The GTO Program with HARPS-N@TNG

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HARPS-N@TNG Project Schedule

Milestone	Date
Kick Off	September 1st, 2010
Start of integration	October 1st, 2011
Acceptance Geneva	January 1st, 2012
Commissioning	March/April 2012
Inauguration	April 23rd, 2012
Start of operations	May 1st, 2012
Open time	August 1st, 2012

- **First agreement for GTO in exchange of full access by INAF to HARPS-N@TNG : late 2010**
- **First GTO agreement: 80 nights/yr for 5 years (2012-2017)**
- **GTO agreement renewed for an additional 80 nights/yr 5 years (2017 - 2022)**
- **Ongoing discussions for second renewal of the GTO agreement**

GTO Consortium & Science Team

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GTO Consortium:

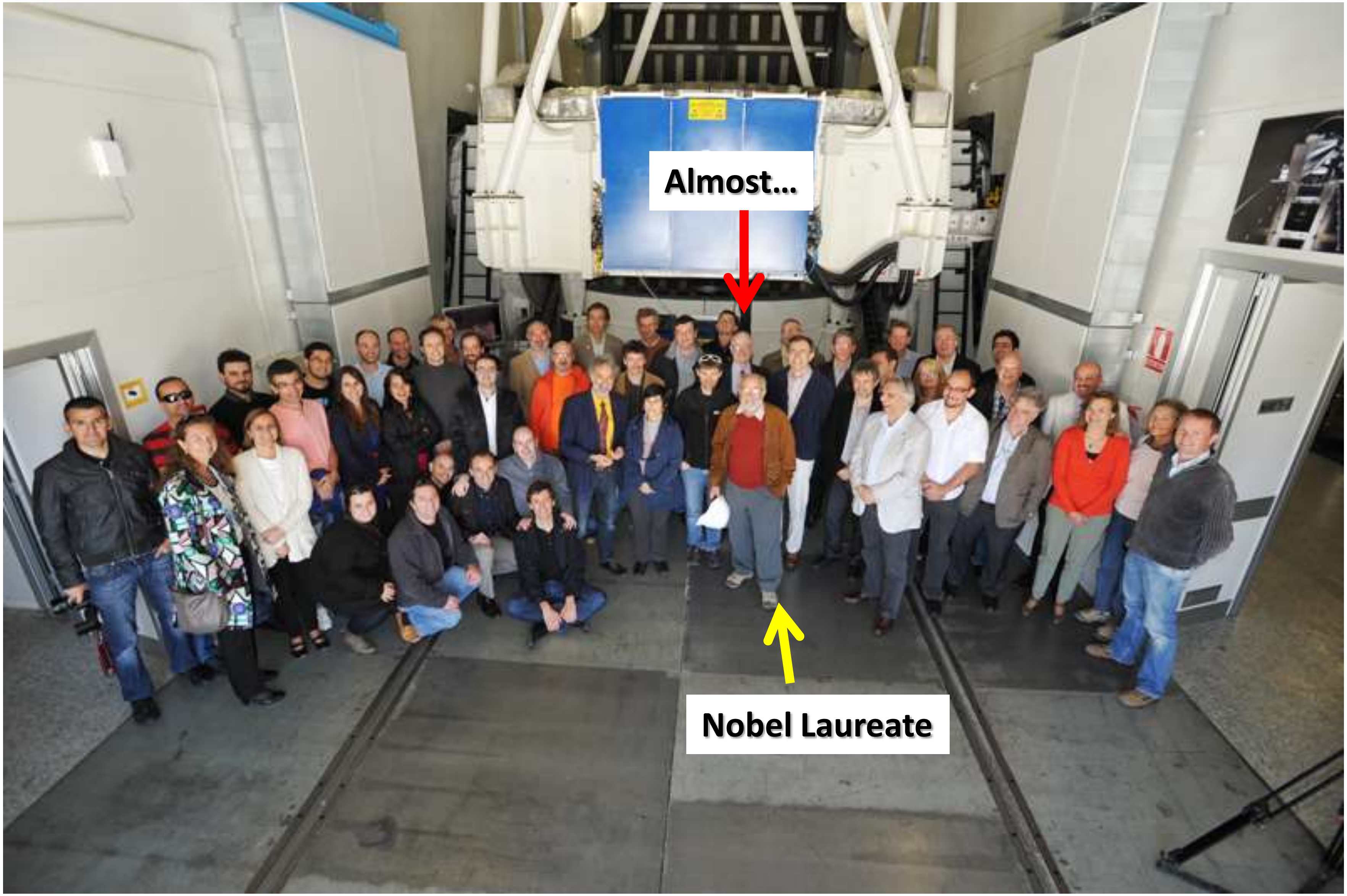
Geneva Observatory (Head), CfA (Cambridge), Harvard University, INAF-TNG, University of St. Andrews, University of Edinburgh, Queens University Belfast

HARPS-N Science Team:

Andrew Collier-Cameron, David Charbonneau, Xavier Dumusque, *David Latham*, Mercedes Lopez-Morales, Christophe Lovis, <u>Michel Mayor</u>, <u>*Giusi Micela*</u>, Francesco Pepe, David Phillips, <u>*Giampaolo Piotto*</u>, Ken Rice, Dimitar Sasselov, Damien Ségransan, <u>*Alessandro Sozzetti*</u>, Andrew Szentgyorgyi, Stéphane Udry, Chris A. Watson and **about 20 collaborators (9 Italian)**

HARPS-N ST 'manages' GTO organization, preparation, observation, analysis and publication
The Chairperson is appointed on a yearly basis rotating amongst the participants

HARPS-N Inauguration at TNG



HARPS-N GTO Science

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1) PRIMARY PROJECT (80% of GTO time):

a) determining the masses of transiting Kepler, K2 and TESS Earth-size planets, super-Earths and mini-Neptunes in various orbits with enough precision to distinguish between volatile-rich (e.g., high-pressure water ice shells and/or H/He atmospheric envelopes) and predominantly iron-silicate compositions, and investigate possible dependences on planet mass and irradiation level (PP1a);

b) confirming temperate terrestrial planets around G5V stars or later (PP1b);

c) characterizing the architecture of systems with small planets by searching for non-transiting planets both in close-in or wide orbits. (PP1c)

2) SECONDARY PROJECT (20% of GTO time):

- Search for low-mass, rocky planets and multiple systems around bright, low-activity, northern solar-type stars (SP)

INAF’s Role in GTO Science

- Funding of a relevant component of GTO activities (2013-2017: EU FP7-SPACE ETAEARTH project, PI A. Sozzetti. Funded 3 postdocs in Italy, 3 in the UK, one in the US and in Switzerland)
- Out of the ~40 refereed papers published (with over 1000 citations), about 1/3 have been led by INAF researchers & associates

In >9 years of GTO Science…

- > 7000 observing hours allocated
- > 24,000 exposures
- > 4500 hours of open shutter
- 62% open-shutter efficiency

Improvements in science output also due to coordination and collaboration with the GAPS/GAPS2 LPs (observing time sharing, conflict resolution and actual collaboration on specific targets).

GTO Science Highlights: Summary

i) The first Earth-size planet with a mass measured: Kepler-78b (Pepe et al. 2013, Nature);

ii) The first mega-Earth: Kepler-10c (Dumusque, Bonomo et al. 2014; Bonomo et al., in prep.);

iii) The first super-Neptune: Kepler-101b (Bonomo, Sozzetti et al. 2014);

iv) Small planets, diverse compositions (Dressing et al. 2015; Vanderburg et al. 2015; 2017; Christiansen et al. 2017);

v) The nearest transiting exoplanet system to the Sun (Motalebi et al. 2015, Gillon et al. 2017);

vi) Ultra-short-period planets with rocky (possibly lava ocean) compositions such as K2-141b (Malavolta et al. 2018) and K2-312b/HD80653b (Frustagli, Poretti et al. 2020);

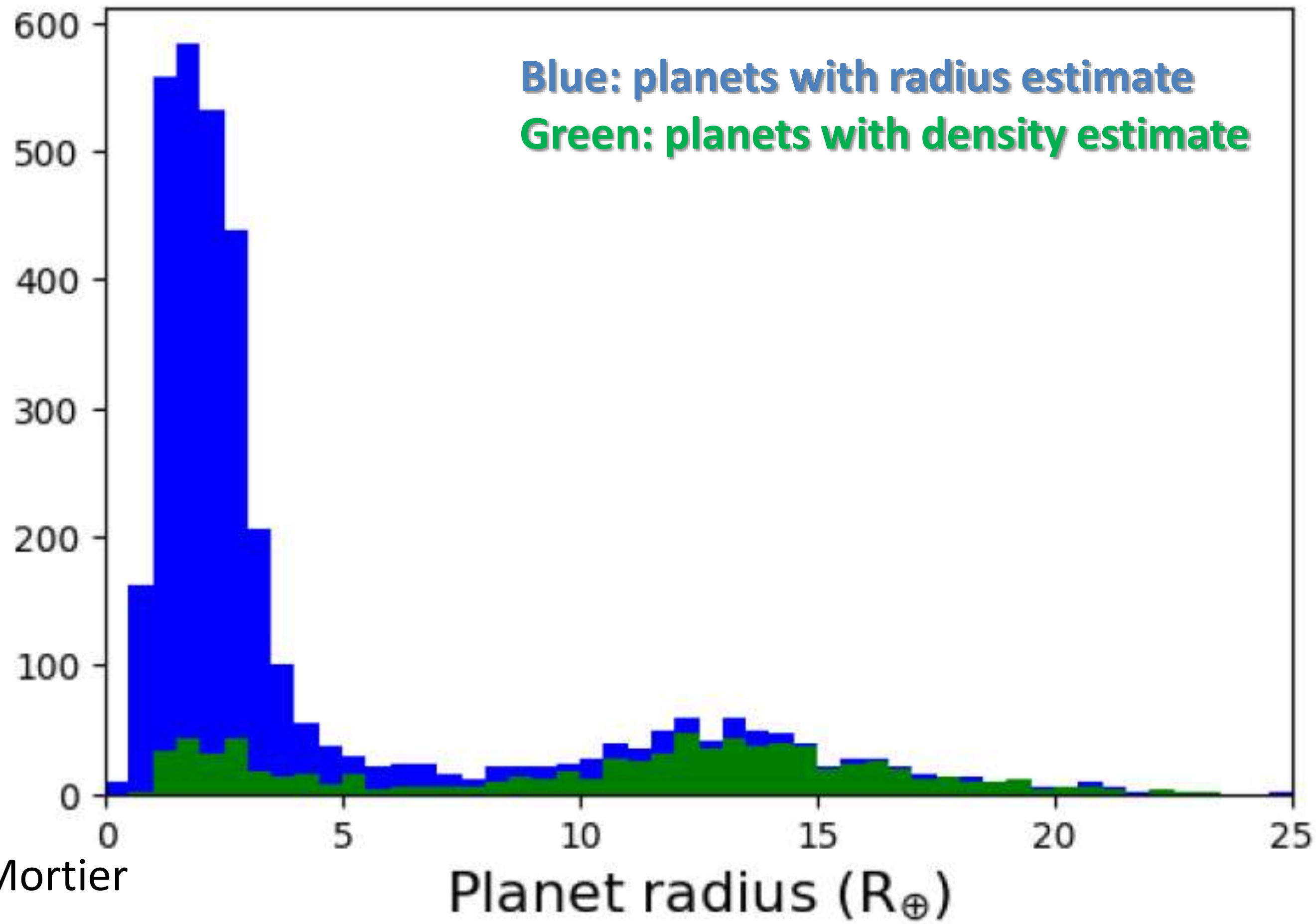
vii) K2-36: two planets with close orbits but different compositions (Damasso et al. 2019);

viii) K2-3: three sub-Neptunes, the outermost of which orbits in the habitable zone (Damasso, Bonomo et al. 2018);

ix) The first system likely sculpted by giant impacts: Kepler-107 (Bonomo et al. 2019, Nature Astronomy);

x) Long-period giant companions in small-planet systems (in prep: Malavolta et al., Frustagli et al., Bonomo et al.).

Densities of Small Planets

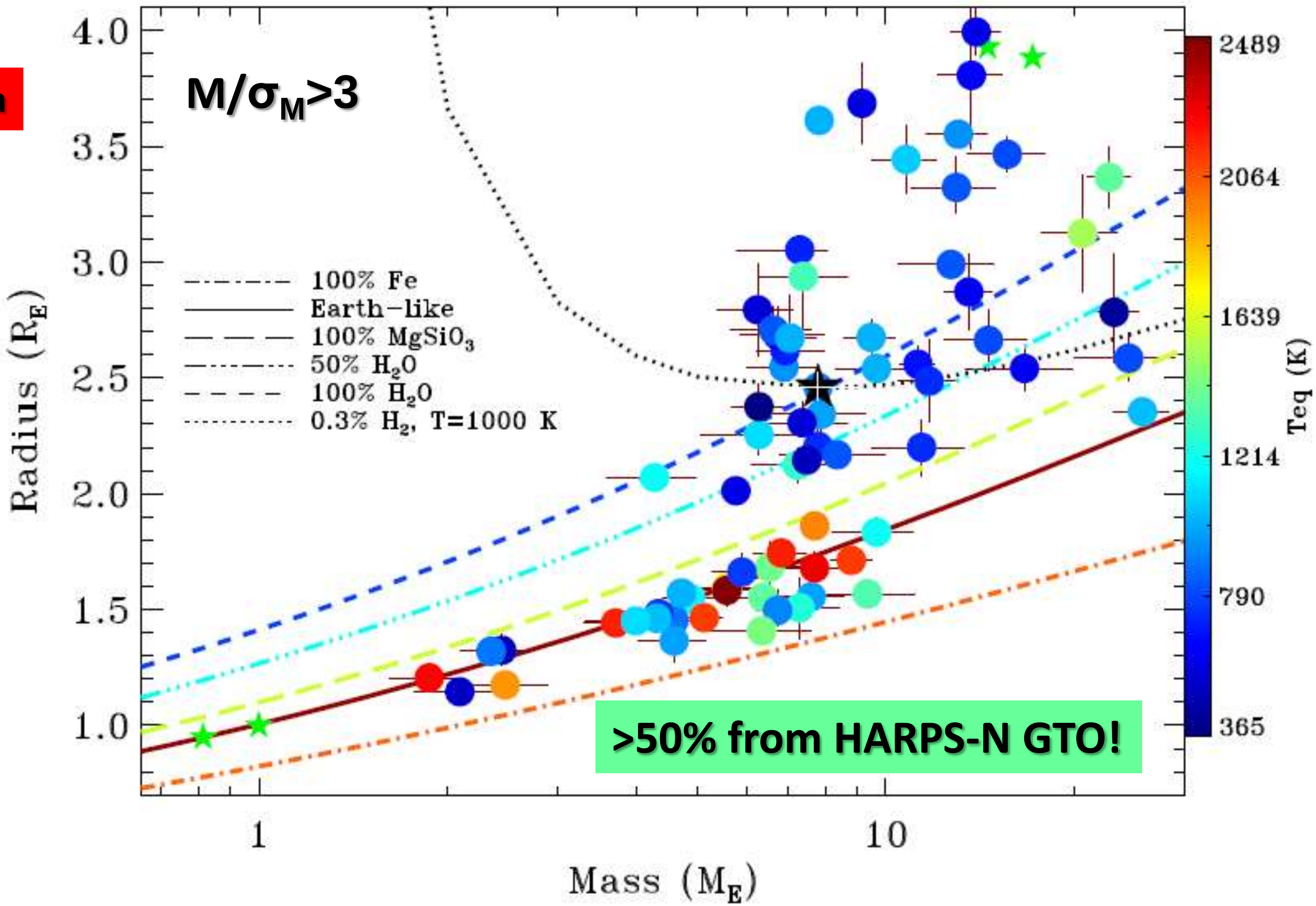


Credits: A. Mortier

Precise masses/densities of small planets are key to estimate their atmospheric scale heights and thus select those best suited for atmospheric characterization with, e.g. JWST and Ariel.

M-R Relation: Small Planets

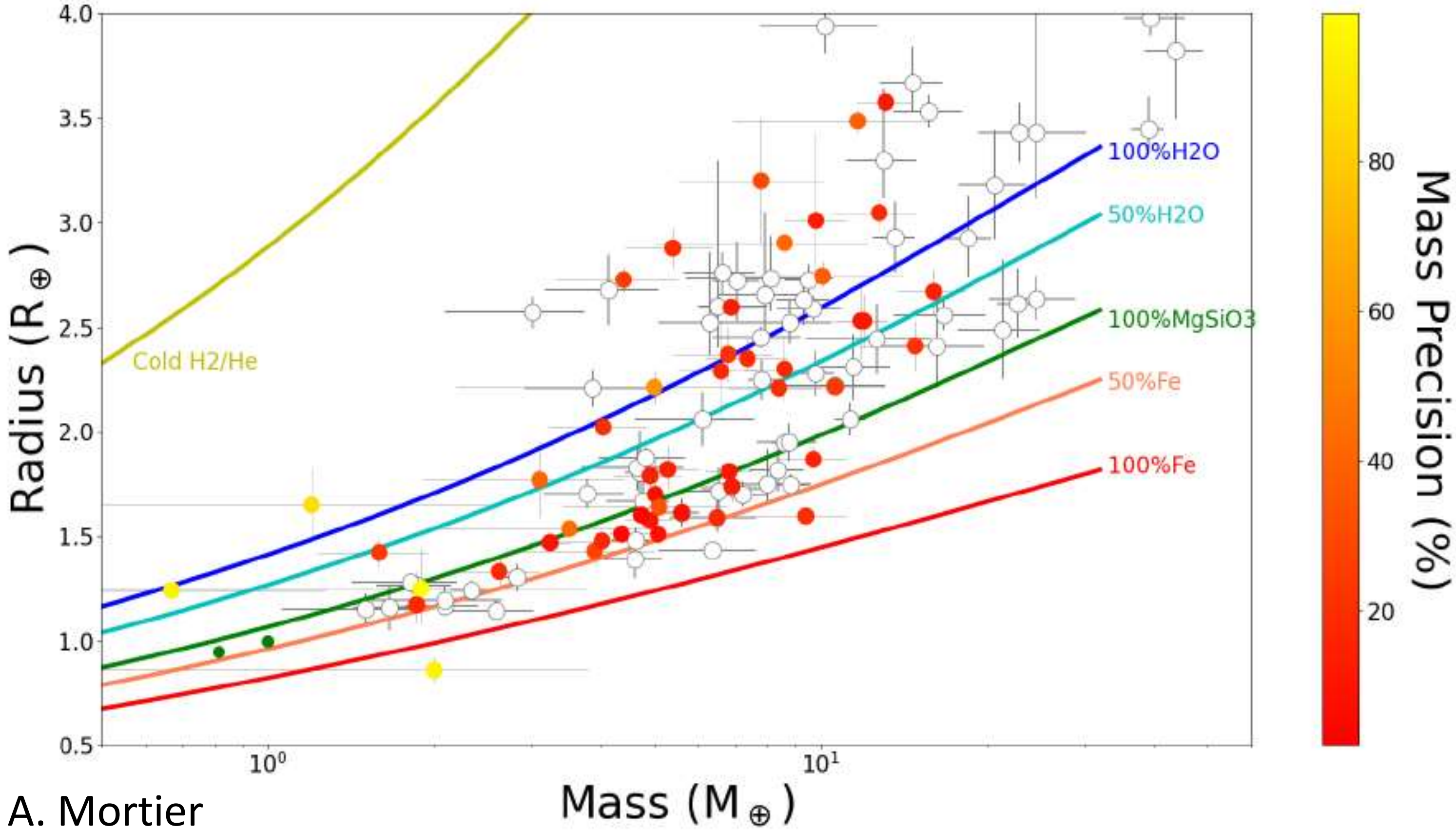
PP 1a



>50% from HARPS-N GTO!

M-R Relation: Small Planets

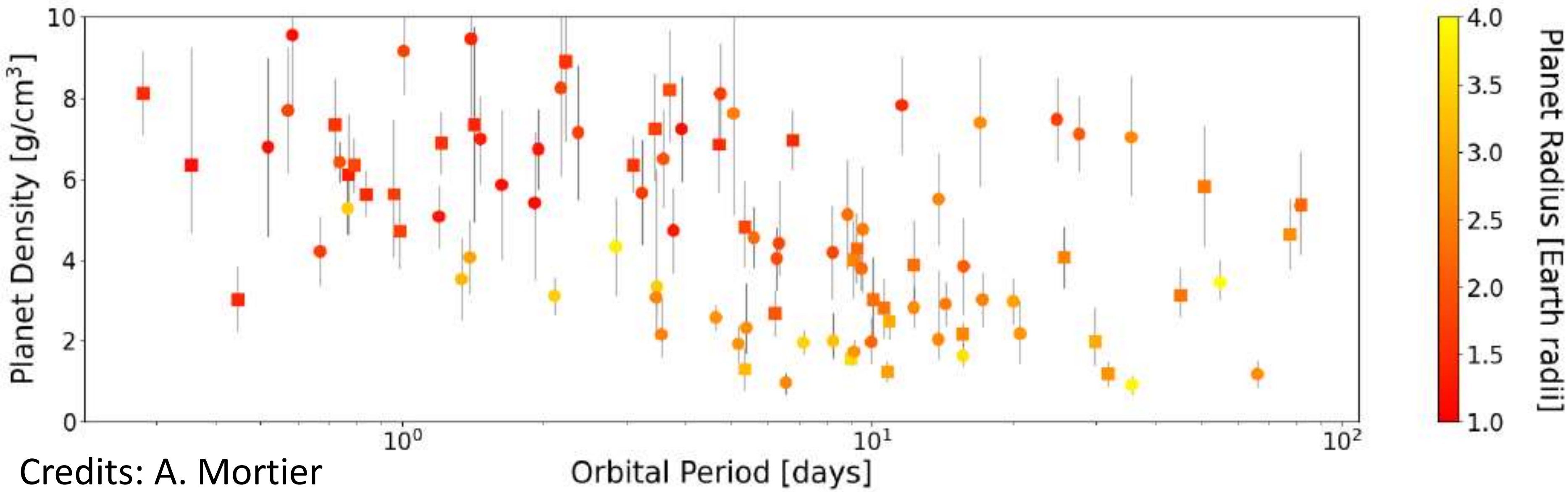
PP 1a



Credits: A. Mortier

(HARPS-N GTO data: Bonomo et al. 2014, 2019; Buchhave et al. 2016; Christiansen et al. 2017; Cloutier et al. 2020a,b,2021; Damasso et al. 2018, 2019; Dressing et al. 2015; Dubber et al. 2019; Frustagli et al. 2020; Gettel et al. 2016; Gillon et al. 2017; Haywood et al. 2018; Kosiarek et al. 2019; Lacedelli et al. 2021; Lopez-Morales et al. 2016; Malavolta et al. 2017, 2018; Mayo et al. 2019; Mortier et al. 2018, 2020; Pepe et al. 2013; Rajpaul et al. 2017, 2021; Rice et al. 2019; Santerne et al. 2021; Vanderburg et al. 2015, 2017. Non-HARPS-N Collaboration data: exoplanet.eu)

From Ultra-Short to Long Periods



Credits: A. Mortier

K2-141b: 0.2803244 d - 1.51 $R_\oplus$ - 5.08$M_\oplus$ (Malavolta et al. 2018)
Kepler-78b: 0.3550 d - 1.173 $R_\oplus$- 1.86$M_\oplus$ (Pepe et al. 2013)
WASP-47e: 0.79 d - 1.81 $R_\oplus$- 6.83$M_\oplus$ (Vanderburg et al. 2017)
TOI-561b: 0.446578 d - 1.423 $R_\oplus$ - 1.59$M_\oplus$ (Lacedelli et al. 2021)
TOI-1634b: 0.989 d - 1.79 $R_\oplus$ - 4.91$M_\oplus$ (Cloutier et al. 2021)
K2-263b: 50.8 d - 2.41 $R_\oplus$ - 14.8$M_\oplus$ (Mortier et al. 2018)
TOI-561e: 77.2 d - 2.67 $R_\oplus$ - 16.0$M_\oplus$ (Lacedelli et al. 2021)
Kepler-538b: 81.73778 d - 2.215 $R_\oplus$ - 10.6$M_\oplus$ (Mayo et al. 2019)

PP 1a

Systems with non-transiting planets

- **<u>Kepler-20</u>**: 2 terrestrials, 3 sub-Neptunes, a non transiting super-Neptune

- **<u>K2-111</u>**: a metal-poor super-Earth around a metal-poor star, with a non-transiting, near-resonant Neptune-type companion

- **<u>WASP-47</u>**: a super-Earth and a sub-Neptune with a hot Jupiter in between and a cold gas giant

- **<u>HD 3167</u>**: a rocky super-Earth, a warm sub-Neptune, and a non-transiting super-Earth between them

- **<u>Kepler-454</u>**: a close-in sub-Neptune, a cold Jupiter, a distant companion

- **<u>HD 80653</u>**: An ultra-short period rocky super-Earth with a distant companion

PP 1c

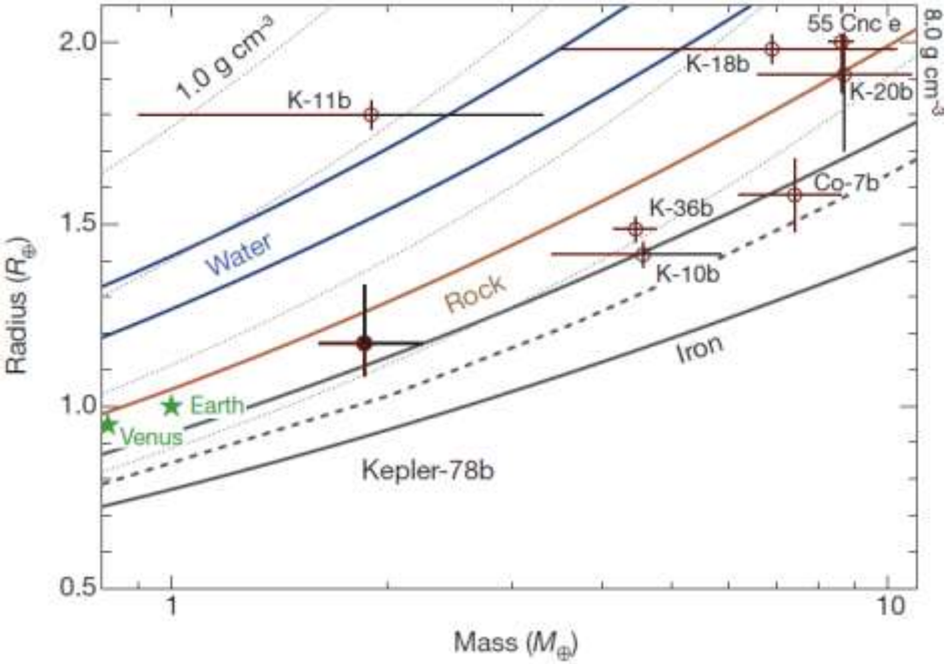
PP 1a

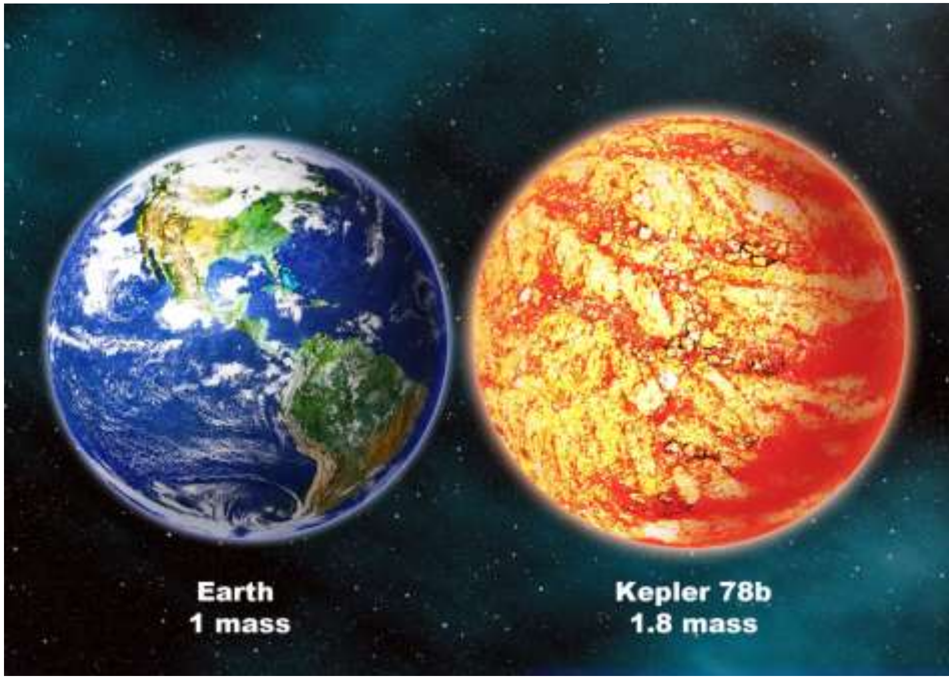
LETTER

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], Keith Horne[2], Mercedes Lopez-Morales[3], Christophe Lovis[1], Luca Malavolta[10,11], Michel Mayor[1], Giusi Micela[12], Fatemeh Motalebi[1], Valerio Nascimbeni[11], David Phillips[3], Giampaolo Piotto[10,11], Don Pollacco[13], Didier Queloz[1,14], Ken Rice[15], Dimitar Sasselov[3], Damien Ségransan[1], Alessandro Sozzetti[6], Andrew Szentgyorgyi[3] & Christopher A. Watson[16]



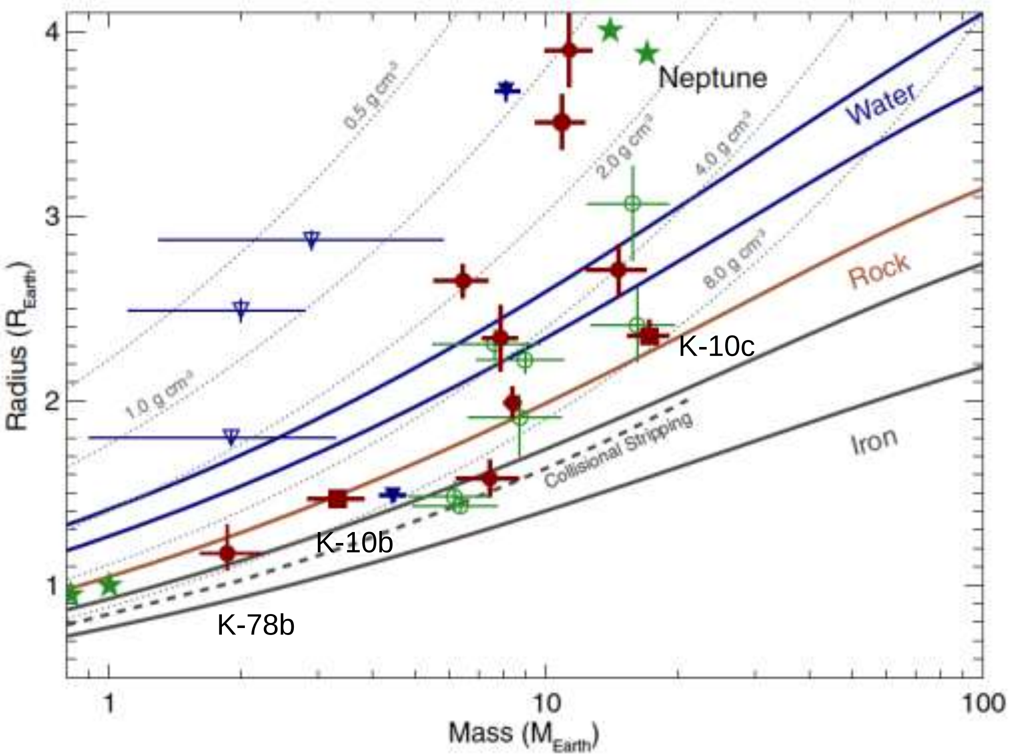


Kepler-78b: The closest thing to Earth ever detected!

But: P=8.5 hrs, T_{eq} =3000 K - Alas... Far From Habitable!

Kepler-10c

Kepler-10c:
The Godzilla of Super-Earths!



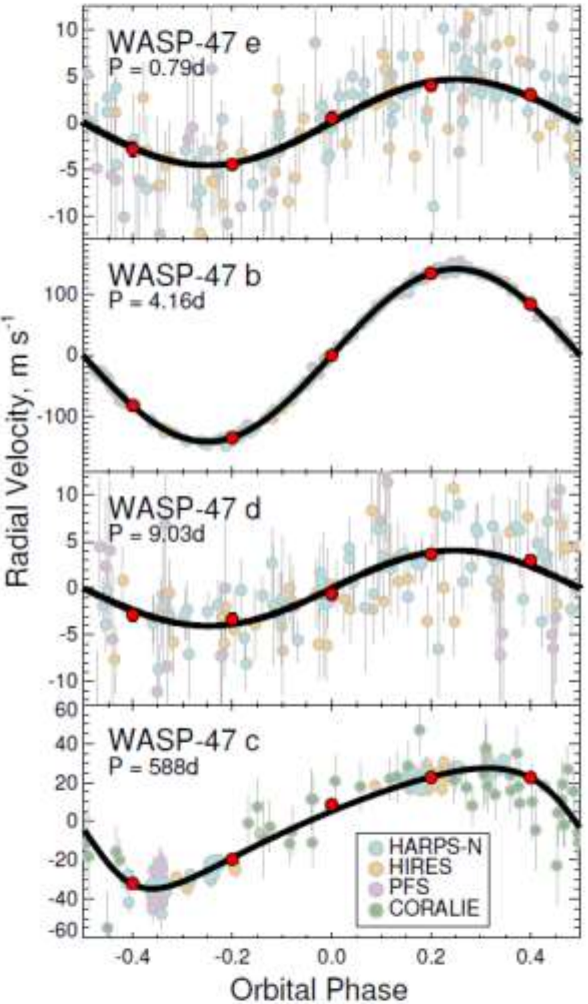
(Dumusque, Bonomo, Haywood et al. 2014, A&A)

PP 1a

P=45 d, warm, not temperate

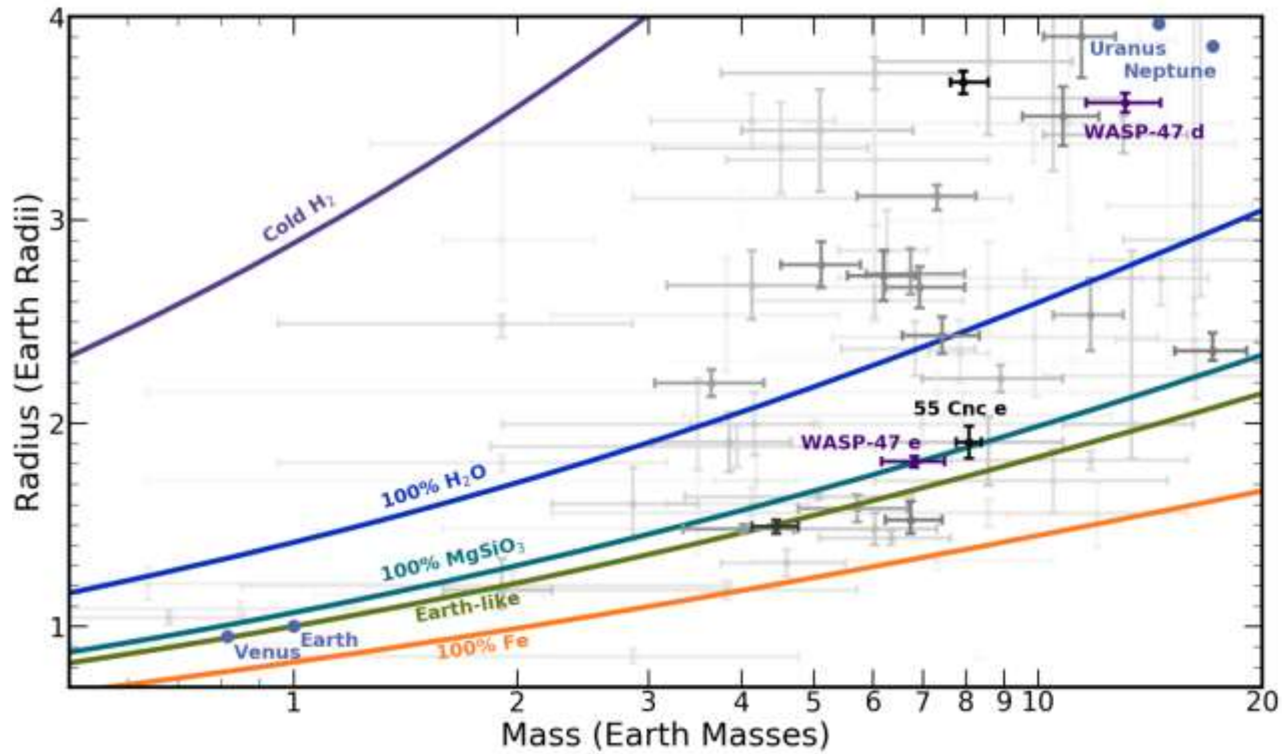
The WASP-47 System

PP 1a



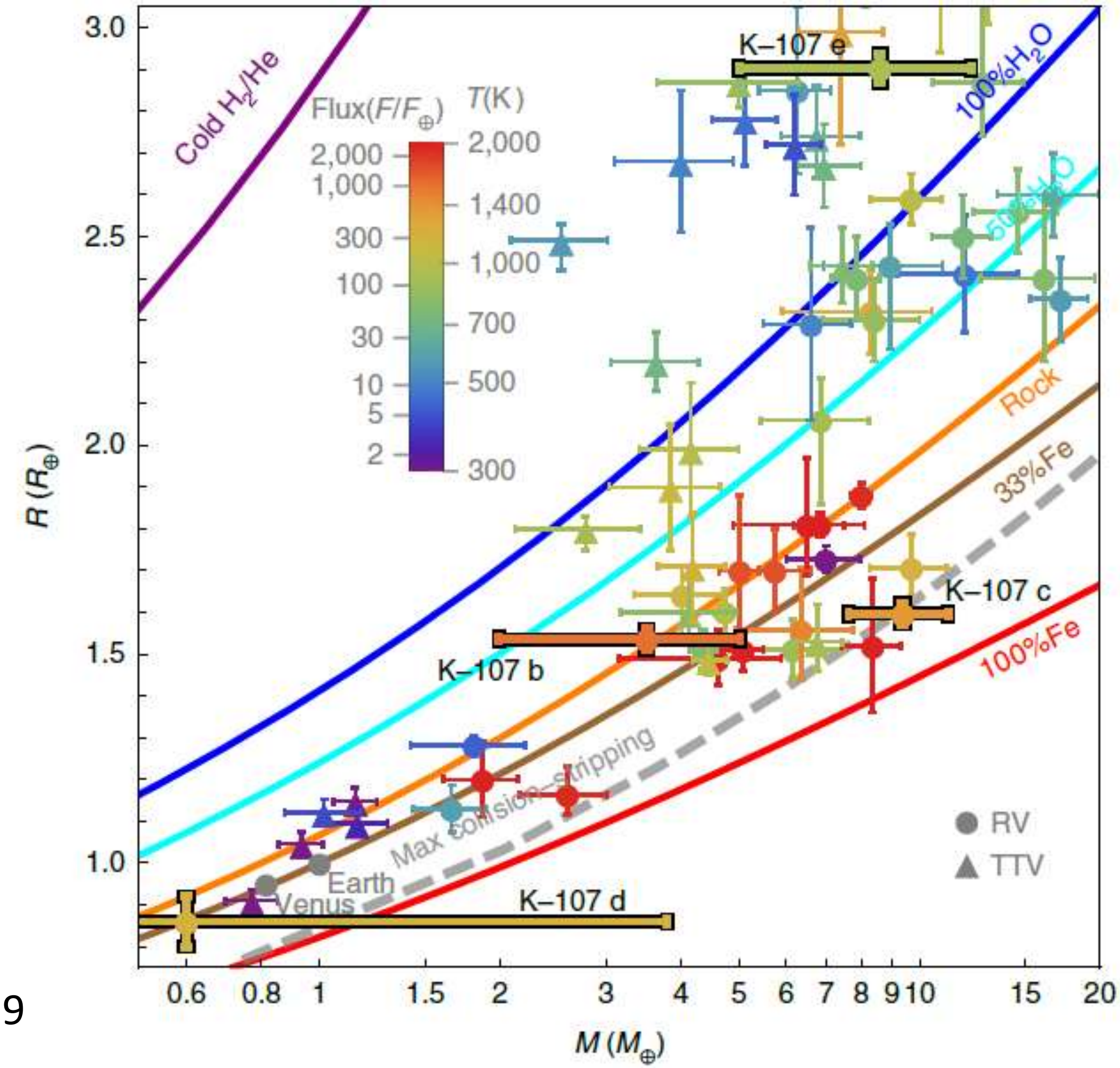
WASP-47 e is not Earth-like, even at P=0.79d!

Vanderburg et al. AJ 2017



The Kepler-107 System

Kepler-107c:
A COSMIC COLLISION?

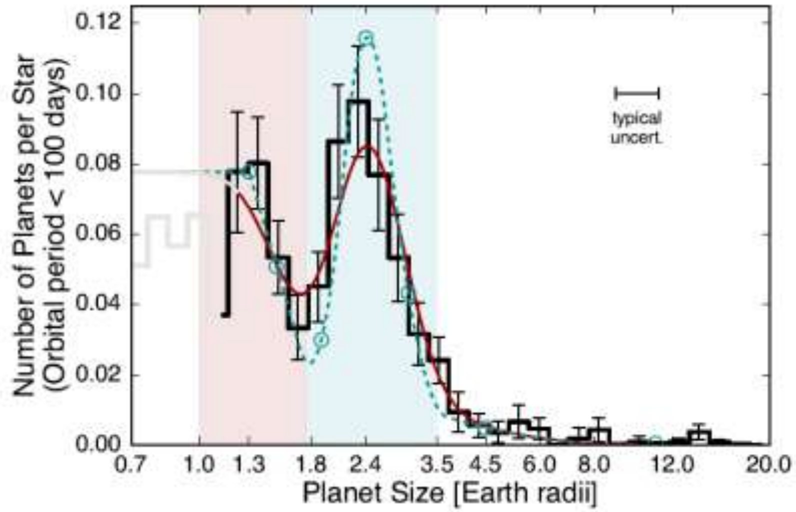


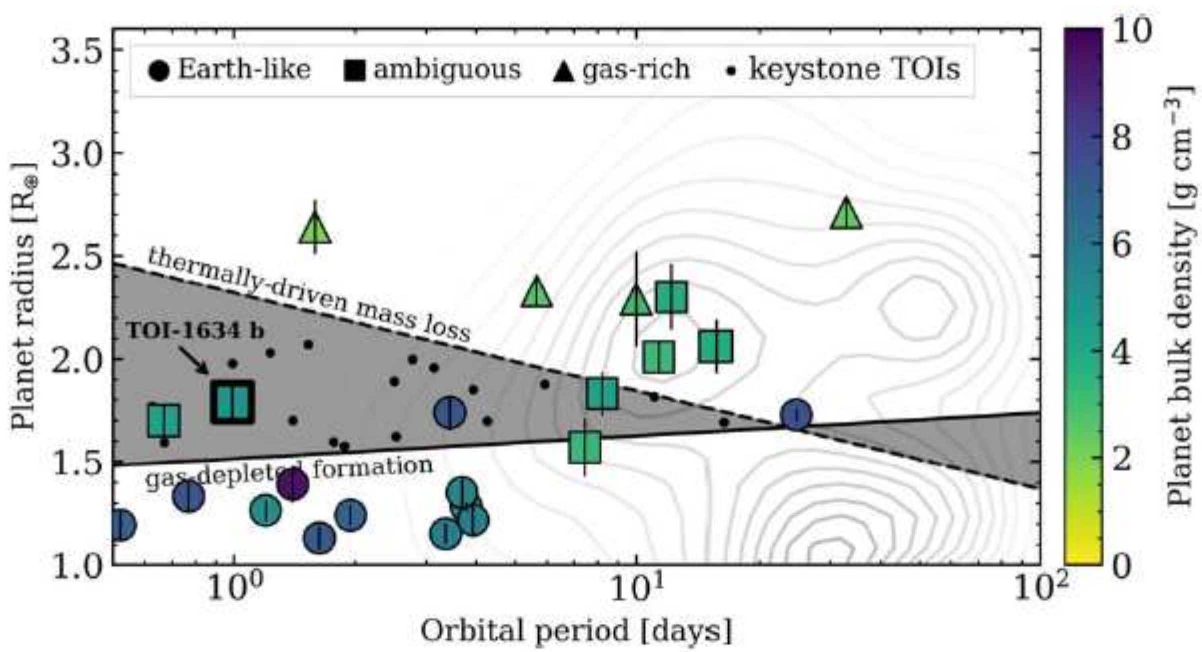
Bonomo et al. 2019

PP 1a

M dwarf planets around the radius valley

PP 1a



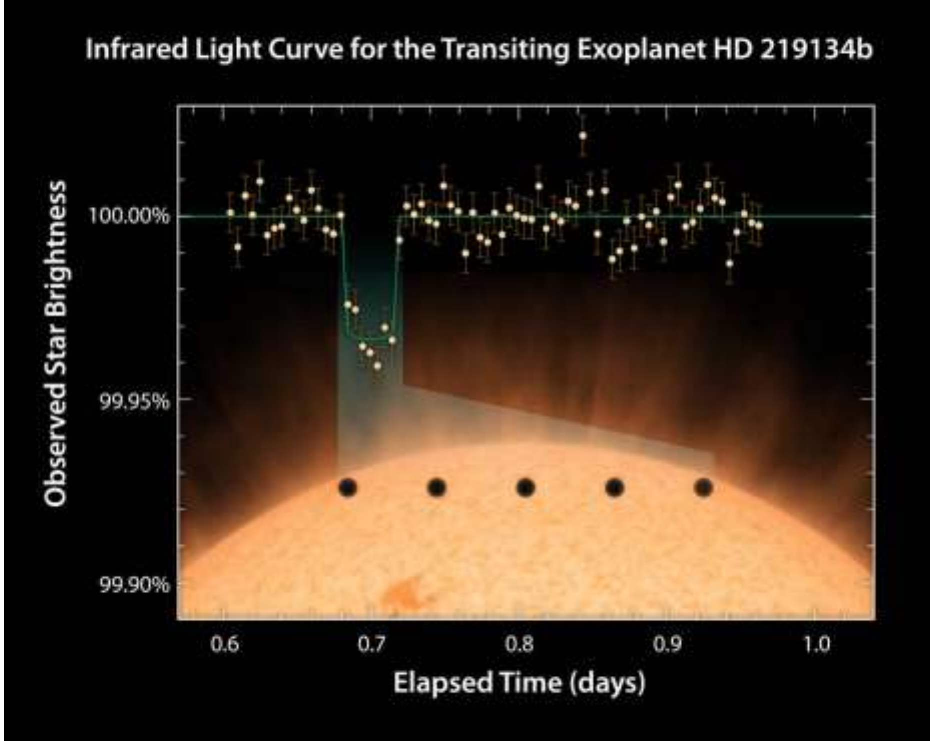


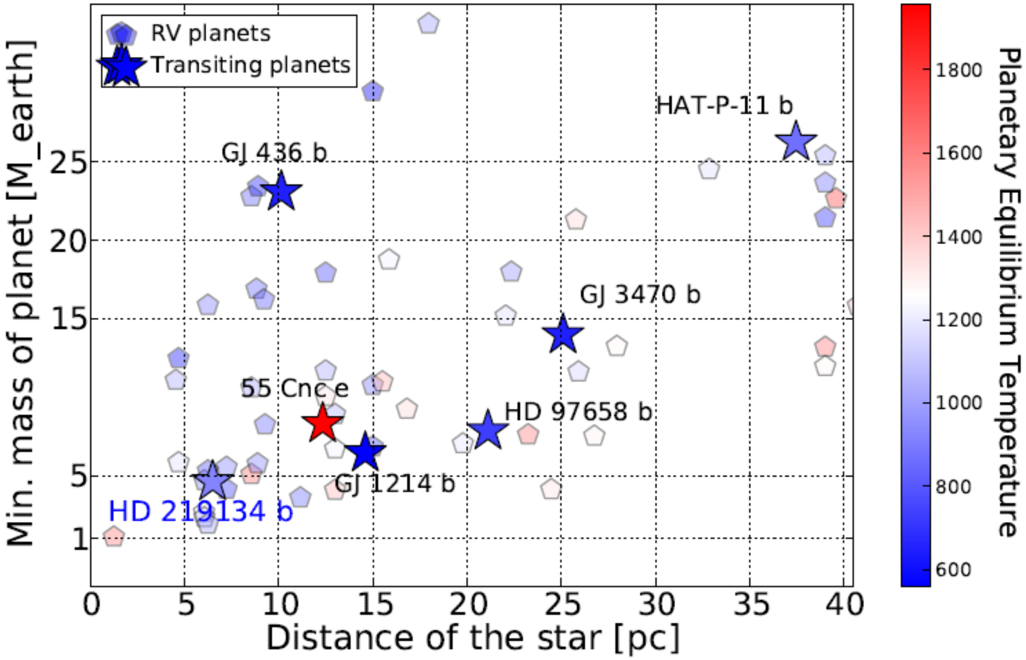
Cloutier et al. 2021

SP

HARPS-N RPS:

Kick-off with a bang!





HD219134b:
A transiting Super Earth at 6.5 pc from the Sun!

Motalebi et al. 2015

nature astronomy | LETTERS
PUBLISHED: 2 MARCH 2017 | VOLUME: 1 | ARTICLE NUMBER: 0056

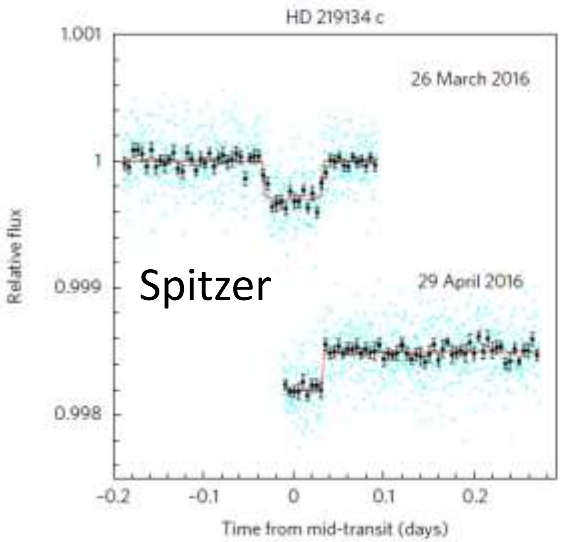
SP

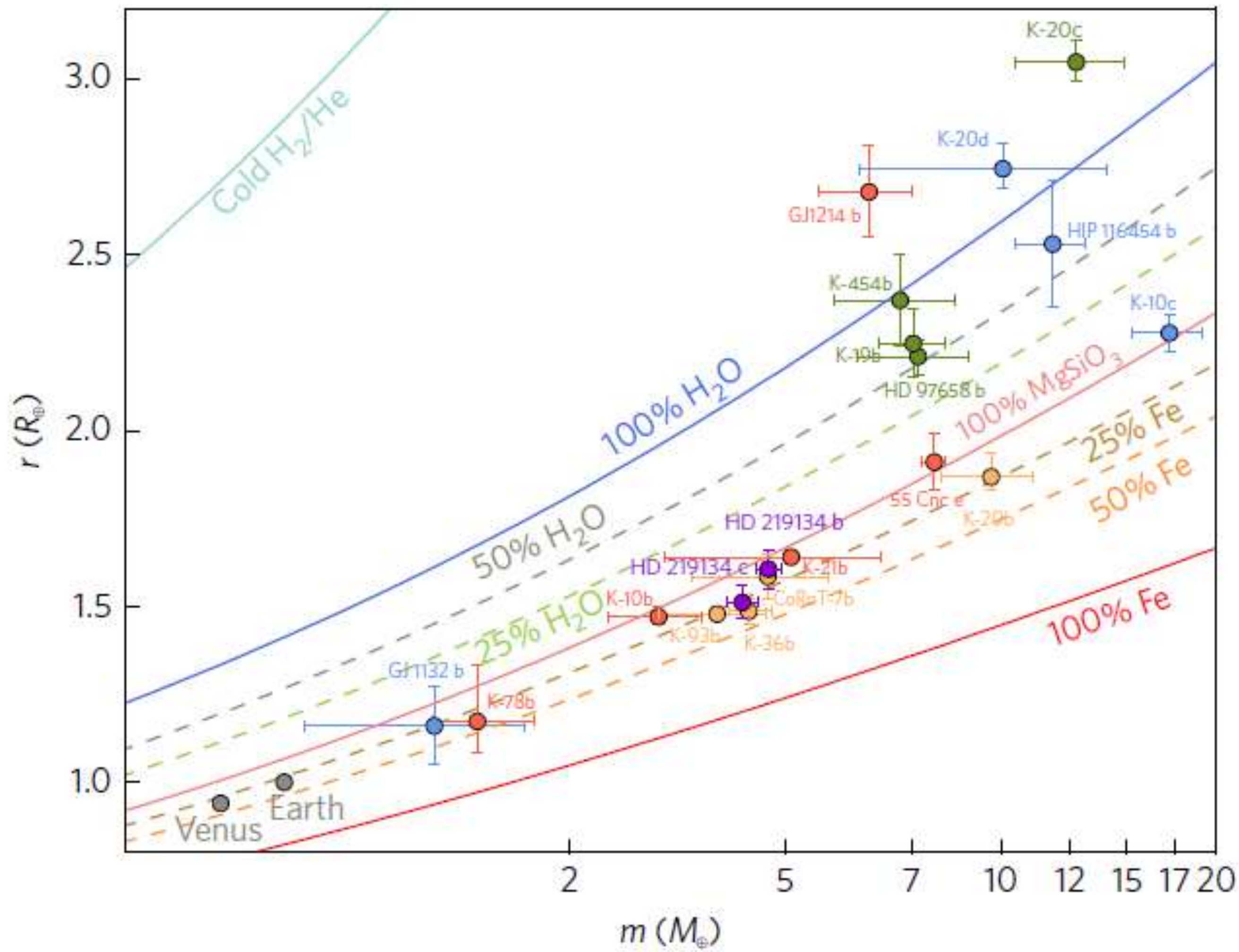
Two massive rocky planets transiting a K-dwarf 6.5 parsecs away

Michaël Gillon, Brice-Olivier Demory, Valérie Van Grootel, Fatemeh Motalebi, Christophe Lovis, Andrew Collier Cameron, David Charbonneau, David Latham, Emilio Molinari, Francesco A. Pepe, Damien Ségransan, Dimitar Sasselov, Stéphane Udry, Michel Mayor, Giuseppina Micela, Giampaolo Piotto and Alessandro Sozzetti

Harps-N

HD219134c transits too!

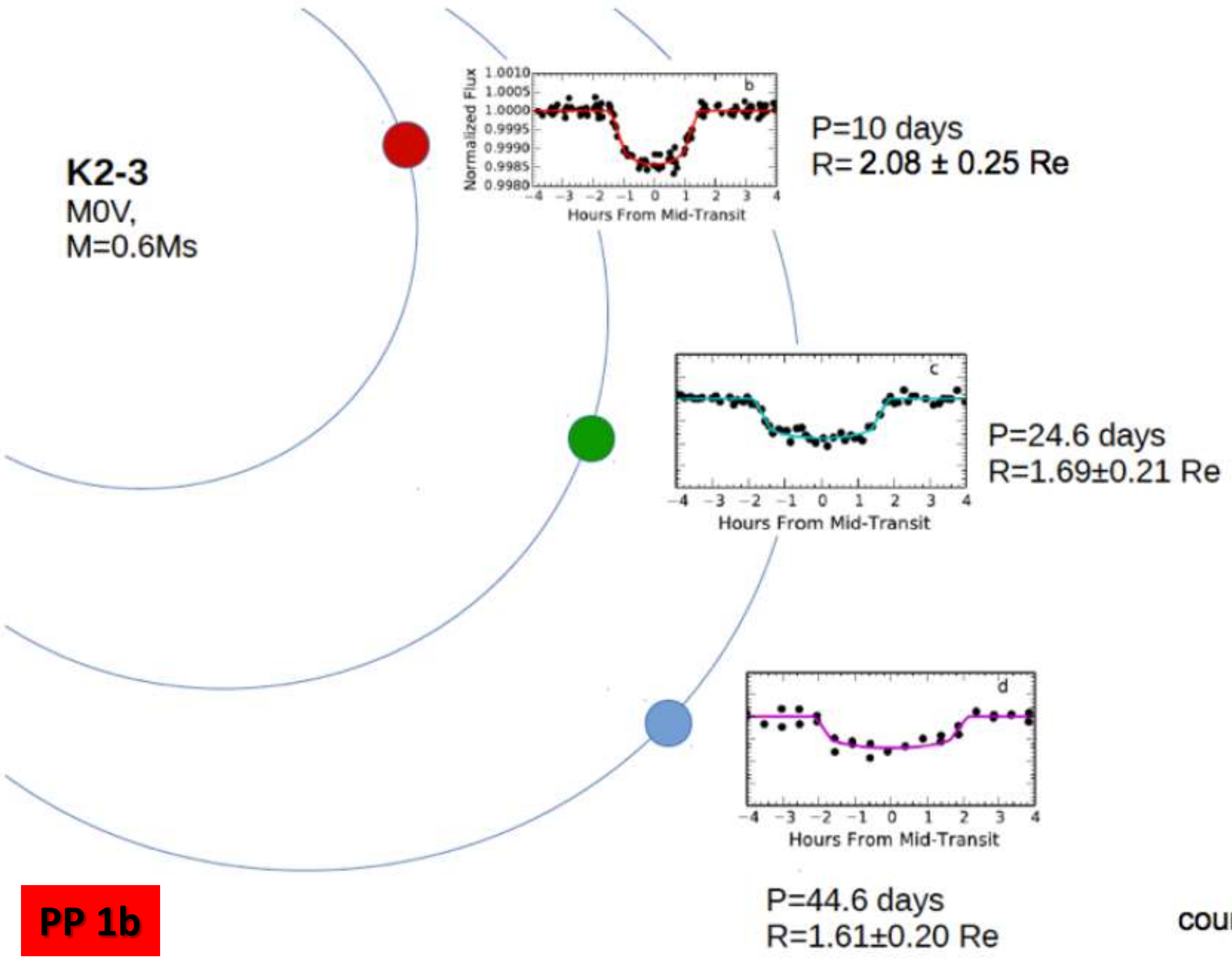




Great case study:

- R_p and M_p good to 1%
- Dayside atmospheric studies with JWST

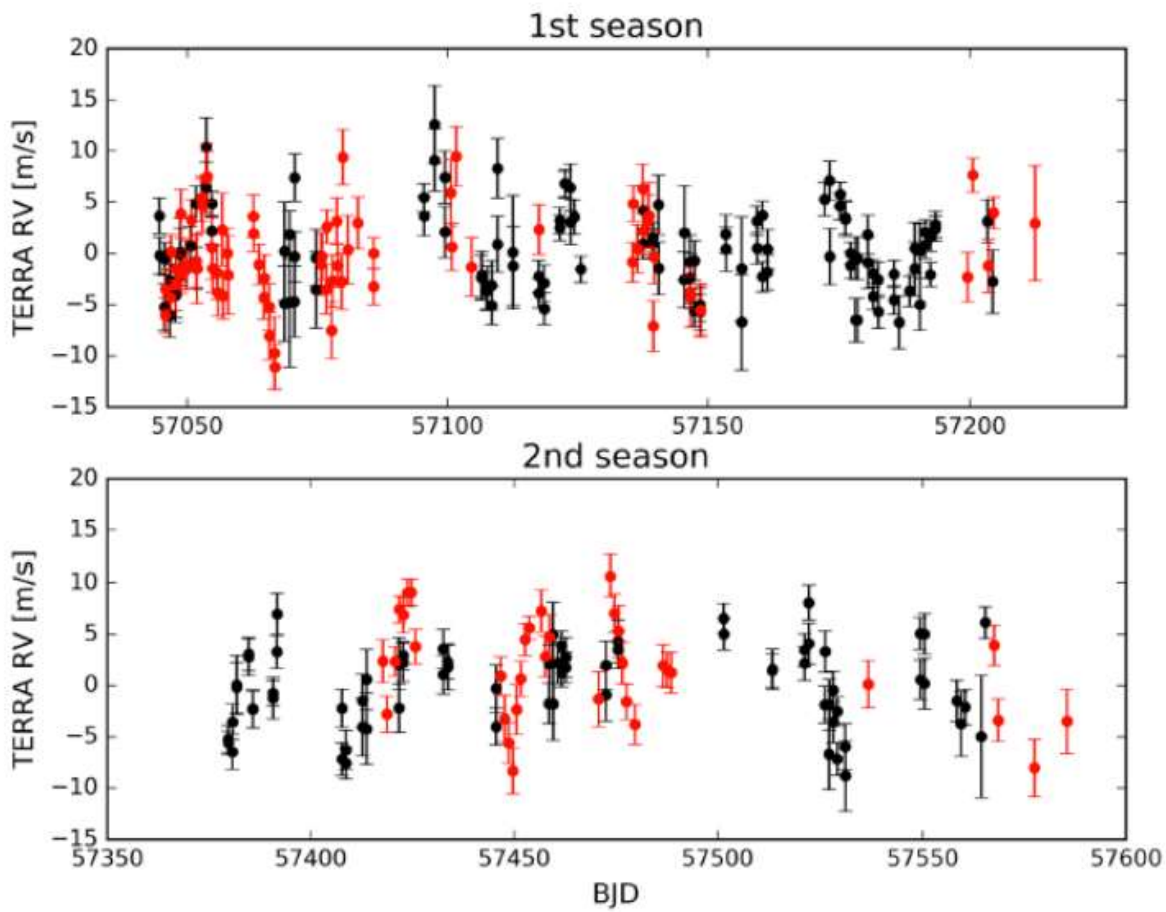
K2-3: a planetary system orbiting a M0V star with an outer 1.6 R⊕ planet in the HZ



PP 1b

courtesy by M. Damasso

A Seminal GTO-GAPS Collaboration



PP 1b

red circles: 105 HARPS RVs
black circles: 184 HARPS-N RVs

Eyes on the K2-3 system of sub-Neptunes

PP 1b

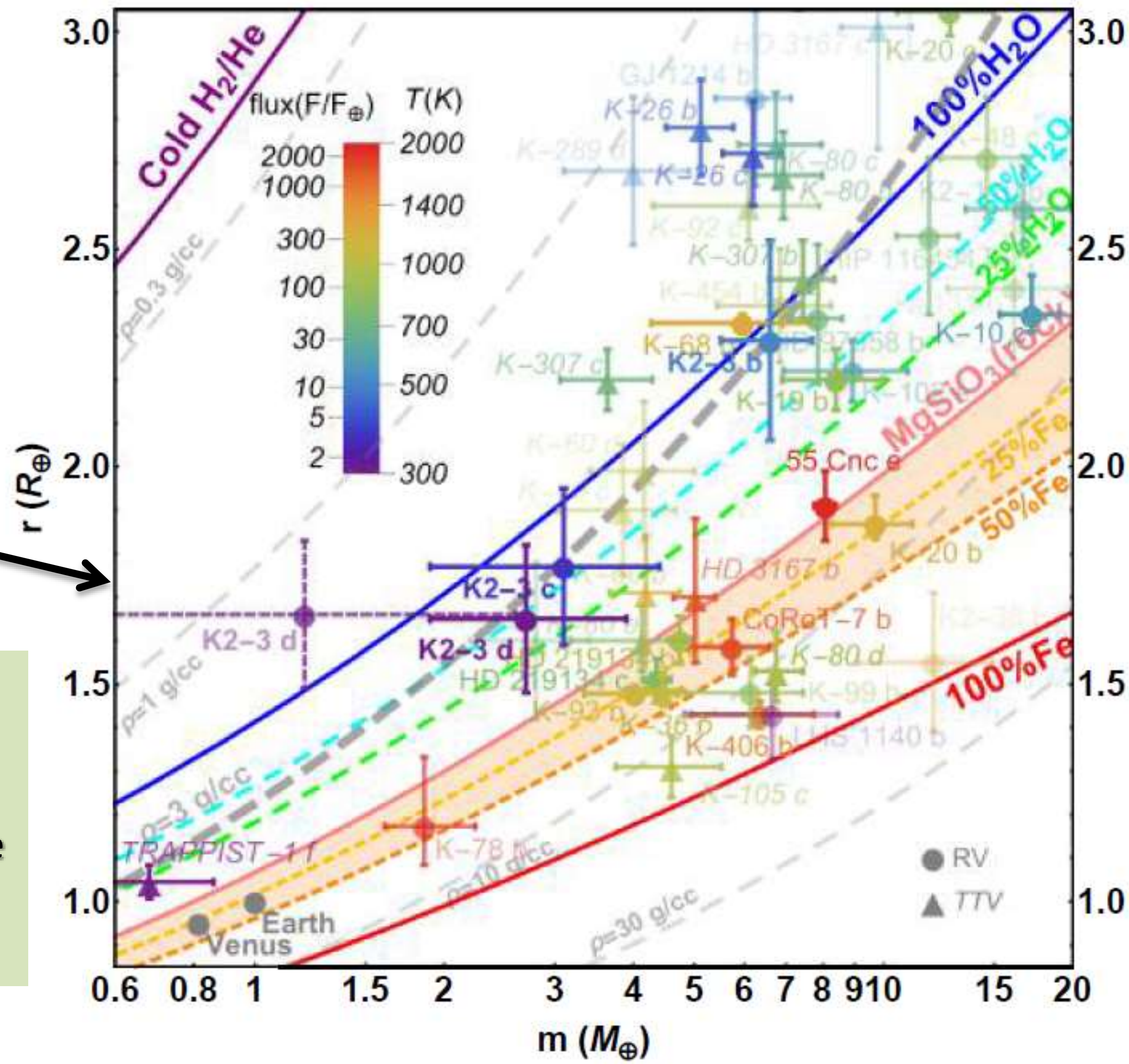
Stellar signal:

2.8 m/s @ 40 days

Planetary signals:

3.0 (b), 1.0 (c), and < 1 (d) m/s

In the HZ of a M0 dwarf



High-cadence dataset essential for RV modeling of stellar activity and planetary signals simultaneously using innovative tools (Gaussian Processes) in a Bayesian framework

Damasso et al. A&A 2018

What's next?

- The GTO program has proven HARPS-N@TNG to be the leading RV instrument for ground-breaking exoplanetary science in the Northern hemisphere.

- July 31st 2022: end of current GTO agreement.

- Discussions and negotiations are now starting to form the basis of a second renewal of the agreement .

- Scientific goals designed to exploit the opportunities that will arise in the 2023-2028 timeframe (new data, new missions…) for cutting-edge science with small exoplanet systems.

- Enhanced interaction with other teams (e.g. GAPS) desirable.