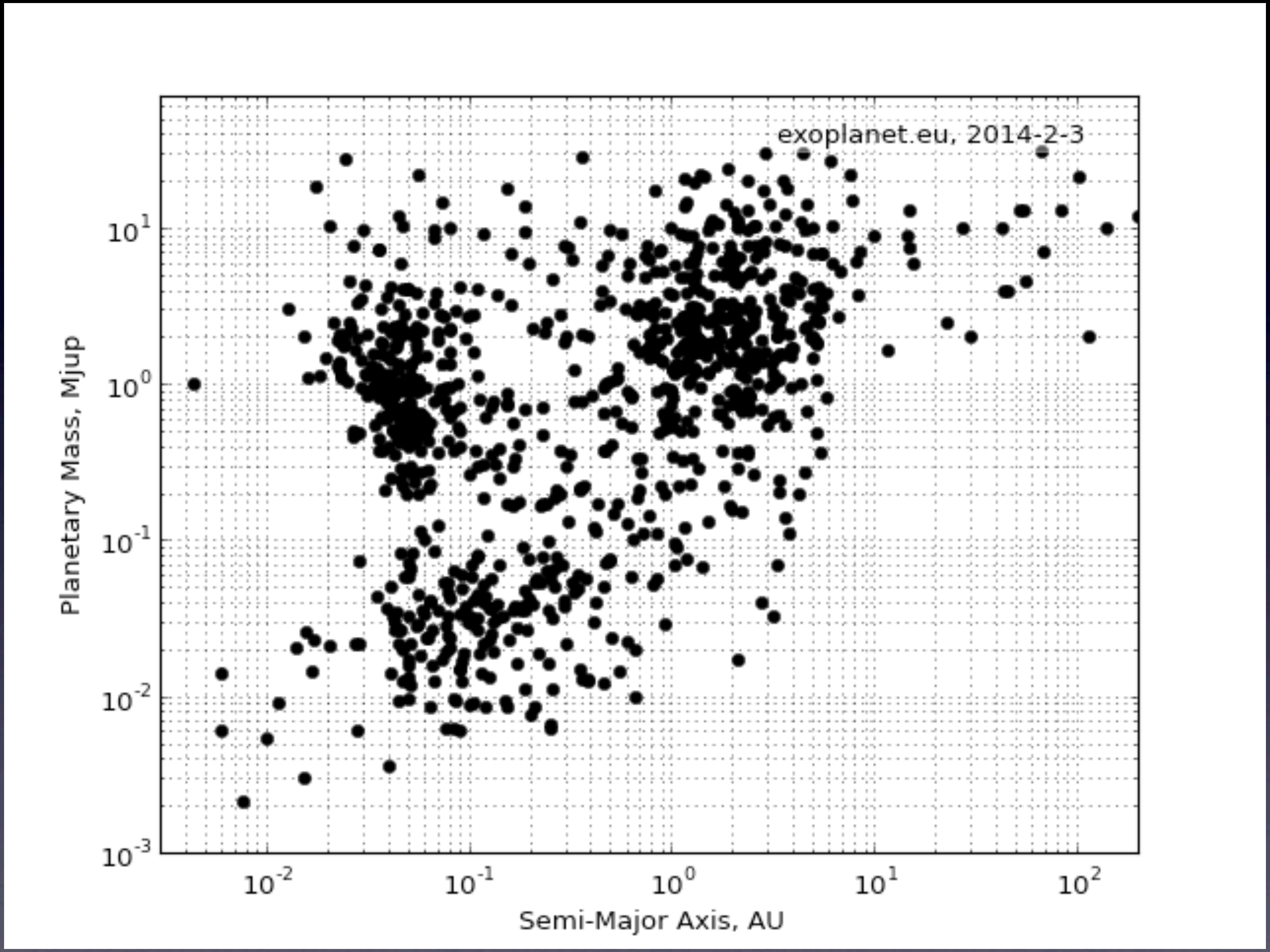
Exoplanet Observations with the E-ELT, ESO Garching, 3-6 February 2014

Planetary Populations through Detection Surveys

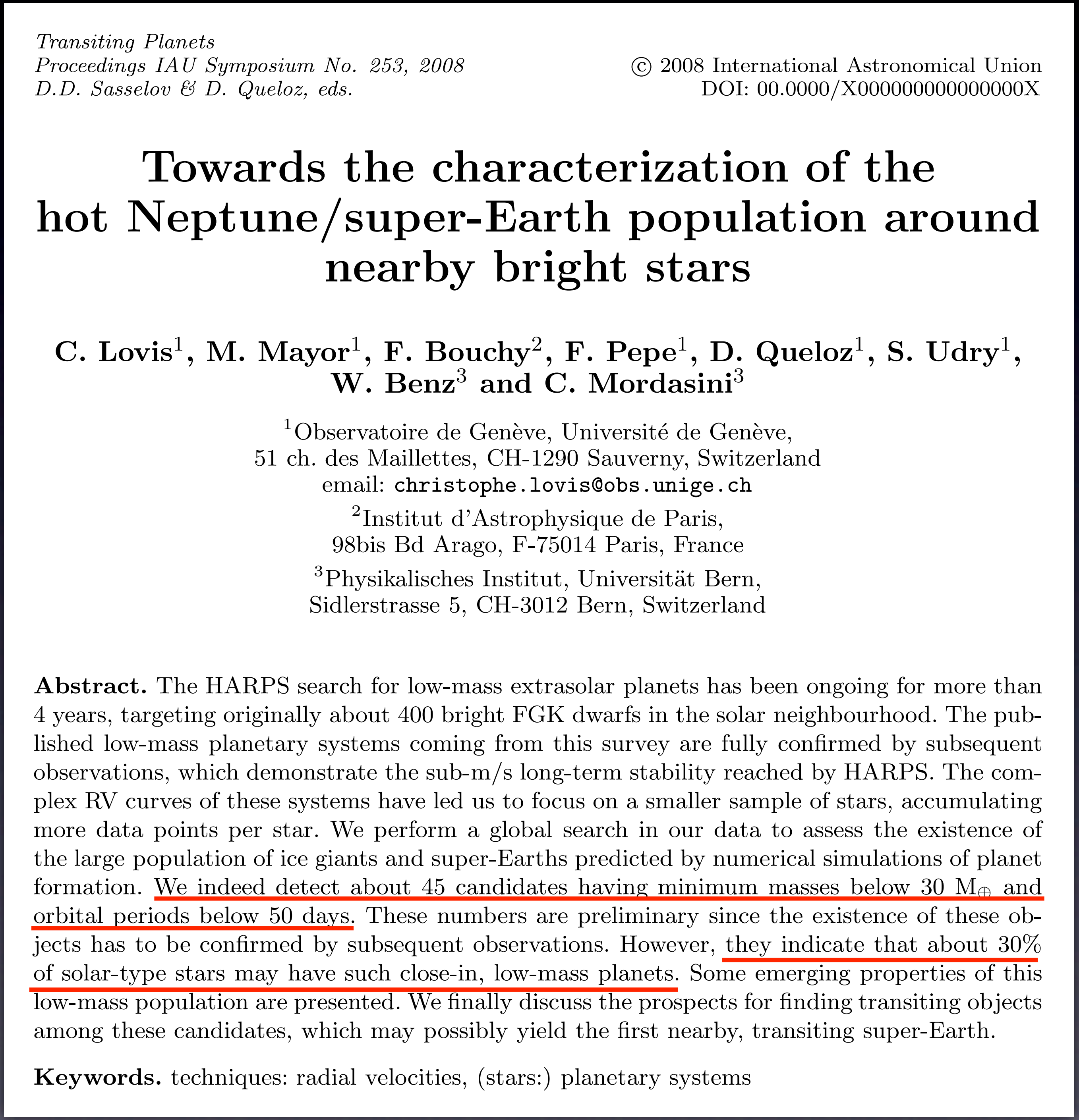
Christophe Lovis
University of Geneva

The Exoplanet Census as of 2014



From exoplanet.eu

2008: The Rise of Low-Mass Exoplanets



Transiting Planets
Proceedings IAU Symposium No. 253, 2008
D.D. Sasselov & D. Queloz, eds.

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DOI: 00.0000/X000000000000000X

Towards the characterization of the hot Neptune/super-Earth population around nearby bright stars

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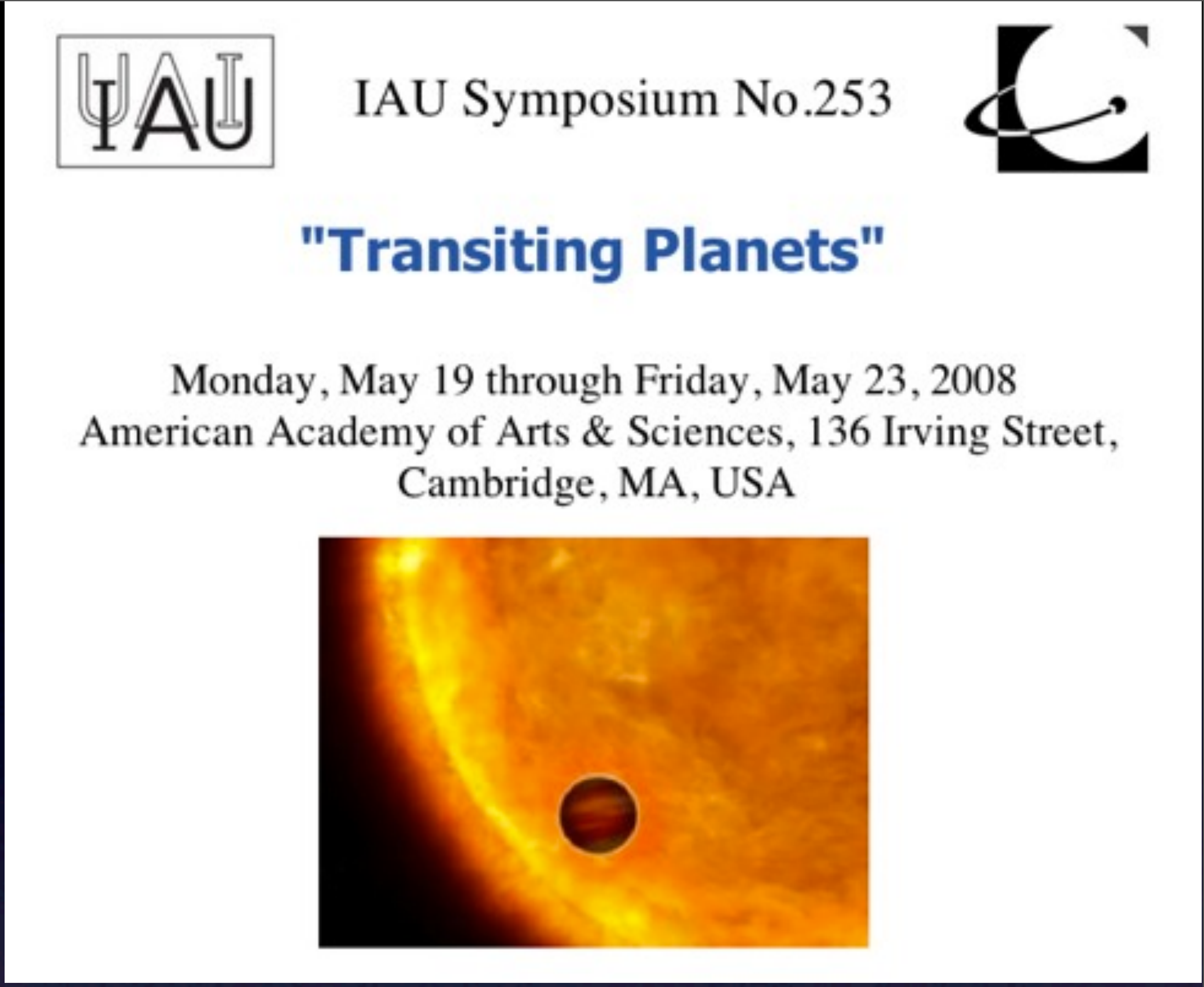
Abstract. The HARPS search for low-mass extrasolar planets has been ongoing for more than 4 years, targeting originally about 400 bright FGK dwarfs in the solar neighbourhood. The published low-mass planetary systems coming from this survey are fully confirmed by subsequent observations, which demonstrate the sub-m/s long-term stability reached by HARPS. The complex RV curves of these systems have led us to focus on a smaller sample of stars, accumulating more data points per star. We perform a global search in our data to assess the existence of the large population of ice giants and super-Earths predicted by numerical simulations of planet formation. We indeed detect about 45 candidates having minimum masses below 30 $M_\oplus$ and orbital periods below 50 days. These numbers are preliminary since the existence of these objects has to be confirmed by subsequent observations. However, they indicate that about 30% of solar-type stars may have such close-in, low-mass planets. Some emerging properties of this low-mass population are presented. We finally discuss the prospects for finding transiting objects among these candidates, which may possibly yield the first nearby, transiting super-Earth.

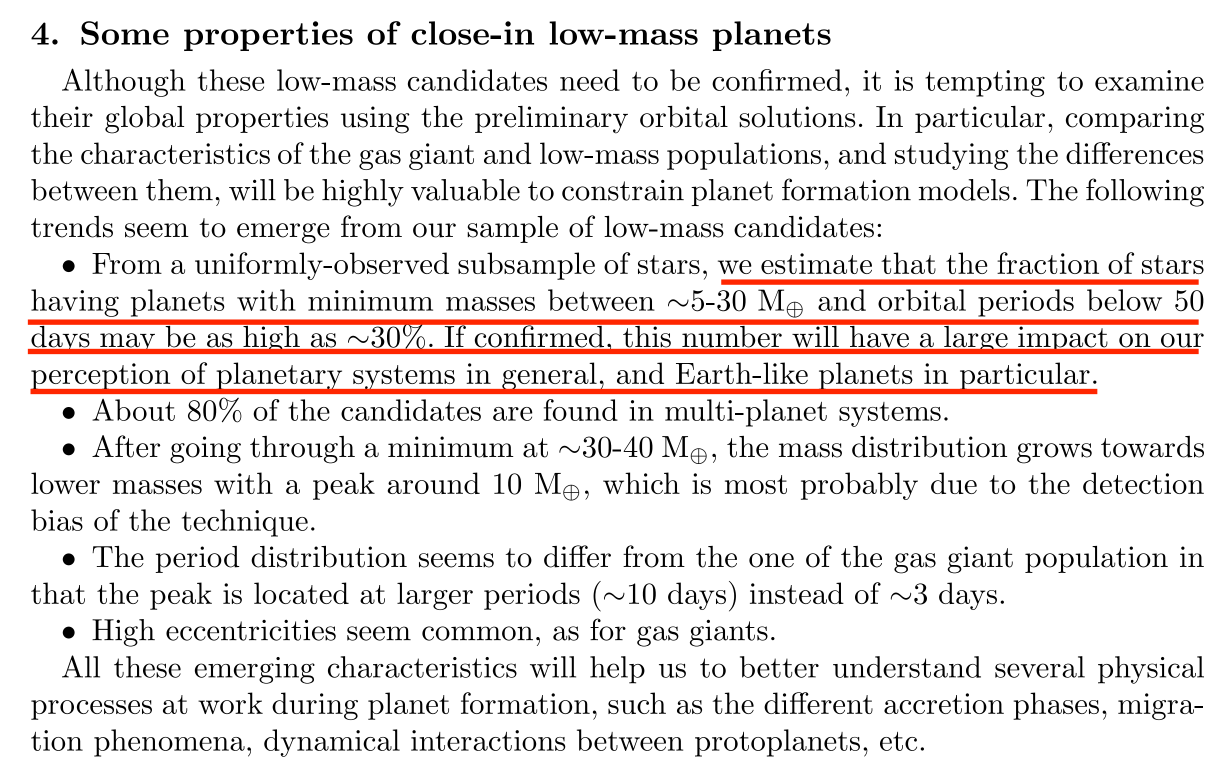
Keywords. techniques: radial velocities, (stars:) planetary systems



IAU Symposium No.253

"Transiting Planets"

Monday, May 19 through Friday, May 23, 2008
American Academy of Arts & Sciences, 136 Irving Street,
Cambridge, MA, USA



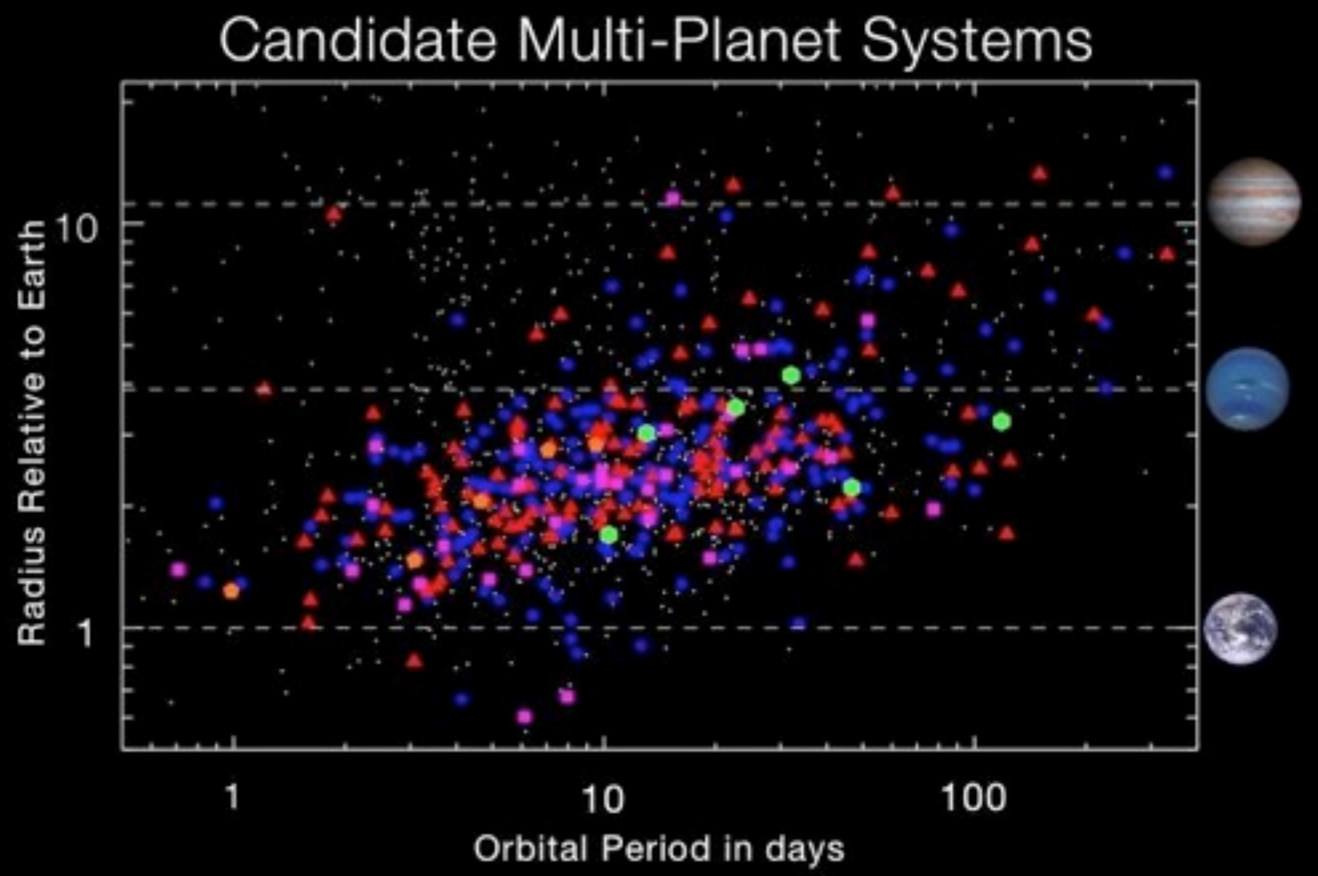
4. Some properties of close-in low-mass planets

Although these low-mass candidates need to be confirmed, it is tempting to examine their global properties using the preliminary orbital solutions. In particular, comparing the characteristics of the gas giant and low-mass populations, and studying the differences between them, will be highly valuable to constrain planet formation models. The following trends seem to emerge from our sample of low-mass candidates:

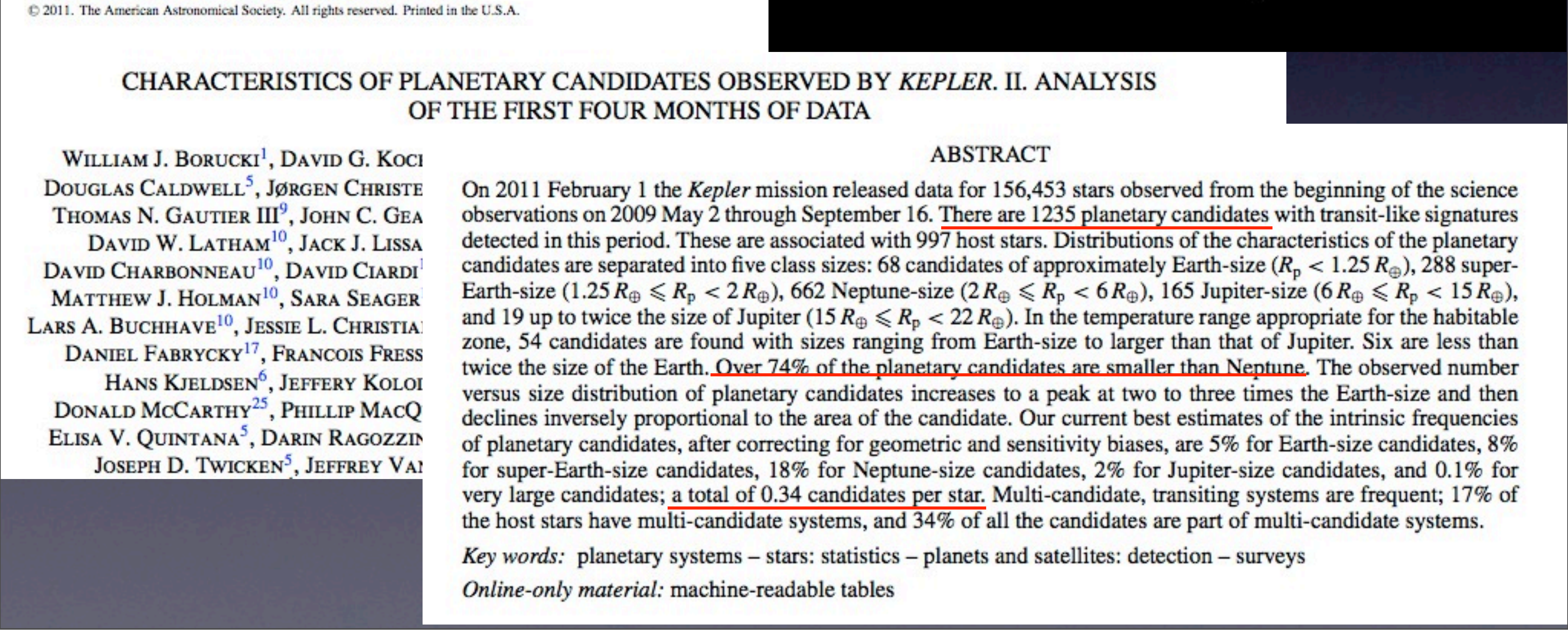
- From a uniformly-observed subsample of stars, we estimate that the fraction of stars having planets with minimum masses between ∼5-30 $M_\oplus$ and orbital periods below 50 days may be as high as ∼30%. If confirmed, this number will have a large impact on our perception of planetary systems in general, and Earth-like planets in particular.
- About 80% of the candidates are found in multi-planet systems.
- After going through a minimum at ∼30-40 $M_\oplus$, the mass distribution grows towards lower masses with a peak around 10 $M_\oplus$, which is most probably due to the detection bias of the technique.
- The period distribution seems to differ from the one of the gas giant population in that the peak is located at larger periods (∼10 days) instead of ∼3 days.
- High eccentricities seem common, as for gas giants.

All these emerging characteristics will help us to better understand several physical processes at work during planet formation, such as the different accretion phases, migration phenomena, dynamical interactions between protoplanets, etc.

2011: The Kepler Revolution



The Astrophysical Journal, 736:19 (22pp), 2011 July 20



CHARACTERISTICS OF PLANETARY CANDIDATES OBSERVED BY *KEPLER*. II. ANALYSIS OF THE FIRST FOUR MONTHS OF DATA

William J. Borucki[1], David G. Koc
Douglas Caldwell[5], Jørgen Christe
Thomas N. Gautier III[9], John C. Gea
David W. Latham[10], Jack J. Lissa
David Charbonneau[10], David Ciardi
Matthew J. Holman[10], Sara Seager
Lars A. Buchhave[10], Jessie L. Christia
Daniel Fabrycky[17], Francois Fress
Hans Kjeldsen[6], Jeffery Kolo
Donald McCarthy[25], Phillip MacQ
Elisa V. Quintana[5], Darin Ragozzin
Joseph D. Twicken[5], Jeffrey Va

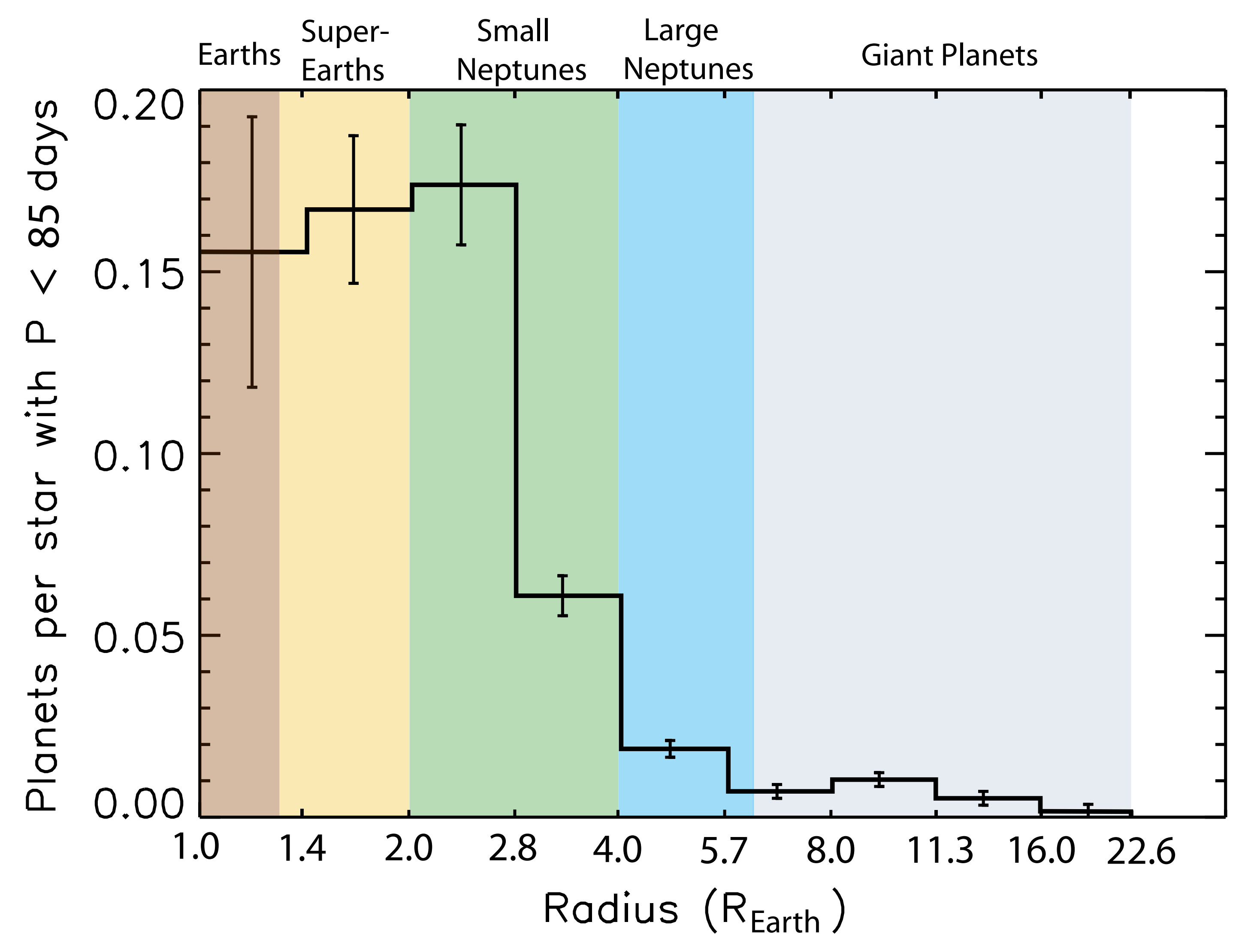
ABSTRACT

On 2011 February 1 the *Kepler* mission released data for 156,453 stars observed from the beginning of the science observations on 2009 May 2 through September 16. There are 1235 planetary candidates with transit-like signatures detected in this period. These are associated with 997 host stars. Distributions of the characteristics of the planetary candidates are separated into five class sizes: 68 candidates of approximately Earth-size ($R_p < 1.25\,R_\oplus$), 288 super-Earth-size ($1.25\,R_\oplus \leqslant R_p < 2\,R_\oplus$), 662 Neptune-size ($2\,R_\oplus \leqslant R_p < 6\,R_\oplus$), 165 Jupiter-size ($6\,R_\oplus \leqslant R_p < 15\,R_\oplus$), and 19 up to twice the size of Jupiter ($15\,R_\oplus \leqslant R_p < 22\,R_\oplus$). In the temperature range appropriate for the habitable zone, 54 candidates are found with sizes ranging from Earth-size to larger than that of Jupiter. Six are less than twice the size of the Earth. Over 74% of the planetary candidates are smaller than Neptune. The observed number versus size distribution of planetary candidates increases to a peak at two to three times the Earth-size and then declines inversely proportional to the area of the candidate. Our current best estimates of the intrinsic frequencies of planetary candidates, after correcting for geometric and sensitivity biases, are 5% for Earth-size candidates, 8% for super-Earth-size candidates, 18% for Neptune-size candidates, 2% for Jupiter-size candidates, and 0.1% for very large candidates; a total of 0.34 candidates per star. Multi-candidate, transiting systems are frequent; 17% of the host stars have multi-candidate systems, and 34% of all the candidates are part of multi-candidate systems.

Key words: planetary systems – stars: statistics – planets and satellites: detection – surveys

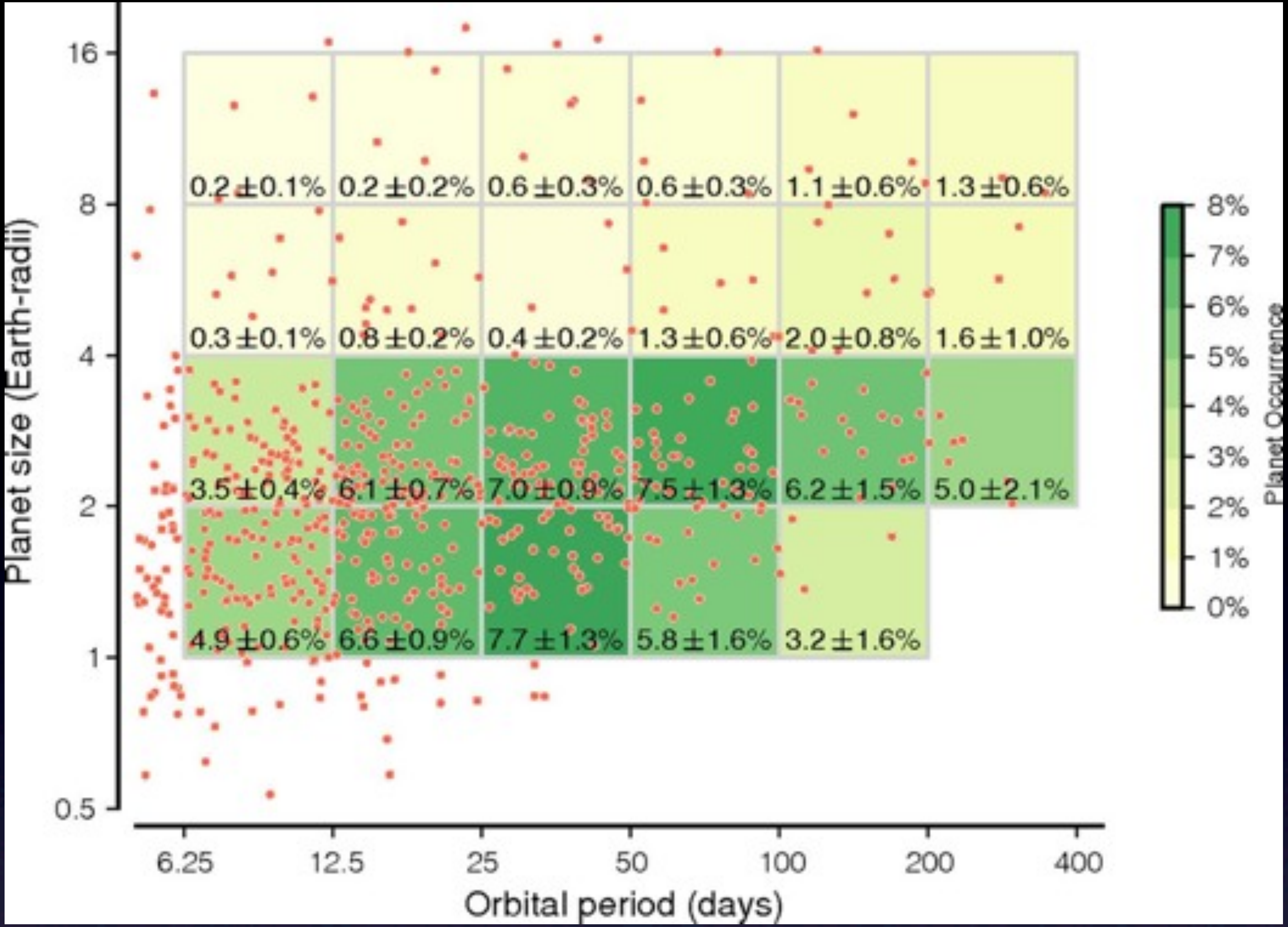
Online-only material: machine-readable tables

Exoplanet Populations from Kepler

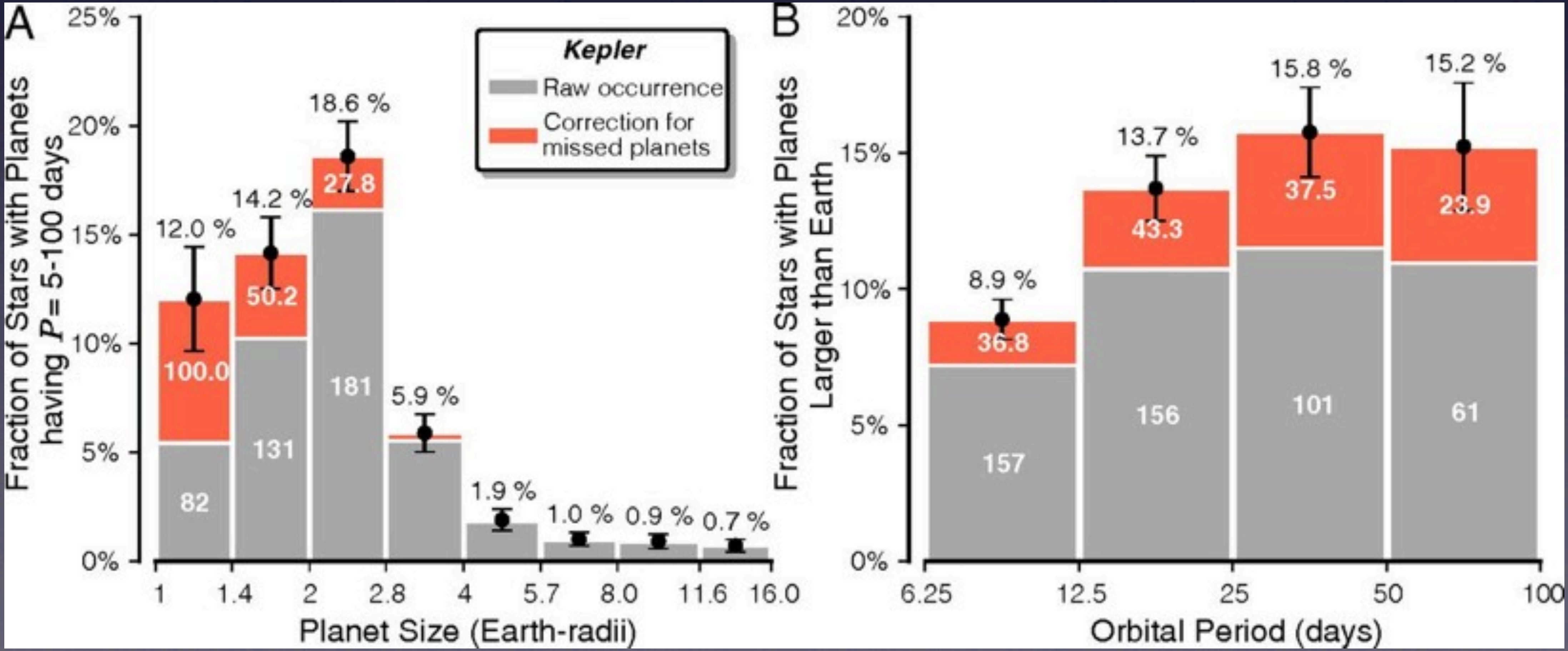


Fressin et al. 2013, see also Dong & Zhu 2013

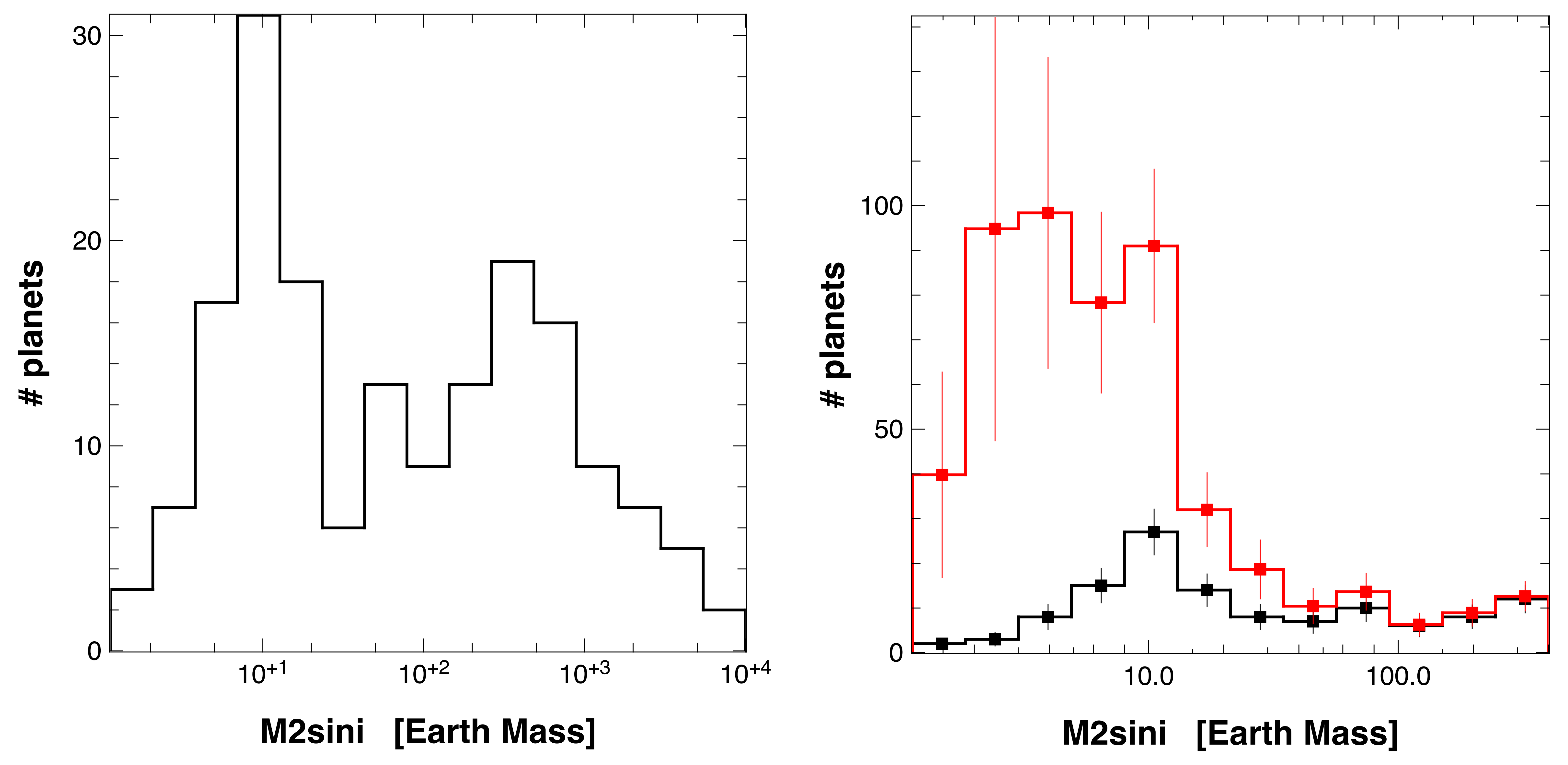
Exoplanet Populations from Kepler



Petigura et al. 2013

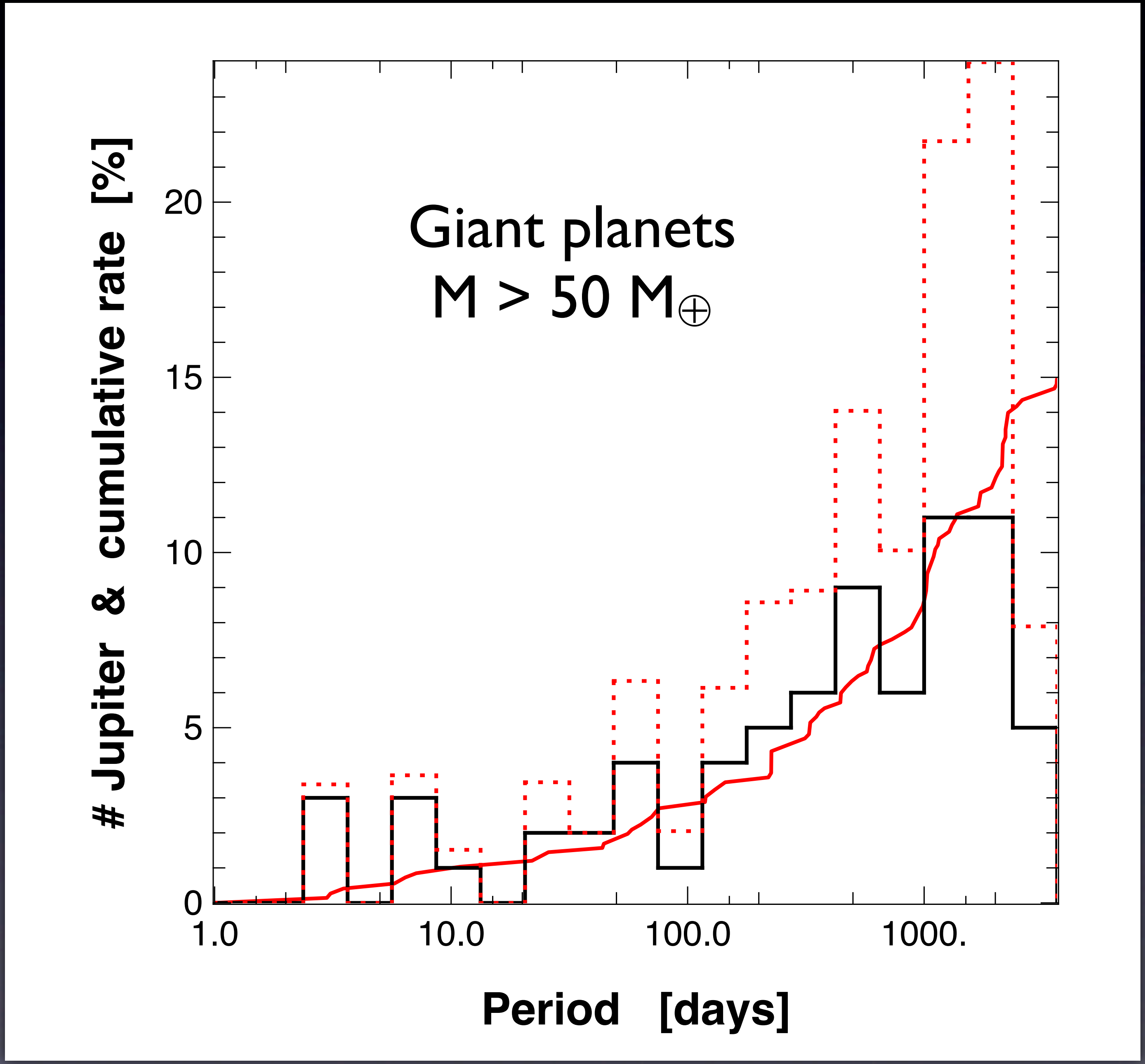


Exoplanet Populations from the HARPS-CORALIE RV Surveys



Mayor et al. 2011

Exoplanet Populations from the HARPS-CORALIE RV Surveys

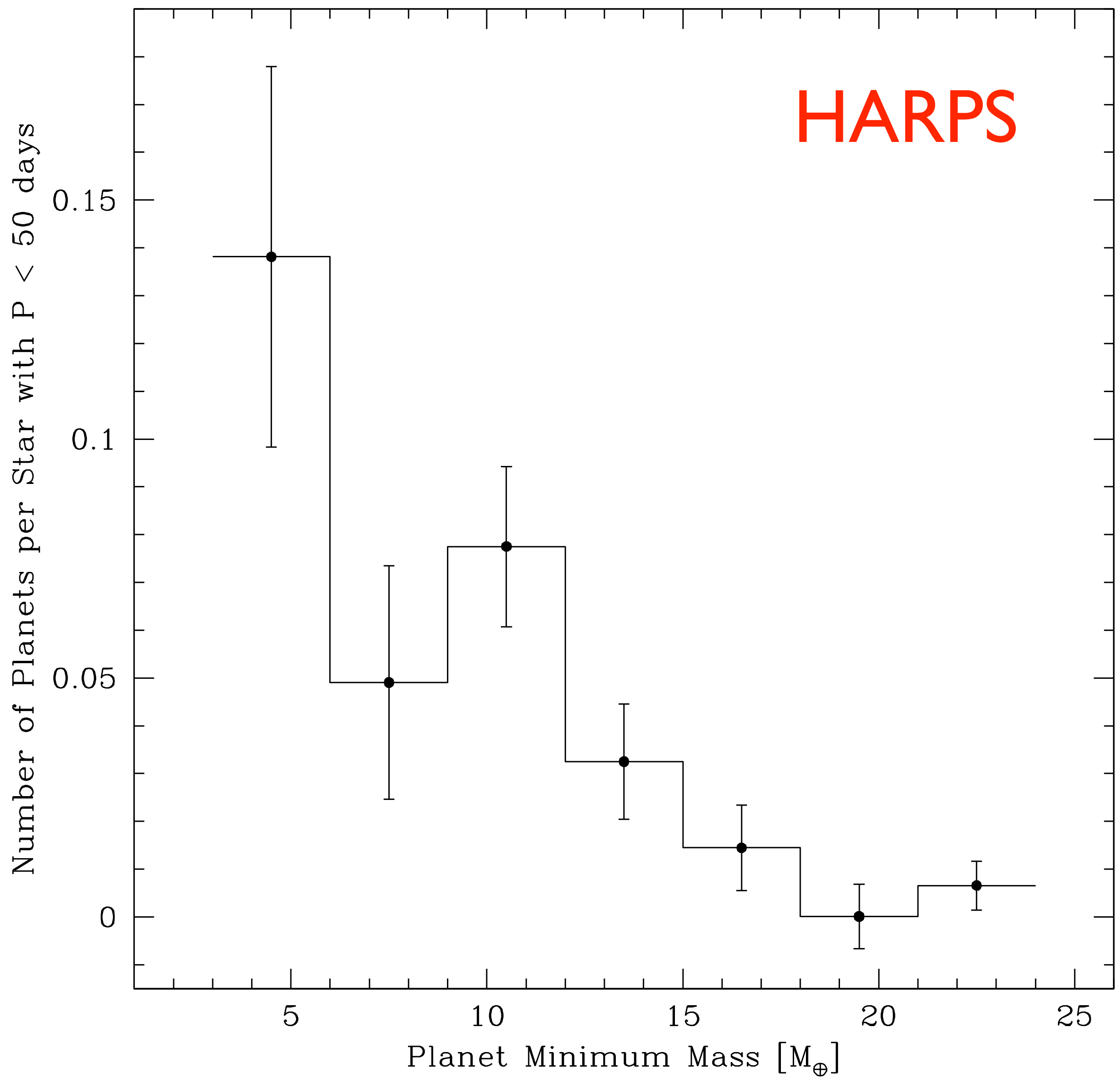


Mayor et al. 2011

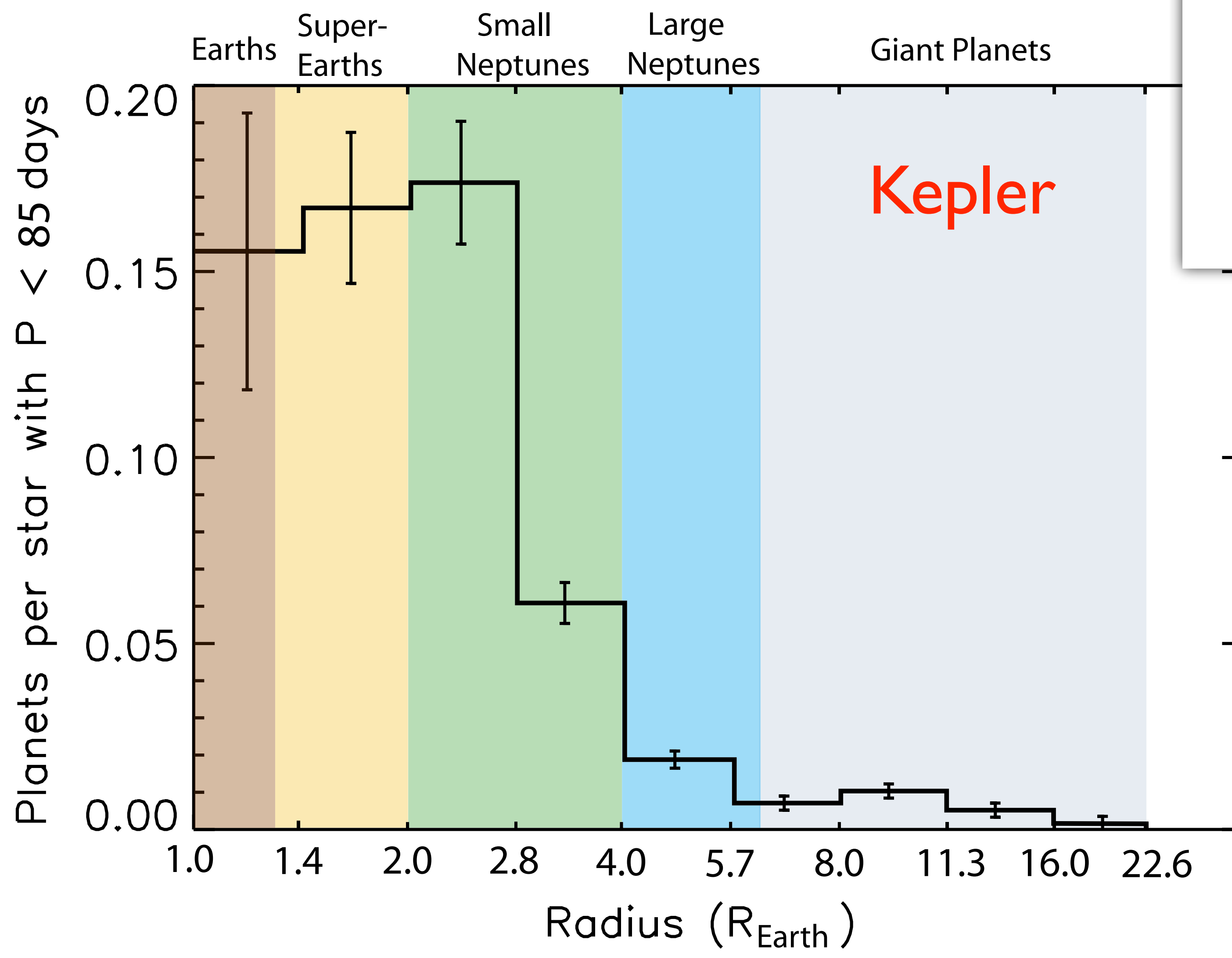
HARPS / Kepler Comparisons

- HARPS provides the debiased and normalized distribution of planet minimum masses down to Msini ≈ 3 $M_\oplus$ for periods < 50 days
- Kepler provides the debiased and normalized distribution of planet radii down to R ≈ 1 $R_\oplus$ for periods < 50-100 days
- The common metric between the two surveys is the average number of planets per star (NPPS) as a function of mass/radius

Unbiased, Normalized Mass and Radius Distributions

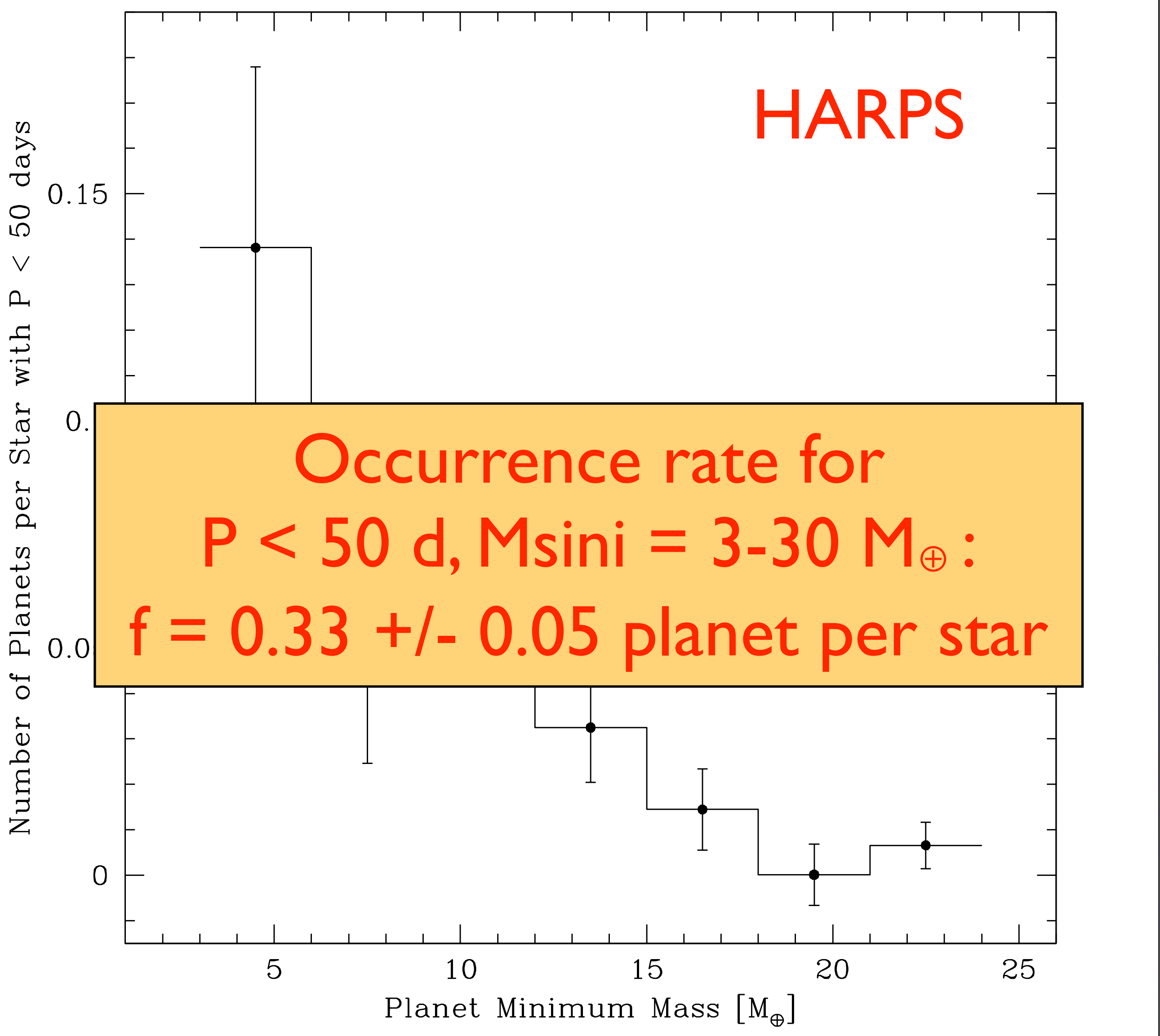


From Mayor et al. 2011



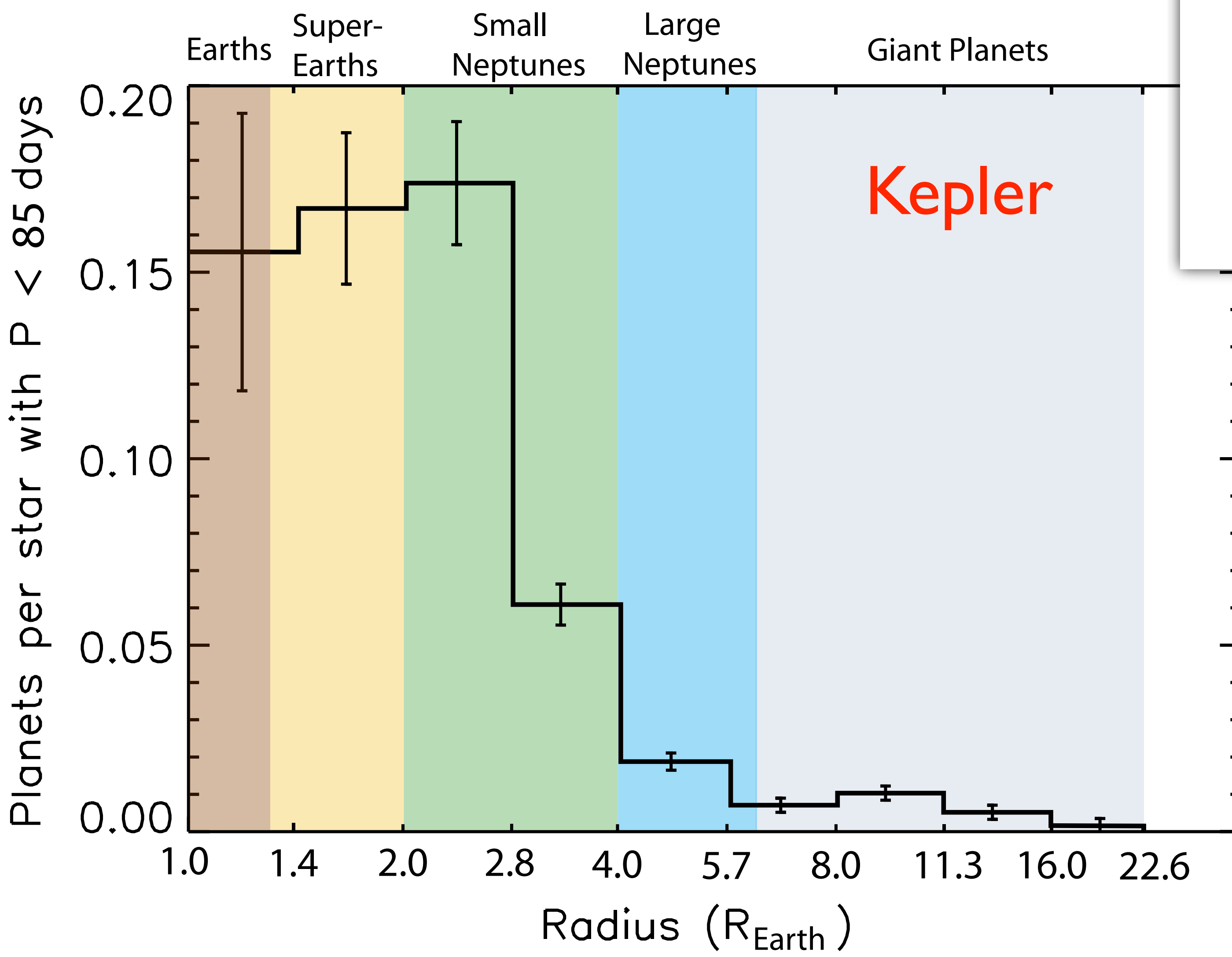
From Fressin et al. 2013

Unbiased, Normalized Mass and Radius Distributions



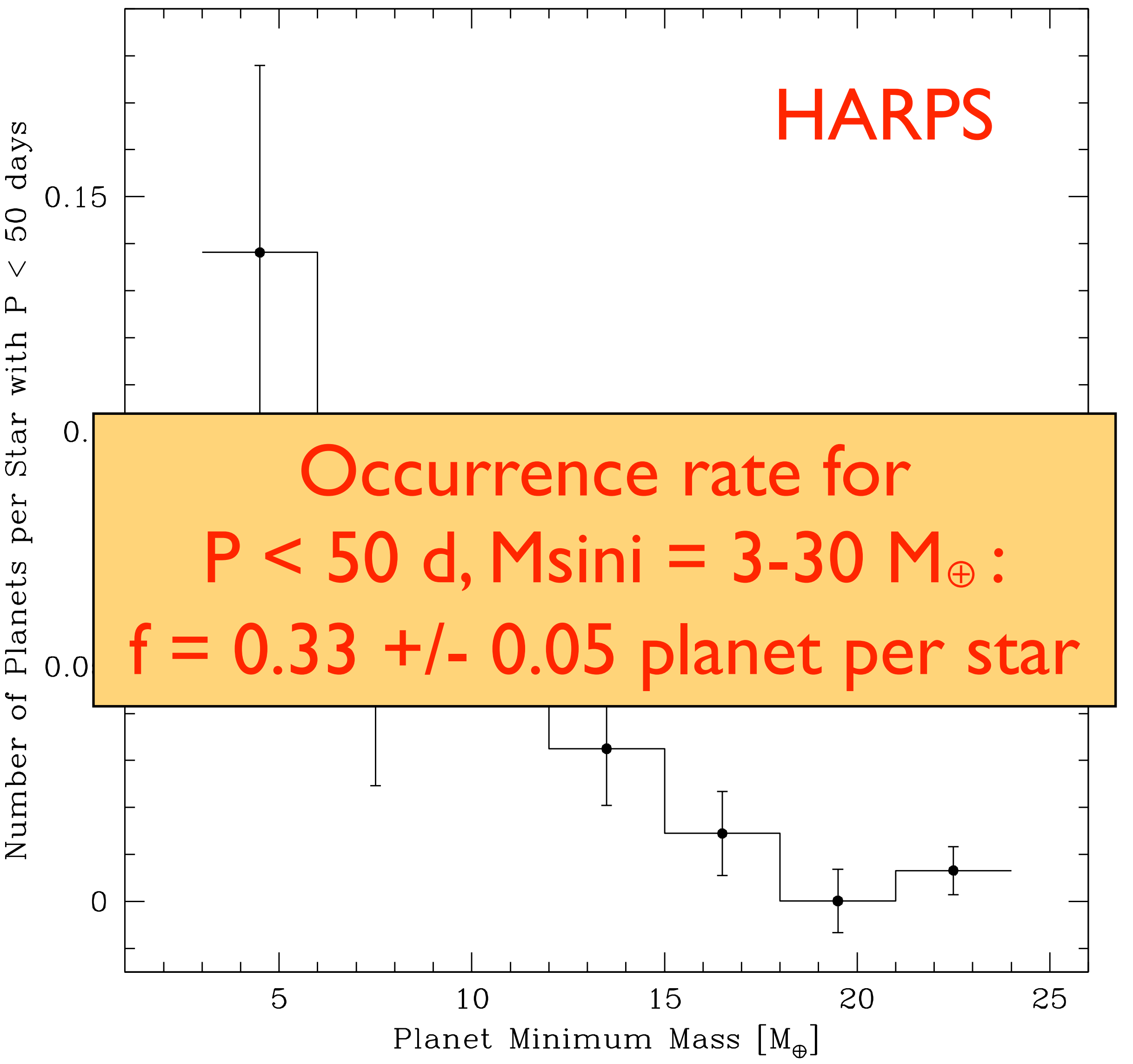
Occurrence rate for
P < 50 d, Msini = 3-30 M⊕ :
f = 0.33 +/- 0.05 planet per star

From Mayor et al. 2011



From Fressin et al. 2013

Unbiased, Normalized Mass and Radius Distributions



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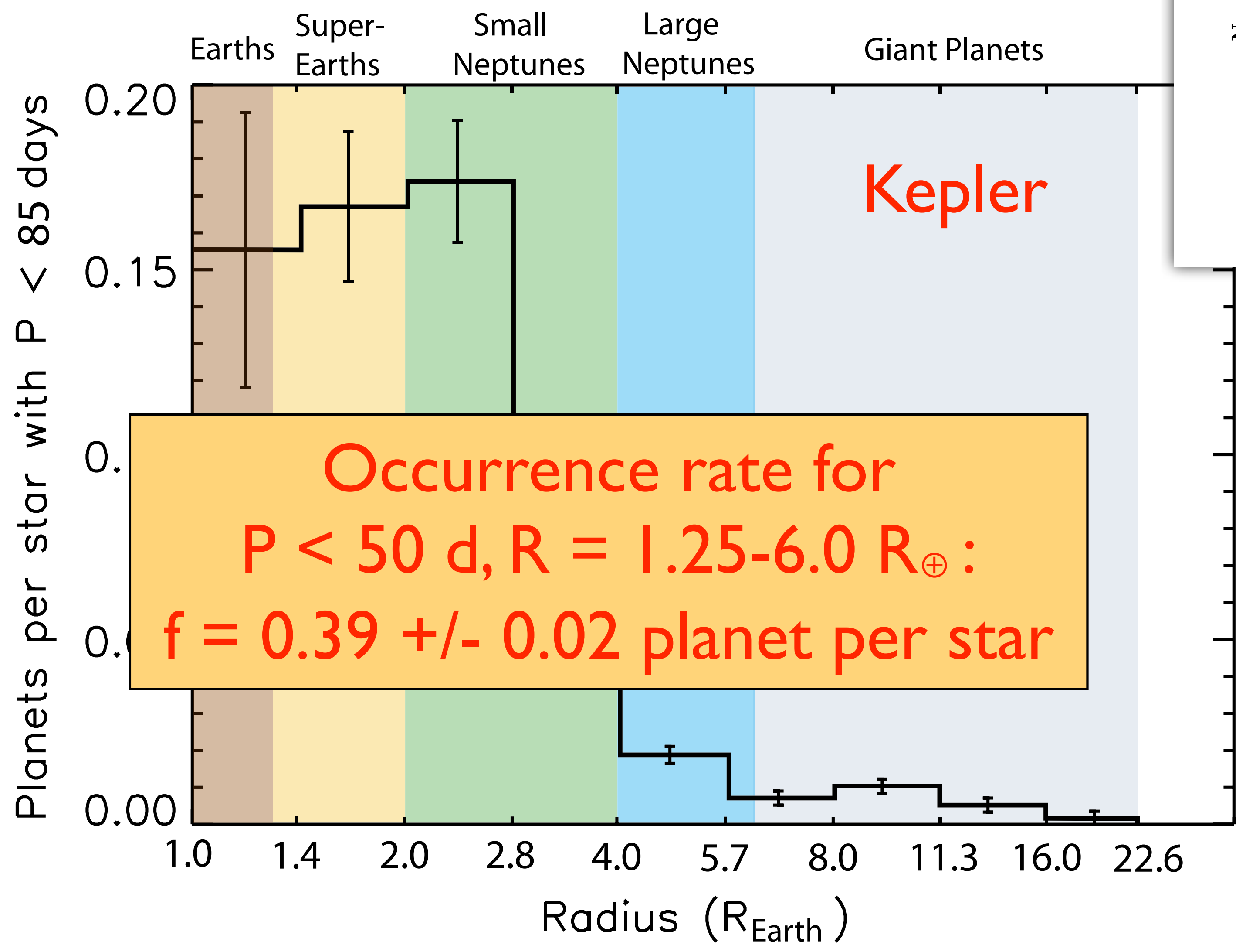
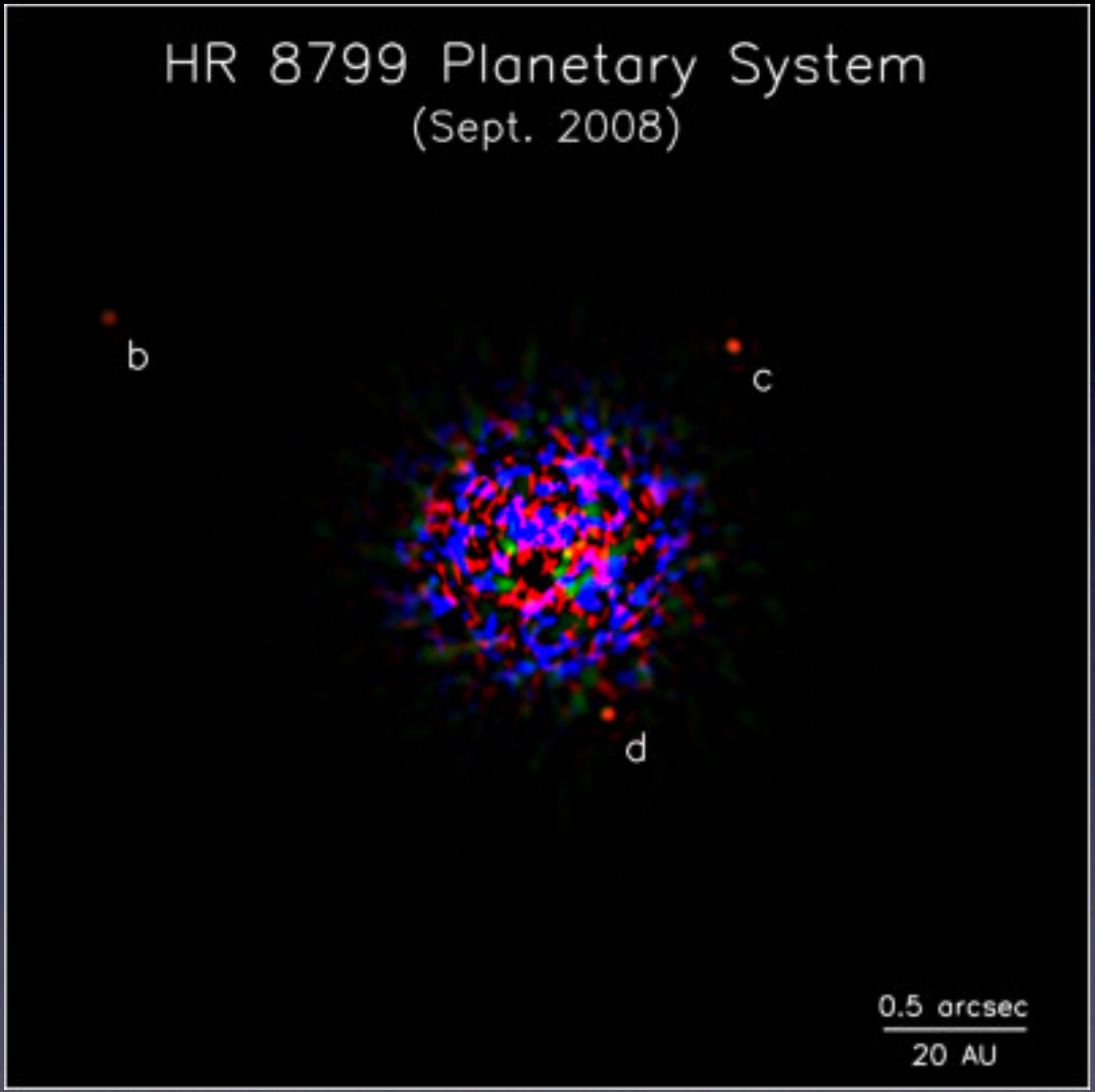


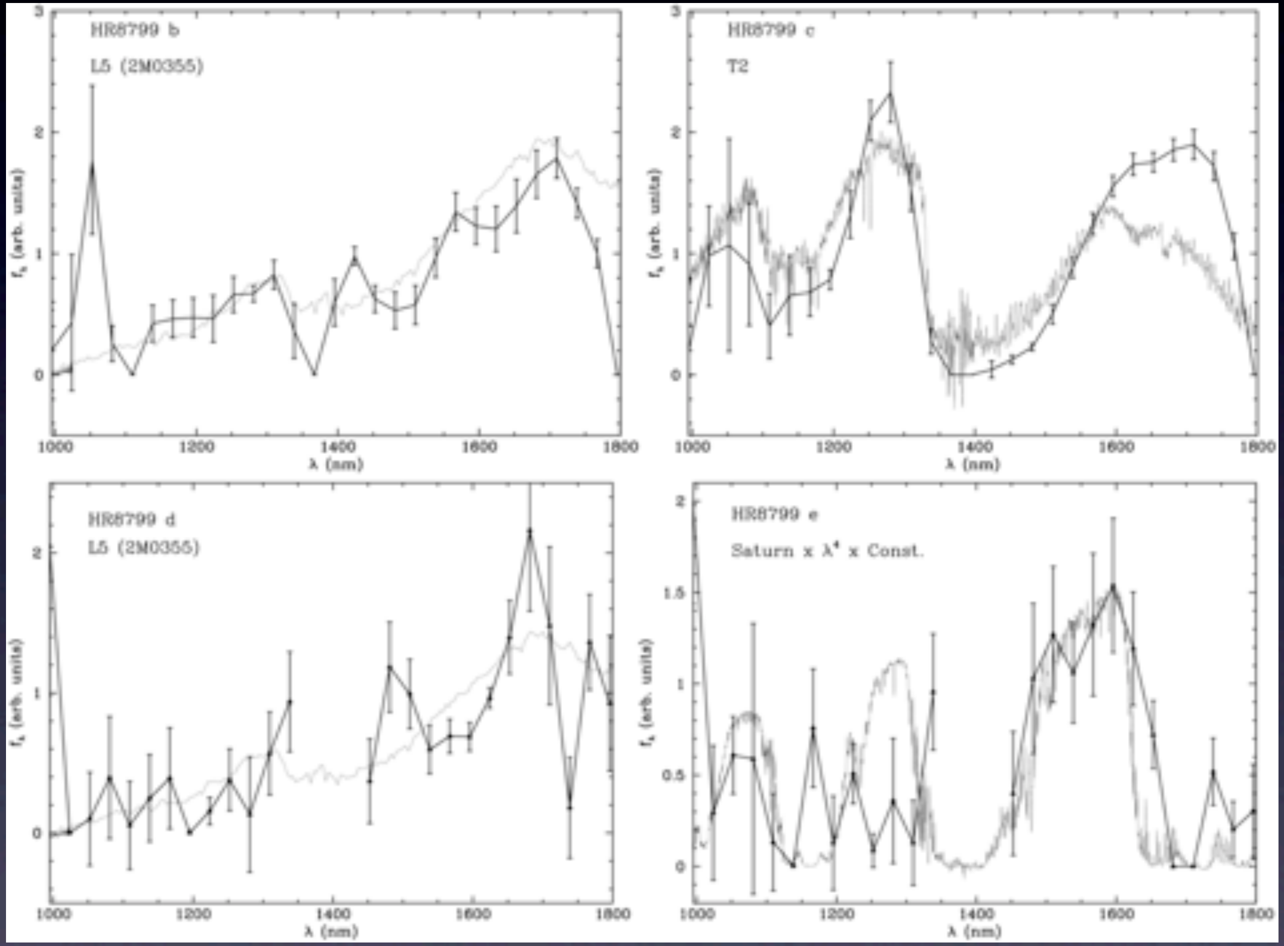
Occurrence rate for
P < 50 d, R = 1.25-6.0 $R_\oplus$:
f = 0.39 +/- 0.02 planet per star

From Fressin et al. 2013

The (Fast) Rise of High-Contrast Imaging and Spectroscopy



Marois et al. 2008



Oppenheimer et al. 2013

A population of super-Jupiters orbiting young 1-2 M☉ stars at 10-100 AU (see B. Biller’s talk)

The Big Questions

- How do planetary systems form?
- How do planetary systems evolve?
- What is the impact of the stellar environment?
- What are the dynamical architectures of planetary systems?
- What is the internal structure of exoplanets, and how does it depend on host star properties, orbital distance, snow line distance, etc?
- What is the chemical composition of exoplanet atmospheres, and how does it depend on host star properties, planet mass, orbital distance, etc?
- How common are rocky planets with physical conditions at the surface permitting liquid water? And actually having liquid water?

The in-depth knowledge of a limited number of planetary systems may help us much more than only partly characterized, disparate samples

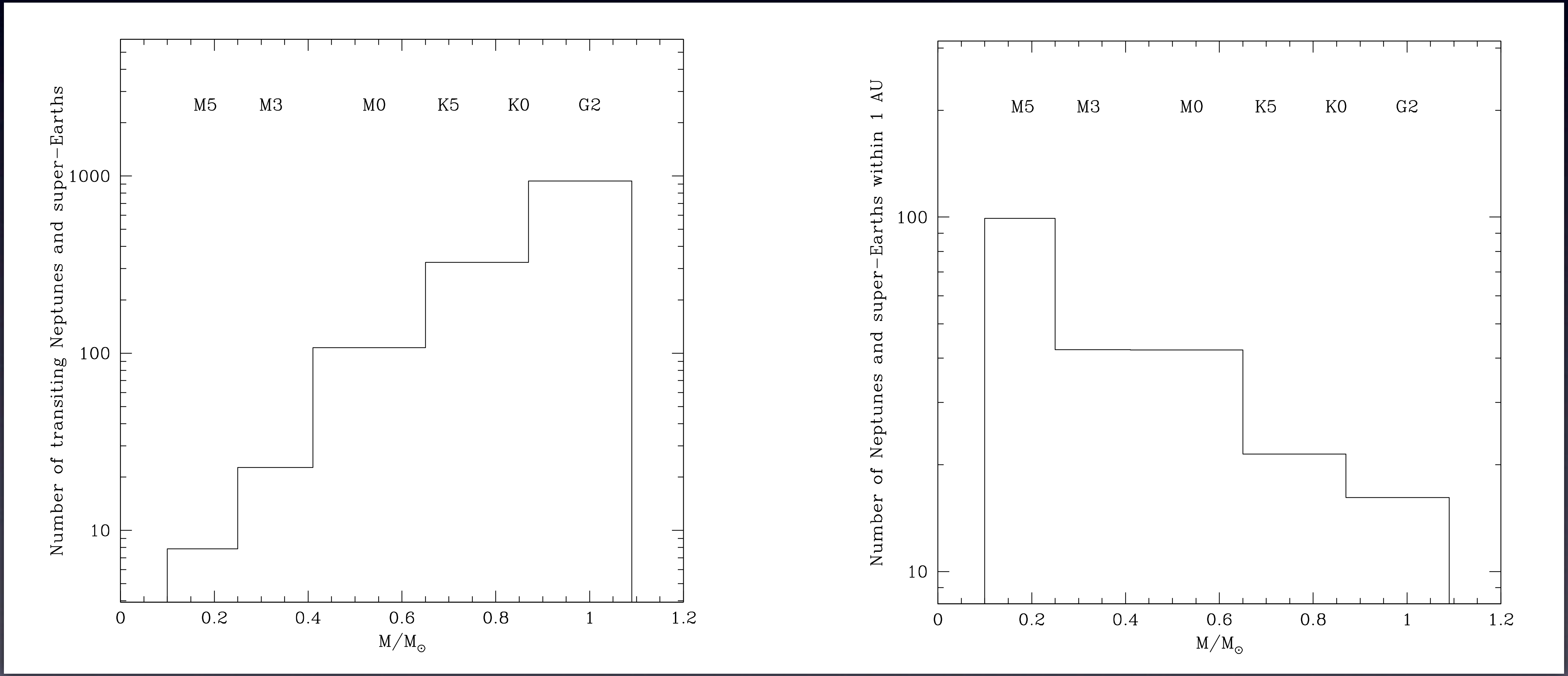
Towards a global picture of planetary systems and their host stars

Property of Interest	*Available Technique*
High-precision stellar properties: mass, radius, Teff, age, [Fe/H], abundances of various elements	High-resolution spectroscopy, long-baseline interferometry, high-precision astrometry (GAIA)
Binarity or multiplicity of the host star	Direct imaging, long-term Doppler velocimetry, astrometry (GAIA)
Existence and properties of debris disks	High-contrast imaging, interferometry
Orbital properties of all dynamically important planets in the system	High-precision transit photometry, long-term Doppler velocimetry, astrometry (GAIA), high-contrast imaging
Mass and radius (➔ density, bulk composition) of the dynamically important planets	High-precision transit photometry, Doppler velocimetry, astrometry (GAIA)
Atmospheric characterization of one or more planet(s)	Transit/eclipse spectrophotometry, high-resolution spectroscopy, high-contrast spectroscopy

The Exoplanet Population in the Solar Neighbourhood

Transiting low-mass planets
Magnitude-limited: K < 9.0
(V < 10.5 at G2, V < 14 at M5)

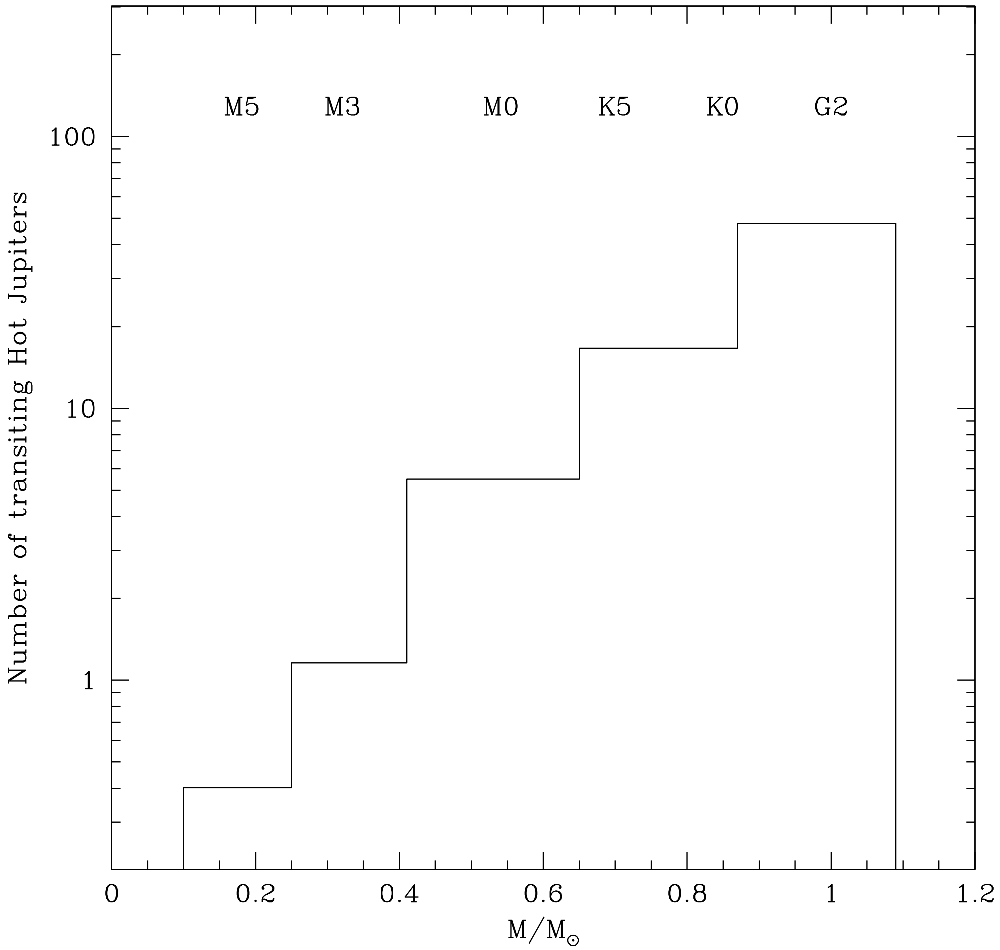
All low-mass planets within 1 AU
Volume-limited: d < 10 pc
(K < 3.4 at G2, K < 8.2 at M5)



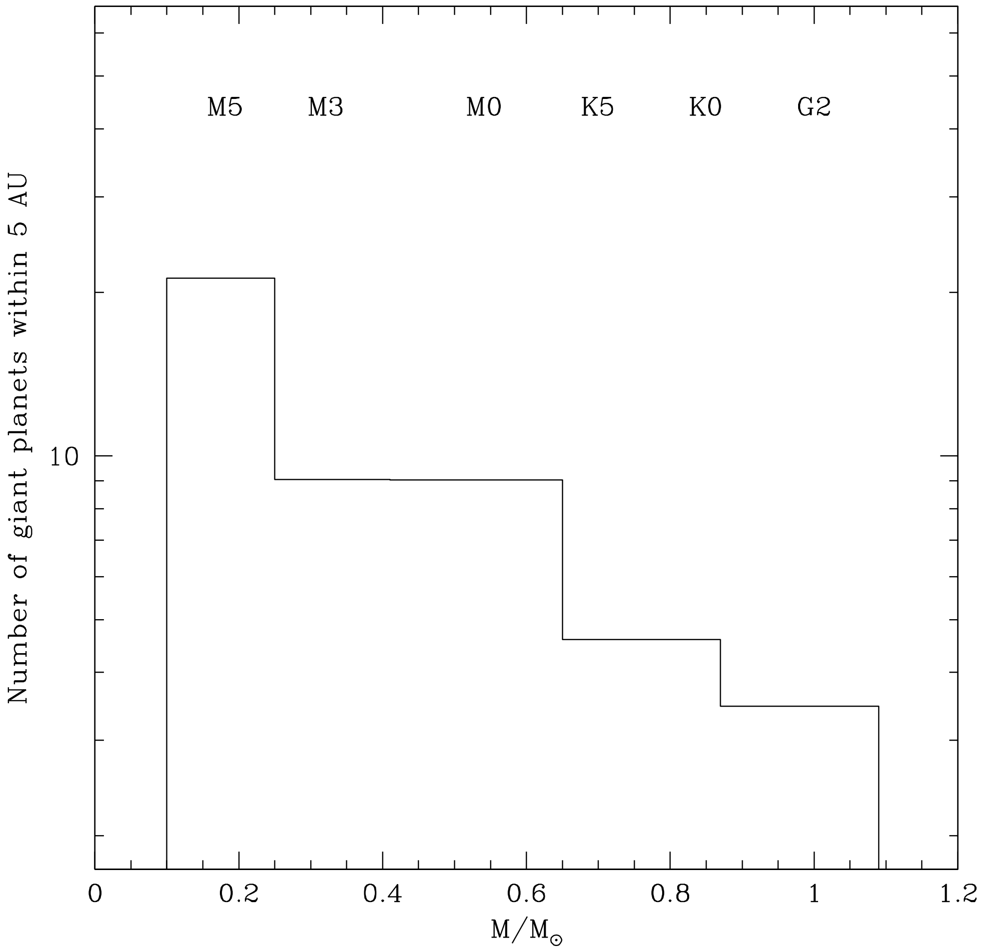
EChO mission reference sample (Ribas & Lovis 2013), see also Crossfield et al. 2013

The Exoplanet Population in the Solar Neighbourhood

Transiting hot Jupiters
Magnitude-limited: K < 9.0
(V < 10.5 at G2, V < 14 at M5)

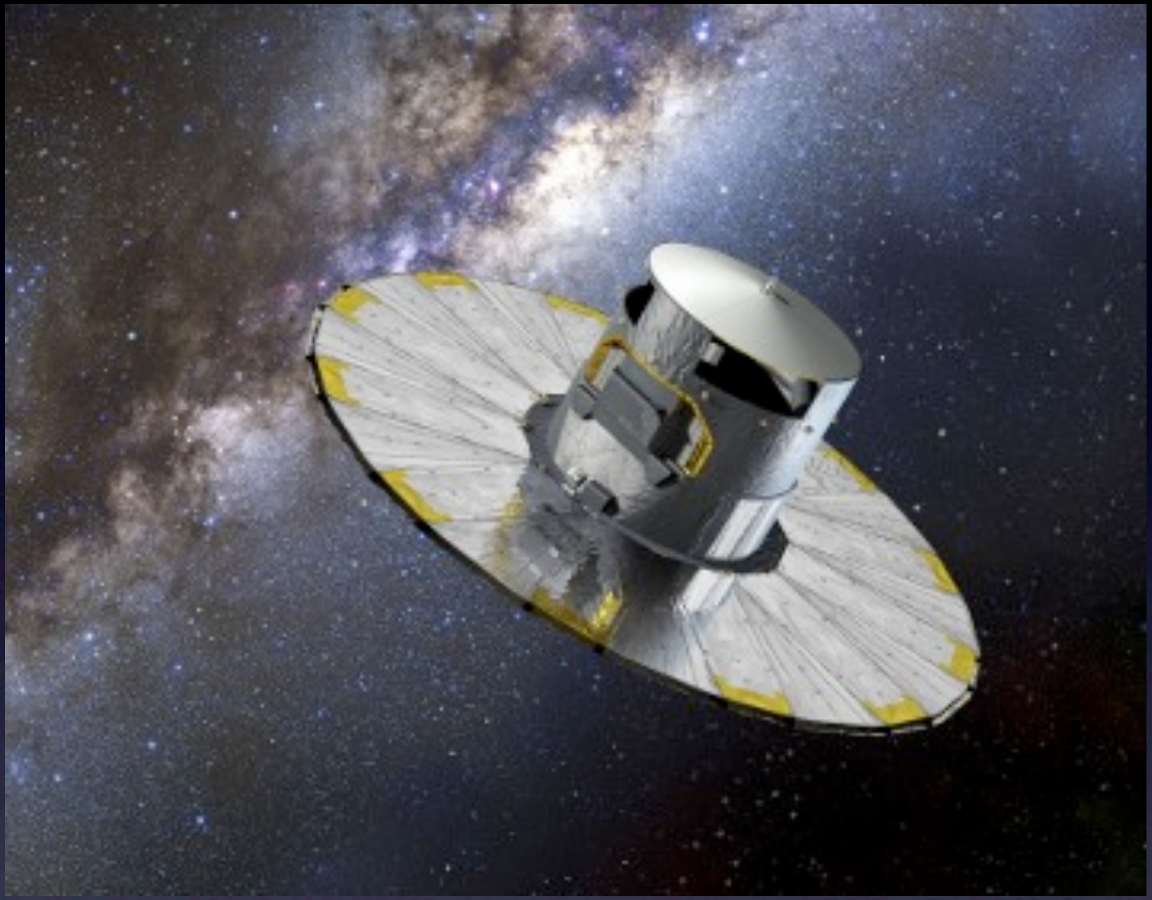


All giant planets within 5 AU
Volume-limited: d < 10 pc
(K < 3.4 at G2, K < 8.2 at M5)



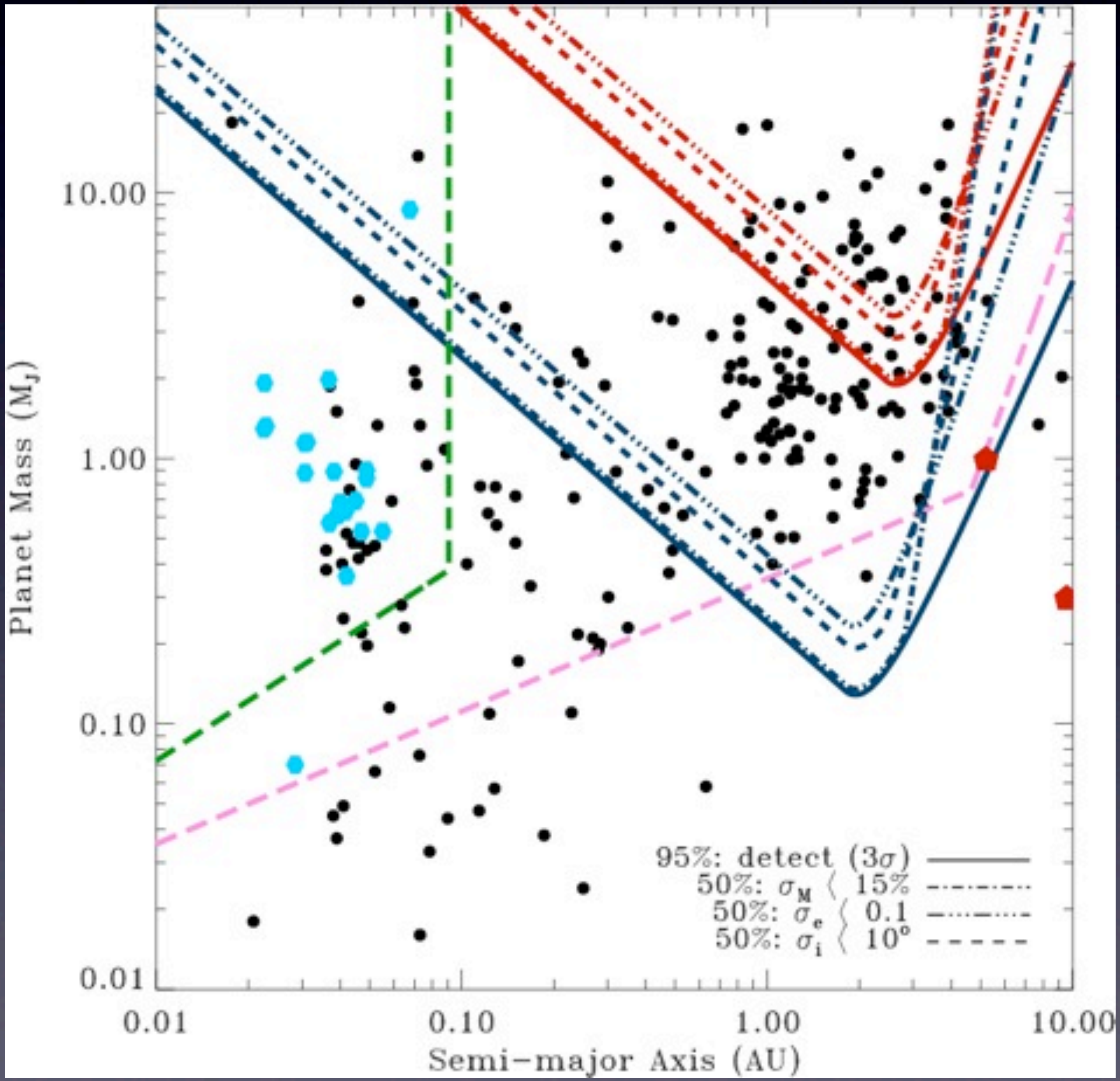
EChO mission reference sample (Ribas & Lovis 2013), see also Crossfield et al. 2013

GAIA Astrometry and Spectrophotometry



Precise knowledge of stellar fundamental parameters: distance, luminosity, Teff, radius

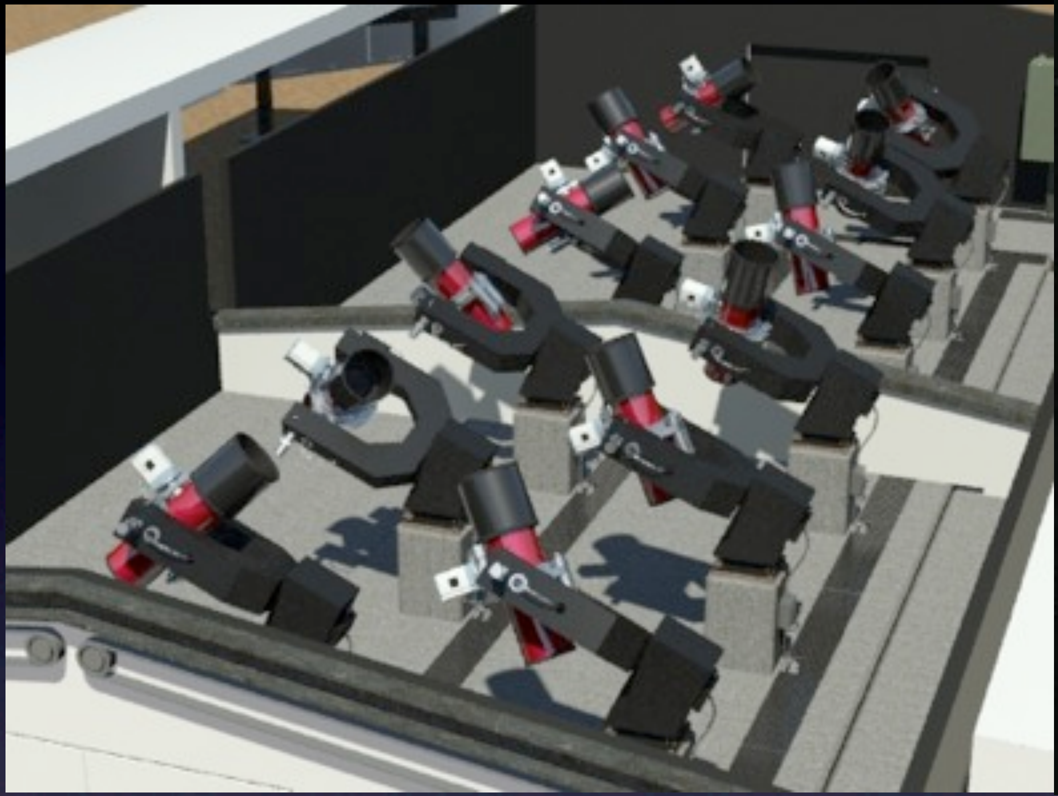
Probing giant exoplanets at intermediate orbital distances



Casertano et al. 2008

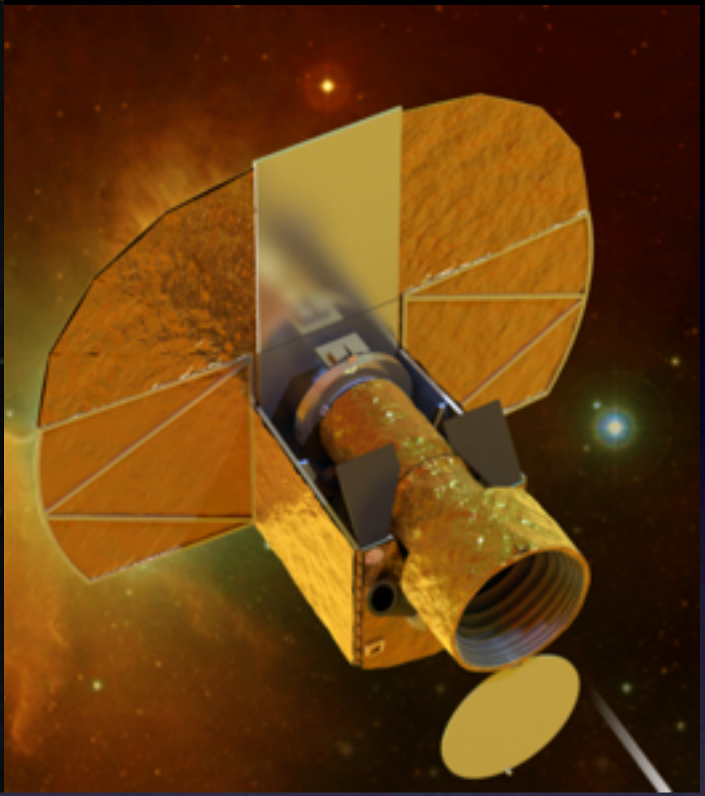
The Solar Neighborhood Transit Search Army

NGTS (2014)

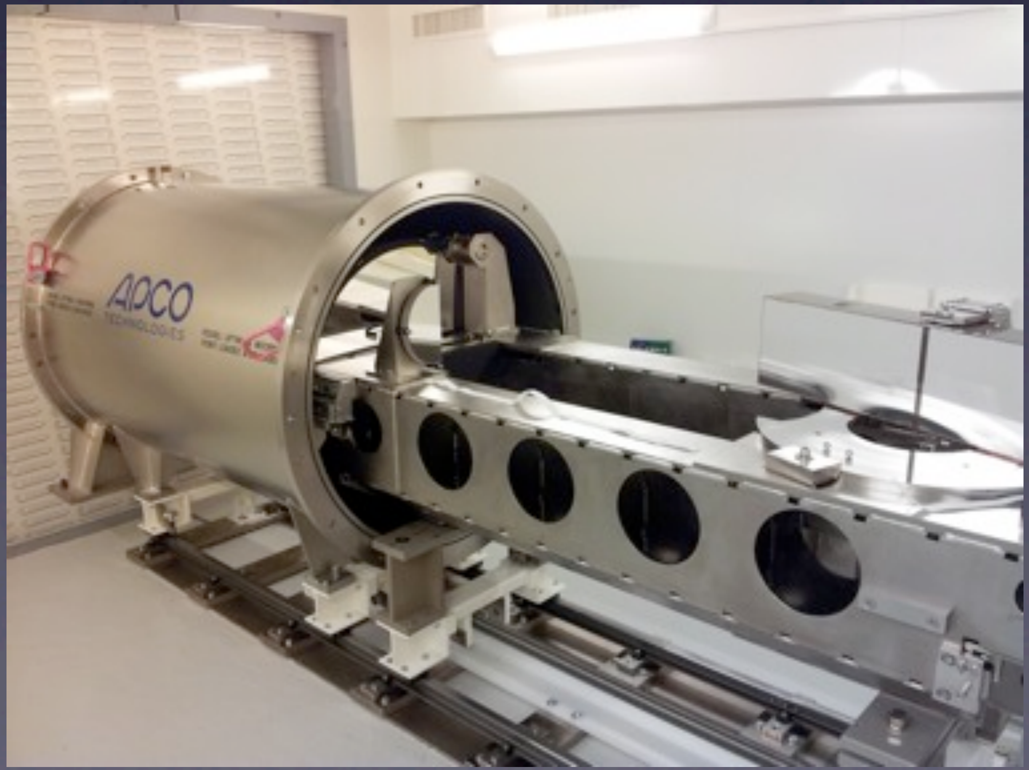


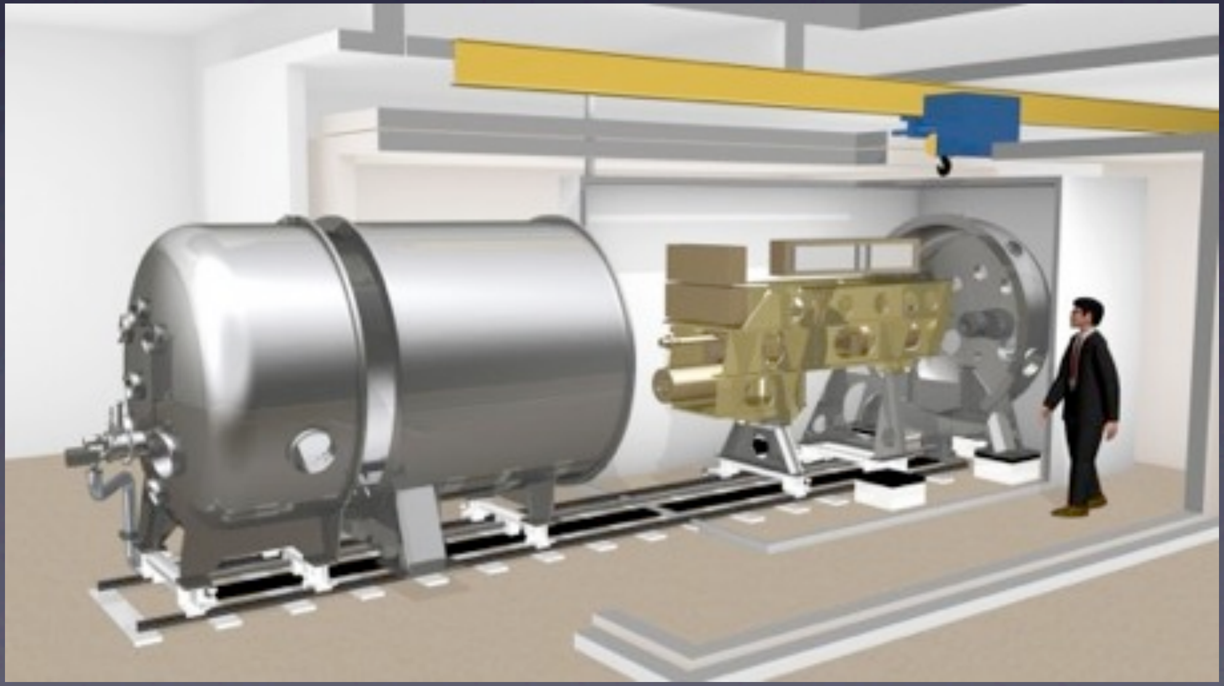
TESS (2017)

CHEOPS (2017)



HARPS
HARPS-N
SOPHIE
CORALIE
Keck/AAT
(operating)

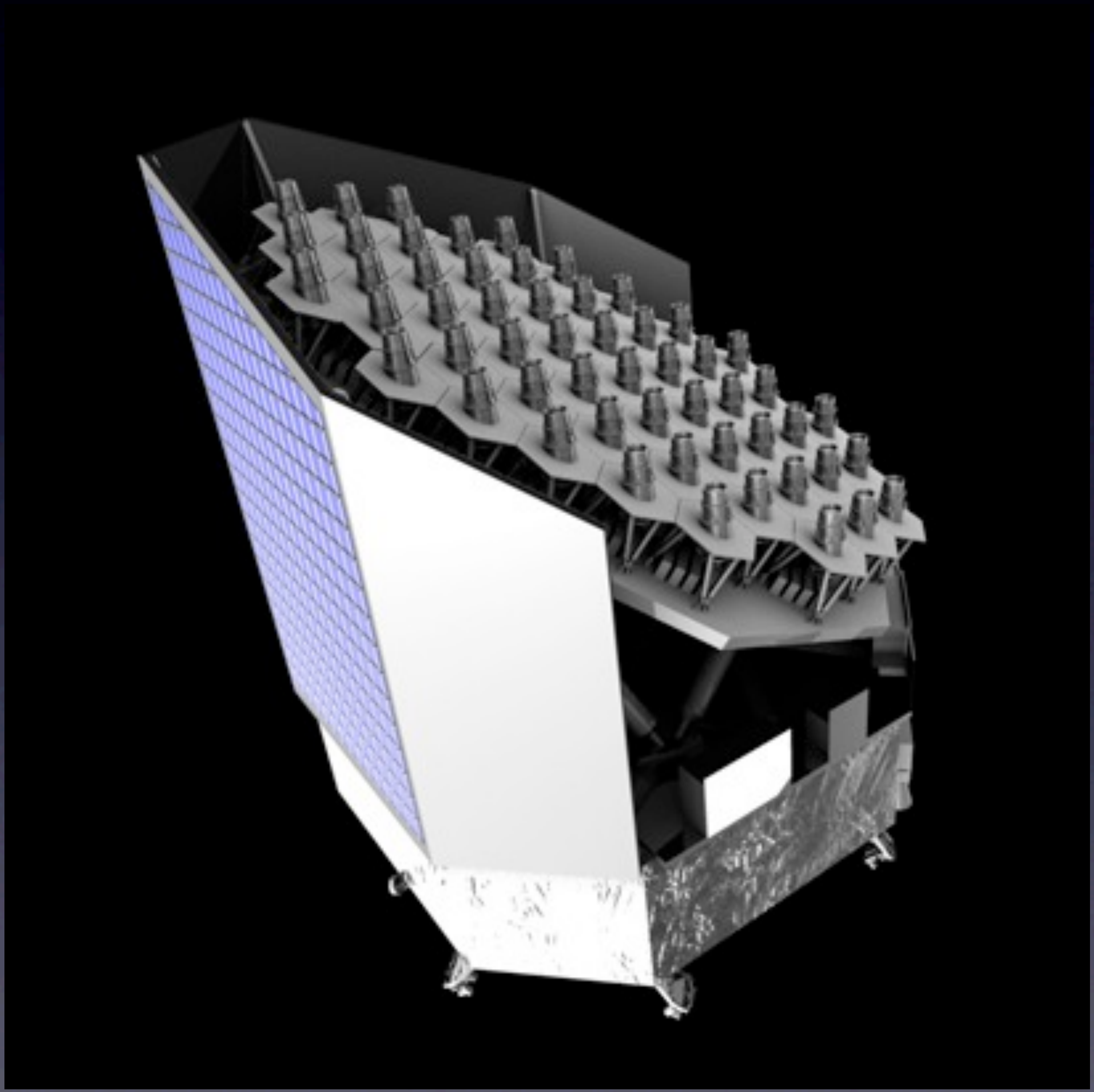




ESPRESSO (2017)

The Solar Neighborhood Transit Search Army

Kepler-K2 (2014)



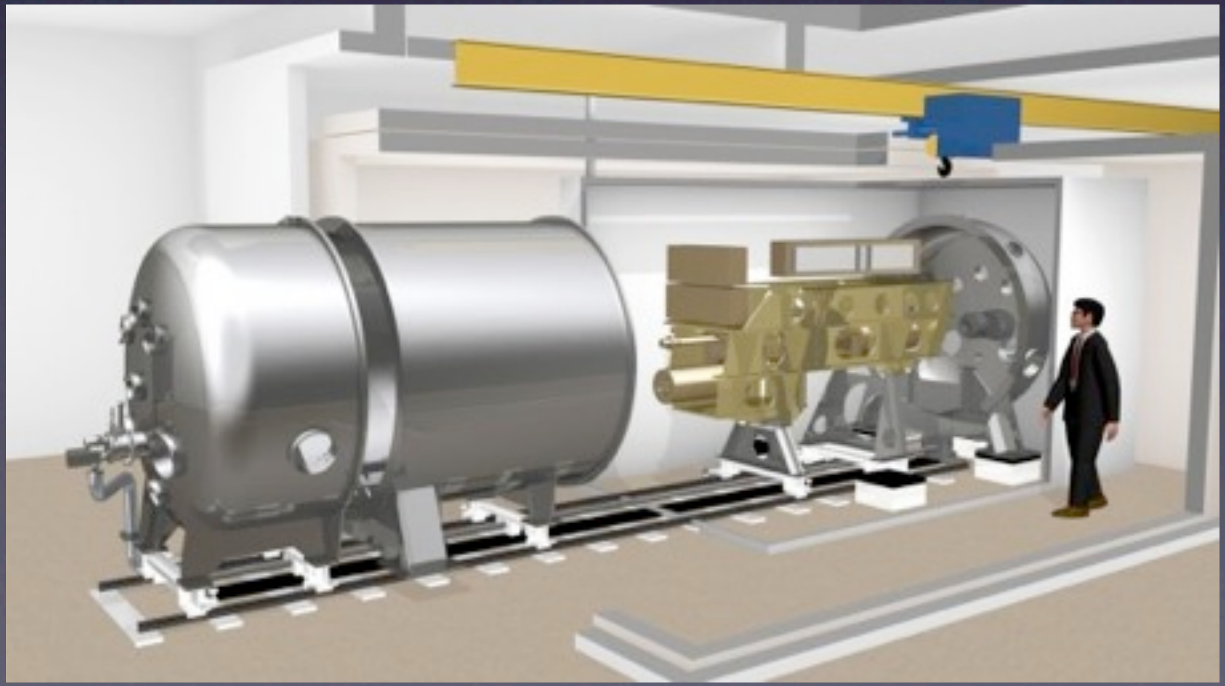
PLATO (2022-2024) ?

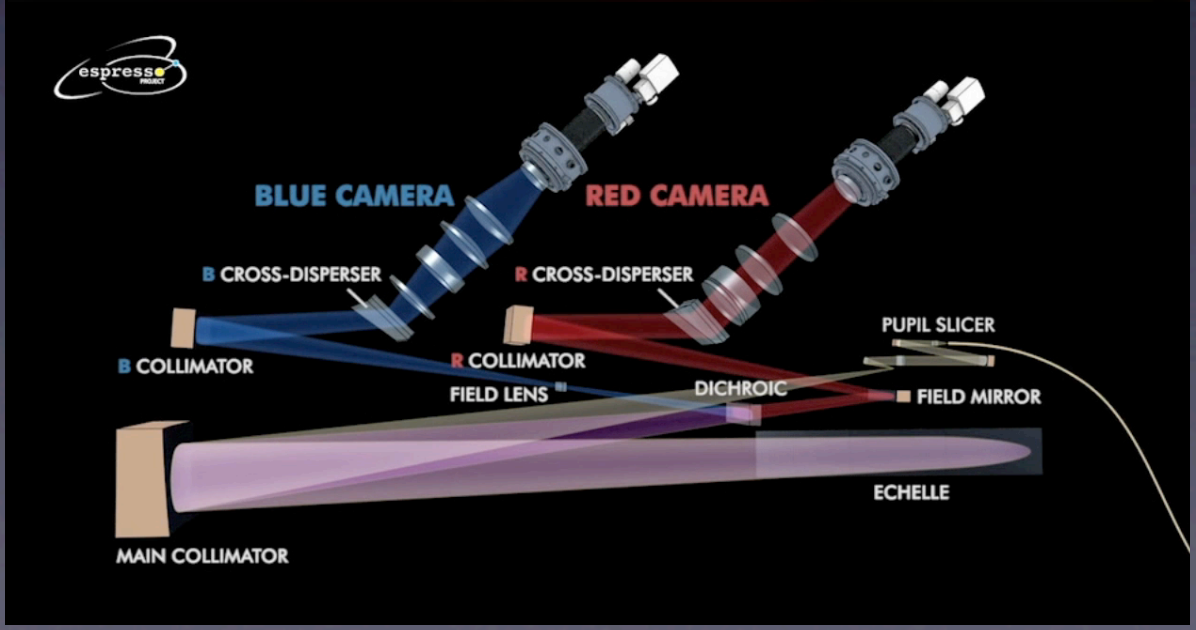
ESPRESSO @ VLT

“Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations”

- Ultra-stable spectrograph for the VLT
- R = 130,000
- Visible, 380-780 nm, blue + red arms
- Can use any of the UTs (Coudé train)

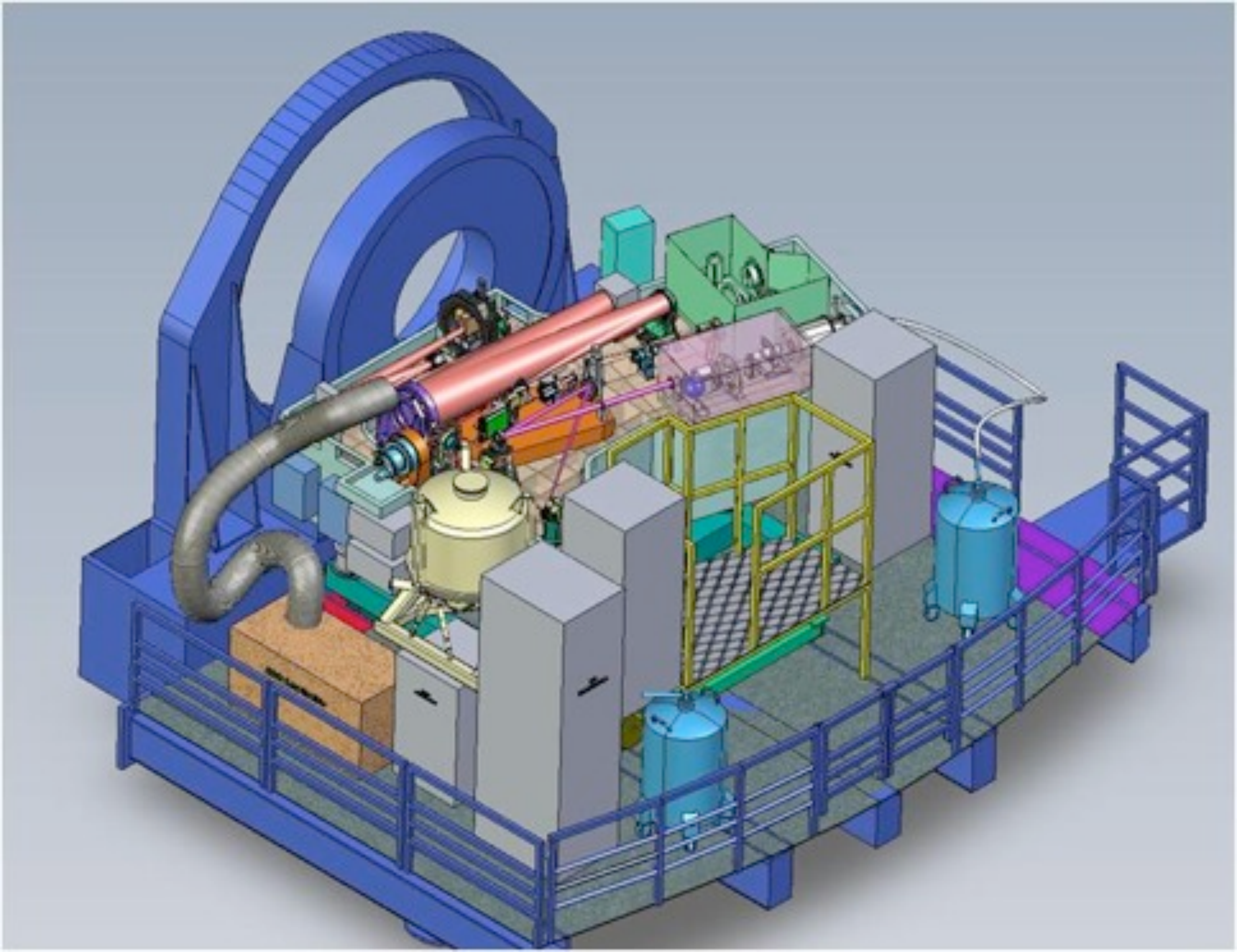
- Consortium: Switzerland, Italy, Portugal, Spain
- FDR: now
- On the sky: end 2016

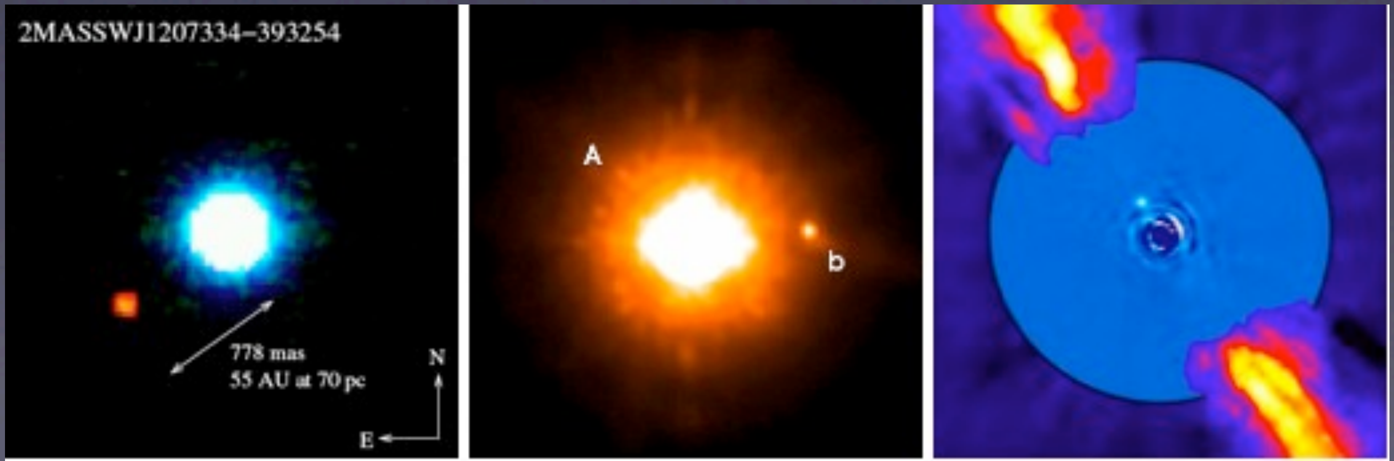


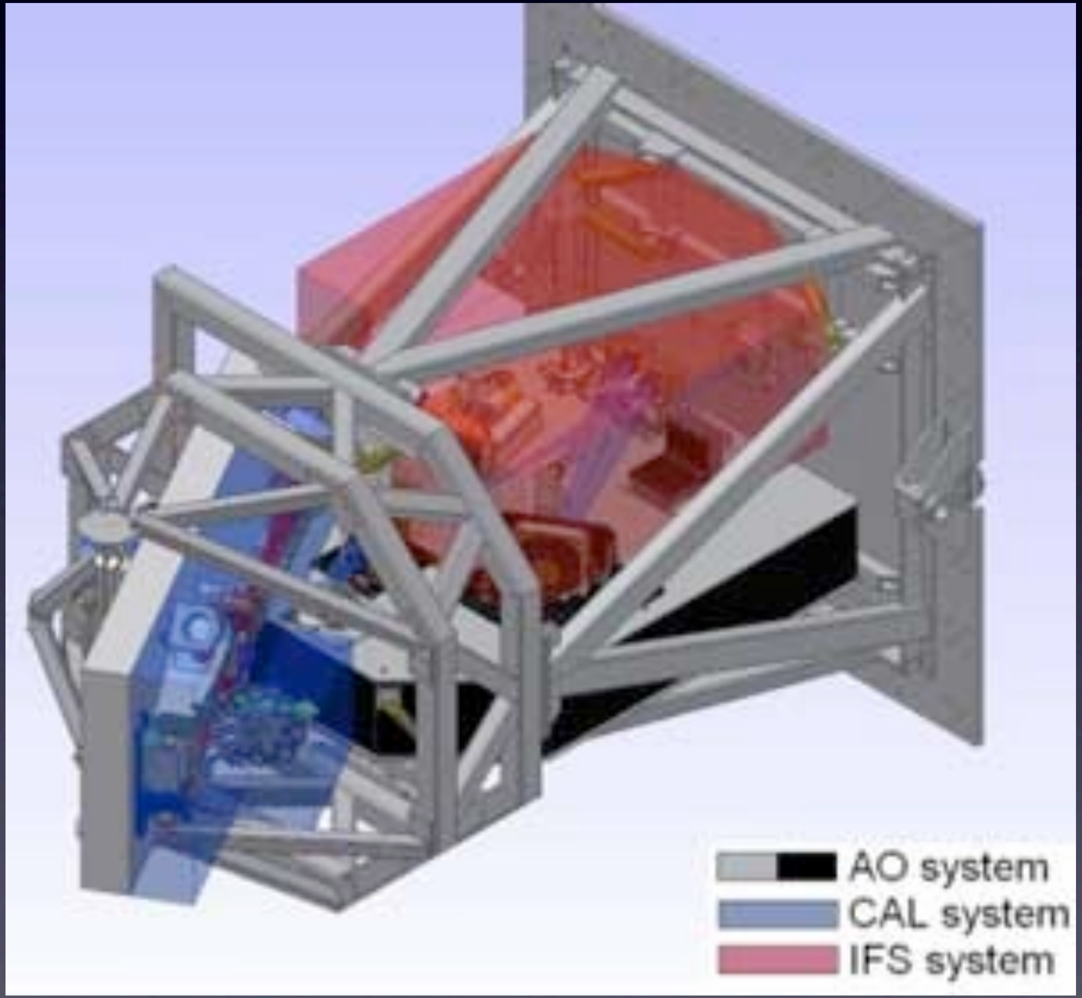


New High-Contrast Planet Imagers

VLT-SPHERE (2014)







Gemini-GPI (2014)

Towards a global picture of planetary systems and their host stars

Property of Interest	*Available Technique*
High-precision stellar properties: mass, radius, Teff, age, [Fe/H], abundances of various elements	High-resolution spectroscopy, long-baseline interferometry, high-precision astrometry (GAIA)
Binarity or multiplicity of the host star	Direct imaging, long-term Doppler velocimetry, astrometry (GAIA)
Existence and properties of debris disks	High-contrast imaging, interferometry
Orbital properties of all dynamically important planets in the system	High-precision transit photometry, long-term Doppler velocimetry, astrometry (GAIA), high-contrast imaging
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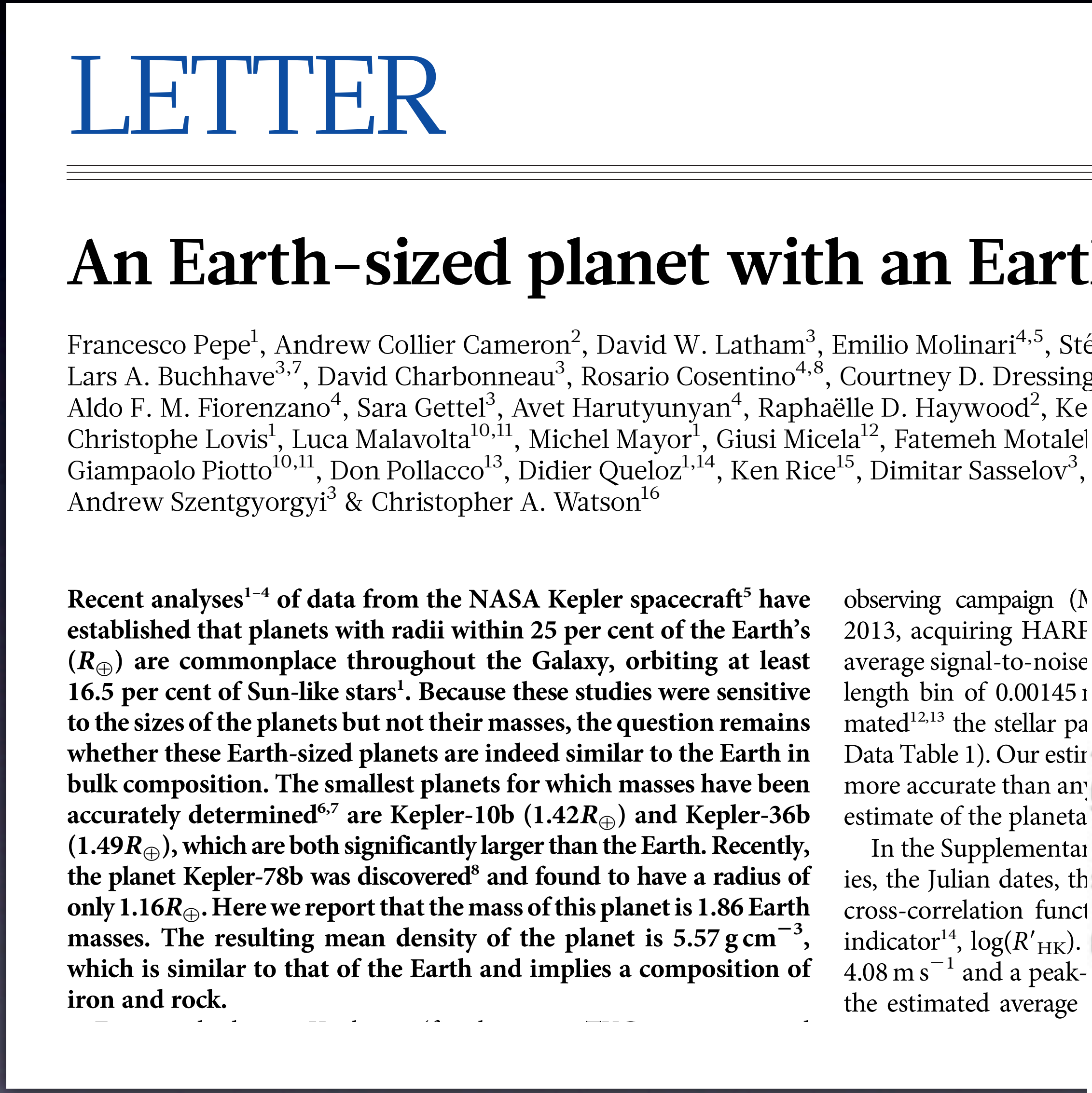
Atmospheric characterization of one or more planet(s)	Transit/eclipse spectrophotometry, high-resolution spectroscopy, high-contrast spectroscopy

Bulk Density and Internal Structure

Combination of precise mass and radius measurements obtained from transit photometry and Doppler velocimetry



LETTER

doi:10.1038/nature12768

An Earth-sized planet with an Earth-like density

Francesco Pepe[1], Andrew Collier Cameron[2], David W. Latham[3], Emilio Molinari[4,5], Stéphane Udry[1], Aldo S. Bonomo[6], Lars A. Buchhave[3,7], David Charbonneau[3], Rosario Cosentino[4,8], Courtney D. Dressing[3], Xavier Dumusque[3], Pedro Figueira[9], Aldo F. M. Fiorenzano[4], Sara Gettel[3], Avet Harutyunyan[4], Raphaëlle D. Haywood[2], Ke
Christophe Lovis[1], Luca Malavolta[10,11], Michel Mayor[1], Giusi Micela[12], Fatemeh Motalel
Giampaolo Piotto[10,11], Don Pollacco[13], Didier Queloz[1,14], Ken Rice[15], Dimitar Sasselov[3],
Andrew Szentgyorgyi[3] & Christopher A. Watson[16]

Recent analyses[1–4] of data from the NASA Kepler spacecraft[5] have established that planets with radii within 25 per cent of the Earth's ($R_\oplus$) are commonplace throughout the Galaxy, orbiting at least 16.5 per cent of Sun-like stars[1]. Because these studies were sensitive to the sizes of the planets but not their masses, the question remains whether these Earth-sized planets are indeed similar to the Earth in bulk composition. The smallest planets for which masses have been accurately determined[6,7] are Kepler-10b (1.42$R_\oplus$) and Kepler-36b (1.49$R_\oplus$), which are both significantly larger than the Earth. Recently, the planet Kepler-78b was discovered[8] and found to have a radius of only 1.16$R_\oplus$. Here we report that the mass of this planet is 1.86 Earth masses. The resulting mean density of the planet is 5.57 g cm^{-3}, which is similar to that of the Earth and implies a composition of iron and rock.

observing campaign (M
2013, acquiring HARP
average signal-to-noise
length bin of 0.00145 r
mated[12,13] the stellar pa
Data Table 1). Our estir
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estimate of the planeta

In the Supplementar
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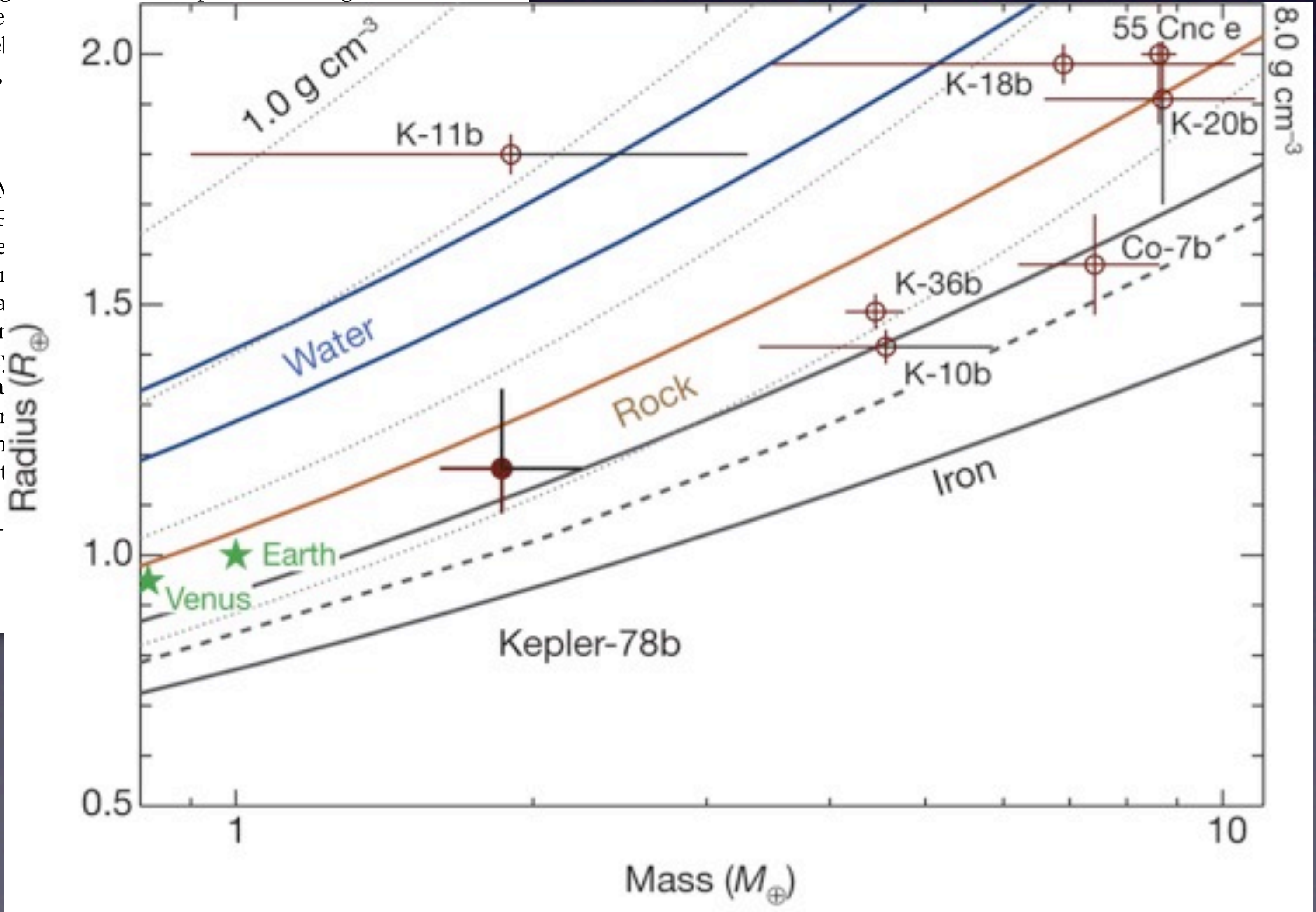
cross-correlation funct
indicator[14], log(R'_{HK}).
4.08 m s^{-1} and a peak-
the estimated average



Pepe et al. 2013

Towards a global picture of planetary systems and their host stars

	Property of Interest	*Available Technique*	
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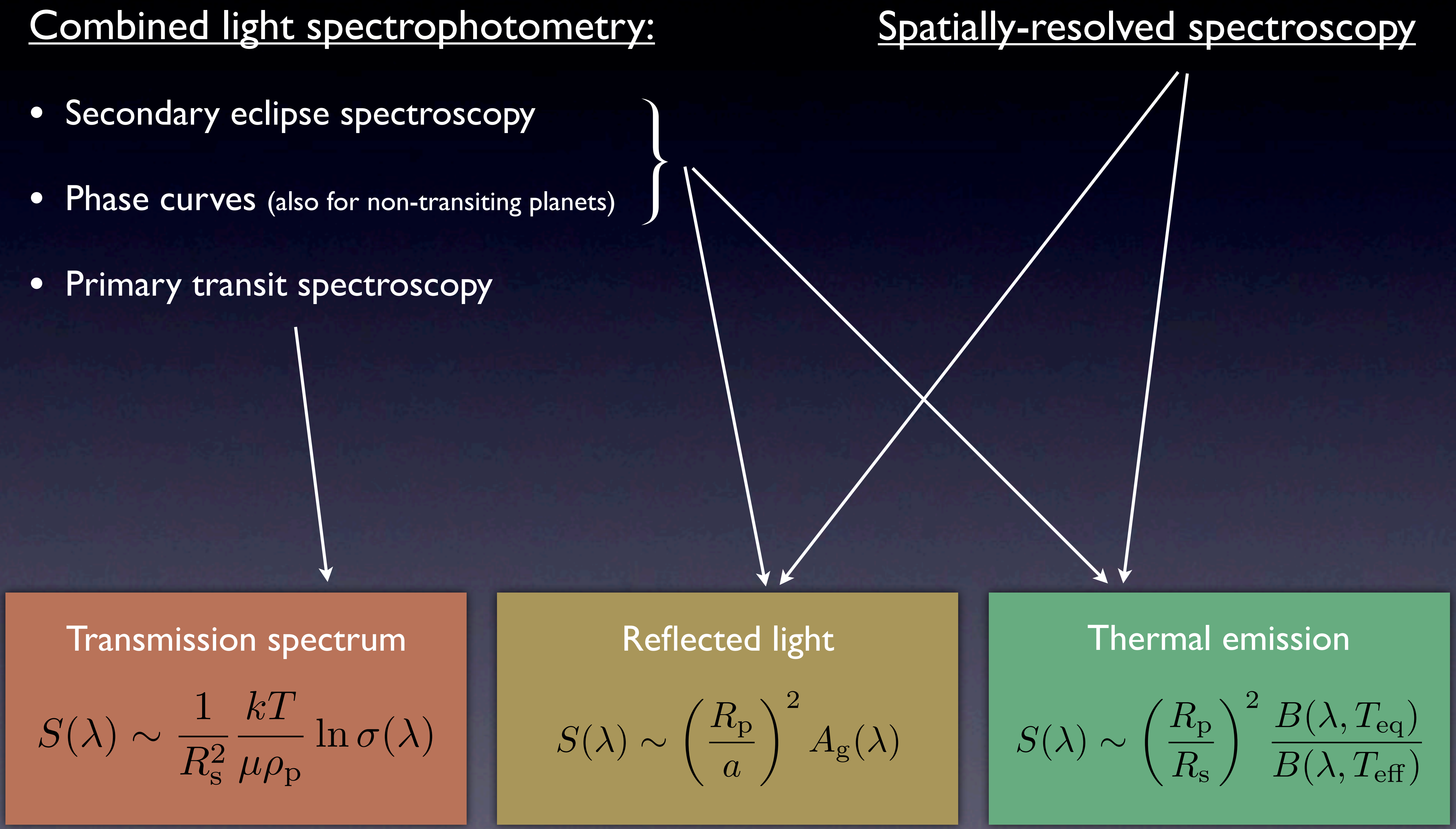
E-ELT	Atmospheric characterization of one or more planet(s)	Transit/eclipse spectrophotometry, high-resolution spectroscopy, high-contrast spectroscopy	*E-ELT*

Atmospheric Characterization



Combined light spectrophotometry:

- Secondary eclipse spectroscopy
- Phase curves (also for non-transiting planets)
- Primary transit spectroscopy

Spatially-resolved spectroscopy

Transmission spectrum

$$S(\lambda) \sim \frac{1}{R_\mathrm{s}^2} \frac{kT}{\mu \rho_\mathrm{p}} \ln \sigma(\lambda)$$

Reflected light

$$S(\lambda) \sim \left(\frac{R_\mathrm{p}}{a} \right)^2 A_\mathrm{g}(\lambda)$$

Thermal emission

$$S(\lambda) \sim \left(\frac{R_\mathrm{p}}{R_\mathrm{s}} \right)^2 \frac{B(\lambda, T_\mathrm{eq})}{B(\lambda, T_\mathrm{eff})}$$

Atmospheric Characterization

Planet/star combination	**Transmission**	**Reflected light**	**Thermal emission**
Mini-Neptune, a = 0.1 AU, Teq = 700 K, K0 star, d = 10/30 pc (non-transiting/transiting)	10^{-4}	10^{-6} @ λ=1.0 μm s = 2 λ/D	10^{-5} @ λ=3.5 μm s = 0.6 λ/D
Super-Earth, a = 0.1 AU, Teq = 255 K, M4 star, d = 5/15 pc (non-transiting/transiting)	10^{-5}	10^{-7} @ λ=1.0 μm s = 4 λ/D	10^{-5} @ λ=10 μm s = 0.4 λ/D
Jupiter, a = 2 AU, Teq = 180 K, G2 star, d = 15/110 pc (non-transiting/transiting)	10^{-5}	10^{-8} @ λ=1.0 μm s = 27 λ/D	10^{-7} @ λ=10 μm s = 2.7 λ/D
Young Jupiter, a = 10 AU, Teq = 1200 K, G2 star, d = 30 pc (non-transiting)	N/A	10^{-9} @ λ=1.0 μm s = 67 λ/D	10^{-4} @ λ=2.0 μm s = 33 λ/D
...	...	...	...

Towards “mission reference samples” for HIRES, METIS, EPICS, ...