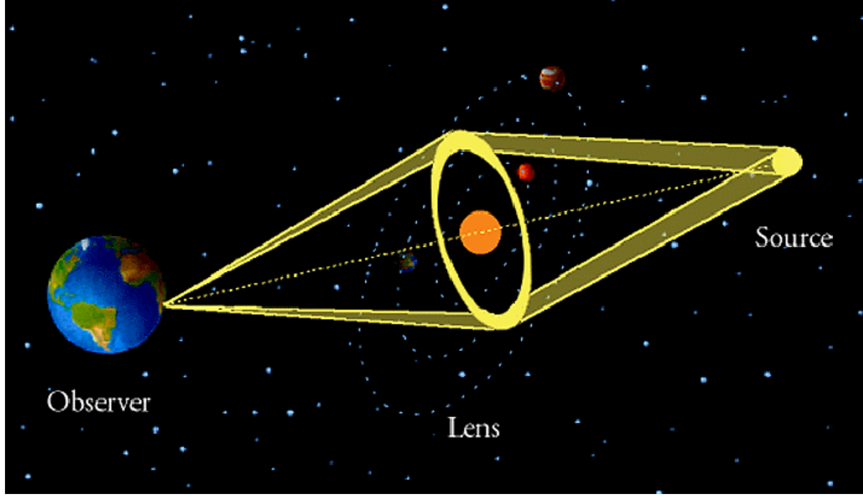
Jean-Philippe Beaulieu

Institut d’Astrophysique de Paris, University of Tasmania

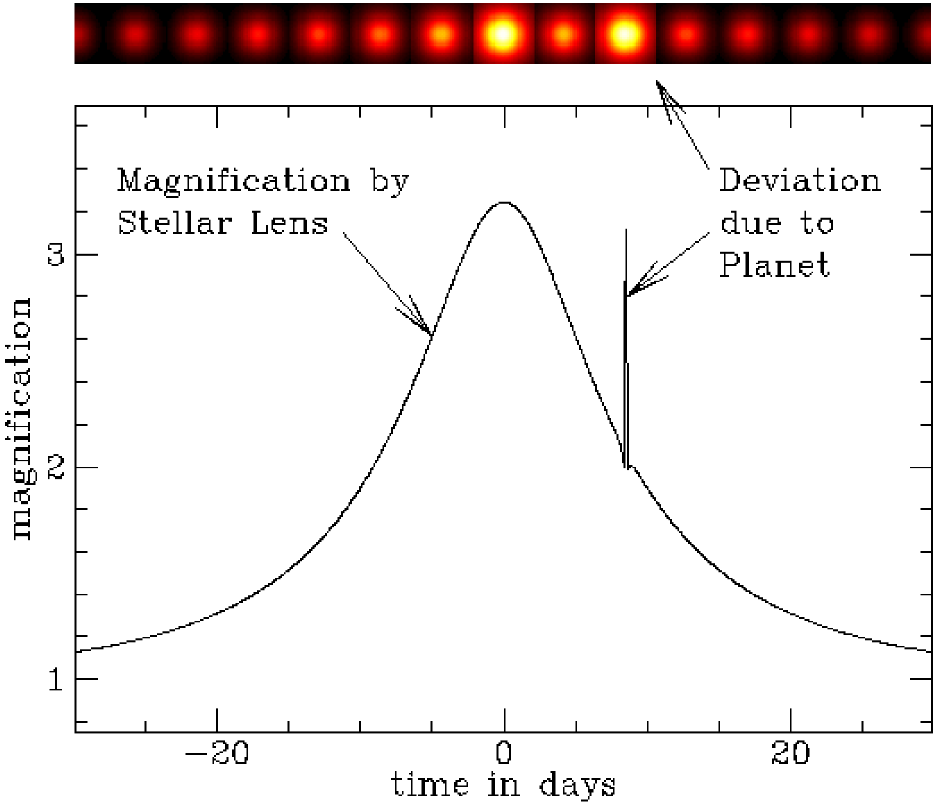
Partners in crime : PLANET collaboration, D Bennett, C. Ranc, E.Bachelet, N. Rektsini, S. Terry, A. Bhatacharya, A Cassan, A. Cole, C. Danielski, J. Blackman, K. Vandorou, M. Gilles

Euclid, Roman : E. Kerins, M. Penny, V. Bozza, E. Thygesen, H. Verma, J.C. Cuillandre

Gould et Loeb 1992 : « Planets in a solar-like system positioned half-way to the Galactic center should leave a noticeable signature (magnification larger than 5 percent) on the light curve of a gravitationally lensed bulge star in about 20 percent of the microlensing events. »



January 1995 : No planet detected so far.
Microlensing looks promising.
Jupiter is very easy !



Two approaches :

Alerts from existing surveys (MACHO, OGLE, EROS, MOA)
Using existing telescopes for a network (PLANET, uFUN).

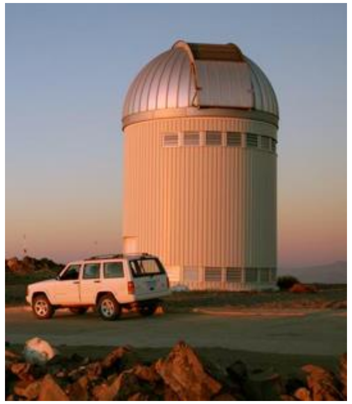
A survey telescope & follow up telescopes (2m class).
(From 2016, OGLE, MOA, KMTNET, LCOGT)

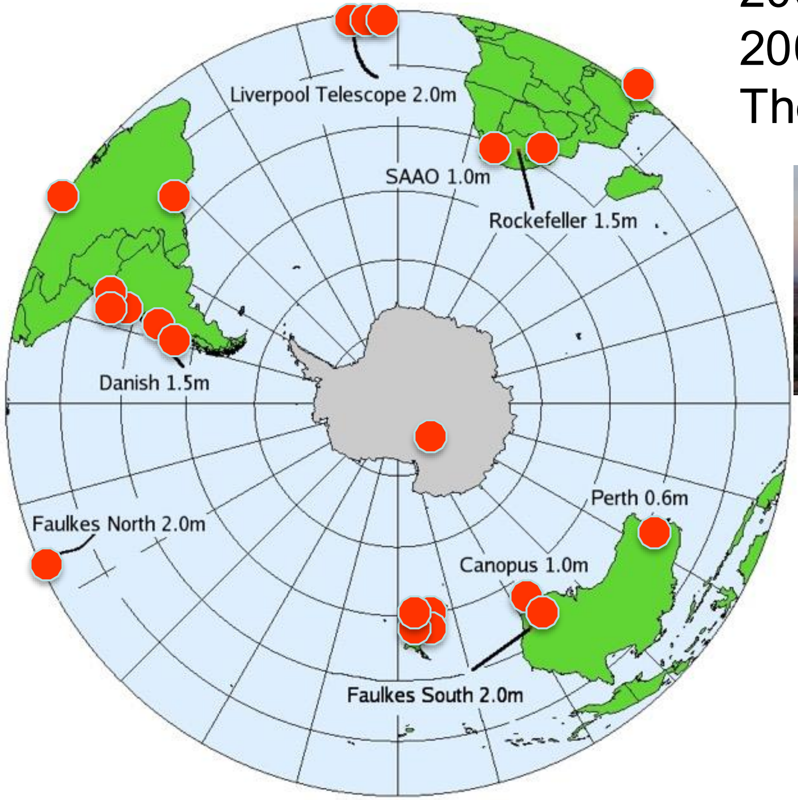
OGLE, MOA, PLANET, uFUN

Network of 1 m class telescopes, round the clock observations, online analysis.

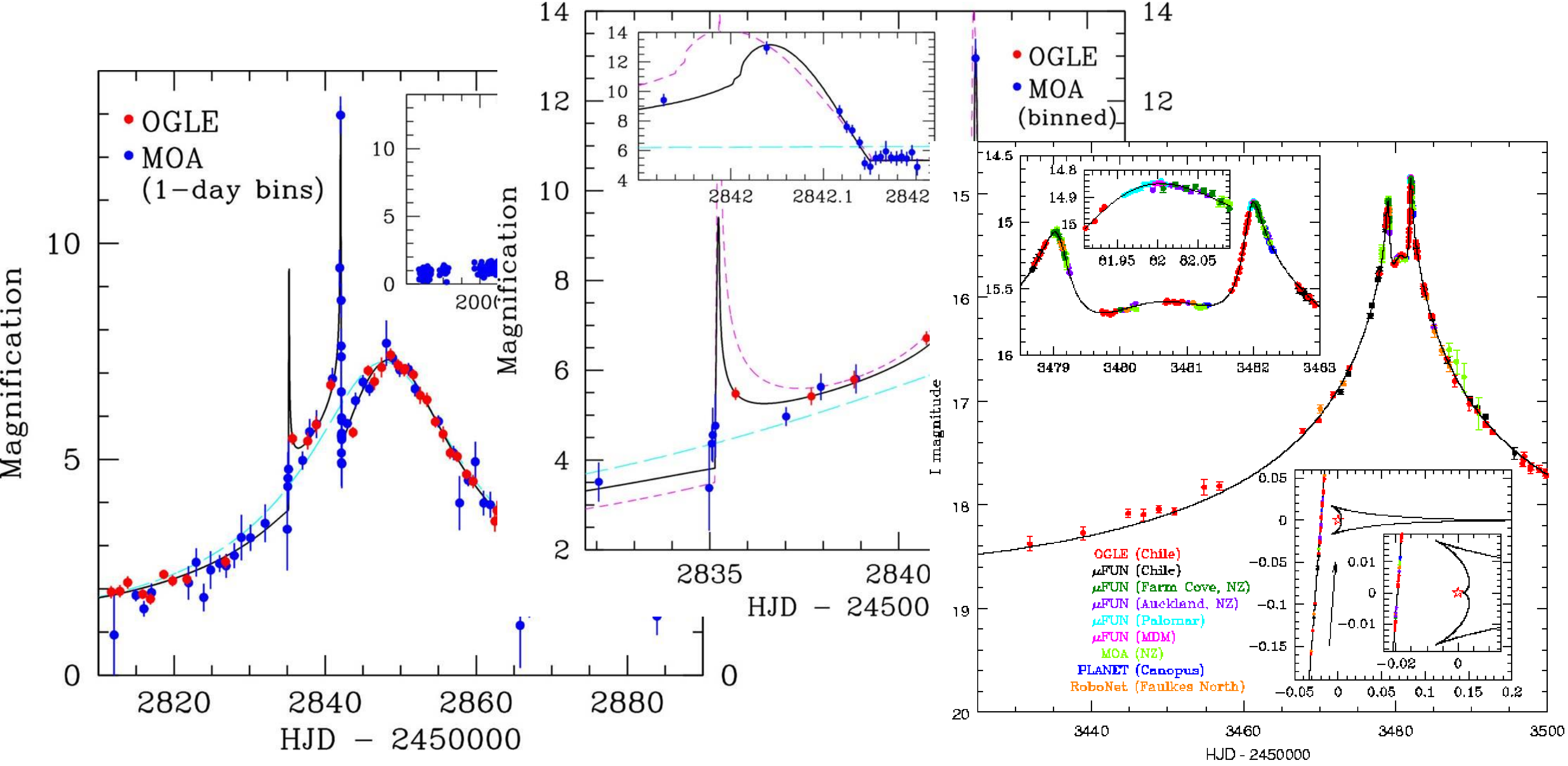
From 4 telescopes, to a fleet of 45+ telescopes on alert
Including DOME C

2003, first planet
2005, 3 planets
2007-2013: 4-7 planets/Yr
Then, 10-15 planets / year



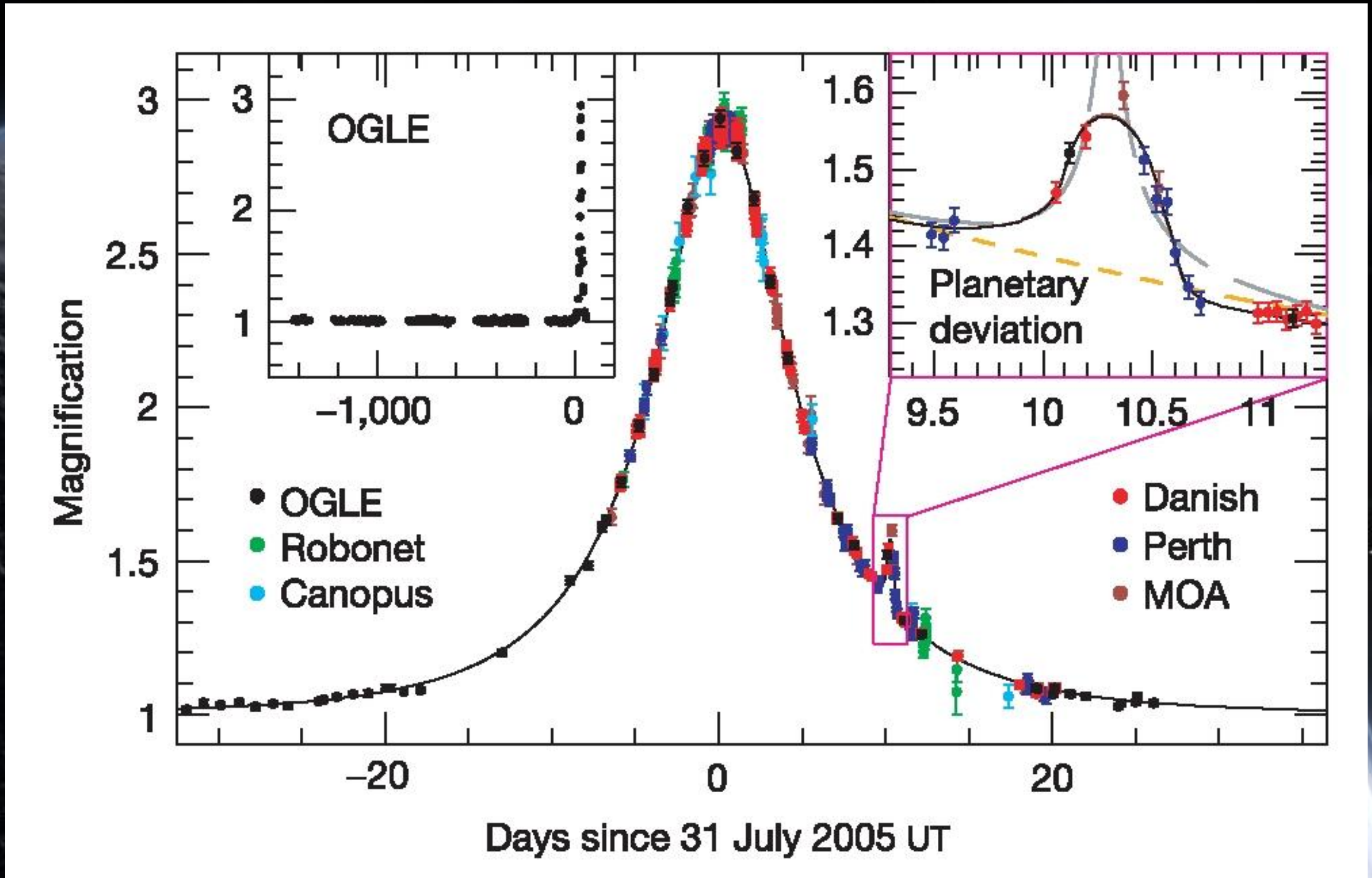


First 2 Gazeous planets led by MOA and OGLE *(Bond et al. 2003, Udalski et al. 2005)*



A first frozen super Earth

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



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

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

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

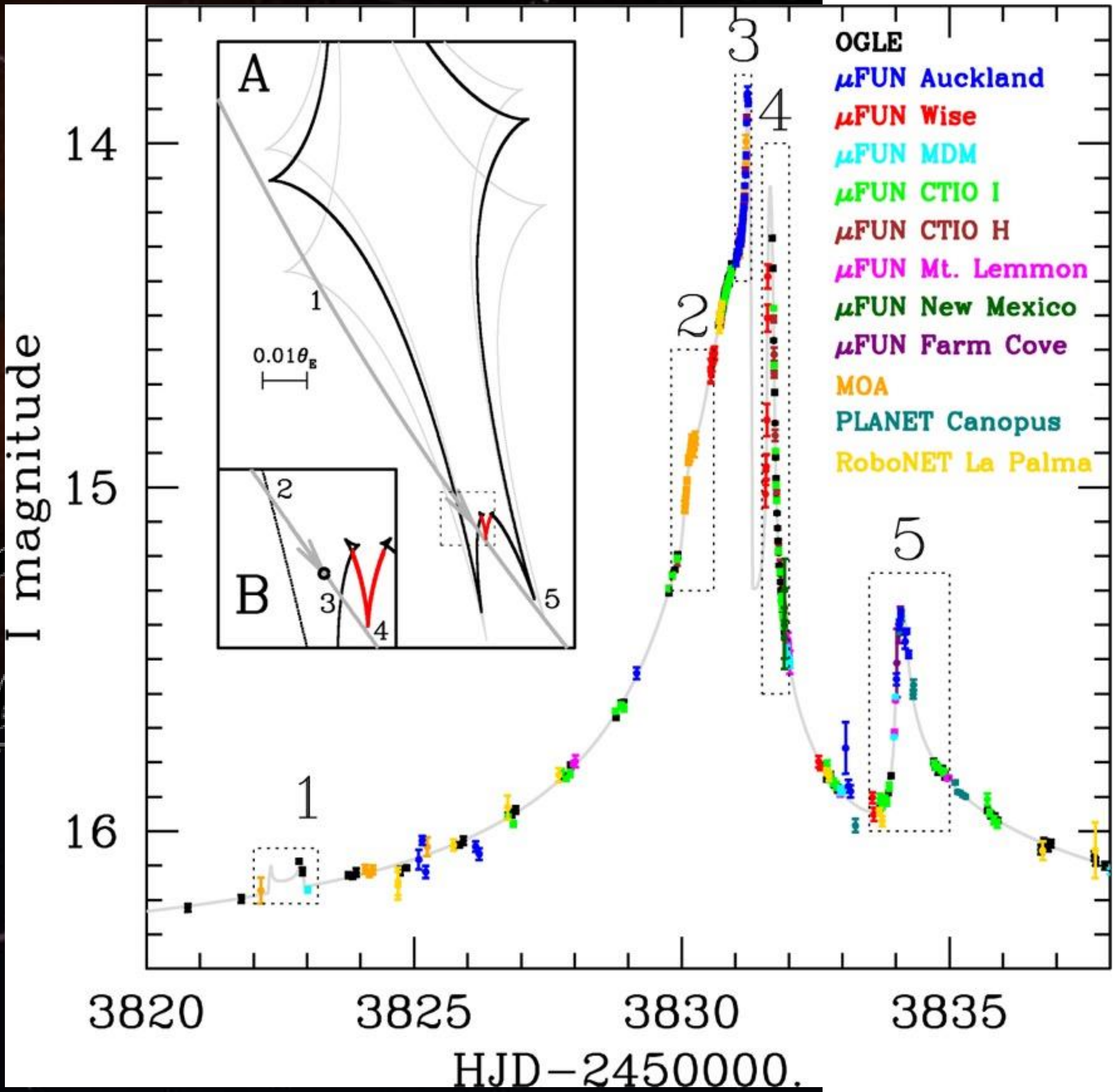
Beaulieu et al., 2006, Nature (PLANET, OGLE, MOA)

A scale ½ solar system

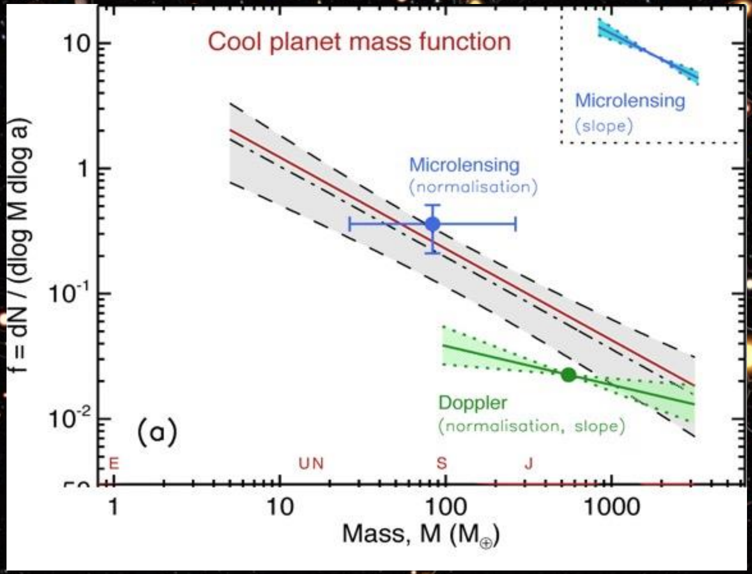
A small star (1/2 sun)

Two gazeous planets like Jupiter and Saturn
Big planet is 0.7 Jupiter at 2.3 AU
Second planet is 0.3 Jupiter at 4.6 AU

Gaudi et al., 2008, Science, Bennett et al. 2010, ApJ



2012 : having a planet is the rule for star is our Galaxy

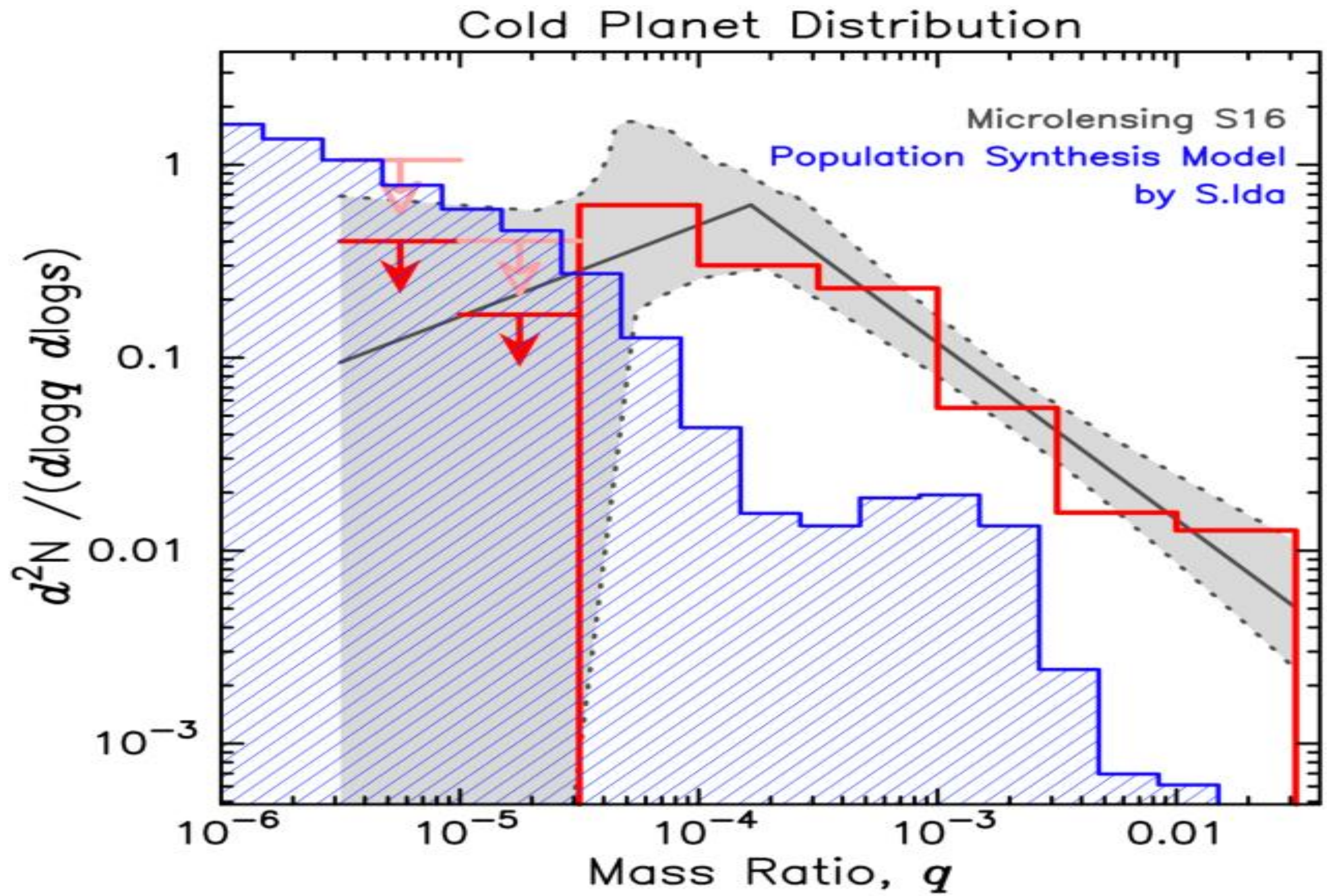


Cool Neptunes (10-30 $M_\oplus$) and super-Earths (5-10 $M_\oplus$), however, are even more common: Their respective abundances per star are 52^{+22}_{-29} % and 62^{+35}_{-37} %.
17^{+6}_{-9} %of stars host Jupiter-mass planets (0.3-10 MJ).

Cassan A., et al., 2012, Nature

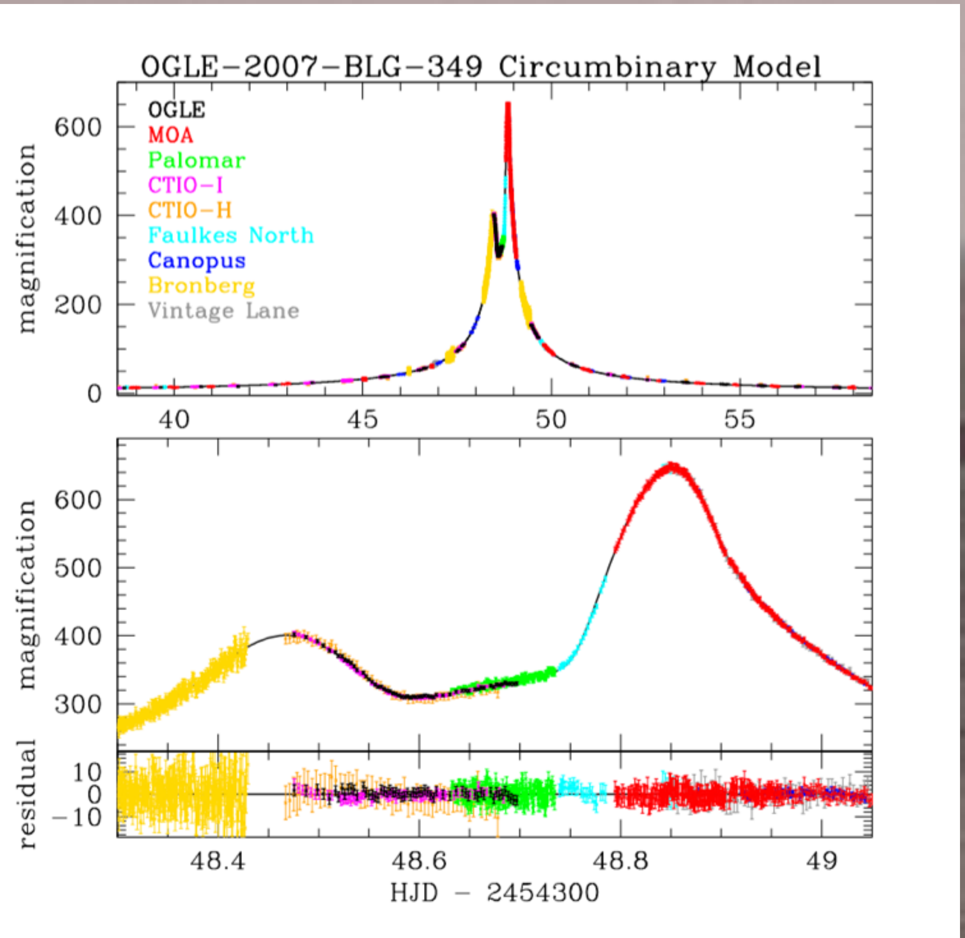
Cold planet mass function from MOA 2007-2012

Change of slope of the mass function in the Neptune/mini-Neptune regime



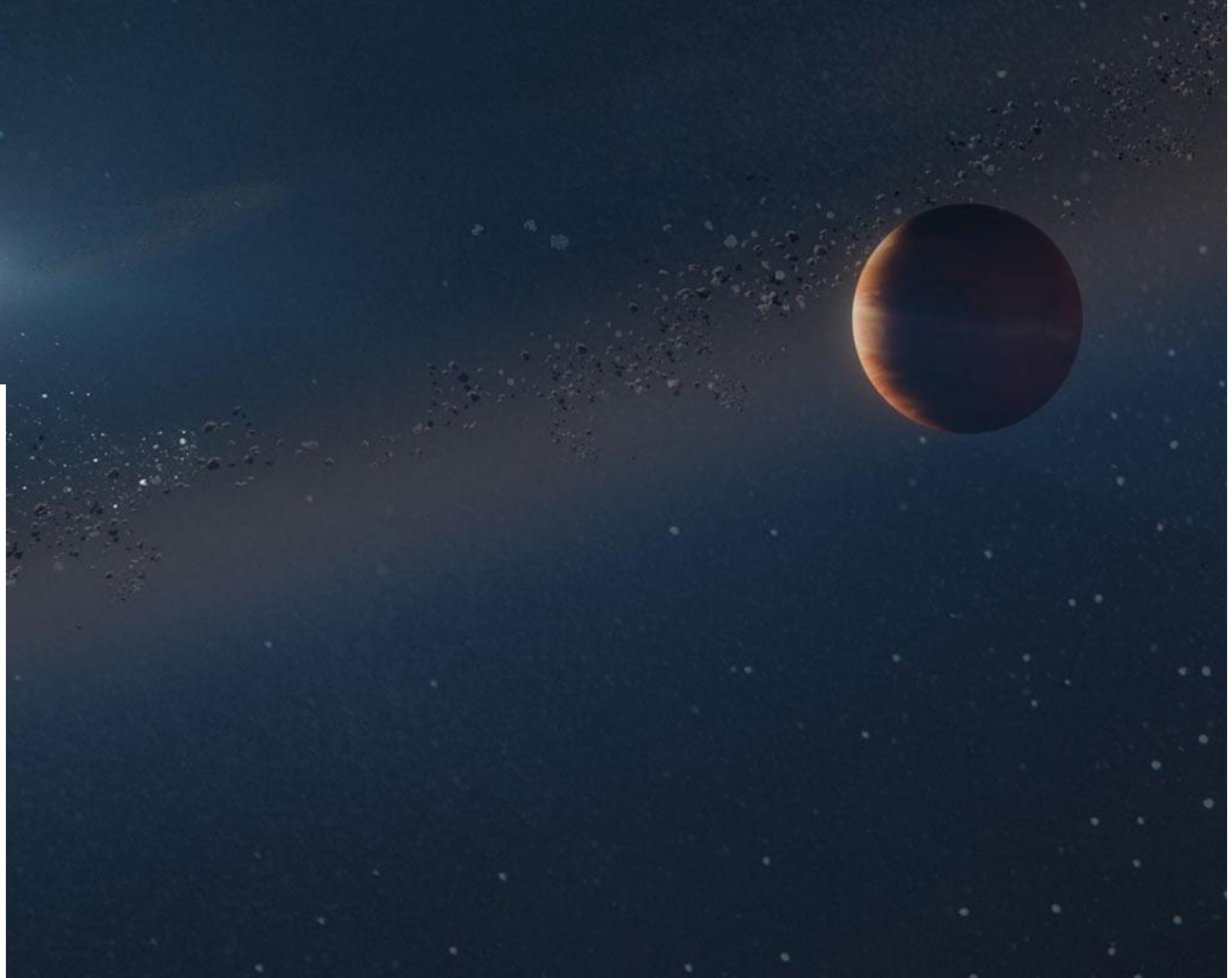
Suzuki et al., 2016

Circumbinary planet by microlensing



White dwarf 0.6 Mo orbited by 1.5 Jupiter

Bachlelet et al.? 2012, Blackman et al., 2021, JWST in 2025…



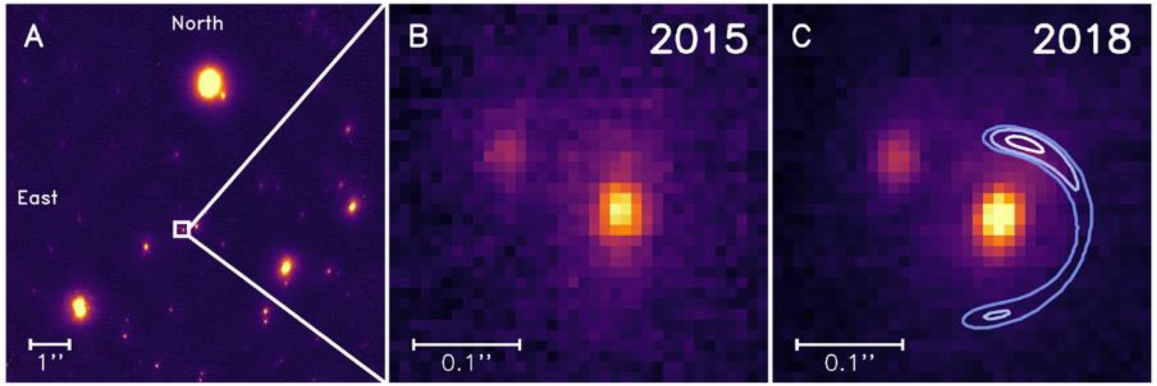
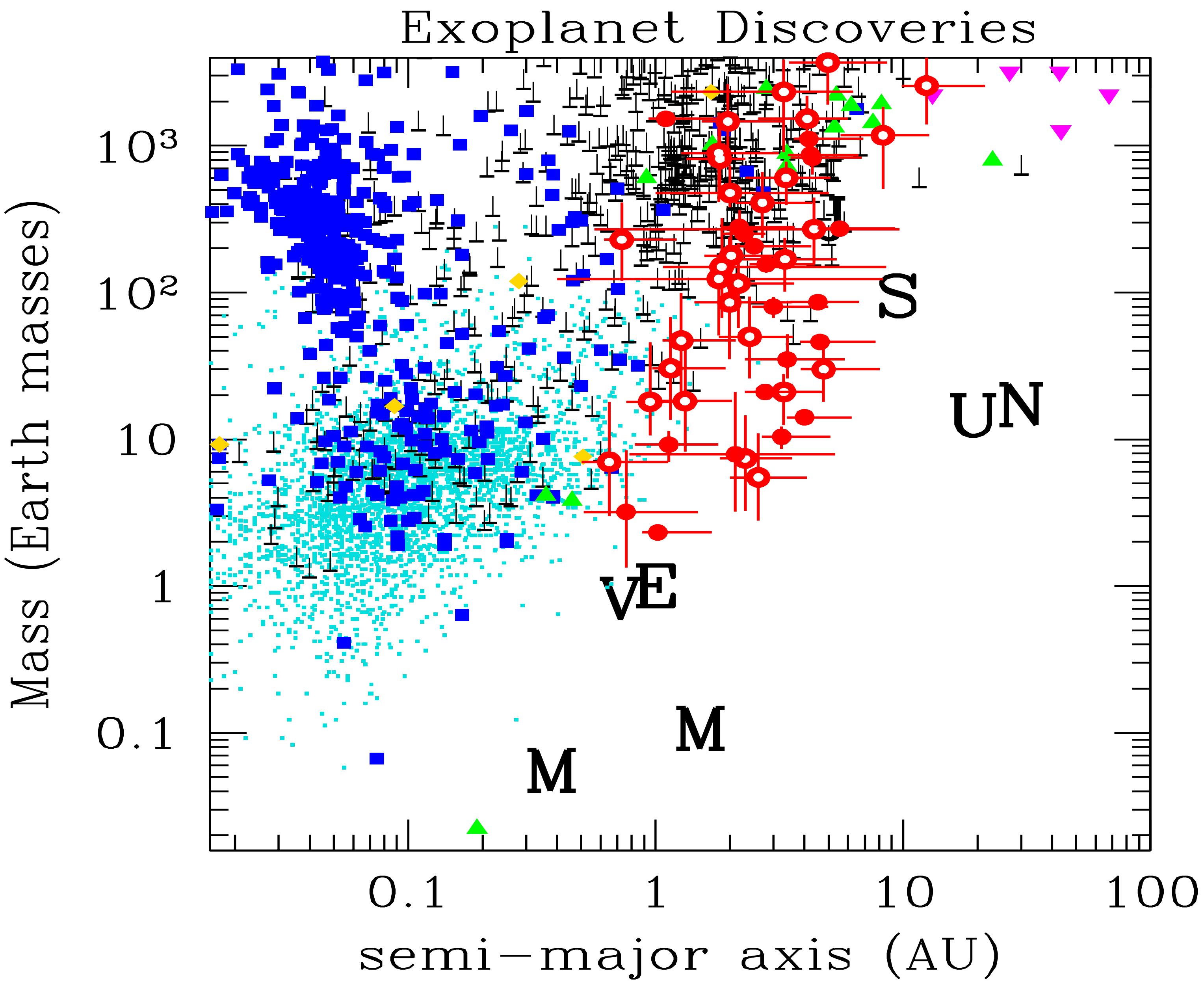


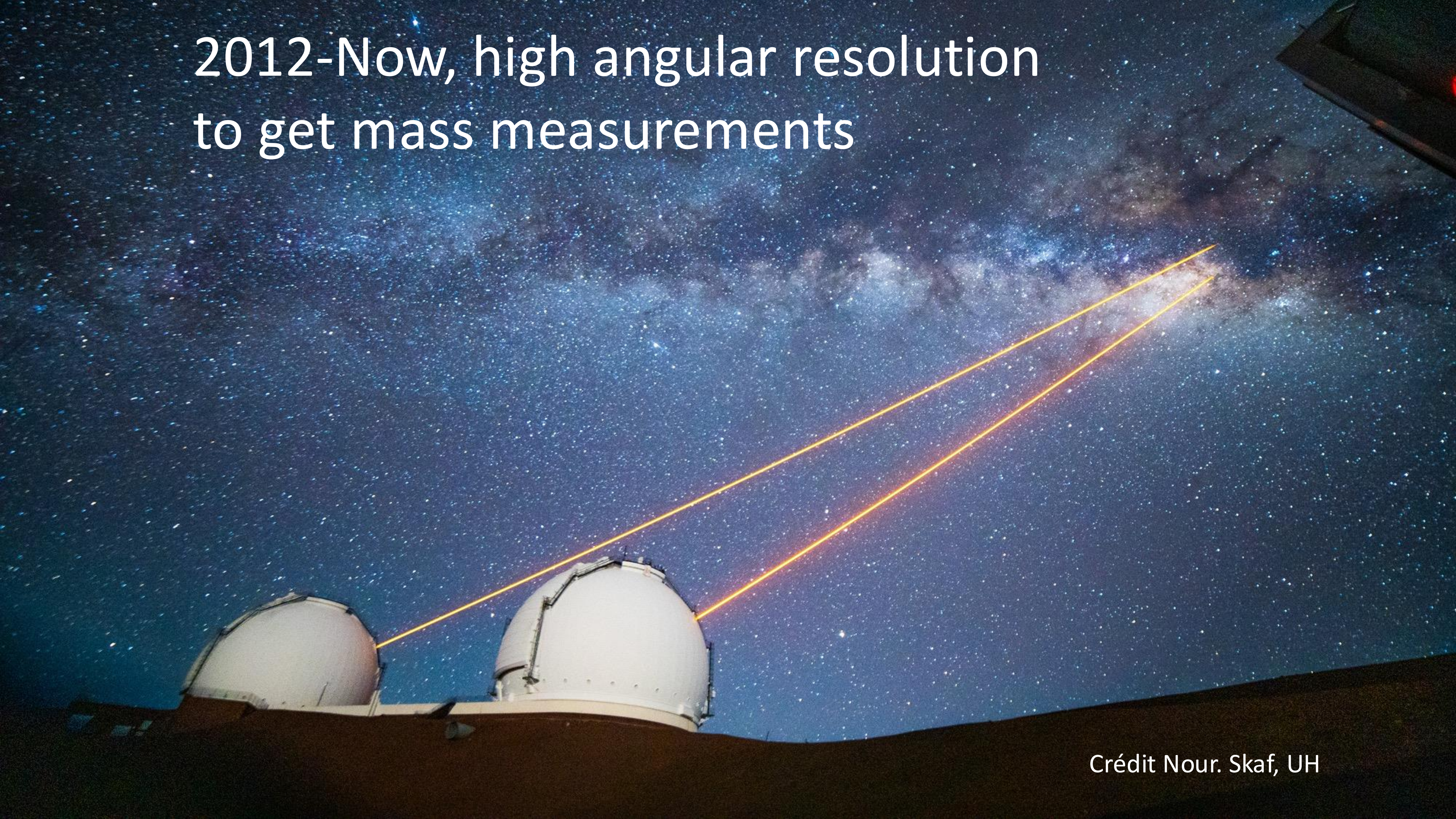
Figure 1. H-band adaptive optics imaging of MOA 2010-BLG-477 from the KECK observatory a. A crop of a narrow-camera H-band image obtained with the NIRC2 imager in 2015 centered on MOA 2010-BLG-477 with an 8 arcsec field of view. **b.** A 0.36 arcsec zoom of the same image. The bright object in the center is the source. To the north-east (the upper left) is an unrelated $H = 18.52 \pm 0.05$ star 123 mas from the source. **c.** The field in 2018. The contours indicate the likely positions of a possible main sequence host (probability of 0.393, 0.865, 0.989 from light to dark blue) using constraints from microlensing parallax and lens-source relative proper motion.

Planet discoveries by methods

- Doppler discoveries in black
- Transit discoveries are blue squares
- Gravitational microlensing discoveries in red
- Direct detection, and timing are magenta and green triangles
- Kepler candidates are cyan spots

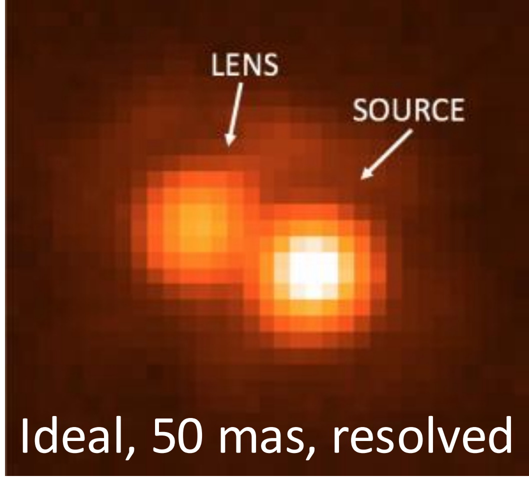


2012-Now, high angular resolution to get mass measurements

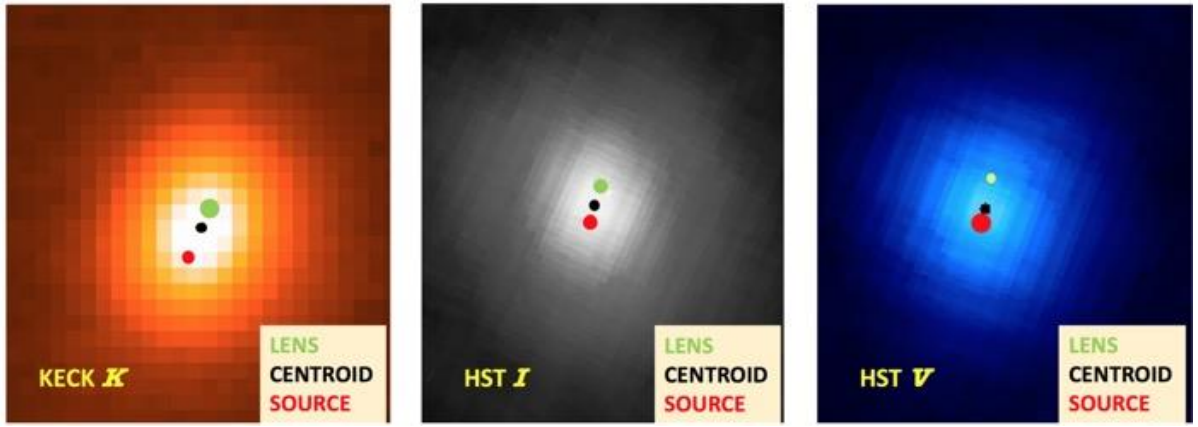


Crédit Nour. Skaf, UH

Impact of relative source-lens measurements on microlensing modeling. Example with ground, KECK and HST.



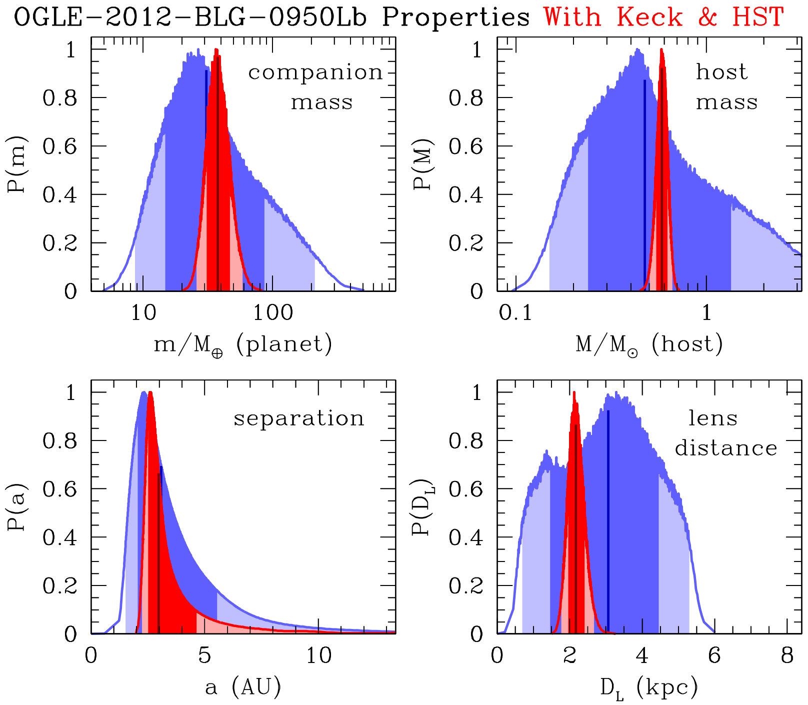
Most of the time, not resolved, but measuring elongation is enough



Proper motions ~2-10 mas/Yr, magnitudes in the range H~ 18-23, high extinction and very crowded

We need several years baseline and we get masses to 10%.

Without, masses are known often only to 50-100 %.



Demographics from Roman & Euclid Space telescopes

Wide field imager in space, in the IR to observe small stars in the Bulge (H~21)
Monitoring small stars to get small mass planets

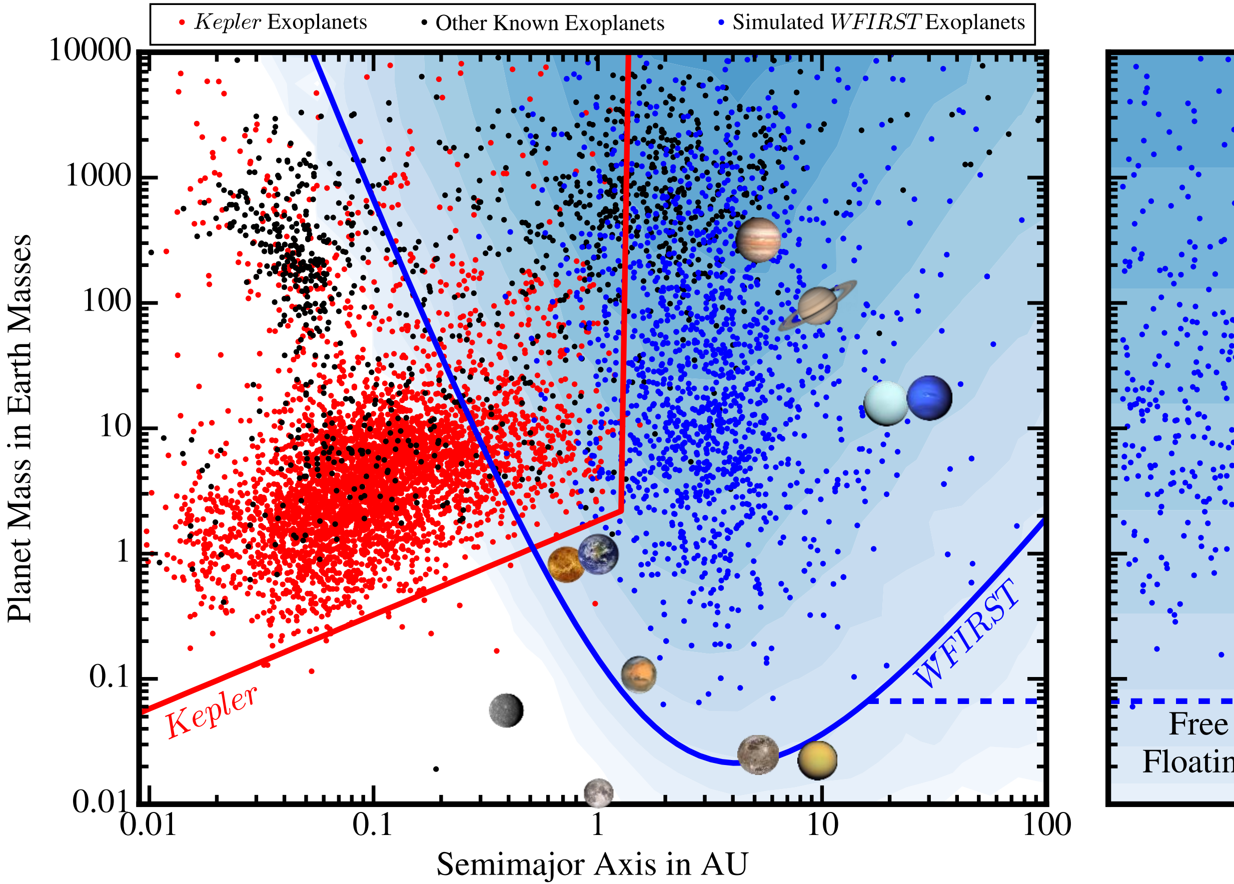
Currently :

- Roman survey from 2027-2028
- 1200+ planets down to the mass of Ganymede
- A revolution like Kepler for hot planets.

- Survey of Euclid of Roman fields in March 2025

Euclid will allow to measure source/lens of Roman Planetary events from year-1, and will be key to provide a first Mass Function for cold planets.

The mass measurement precision varies as the cube of the observing time baseline. It is key for the full Roman planet demographics to have 2025 Euclid obs.



Parallax from simultaneous Euclid-Roman observations can measure the masses of free-floating planets.

(Bachelet & Penny 2019, Bachelet et al. 2022)

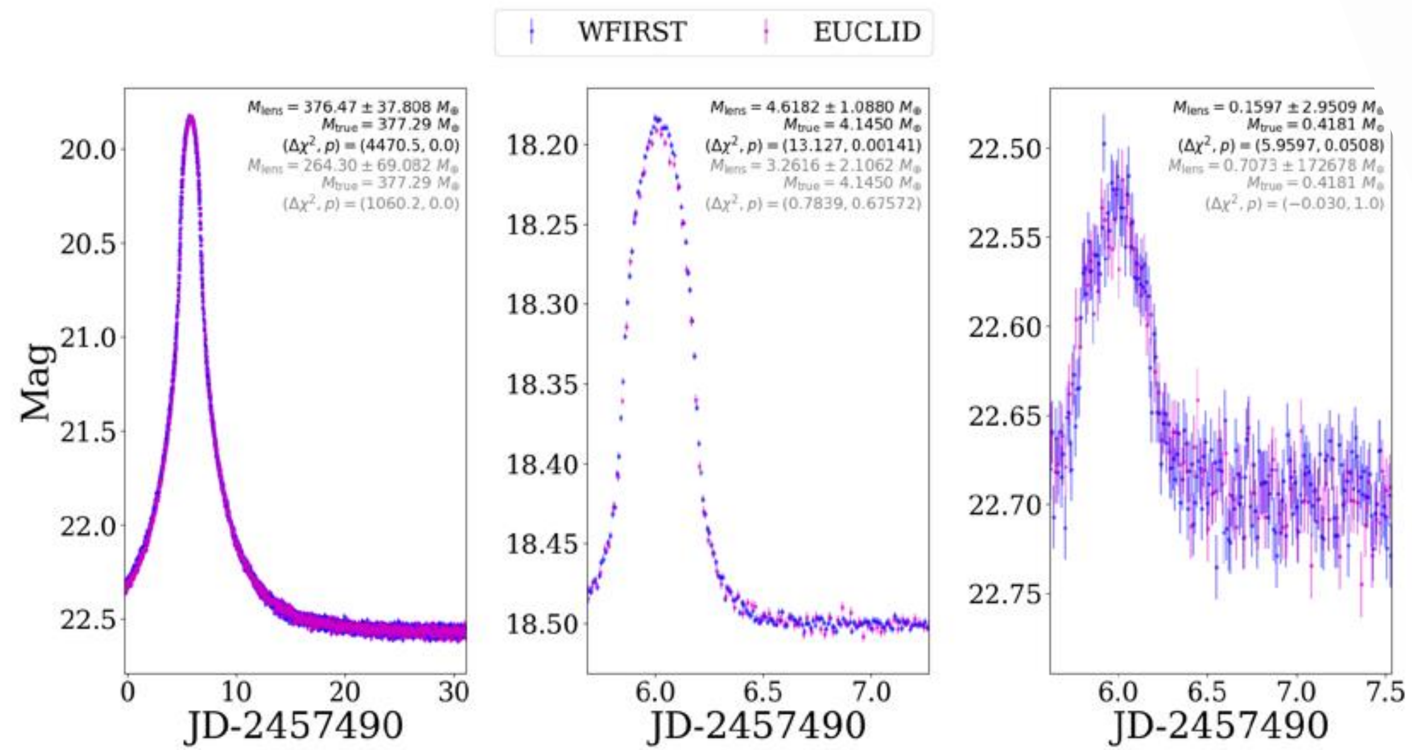
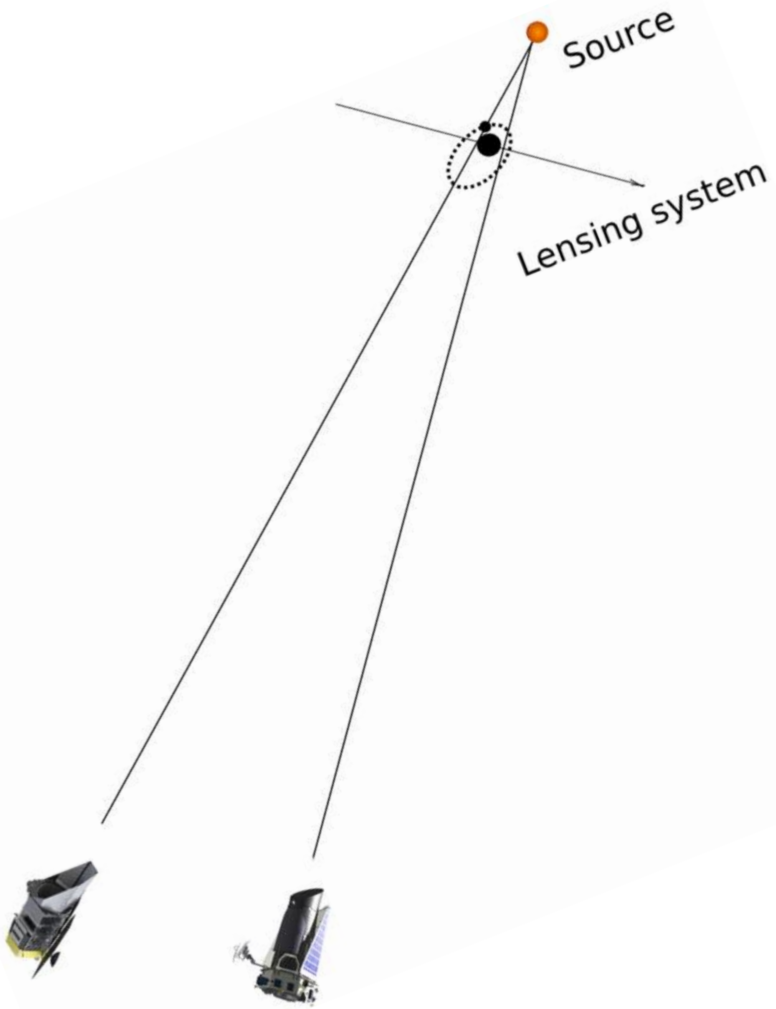
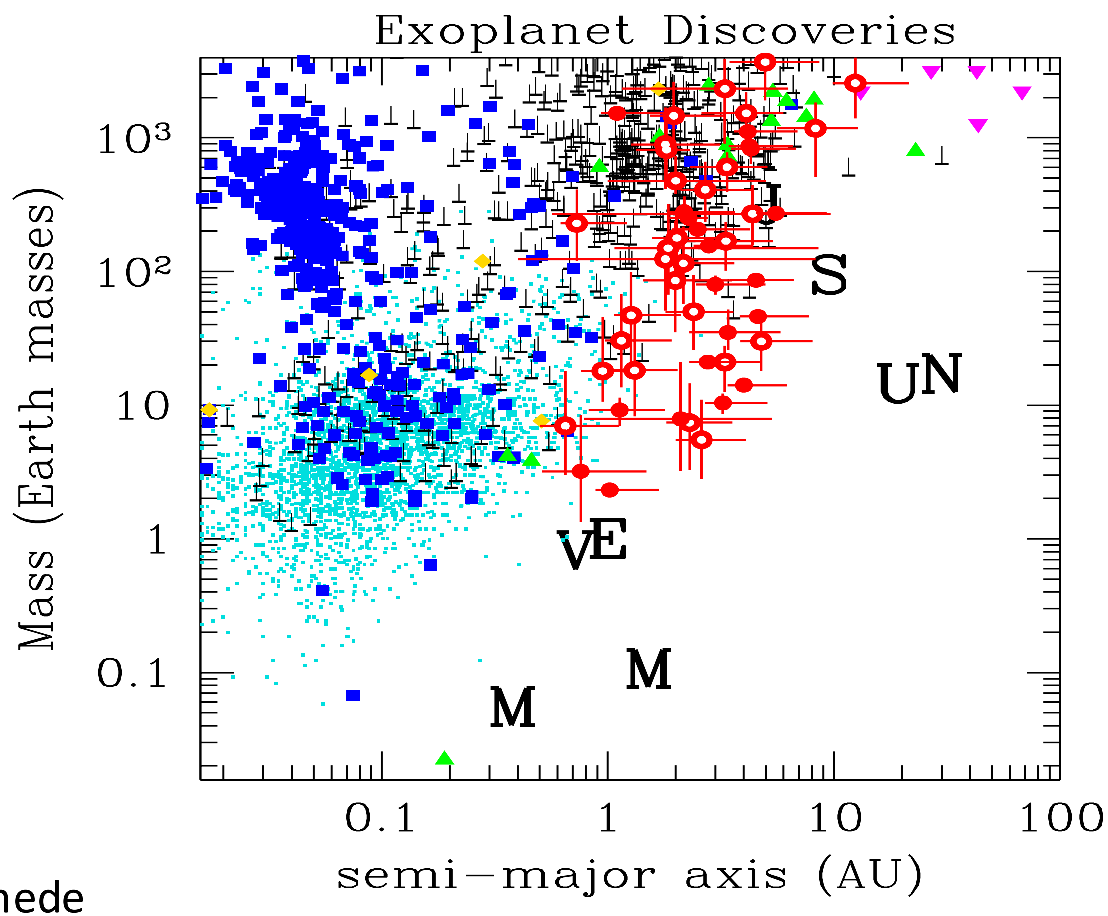


Fig. 1. Three simulated examples of microlensing events due to FFP lenses as seen by EUCLID and ROMAN. Best-fit parameters based only on ROMAN data are presented in gray in the top-right of each figure, while shown in black are best-fit solutions using both datasets. Note that the shifts in time and magnification due to the parallax are too small to be visible. Magnitudes are artificially aligned to the ROMAN system for the plotting.



Concluding remarks, 30 years of microlensing planet hunting



A statistical method, probing cold planets down to few Earth mass
~ 200 planets discovered to date, from few Earth to Brown dwarfs
Planets around stars 0.08-1 Mo, max sensitivity at few AU
Super-Earth and mini-Neptune far more abundant than Jupiters

Getting lens with KECK, HST, JWST
Getting RV of companion (with Isabelle Boisse !)

Circumbinary planets, planet around white dwarf
Mass function
Free-floating planets (10 Mearth and below)

Roman will discover 1200+ bound planets, down to the mass of Ganymede
1000 free-floating planets (down to below 1 Mearth)

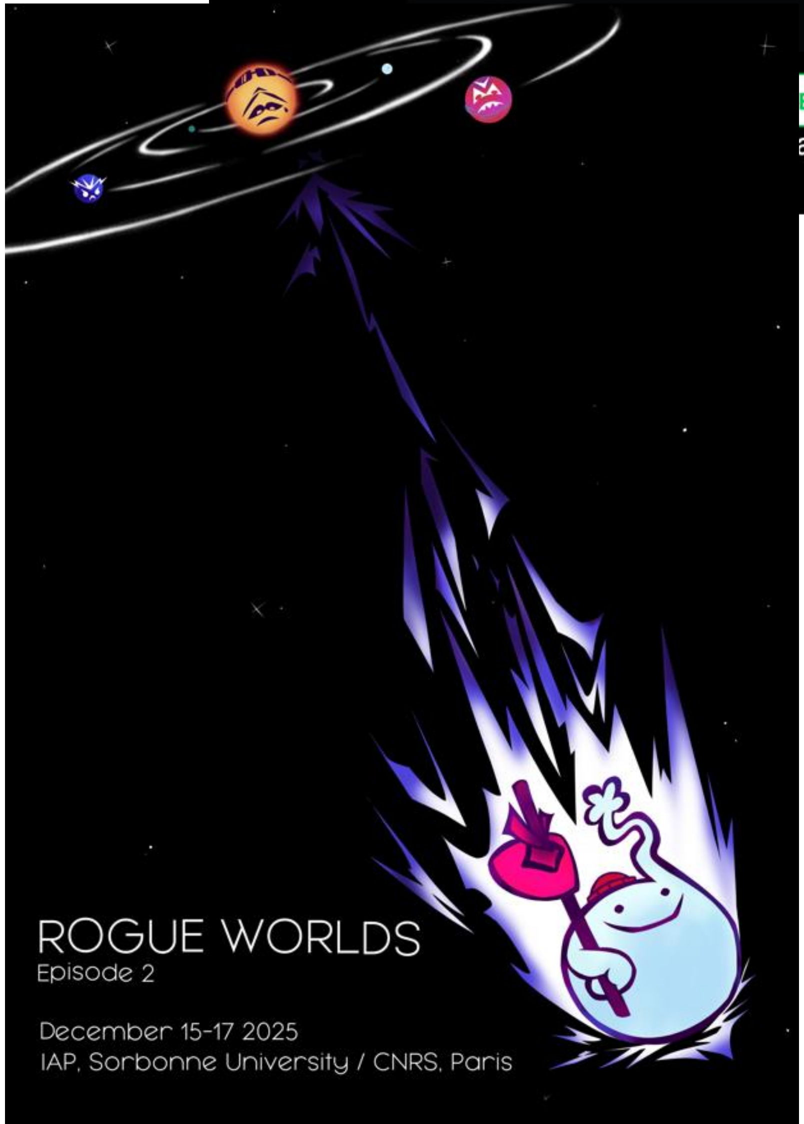
Euclid observations on March 2025 to get masses at 10 % for Roman planets to be discovered

Post-2028, simultaneous Euclid-Roman, mass measurement of individual free-floating planets

ROGUE WORLDS TWO

A MISSING STAR STORY

Rogue Worlds Strike Back, Episode 2



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Scientific rationale

Free-floating, or "rogue", planetary-mass objects have been discovered wandering through the Galaxy unbound to any star. The origins of these objects remain poorly understood, and likely involve a combination of many different processes relevant to star and planet formation. Direct imaging surveys of young star-forming regions have already found hundreds of high-mass rogue planets, though it remains an ongoing theoretical challenge to determine what fraction represent ejected planets as opposed to aborted stellar embryos. Meanwhile, upcoming microlensing missions such as the Nancy Grace Roman telescope are poised to vastly increase our sample of free-floating planets at masses extending to Earth-mass and below, opening a new window into their origin and demographics.

Rogue Worlds 2 is a 3-day workshop designed to bring together researchers at the forefront of different aspects of the study of free-floating planets, including microlensing (ground- and space-based), direct imaging, and modeling of stellar and planetary dynamics. The format of the workshop is designed to promote discussion and foster collaboration, bringing together researchers across a wide array of fields to make new progress on our understanding of rogue worlds and the systems they leave behind.