GAPS

Global Architecture of Planetary Systems

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GAPS results

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iaps

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FACULTÉ DES SCIENCES

CSIC

GAPS facts

- ~314 allocated nights
- Started August 2012
- >7100 spectra
- ~ 300 targets
- 20 accepted papers, many others in preparation or close to the submission

Scientific themes

The exploration of the diversity of architectures of planetary systems

How the architectures are linked to the environments?

- Radiations and stellar properties (age, mass, metallicity, activity,..)
- Environment (presence of additional planets, crowded environments)

Explored both by **searching for new planets** and better **characterization of known systems**

GAPS

Scientific questions

- Frequency and properties of exoplanets around early M dwarfs
- Frequency and properties of exoplanets around metal poor stars
- Impact of open-cluster environment on frequency and architectures of planetary systems
- Impact of the presence of giant planets in wide orbits on the presence of low mass planets in close orbits (scaled Solar System-like)
- How frequently are hot Jupiters accompanied by planets in wide orbits
- Spin-orbit alignement in planetary systems
- How tides shape the orbital properties of hot Jupiters and how they interact with their host stars

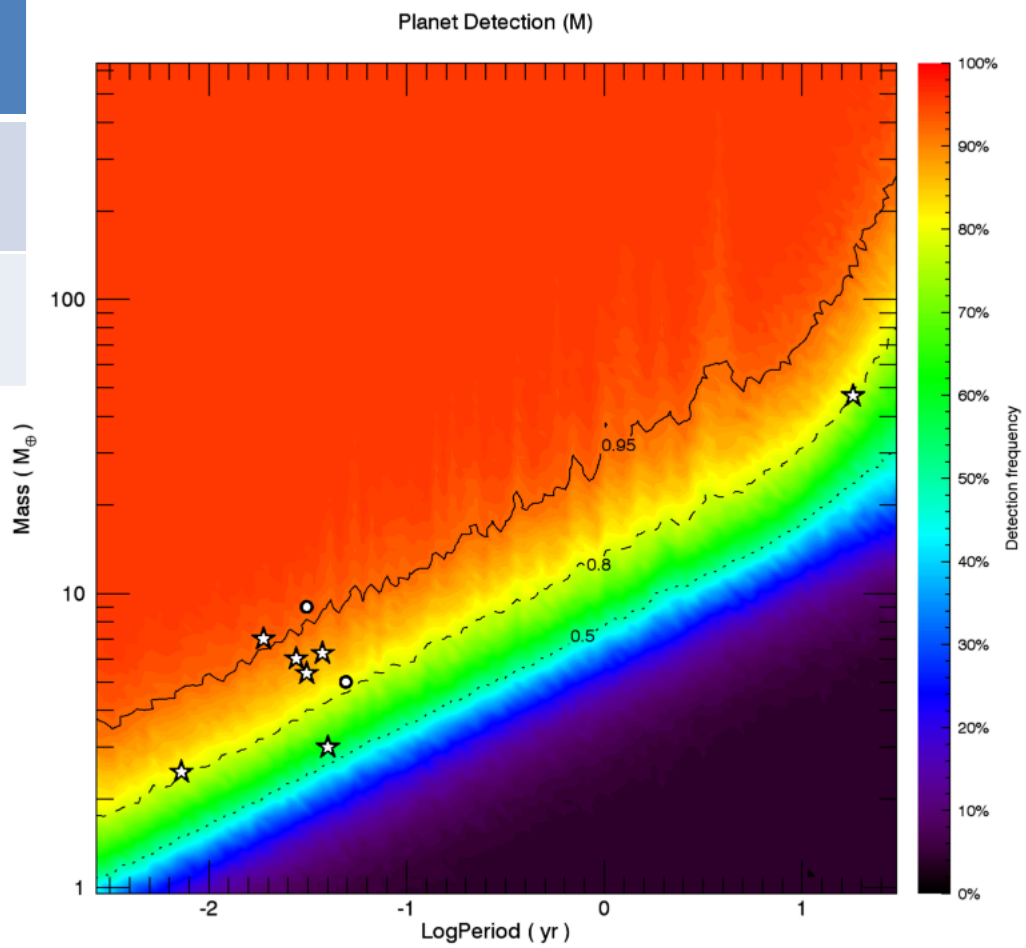
GAPS Challenges and solutions

- The role of scheduling
- The role of activity even in the quietest stars *(see A. Ghedina talk on solar telescope)*
- Typically high multiplicity of low mass planets in close orbits
- Gaussian process and RV challenge: applying the traditional expertise of our community on stellar activity to planet detection
- Need of dense sampling and large number of measurements when activity modeling is needed (>100 in many cases)
- Joint scheduling with HARPS-N GTO implemented since AOT34 for better monitoring of the hottest targets

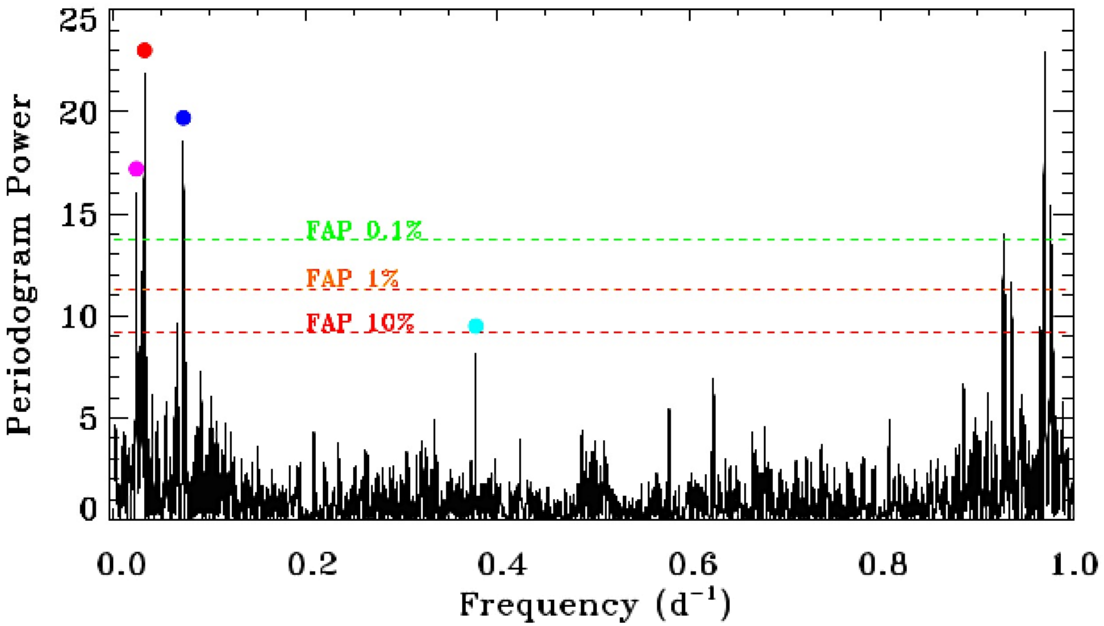
Planets around early M dwarfs

Planet frequency	M	Field G dwarfs
P<50d $M<30\ M_E$	$20.0^{+9.1}_{-5.3}$	38.8±7.1
P<100d $M<30\ M_E$	$20.0^{+9.1}_{-5.3}$	47.9±8.5

- Super-Earths moderately frequent around early M dwarfs
- Predominance of short periods and multiple systems



GAPS Planet detections: GJ 3998 b & c



Super Earths system around an M dwarf

Affer et al. 2016

HADES *(HArps-n red Dwarf Exoplanet Survey):*
GAPS + ICE + IAC

Msini ~ 2.5 M_{Earth} P = 2.6 d e = 0 K = 1.8 m/s
Msini ~ 6 M_{Earth} P = 13.7d e = 0.06 K = 2.7 m/s

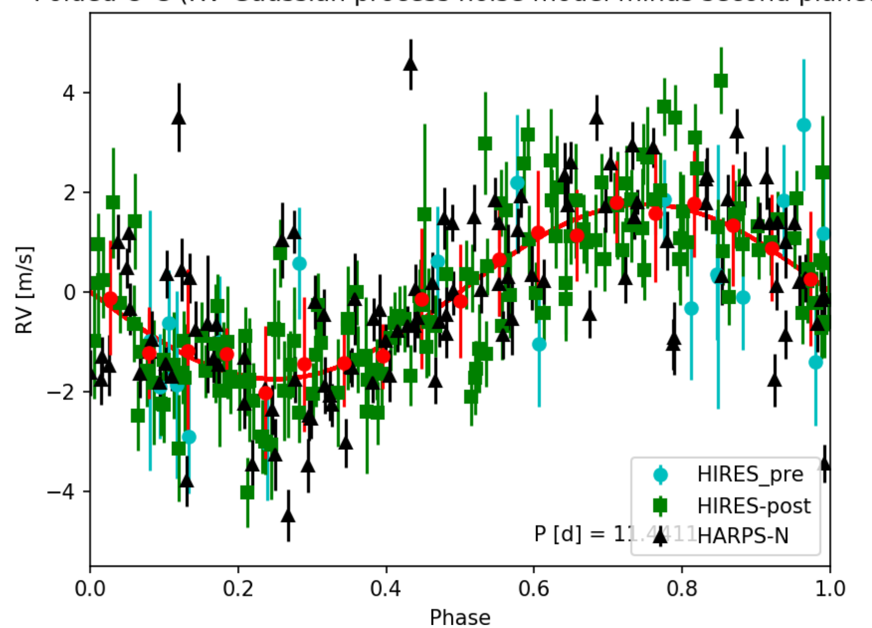
- P = 30.7 d: rotational period of the star
- P = 42.5 d: modulation of the stellar variability due to differential rotation
- P = 2.6 d: orbital period of GJ 3998b
- P = 13.7 d: orbital period of GJ 3998c

Planet detections: GJ 15 A

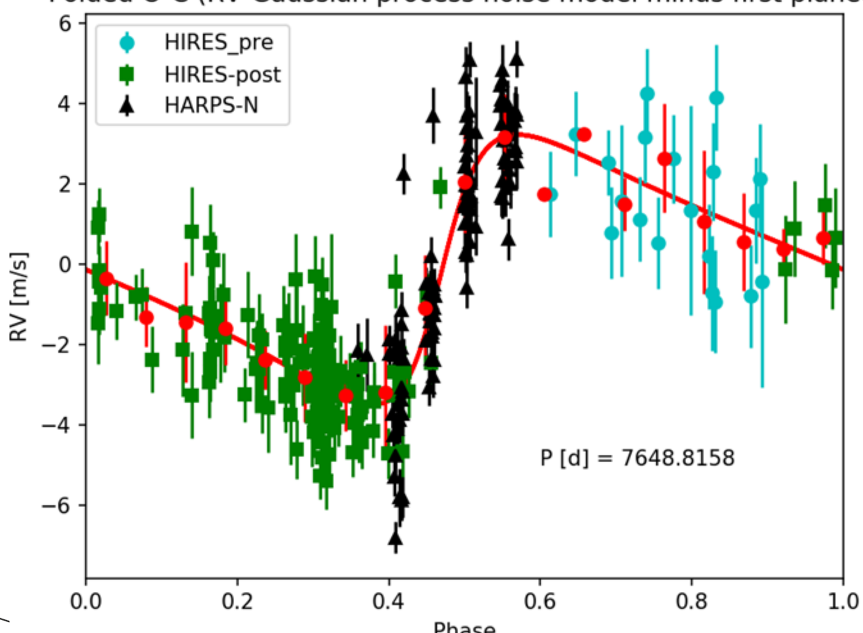
Composite planetary system in the binary GJ 15

- Eccentric neptune-size planet around M-dwarf;
- Inner planet orbit refined;
- Planet-star orbital interactions (Kozai effect?)

Folded O-C (RV-Gaussian process noise model minus second planet)



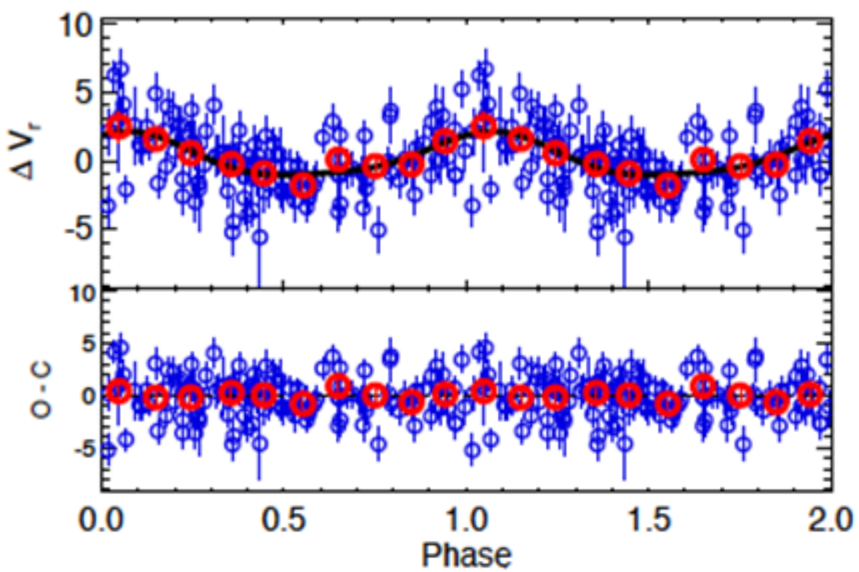
Folded O-C (RV-Gaussian process noise model minus first planet)



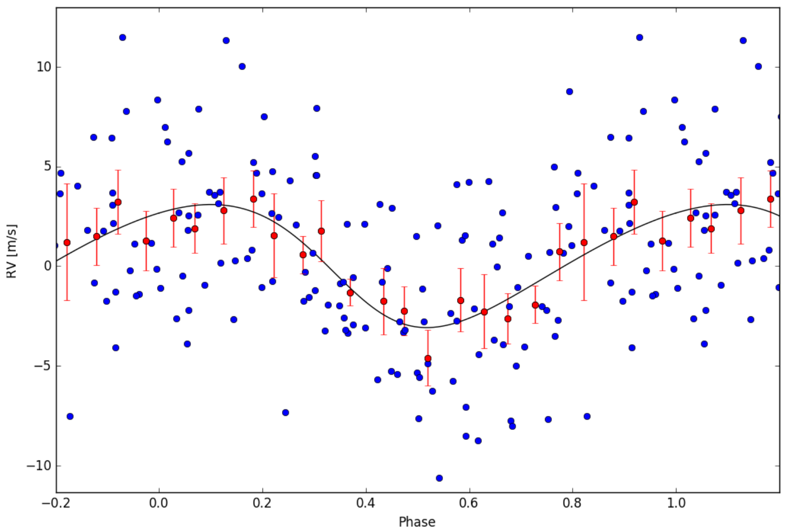
	GJ 15A b	GJ 15A c	GJ 15B
Period	11.4 d	21 yr	1300 yr
Mass	3.2 M_E	45 M_E	0.3 Msun
a (AU)	0.07	5.7	150
e	0.0	0.51	0.6

Pinamonti et al., in preparation

New low mass planets around M dwarfs



	GJ 3492 b	GJ 625b
Period	6.9 d	14.6 d
Mass	7 M_E	3 M_E
e	0.0	0.18

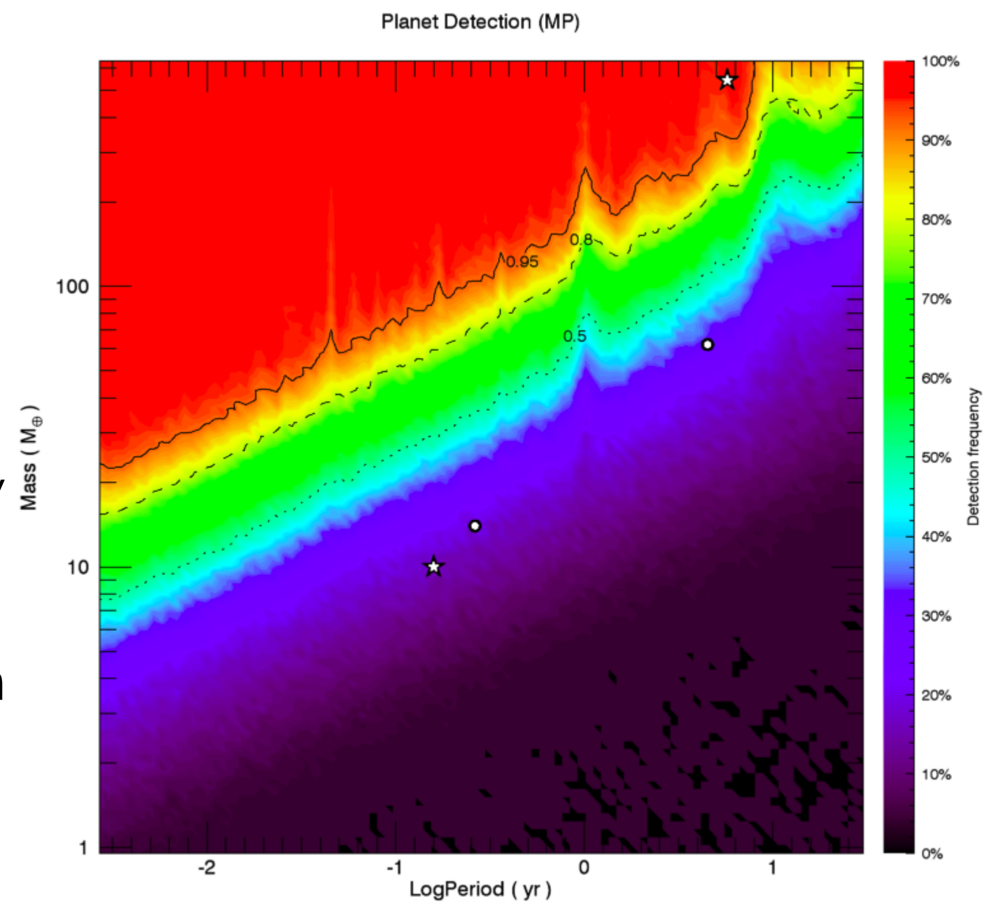


Perger et al., in preparation
Suarez et al. in preparation

Planets around metal-poor stars

Planet frequency	Metal poor stars	Field G dwarfs
P<50d $M<30\ M_E$	<8.4	38.8±7.1
P<100d $M<30\ M_E$	$16.6^{+15.4}_{-8.2}$	47.9±8.5

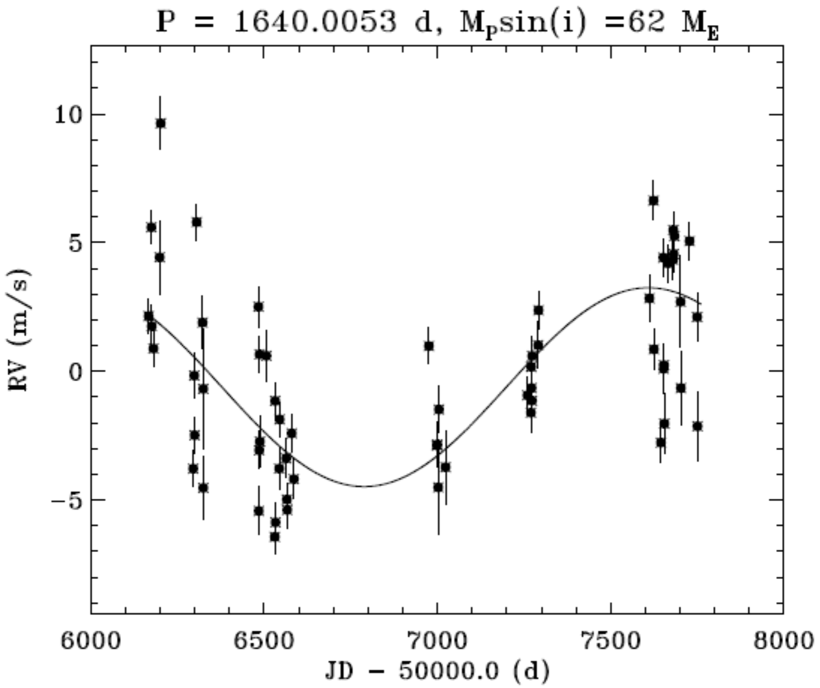
- ❑ Negative impact of metallicity extends to low-mass planets
- ❑ Lack of short-period planets and similar frequency of warm Neptunes
- ❑ Evidence of metallicity dependence of orbital migration?

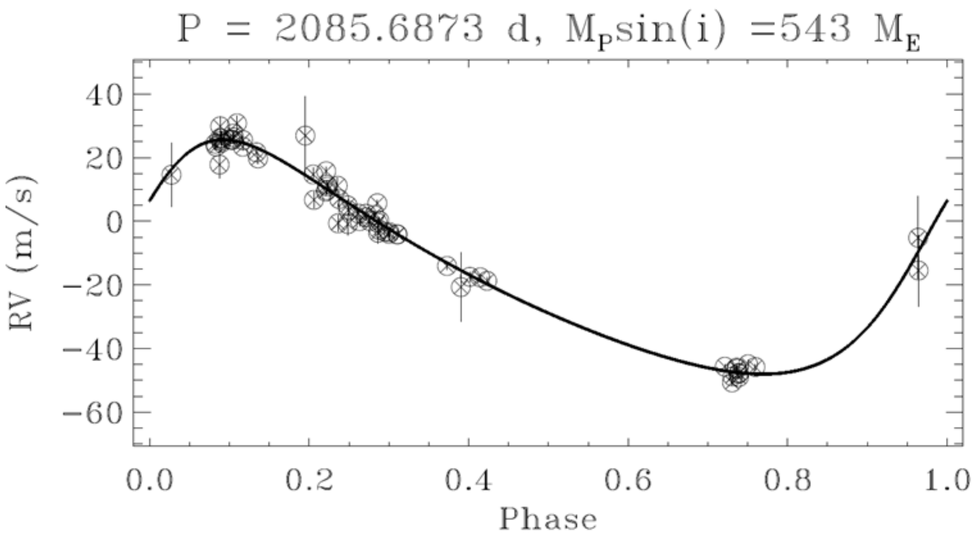


Long period giant planets around metal-poor stars

Two Long-Period Giant Planets

- Both in the high-[Fe/H] tail of the sample;
- MP31: combined HIRES/HARPS-N solution;
- MP3: the lowest-mass giant

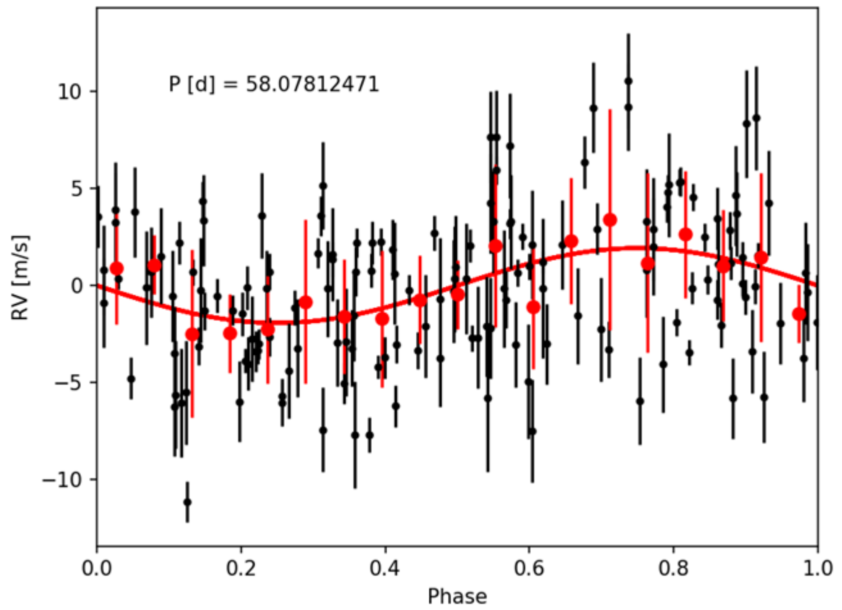


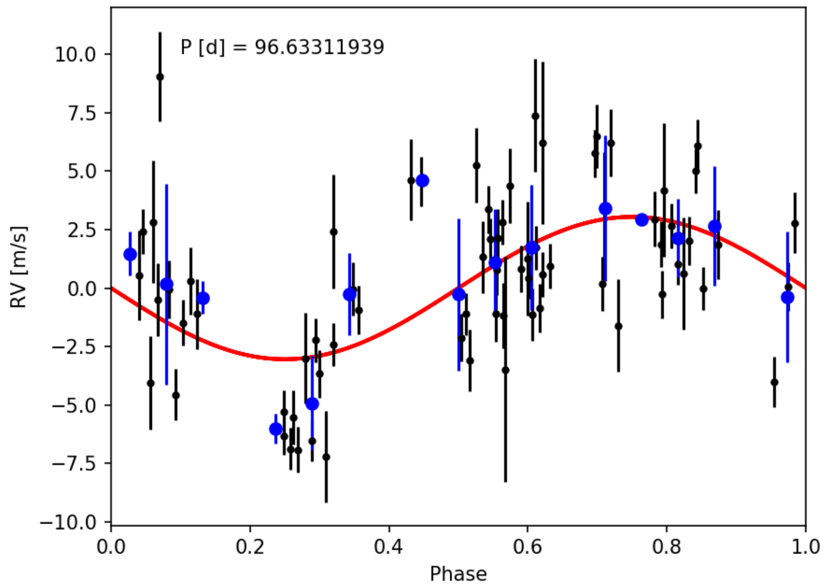


System	MP3	MP31
Period	1640 d	2086 d
Msini	62 M_E	543 M_E
Mstar	0.83 M_{sun}	0.73 M_{sun}
[Fe/H]	-0.65	-0.74

‘Metal-poor’ Warm Neptunes

System	MP4	MP12
Period	96.6 d	58.1 d
Msini	14 M_E	10 M_E
Mstar	0.89 M_{sun}	0.54 M_{sun}
[Fe/H]	-0.66	-1.73



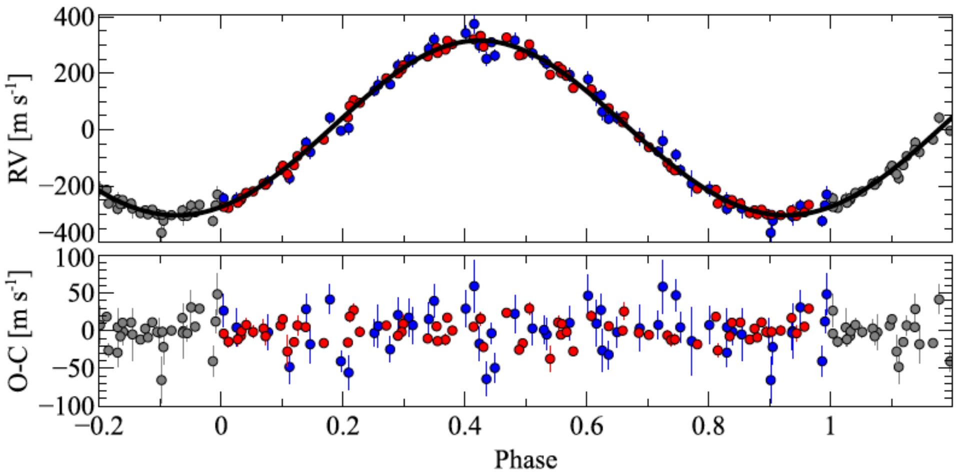


Two intermediate-period Neptunes

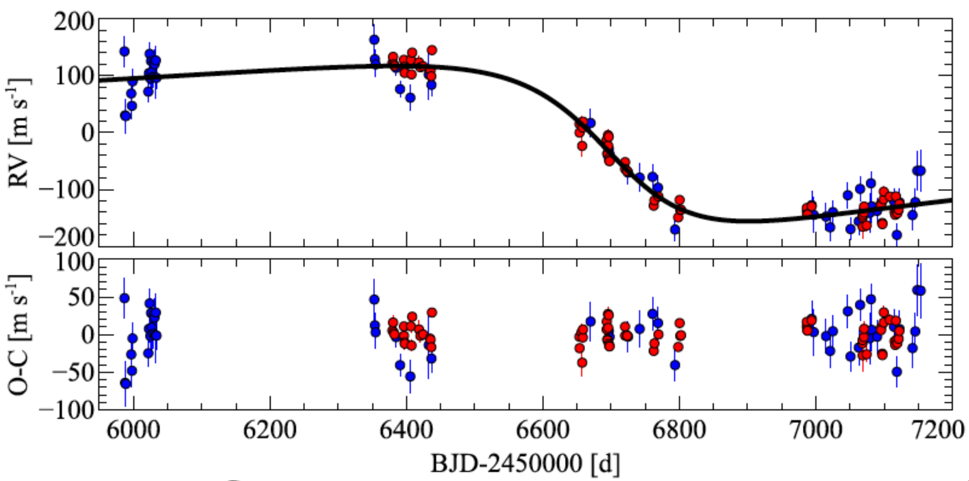
- The lowest [Fe/H] Neptune-type planets;
- RV amplitudes of 2 m/s
- MP4: earliest type primary with [Fe/H] < -0.5
- MP12: 163 HIRES/HARPS-N data;
- MP12: a halo sub-dwarf!

First planetary system in OC

70 HARPS-N + 36 TRES observations of the known Hot Jupiter around Pr 0211 (Quinn et al. 2012), additional photometric observations (STELLA)



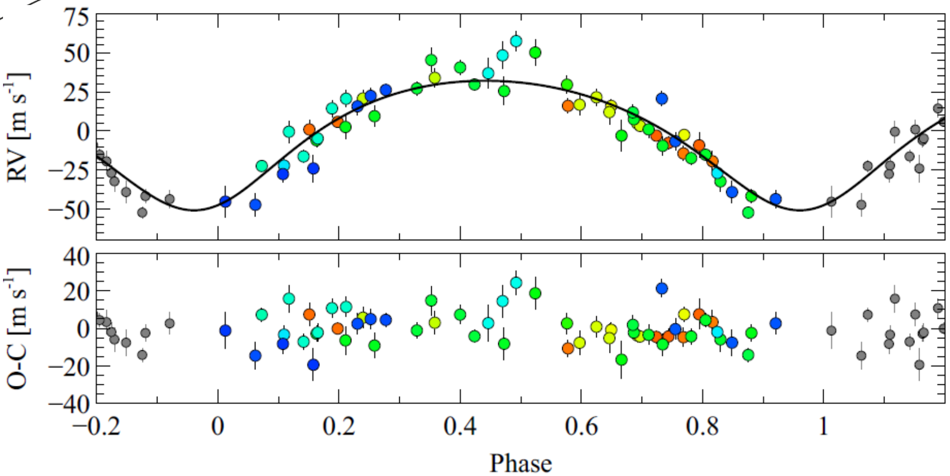
Parameter	Pr0211b	Pr0211c	unit
P	$2.14609 \pm 2 \cdot 10^{-5}$	4364^{+3237}_{-1327}	days
K	309.7 ± 2.5	136 ± 4	m s^{-1}
ϕ	153.0 ± 0.4	259 ± 4	deg
$\sqrt{e} \sin \omega$	-0.03 ± 0.06	0.79 ± 0.07	
$\sqrt{e} \cos \omega$	$0.12^{+0.04}_{-0.06}$	-0.17 ± 0.08	
e	0.019 ± 0.009	0.65 ± 0.11	
ω	344 ± 28	103 ± 6	deg
$M_p \sin i$	1.91 ± 0.02	8.1 ± 0.2	M_{jup}
a	0.03210 ± 0.00009	$5.2^{+2.3}_{-1.1}$	AU

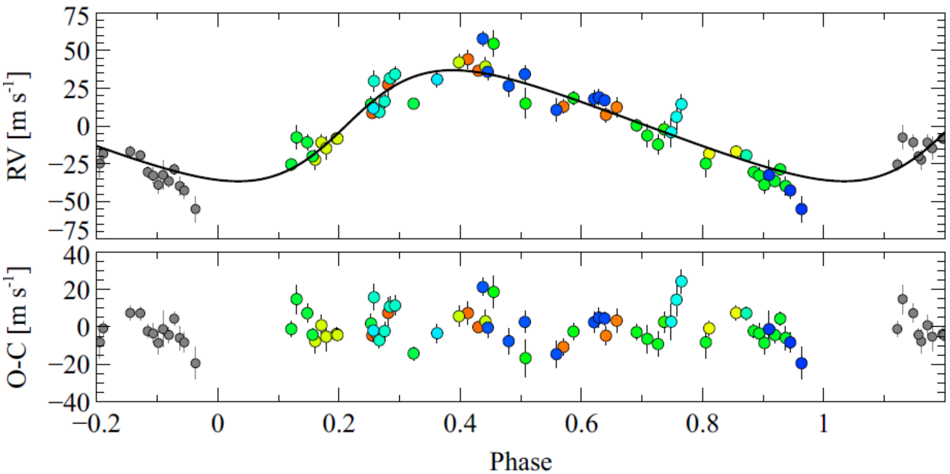


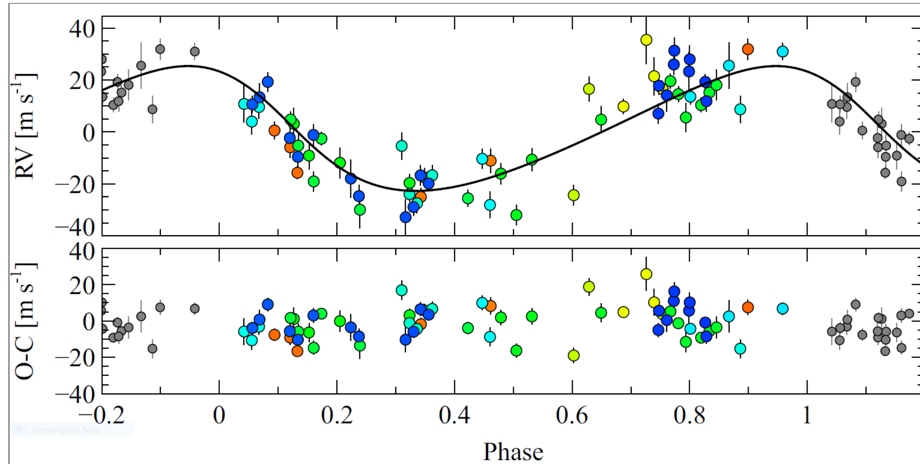
- HJ in nearly circular orbit
- Long period Jupiter in high eccentricity orbit
- Architecture possible signature of dynamical interactions in star cluster
- Activity in this target stronger with respect to other M44 targets

Malavolta et al., 2016

GAPS Two new planetary systems in Praesepe







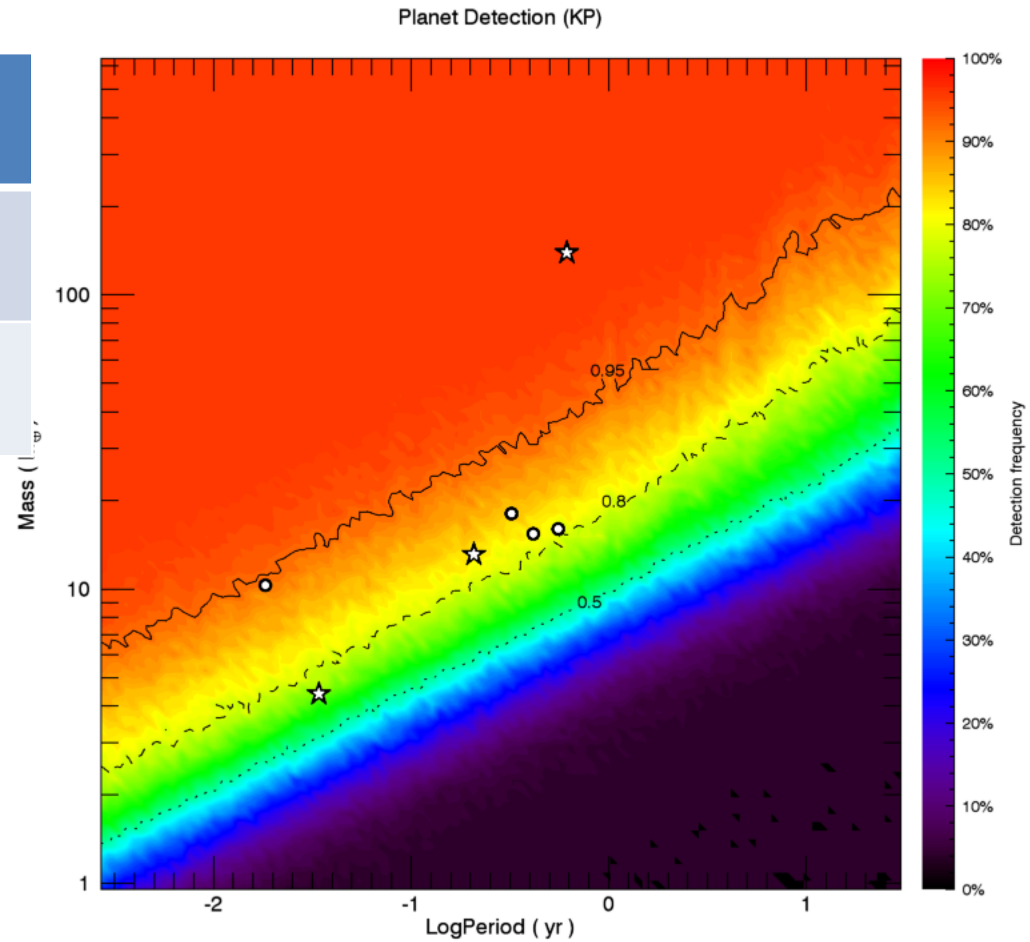
	OC 107b	OC 116b	OC 116c
P	78.3 d	42.0 d	113.9d
Mass	0.47 M_J	0.64 M_J	0.78 M_J
e	<0.24	<0.28	<0.30
Prot	9.1	9.4	

- Detections made possible by modeling of stellar activity

Malavolta et al., in preparation

Stars with long period giant planets

Planet frequency	Stars with planets	Field G dwarfs
P<50d $M<30\ M_E$	$5.9^{+11.2}_{-1.9}$	38.8±7.1
P<100d $M<30\ M_E$	$11.7^{+12.1}_{-4.0}$	47.9±8.5



Significant deficit of low-mass planets (Neptunes and super-Earths) around stars with long-period giant planets (particularly at short periods)

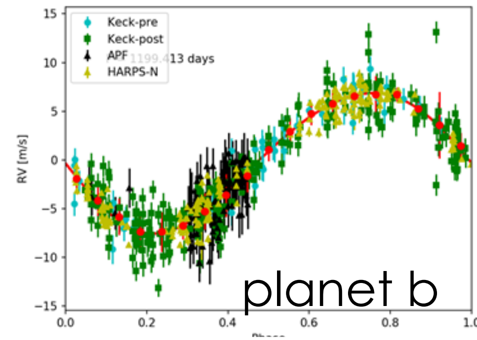
Disentangle the planetary and activity signals: HD164922

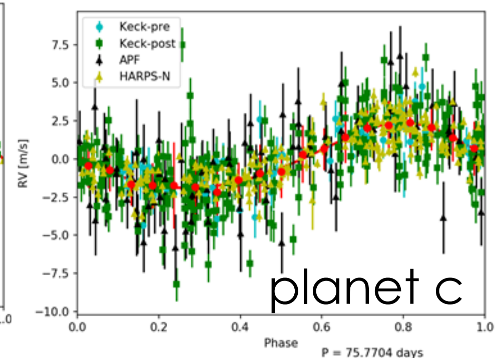
Butler et al 2006: HD164922 b

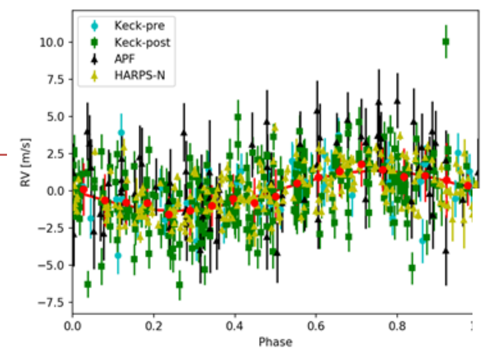
HARPS-N

- **Season1, S2:** periodicity at 20 d (now identified as the 1st harmonic of P_{rot}) + 12.46 d
- **End of S3:** first evidence of the period found in the Keck residuals (~76 d)

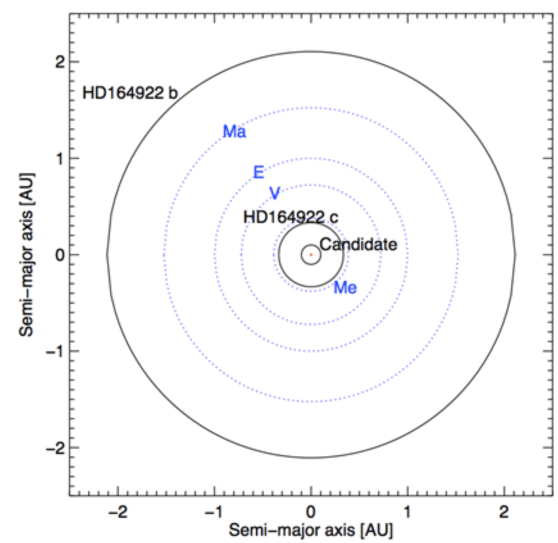
Fulton et al. 2016: HD164922 c confirmed with ~400 RV data







Gaussian Processes seem to support the presence of planet d



Suitable target for CHEOPS

	Planet b	Planet c	Candidate
Period [days]	1199.4 ± 5	75.77 ± 0.05	12.459 ± 0.002
***M sini* [M_{Earth}]**	109 ± 5	13 ± 1	4.4 ± 0.5
Semi-amplitude [m/s]	7.2 ± 0.3	2.1 ± 0.2	1.3 ± 0.1

Transiting planets

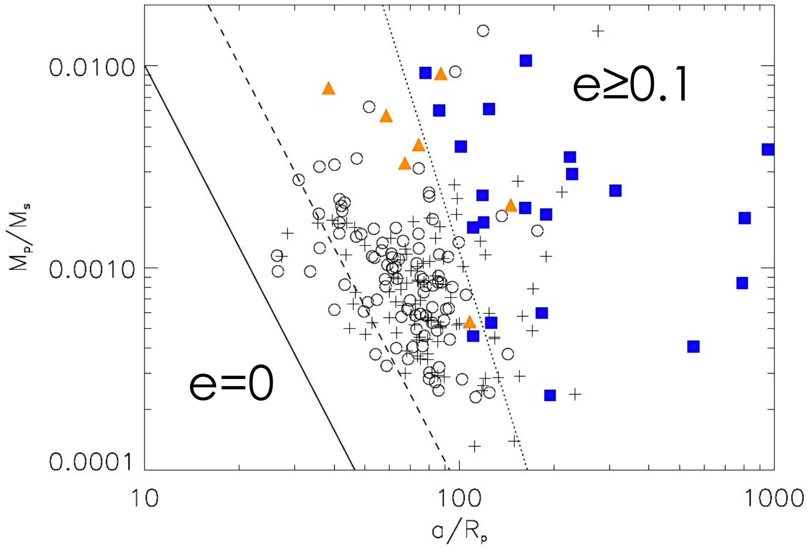
Bonomo et al. 2017

Homogenous analysis of **231 transiting giant planets** (45 observed within GAPS) through a dedicated Bayesian DE-MCMC tool:

- The largest uniform catalog of giant planet orbital and physical parameters
- Significant refinement of the orbital solution for some target (eccentricity)
- Monitoring of RV long-term trends (to find additional distant companions)
- Goal: understand the migration of short-period giant planets

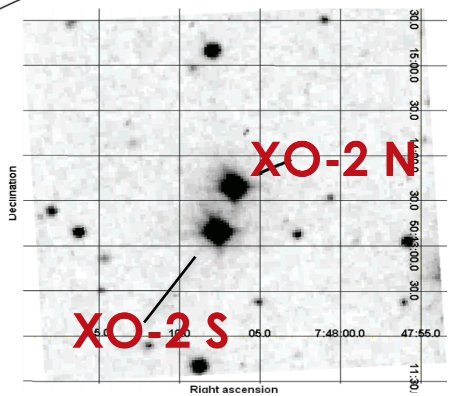
The distribution of a/a_R (semi-major axis VS Roche limit) points toward a **high-eccentricity migration** scenario, but it is not exclusive (a few evidence of disk migration)

Tidal diagram: orbital parameters are shaped by tides



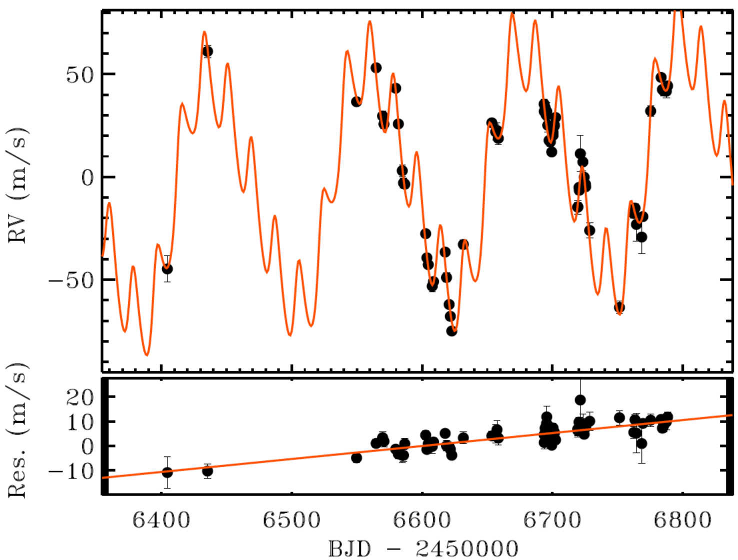
Planets with e ≥ 0.1 can be the result of migration from highly eccentric orbits (planet-planet scattering, Kozai-Lidov perturbations, or secular chaos)

Planet detections: XO-2 S b & c

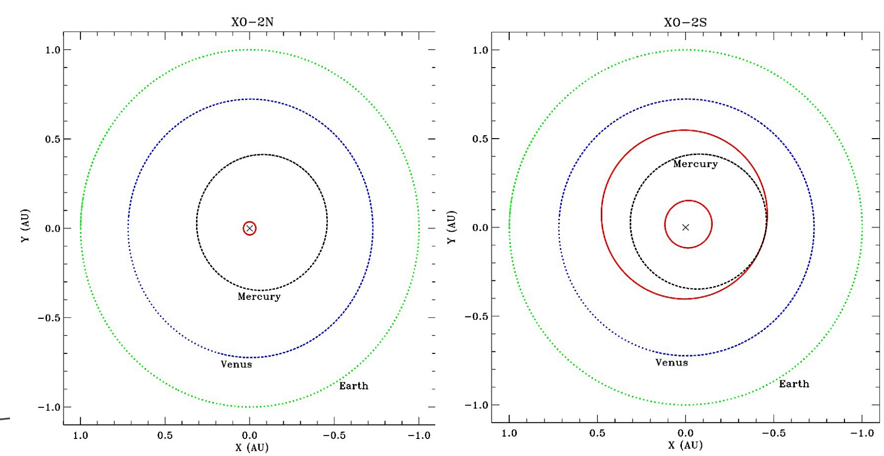


Burke et al. 2007: Hot Jupiter transiting XO-2 N
Desidera et al. 2014: 2 planets around XO-2S
First case of binary system on which both components host planets

	XO-2 Sb	XO-2 Sc
P [d]	18.157	120.80
m sini [M_J]	0.259	1.370
e	0.180	0.153



Laboratory for planet formation process:

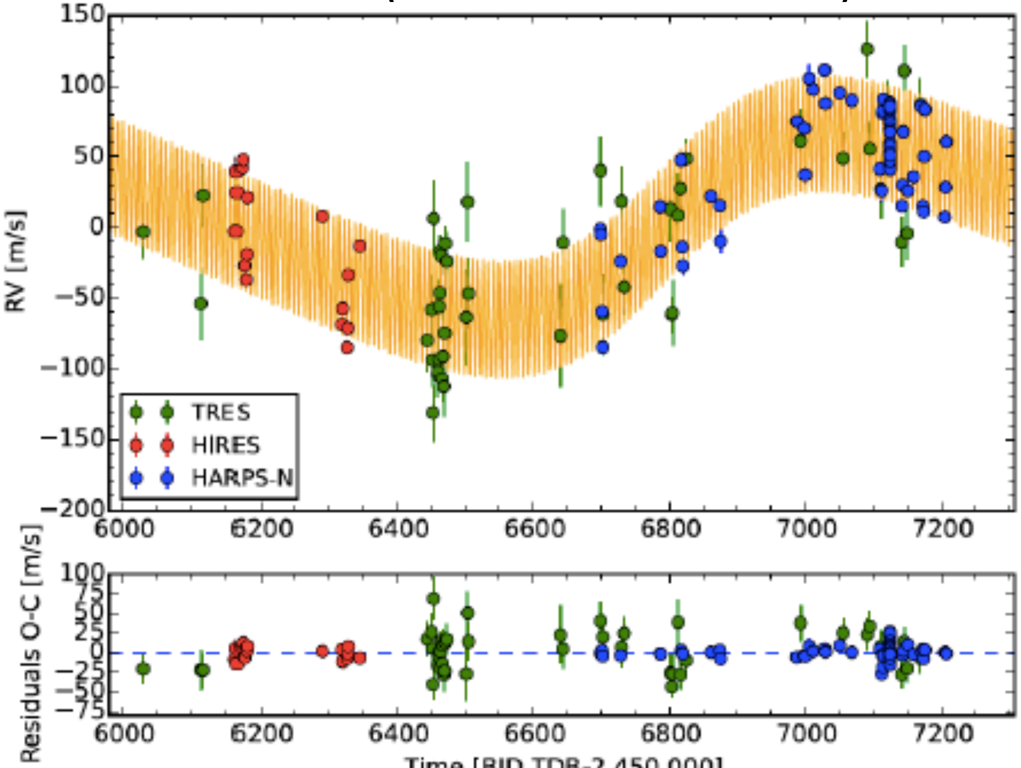


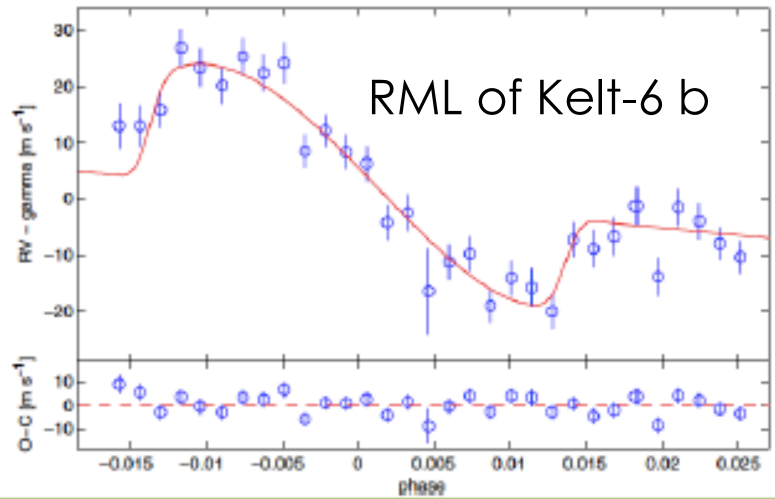
Abundance difference between the components correlated with condensation temperature

Desidera et al. 14, Damasso et al 15, Biazzo et al. 15

Long-period companions around stars with Hot Jupiters: Kelt-6 c

Kelt-6 b, Saturn-mass planet orbiting a late-F star (Collins et al. 2014)





	Kelt-6 b	Kelt-6 c
Period	7.8 d	1276 ± 74 d
Mass	0.44 M_J	3.7 M_J
e	0.03	0.2
λ	-36 ± 11	-

Damasso et al. 2015b

Several additional long-period trends identified

System spin-orbit alignment through Rossiter effect

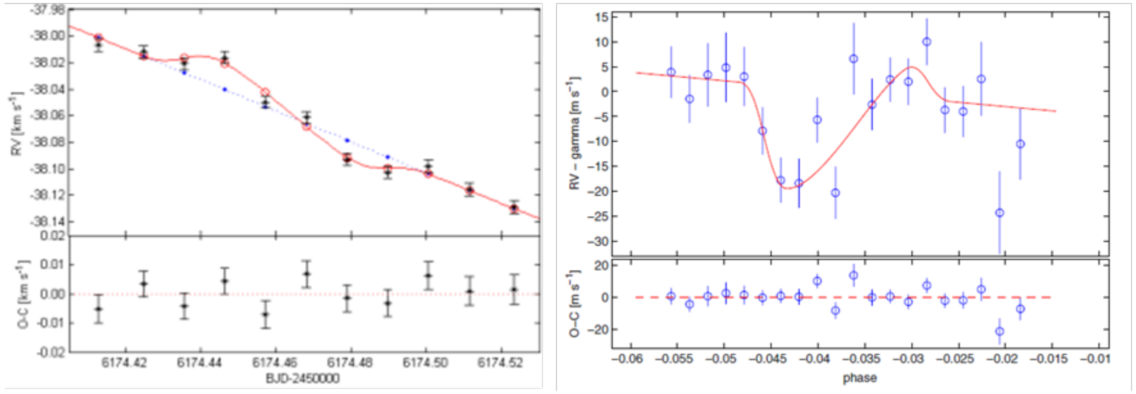
Focus on late-type stars, previously quite under-represented in the literature

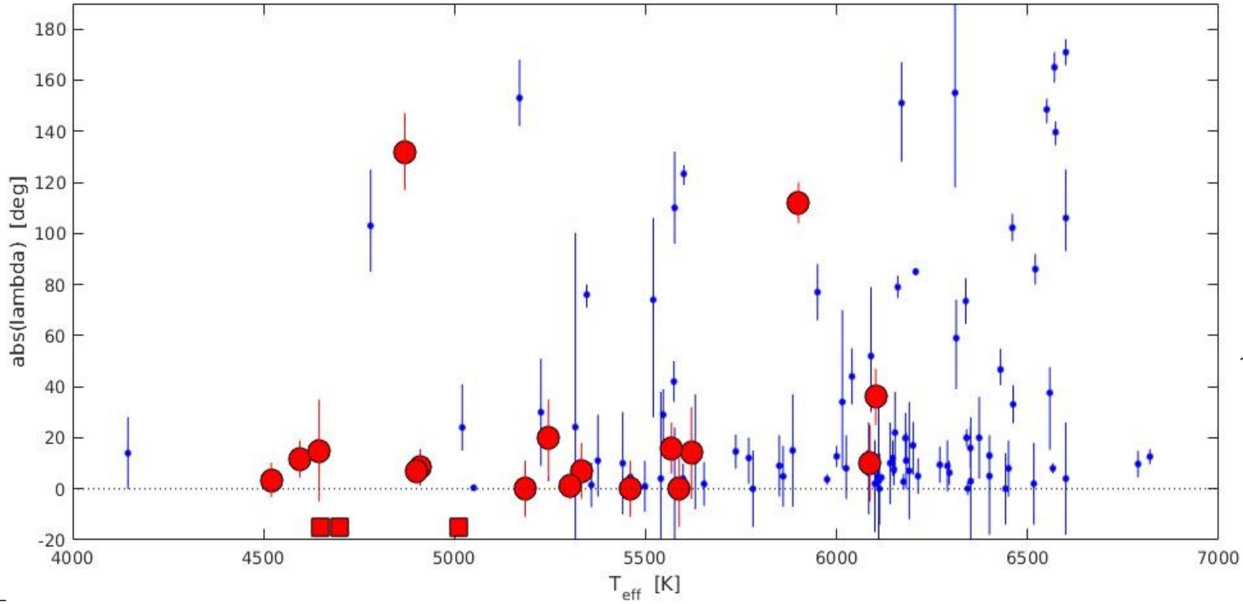
Most systems aligned but some cases highly misaligned

Important role of stellar tides

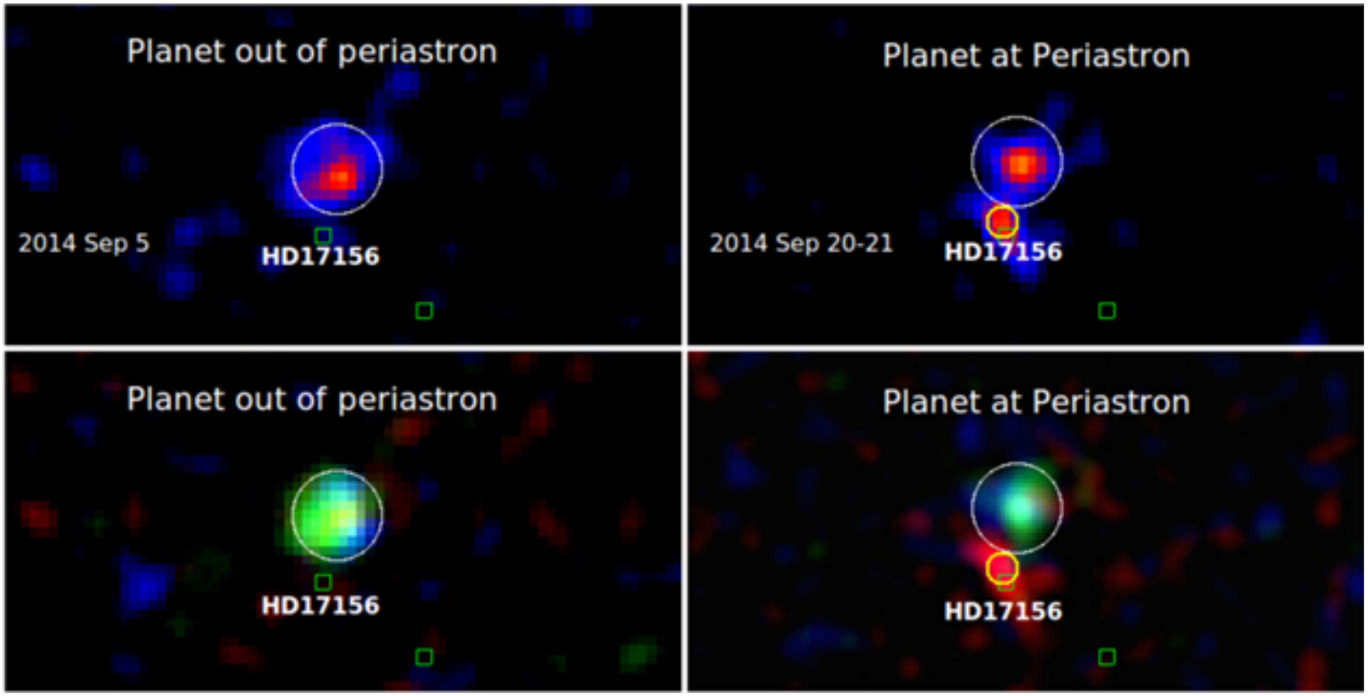
Some 3D alignment determinations when including photometric rotation periods

Covino et al. 2013; Esposito et al. 2014; 2017 Mancini et al. 2016





Star-planet interaction in a highly eccentric planetary system

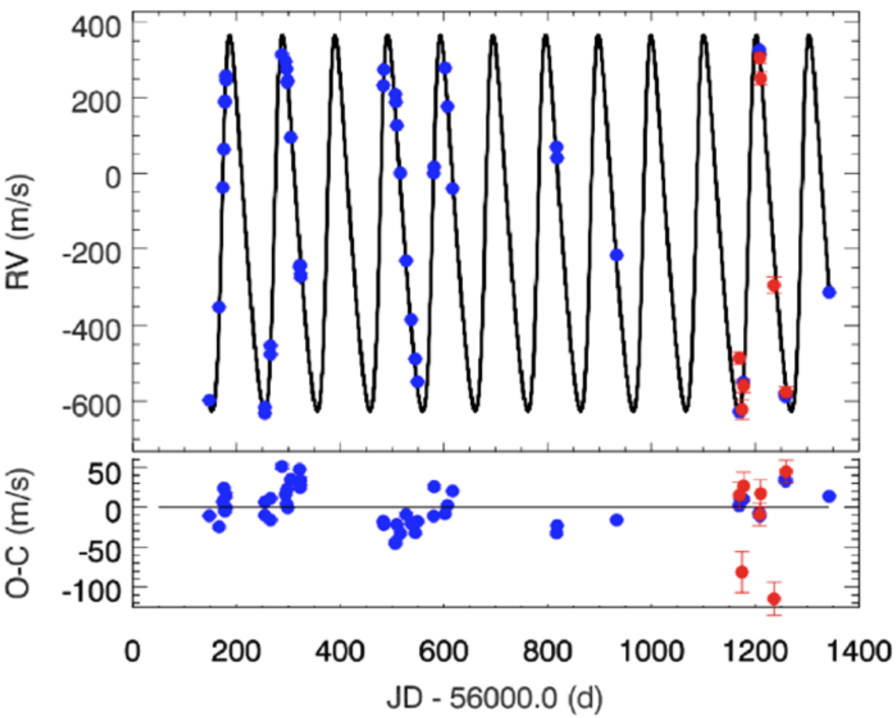


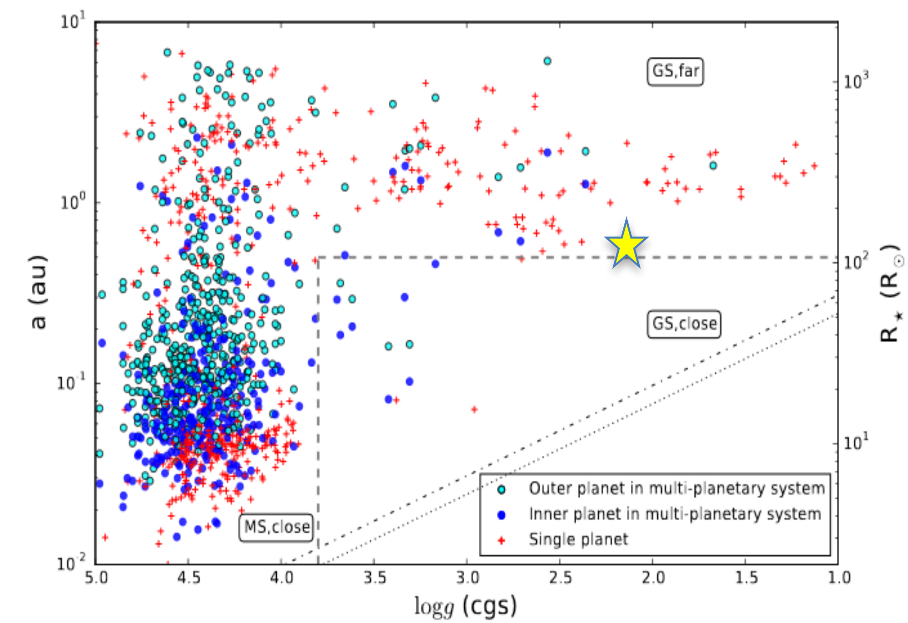
Strong increase in X-ray luminosity and chromospheric emission close to periastron passage of the planet around HD 17156 in a highly eccentric orbit

Maggio et al. 2015

Planet detections: TYC 4282

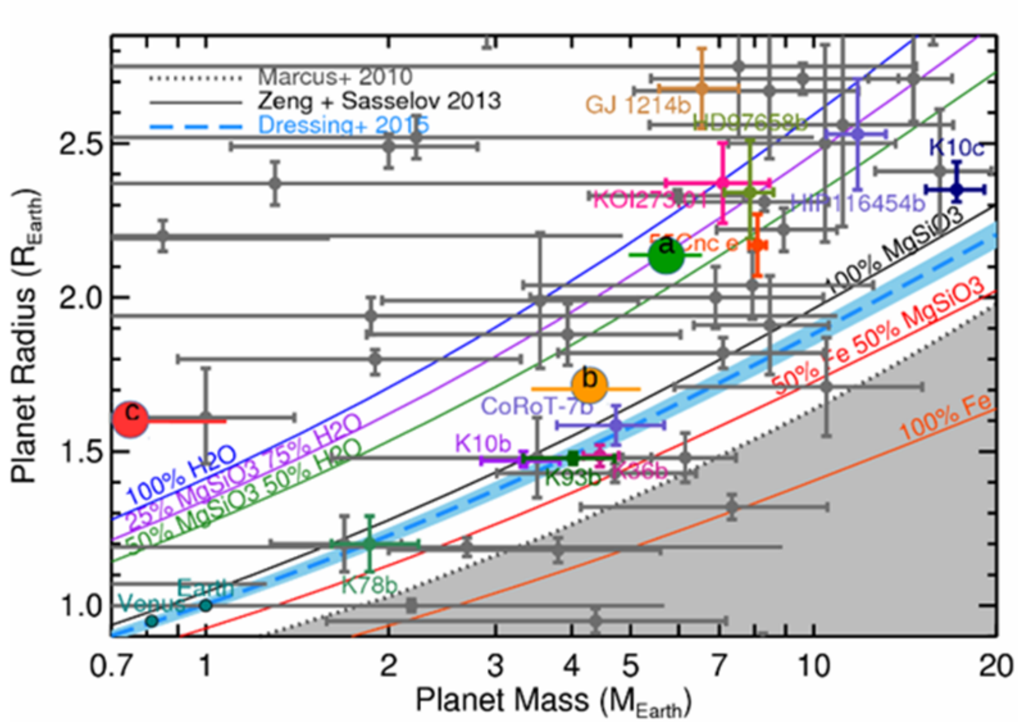
Planet around a thick disk giant star
Validation of GIARPS concept through quasi-simultaneous HARPS and GIANO observations





Gonzalez et al., being submitted

Planet characterization: K2-3



- ❑ Planetary system with 3 transiting planets discovered by K2 (one in the habitable zone).
- ❑ Characterization only feasible with intensive joint campaign with HARPS-N (GAPS + GTO) and HARPS. 290 spectra overall

Additional results

- Planet rejection: ***Desidera et al. 2013***
- Major refinements for Tres-4: ***Sozzetti et al. 2015***
- Asteroseismology and SPI for τ Boo: ***Borsa et al. 2015***
- Characterization of HD 108874: ***Benatti et al. 2016***

- Stellar parameters of early-M dwarfs ***Maldonado et al. 2015***
- M dwarfs activity characterization***: Maldonado et al. 2016; Scandariato et al. 2016***
- M dwarf survey simulations***: Perger et al. 2016***

AOT35 plan

- Observations focused on the confirmation of best candidates
- Joint scheduling with GTO allows to distribute the observing time on 2x nights,
- Intensive sampling mandatory for disentangling low-amplitude activity and Keplerian signals (see Pale Blue Dot Campaign on Proxima)

Summary of planet detections

Planet	Period	e	Msini	Remarks
XO-2Sb	18.1d	0.18	0.26 Mjup	**First binary system with both components hosting planets**
XO-2Sc	120.8d	0.15	1.37 Mjup	
Kelt 6c	1276d	0.20	3.7 Mjup	+ Hot Jupiter
Pr 201c	4364 d	0.65	8.1 Mjup	+ HJ **First planetary system in a cluster**
GJ 3998b	2.6 d		2.5 Mearth	**Lowest mass planets detected by GAPS**
GJ 3998c	13.7 d	0.06	6.0 M earth	
GJ 15Ac	21 yr	0.51	45 Mearth	+ close SuperEarth + binary
GJ 625	14.6 d	0.18	3.0 Mearth	
GJ 3492b	6.9d		6.0 Mearth	
TYC 4282	101.6d	0.20	10.0 Mjup	Giant host star
OC 107b	78.3d	<0.24	0.47 Mjup	
OC 116b	42.0d	<0.28	0.64 Mjup	
OC 116c	113.9d	<0.30	0.78 Mjup	
MP31	2086 d	0.40	543 Mearth	
MP3	1640 d		62 Mearth	
MP4	96.6d		14 Mearth	
MP12	58.1d		10 Mearth	**Halo subdwarf host**
HD 164922d	12.4 d		4.4 MEarth	+ 2 planets

Summary of planet detections

GAPS

Planet	Period	e	Msini	Remarks
XO-2Sb	18.1d	0.18	0.26 Mjup	**First binary system with both components hosting planets**
XO-2Sc	120.8d	0.15	1.37 Mjup	
Kelt 6c	1276d	0.20	3.7 Mjup	+ Hot Ju[illegible]
Pr 201c	4364 d	0.65	8.1 Mjup	+ H[illegible] **system in a cluster**
GJ 3998b	2.6 d		2.5 Mearth	[illegible]**ets detected by GAPS**
GJ 3998c	13.7 d	0.06	6.0 M earth	
GJ 15Ac	21 yr	0.51	45 Me[illegible]	[illegible]se SuperEarth + binary
GJ 625	14.6 d	0.18	[illegible]	
GJ 3492b	6.9d	[illegible]	[illegible]	
TYC 4282	101.6d	[illegible]	[illegible]jup	Giant host star
OC 107b	78.3d	[illegible]	[illegible].47 Mjup	
OC 116b	42[illegible]	[illegible]	0.64 Mjup	
OC 116c	[illegible]	[illegible].30	0.78 Mjup	
MP31	[illegible]	0.40	543 Mearth	
MP[illegible]	[illegible]d		62 Mearth	
MP4	96.6d		14 Mearth	
MP12	58.1d		10 Mearth	**Halo subdwarf host**
HD 164922d	12.4 d		4.4 MEarth	+ 2 planets

All new low mass planets detected by GAPS suitable target for CHEOPS space missions

GAPS Scientific questions

- Frequency and properties of exoplanets around early M dwarfs
- Frequency and properties of exoplanets around metal poor stars
- Impact of open-cluster environment on frequency and architectures of planetary systems
- Impact of the presence of giant planets in wide orbits on the presence of low mass planets in close orbits (scaled Solar System-like)
- How frequently are hot Jupiters accompanied by planets in wide orbits
- Spin-orbit alignement in planetary systems
- How tides shape the orbital properties of hot Jupiters and how they interact with their host stars

GAPS Answers to scientific questions

- Moderately frequent super-Earth planets at small separation around early M dwarfs. Often multiple systems
- Lack of hot Neptunes and Super-Earths around metal-poor stars, frequency of warm neptunes similar to solar-type stars
- Evidence for impact of metallicity on orbital migration?
- No paucity of planets in open clusters
- Possible signatures of dynamical interactions in the architectures
- Negative impact of the presence of outer giant planets on inner low-mass planets
- Decisive role of tides in shaping the properties of close-in planets revealed by eccentricity +spin-orbit determination
- Erratic nature of SPI, role of planet eccentricity?

GAPS Conclusions

- GAPS definitely successful program, several very interesting results
- **Benchmark planet detections**, such as first binary system with both components hosting planets, first planetary system in a cluster, a warm neptune around a very metal poor halo star
- **Relevant results from preliminary statistical analysis**, some completely new (paucity of low-mass close-in planets in stars with long-period giant planets, abundance of warm neptunes around metal-poor stars)
- Revealed **great diversity of planetary system in different environments**
- Next step: looking at the **origin** of such a diversity using **GIARPS**. See A. Bonomo talk