DETECTING HABITABLE EXOPLANETS BY THE ROMAN TELESCOPE

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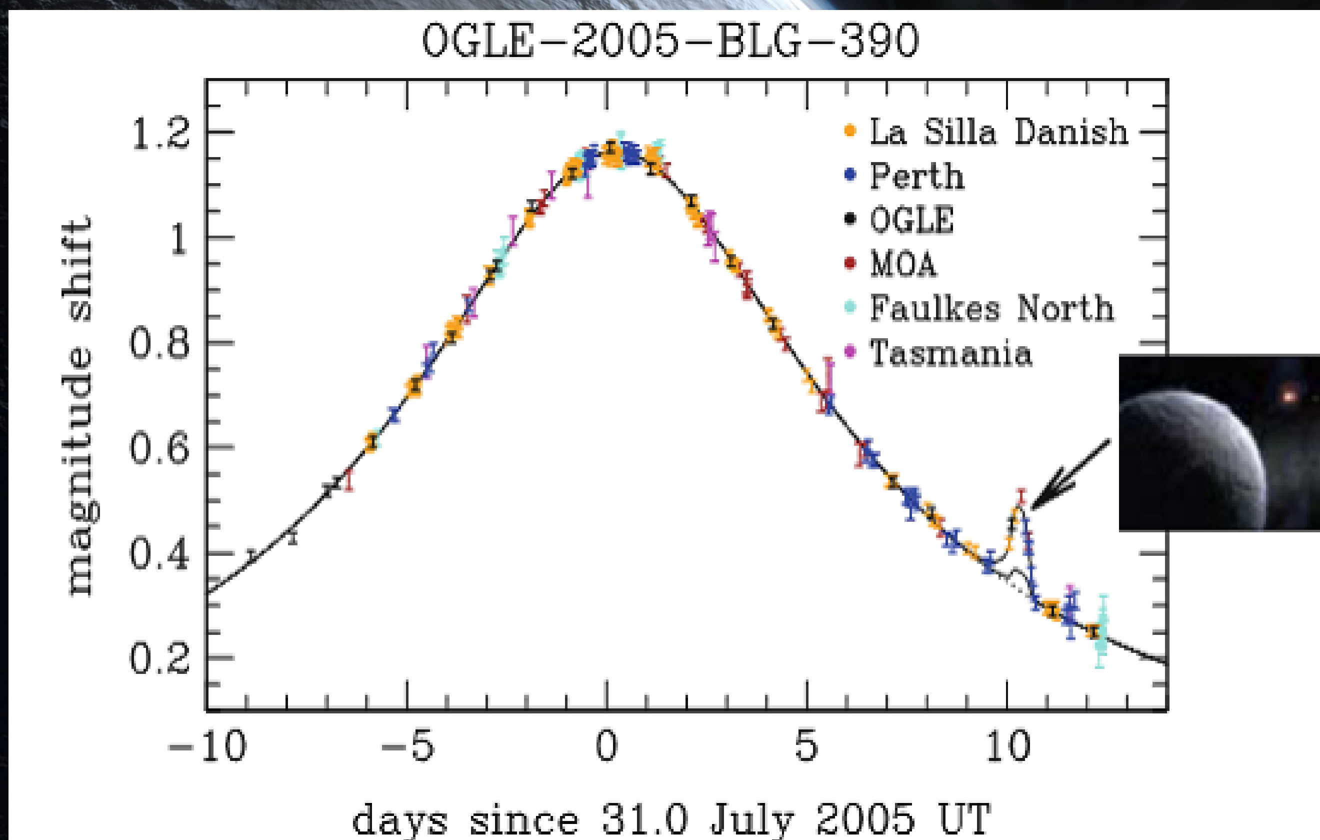
Detecting exo-planets through gravitational microlensing *(Refesdal 1966):*

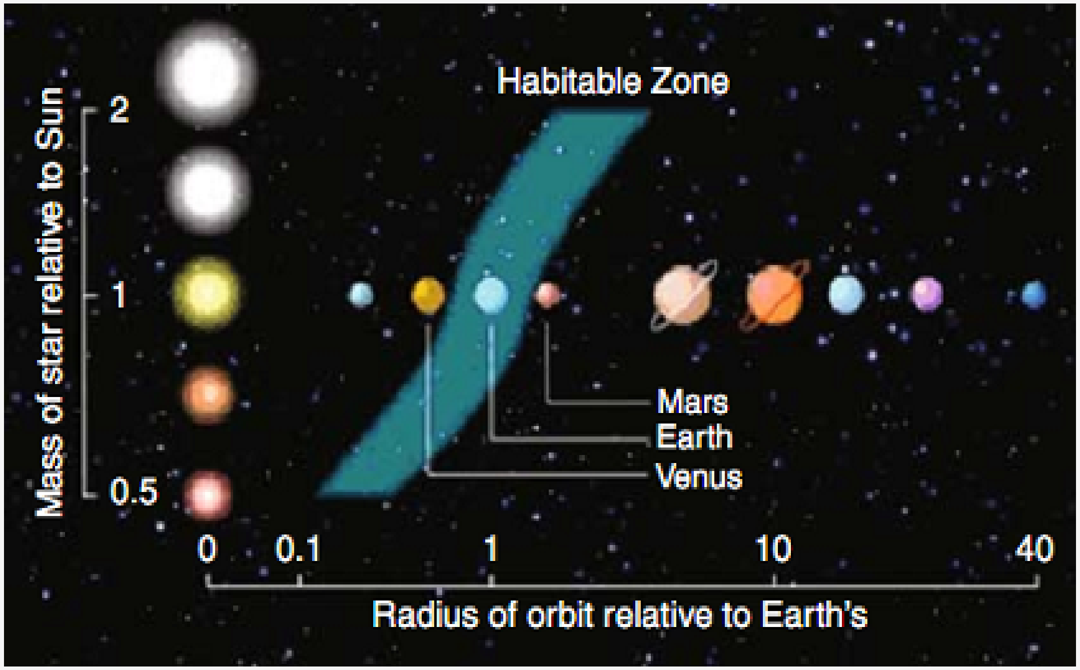
If there is any exo-planet at the projected distance ~ RE, the exo-planet perturbs the light of images:



Beaulieu et al., 2006, Nature,

Habitable Zone: The existence of a liquid bio-solvent is one of the necessary factors for life. Liquid water is the best candidate that exits in a wide temperature range, i.e. [273, 373] K

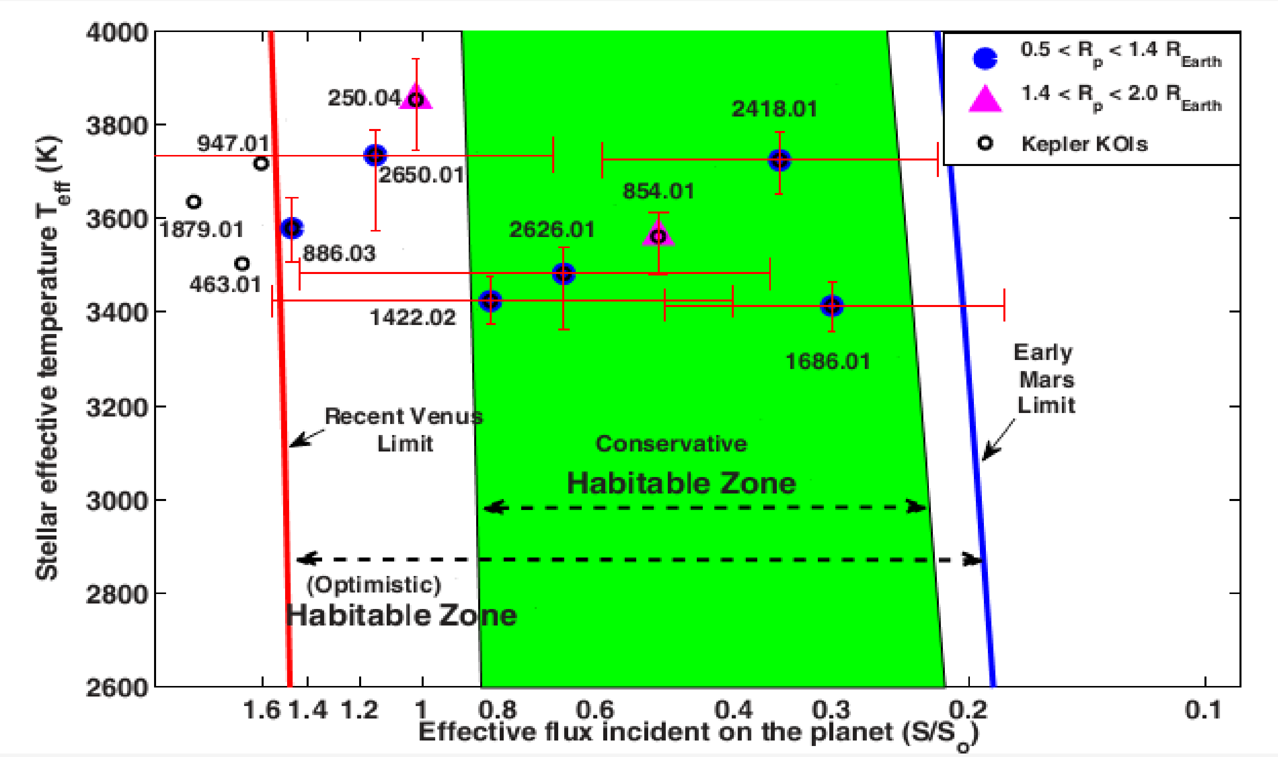
$$T_p = T_* \sqrt{\frac{R_*}{s}} [f(1 - A_B)]^{1/4},$$



Other factors: Atmospheric pressure over the planet's surface, stellar winds, magnetic fields, eccentricity, greenhouse (CO_2, H_2O, ...), variability of the host star, bond albedo (AB), re-radiation factor (f), etc.

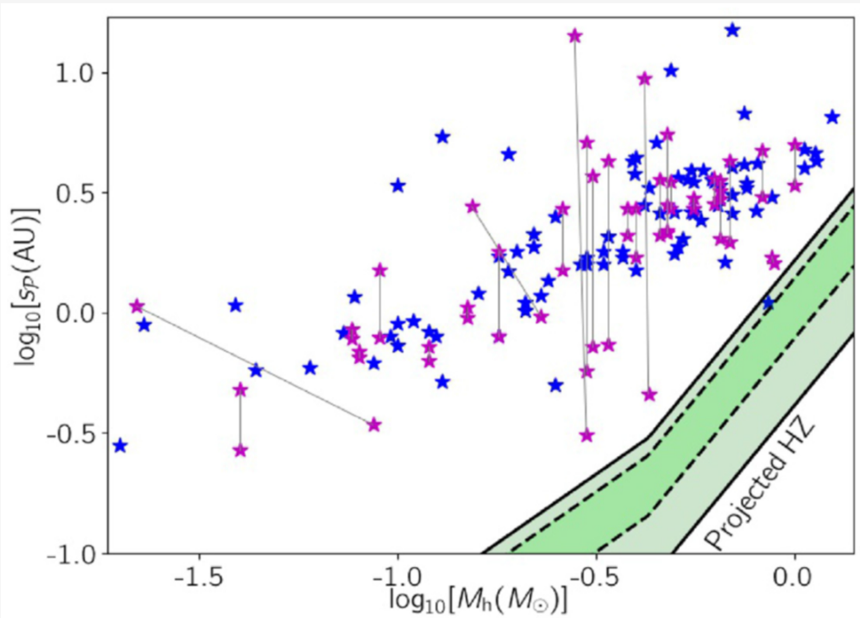
Optimistic and Conservative Habitable Zone (OHZ, CHZ)

- The outer and inner boundaries of the OHZ: a thick atmosphere with a strong greenhouse effect and a thin atmosphere with a weak greenhouse effect are assumed.
- In our solar system: OHZ is [0.5, 2.0] AU (where temperature is between 203-405 K), CHZ is [0.95, 1.67]AU (where temperature is between 228-294 K)



Kopparapu, et al., 2013, ApJ

More than 100 exoplanets were detected by microlensing, One in the habitable zone (MOA-2011-BLG-293Lb; Batista V., et. al., 2015, ApJ, 808, 170).
The total number of exoplanet detected up to now is more than 4500 and among them 150 are within the OHZ of their parent stars, most of them were discovered by radial velocimetry (http://www.hzgallery.org/)



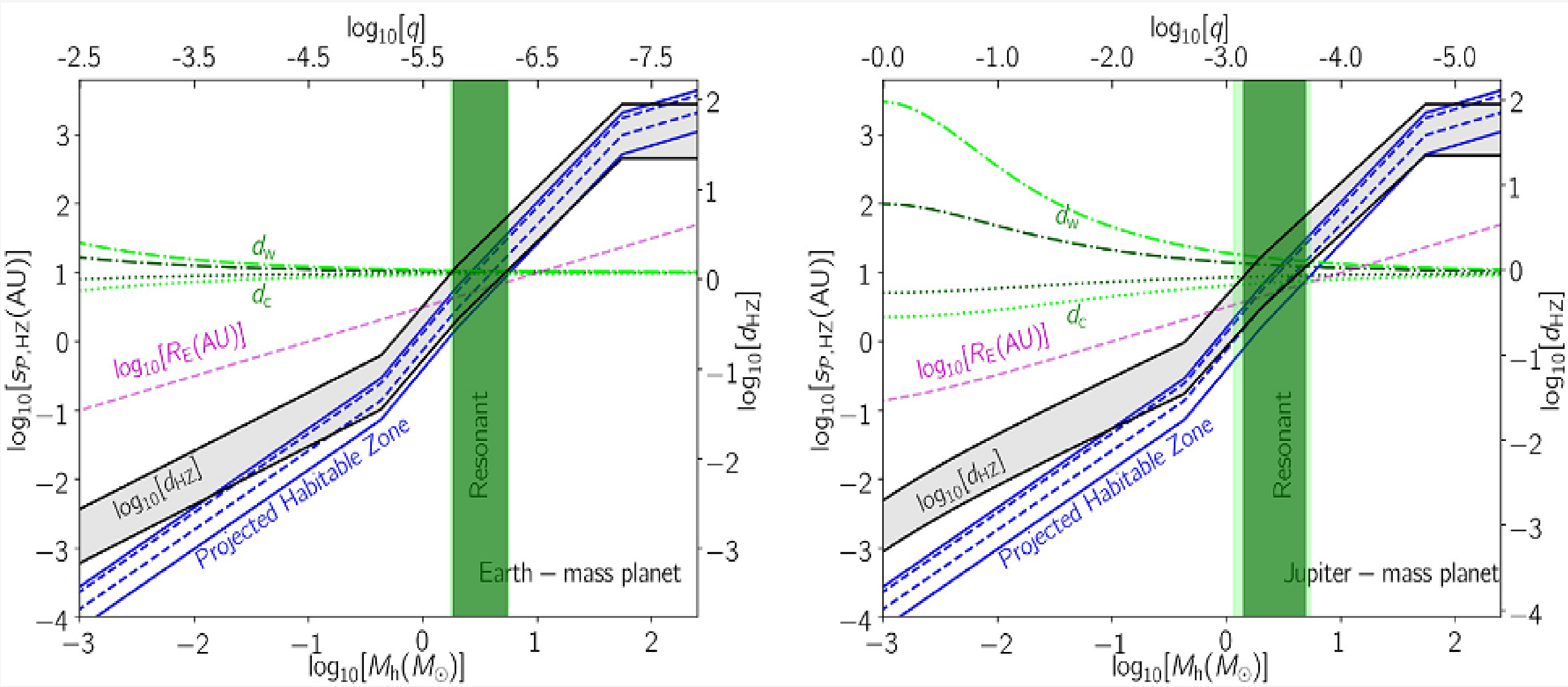
$$s_{\mathrm{HZ,\,i}}(\mathrm{AU}) = s_{\mathrm{HZ,\,i},\,\odot}\sqrt{L_{\mathrm{h}}(L_\odot)},$$
$$s_{\mathrm{HZ,\,o}}(\mathrm{AU}) = s_{\mathrm{HZ,\,o},\,\odot}\sqrt{L_{\mathrm{h}}(L_\odot)}.$$

$$L_{\mathrm{h}}(L_\odot) = \begin{cases} 0.23\,[M_{\mathrm{h}}(\mathrm{M}_\odot)]^{2.3} & M_{\mathrm{h}}(\mathrm{M}_\odot) \leq 0.43, \\ [M_{\mathrm{h}}(\mathrm{M}_\odot)]^{4} & 0.43 < M_{\mathrm{h}}(\mathrm{M}_\odot) \leq 2, \\ 1.4\,[M_{\mathrm{h}}(\mathrm{M}_\odot)]^{3.5} & 2 < M_{\mathrm{h}}(\mathrm{M}_\odot) \leq 55, \\ 32000 M_{\mathrm{h}}(\mathrm{M}_\odot) & M_{\mathrm{h}}(\mathrm{M}_\odot) > 55. \end{cases}$$

Most of habitable planetary systems make close caustic configurations with very small planetary signatures, which are barely detectable. Roman with improved cadence (~15 min) can potentially detect such small planetary perturbations in microlensing light curve.

The projection factor is 0.79

OHZ, CHZ edges projected on the sky plane (solid and dashed blue lines), Einstein radius (dashed magenta), OHZ projected and normalized (solid black lines)



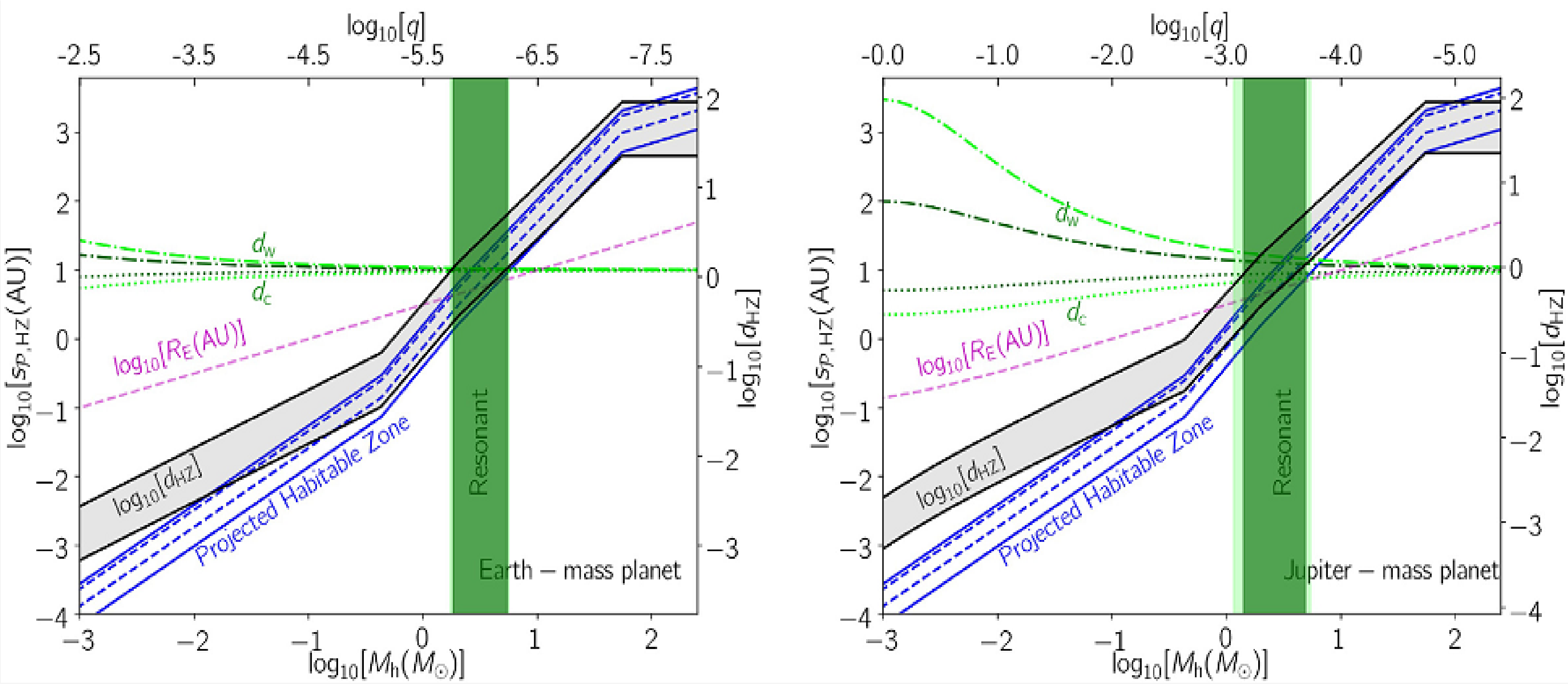
Near-resonance region (lime lines, Yee et. al., 2020): [dc^3, dw^1.8]

$$d_{\mathrm{HZ}} = \frac{s_{\mathcal{P},\mathrm{HZ}}}{R_{\mathrm{E}}} \propto \begin{cases} [M_{\mathrm{h}}(\mathrm{M}_\odot)]^{0.65}, & M_{\mathrm{h}}(\mathrm{M}_\odot) \leq 0.43, \\ [M_{\mathrm{h}}(\mathrm{M}_\odot)]^{1.5}, & 0.43 < M_{\mathrm{h}}(\mathrm{M}_\odot) \leq 2. \end{cases}$$

$$d_c^8 = \frac{(1+q)^2}{27q}\left(1 - d_c^4\right)^3,$$

$$d_w^2 = \frac{(1+q^{1/3})^3}{1+q}.$$

In this plot Dl=6.5, Ds=8.0kpc



Habitable planets around host stars with mass less than 0.5 solar mass generate ***close caustic topologies***, for all values of the lens distance in the range Dl ∈[0.08, 7.92] kpc. However, the size of these planetary caustics depends on <u>the mass ratio</u>. For Earth and Jupiter-mass planets around main-sequence stars, the resulting mass ratios are log[q]~ −5.0,−2.5, respectively.

Resonance configurations happen for the host stars with the mass of M ∈ [0.64, 5.62]solar mass and M ∈[0.61,6.03] solar mass for an Earth- and Jupiter-mass planets (mostly for either x<0.1 or x>0.9)

Doing a Monte-Carlo simulation: Indicating the Roman ability to discern habitable planets

1) Simulating microlensing events toward (l,b)= (1.3,−0.89), (0.9,−0.89), (1.3,−1.63), (0.9,−1.63), (0.5,−1.63), (0.1,−1.63), and (−0.3,−1.63)

Source positions, their photometry properties (based on Besancon model), extinction map, lens locations, blending effect (specially due to bright lenses), lens and source velocities, lensing parameters, etc.

$$\frac{dN}{d\Omega} \propto D_s^2\, dD_s \sum_{i=1}^{4} \rho_i(D_s)$$

$$\Gamma(D_l) \propto \sqrt{\frac{D_l(D_s - D_l)}{D_s}} \sum_{i=1}^{4} \rho_i(D_l,\ l,\ b),$$

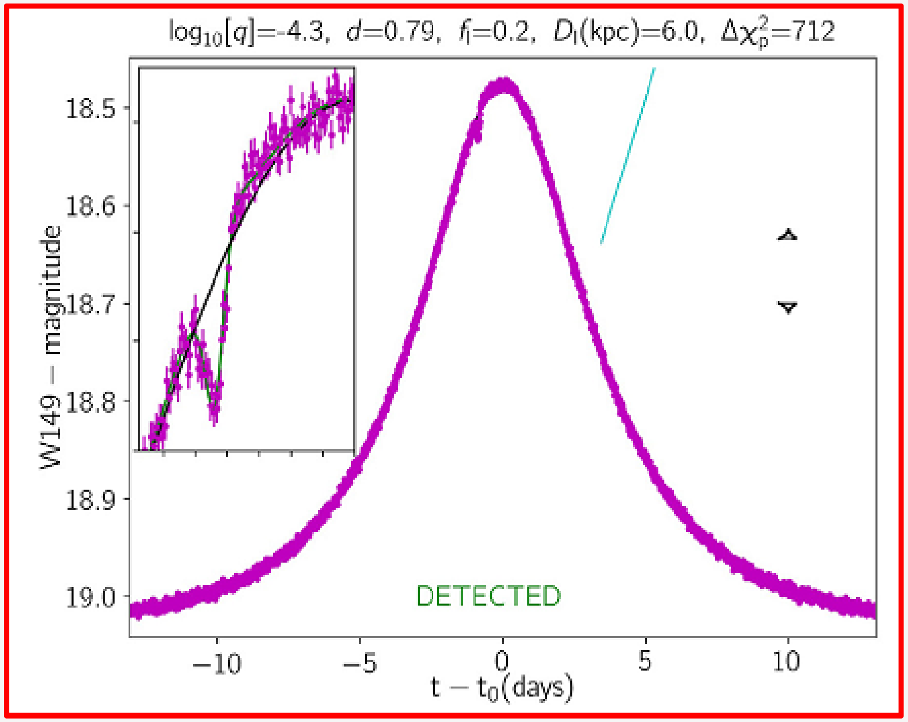
$$N_{\rm PSF}(l,\ b) = \int_{D_s} n_t(l,\ b,\ D_s)\, dD_s\, D_s^2\, \Omega_{\rm PSF},$$

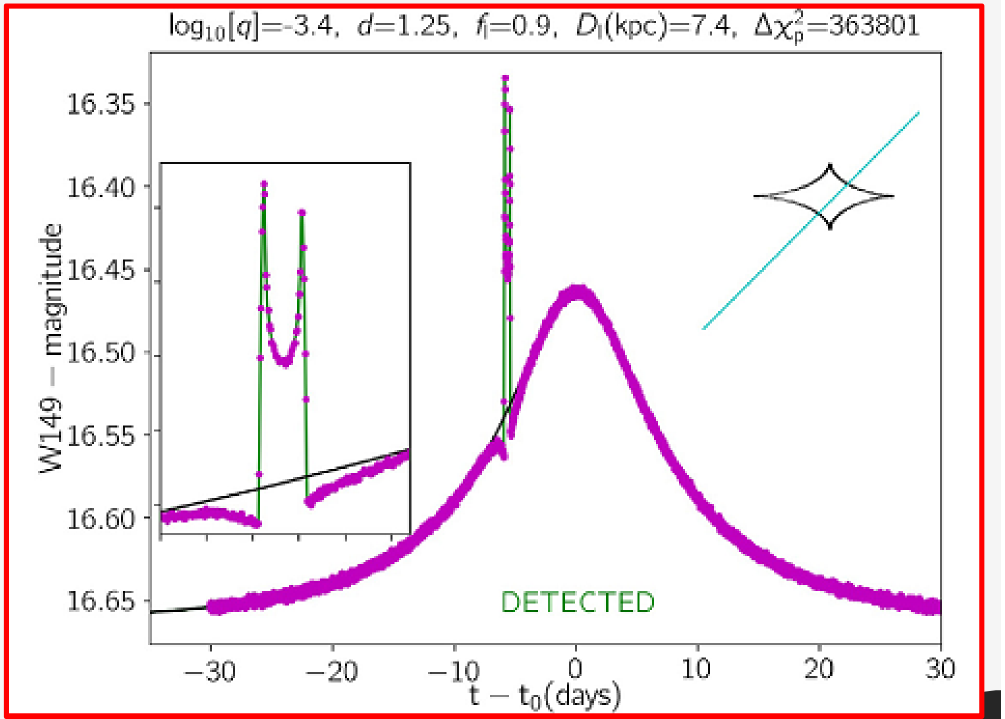
$$f_l = \frac{F_l}{F_* + \sum_i F_i},$$

2)Generating synthetic data points taken by Roman (cadence, photometry errors, seasonal gaps,)

3) Extracting the events with detectable planetary signatures based on chi-squared criterion.

- **Two examples**





Detection Efficiency:

For each simulated microlensing event, we assume that one exoplanet is located in the OHZ of the lens object and choose the semi-major axis of its orbit uniformly inside OHZs. We assume the planet's orbit around its host star is circular and project it on the sky plane by considering a uniform cos (i) (i is the inclination angle.)

Low Sensitivity (LS): $\Delta\chi^2 > 300$
High Sensitivity (HS): $\Delta\chi^2 > 800$

M_p	$\epsilon_{OHZ,LS}$ [%]	$\epsilon_{OHZ,HS}$ [%]	$\epsilon_{CHZ,LS}$ [%]	$\epsilon_{CHZ,HS}$ [%]	$<D_l>$ (kpc)	$<M_h>$ ($M_\odot$)	$<f_l>$ ($M_\odot$)	$<m_{W149}>$ (mag)	$<t_E>$ (d)	$<d>$	$f_c: f_i: f_w$ (%)	f_{si} (%)
$M_\oplus$	0.02	0.01	0.01	0.01	7.5	0.83	0.35	18.0	21.2	0.78	85 : 1 : 14	5
$10M_\oplus$	0.14	0.09	0.13	0.09	7.2	0.58	0.26	18.8	18.3	0.63	84 : 4 : 12	11
$100M_\oplus$	1.75	1.5	1.86	1.60	6.8	0.31	0.14	19.2	16.7	0.28	96 : 2 : 2	4
M_J	5.20	5.01	5.47	5.29	6.7	0.28	0.12	19.1	17.7	0.22	97 : 1 : 2	3
$5M_J$	17.03	16.98	17.94	17.89	6.5	0.28	0.11	19.0	19.0	0.17	98 : 1 : 1	2
$10M_J$	25.43	25.41	26.79	26.77	6.5	0.29	0.10	19.0	19.7	0.15	98 : 1 : 1	2

The Roman detection efficiency increases by enhancing the mass of planets. Their relation is almost linear for planets with the mass < MJ, but it increases slowly for planets heavier than MJ.

M_p	$\epsilon_{OHZ,LS}$ [%]	$\epsilon_{OHZ,HS}$ [%]	$\epsilon_{CHZ,LS}$ [%]	$\epsilon_{CHZ,HS}$ [%]	$<D_l>$ (kpc)	$<M_h>$ ($M_\odot$)	$<f_l>$ ($M_\odot$)	$<m_{W149}>$ (mag)	$<t_E>$ (d)	$<d>$	$f_c: f_i: f_w$ (%)	f_{si} (%)
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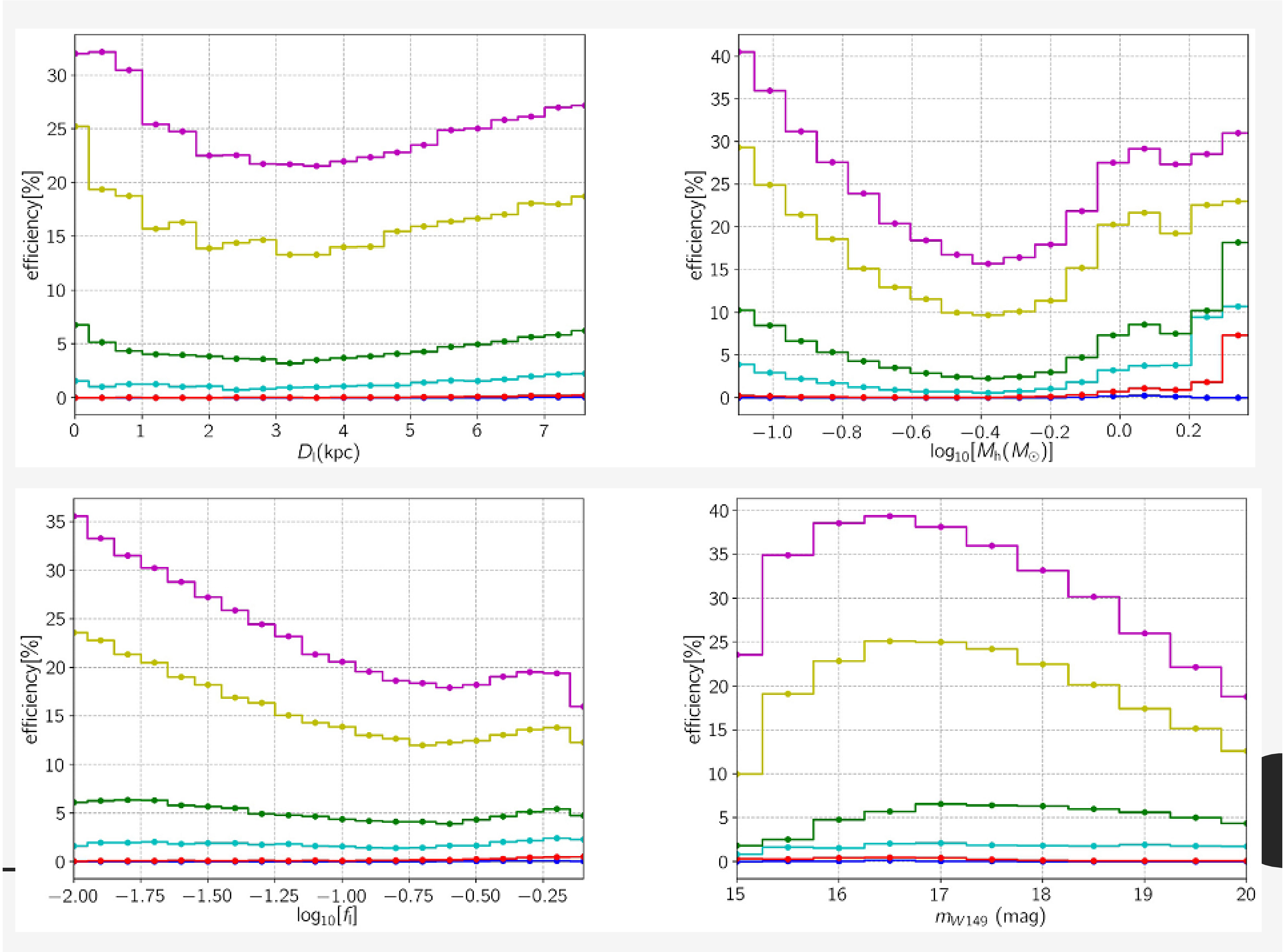
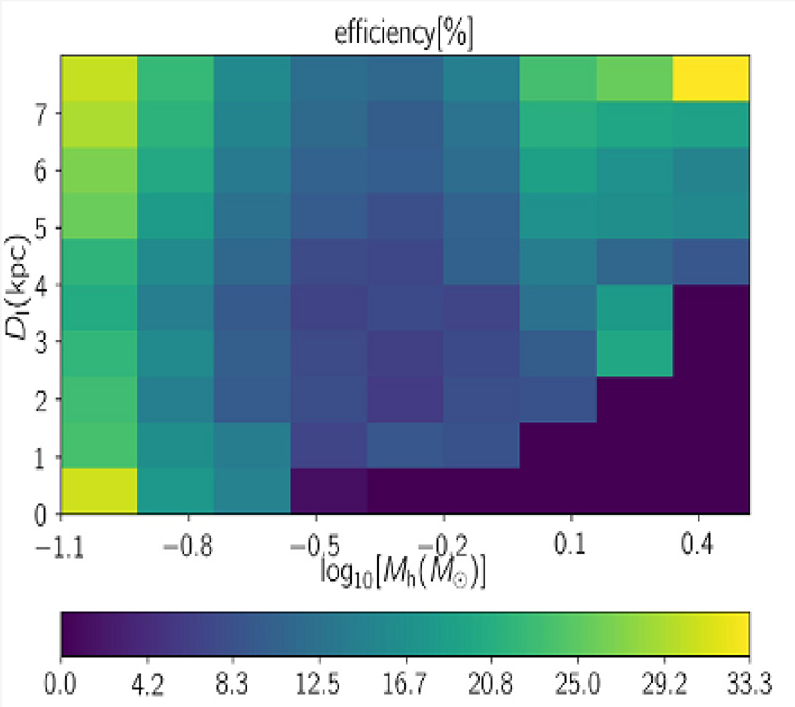
Only ~***0.01 percent and 0.1 percent of Earth and super Earth-mass planets*** in HZs are detectable in the Roman observations. Habitable Earth-mass planets are detectable when they rotate around G- and K-type stars located at a distance beyond 7 kpc from the observer. The brightness of their primary lenses is considerable. These planetary systems produce rather close or wide caustic topologies.

5–25 per cent of Jupiter and super Jupiter-mass planets within HZs are detectable by Roman. In these detectable events, the primary lens objects are most often M-dwarfs (as usual), resulting less blending effect from the brightness of host objects. These planetary systems make mainly close caustic topologies.



efficiency[%]
D_l(kpc)
efficiency[%]
$\log_{10}[M_h(M_\odot)]$
efficiency[%]
$\log_{10}[f_l]$
efficiency[%]
m_{W149} (mag)



The size caustics:

$$\Delta_c \propto 4q/(d - 1/d)^2 \text{ and } \Delta_p \propto \sqrt{q}\, d^3$$

The size of caustics due to class (a) is larger than others

- (a)The events with Ml> 0.6 solar mass, while their microlens systems are very far (inside the Galactic bulge), Dl>7kpc. q~0.001, but d >0.17. The parallax amplitude is very small <0.02 mas. Orbital periods P>100 days.
- (b)The events with M <0.1 solar mass, while their microlens systems are very close to the observer Dl <1 kpc. q> 0.01 and d<0.04. The parallax amplitude is very large >0.87 mas. Orbital periods P<7 days.
- (c)The events with M <0.1 solar mass, while their microlens systems are very close to the Galactic bulge Dl >7 kpc. q> 0.01 and d<0.04. The parallax amplitude is very small <0.02 mas. Orbital periods P<7 days.

A realistic simulation:

- Each source star has a planet at a random distance and with a random mass. Microlensing planet mass function (Udalski, et al. 2018) in [0.00001, 0.06]:

$$\frac{\mathrm{d}N}{\mathrm{d}\log_{10} q} \propto \begin{cases} q^{0.73} & q \lesssim 2 \times 10^{-4}, \\ q^{-0.93} & q > 2 \times 10^{-4}. \end{cases}$$

- Opik's Law (Opik 1924) in [0.01, 100]AU:

$$\mathrm{d}N/\mathrm{d}s \propto 1/s,$$

Properties of detectable events:

	$<M_p>$ M_J	$<D_l>$ (kpc)	$<M_h>$ ($M_\odot$)	$<f_l>$	$<m_{W149}>$ (mag)	$<t_E>$ (d)	$<d>$	$<R_E>$ (au)	f_c: f_i: f_w (%)	f_{si} (%)	ϵ_p (%)	ϵ_{HZ} (%)	N_{HZ}	$\epsilon_{HZ,\mathcal{P}}$ (%)	$N_{HZ,\mathcal{P}}$
							OHZ planetay microlensing								
LS	2.71	6.89	0.51	0.24	19.5	23.1	0.29	1.63	96 : 3 : 1	5.1	3.00	3.35	27	4.29	35
HS	2.76	6.90	0.53	0.25	19.3	24.7	0.30	1.70	95 : 4 : 1	6.0	2.79	3.13	24	4.07	31
							CHZ planetay microlensing								
LS	2.57	6.63	0.43	0.22	19.5	18.4	0.31	1.43	95 : 3 : 2	7.2	3.00	1.79	15	2.76	22
HS	2.60	6.69	0.44	0.23	19.4	19.2	0.33	1.47	94 : 4 : 2	8.4	2.79	1.65	12	2.62	20

- ❖ The fractions of these planetary events that their planets locate in the OHZs and CHZs are 3.35, 1.79%.
- ❖ Fraction of detectable microlensing events (projected in the OHZs and CHZs) are ~ 4.3, 2.8%.

- ❖ By applying LS criterion for detectability of planetary signatures, the number of detectable planets in the OHZs and CHZs is 27 and 15, respectively. Roman will detect 35 exoplanets with projected distances in the OHZs, which 22 of them have projected distances in CHZs.

These planets are most often rotating around K-type stars, which are, on average, at the distance farther than 6.7 kpc from us. Targets in these events are on average as bright as 19.5 mag in the W149 filter at the baseline. Some part of this brightness is due to the primary lens.

- **Thank you for your attention**