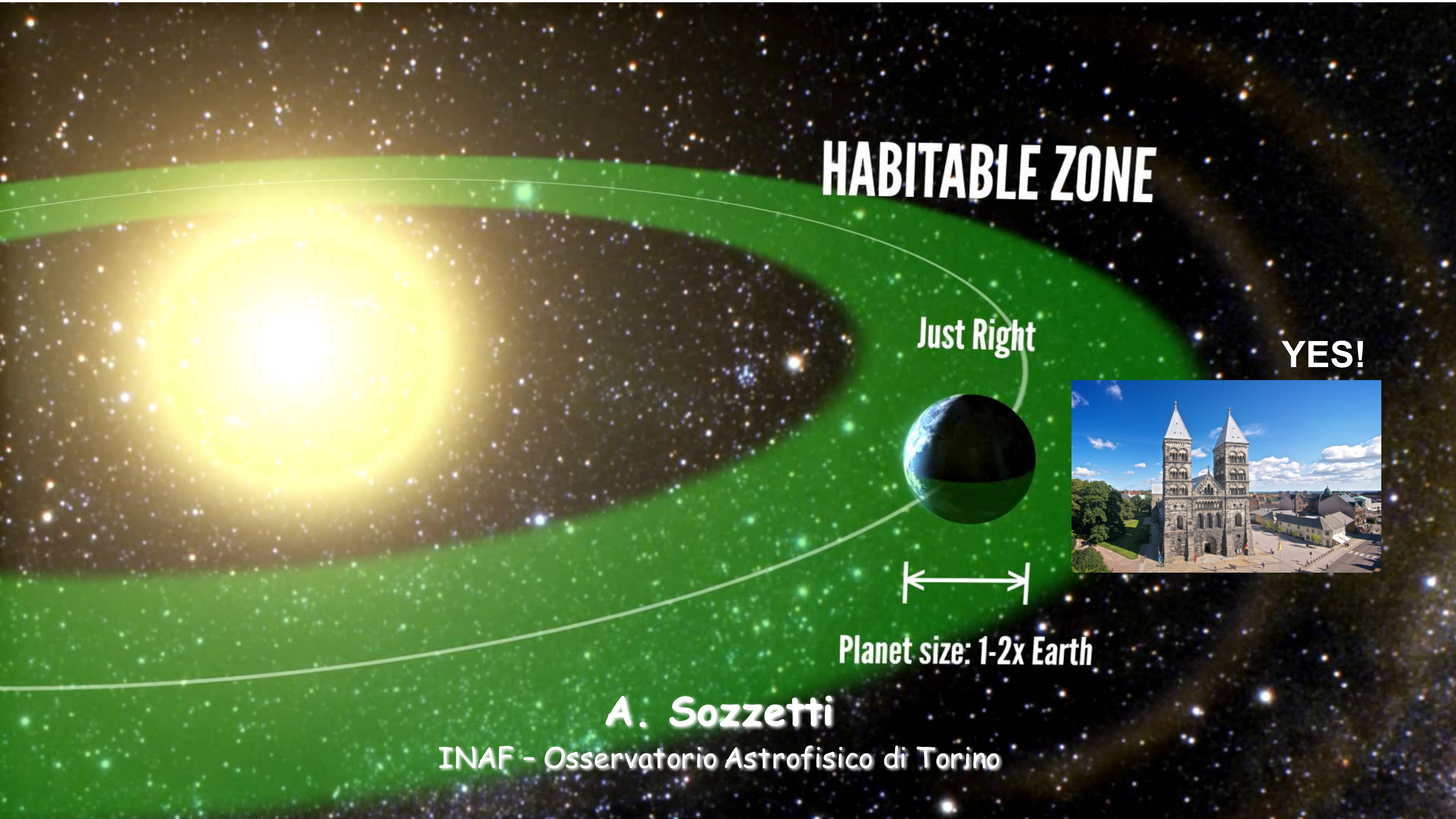
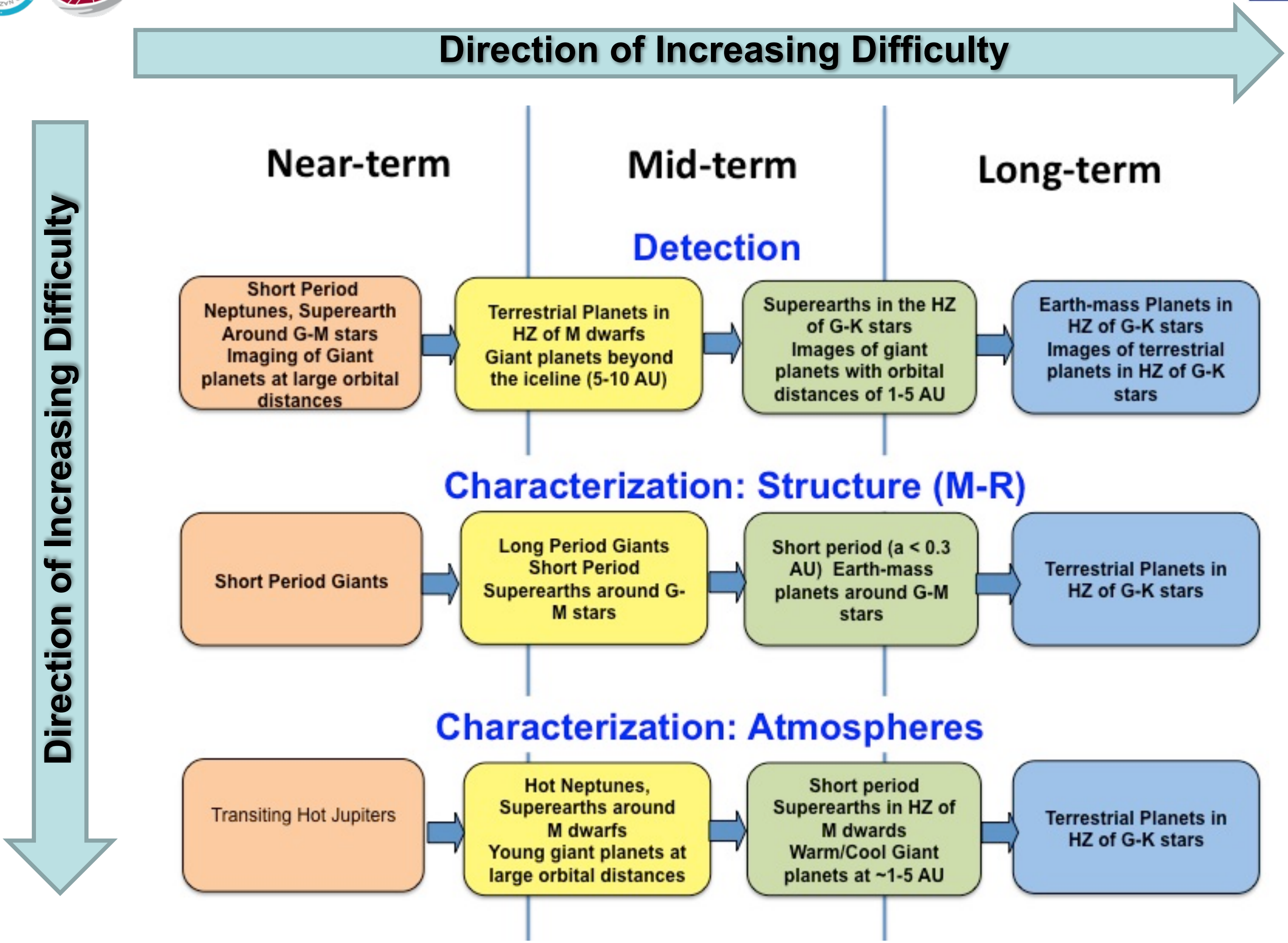
Exoplanetary Science in the Gaia Era



A. Sozzetti

INAF – Osservatorio Astrofisico di Torino



Direction of Increasing Difficulty

Direction of Increasing Difficulty

Near-term

Mid-term

Long-term

Detection

Short Period Neptunes, Superearth Around G-M stars
Imaging of Giant planets at large orbital distances

Terrestrial Planets in HZ of M dwarfs
Giant planets beyond the iceline (5-10 AU)

Superearths in the HZ of G-K stars
Images of giant planets with orbital distances of 1-5 AU

Earth-mass Planets in HZ of G-K stars
Images of terrestrial planets in HZ of G-K stars

Characterization: Structure (M-R)

Short Period Giants

Long Period Giants
Short Period Superearths around G-M stars

Short period (a < 0.3 AU) Earth-mass planets around G-M stars

Terrestrial Planets in HZ of G-K stars

Characterization: Atmospheres

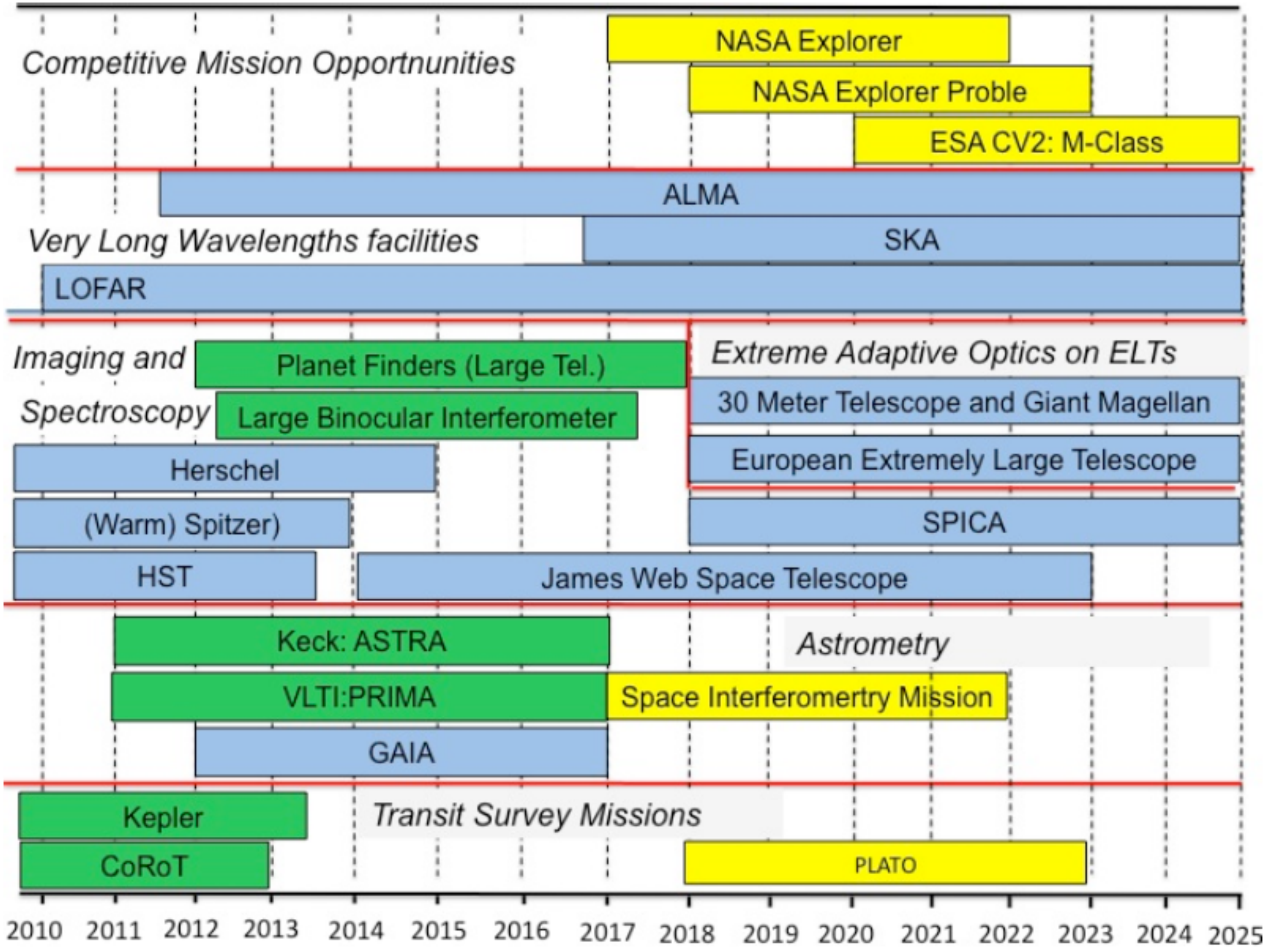
Transiting Hot Jupiters

Hot Neptunes, Superearths around M dwarfs
Young giant planets at large orbital distances

Short period Superearths in HZ of M dwards
Warm/Cool Giant planets at ~1-5 AU

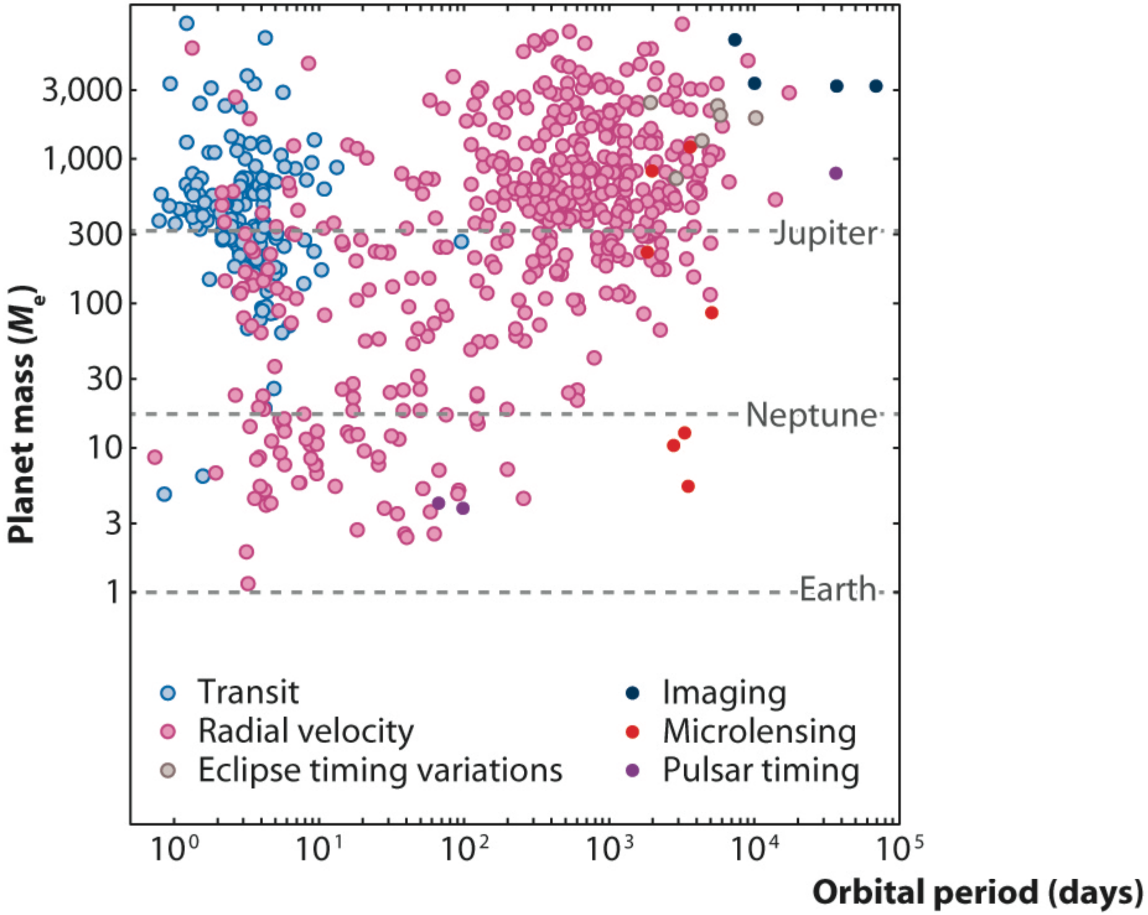
Terrestrial Planets in HZ of G-K stars

EP-RAT Report: http://sci.esa.int/eprat



EP-RAT Report: http://sci.esa.int/eprat

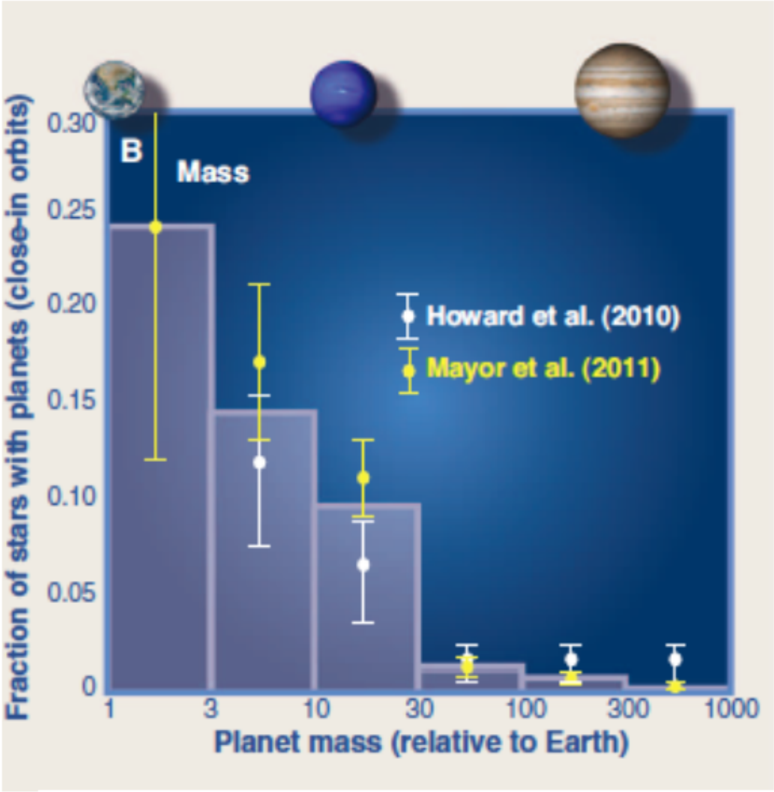
22 Years of Exoplanets

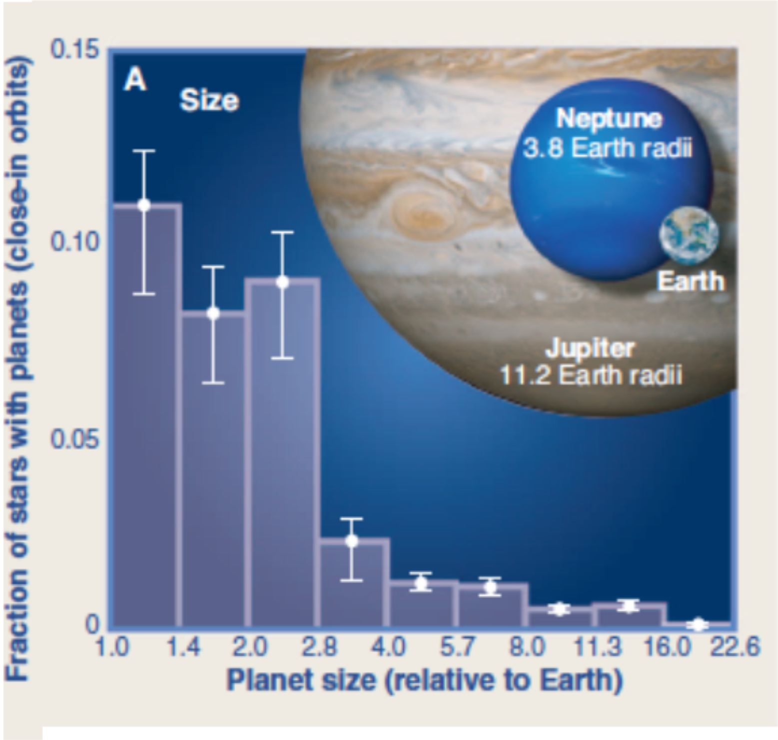


Frequencies: Kepler vs. RVs

Size & mass distributions of planets orbiting G- and K-type stars.

corrected for survey incompleteness for small/low-mass planets

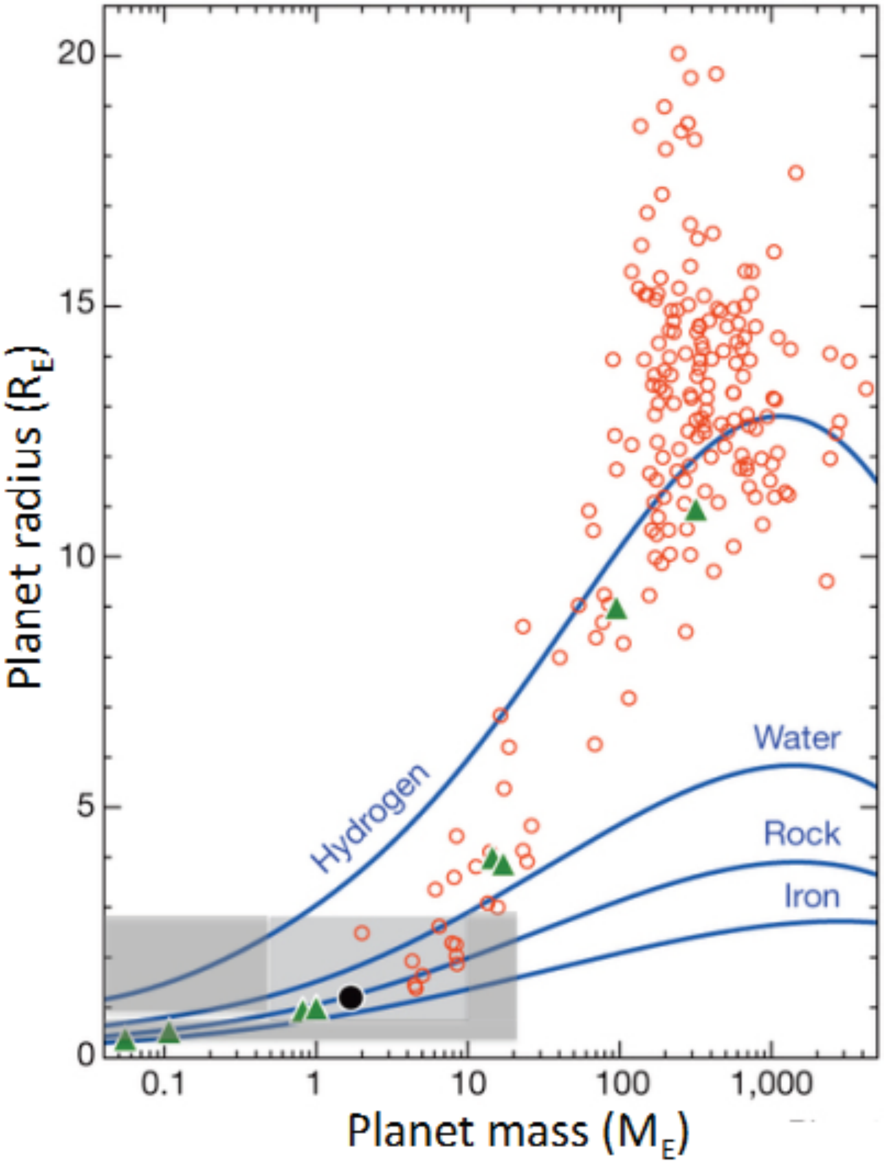




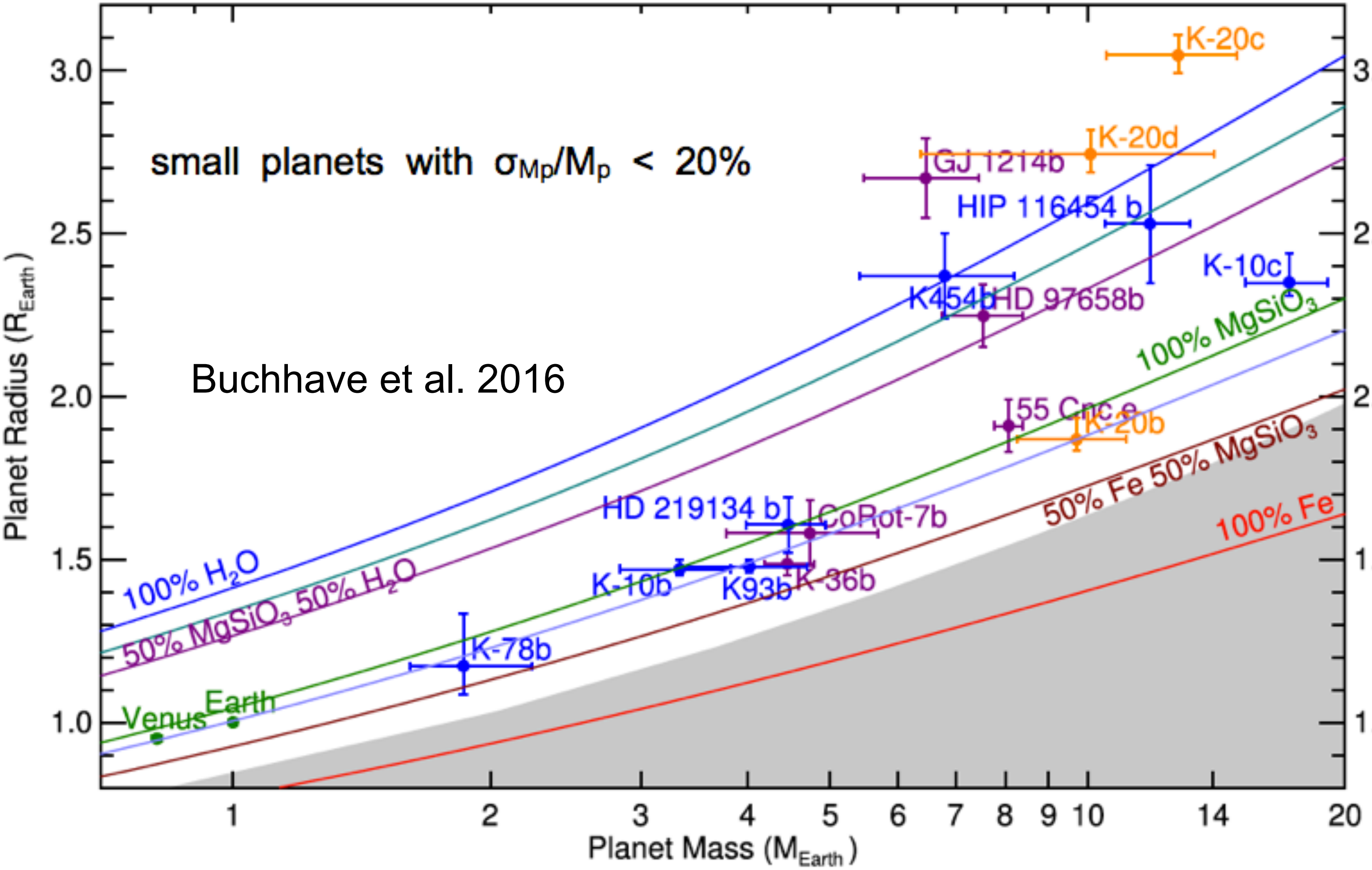
Howard, 2013, Science 340, 572

The Mass-Radius Relation

Howard et al. 2013



Composition of Small Planets



small planets with $\sigma_{Mp}/M_p < 20\%$

Buchhave et al. 2016

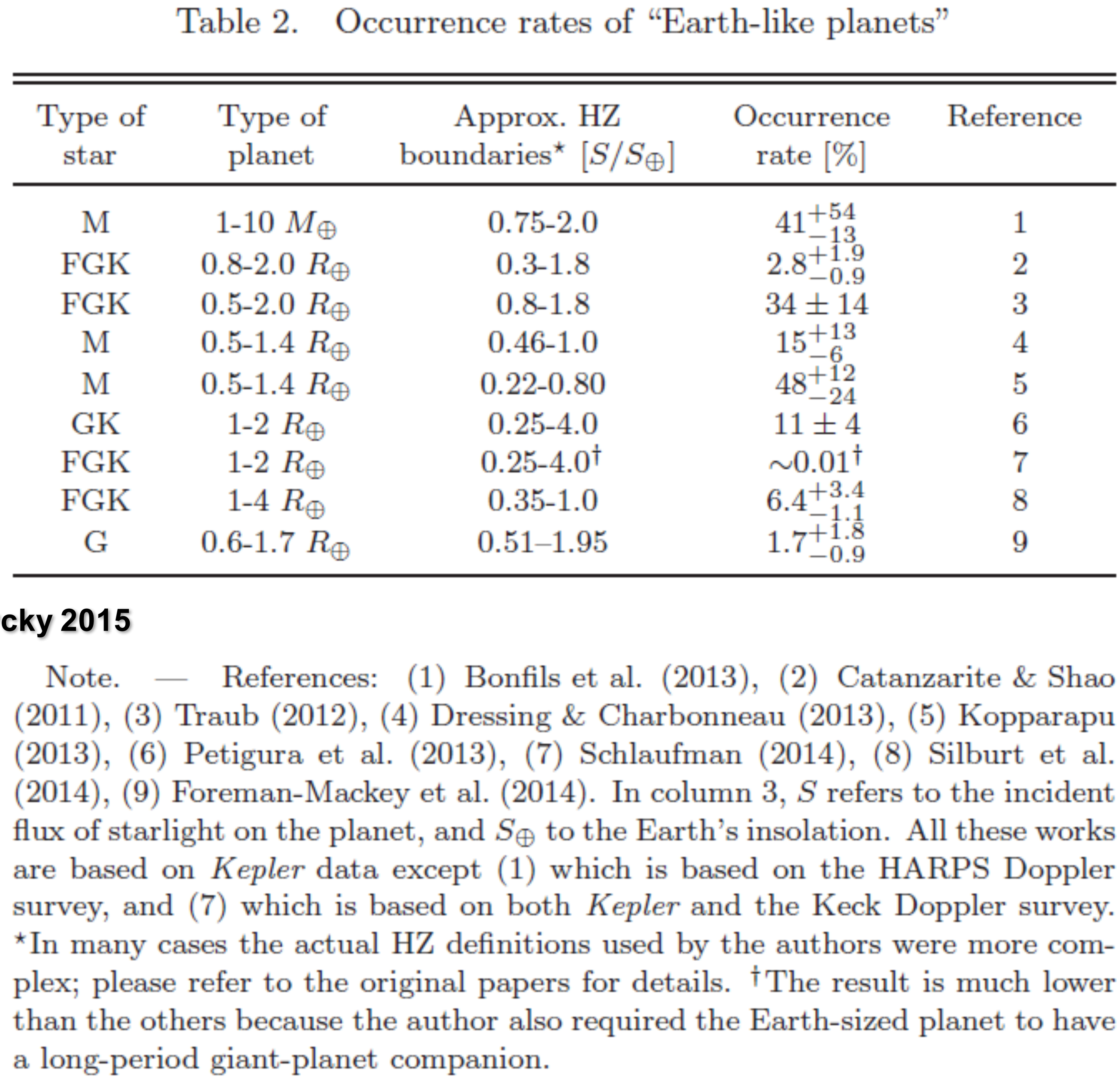


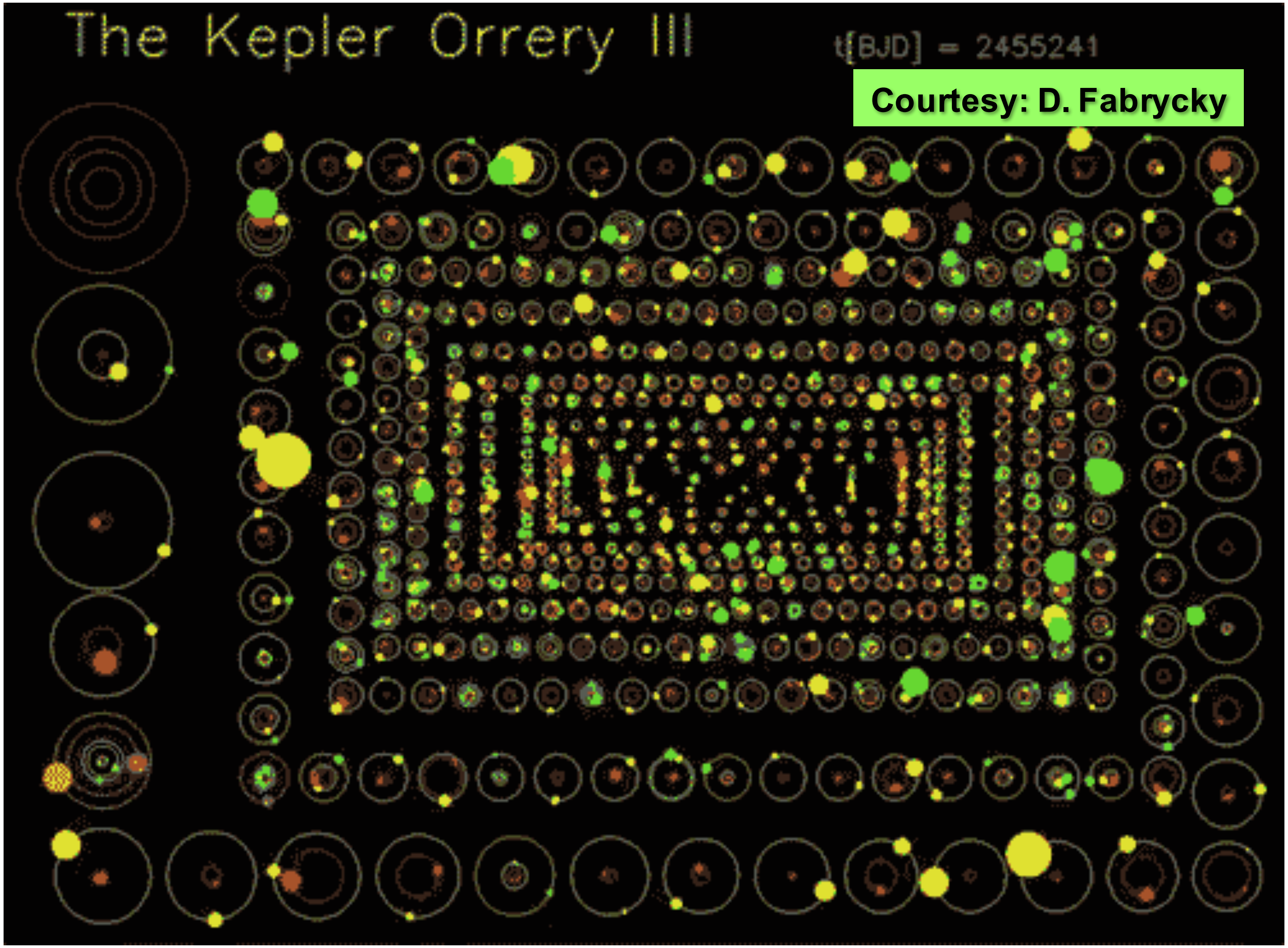
Table 2. Occurrence rates of "Earth-like planets"

Type of star	Type of planet	Approx. HZ boundaries* $[S/S_\oplus]$	Occurrence rate [%]	Reference
M	1-10 $M_\oplus$	0.75-2.0	41^{+54}_{-13}	1
FGK	0.8-2.0 $R_\oplus$	0.3-1.8	$2.8^{+1.9}_{-0.9}$	2
FGK	0.5-2.0 $R_\oplus$	0.8-1.8	34 ± 14	3
M	0.5-1.4 $R_\oplus$	0.46-1.0	15^{+13}_{-6}	4
M	0.5-1.4 $R_\oplus$	0.22-0.80	48^{+12}_{-24}	5
GK	1-2 $R_\oplus$	0.25-4.0	11 ± 4	6
FGK	1-2 $R_\oplus$	0.25-4.0†	$\sim 0.01^\dagger$	7
FGK	1-4 $R_\oplus$	0.35-1.0	$6.4^{+3.4}_{-1.1}$	8
G	0.6-1.7 $R_\oplus$	0.51–1.95	$1.7^{+1.8}_{-0.9}$	9

Winn & Fabrycky 2015

Note. — References: (1) Bonfils et al. (2013), (2) Catanzarite & Shao (2011), (3) Traub (2012), (4) Dressing & Charbonneau (2013), (5) Kopparapu (2013), (6) Petigura et al. (2013), (7) Schlaufman (2014), (8) Silburt et al. (2014), (9) Foreman-Mackey et al. (2014). In column 3, S refers to the incident flux of starlight on the planet, and $S_\oplus$ to the Earth's insolation. All these works are based on *Kepler* data except (1) which is based on the HARPS Doppler survey, and (7) which is based on both *Kepler* and the Keck Doppler survey. *In many cases the actual HZ definitions used by the authors were more complex; please refer to the original papers for details. †The result is much lower than the others because the author also required the Earth-sized planet to have a long-period giant-planet companion.

Transiting Multiple Systems

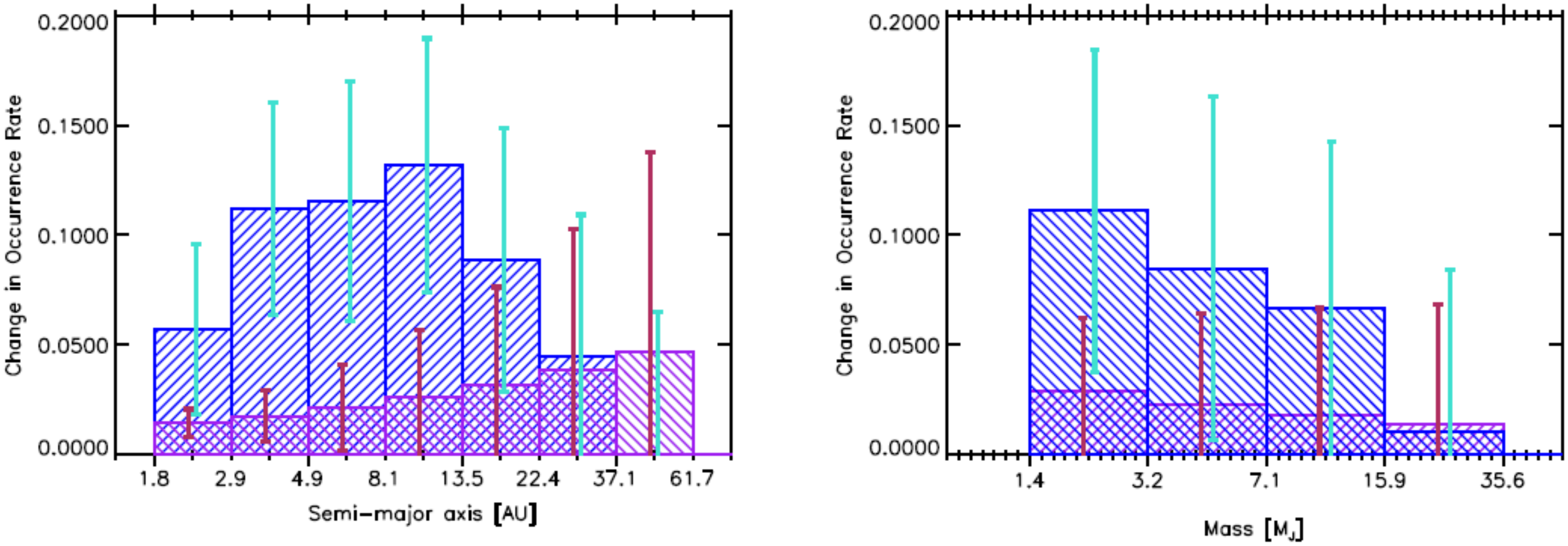


Courtesy: D. Fabrycky

100s' of 'flat' systems, the vast majority with small radii. Most are real!

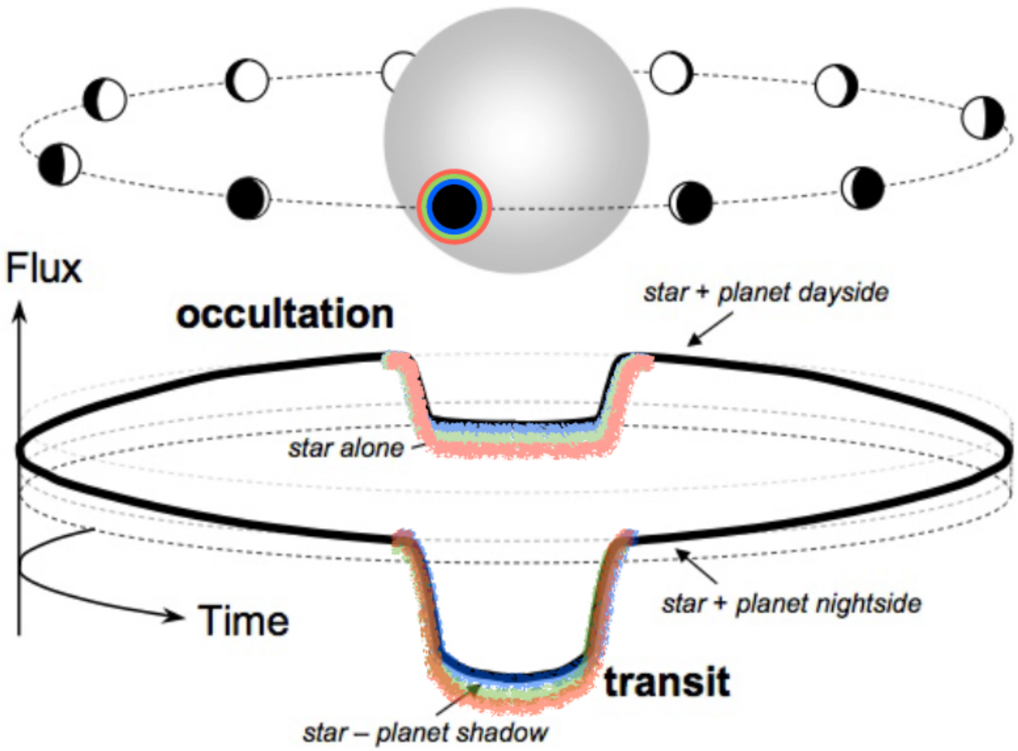
Multiple Systems from RV+HCI

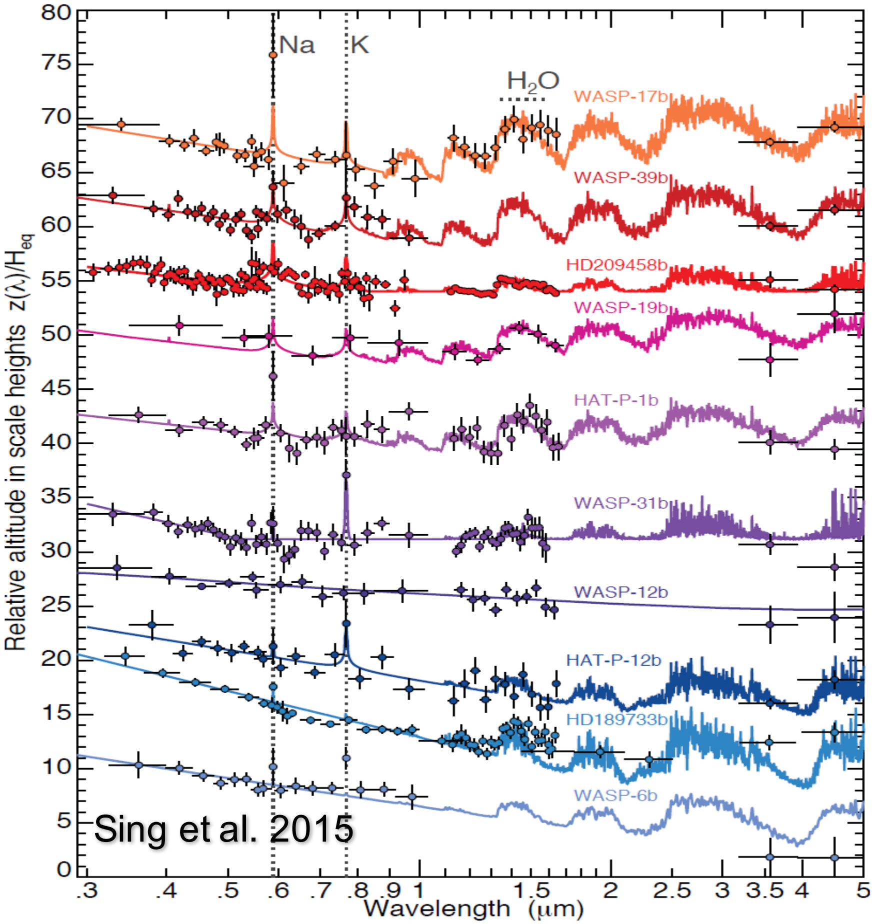
Bryan et al. 2016



>50% of 1-GP systems has additional massive companions

Exoplanet Atmospheres





Sing et al. 2015

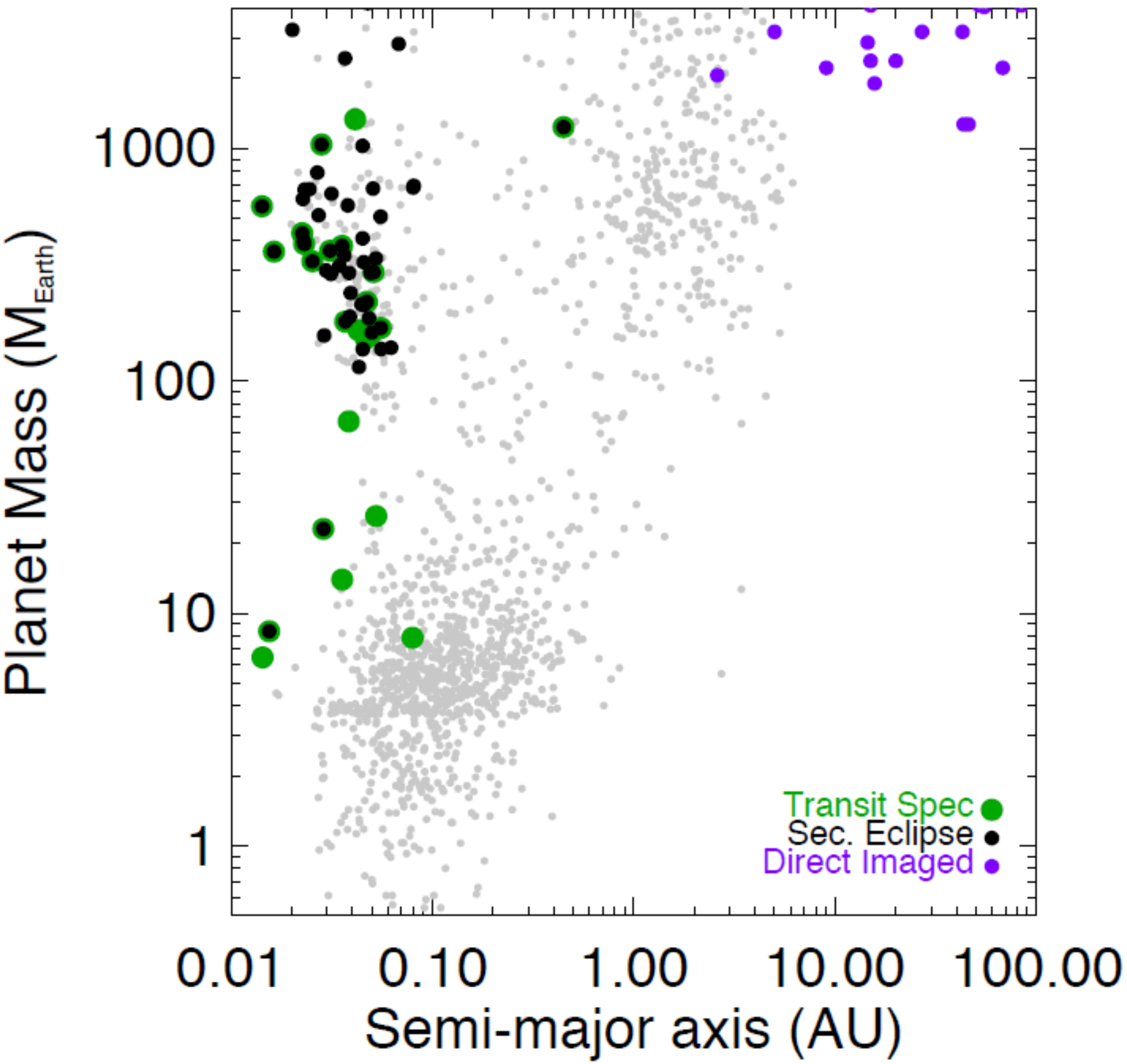
USE:

* multi-band differential photometry (broad or narrow band), imaging
* high-res spectroscopy, multi-object spectroscopy, low-res spectroscopy

GET:

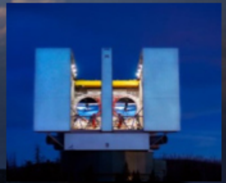
* Albedo, T-p profile, molecular chemistry (dayside)
* Upper atmosphere (clouds, hazes), chemistry, dynamics (nightside)

Characterized Exoplanets



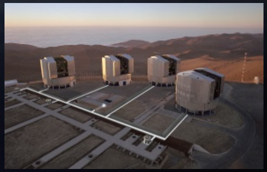
Exoplanet Missions

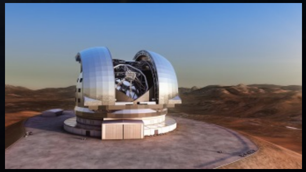

W. M. Keck Observatory


Large Binocular Telescope Interferometer


NN-EXPLORE

\+


VLT


(E-)ELTs

Ground Telescopes with NASA participation

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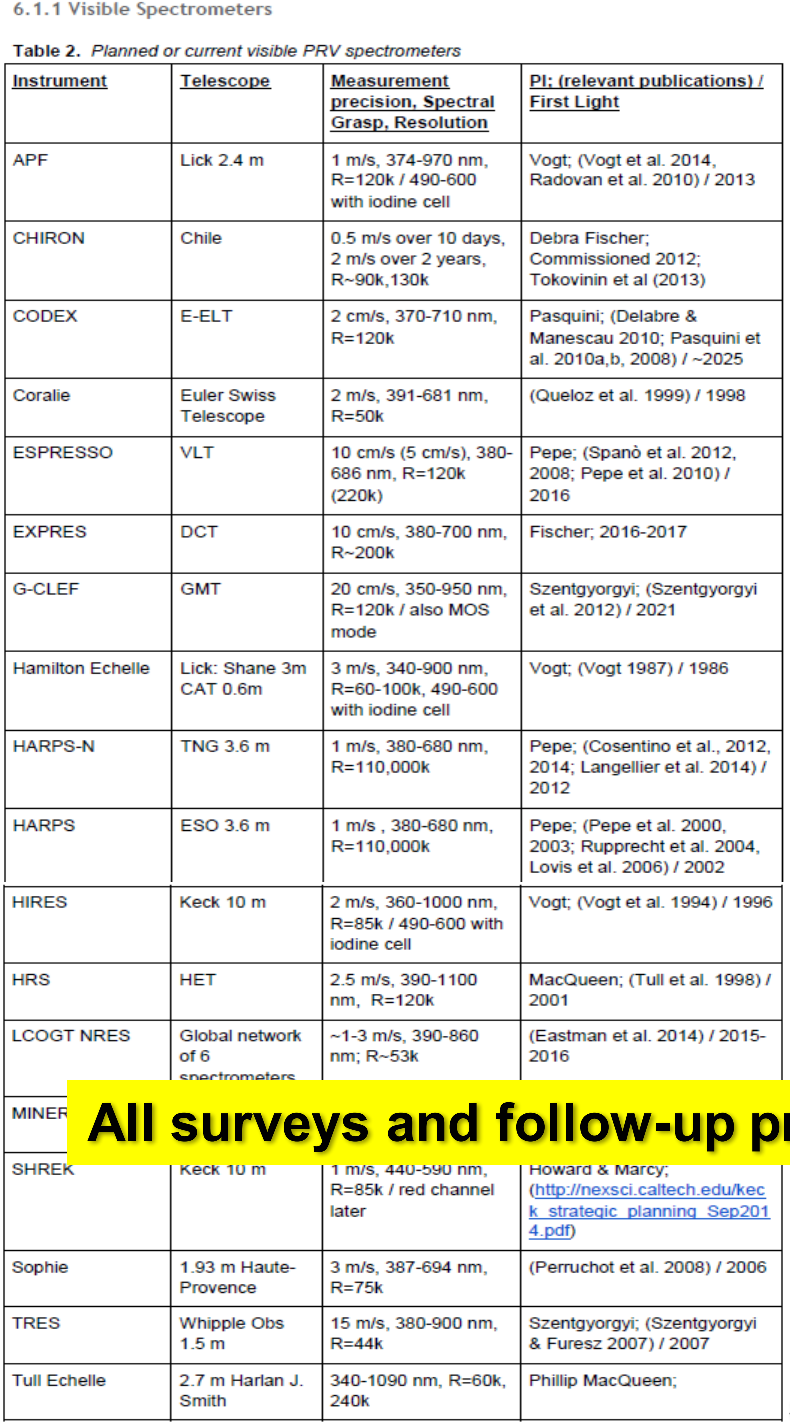
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA



6.1.1 Visible Spectrometers

Table 2. *Planned or current visible PRV spectrometers*

Instrument	Telescope	Measurement precision, Spectral Grasp, Resolution	PI; (relevant publications) / First Light
APF	Lick 2.4 m	1 m/s, 374-970 nm, R=120k / 490-600 with iodine cell	Vogt; (Vogt et al. 2014, Radovan et al. 2010) / 2013
CHIRON	Chile	0.5 m/s over 10 days, 2 m/s over 2 years, R~90k,130k	Debra Fischer; Commissioned 2012; Tokovinin et al (2013)
CODEX	E-ELT	2 cm/s, 370-710 nm, R=120k	Pasquini; (Delabre & Manescau 2010; Pasquini et al. 2010a,b, 2008) / ~2025
Coralie	Euler Swiss Telescope	2 m/s, 391-681 nm, R=50k	(Queloz et al. 1999) / 1998
ESPRESSO	VLT	10 cm/s (5 cm/s), 380-686 nm, R=120k (220k)	Pepe; (Spanò et al. 2012, 2008; Pepe et al. 2010) / 2016
EXPRES	DCT	10 cm/s, 380-700 nm, R~200k	Fischer; 2016-2017
G-CLEF	GMT	20 cm/s, 350-950 nm, R=120k / also MOS mode	Szentgyorgyi; (Szentgyorgyi et al. 2012) / 2021
Hamilton Echelle	Lick: Shane 3m CAT 0.6m	3 m/s, 340-900 nm, R=60-100k, 490-600 with iodine cell	Vogt; (Vogt 1987) / 1986
HARPS-N	TNG 3.6 m	1 m/s, 380-680 nm, R=110,000k	Pepe; (Cosentino et al., 2012, 2014; Langellier et al. 2014) / 2012
HARPS	ESO 3.6 m	1 m/s , 380-680 nm, R=110,000k	Pepe; (Pepe et al. 2000, 2003; Rupprecht et al. 2004, Lovis et al. 2006) / 2002
HIRES	Keck 10 m	2 m/s, 360-1000 nm, R=85k / 490-600 with iodine cell	Vogt; (Vogt et al. 1994) / 1996
HRS	HET	2.5 m/s, 390-1100 nm, R=120k	MacQueen; (Tull et al. 1998) / 2001
LCOGT NRES	Global network of 6 spectrometers	~1-3 m/s, 390-860 nm; R~53k	(Eastman et al. 2014) / 2015-2016
MINER	[illegible]	[illegible]	[illegible]
SHREK	Keck 10 m	1 m/s, 440-590 nm, R=85k / red channel later	Howard & Marcy; (http://nexsci.caltech.edu/keck_strategic_planning_Sep2014.pdf)
Sophie	1.93 m Haute-Provence	3 m/s, 387-694 nm, R=75k	(Perruchot et al. 2008) / 2006
TRES	Whipple Obs 1.5 m	15 m/s, 380-900 nm, R=44k	Szentgyorgyi; (Szentgyorgyi & Furesz 2007) / 2007
Tull Echelle	2.7 m Harlan J. Smith	340-1090 nm, R=60k, 240k	Phillip MacQueen;

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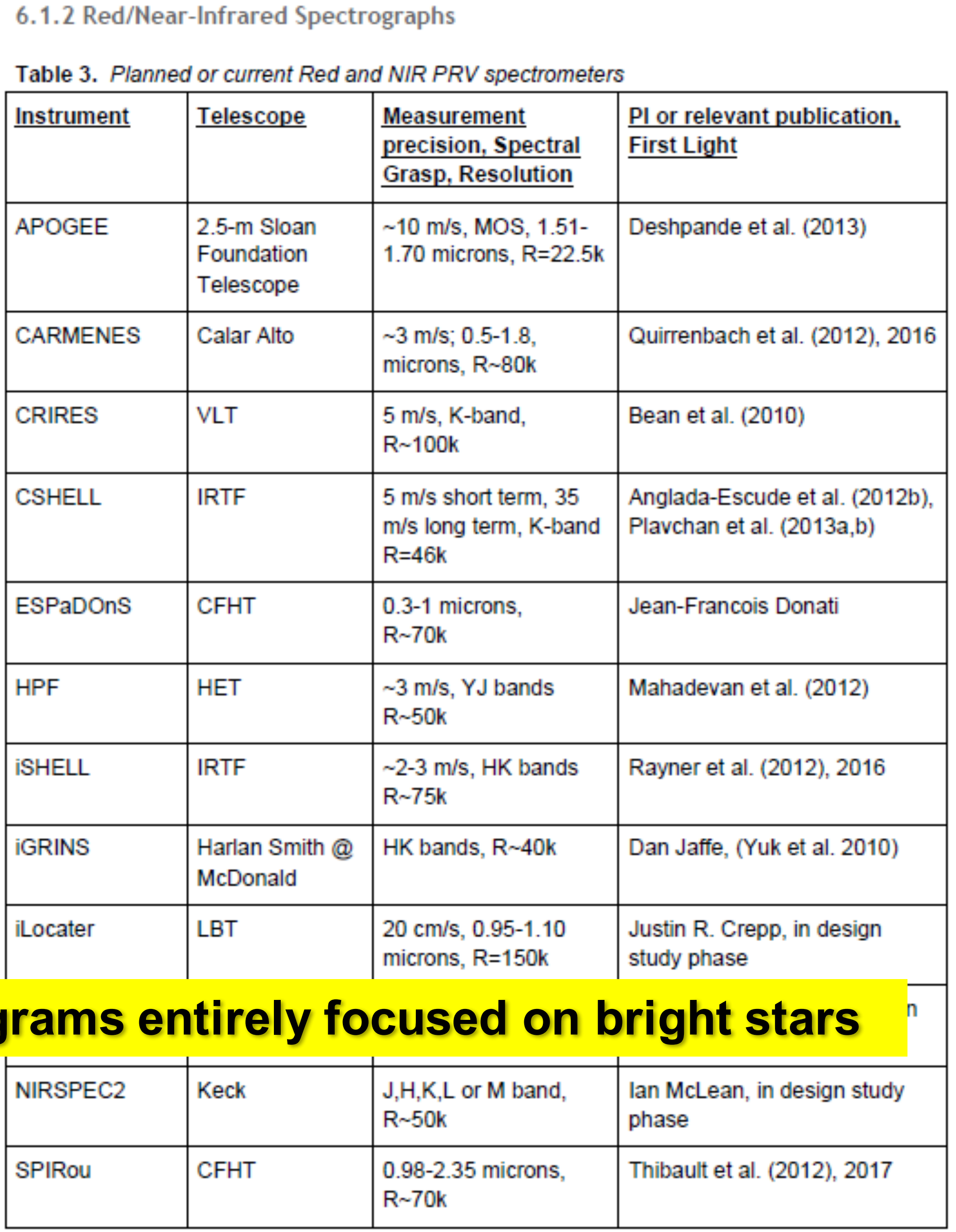


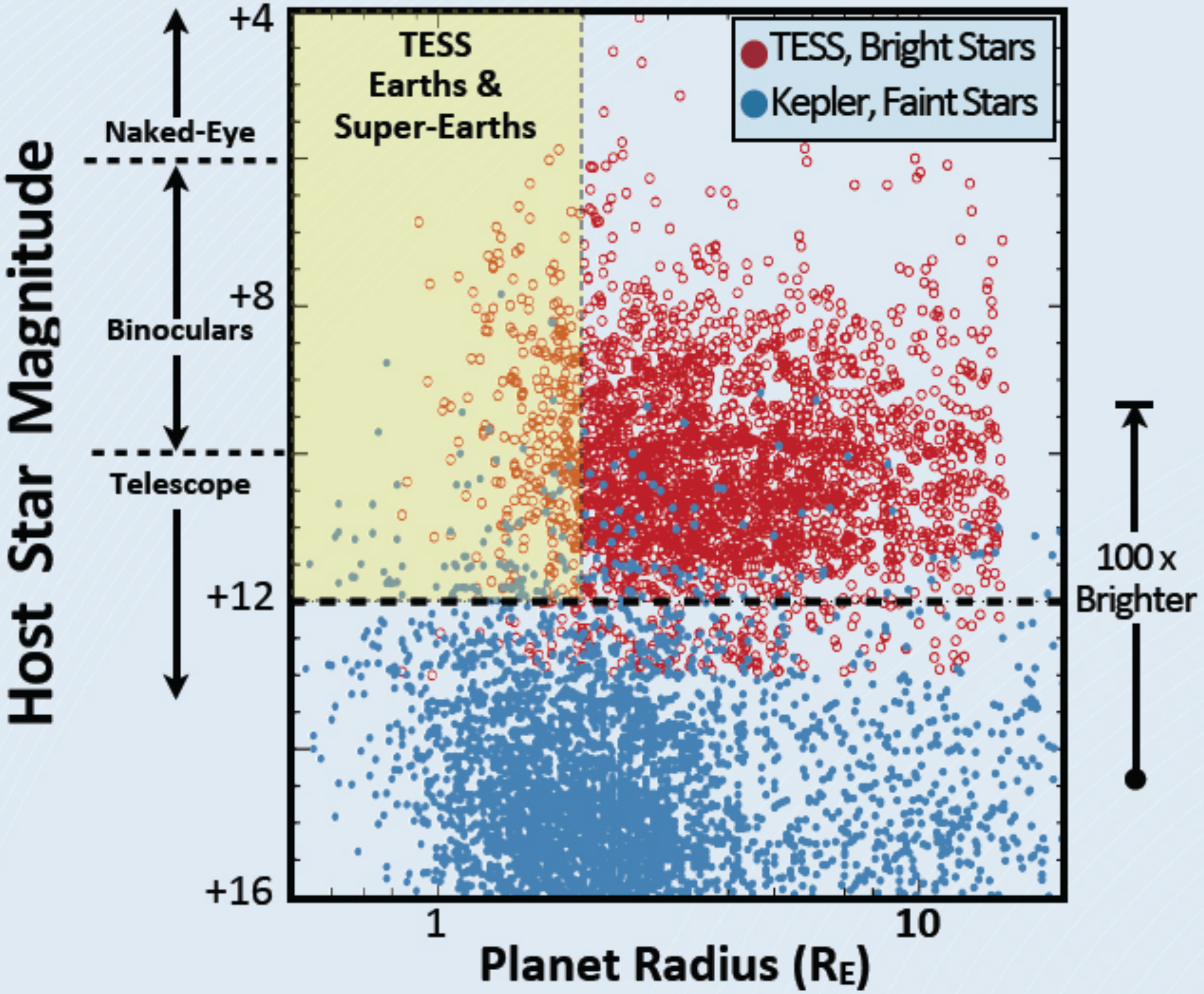
6.1.2 Red/Near-Infrared Spectrographs

Table 3. *Planned or current Red and NIR PRV spectrometers*

Instrument	Telescope	Measurement precision, Spectral Grasp, Resolution	PI or relevant publication, First Light
APOGEE	2.5-m Sloan Foundation Telescope	~10 m/s, MOS, 1.51-1.70 microns, R=22.5k	Deshpande et al. (2013)
CARMENES	Calar Alto	~3 m/s; 0.5-1.8, microns, R~80k	Quirrenbach et al. (2012), 2016
CRIRES	VLT	5 m/s, K-band, R~100k	Bean et al. (2010)
CSHELL	IRTF	5 m/s short term, 35 m/s long term, K-band R=46k	Anglada-Escude et al. (2012b), Plavchan et al. (2013a,b)
ESPaDOnS	CFHT	0.3-1 microns, R~70k	Jean-Francois Donati
HPF	HET	~3 m/s, YJ bands R~50k	Mahadevan et al. (2012)
iSHELL	IRTF	~2-3 m/s, HK bands R~75k	Rayner et al. (2012), 2016
iGRINS	Harlan Smith @ McDonald	HK bands, R~40k	Dan Jaffe, (Yuk et al. 2010)
iLocater	LBT	20 cm/s, 0.95-1.10 microns, R=150k	Justin R. Crepp, in design study phase
[illegible]	[illegible]	[illegible]	[illegible] n
NIRSPEC2	Keck	J,H,K,L or M band, R~50k	Ian McLean, in design study phase
SPIRou	CFHT	0.98-2.35 microns, R~70k	Thibault et al. (2012), 2017

All surveys and follow-up programs entirely focused on bright stars

Credits G. Ricker

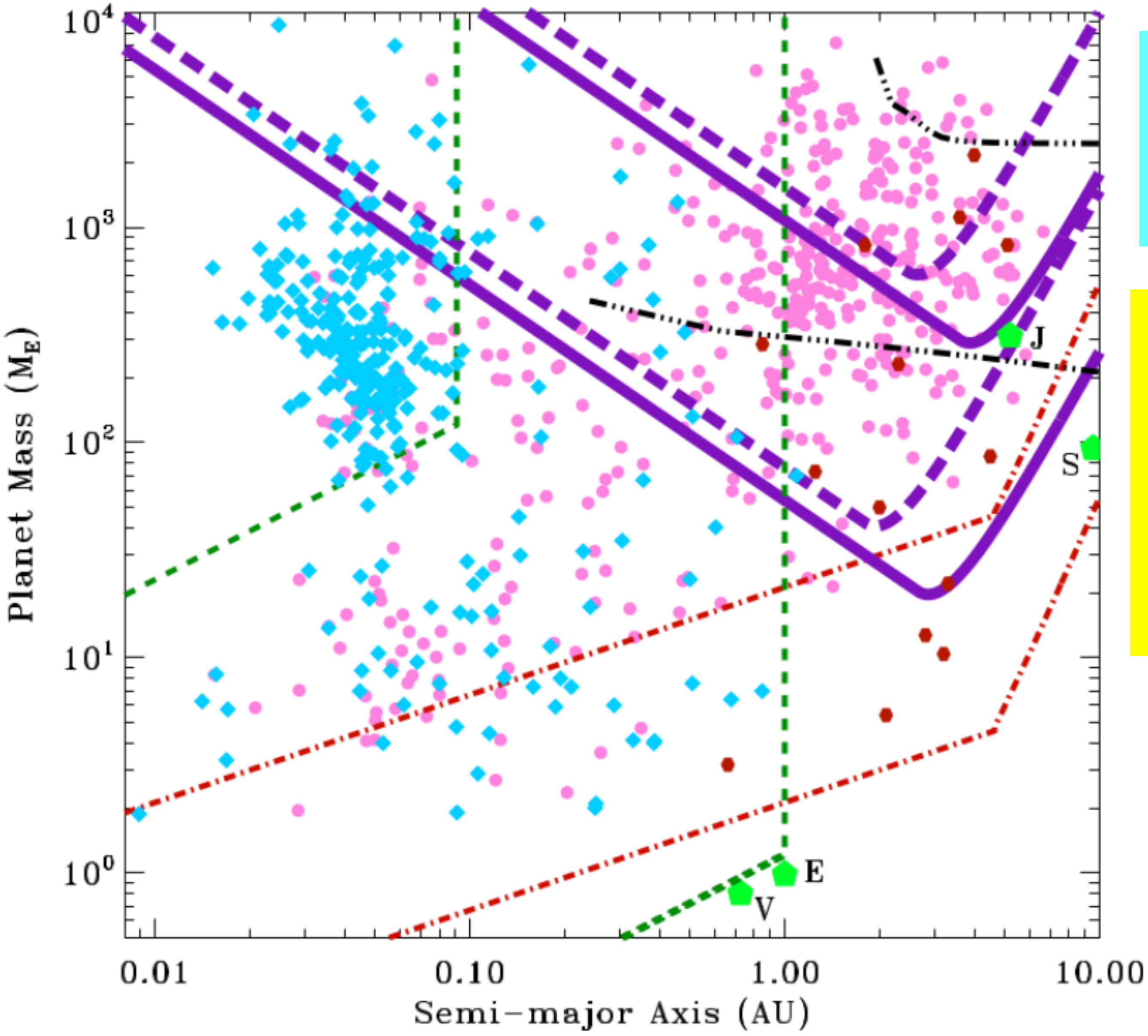


TESS Planets:

Easier to Followup

TESS Will Discover Earths & Super-Earths Orbiting Bright Stars

Is (Will) Gaia (be) competitive?



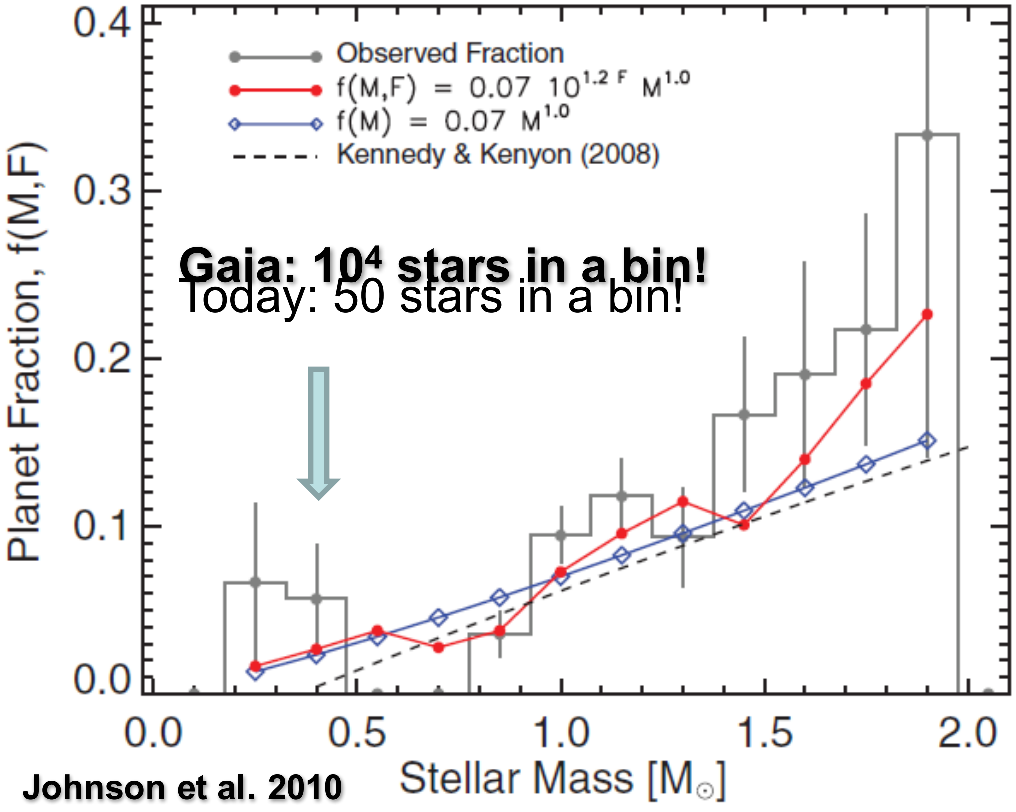
Unbiased, magnitude-limited planet census of maybe 10^6-10^7 stars

On the order of >10^4 NEW gas giants (< 15 M_{JUP}) around A through M dwarfs Numbers might as much as triple for a 10-yr mission

Lattanzi et al. 2000,
Sozzetti et al.2001
Casertano et al. 2008
Perryman et al. 2014
Sozzetti et al. 2014
Sahlmann et al. 2014

The Gaia Legacy

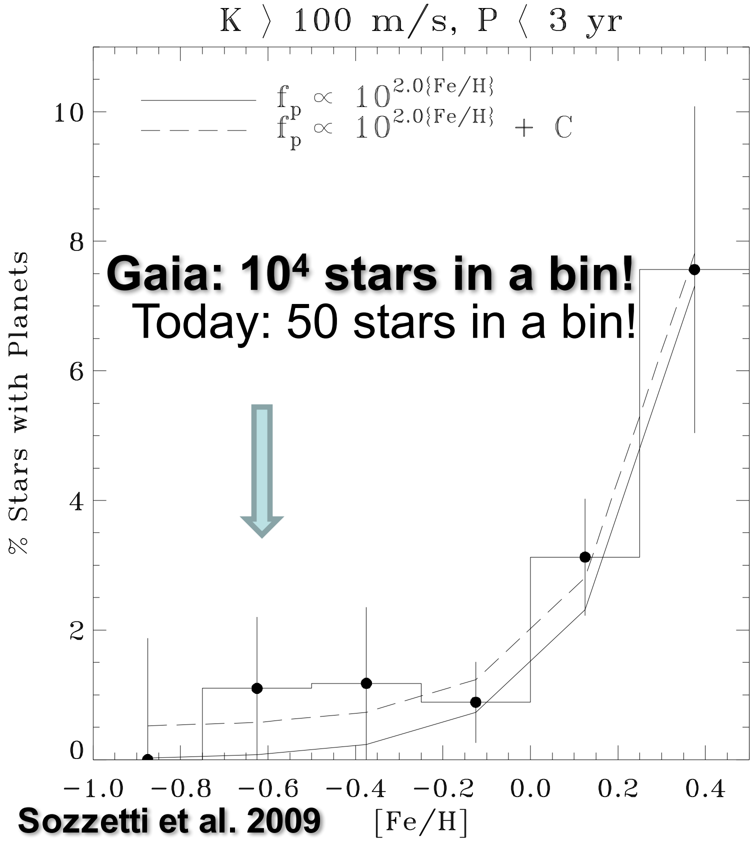
How do giant planets properties (mass, orbit) depend on those of the host stars?



Gaia: 10^4 stars in a bin!

Today: 50 stars in a bin!

Johnson et al. 2010



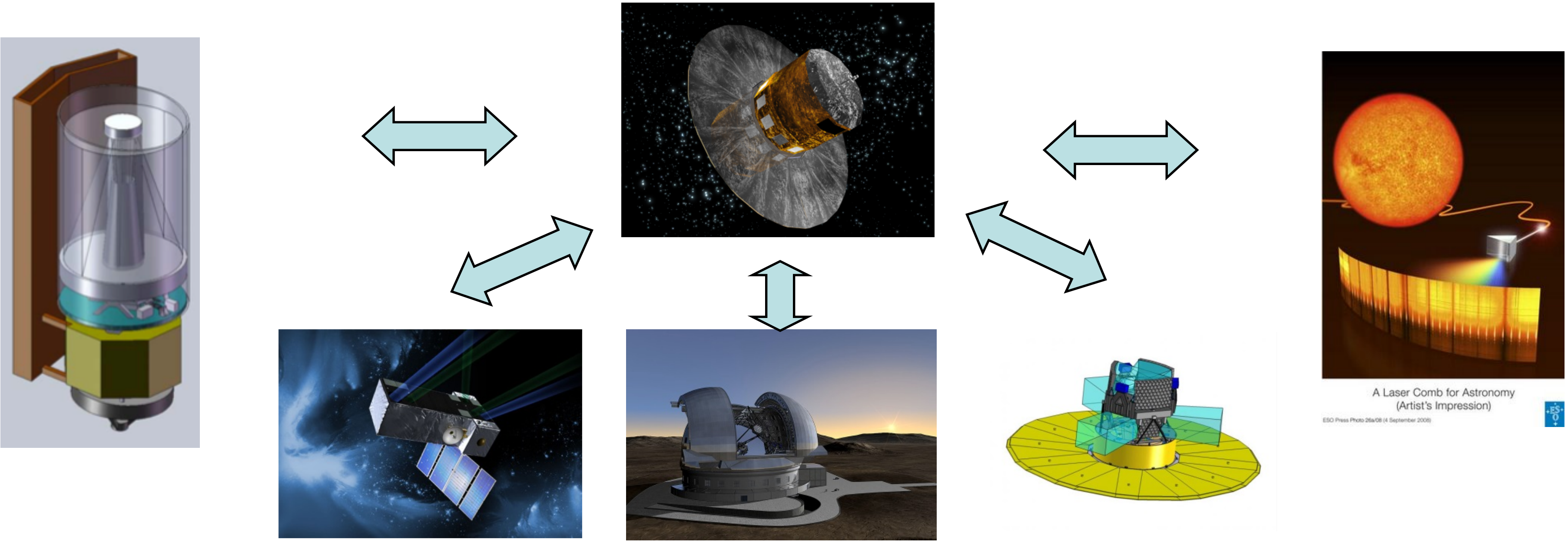
Gaia: 10^4 stars in a bin!

Today: 50 stars in a bin!

Sozzetti et al. 2009

Gaia will test the fine structure of GP parameters distributions and frequencies (including the GP/BD transition), and investigate their changes as a function of stellar mass, metallicity, and age with unprecedented resolution

Gaia - Synergies



- **Gaia & spectroscopic characterization observatories (e.g., JWST, E-ELT)**
- **Gaia & transit surveys from the ground (e.g., WASP, HAT, APACHE, NGTS) and in space (CoRoT, Kepler, K2, TESS, PLATO)**
- **Gaia & direct imaging observatories (e.g., SPHERE/VLT, PCS/E-ELT, WFIRST)**
- **Gaia & RV programs (e.g., HARPS(-N), ESPRESSO, CARMENES, and the likes)**
- **Gaia & ground-based and space-borne astrometry**

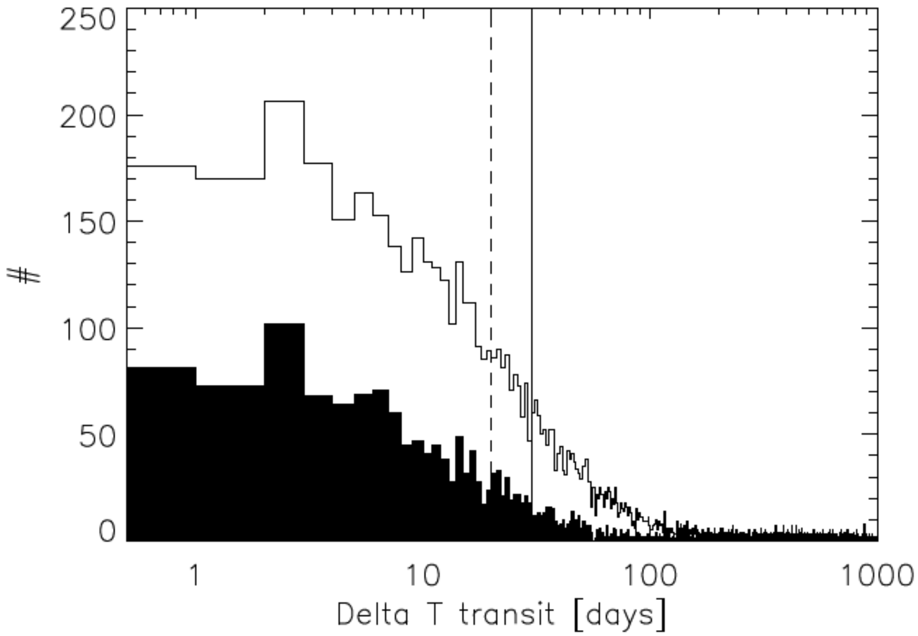
Target Selection/Characterization

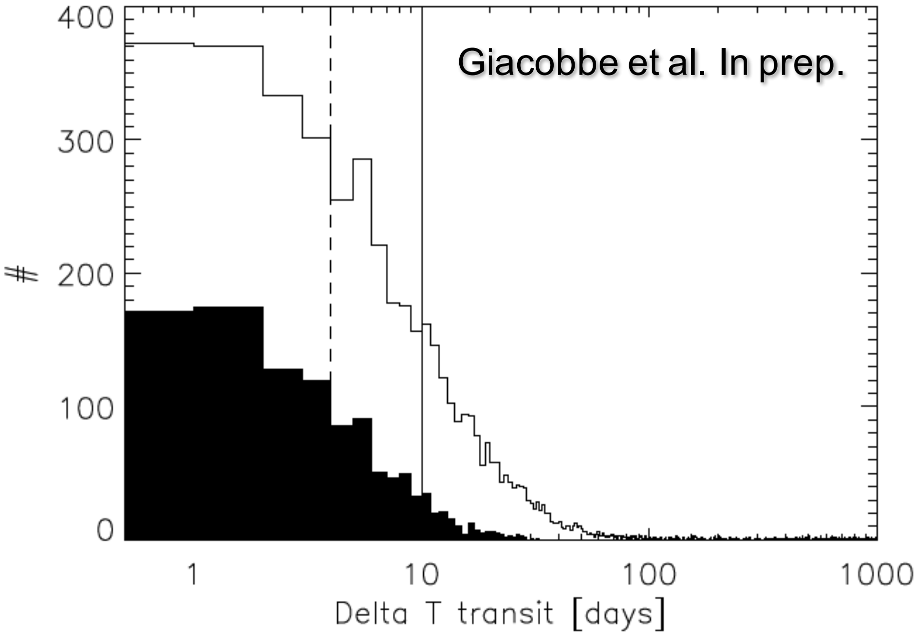
- Gaia remains the elected primary source of the TESS/PLATO input catalogs of >2x10^6 bright dwarf stars (with negligible giant star contaminants)

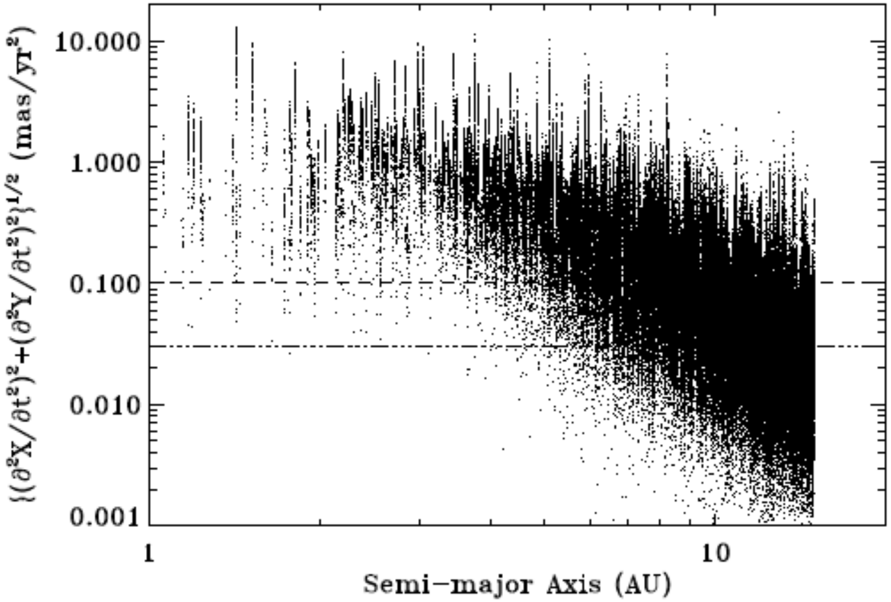
- It will allow for significant reduction in astrophysical false positives (know what's in the pixel!)

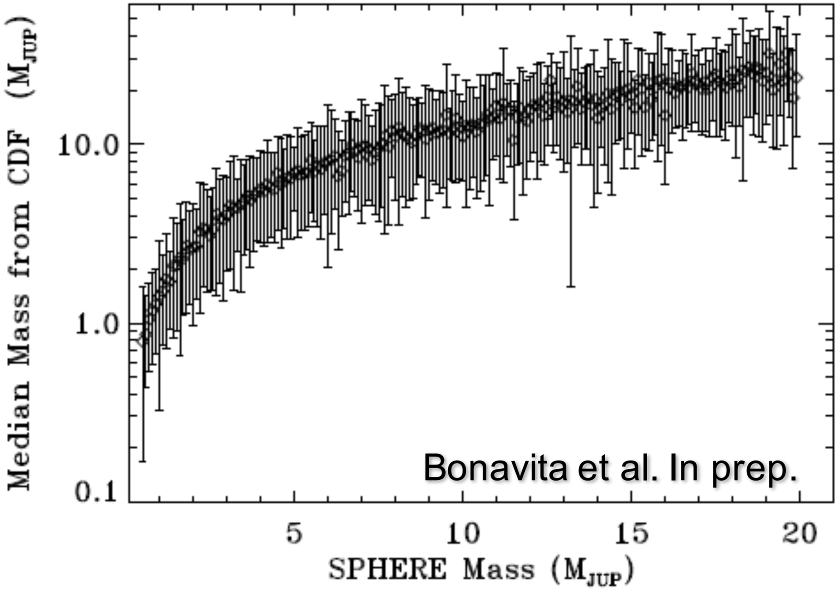
- Gaia parallaxes will make system parameters (mass, radius, and density) both precise AND accurate

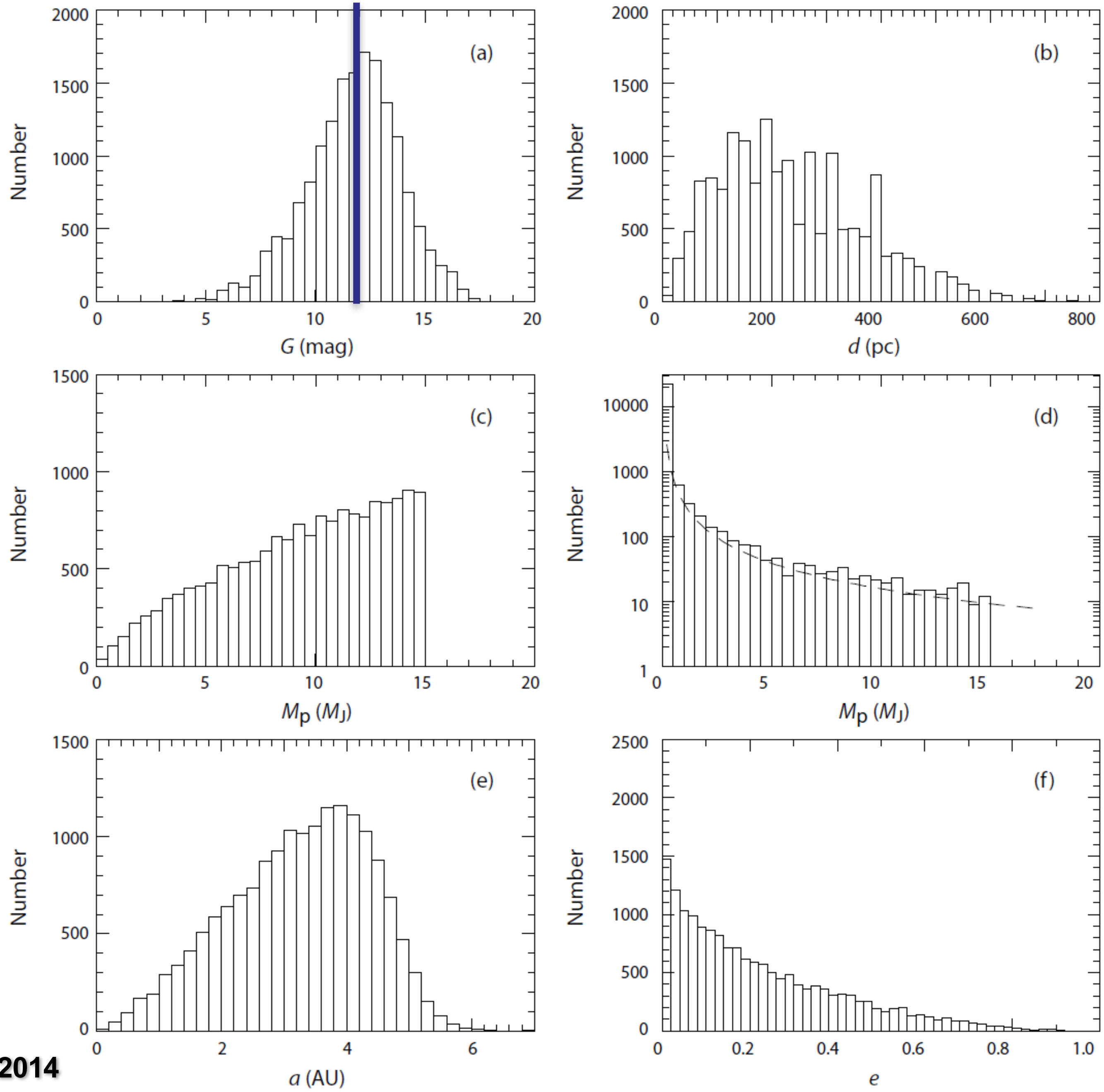
Two Examples




Giacobbe et al. In prep.




Bonavita et al. In prep.



Perryman et al. 2014

Multiple Systems with Gaia

- Additional giants (Observed): f_p >25% [$a < 10$ AU, M_p 0.1-20 M_{JUP}]
- In 60 systems, 47% have both with astrometric SNR = $(\alpha/\sigma)\sqrt{N_{tr}} > 5$
- 77% (resp. 89%) with P< 5 yr (resp. < 10 yr)
- ALL around V < 12 mag stars ⟹ EXTRAPOLATE
- Combine Perryman et al. (2014) numbers with Casertano et al. (2008) metrics for multiple planet orbit reconstruction:
- $T_{mission}$= 5 yr:
  >2500 two-planet systems with masses good to 15%-20%, around 250-300 meaningful coplanarity measurements
- $T_{mission}$= 10 yr:
  >6000 two-planet systems with masses good to 15%-20%, around 550-600 meaningful coplanarity measurements

Exoplanets in the Gaia Era

- **Transiting systems** to remain pivotal in the game for a while
- Eventually, **direct imaging** of mature, not-so-wide separation systems will happen
- Systems optimal for atmospheric characterization and habitability studies ouf of direct reach of Gaia, but **indirect contribution crucial**
- **Characterization of systems architectures** (*including true Solar-System analogs*) across orders of magnitude in mass and orbital separation and as function of host's properties **CANNOT DO WITHOUT Gaia**

But for many a question one can ask, e.g.:

1) *What is the frequency of solar system analogs?*
2) *Are (single and multiple) super Earths accompanied by giant planets?*
3) *How do gas giants planets affect the presence of terrestrial planets?*
4) *What is the true mass distribution of gas giants beyond the snow line?*

Answers can be reached only by maximizing the synergy potential of Gaia data

Lennart et al., do the impossible for that 0.01% of bright stars!