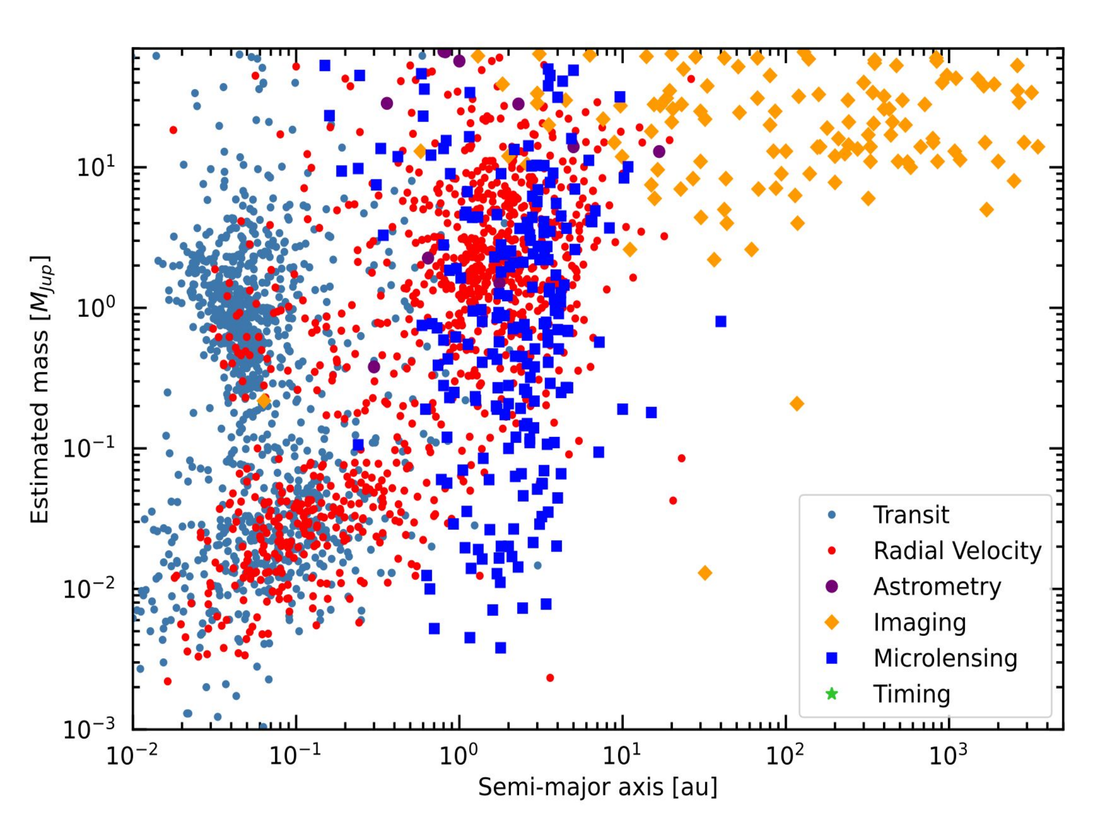
Architecture of planetary systems

Arthur Vigan & Xavier Bonfils

(Empiral) parameter space

- Exploration of a vast parameter space
- Large number of detections
- Sample large enough to identify several classes of objects → comparative planetology!



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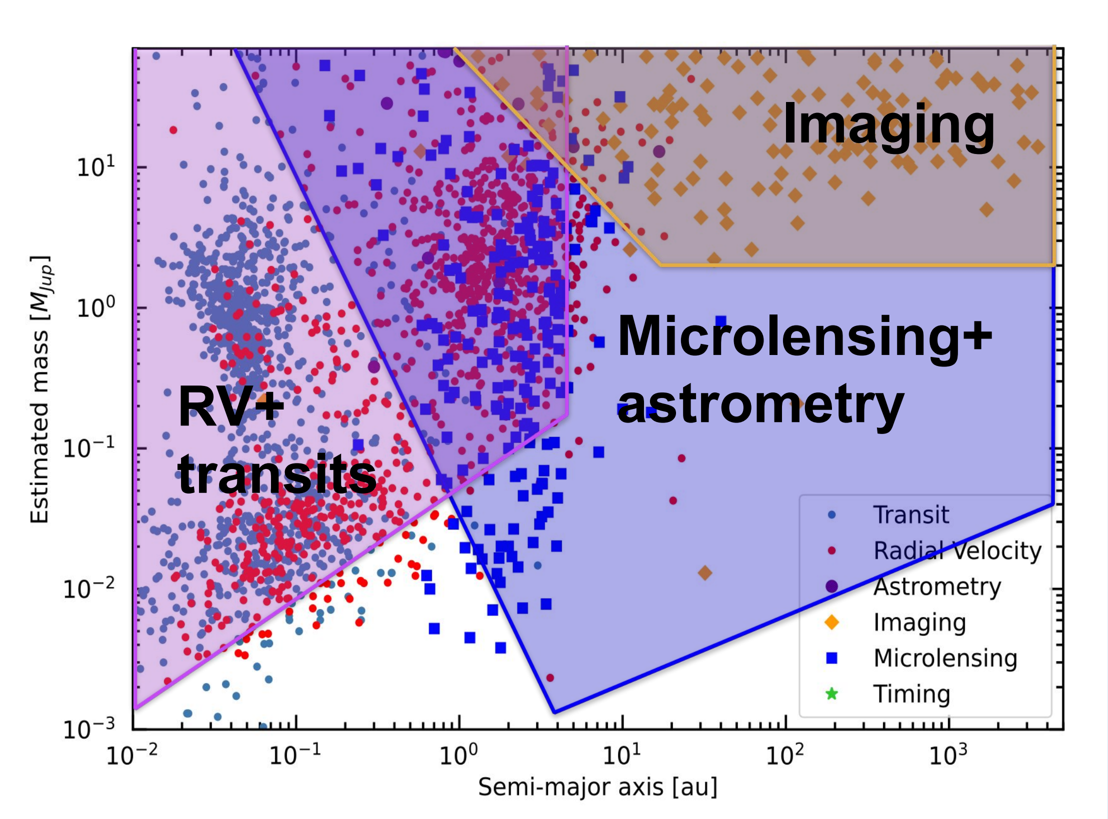
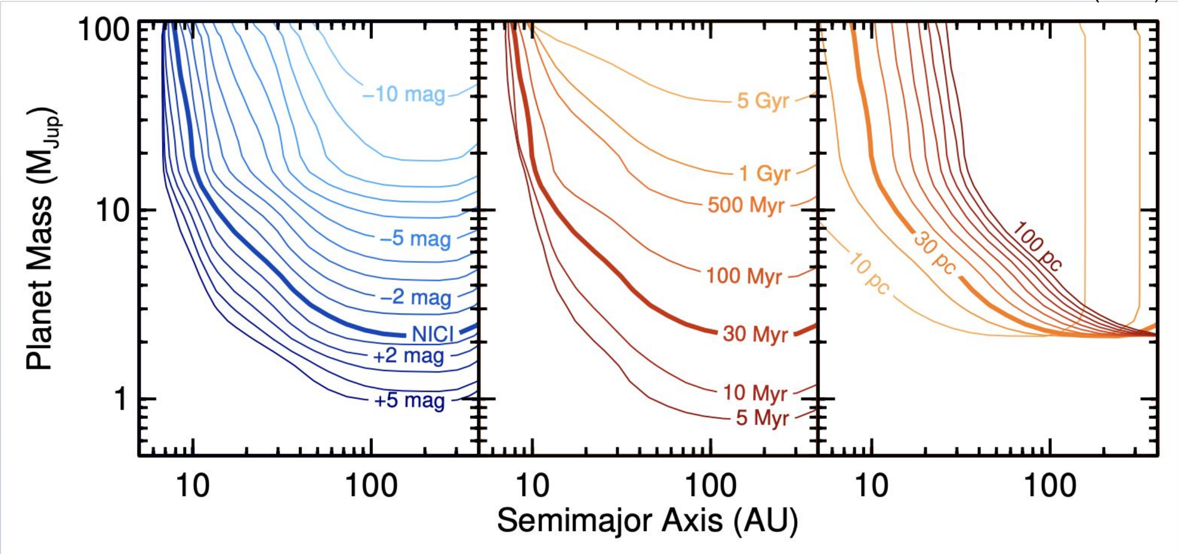


Biases in large surveys

- Astrophysical biases:
  - Age
  - Distance
  - Stellar magnitudes
  - Rotation
  - …
- Instrumental limitations
  - Contraste
  - Stellar magnitudes (AO)
  - Photon noise
  - Accuracy in velocity
  - …
- Theoretical biases:
  - Mass determination using evolutionary tracks!
  - …

Bowler (2016)



Important to debias the results!
(as much as possible)

Statistical properties from RV and transit

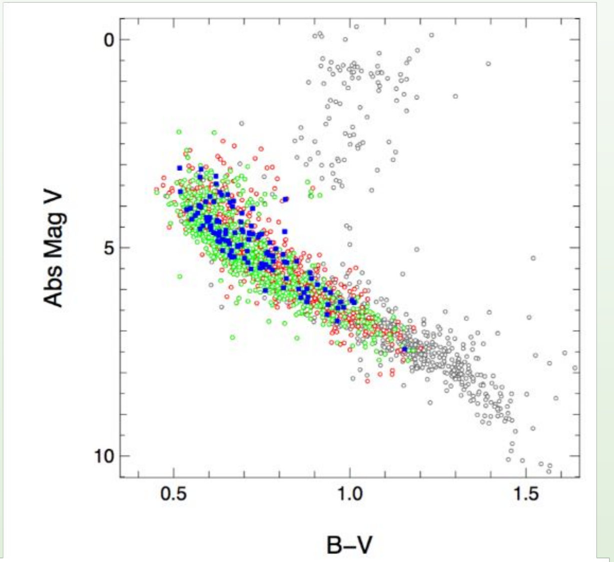
The HARPS search for southern extra-solar planets

XXXIV. Occurrence, mass distribution and orbital properties of super-Earths and Neptune-mass planets★

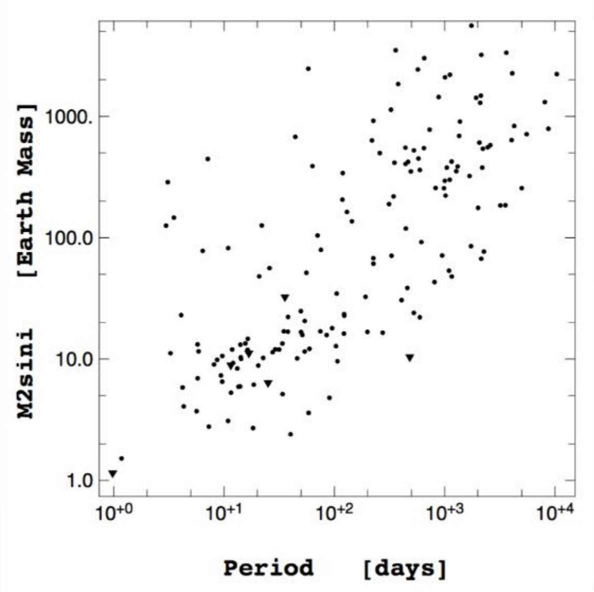
M. Mayor[1], M. Marmier[1], C. Lovis[1], S. Udry[1], D. Ségransan[1], F. Pepe[1], W. Benz[2], J.-L. Bertaux[3], F. Bouchy[4], X. Dumusque[1], G. LoCurto[5], C. Mordasini[6], D. Queloz[1], and N.C. Santos[7,8]

Mayor et al. (2011) astro-ph/1109.2497

see also
Lovis et al. (2008) proc. in IAUS253

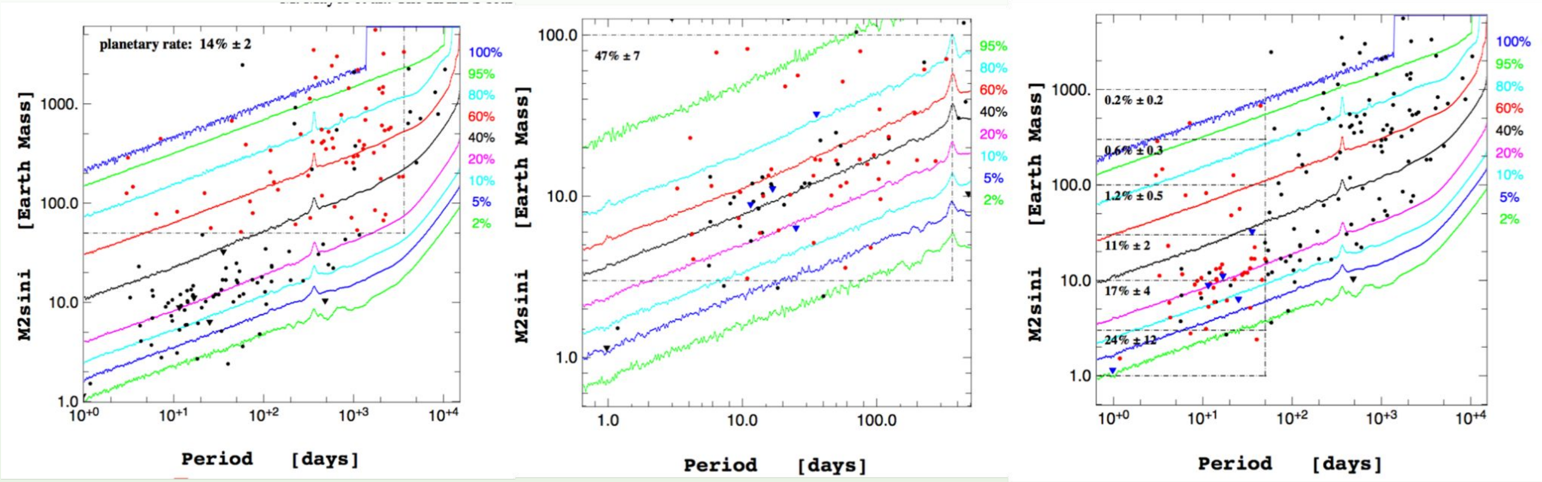


- HARPS: 8 yr, 376 stars
- CORALIE: 13 yr, 1650 stars



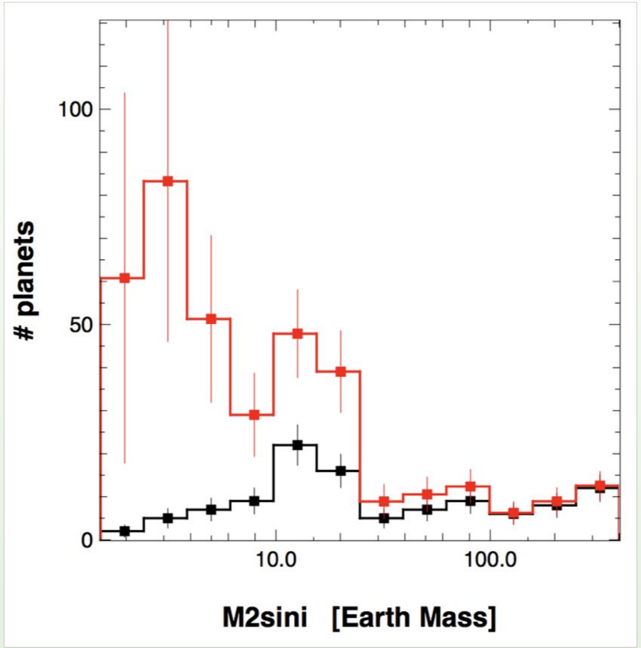
- >150 detections
- at the time, >80% of planets with K1<4m/s

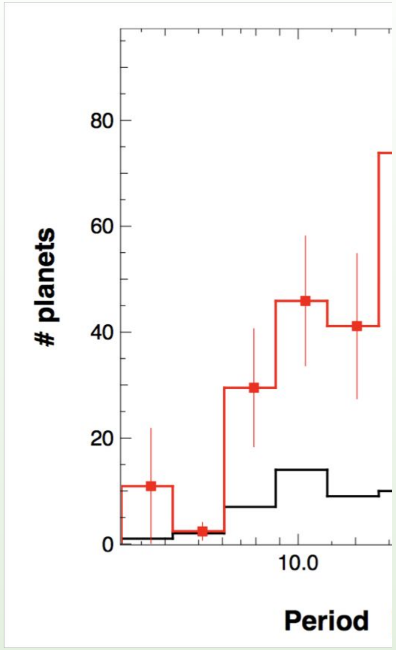
HARPS Mass-Period diagram



Mass limits	Period limit	Planetary rate based on published planets	Planetary rate including candidates	Comments
> 50 $M_\oplus$	< 10 years	13.9 ± 1.7 %	13.9 ± 1.7 %	Gaseous giant planets
> 100 $M_\oplus$	< 10 years	9.7 ± 1.3 %	9.7 ± 1.3 %	Gaseous giant planets
> 50 $M_\oplus$	< 11 days	0.89 ± 0.36 %	0.89 ± 0.36 %	Hot gaseous giant planets
Any masses	< 10 years	65.2 ± 6.6 %	75.1 ± 7.4 %	All "detectable" planets with P < 10 years
Any masses	< 100 days	50.6 ± 7.4 %	57.1 ± 8.0 %	At least 1 planet with P < 100 days
Any masses	< 100 days	68.0 ± 11.7 %	68.9 ± 11.6 %	F and G stars only
Any masses	< 100 days	41.1 ± 11.4 %	52.7 ± 13.2 %	K stars only
< 30 $M_\oplus$	< 100 days	47.9 ± 8.5 %	54.1 ± 9.1 %	Super-Earths and Neptune-mass planets on tight orbits
< 30 $M_\oplus$	< 50 days	38.8 ± 7.1 %	45.0 ± 7.8 %	As defined in Lovis et al. (2009)

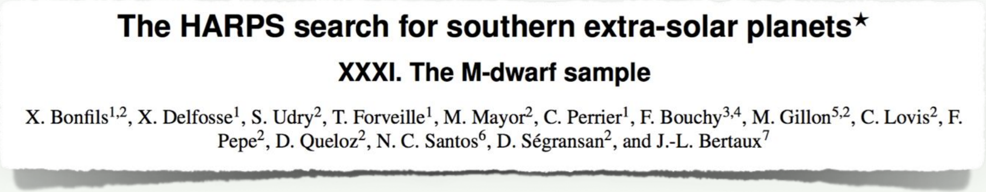
HARPS Mass and Period histograms



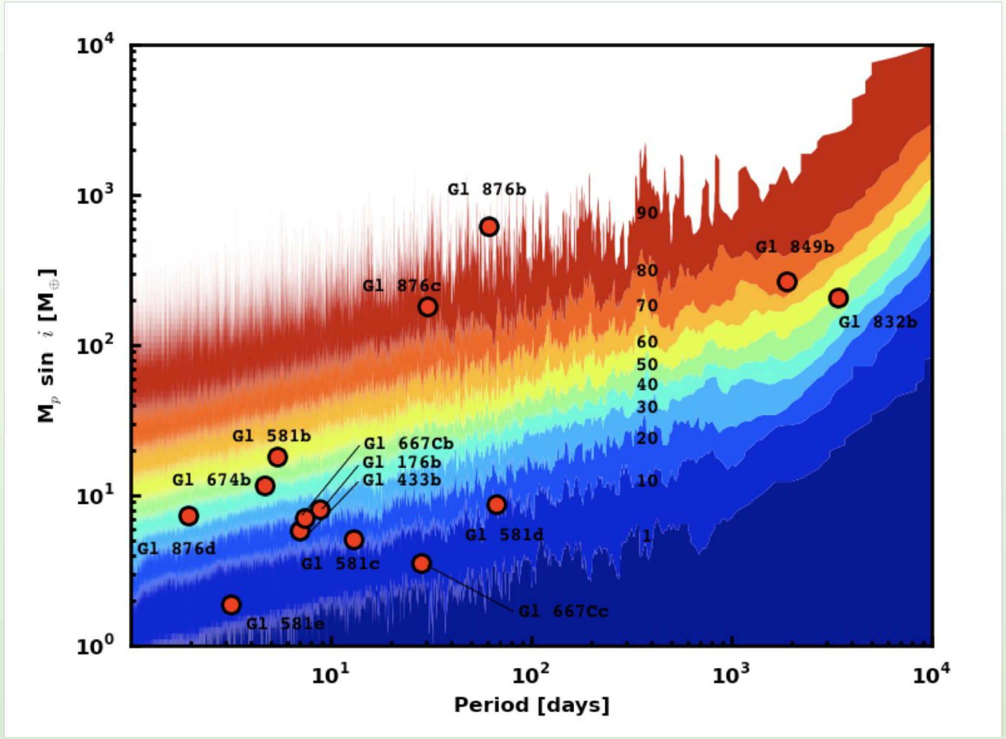


HARPS Multiplicity

- m sin i < 30 Mearth: multiplicity > 70%
- m sin i > 30 Mearth: multiplicity ~ 25%



Bonfils et al. (2013)
astro-ph/1109.2497

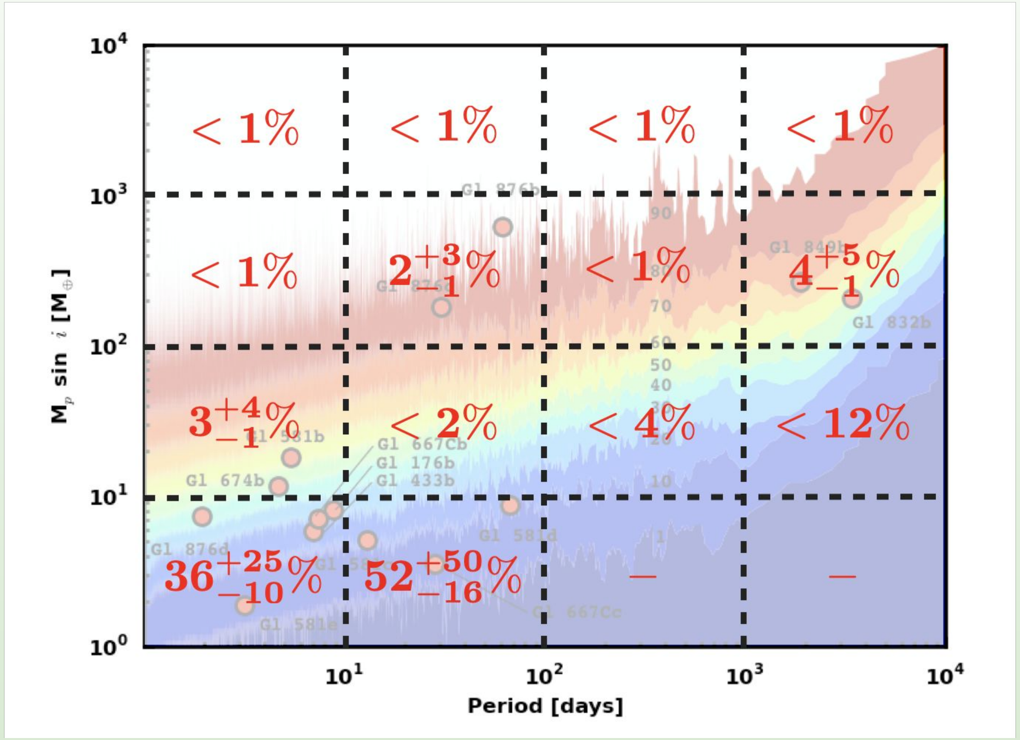


The HARPS search for southern extra-solar planets★

XXXI. The M-dwarf sample

X. Bonfils[1,2], X. Delfosse[1], S. Udry[2], T. Forveille[1], M. Mayor[2], C. Perrier[1], F. Bouchy[3,4], M. Gillon[5,2], C. Lovis[2], F. Pepe[2], D. Queloz[2], N. C. Santos[6], D. Ségransan[2], and J.-L. Bertaux[7]

Bonfils et al. (2013)
astro-ph/1109.2497



CARMENES 2021

Sabotta et al.: Planet occurrence rates from a subsample of 71 CARMENES M dwarfs

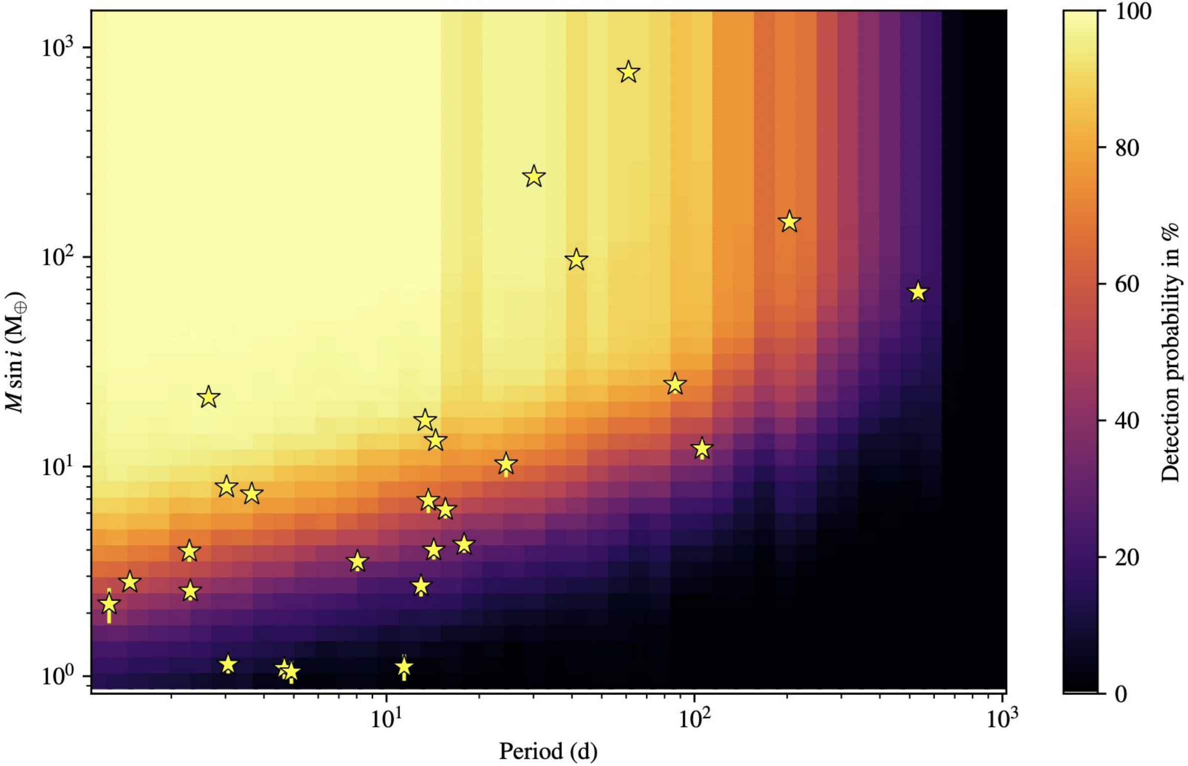
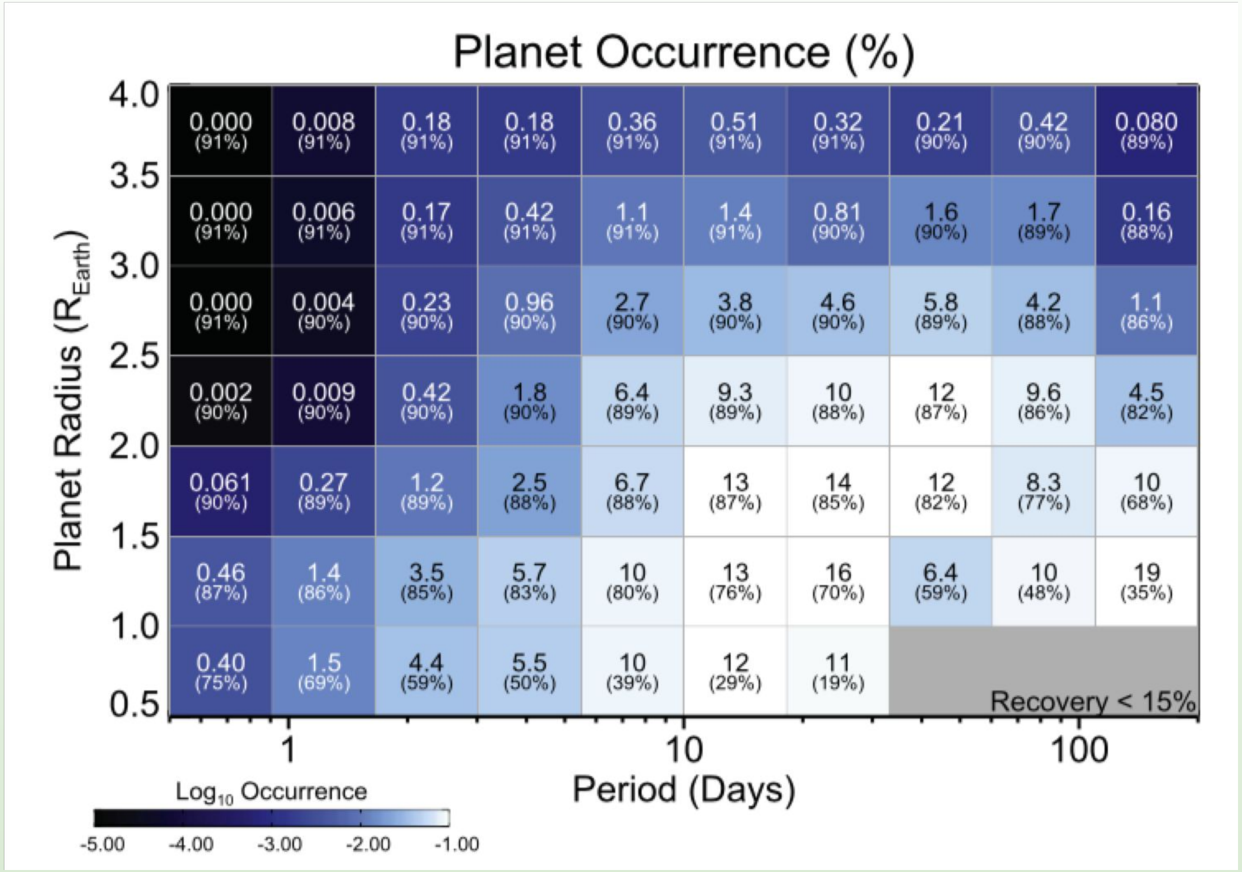


Fig. 2. CARMENES GTO survey detection completeness for the subsample of 71 stars. The color map indicates the average detection probability of the corresponding period-mass combination. Yellow stars indicate planets discovered by CARMENES (error bars are sometimes smaller than the marker size).

Dressing & Charbonneau (2015)



s://exoplanetarchive.ipac.caltech.edu/docs/occurrence_rate_papers.html

NASA Exoplanet Archive
NASA Exoplanet Science Institute

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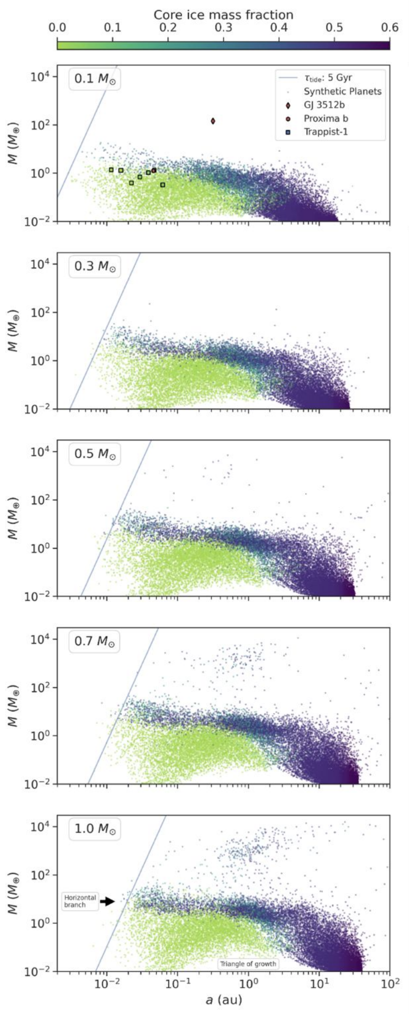
Planet Occurrence Rate Papers

This page contains a compilation of published, refereed papers that derive planet occurrence rates. To suggest a paper for inclusion on this page, please submit a Helpdesk ticket.

Author(s) and Publication Year	Title	Publication
Kunimoto et al. (2021)	Combining Transit and Radial Velocity: A Synthesized Population Model	AJ 161 69
Bryson et al. (2021)	The Occurrence of Rocky Habitable-zone Planets around Solar-like Stars from Kepler Data	AJ 161 36
Poleski et al. (2021)	Wide-Orbit Exoplanets are Common. Analysis of Nearly 20 Years of OGLE Microlensing Survey Data	AcA 71 1
Jin, Sheng (2021)	Relative occurrence rates of terrestrial planets orbiting FGK stars	MNRAS 502 5302
Yang, Jia-Yi, Xie, Ji-Wei, & Zhou, Ji-Lin (2020)	Occurrence and Architecture of Kepler Planetary Systems as Functions of Stellar Mass and Effective Temperature	AJ 159 164
Bashi et al. (2020)	Occurrence rates of small planets from HARPS: Focus on the Galactic context	A&A 643 A106
Lu, Schlaufman, & Cheng (2020)	An Increase in Small-planet Occurrence with Metallicity for Late-type Dwarf Stars in the Kepler Field and Its Implications for Planet Formation	AJ 160 253
Bryson et al. (2020)	A Probabilistic Approach to Kepler Completeness and Reliability for Exoplanet Occurrence Rates	AJ 159 6
Kunimoto & Bryson (2020)	Comparing Approximate Bayesian Computation with the Poisson-Likelihood Method for Exoplanet Occurrence Rates	RNAAS 4 83
Kunimoto & Matthews (2020)	Searching the Entirety of Kepler Data. II. Occurrence Rate Estimates for FGK Stars	AJ 159 248
Bryson (2020)	Exoplanet Occurrence Rates of Mid M-dwarfs Based on Kepler DR25	RNAAS 4 3
Dai et al. (2019)	Planet Occurrence Rate Correlated to Stellar Dynamical History: Evidence from Kepler and Gaia	AJ 162 46
Bashi & Zucker (2019)	Small Planets in the Galactic Context: Host Star Kinematics, Iron, and Alpha-element Enhancement	AJ 158 61
Hsu, Ford, & Ragozzine (2019)	Occurrence Rates of Planets Orbiting FGK Stars: Combining Kepler DR25, Gaia DR2, and Bayesian Inference	AJ 158 109
He, Ford, & Ragozzine (2019)	Architectures of exoplanetary systems - I. A clustered forward model for exoplanetary systems around Kepler's FGK stars	MNRAS 490 4575
Herman, Zhu, & Wu (2019)	Revisiting the Long-period Transiting Planets from Kepler	AJ 157 248
Kawahara & Masuda (2019)	Transiting Planets Near the Snow Line from Kepler. I. Catalog	AJ 157 218
Mulders et al. (2019)	The Exoplanet Population Observation Simulator. II. Population Synthesis in the Era of Kepler	ApJ 887 157
Grunblatt et al. (2019)	Giant planet occurrence within 0.2 au of low-luminosity red giant branch stars with K2	AJ 158 227
Fernandes et al. (2019)	Hints for a Turnover at the Snow Line in the Giant Planet Occurrence Rate	ApJ 874 81
Hardegree-Ullman et al. (2019)	Kepler Planet Occurrence Rates for Mid-type M Dwarfs as a Function of Spectral Type	AJ 158 75
Bryan et al. (2018)	An Excess of Jupiter Analogs in Super-Earth Systems	AJ 157 52
van Sluijs, L. and Van Eylen, V. (2018)	The occurrence of planets and other substellar bodies around white dwarfs using K2	MNRAS 474 4603
Mulders et al. (2018)	The Exoplanet Population Observation Simulator. I. The Inner Edges of Planetary Systems	AJ 156 24
Pascucci et al. (2018)	A Universal Break in the Planet-to-star Mass-ratio Function of Kepler MKG Stars	ApJ 856L 28
Narang et al. (2018)	Properties and occurrence rates of Kepler exoplanet candidates as a function of host star metallicity from the DR25 catalog	AJ 156 24
Meyer et al. (2018)	M Dwarf Exoplanet Surface Density Distribution: A Log-Normal Fit from 0.07-400 au	A&A 612 L3
Zhu et al. (2018)	About 30% of Sun-like Stars Have Kepler-like Planetary Systems: A Study of their Intrinsic Architecture	ApJ 860 101
Petigura et al. (2018)	The California-Kepler Survey. IV. Metal-rich Stars Host a Greater Diversity of Planets	AJ 155 89
Fulton et al. (2017)	The California-Kepler Survey. III. A Gap in the Radius Distribution of Small Planets	AJ 154 109
Meshkat et al. (2017)	A Direct Imaging Survey of Spitzer detected debris disks: Occurrence of giant planets in dusty systems	AJ 154 245
Mróz et al. (2017)	No large population of unbound or wide-orbit Jupiter-mass planets	Nature 548 183



The New Generation Planetary Population Synthesis (NGPPS)

IV. Planetary systems around low-mass stars★

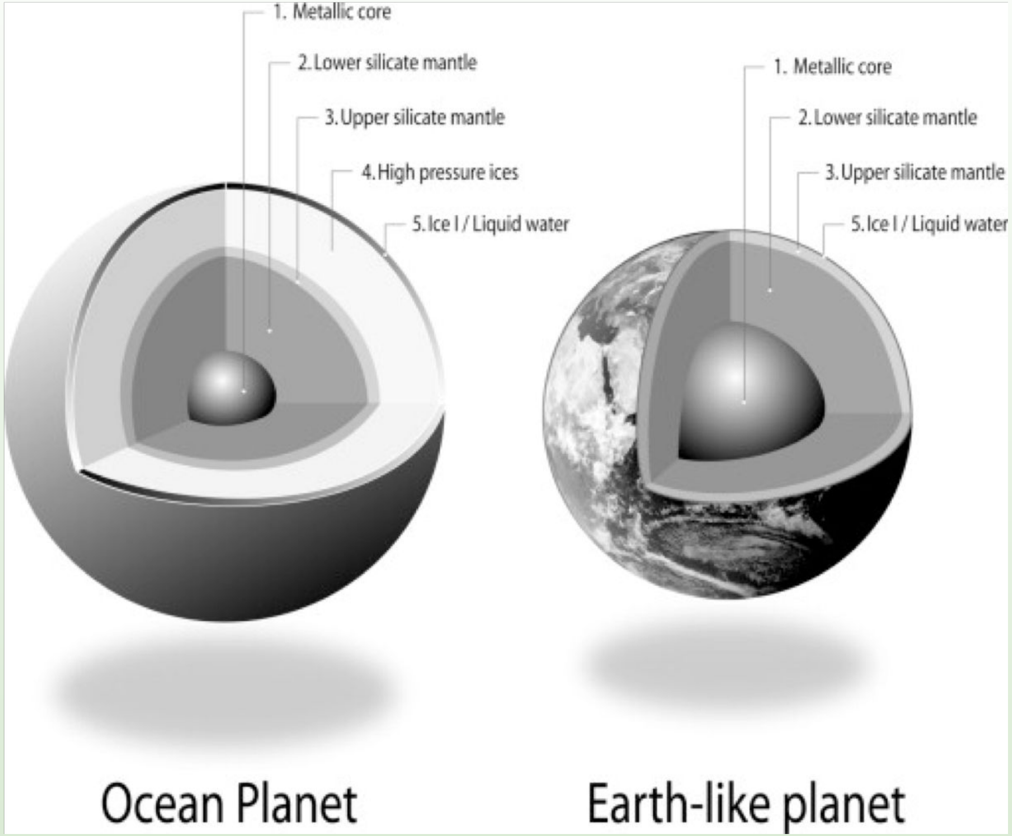
R. Burn[1,2], M. Schlecker[2], C. Mordasini[1], A. Emsenhuber[1,3], Y. Alibert[1], T. Henning[2], H. Klahr[2] and W. Benz[1]

Table 3. Fraction of systems with specific planetary types for the different stellar mass populations with initially 50 lunar-mass embryos

	Stellar mass ($M_\odot$)				
Type	0.1	0.3	0.5	0.7	1.0
$M > 1\,M_\oplus$	0.44	0.77	0.88	0.91	0.95
Earth-like	0.70	0.88	0.89	0.89	0.84
Super Earth	0.19	0.54	0.71	0.78	0.79
Neptunian	0.01	0.08	0.17	0.22	0.27
Sub-giant	0.00	0.00	0.02	0.03	0.05
Giant	0.00	0.00	0.02	0.09	0.19
Temperate zone	0.35	0.66	0.70	0.66	0.57

Statistical properties
- mass-radius
- the radius gap

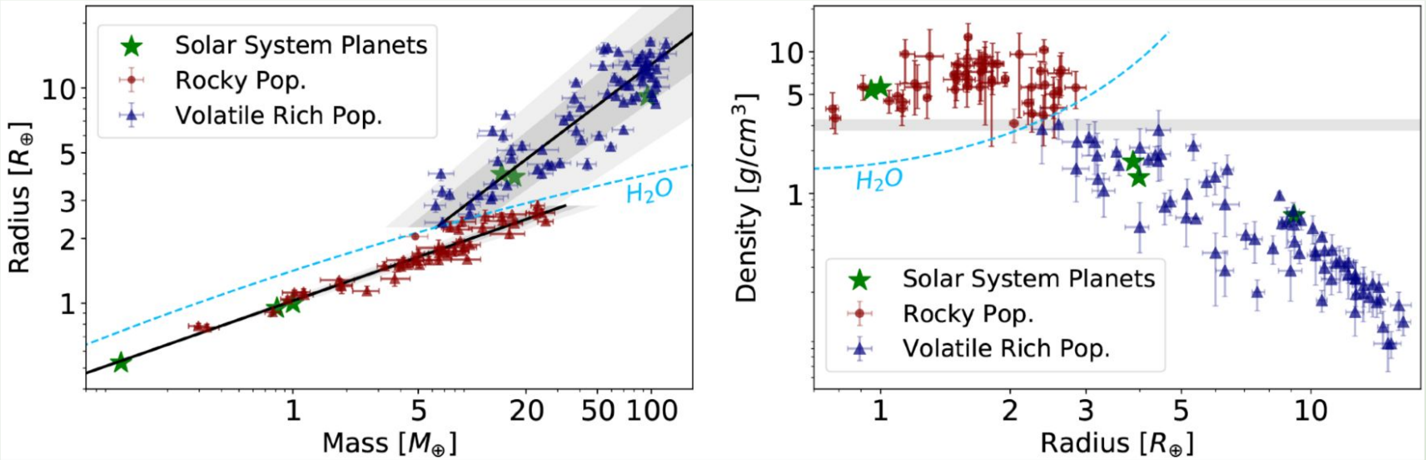
Combination : Mass-radius relations



A&A 634, A43 (2020)

Revisited mass-radius relations for exoplanets below 120 $M_\oplus$

J. F. Otegi[1,2], F. Bouchy[2] and R. Helled[1]

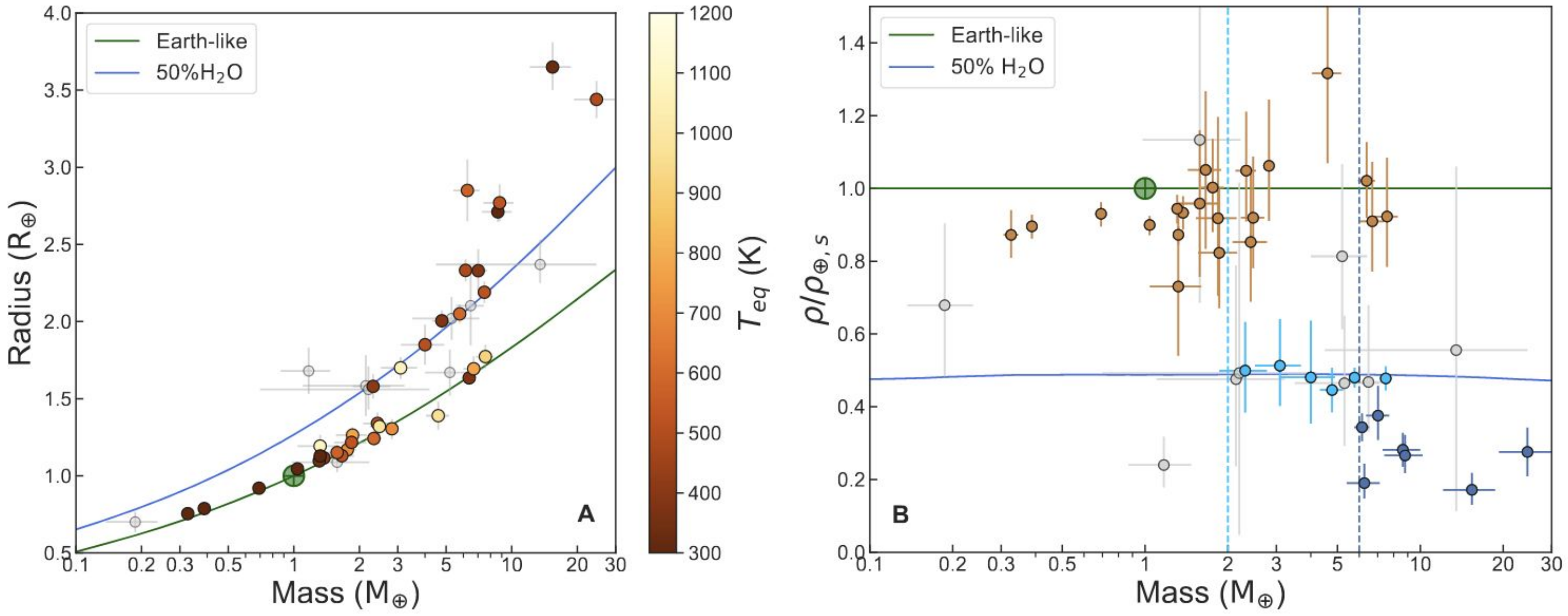


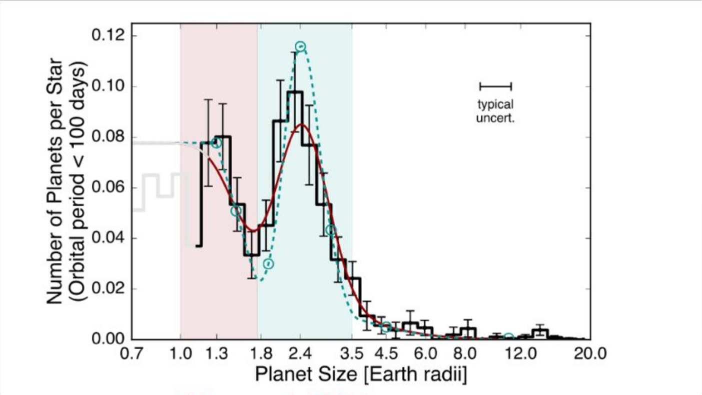
$$R = \begin{cases} (1.03 \pm 0.02)\, M^{(0.29\pm0.01)}, & \text{if } \rho > 3.3\ \mathrm{g\,cm^{-3}} \\ (0.70 \pm 0.11)\, M^{(0.63\pm0.04)}, & \text{if } \rho < 3.3\ \mathrm{g\,cm^{-3}}, \end{cases}$$

$$M = \begin{cases} (0.90 \pm 0.06)\, R^{(3.45\pm0.12)}, & \text{if } \rho > 3.3\ \mathrm{g\,cm^{-3}} \\ (1.74 \pm 0.38)\, R^{(1.58\pm0.10)}, & \text{if } \rho < 3.3\ \mathrm{g\,cm^{-3}}. \end{cases}$$

Density, not radius, separates rocky and water-rich small planets orbiting M dwarf stars

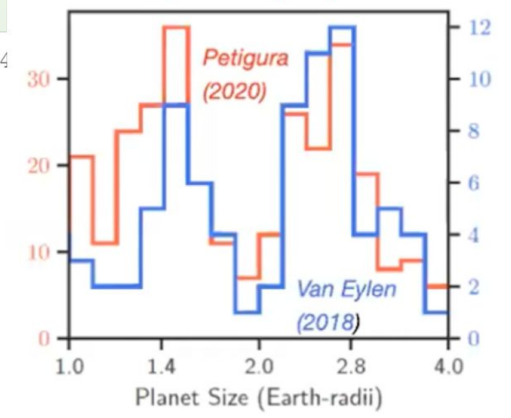
Rafael Luque[1,2,*] & Enric Pallé[3,4,†]



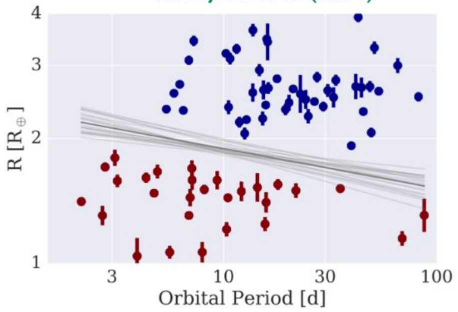


Fulton et al. (2017)

Petigura et al. (2020)



Van Eylen et al. (2018)

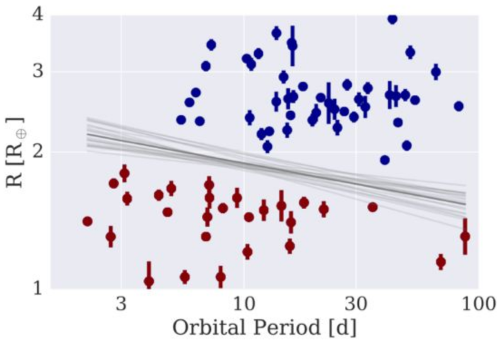


- Fulton et al. (2017)
- van Eylen et al. (2018)
- See also Petigura (2020)

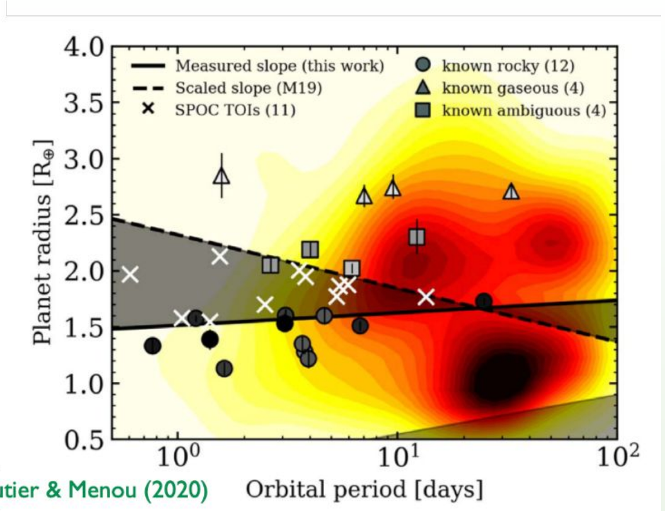
- rocky transition @ ~1.8 Rearth
- might correlate with P

- Rocky vs volatile-rich
  + H/He enveloppe

- 1.8 Rp ~ 8 Mearth
- below TESS sensitivity?

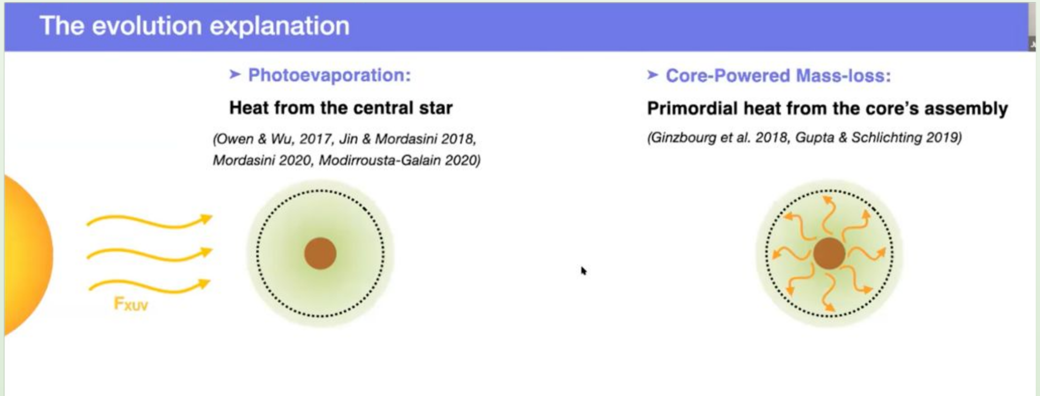


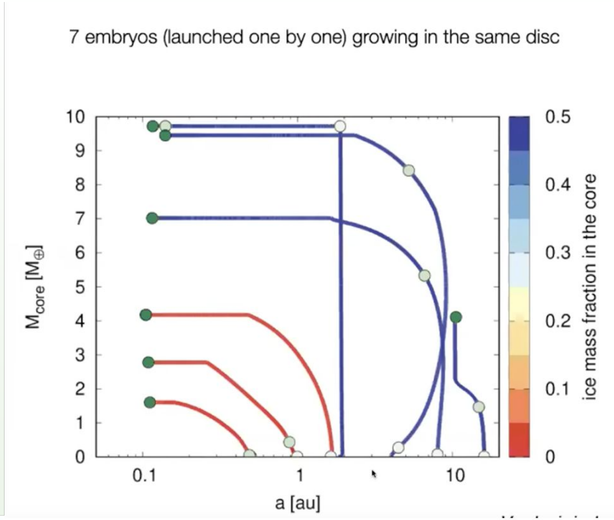
Van Eylen et al. (2020)



Cloutier & Menou (2020)

Venturini et al. (TESS Science Conf.)

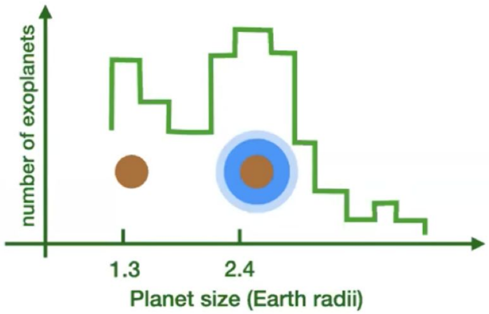




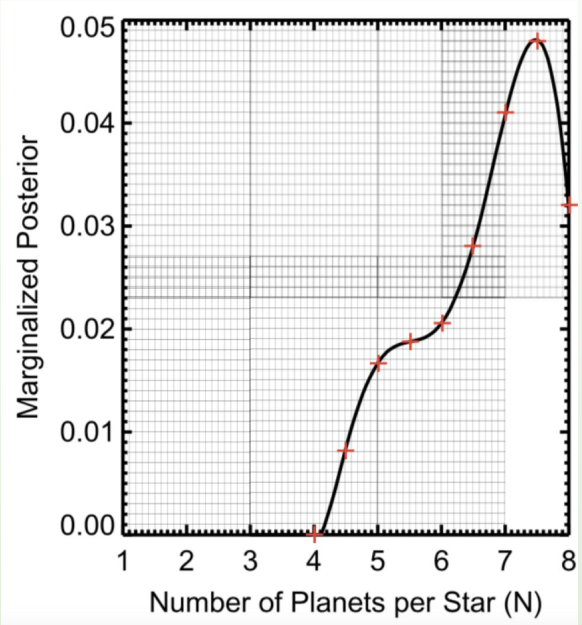
Venturini (TESS Science Conf.)

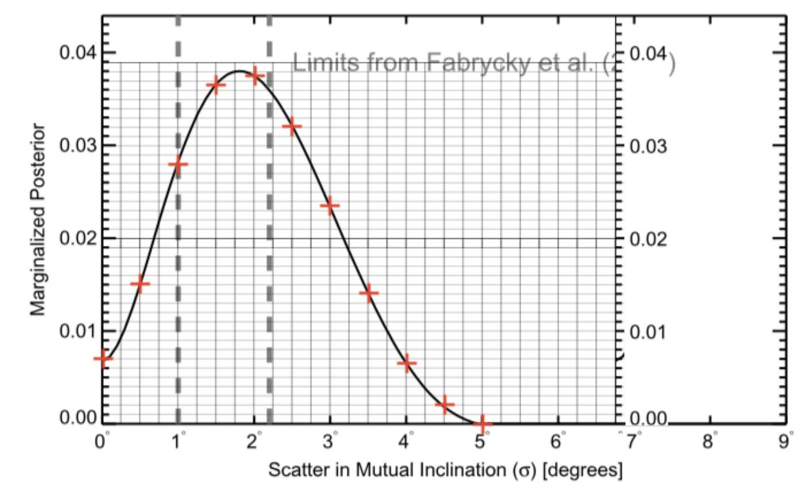
Venturini et al. (2020, A&A)

- Due to the change of the pebbles' properties at the water ice line, pebble accretion leads to two distinct core populations: icy and large vs. rocky and small cores.
  - **Such bimodality from birth leaves a "valley" imprint on the size distribution of short period exoplanets.**
  - Atmospheric escape after formation must take place the get the bare rocky cores of the first peak.
  - Processes that hinder gas accretion and/or promote atmospheric escape must take place to account for the second peak. Also to better agree with the mass-radius of short period exoplanets.



Statistical properties of multi-planets





Ballard & Johnson (2016)

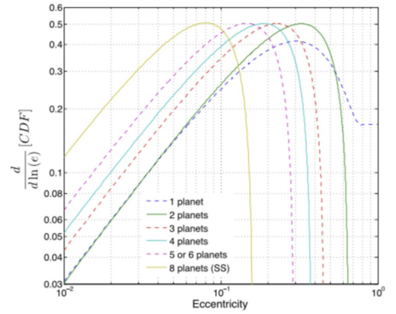
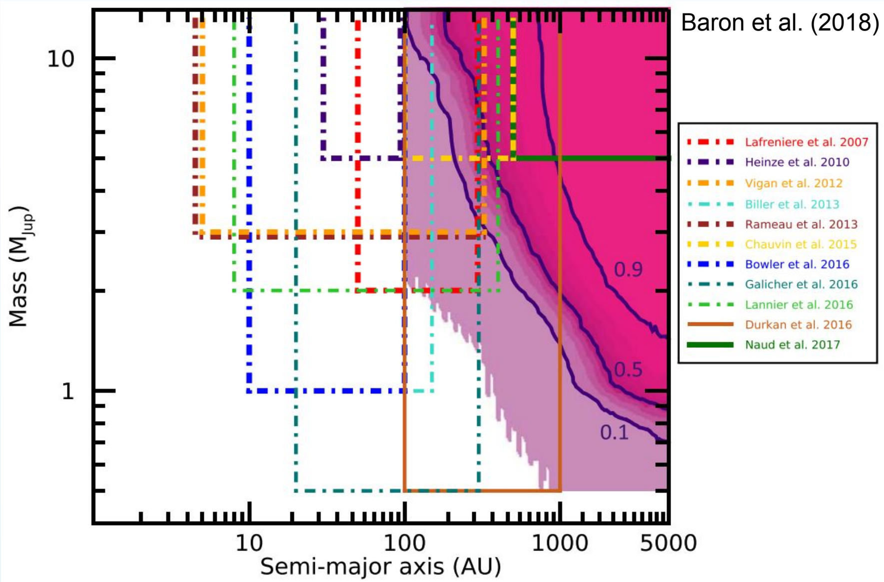


Fig. 4. Eccentricity probability density distributions for various multiplicities based on polynomial fits to the cumulative distribution functions (CDF). Lower-eccentricity systems are more likely to belong to higher-multiplicity systems. Second-order polynomials were fit to the cumulative distributions for all multiplicities except the single-planet systems, in which case a third-order polynomial was used.

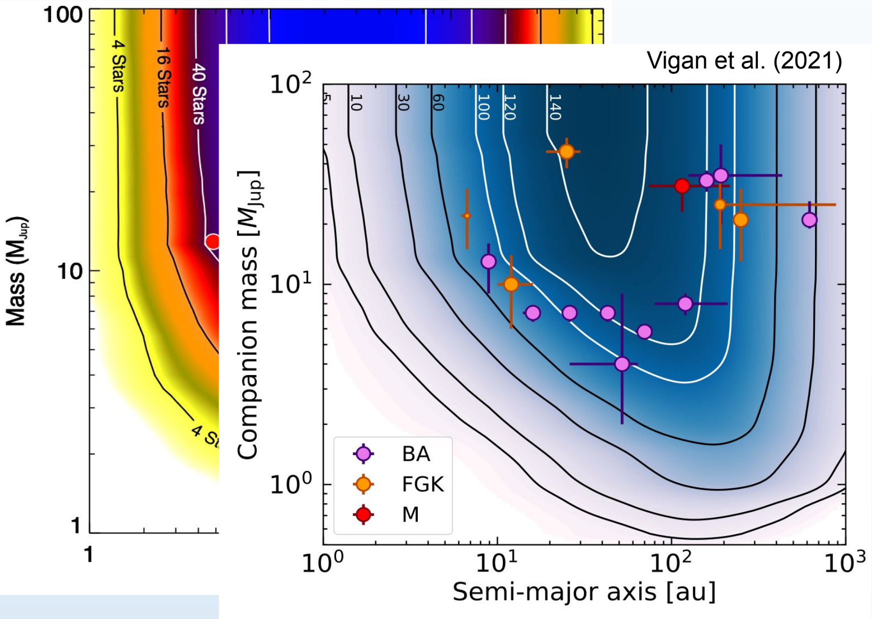
Linbach & Turner (2015)

Statistical properties
Of distant companions

Giant planets at large separations: occurrence



Nielsen et al. (2019)



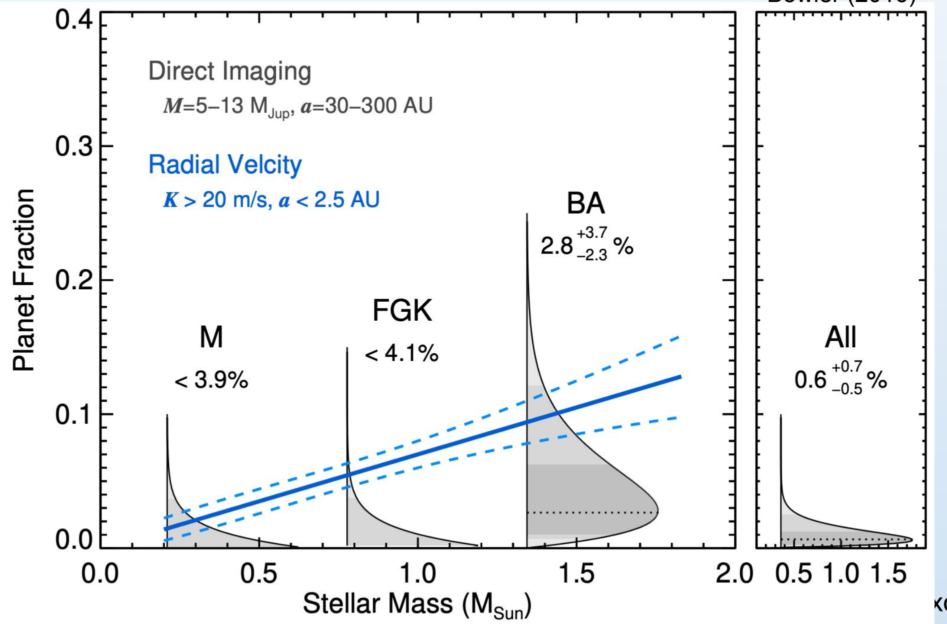
Large range of values depending on the adopted boundaries in mass/separation, spectral types, and assumed planet distributions, but globally:

10-100 au	100-300 au	>500 au
5-10 %	**5-10 %**	**<1%**

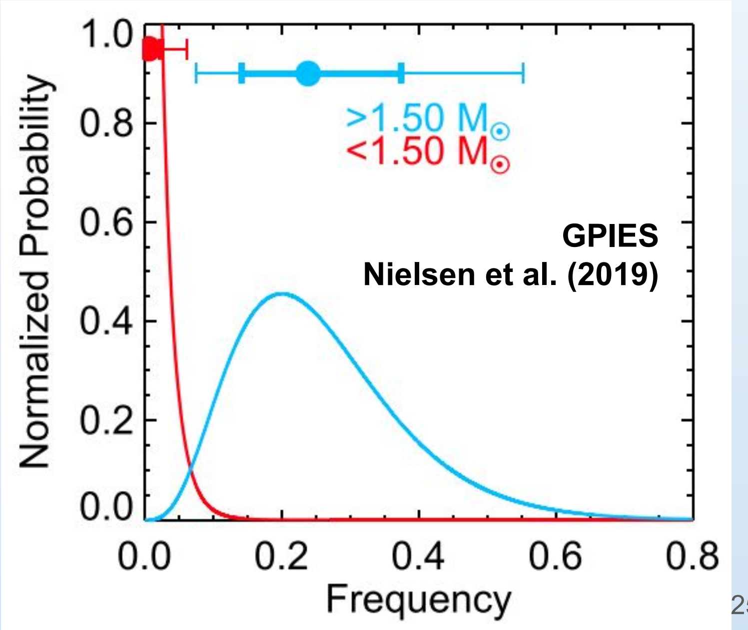
Giant planets at large separations: occurrence

- Strong correlation with the host spectral type
  - Trend identified with early detections (β Pic, HR8799, Fomalhaut) + RV on evolved A stars (Johnson et al. 2010, 2011)
  - Confirmed with dedicated surveys (Vigan et al. 2012; Rameau et al. 2013) + SHINE + GPIES

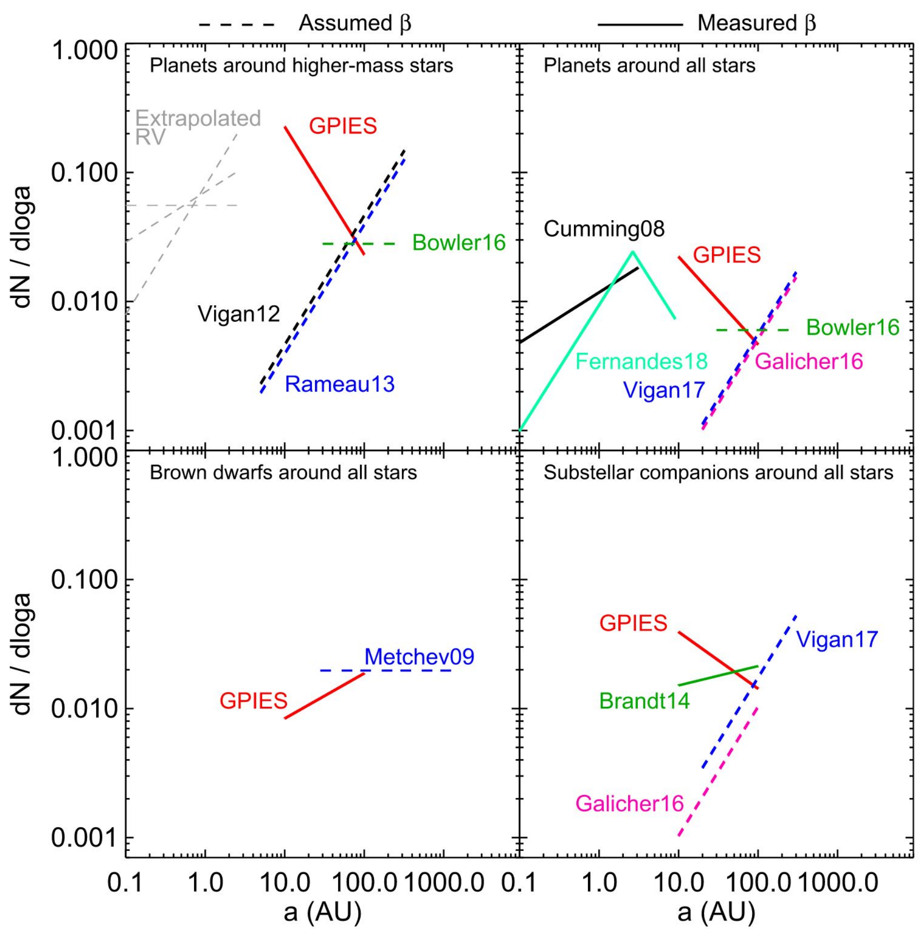
Bowler (2016)



xo-ELT



Giant planets at large separations: occurrence



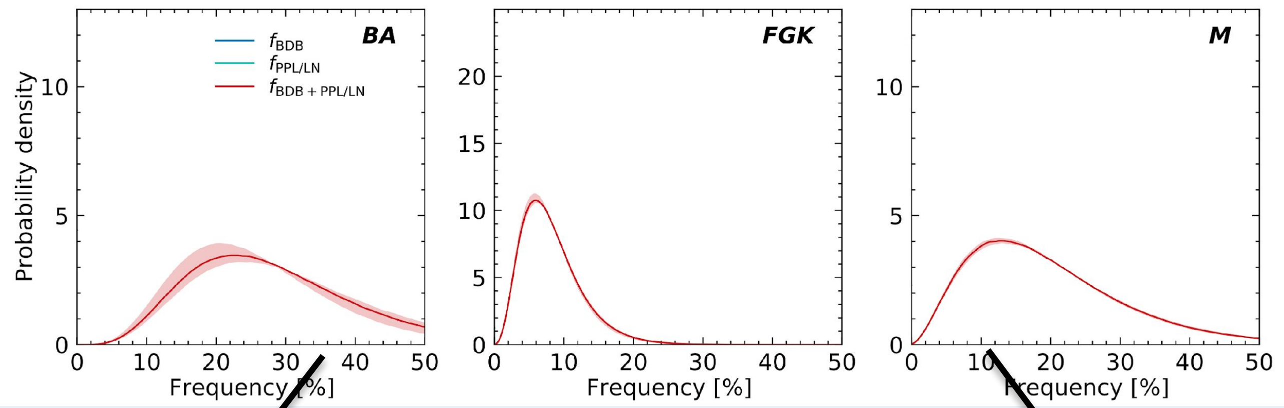
$$\frac{d^2N}{dm\,da} = f\ C_1\ m^{\alpha}\ a^{\beta}\left(\frac{M_*}{1.75\ M_\odot}\right)^{\gamma}$$

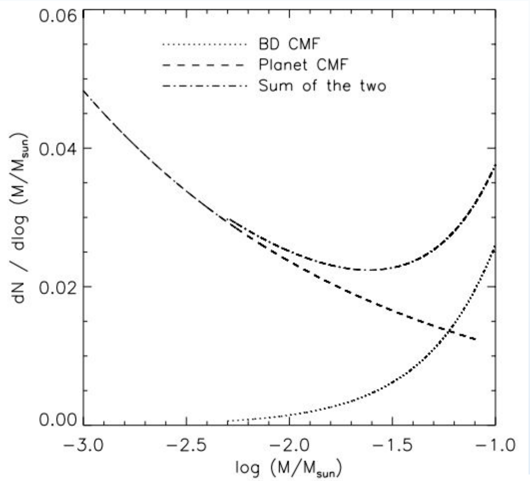
- Purely empirical underlying distribution of planets in mass/semi-major axis
- Not physically realistic, limited, and potentially optimistic
- Enough detections to fit these parameters based on the results of large surveys

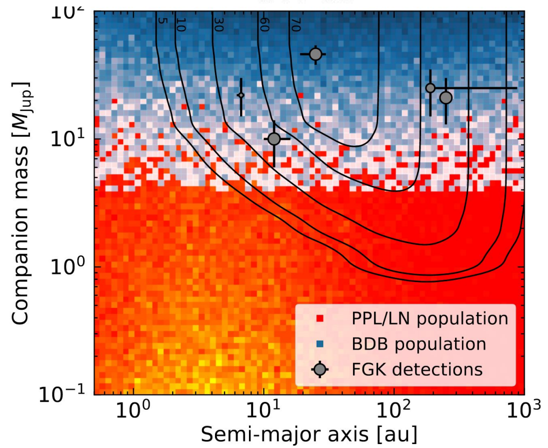
Exo-ELT

Giant planets at large separations: formation

Regianni & Meyer (2013) + Meyer (2018)







Massive companions ⇔ small q (<1-5%)

Change in dominant formation channel

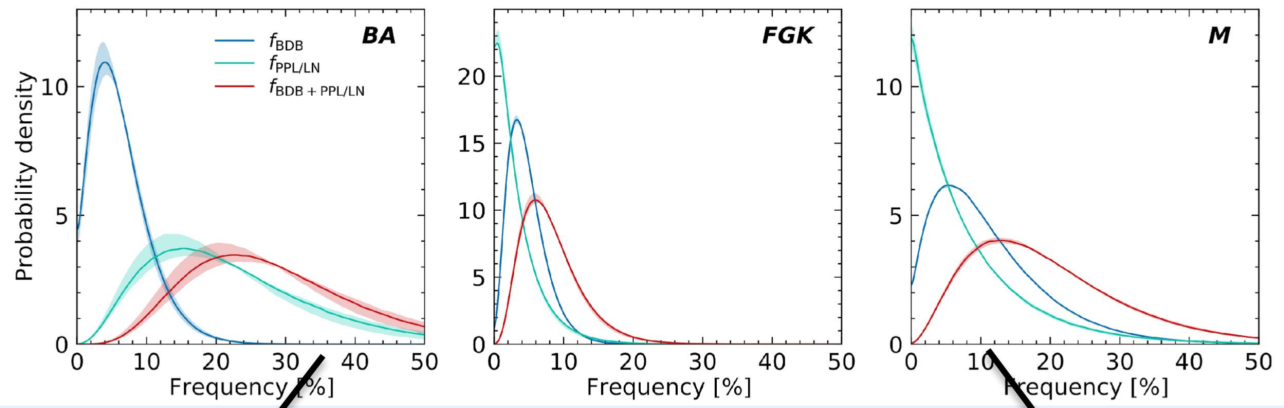
Massive companions ⇔ moderate q (10-20%)

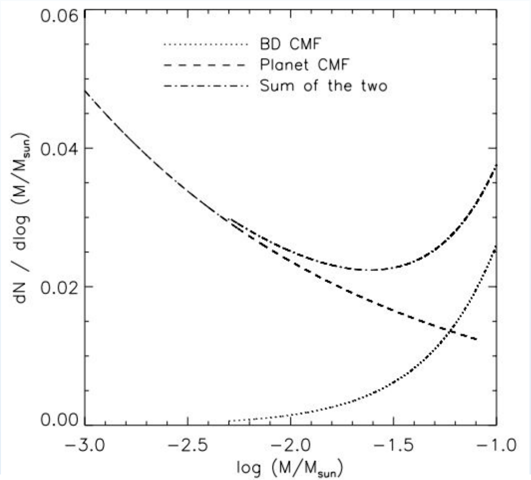
"Planetary" part dominates

"Binary" part dominates

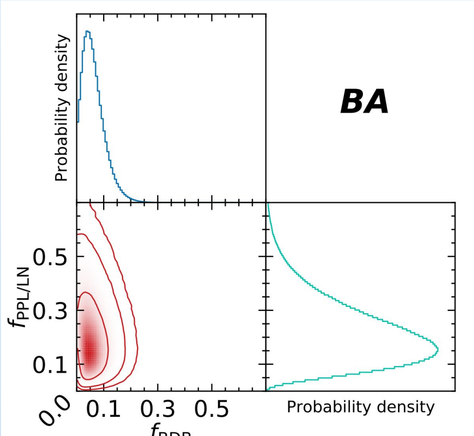
Giant planets at large separations: formation

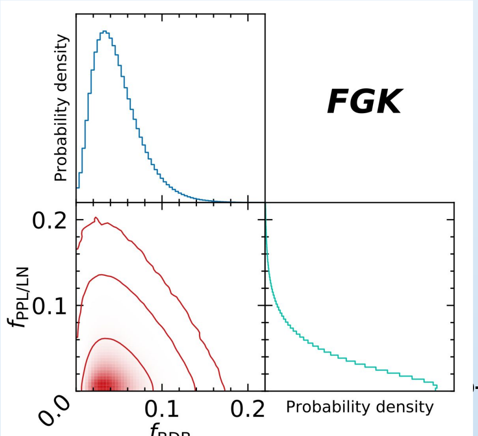
Regianni & Meyer (2013) + Meyer (2018)

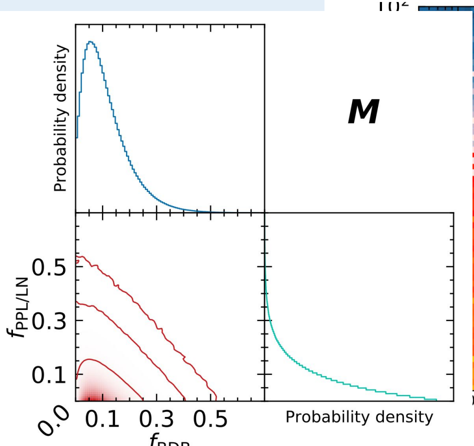


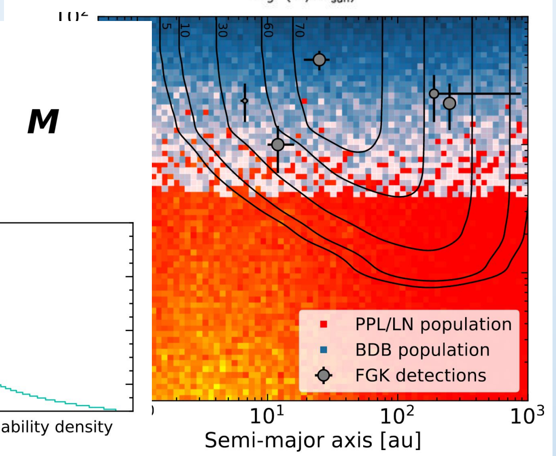


Change in dominant formation channel

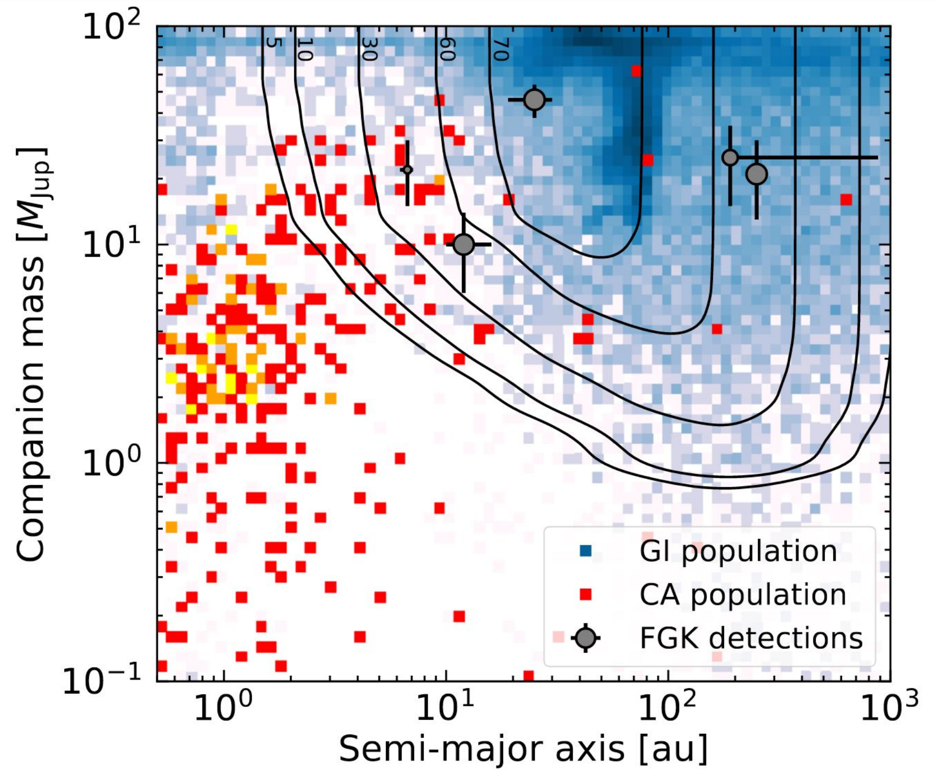








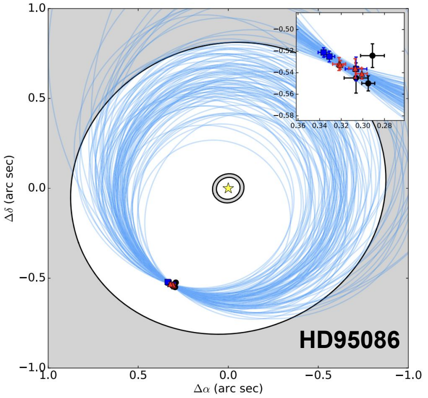
Giant planets at large separations: formation

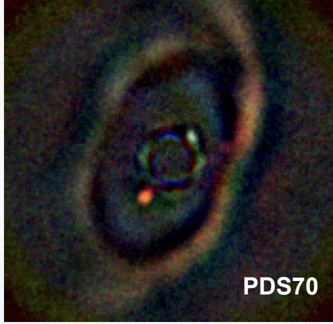


- Next logical step: direct comparison with population synthesis models
- ⚠️ Many simplifications in the populations
- Current view of giant planet formation around FGK stars:
  - Slight predominance of CA
  - TBC with larger sample, updated models
  - + extension at all spectral types

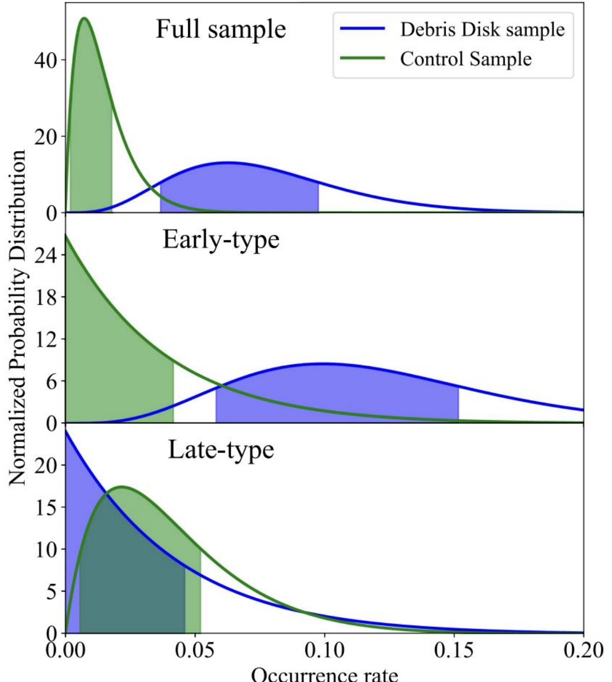
Disk-planet connection

- Planets form in disks 🙄
- Several known companions in systems with a disk: β Pic, HR8799, HD95086, PDS70, …
- Multiple targeted surveys looking at stars with known debris disks (imaging or SED fitting)
- Special interest for systems with a "double belt":
  - Warm inner asteroid-like belt
  - Dust-free gap
  - Cool outer belt
- E.g. Meshkat et al. (2017)
  - Marginally significant difference between the "disk sample" and the "control sample"
  - Need to be explored with larger samples





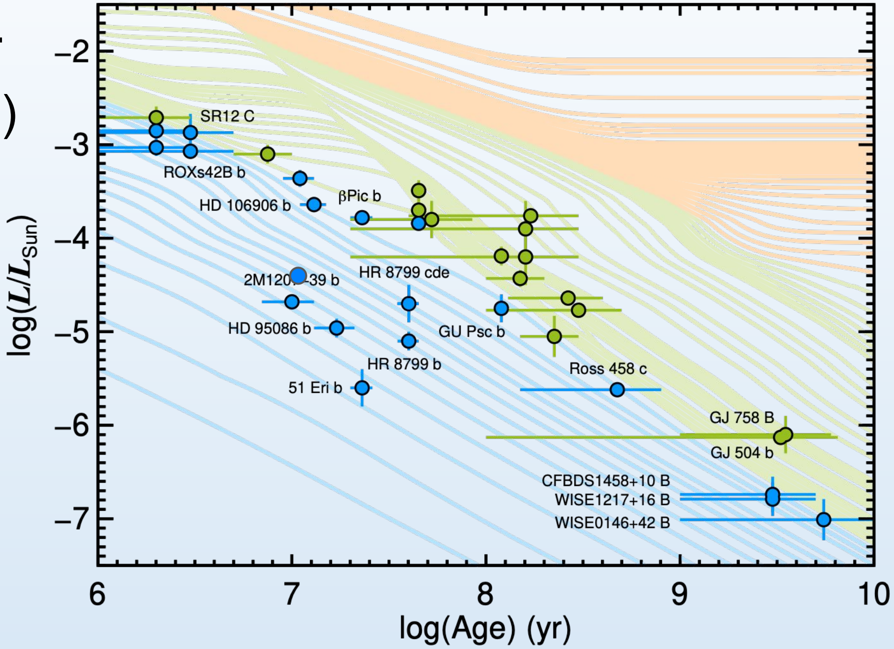
Meskat et al. (2017)

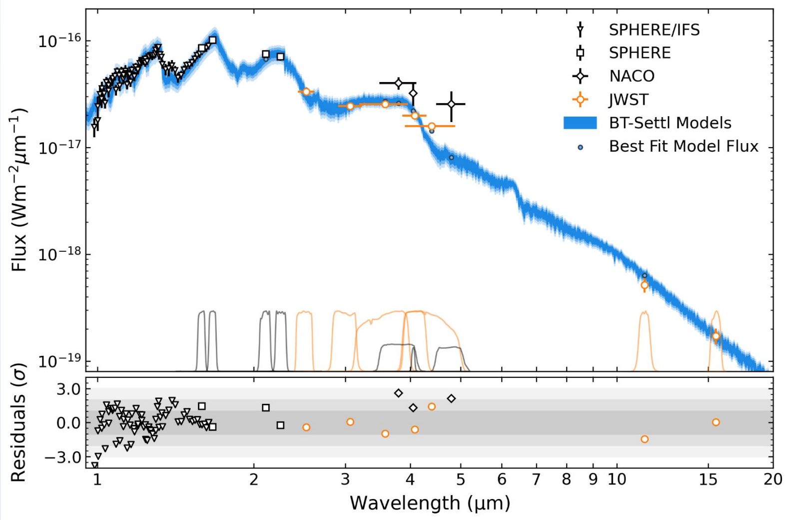


Bolometric luminosity & mass of substellar companions

- Companions over a wide range of ages and luminosities
- Informs about formation process → cold vs. warm vs. hot (Marley 2007; Mordasini 2017)
- Luminosity measurements are going to increase with JWST! (e.g. Carter 2022)

Bowler (2016)
Tracks from Burrows et al. (1997)

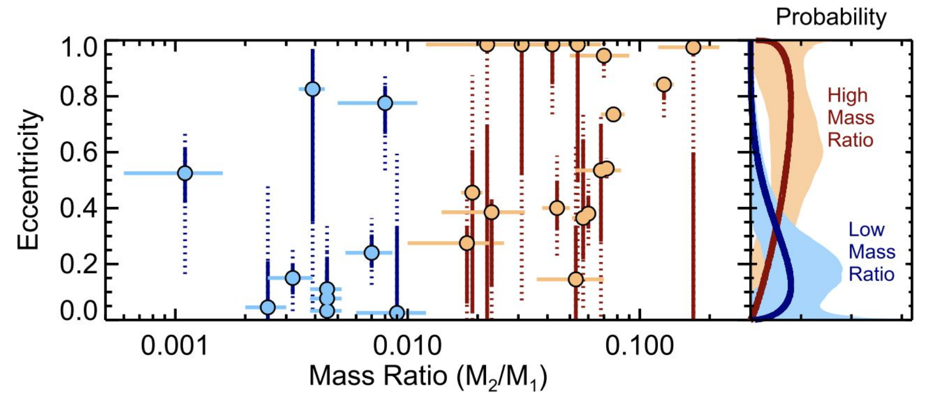


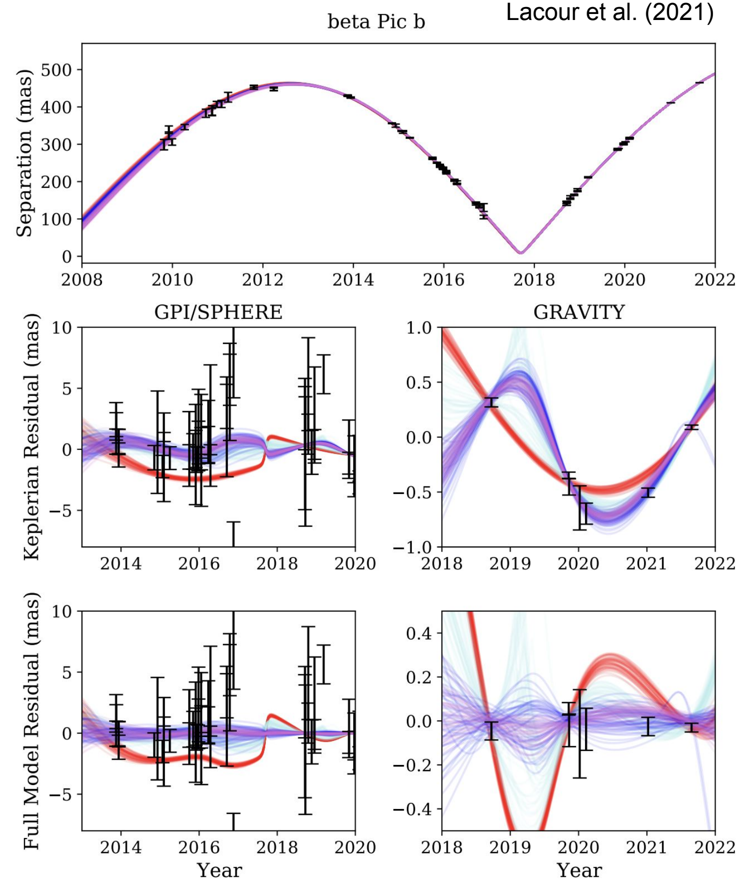


The *JWST* Early Release Science Program for Direct Observations of Exoplanetary Systems I: High Contrast Imaging of the Exoplanet HIP 65426 b from 2–16 μm

Aarynn L. Carter [1], Sasha Hinkley [2], Jens Kammerer [3], Andrew Skemer [1], Beth A. Biller [4], Jarron M. Leisenring [5], Maxwell A. Millar-Blanchaer [6], Simon Petrus [7,8], Jordan M. Stone [9]

Orbits





- Study of Bowler et al. (2020) on eccentricity:
  - Different regimes as a function of mass ratio
  - Small sample, small orbital coverage
- ExoGRAVITY (PI Lacour):
  - High-accuracy relative astrometry
  - Determination of orbits for a significant sample of companions
  - Multi-planet analysis from perturbed Keplerian motion

Gravitational microlensing

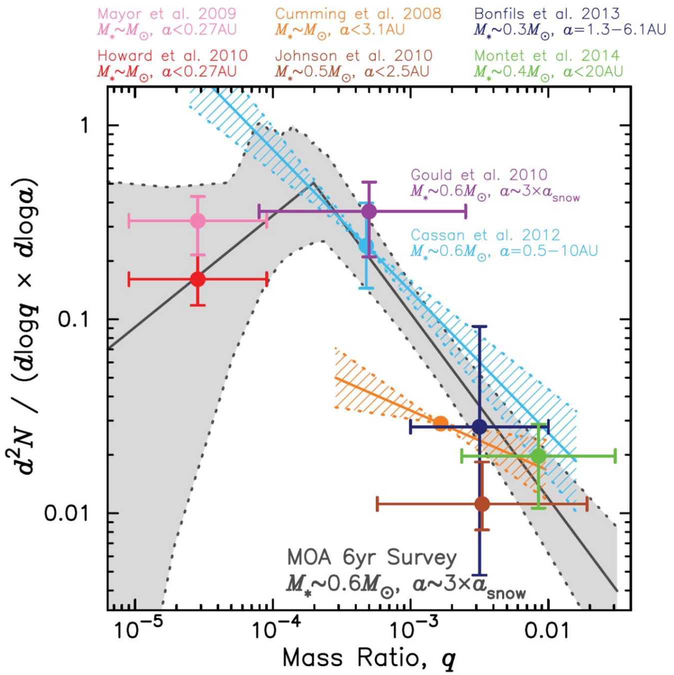


FIGURE 2.5 A broken power-law fit to the frequency of planets per log mass ratio q per log semimajor axis a, as a function of planet/star mass ratio q, as measured by the Microlensing Observations in Astrophysics (MOA) microlensing survey, is shown as the black dotted line. The uncertainty around this fit is shown as the gray shaded region. This frequency is compared to several other results on the frequency of planets in this plane using various methods and for various ranges of mass ratio and semimajor axis, as labeled. SOURCE: Suzuki et al. (2016).

- Probe populations down to
  - Large orbital separations
  - Small planetary masses
- Complementarity with imaging… but limited for follow-up
- Very efficient at population level
- Some interesting results:
  - Sumi 2011: large population of free-floating Jupiter-like objects
  - Suzuki 2016: break in the mass function at q^{-4} (~20 M⊕ for ~0.6M⊙)

Landscape when ELT will start operations

Priorités

- Inventaires des planètes proches
- transits

Continuous exploration of the parameter space.

- RV (ESPRESSO, NIRPS, CARMENES, ….)
- TESS, PLATO
  + SOL (SPECULOOS, EXTRA, …)

High incompleteness

Sabotta et al.: Planet occurrence rates from a subsample of 71 CARMENES M dwarfs

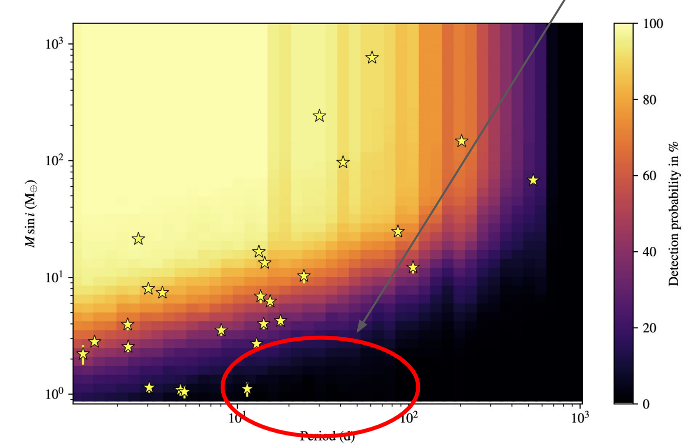
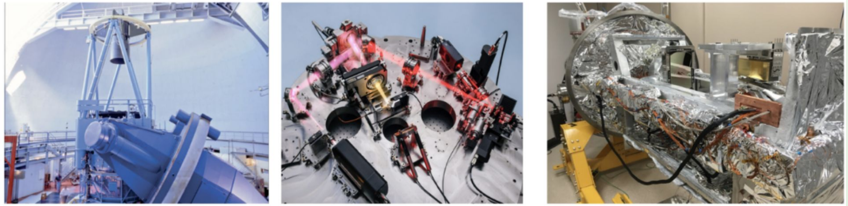
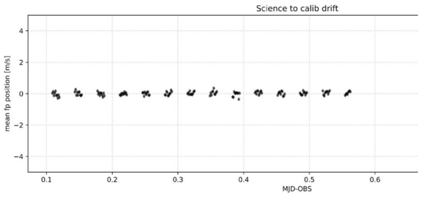


Fig. 2. CARMENES GTO survey detection completeness for the subsample of 71 stars. The color map indicates the average detection probability of the corresponding period-mass combination. Yellow stars indicate planets discovered by CARMENES (error bars are sometimes smaller than the marker size).

HARPS + NIRPS

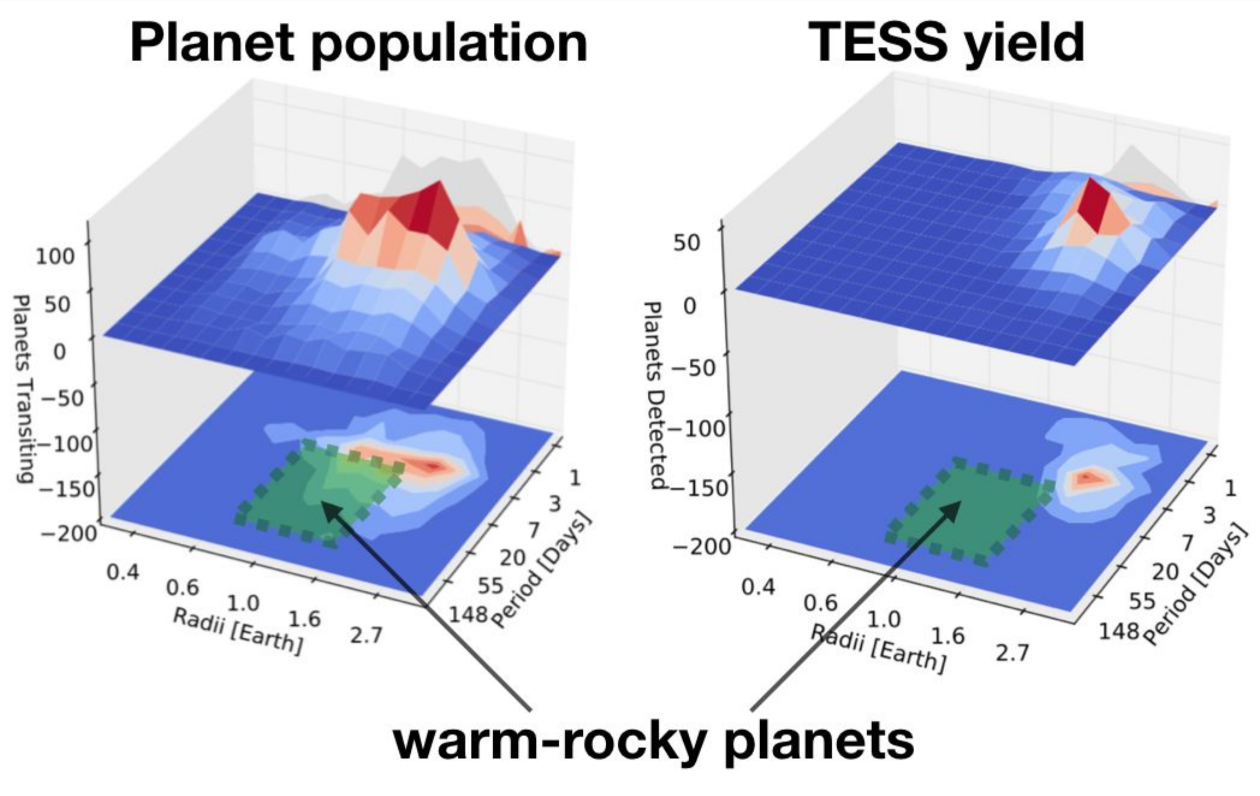




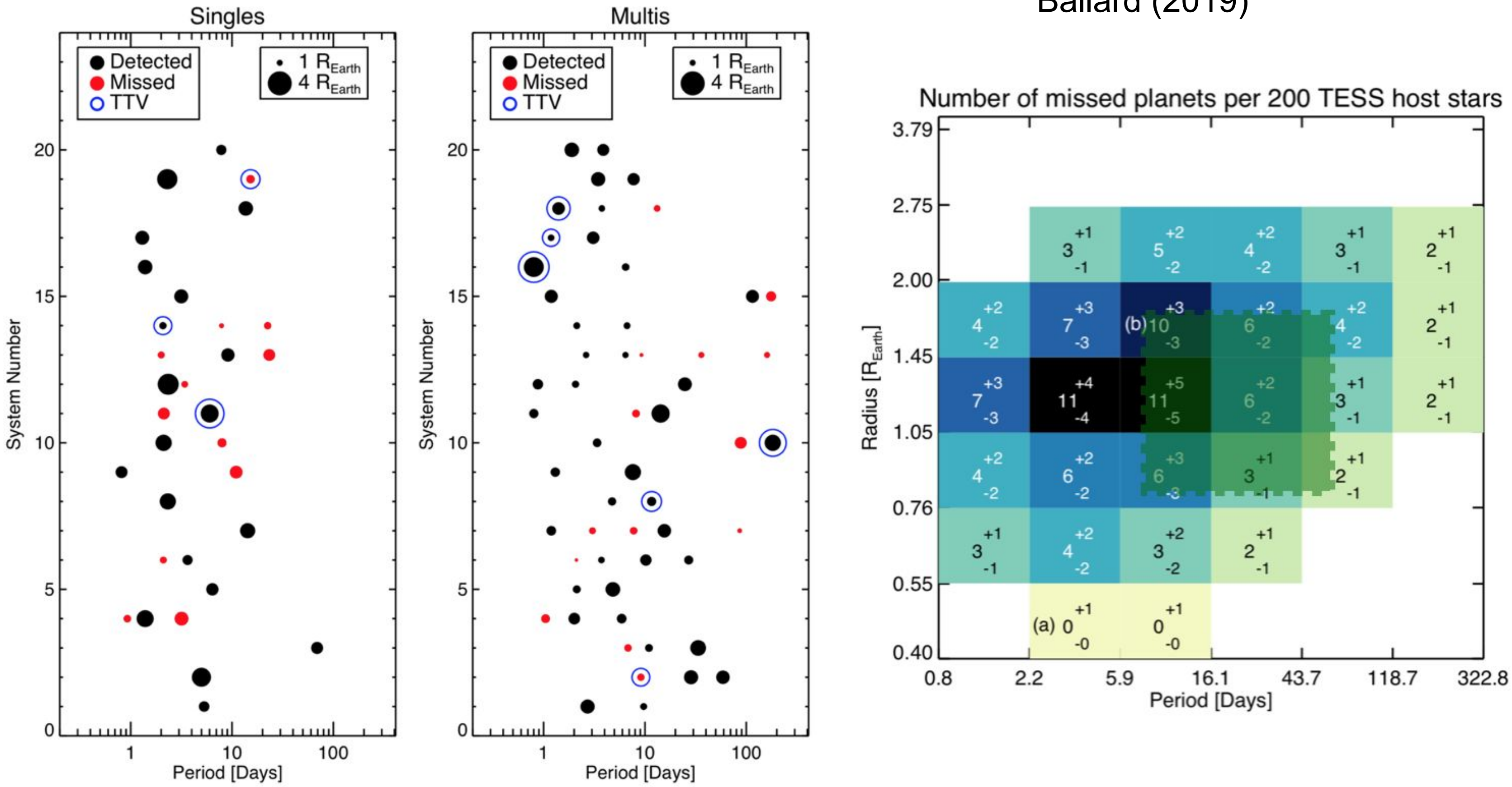
Spec Type	Teff	V	J	H	HARPS σ_{RV}	NIRPS σ_{RV}
K7V	4000	12.2	9.6	9.0	2.8 m/s	3.6 m/s
M1V	3700	12.9	9.6	9.0	5.3 m/s	3.0 m/s
M4V	3200	14.0	9.6	9.0	4.8 m/s	2.2 m/s
M6V	2800	15.9	9.6	9.0	8.6 m/s	1.8 m/s

Census of exo-earths ?

Stevenson+ 2019



Ballard (2019)

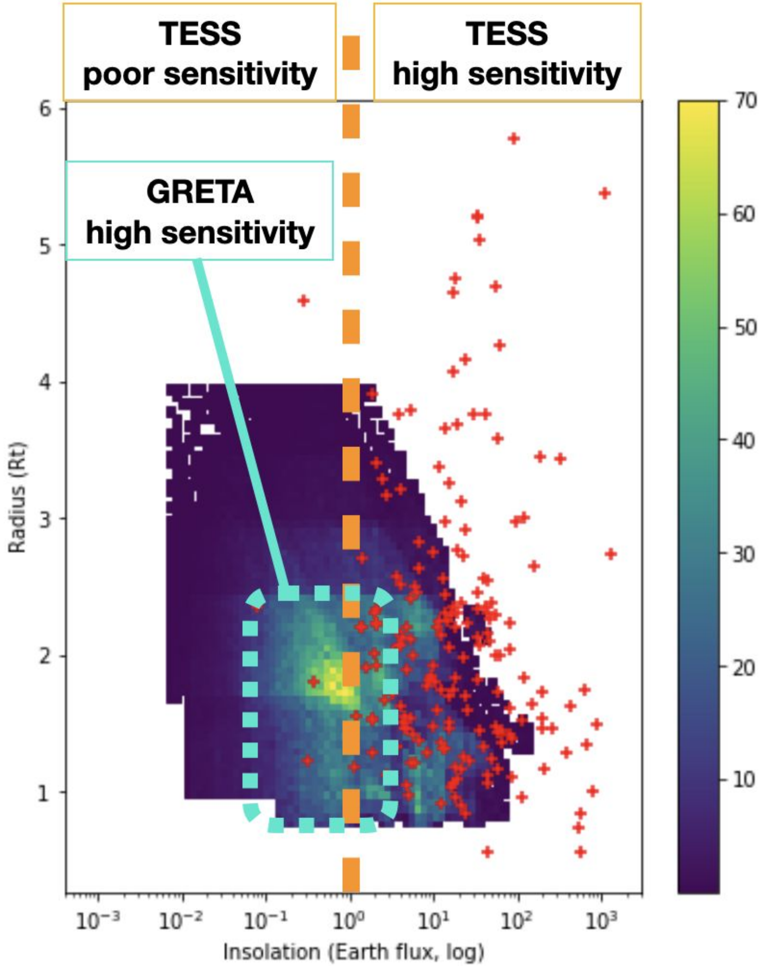


"Among [...] 200 TESS hosts to one or more detected planets, 116+/-28 planets [are] missed. Transit follow-up efforts with the photometric sensitivity to detect an Earth or larger around a mid-M dwarf, even with very modest period completeness, [...] readily result in additional planet discoveries."

Deep Search project

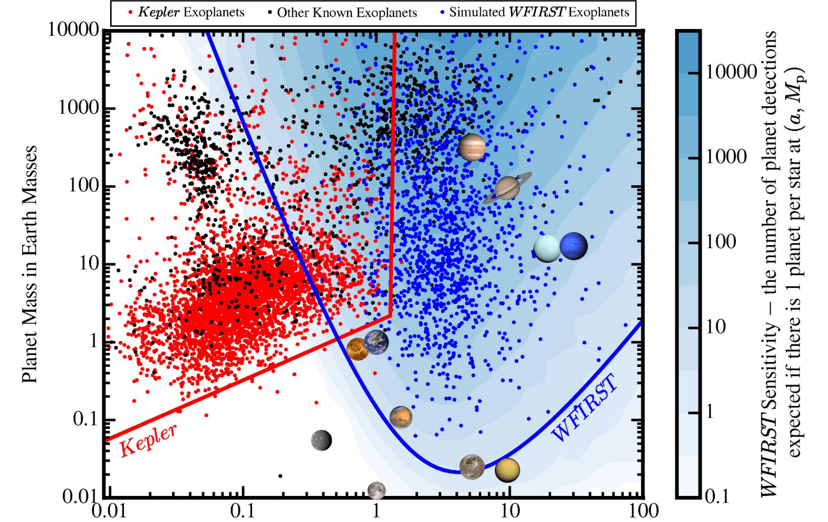
- Now anchored in actual TESS detections
- Follow-up with transit photometry (ExTrA, CHEOPS…)
- & radial velocity (HARPS+NIRPS, ESPRESSO)

Planets are already discovered this way
E.g. LHS1140c, SPECULOS-2c, …

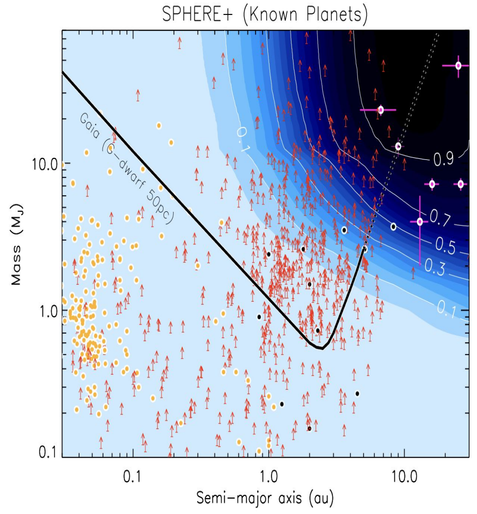


Microlensing, astrometry, imaging

- Microlensing:
  - Roman Space Telescope/WFI
  - Maybe combined with a Euclid survey to break some degeneracies (still TBC)
  - Huge statistics on distant companions… but follow-up almost impossible
- Astrometry:
  - Gaia DR4
  - Potentially huge sample of candidates
  - Combined with RV → full orbital parameters for a significant number of systems
- Imaging:
  - Final results of SHINE, GPIES, BEAST. Maybe other large surveys, e.g. GPIES North, KPIC?
  - SAXO+ operational
  - Smaller targeted surveys
  - 5 years of JWST → physical parameters for a significant sample of companions



Credit: Penny et al. (2018)
arXiv:1808.02490



What will the ELT do for exoplanet demography?

- Unlikely to have large surveys with the ELT → targeted search & characterization of known (or suspected) systems
  - Gaia candidates
  - Some follow-up of μlensing events at high angular resolution?
- Systems with distant companions:
  - Long periods need long baselines → follow-up for orbital monitoring with ELT
  - Exploration of internal parts of known systems
  - Exomoons and exorings?
- …
-
-
- Complementarity with VLT? Some UTs in survey mode?

Disk connection ?

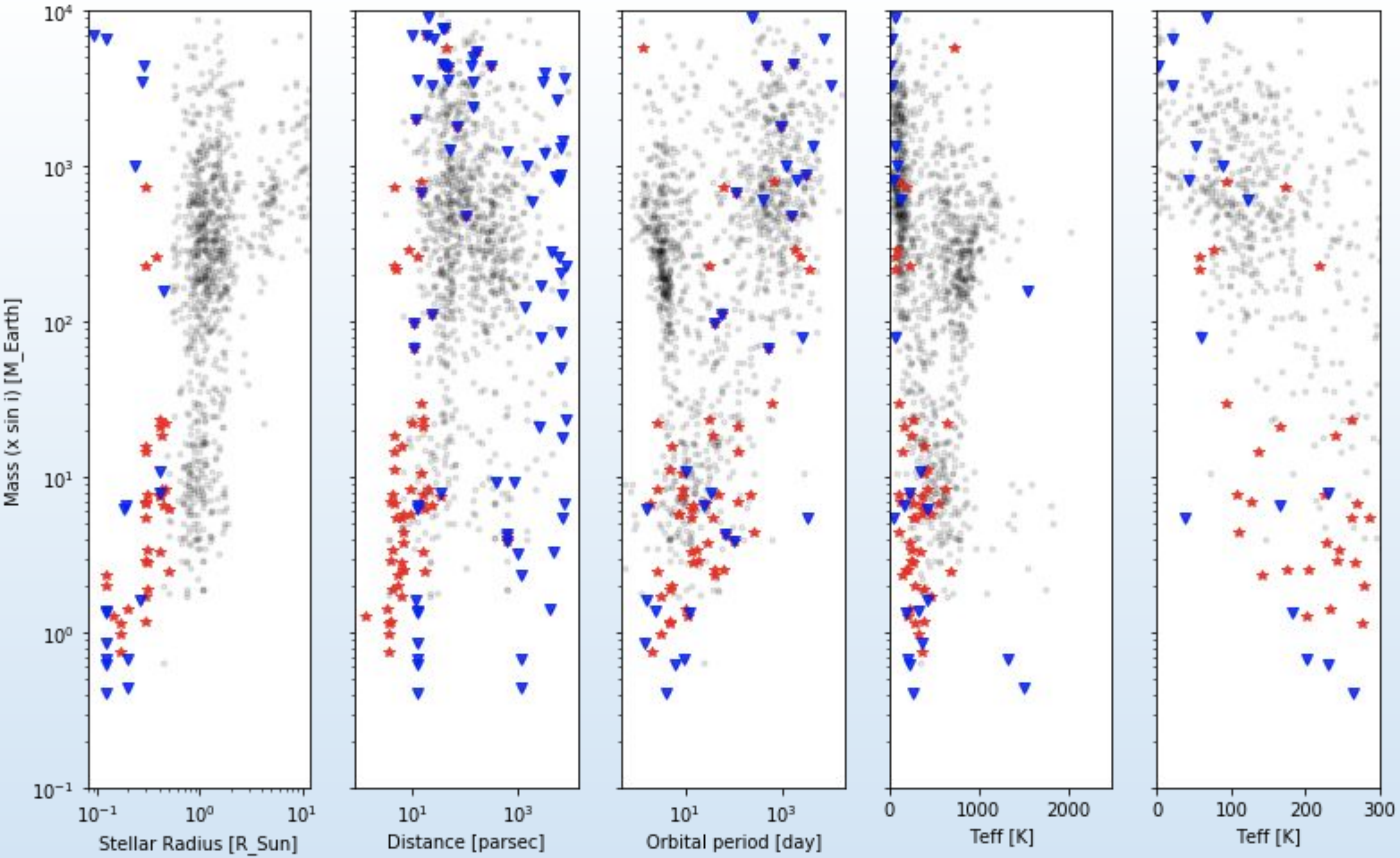
Quel instrument va faire quoi pour l'architecture ?

- Y a t il des lunes ? des anneaux ?
- Imager les régions internes des systèmes connus
- Échantillon de candidats GAIA à caractériser
-

- (VLT en mode survey ?)

Observables et paramètres estimés

Méthode	VR	Transit	Imagerie	Astrométrie	µlentilles
Observables	Vitesse radiale étoile	Luminosité étoile	Luminosité planète Astrométrie relative	Mouvement étoile	Luminosité étoile
Paramètres estimés	M_p.sin(i), paramètres orbitaux	R_p, paramètres orbitaux	M_p (modèles), paramètres orbitaux	M_p, paramètres orbitaux	M_p


Mass (x sin i) [M_Earth]
Stellar Radius [R_Sun]
Distance [parsec]
Orbital period [day]
Teff [K]
Teff [K]