Free-floating planets (and other beasts)

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Free-floating planets (FFPs)

Free-floating planets
Rogue planets
Unbound planets
Solivagant planetary-mass objects (SPlaMOs)

- less massive than the deuterium-burning limit (~13 M_{Jup})
- gravitationally untethered to any star

Caltech Magazine, Spring 2021

AND IT IS THOUGHT THAT SOMETIMES THE COLLISIONS IN YOUNG SOLAR SYSTEMS EJECT PLANETS INTO SPACE.

Free-floating planets (FFPs)

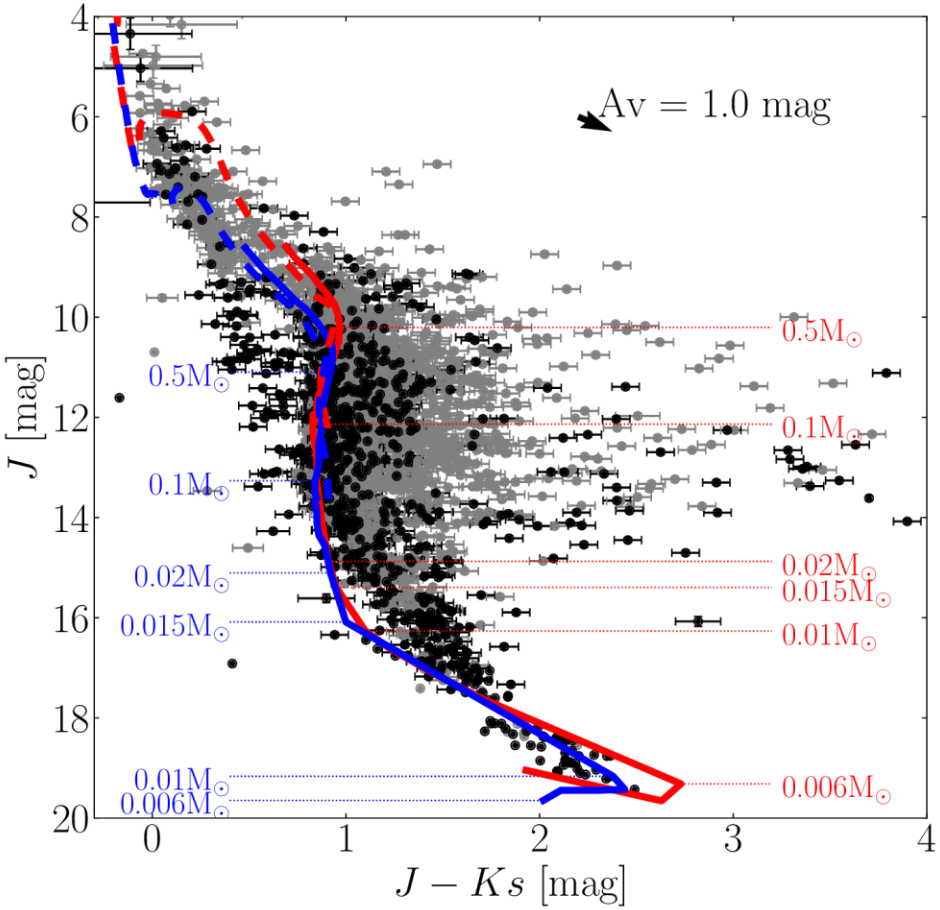
Free-floating planetary-mass objects can be formed:

- through gravitational collapse, in a way similar to that in which stars form,
- around stars, in protoplanetary disks, ejected as a result of dynamical interactions with other planets, stars, etc.

Properties of FFPs can give us better insights into early dynamical evolution of planetary systems

Caltech Magazine, Spring 2021

Planetary-mass objects in young clusters



Miret-Roig+ 2022

If FFPs are young (at most several Myr) and massive enough (>4-5 M_J), they can be directly detected (e.g., Gagne+2017, Lodieu+2021, Miret-Roig+2022)

Planetary-mass objects in young clusters

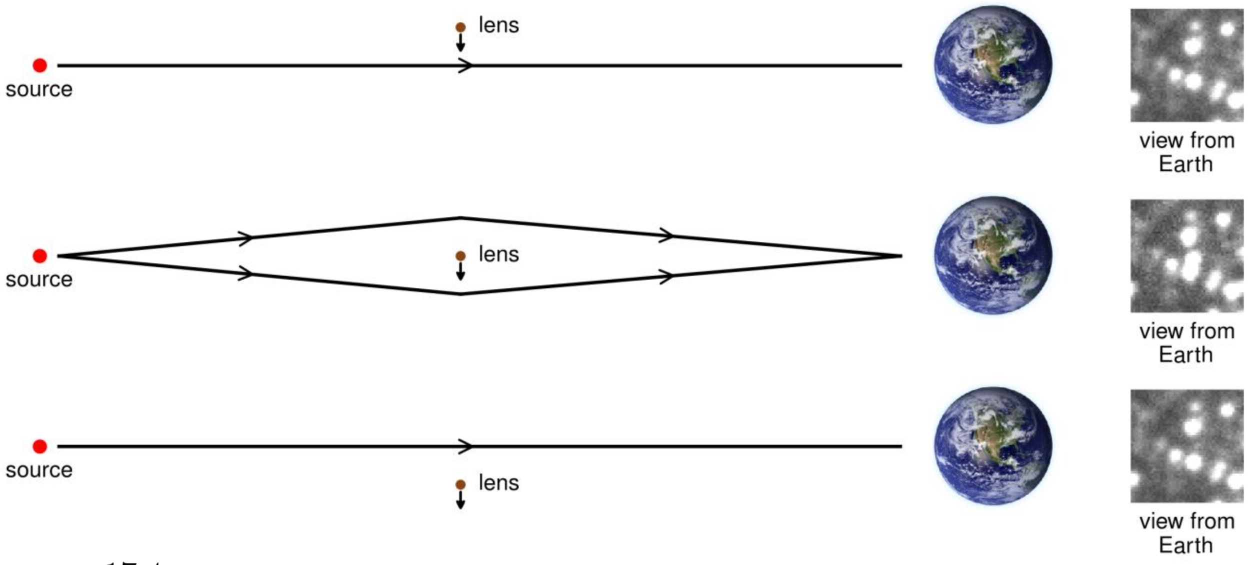
Target	NGC1333	IC348	NGC2024	ONC
Program ID	1202	1229[a]	1190	1256
Instrument	NIRISS	NIRCam	NIRCam	NIRCam
Mode	Slitless spectroscopy	Imaging	Imaging	Imaging
FOV (sqarcmin)	30	20	10	80
On-source time (s)	3100	300	6660	770
Depth (K-mag)	21	23	24	23
Distance (pc)[b]	296	324	414	403
Number of stars[c]	200	500	800	2600
Scheduled for[d]	8–10/2023	8–10/2022	2–3/2023	9–10/2022

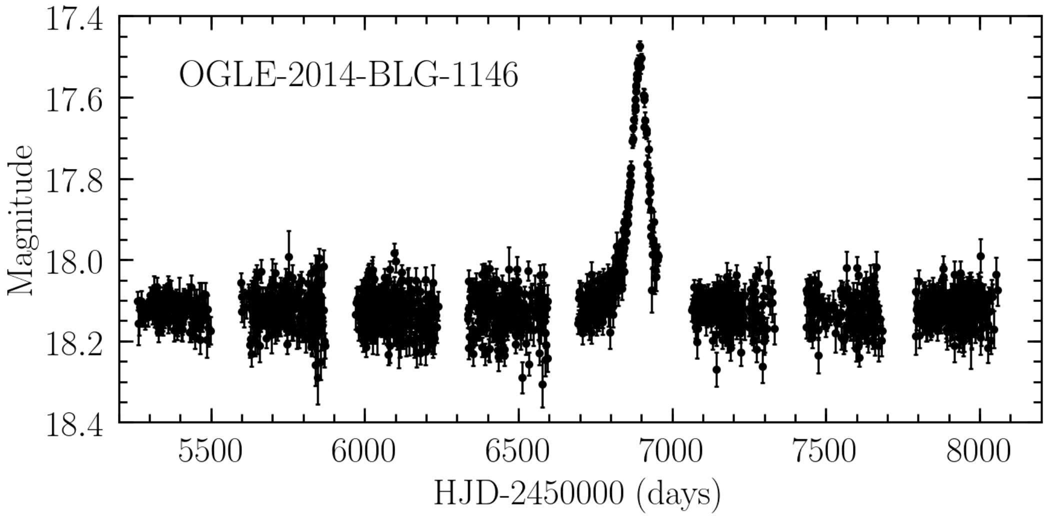
Scholz+2022

If FFPs are young (at most several Myr) and massive enough (>4-5 M_J), they can be directly detected (e.g., Gagne+2017, Lodieu+2021, Miret-Roig+2022)

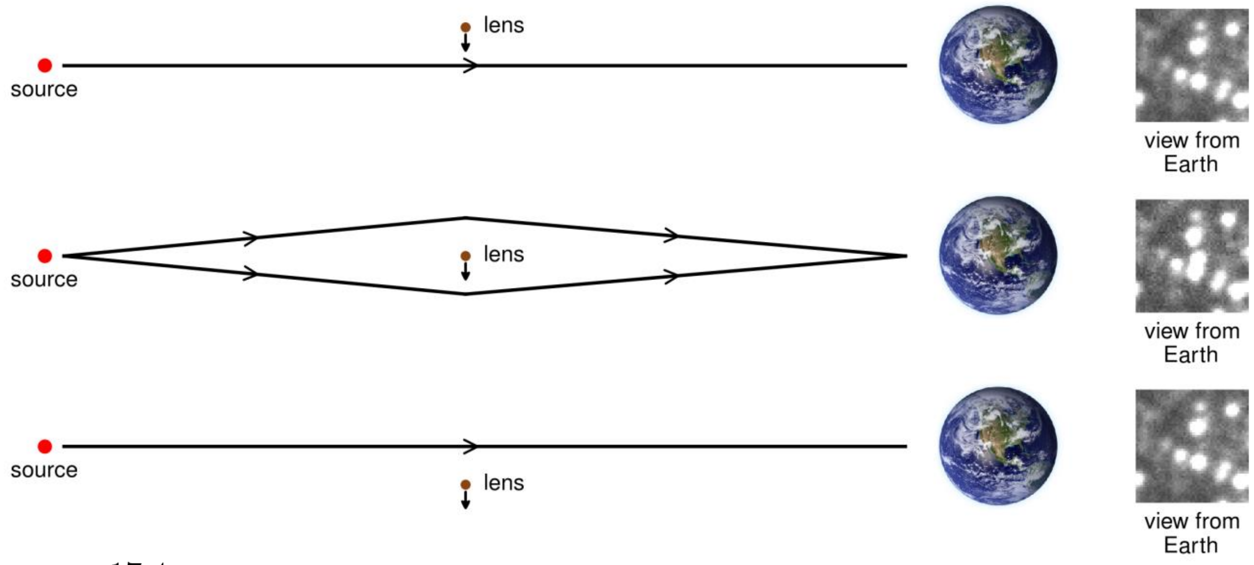
JWST can detect objects as low-mass as ~1 M_J.

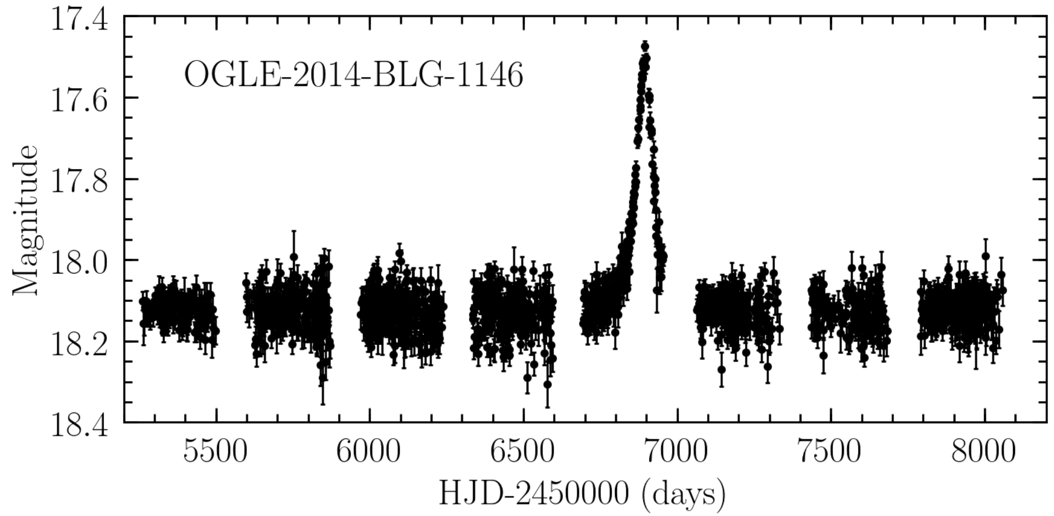
Gravitational microlensing





Gravitational microlensing





Microlensing event timescale

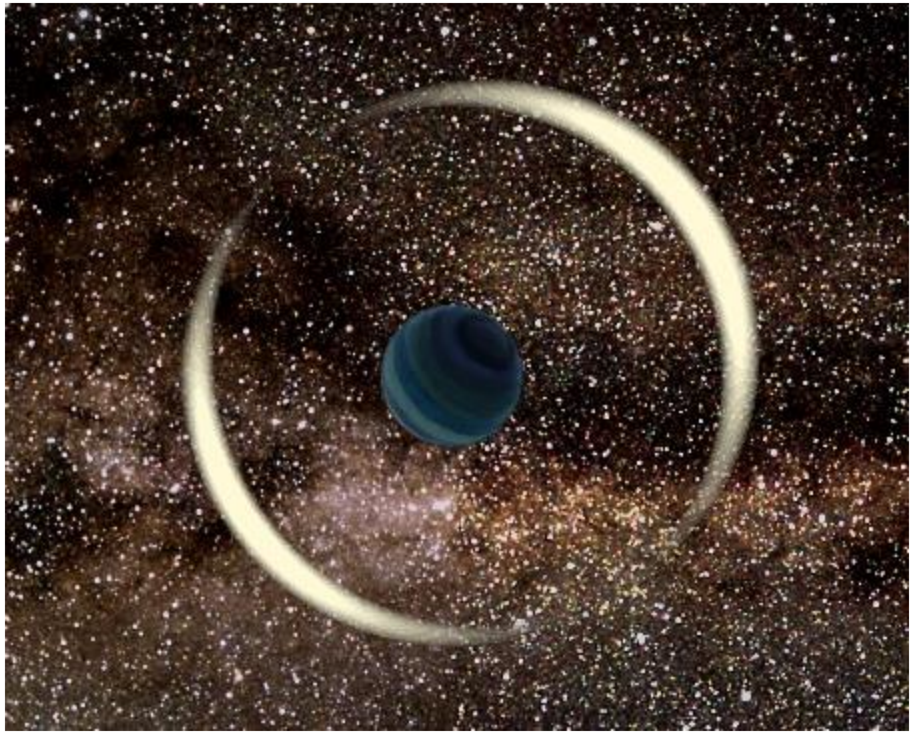
$$t_{\mathrm{E}} \propto \sqrt{M}$$

t_E ~ 20 d (stars)

t_E ~ 1 d (Jupiters)

t_E ~ 0.1 d (Earths)

Gravitational microlensing



Angular Einstein radius:

$$\theta_{\rm E} = 1\,{\rm mas}\sqrt{\frac{M}{1\,M_\odot}}\sqrt{\frac{\pi_{\rm rel}}{0.1\,{\rm mas}}}$$

M – lens mass

π_{rel} – lens-source relative parallax,

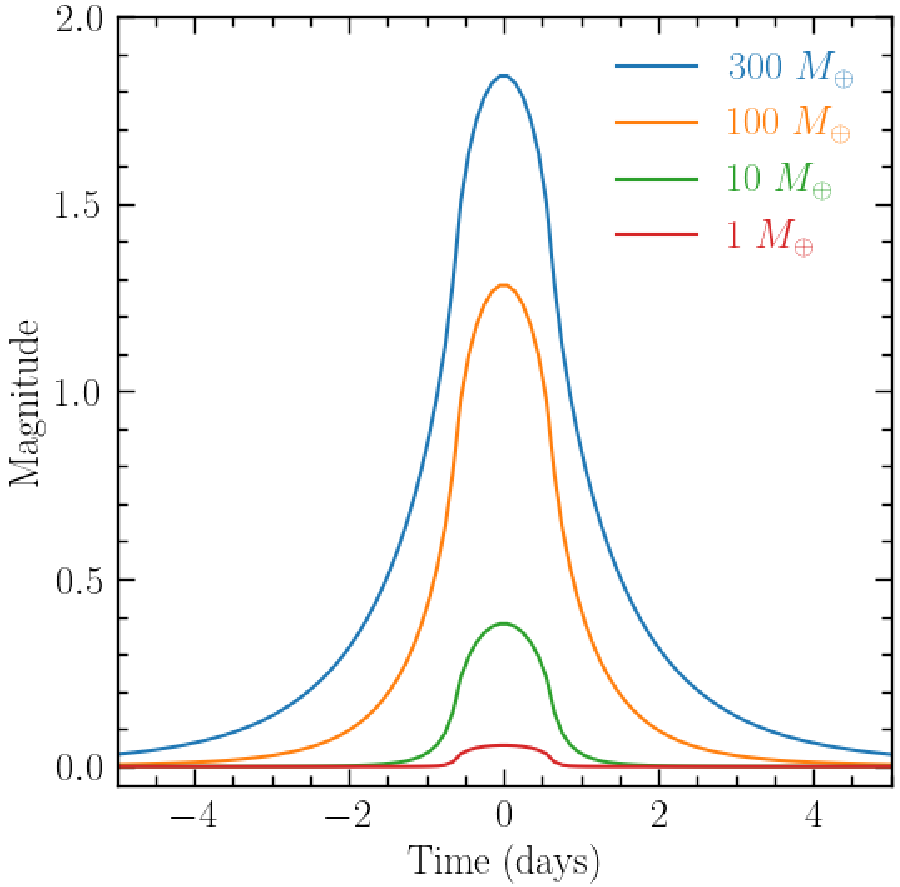
$\pi_{rel} = 1/D_{lens} - 1/D_{source}$

Finite-source effects

microlensing by stars:
$\theta_E >> \theta_*$

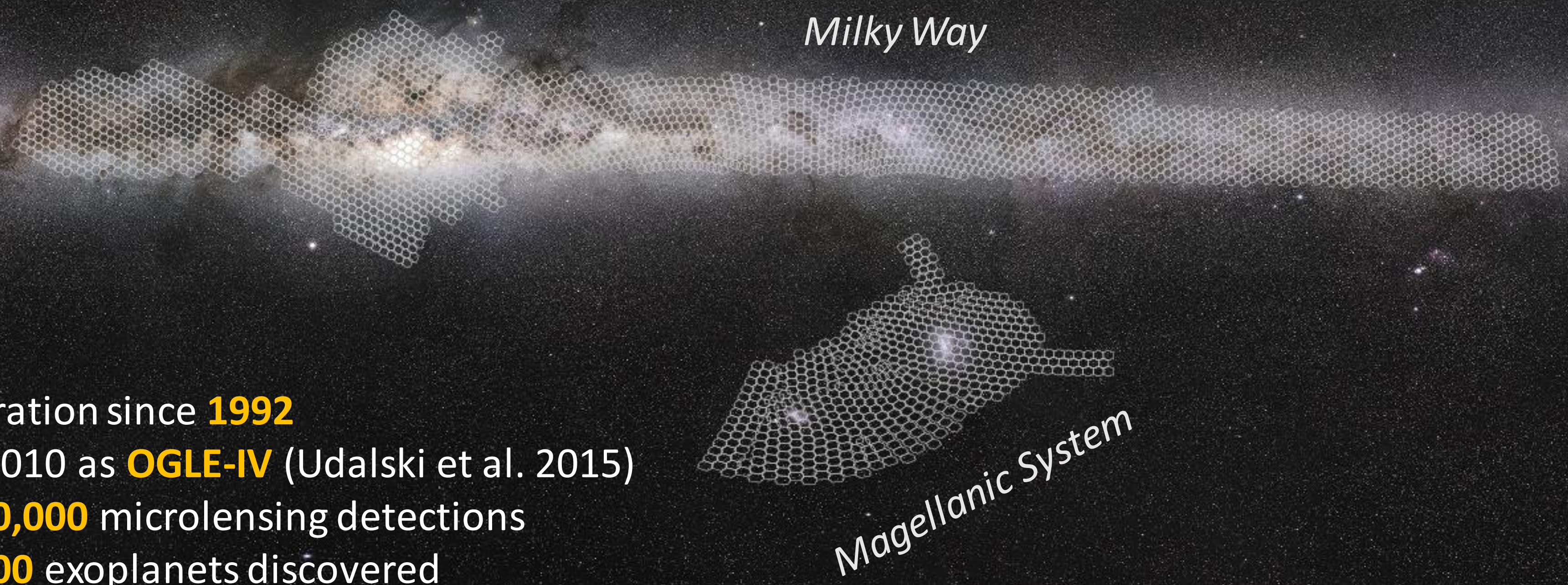
microlensing by planets:
$\theta_E \approx \theta_*$

Finite-source effects



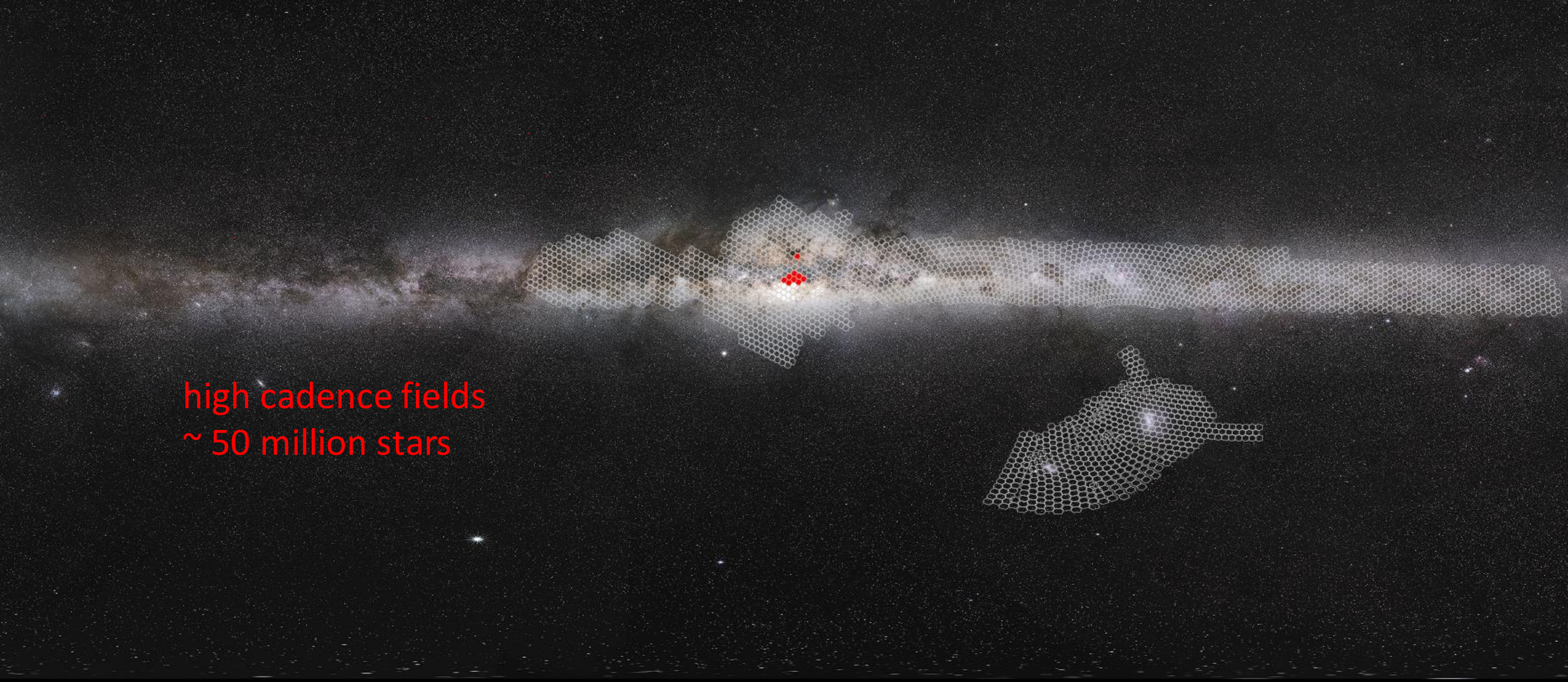
OGLE: Optical Gravitational Lensing Experiment

Warsaw 1.3-m
@ Las Campanas, Chile

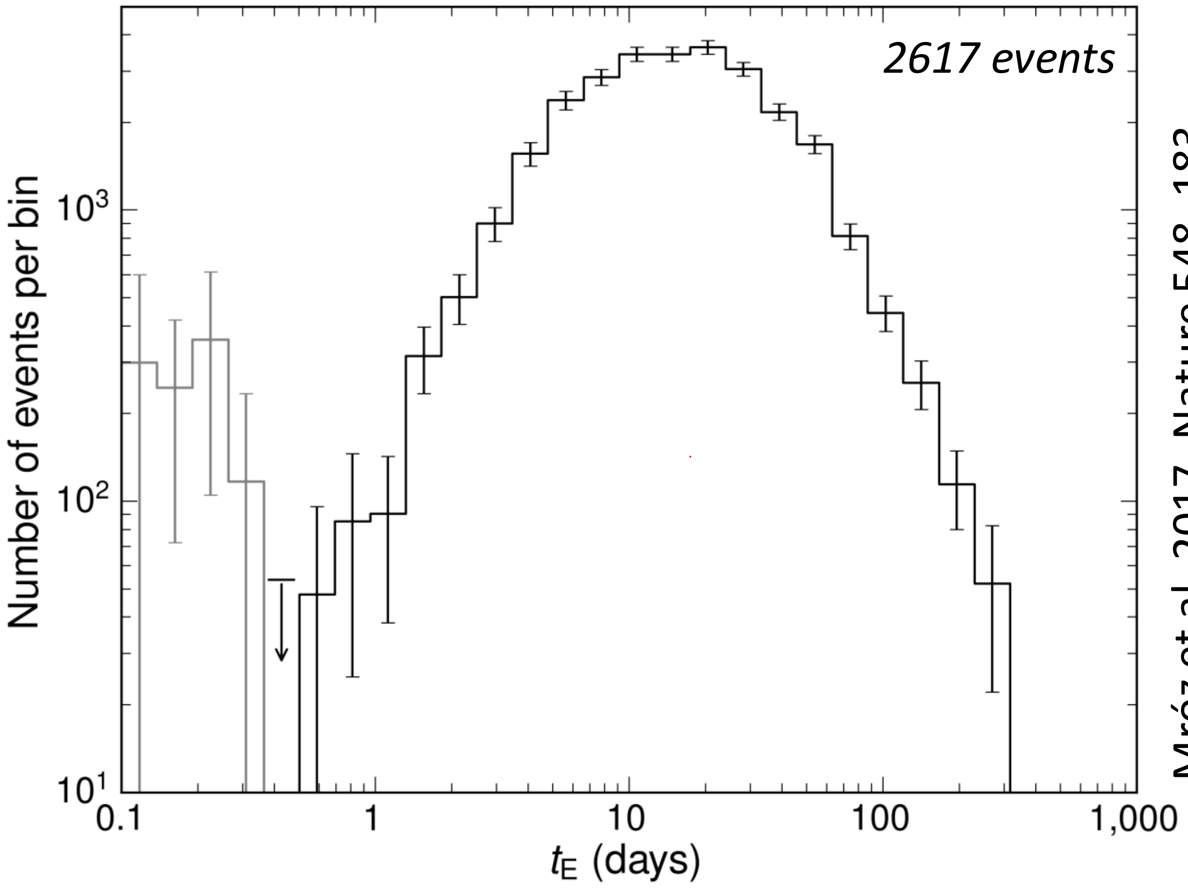


- in operation since **1992**
- since 2010 as **OGLE-IV** (Udalski et al. 2015)
- over **20,000** microlensing detections
- over **100** exoplanets discovered

OGLE: Optical Gravitational Lensing Experiment



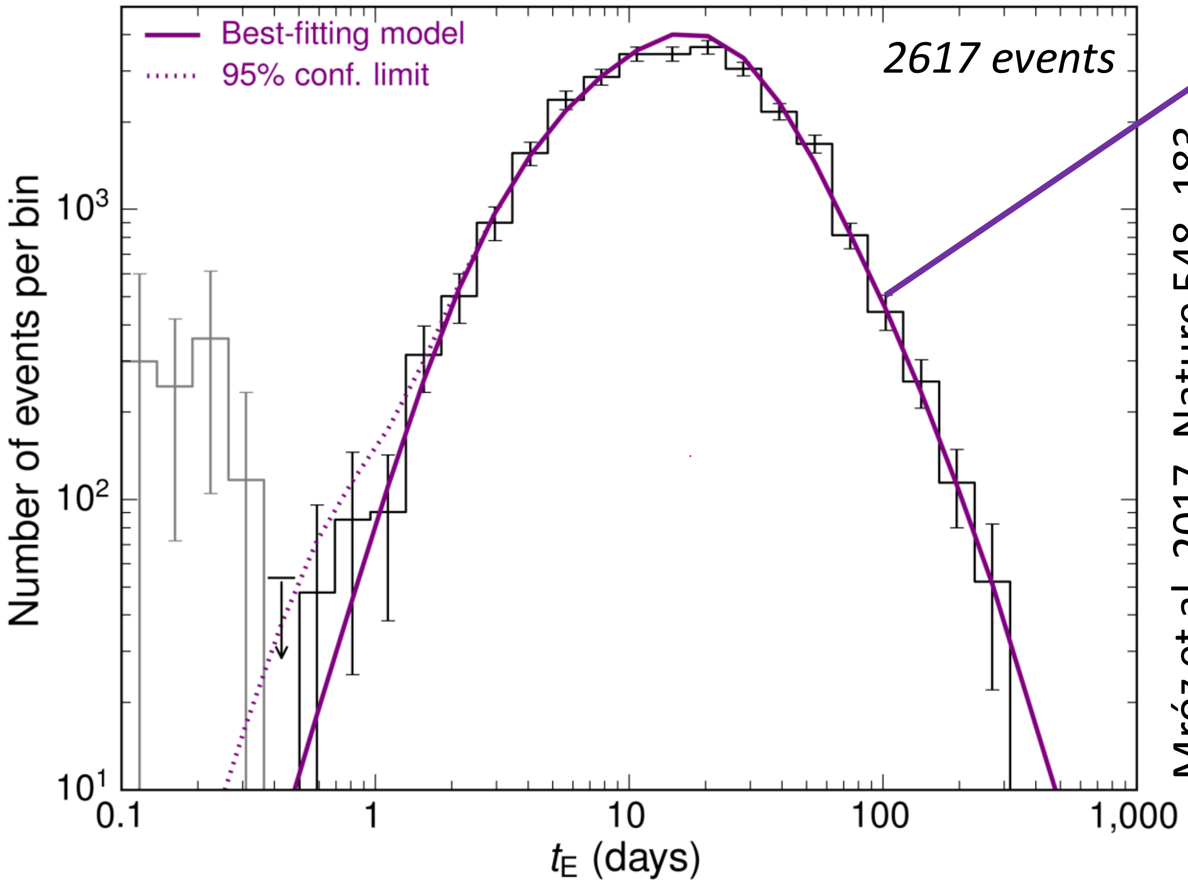
Event timescale distribution



Mróz et al. 2017, Nature 548, 183

Jupiter-mass free-floating planets

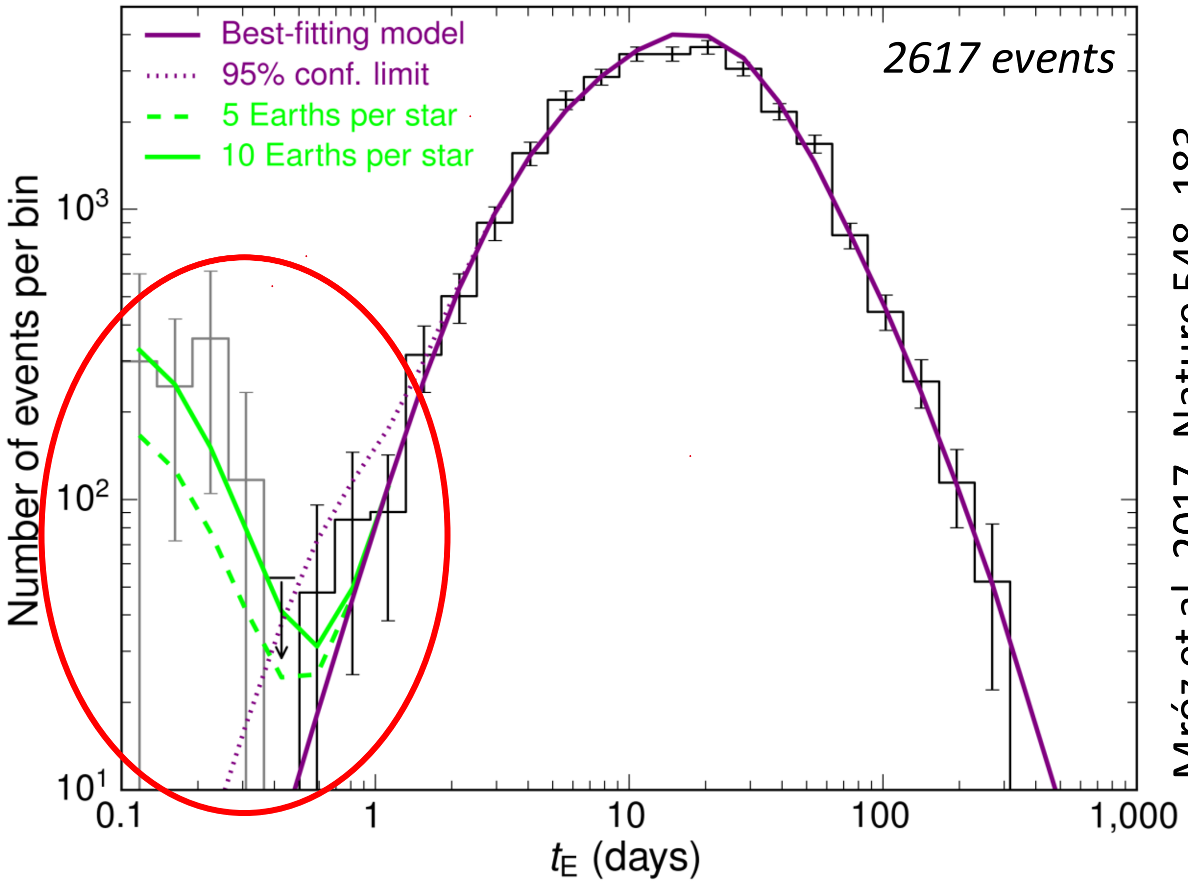
brown dwarfs
and stars



Mróz et al. 2017, Nature 548, 183

95% upper limit: less than 0.25 free-floating Jupiters per star

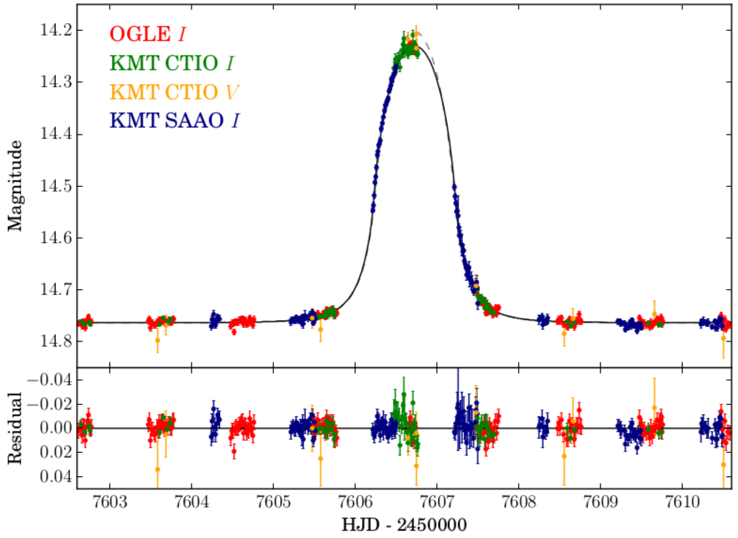
Earth/Neptune-mass free-floating planets

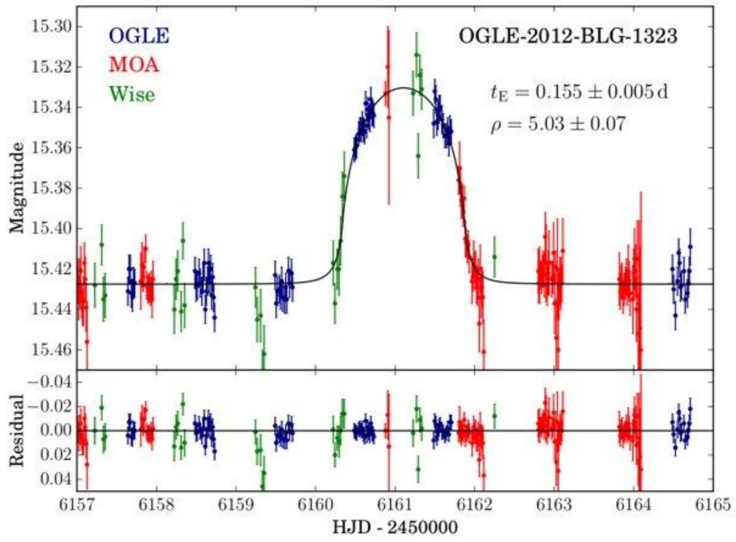


Mróz et al. 2017, Nature 548, 183

We detected a few extremely-short-timescale events: consistent with low-mass FFP being more common than stars (10 ± 4 FFP per star).

Free-floating planet candidates

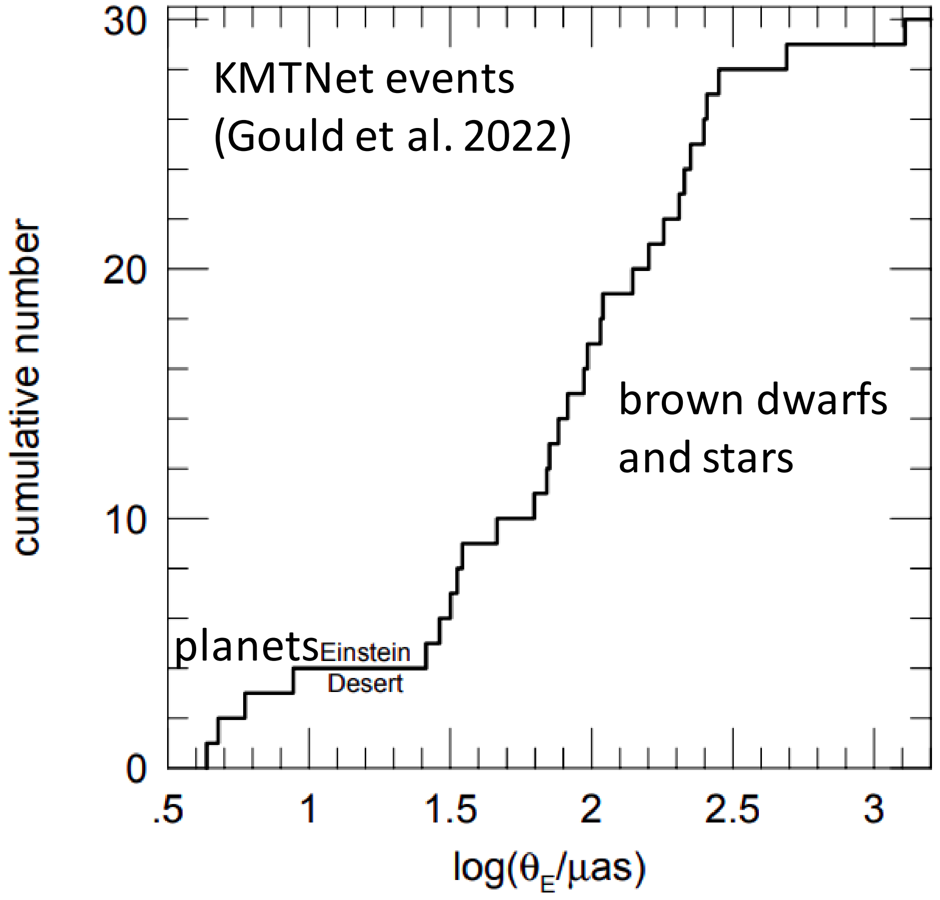




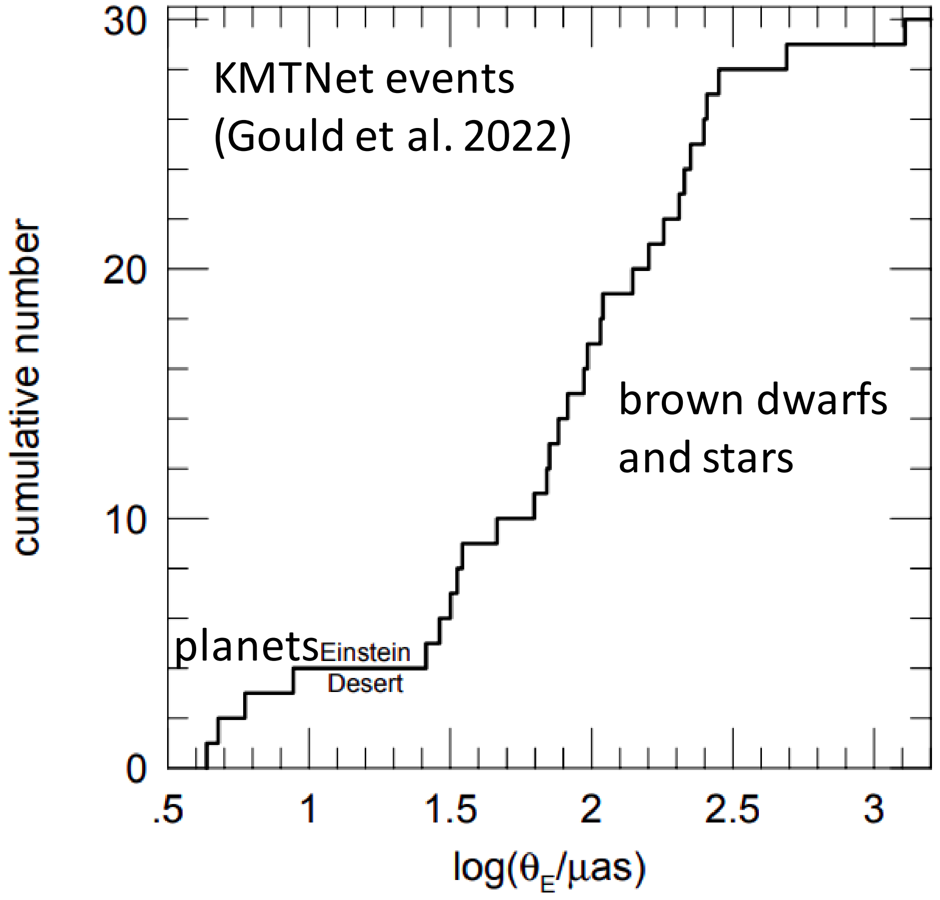
Event	t_E (days)	θ_E (μas)
OGLE-2016-BLG-1928	0.029 ± 0.003	0.842 ± 0.064
OGLE-2012-BLG-1323	0.155 ± 0.005	2.37 ± 0.10
OGLE-2016-BLG-1540	0.320 ± 0.003	9.2 ± 0.5
OGLE-2019-BLG-0551	0.376 ± 0.018	4.35 ± 0.34
KMT-2019-BLG-2073	0.272 ± 0.007	4.77 ± 0.19
KMT-2017-BLG-2820	0.273 ± 0.006	5.97 ± 0.37
MOA-9y-770	0.315 ± 0.017	4.73 ± 0.75
MOA-9y-5919	0.057 ± 0.016	0.90 ± 0.14

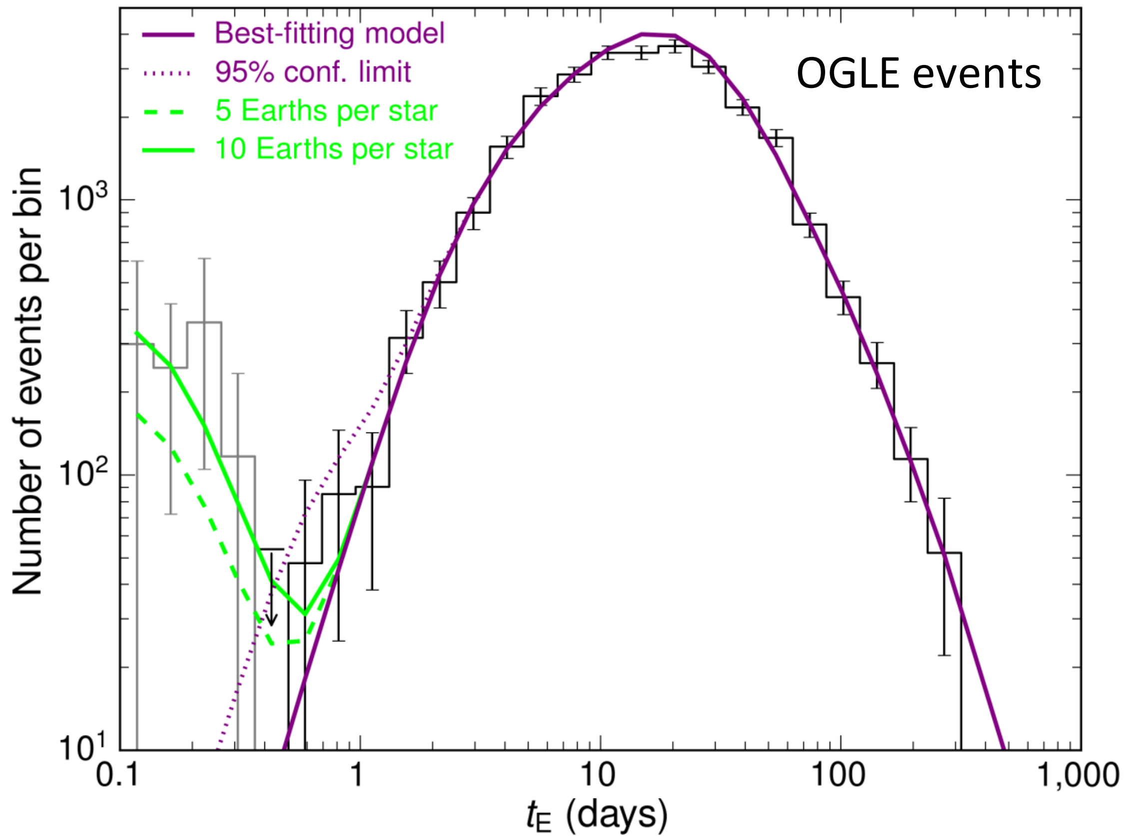
Mróz et al. 2018, 2019, 2020, Kim et al. 2021, Ryu, Mróz et al. 2021, Koshimoto et al. 2023

Einstein desert

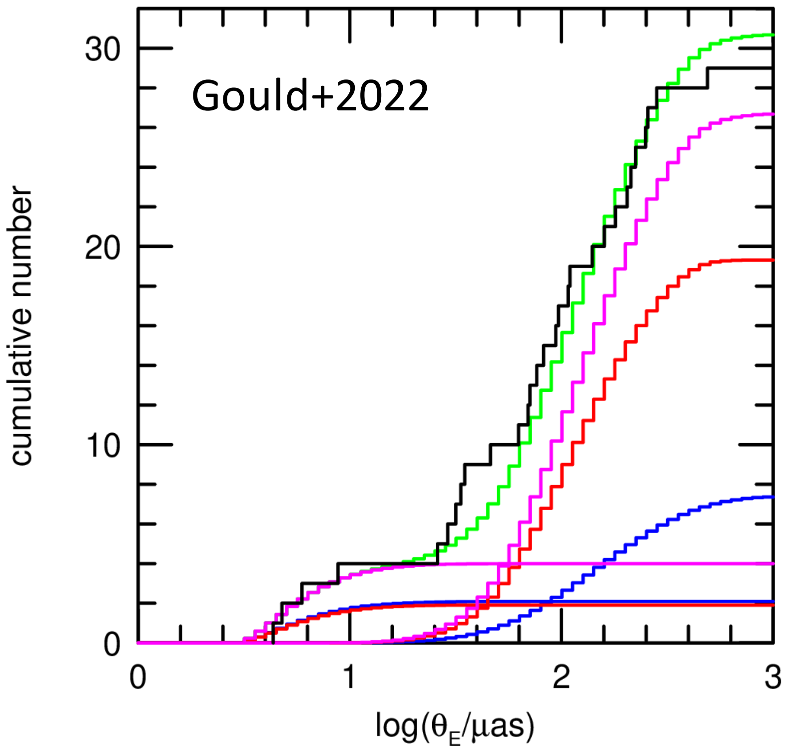


Einstein desert





FFP mass function

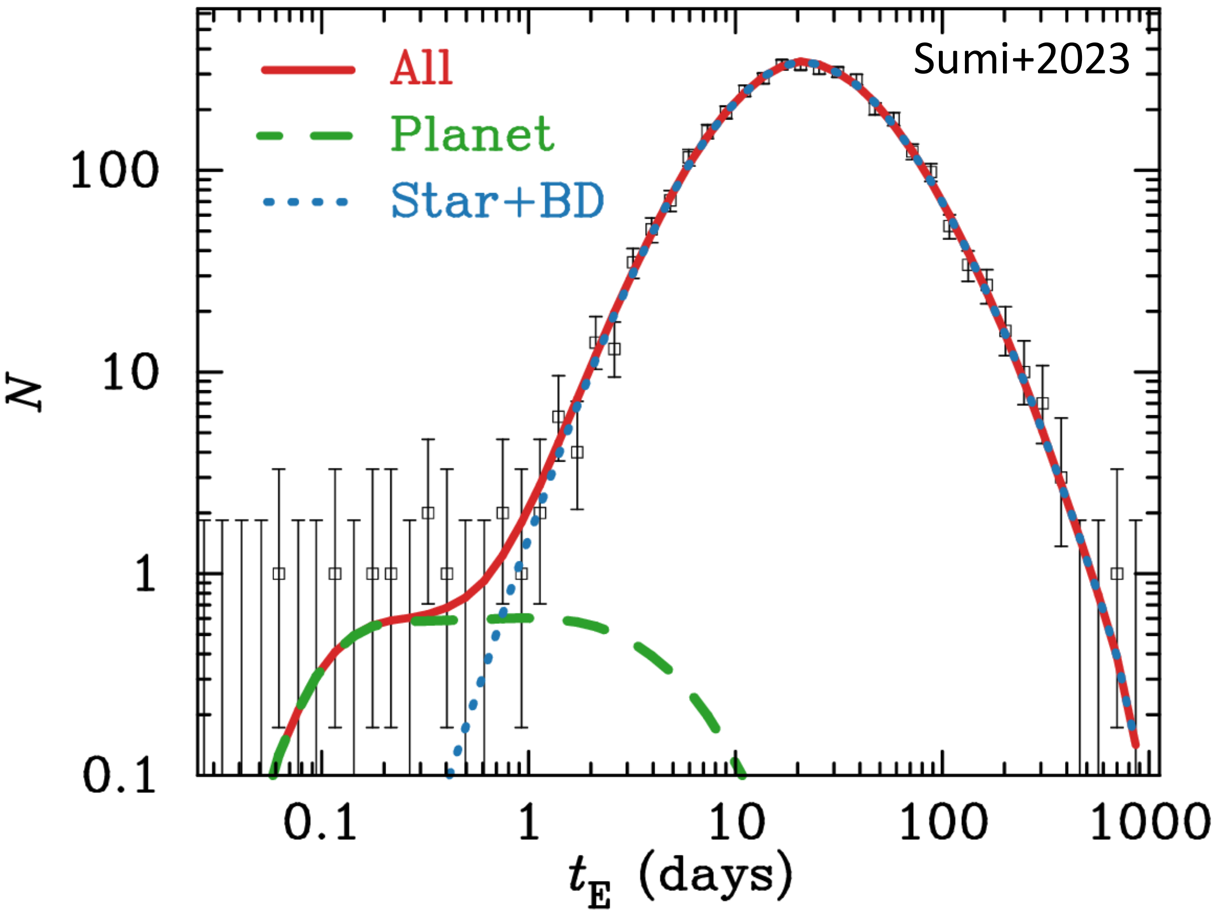


The mass function of FFPs can be described by a power-law function:

$$\frac{dN}{d\log M} = (0.4 \pm 0.2)\left(\frac{M}{38\,M_\oplus}\right)^{-p}\,\mathrm{star}^{-1}$$

with $0.9 \lesssim p \lesssim 1.2$

FFP mass function



- Power-law mass function:

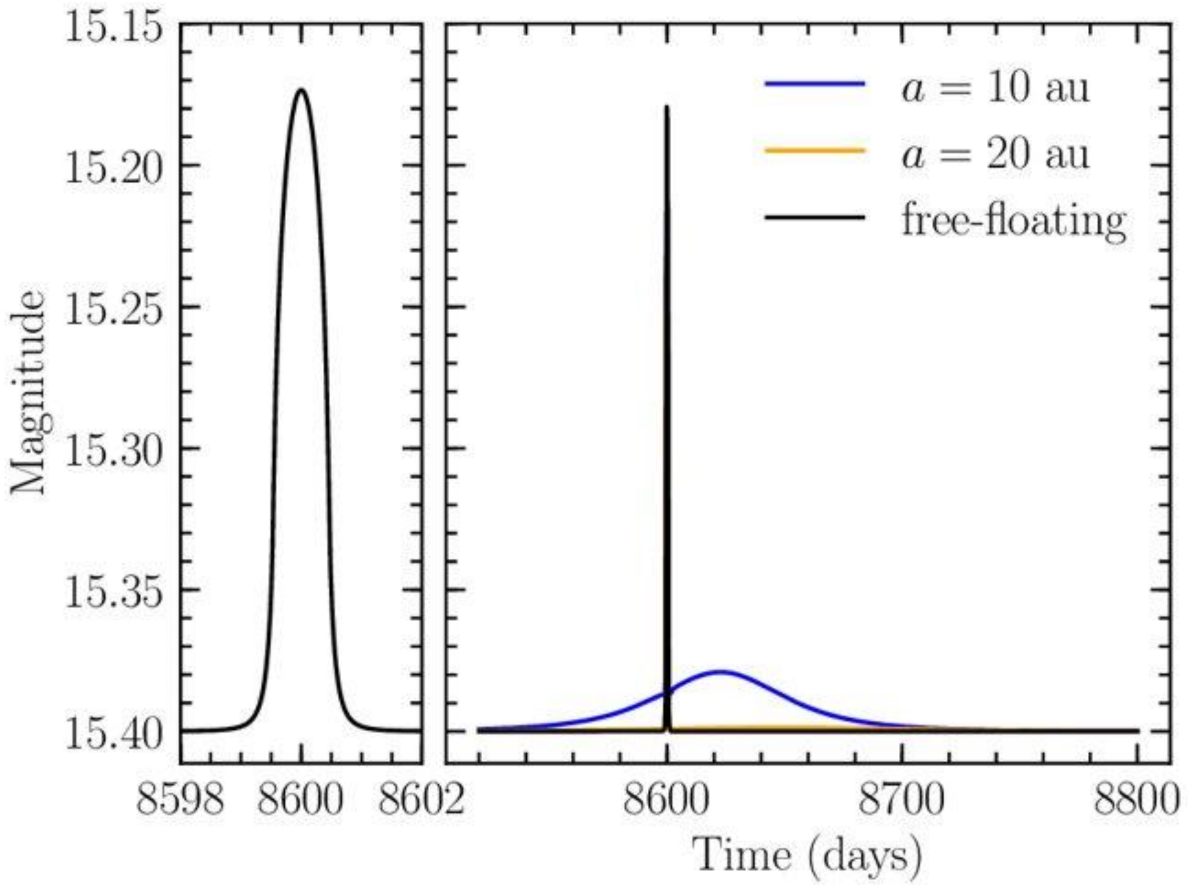
$$\frac{dN}{d\log M} = (0.49^{+0.12}_{-0.32}) \left(\frac{M}{38\,M_\oplus}\right)^{-p} \text{star}^{-1}$$

with $p = 0.94^{+0.47}_{-0.27}$

- Implies that FFPs are common: 7^{+7}_{-5} FFPs/star (from 1 $M_\oplus$ to 13 M_J)
- Number of FFPs is of order or larger than the number of bound planets
- Mass function of bound planets is shaped (partly?) by the ejection process

Free-floating or wide-orbit?

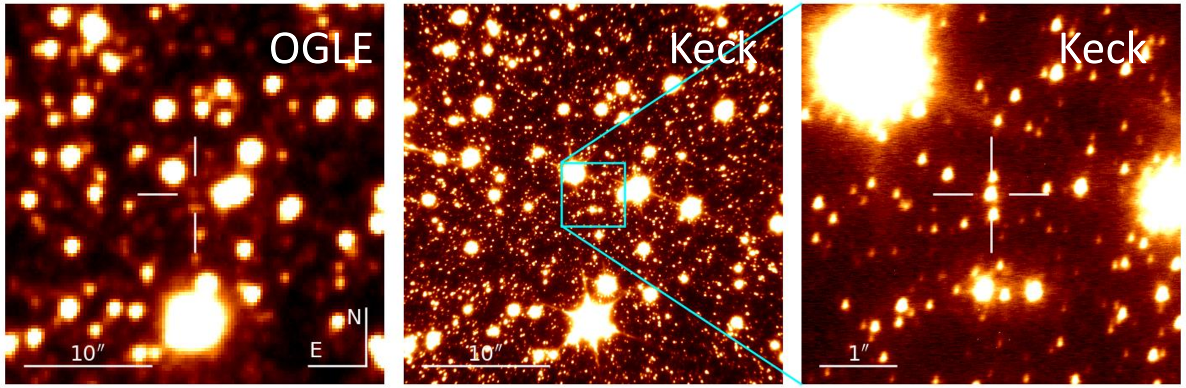
- microlensing data rule out putative stellar companions at < 10 au

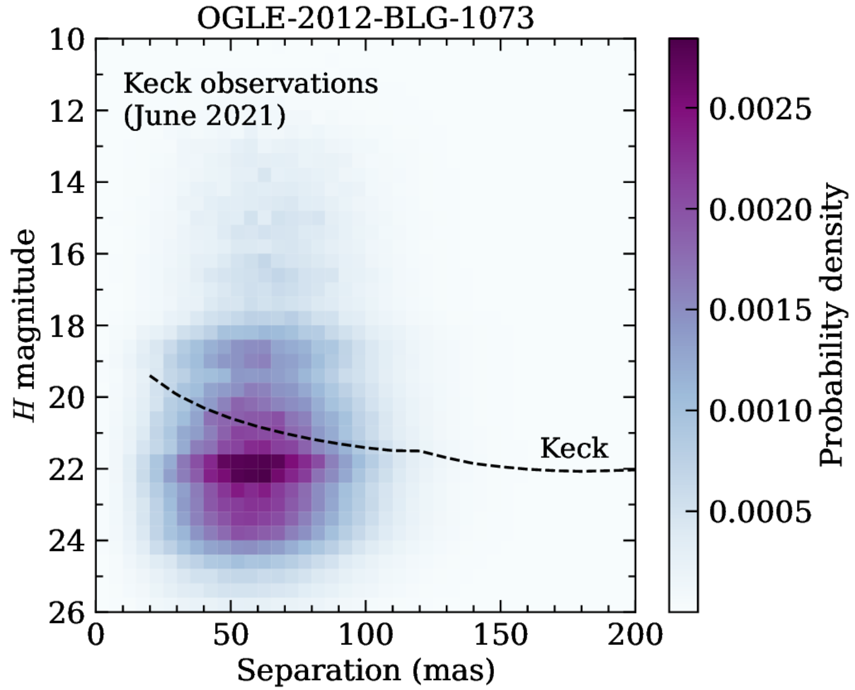


Light curve of a microlensing event by a 2 $M_\oplus$ planet on a 20 au orbit would look like that of a FFP.

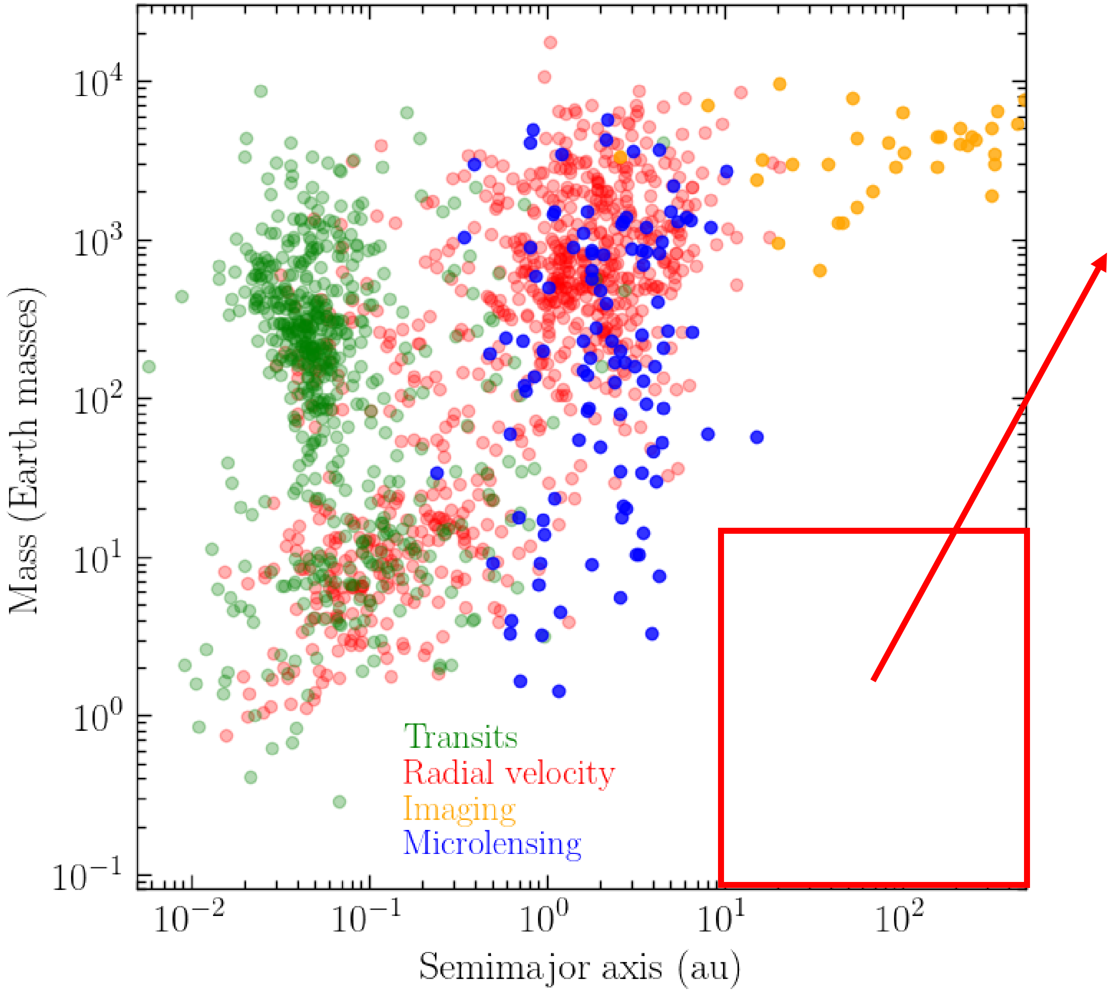
Free-floating or wide-orbit?

- microlensing data rule out putative stellar companions at < 10 au
- lens and source are moving in the sky (~5 mas/yr)
- Keck adaptive-optics observations to search for putative host stars



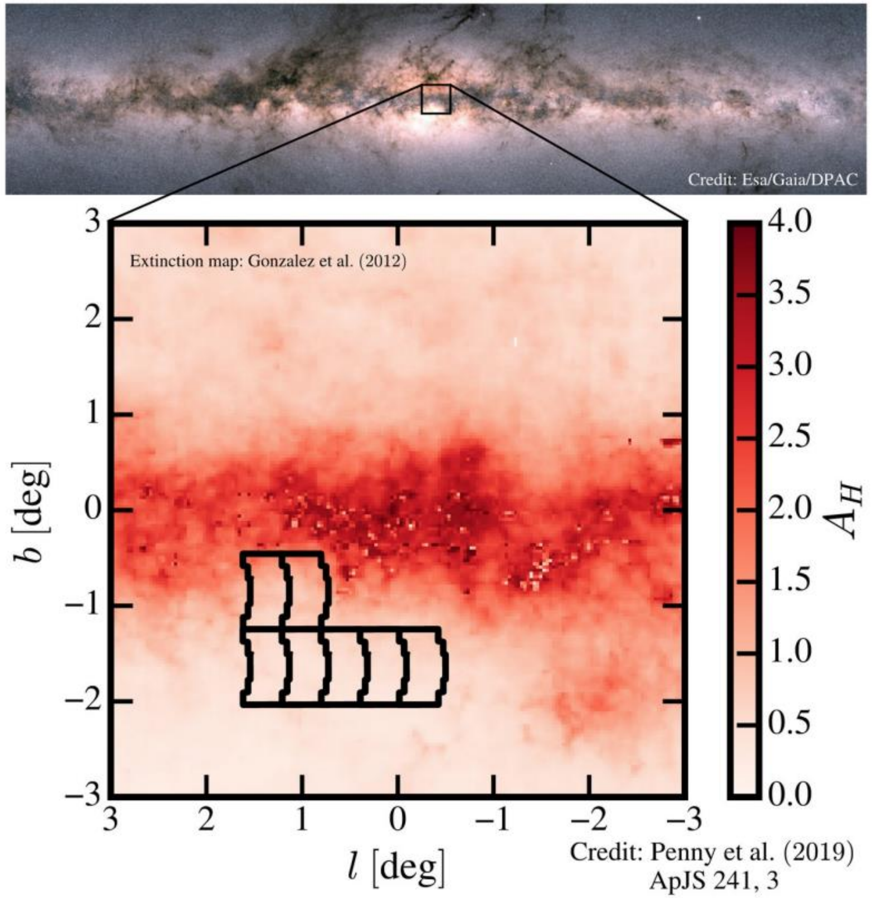


Wide-orbit planets are also cool!



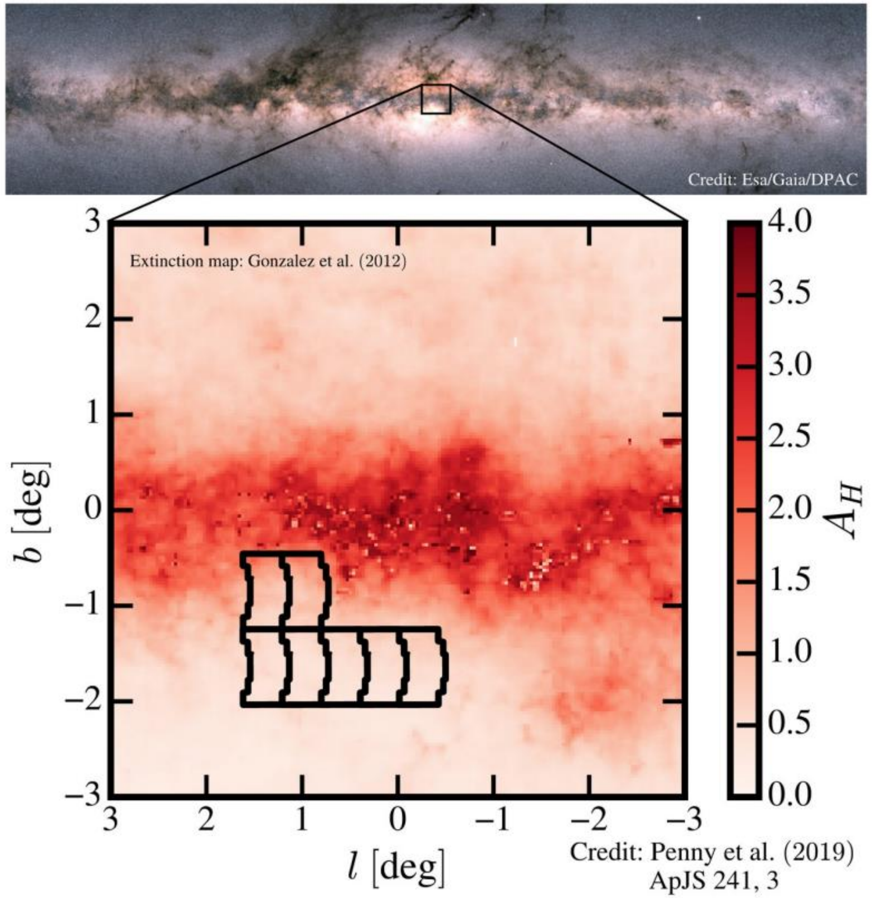
We're probing an empty phase space of low-mass wide-separation planets

Nancy Grace Roman Space Telescope



- 2.4-m telescope with a 0.28 deg^2 Wide Field Instrument (0.48-2 μm)
- Three major surveys – Galactic Bulge Time Domain Survey, High Latitude Time Domain Survey, and High Latitude Wide Area Survey
- Expected launch: by May 2027
- Galactic bulge: 6x 72 day seasons

Nancy Grace Roman Space Telescope



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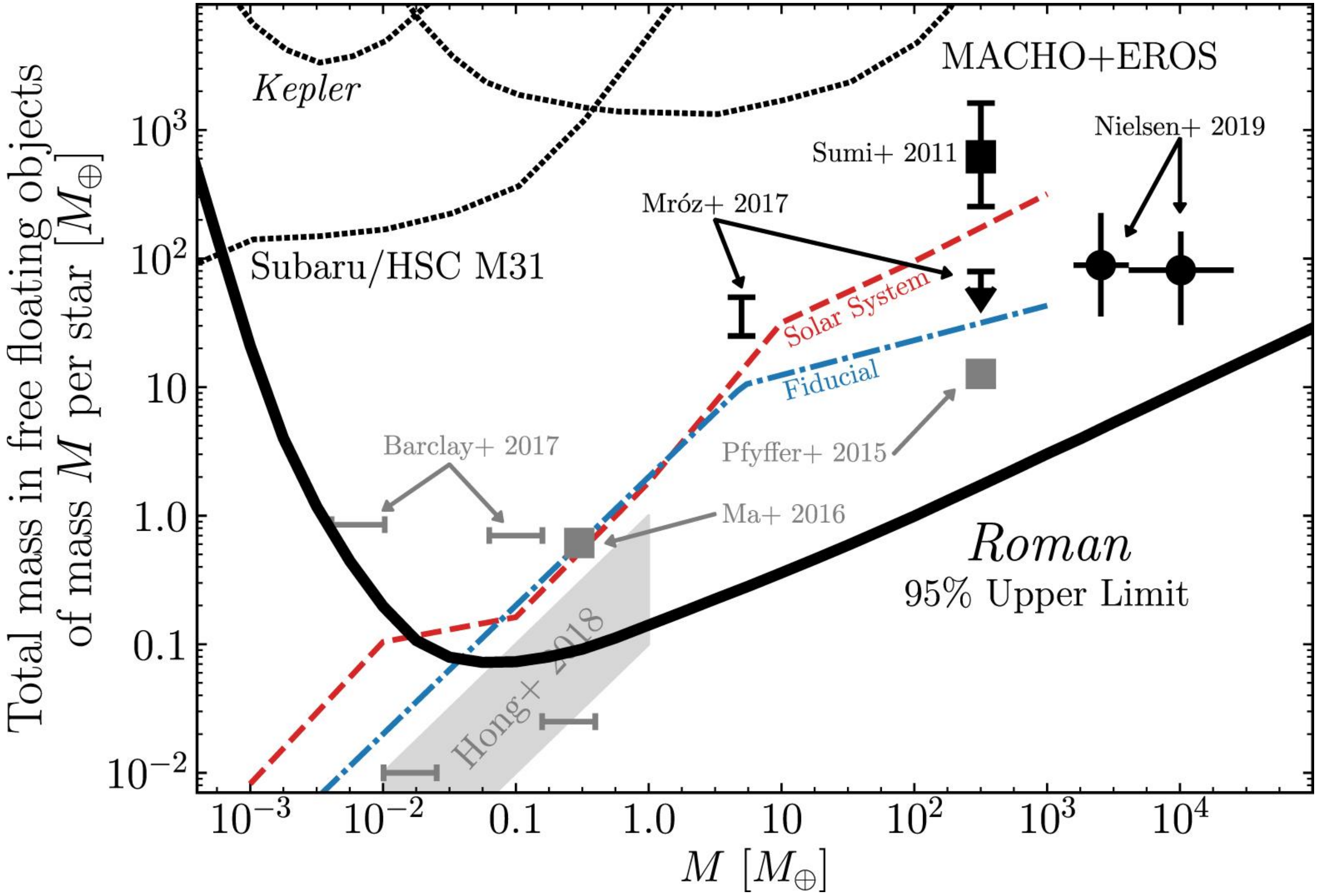
See the poster by **Radek Poleski**

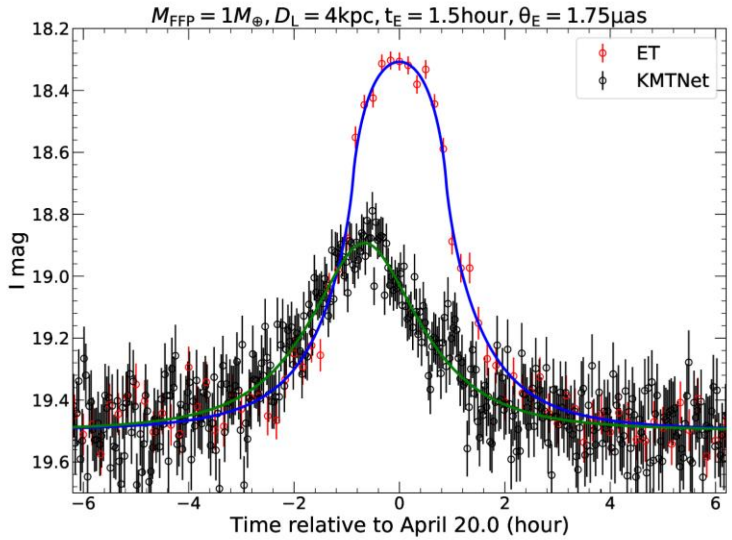
Roman telescope will be more sensitive to FFP

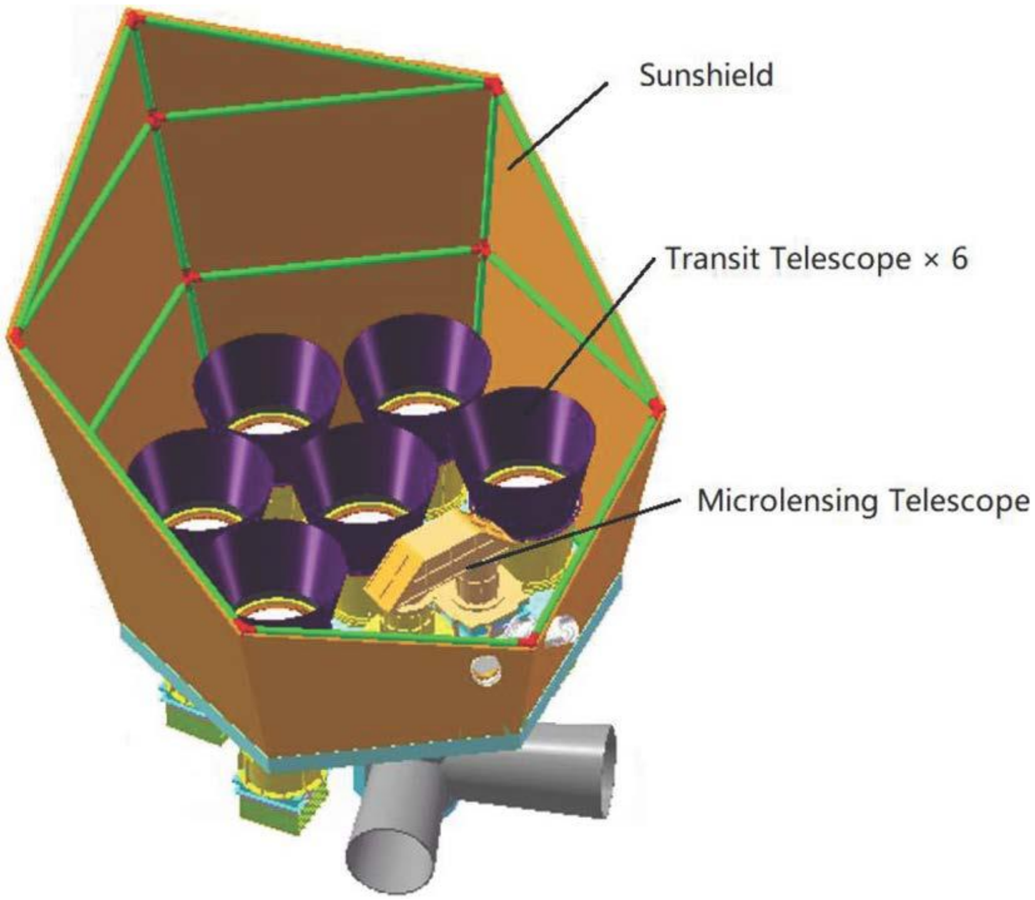


Johnson et al. 2020

Earth 2.0 (ET) mission

- Chinese project to study transiting and microlensing exoplanets
- Expected lauch date: by the end of 2026
- Will contain seven 30-cm telescopes, one dedicated to microlensing
- Is predicted to detect ~600 FFPs and measure masses for ~150 FFPs





Summary

- free-floating planets can be detected with gravitational microlensing
- less than 0.25 free-floating Jupiter-mass planets per star
- Mars- to (super)Earth-mass free-floating / wide-orbit planets are a common (or more common) that bound planets
- mass function of bound planets is shaped (partly?) by the ejection process