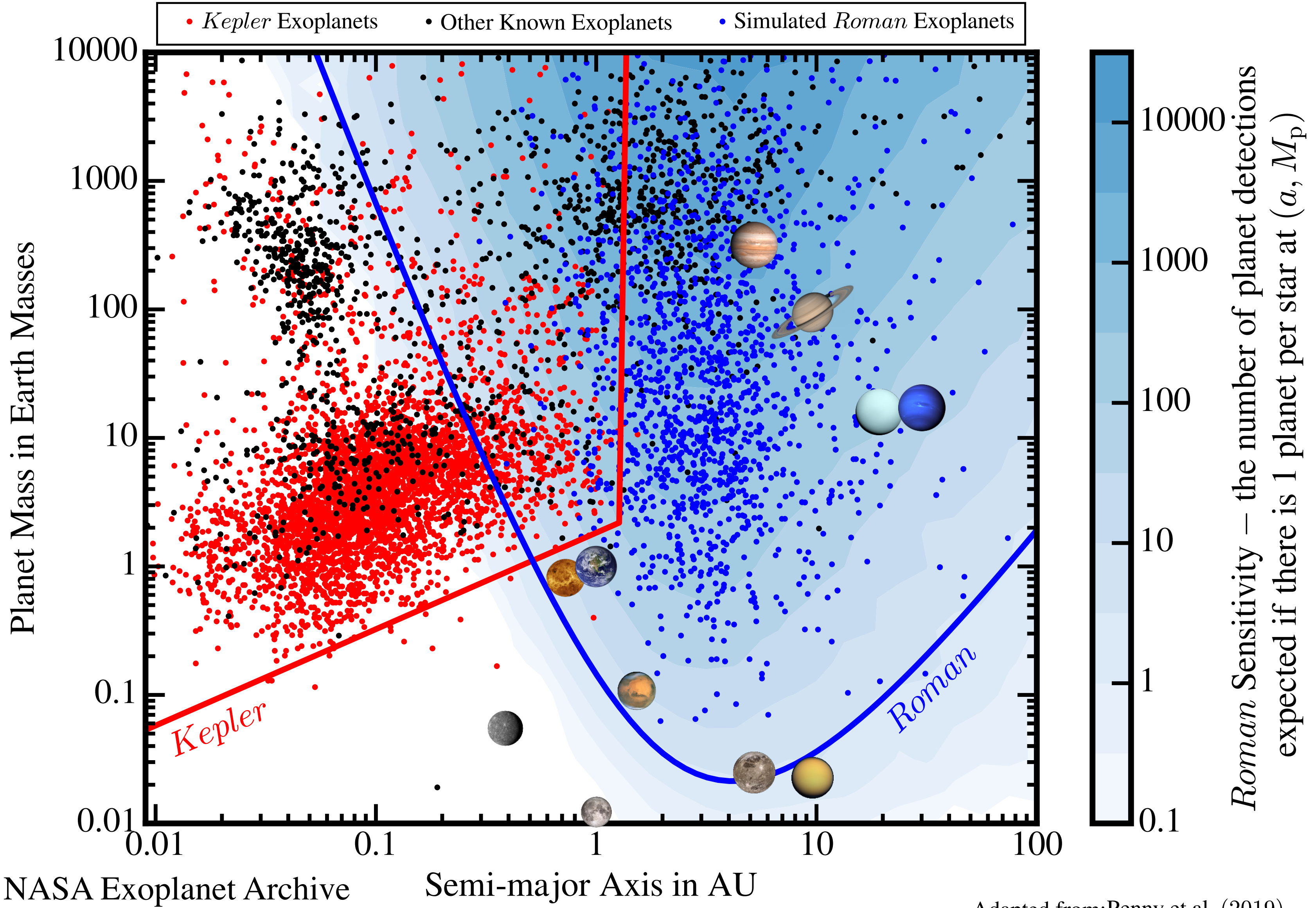
Predictions of the Roman Galactic Bulge Time Domain Survey: Constraints on the Frequency of Earth-Analogs

Samson A. Johnson

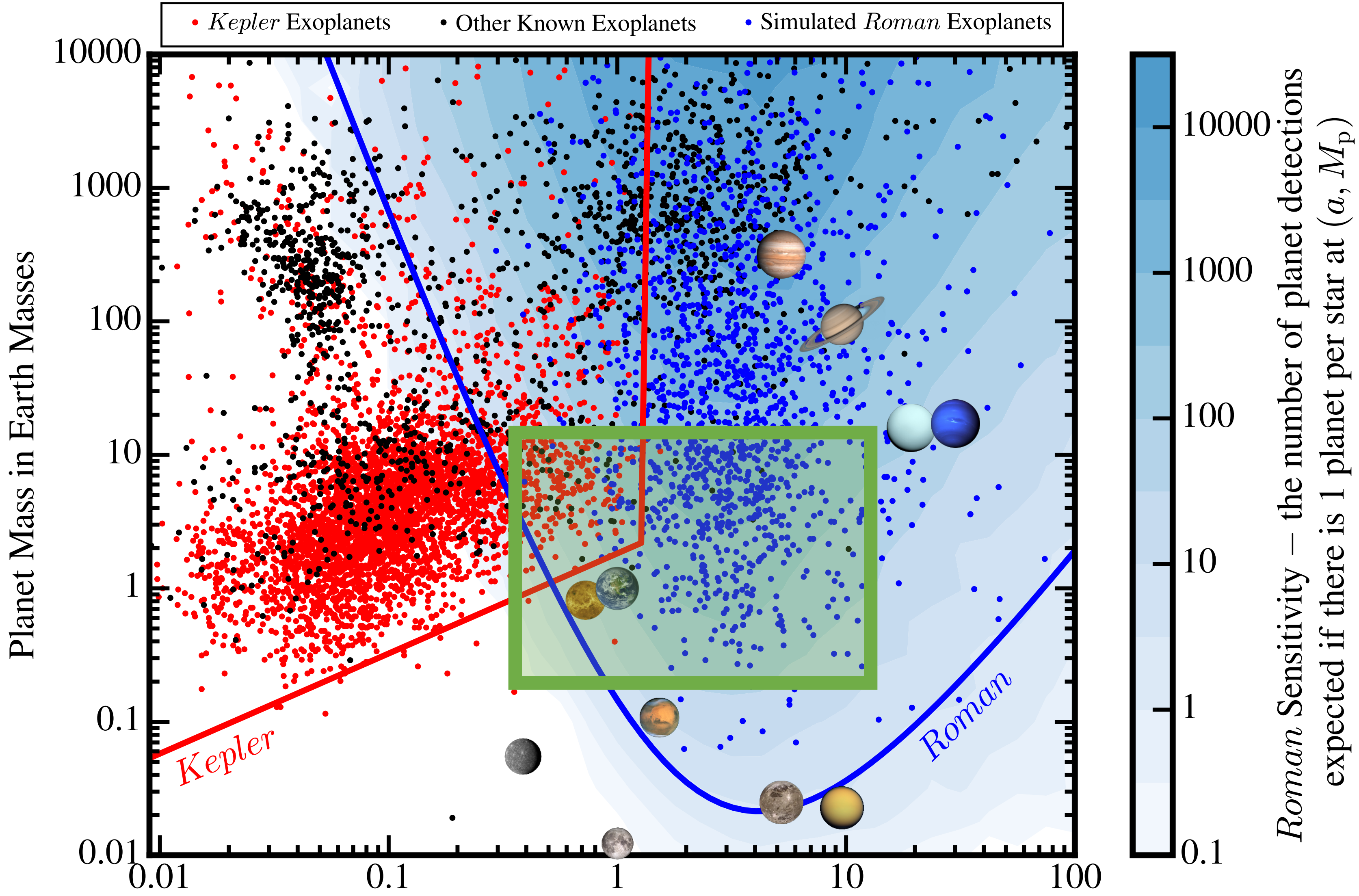
Matthew T. Penny, B. Scott Gaudi, *Roman* GES-SIT

Roman Time Domain Science Conference

2022-02-09



Adapted from: Penny et al. (2019)



NASA Exoplanet Archive

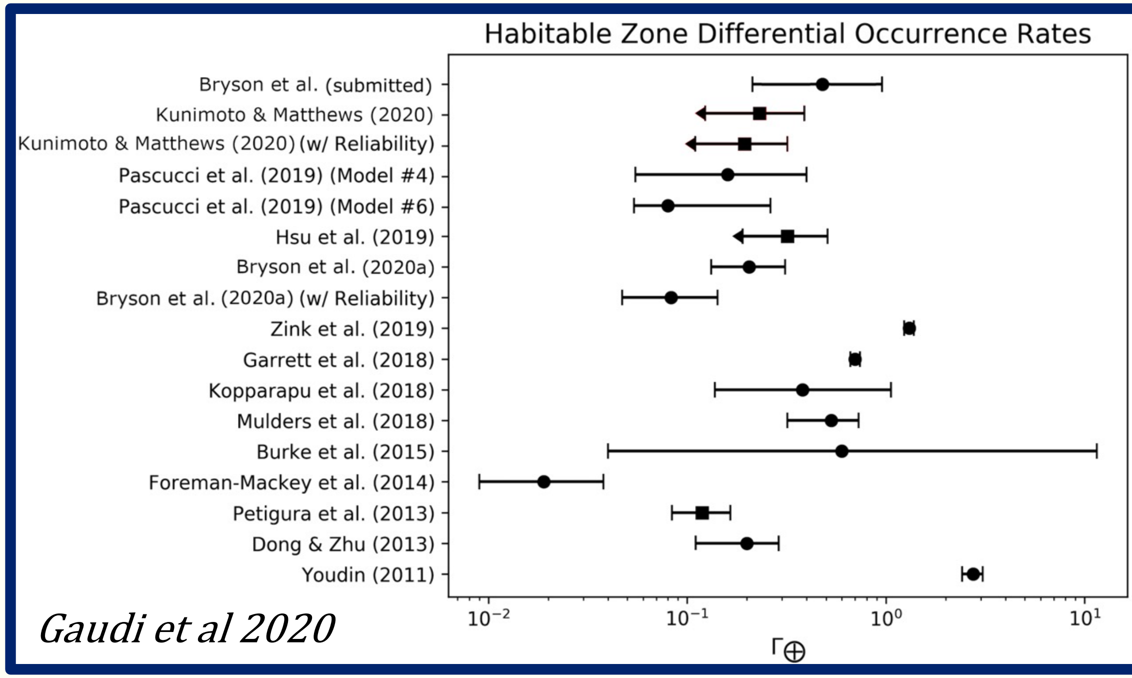
Adapted from:Penny et al. (2019)

ROMAN SPACE TELESCOPE

The Frequency of Earth-Analogs

- Important input for designing future direct imaging missions that can detect and characterize potentially habitable planets.

- Currently best estimate(s) are from *Kepler*
  - Earth-analogs on edge of *Kepler* sensitivity function
  - Relies on extrapolation from shorter-period/larger-radii planets



Gaudi et al 2020

ROMAN SPACE TELESCOPE

HZ and microlensing

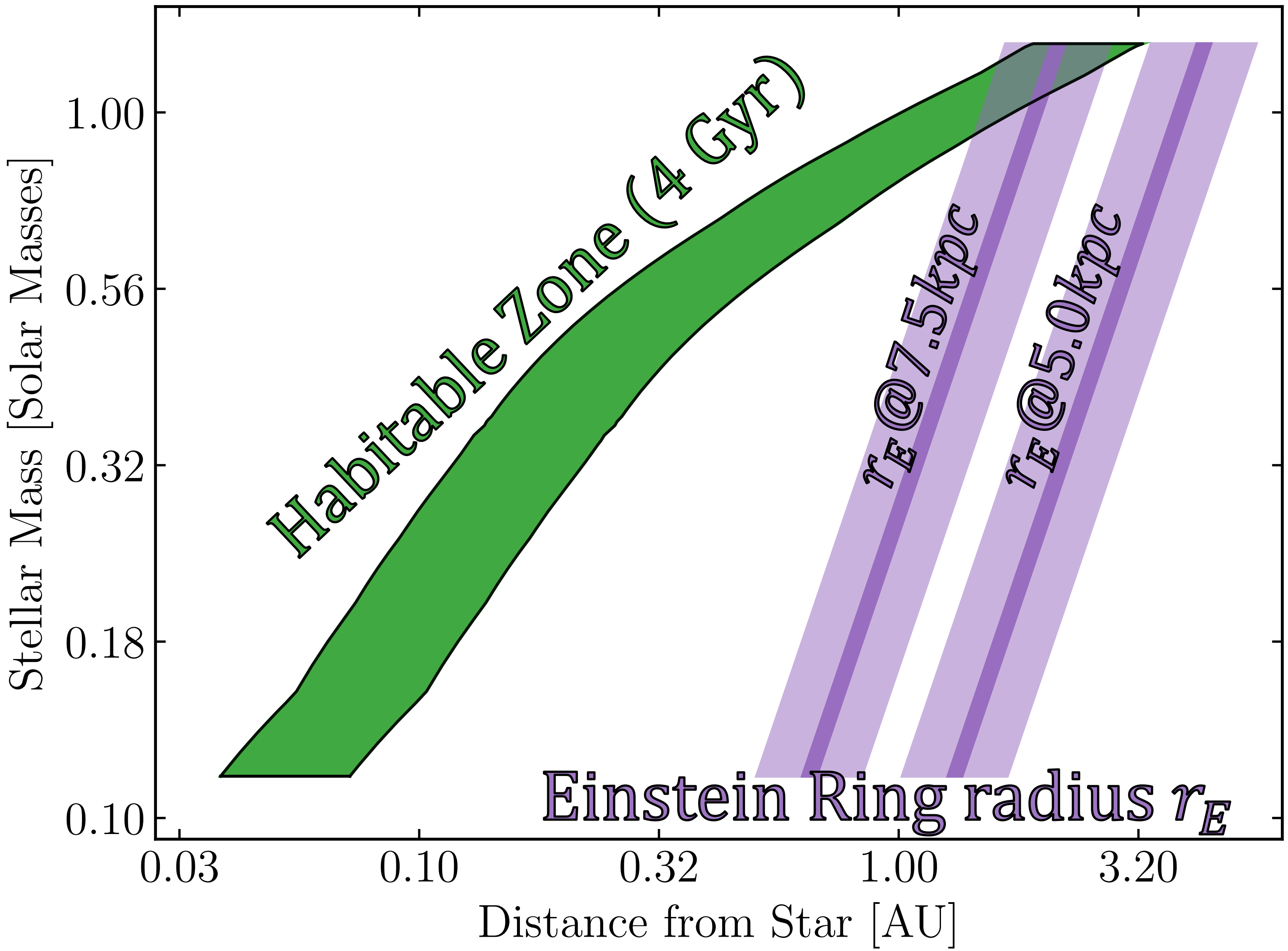
Habitable Zone (Kopparapu+ 2013)

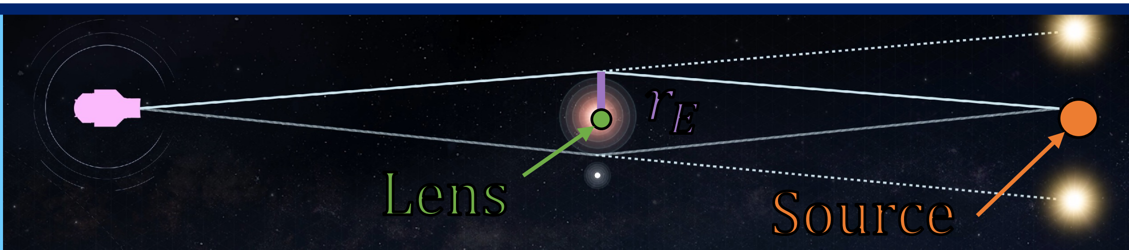
- Function of host mass, age, etc.

Einstein Ring Radius

- Peak sensitivity to planets
- Depends on host (lens) star mass
- Function of lens/source distance

$$r_E = \sqrt{\frac{4GM_L}{c^2}\frac{D_L}{D_S}(D_S - D_L)}$$

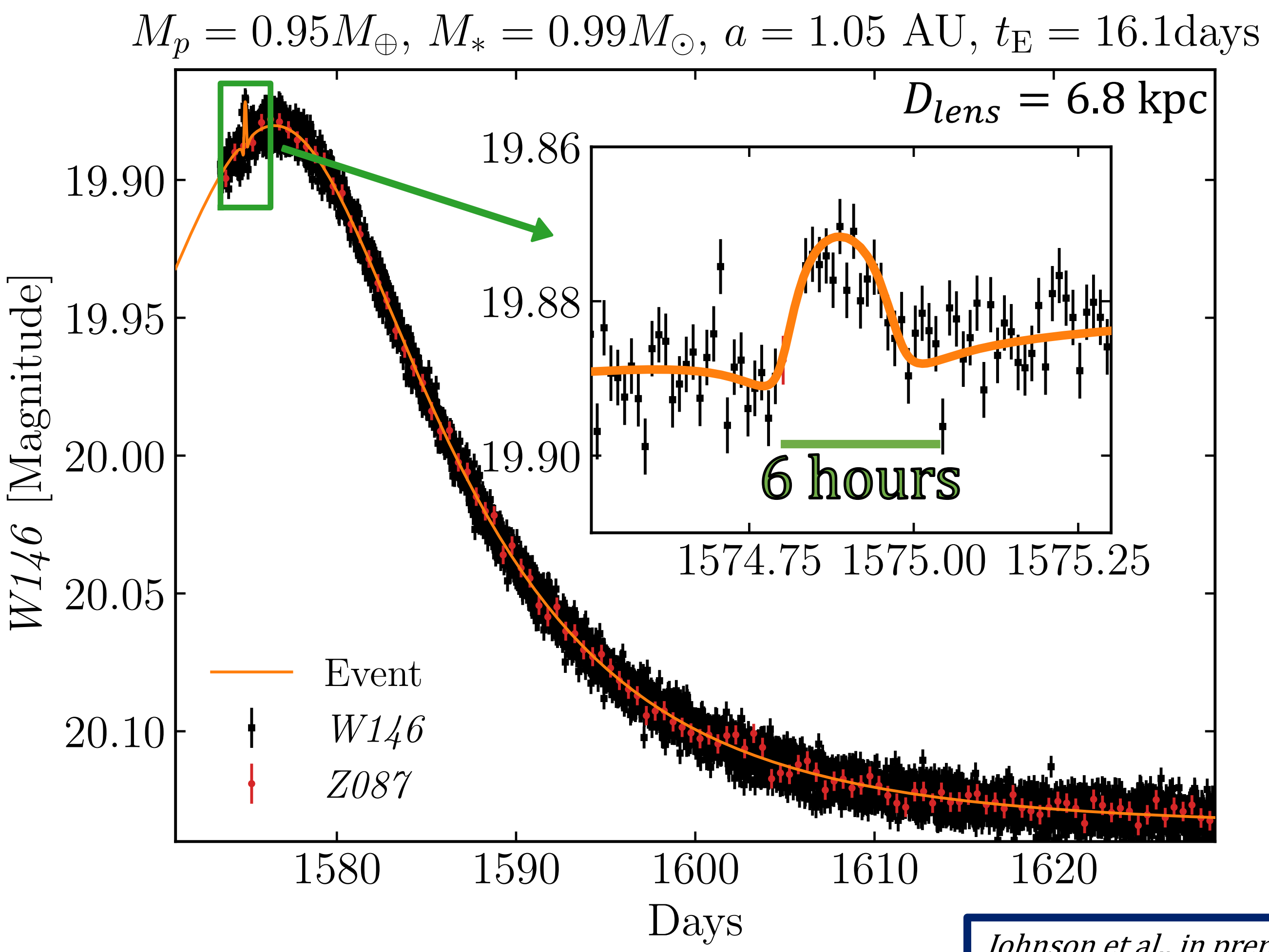




What would an Earth-analog look like to *Roman*?

Survey details

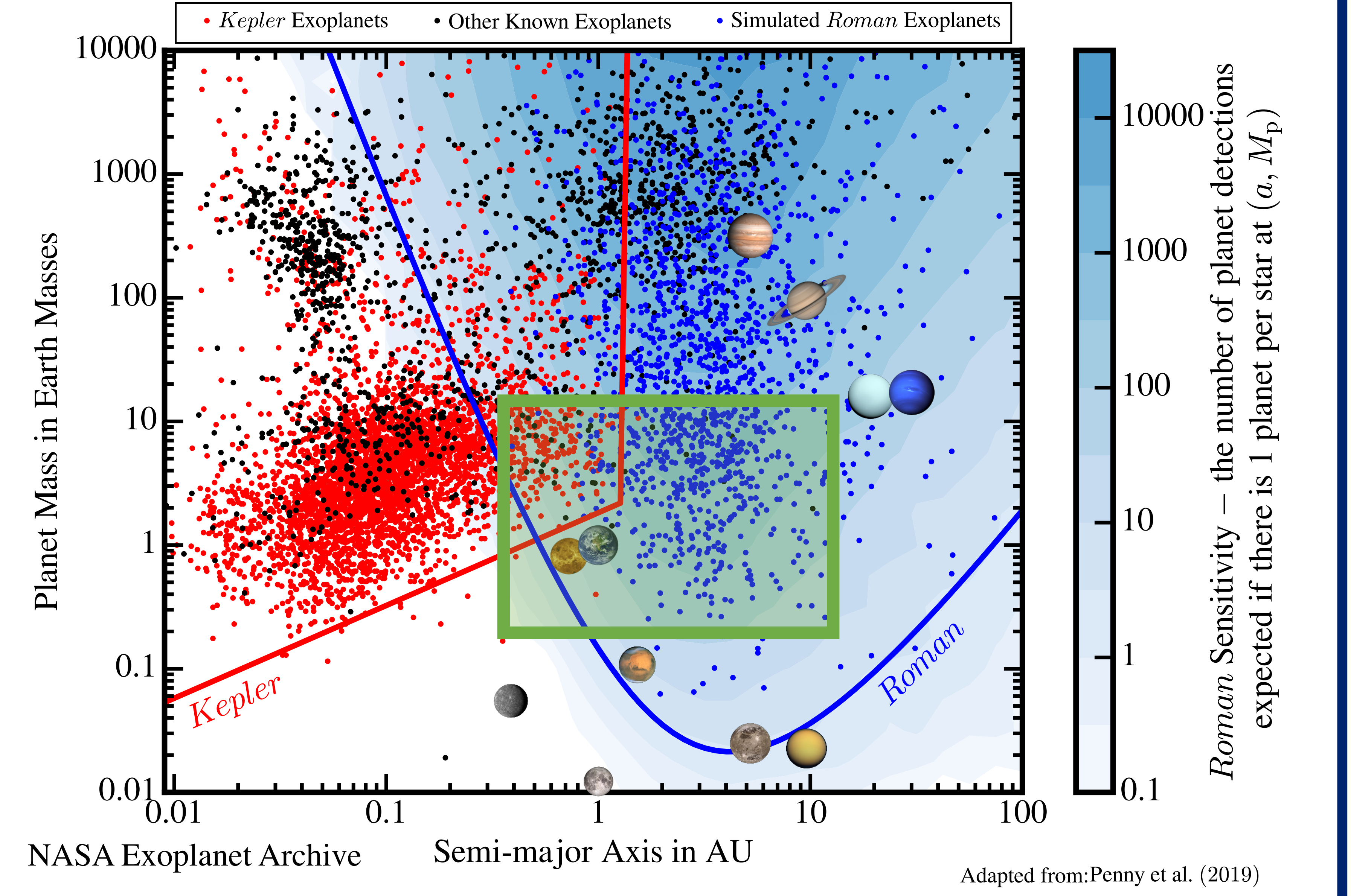
- 0.28 deg^2 FOV, 7 fields
  $\rightarrow \sim 2$ deg^2 total
- Six 72-day seasons
  - $\sim 5-$ year baseline
- 15 min cadence in 1-2 μm bandpass
  - ≤12 hr in 0.8-1 μm bandpass
- 10^8 stars, >30,000 microlensing events



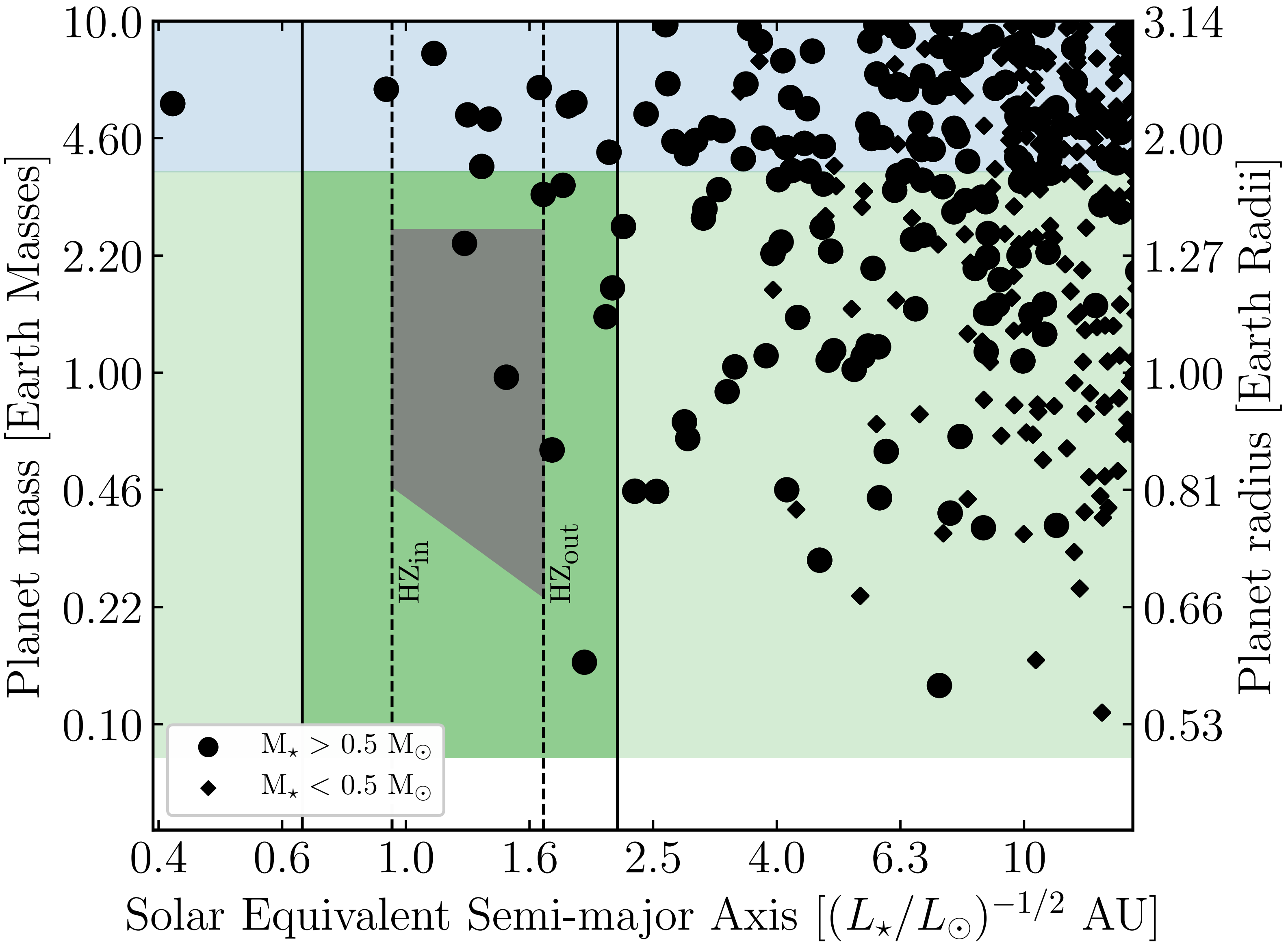
Johnson et al., in prep

Made with VBBL (Bozza+2020) and MulensModel (Poleski+2018)

ROMAN SPACE TELESCOPE



ROMAN SPACE TELESCOPE

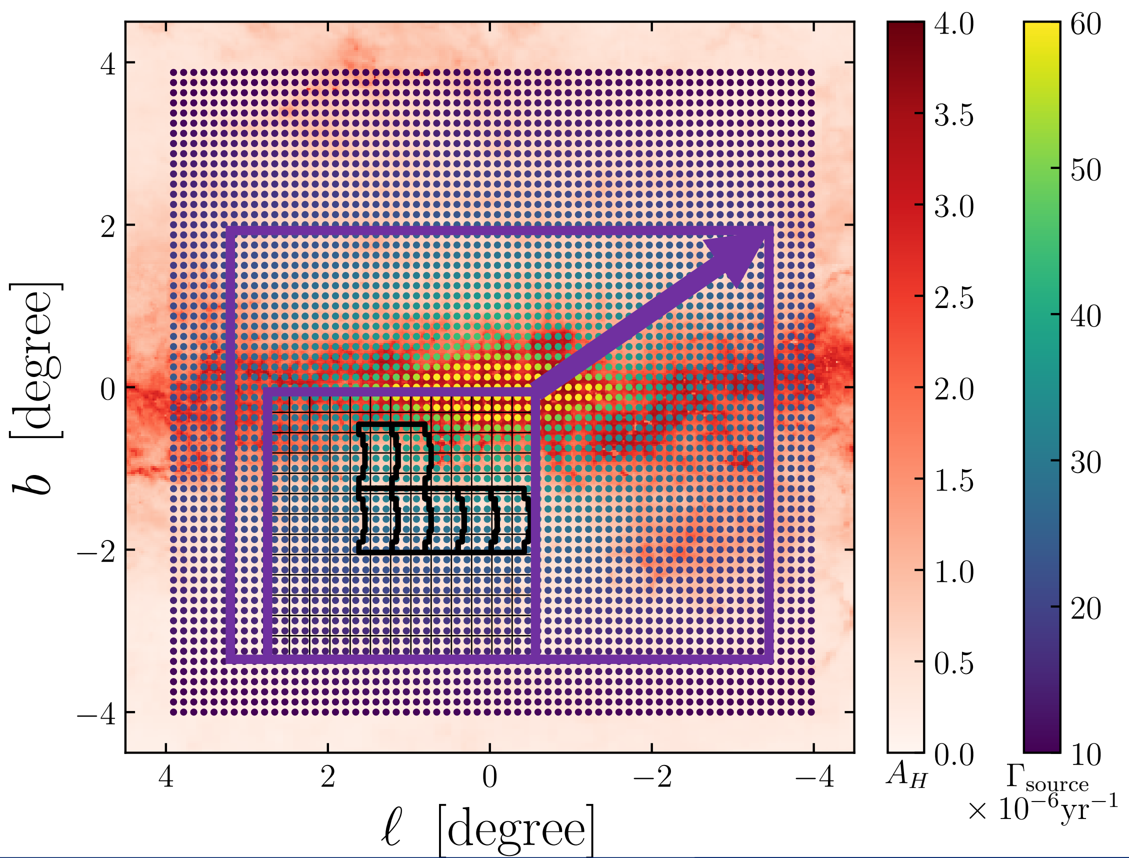


- *M-R relationship from Chen & Kipping (2016)*
- *See HabEx Final Report figure 3.3-9*
- *Modified Cassan et al. 2012 mass function*

Johnson et al., in prep

New Model – Koshimoto et al. 2021

- Increase simulation footprint and number of fields per square degree
- Investigate dependence of planet yield on primary filter cadence
- Fine tune the survey parameters for microlensing yield



Johnson et al., in prep

ROMAN SPACE TELESCOPE

More likely to measure mass of Earth-analog systems

Microlensing is sensitive to the mass ratio between the planet and the host star

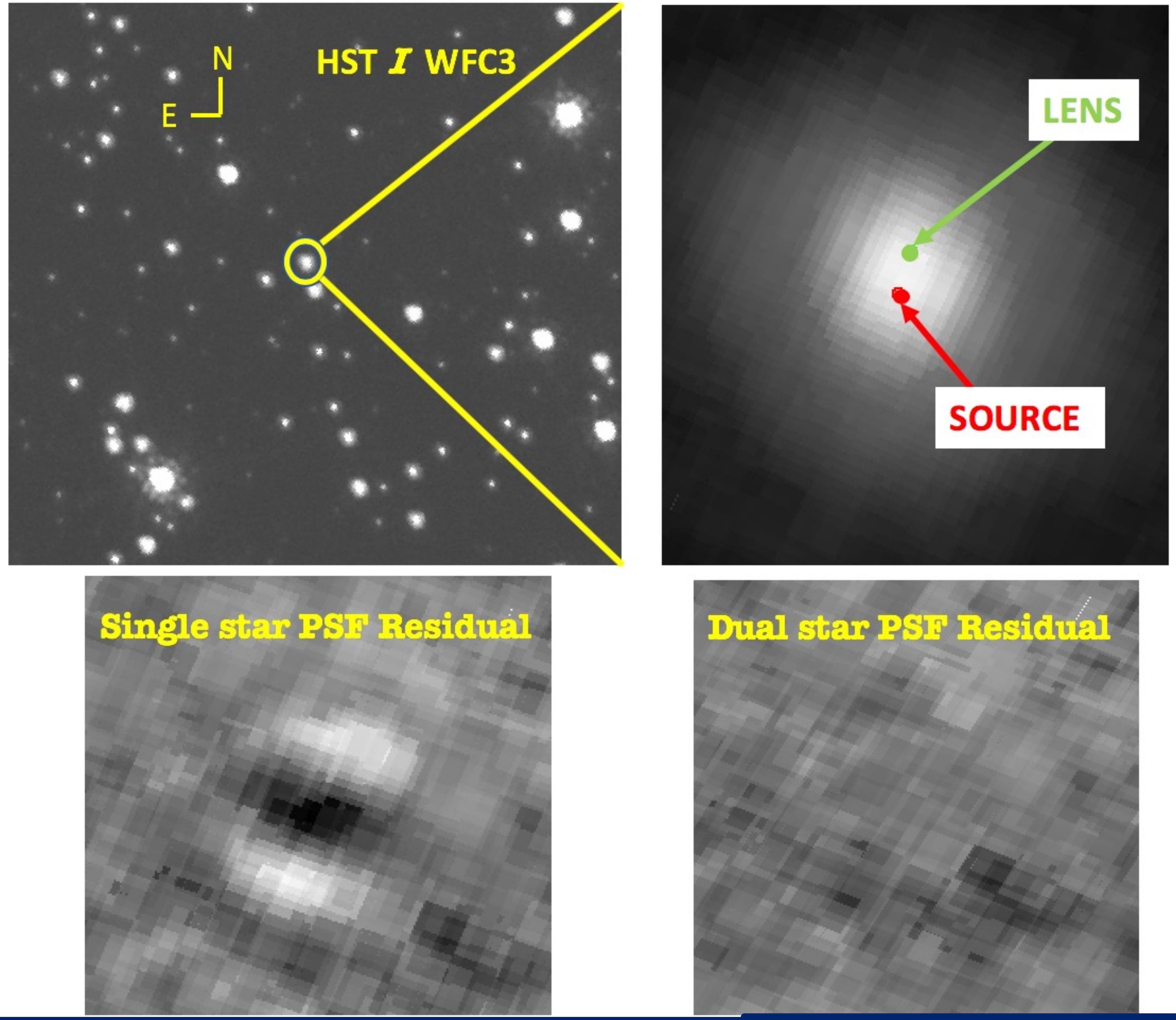
Model of the event

$$t_E = \frac{\theta_E}{\mu_{rel}}$$

$$\theta_E \propto \sqrt{M_*}$$

Use 4.5-year survey-baseline to measure lens-source separation (μ_{rel})

Planets with higher mass (brighter) host stars more likely to have μ_{rel} measured

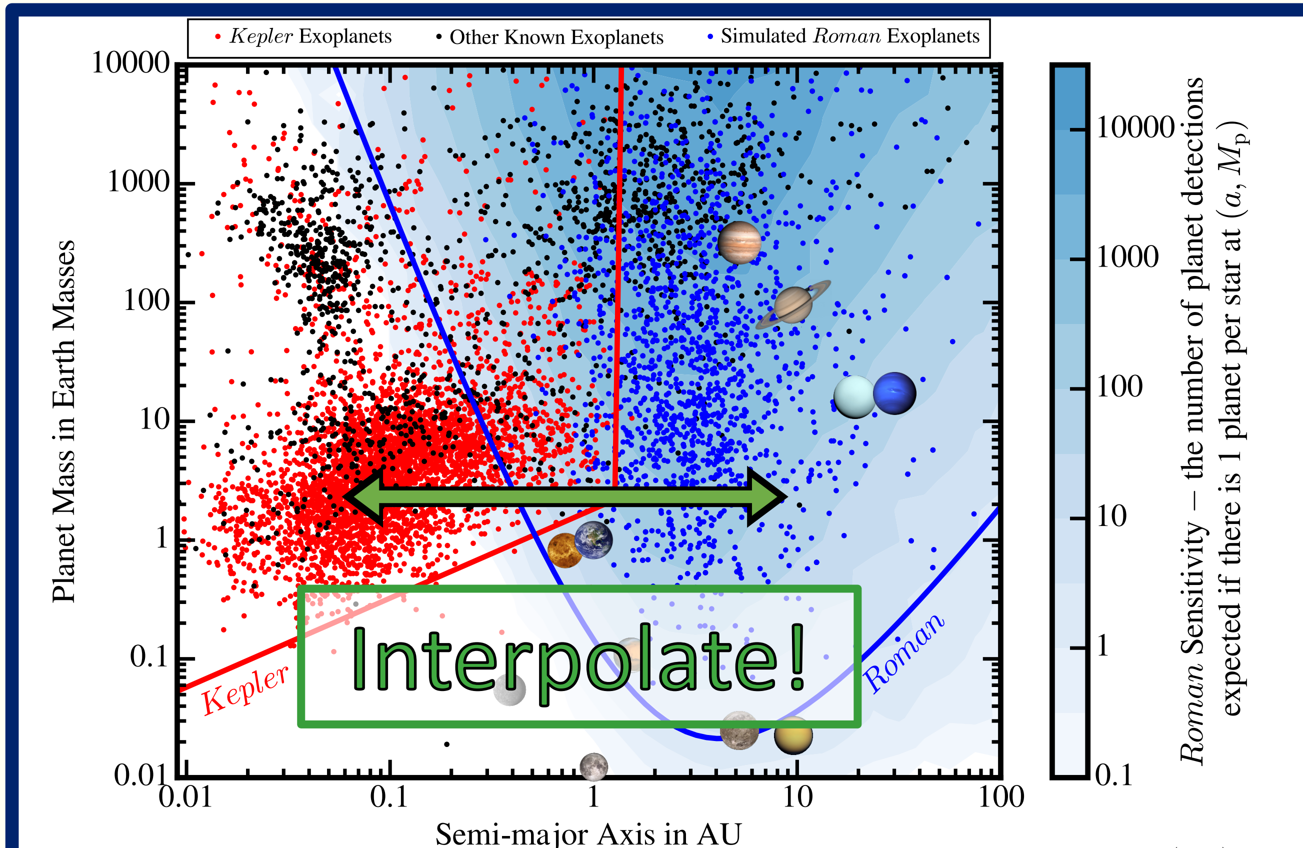


Bhattacharya et al., 2018

ROMAN SPACE TELESCOPE

Further prospects

- Combining *Roman* with *Kepler*
  - Interpolation, not extrapolation
    - Improve Earth-analog frequency estimate
    - System-wide exoplanet demographics
  - Crucial for predicting yields of future space-based direct imaging surveys
  - Complex combined sensitivity function
    - different host-star populations
    - different planet populations?
  - Mass-radius relationship vital

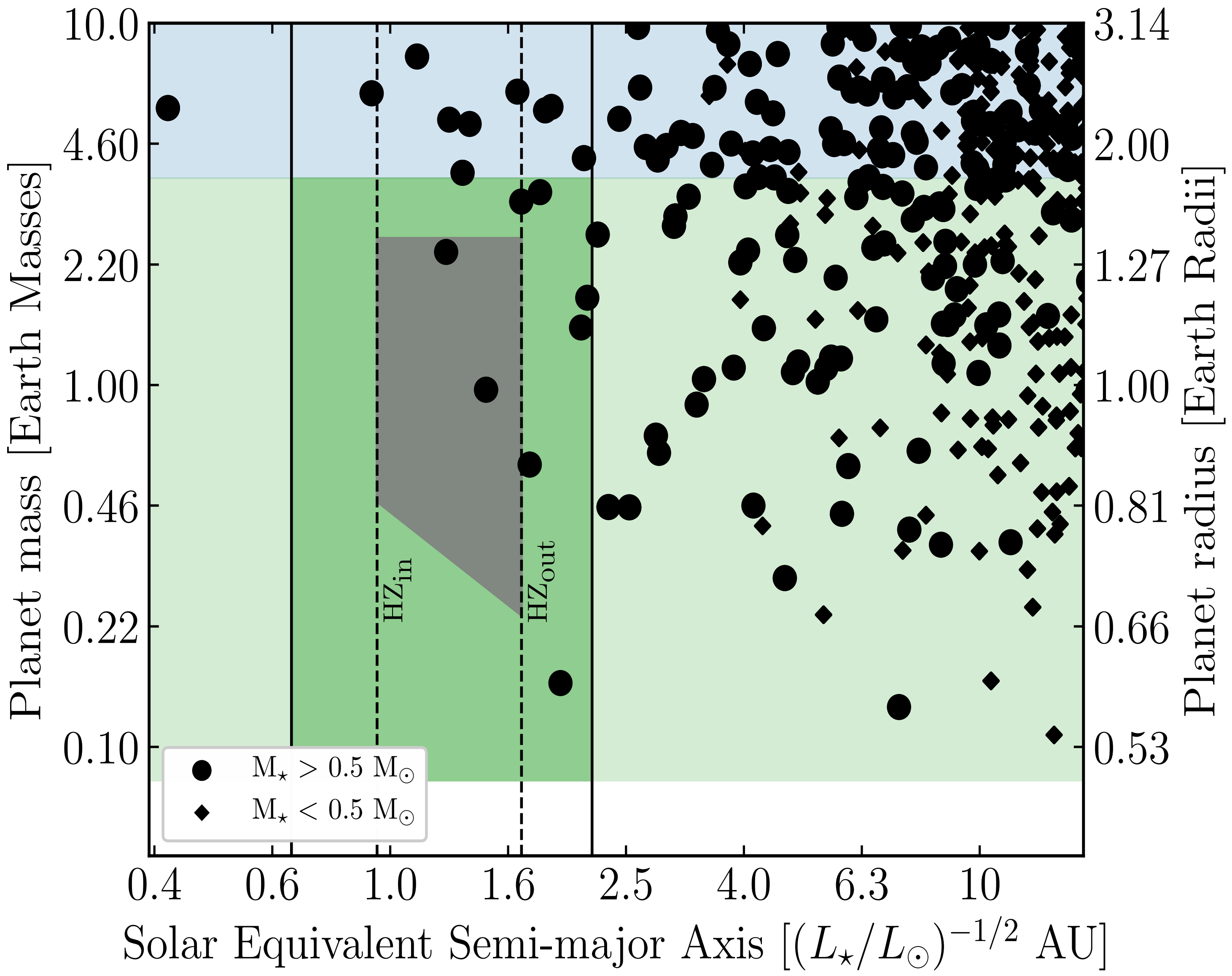


Credit: Penny et al. (2019)

ROMAN SPACE TELESCOPE

Thank you!

- *Roman* will constrain eta-Earth on its own and with *Kepler*
- Incorporating Koshimoto+2021 Galactic model to improve estimates
- Fine tuning the survey parameters for planet yield

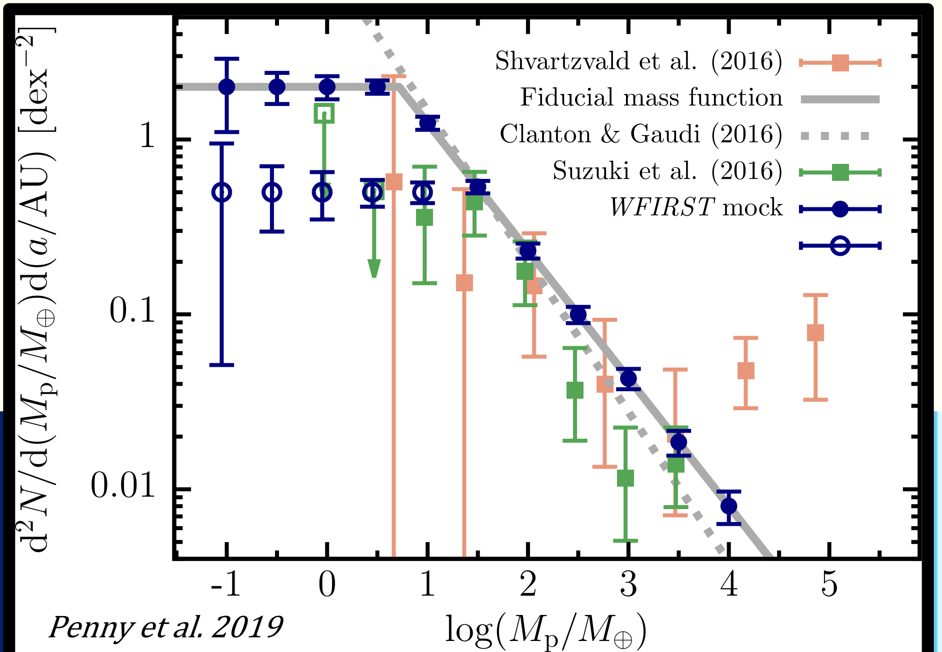


Johnson et al., in prep

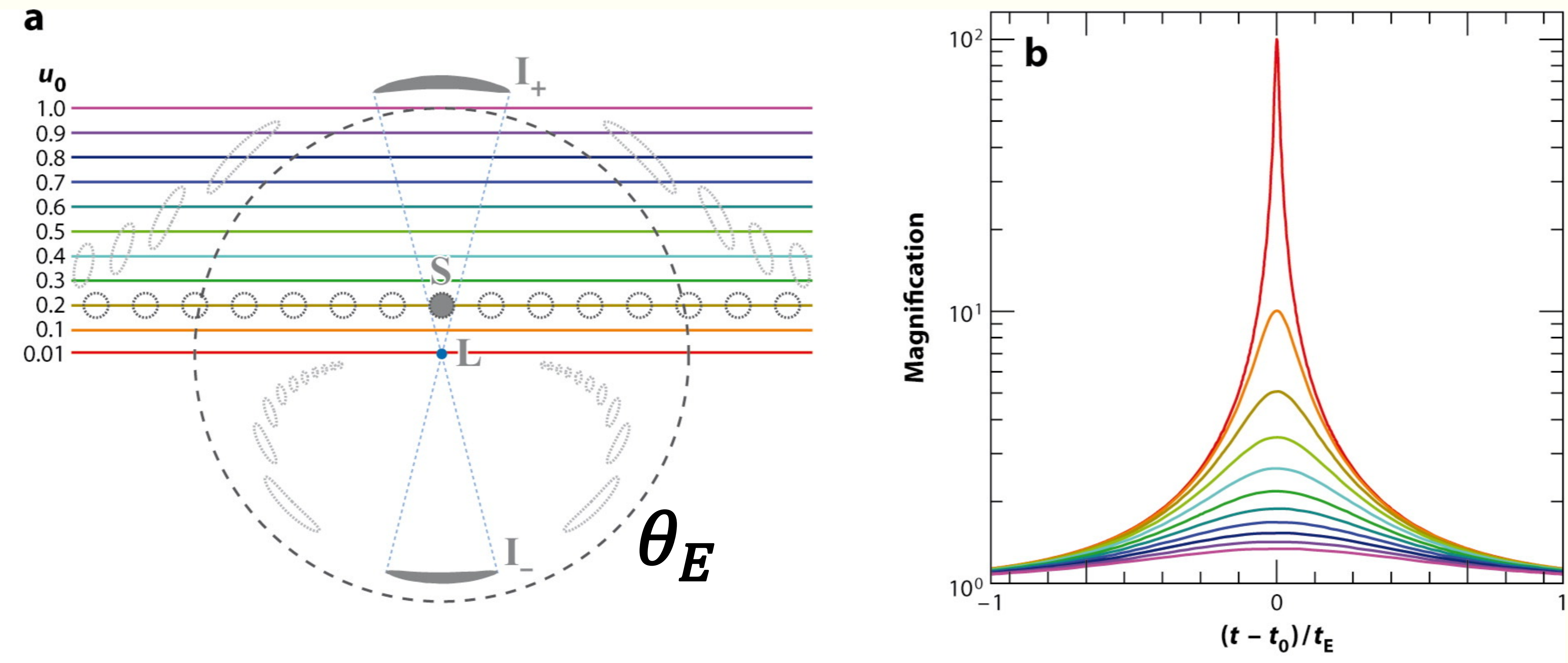
ROMAN SPACE TELESCOPE

Fiducial mass function adapted from *Cassan et al.* 2012

$$\frac{d^2N}{d\log m_p \, d\log a} = \begin{cases} \frac{0.24}{\text{dex}^2}\left(\frac{m_p}{95 M_\oplus}\right)^{-0.74} & \text{for} \quad M_p > 5\, M_\oplus \\ \frac{2}{\text{dex}^2} & \text{for} \quad M_p > 5\, M_\oplus \end{cases}$$



Penny et al. 2019



Gaudi BS. 2012.
Annu. Rev. Astron. Astrophys. 50:411–53

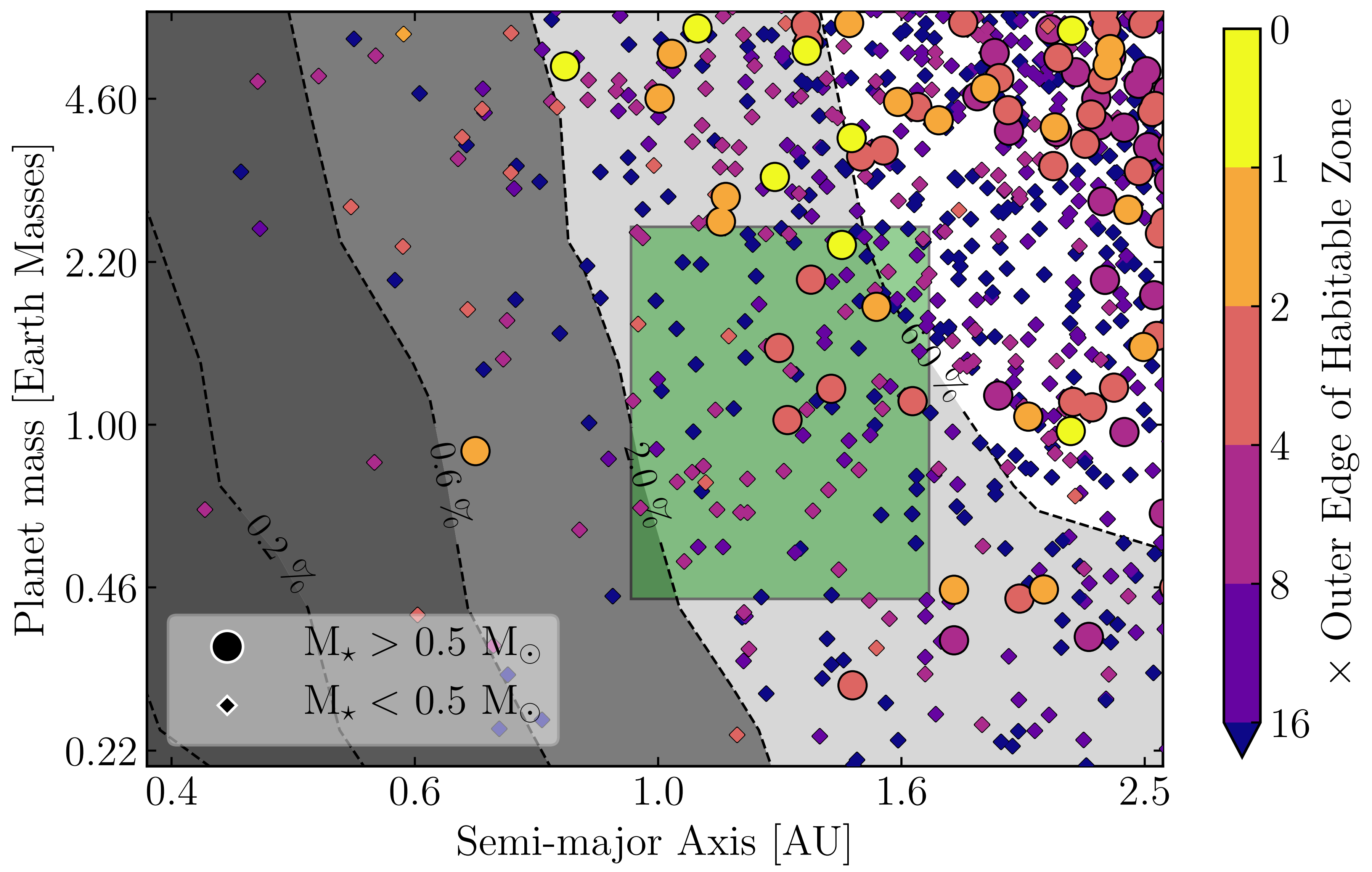
Scaling θ_E and t_E

$$\boldsymbol{\theta_E} \approx 700\mu as\left(\frac{M}{0.5M_\odot}\right)^{\frac{1}{2}} \approx \mathbf{30}\boldsymbol{\mu as}\left(\frac{M}{\boldsymbol{M_J}}\right)^{\frac{1}{2}} \approx \mathbf{2}\boldsymbol{\mu as}\left(\frac{M}{\boldsymbol{M_\oplus}}\right)^{1/2}$$

$$\boldsymbol{t_E} \approx 25days\left(\frac{M}{0.5M_\odot}\right)^{\frac{1}{2}} \approx \mathbf{1}\boldsymbol{day}\left(\frac{M}{\boldsymbol{M_J}}\right)^{\frac{1}{2}} \approx \mathbf{1.5}\boldsymbol{hours}\left(\frac{M}{\boldsymbol{M_\oplus}}\right)^{1/2}$$

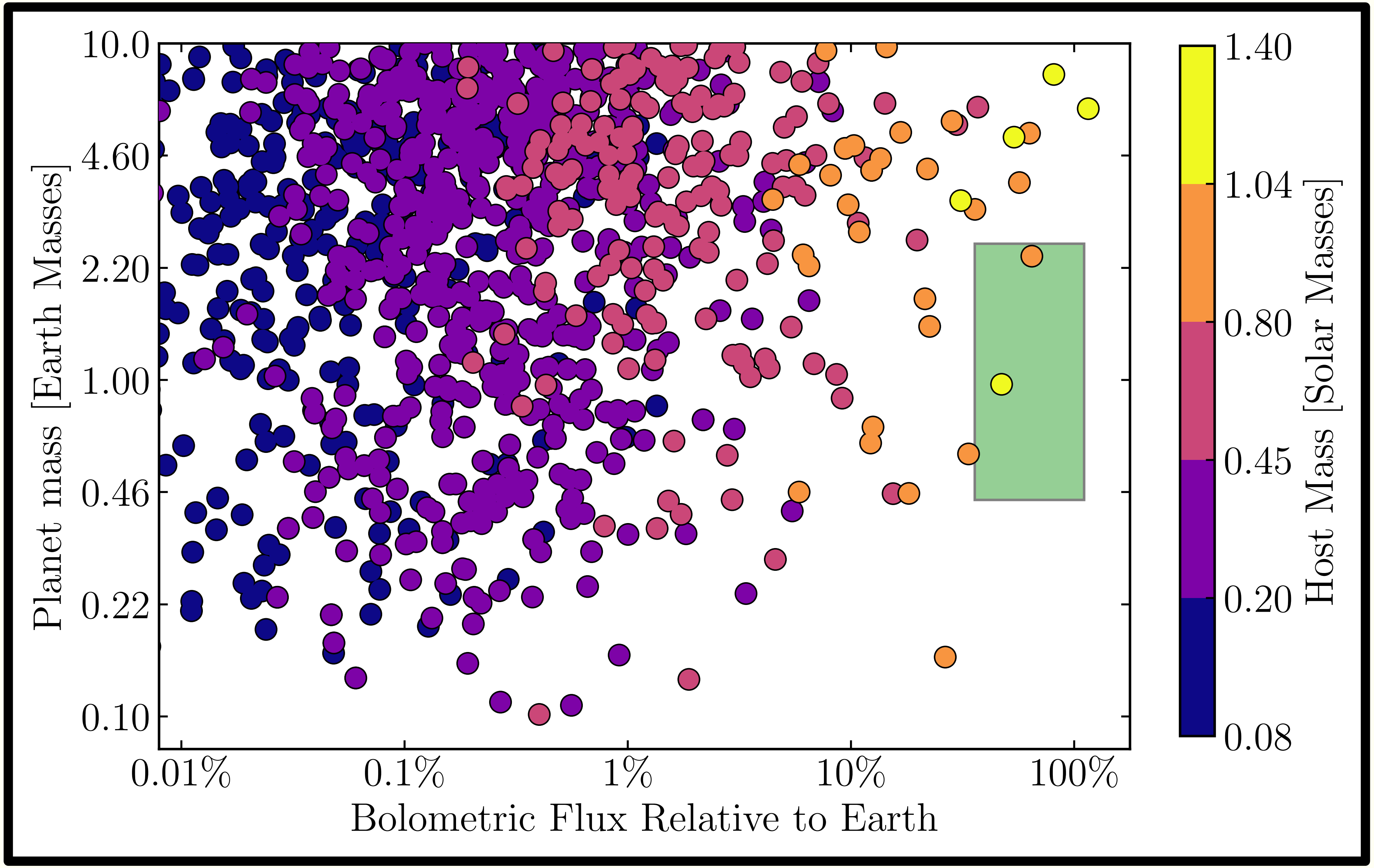
Mission design changes

	IDRM	DRM1	DRM2	AFTA	***WFIRST* Cycle 7**
Reference	Green et al. (2011)	Green et al. (2012)	Green et al. (2012)	Spergel et al. (2015)	—[1,2]
Mirror diameter (m)	1.3	1.3	1.1	2.36	**2.36**
Obscured fraction (area, %)	0	0	0	13.9	**13.9**
Detectors	7×4 H2RG-10	9×4 H2RG-10	7×2 H4RG-10	6×3 H4RG-10	**6×3 H4RG-10**
Plate scale ("/pix)	0.18	0.18	0.18	0.11	**0.11**
Field of view (deg^2)	0.294	0.377	0.587	0.282	**0.282**
Fields	7	7	6	10	**7**
Survey area (deg^s)	2.06	2.64	3.52	2.82	**1.97**
Avg. slew and settle Time (s)	38	38	38	38	**83.1**
Orbit	L2	L2	L2	Geosynchronous	L2
Total Survey length (d)	432	432	266	411**	**432**
Season length (d)	72	72	72	72	**72**
Seasons	6	6	3.7	6	**6**
Baseline mission duration (yr)	5	5	3	6	**5**
Primary bandpass (μm)	1.0–2.0 (W149)	1.0–2.4 (W169)	1.0–2.4 (W169)	0.93–2.00 (W149)	**0.93–2.00 (W149)**
Secondary bandpass (μm)	0.74–1.0 (Z087)	0.74–1.0 (Z087)	0.74–1.0 (Z087)	0.76–0.98 (Z087)	**0.76–0.98 (Z087)**



Johnson et al., in prep

ROMAN SPACE TELESCOPE

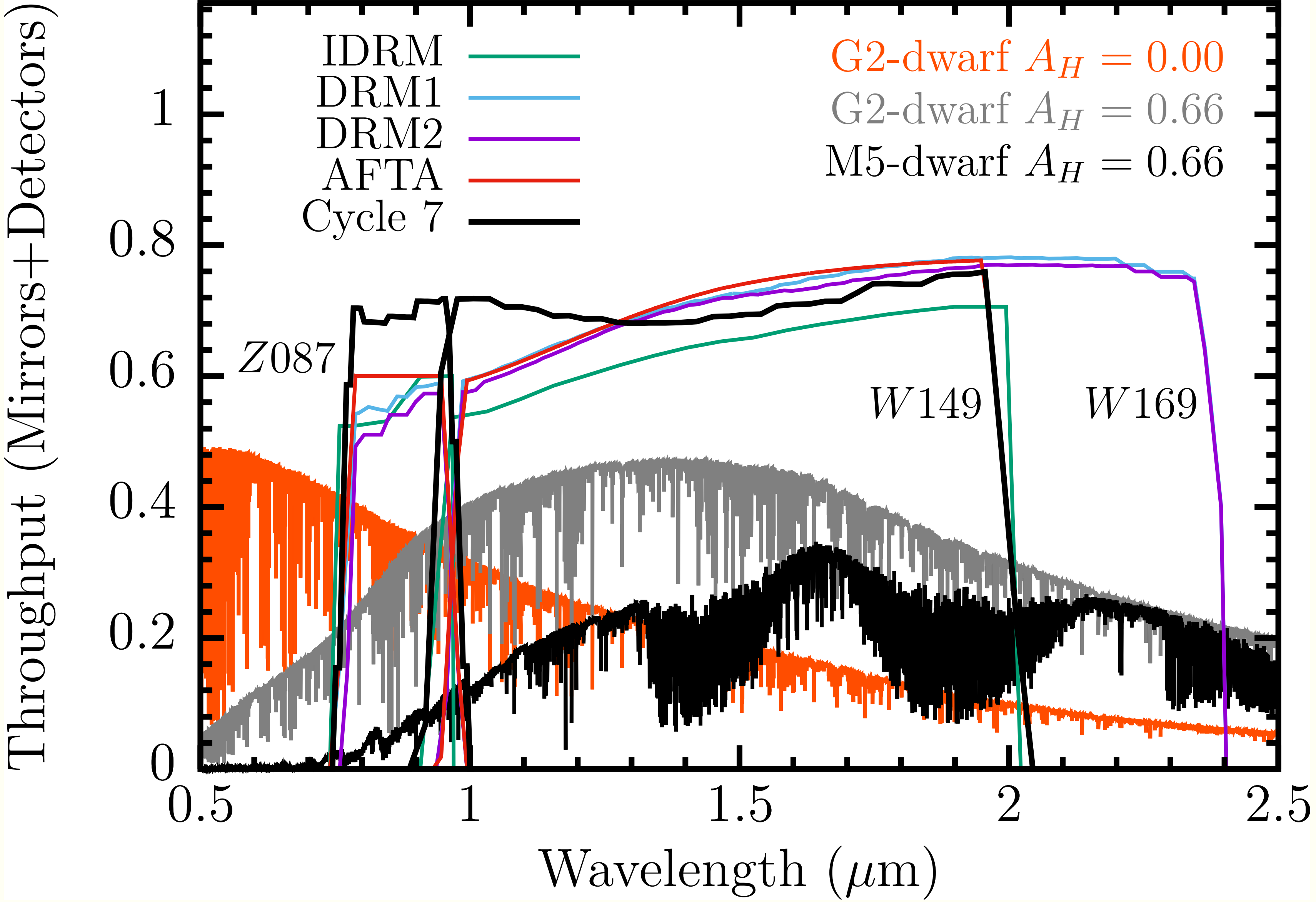


ROMAN
SPACE TELESCOPE

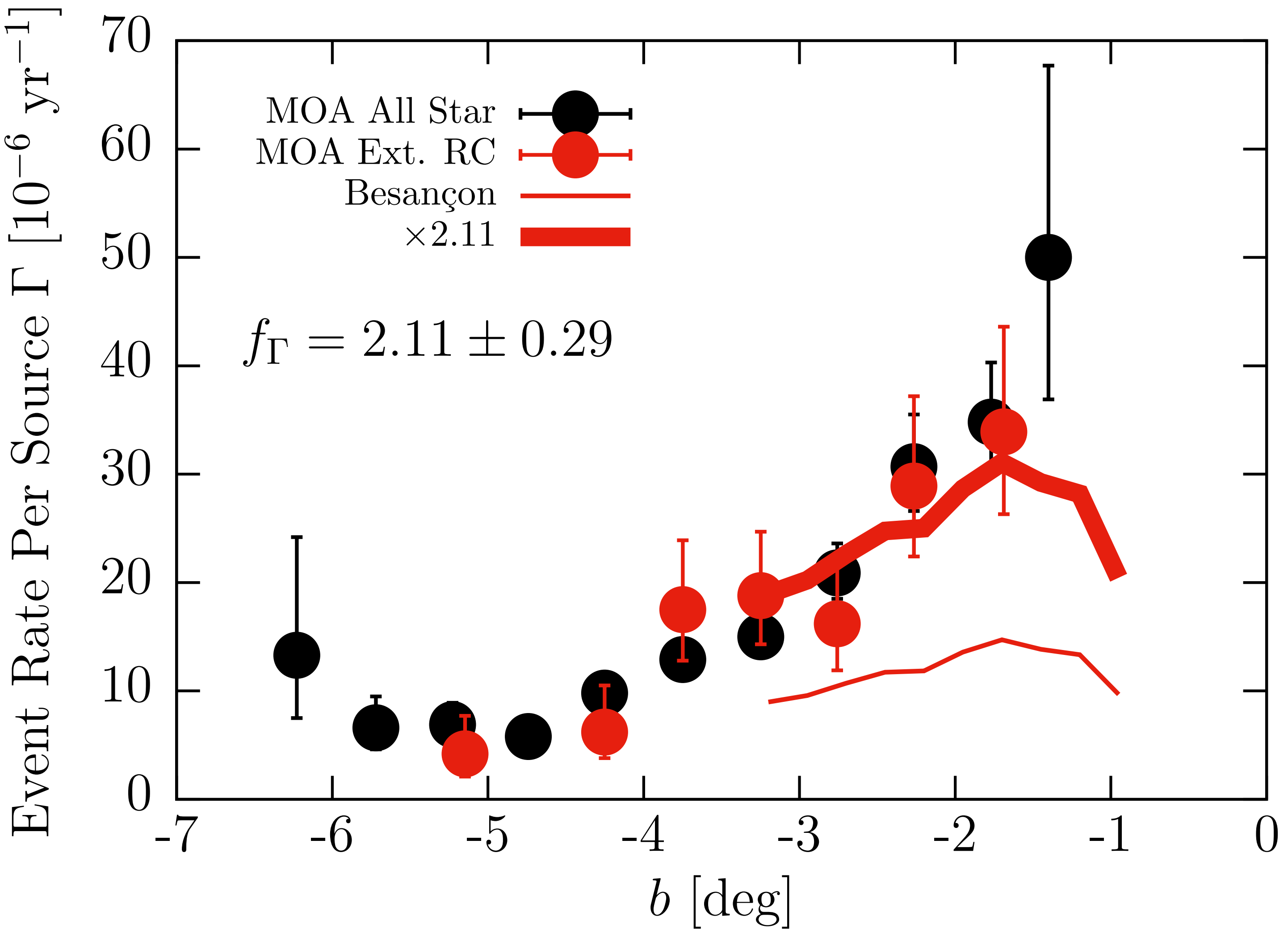
Event rate weighting

$$w_i = 0.25\,\mathrm{deg}^2\, f_{1106WFIRST}\Gamma_{\mathrm{deg}^2}T_{sim}u_{0,max}\;\frac{2\mu_{rel,i}\theta_{E,i}}{W}$$

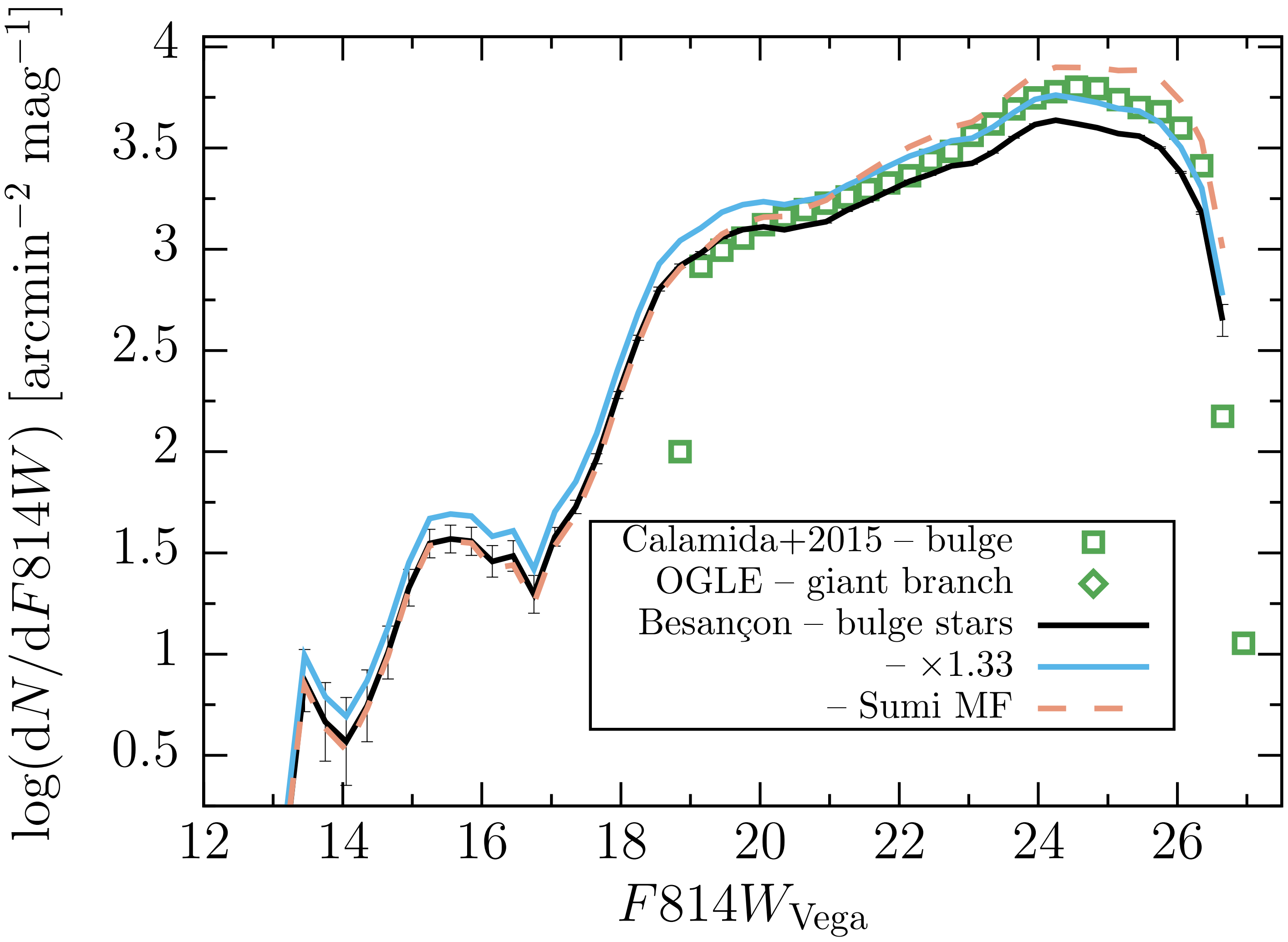
$$W = \sum_i 2\mu_{rel,i}\theta_{E,i}$$



Throughput (Mirrors+Detectors)
Wavelength (μm)
IDRM
DRM1
DRM2
AFTA
Cycle 7
G2-dwarf $A_H = 0.00$
G2-dwarf $A_H = 0.66$
M5-dwarf $A_H = 0.66$
Z087
W149
W169



ROMAN SPACE TELESCOPE



ROMAN SPACE TELESCOPE