her Worlds in the Cosmos? The Search for Planets Similar to Earth and

“Planets hosted by low mass stars”

Michel Mayor
Université de Genève

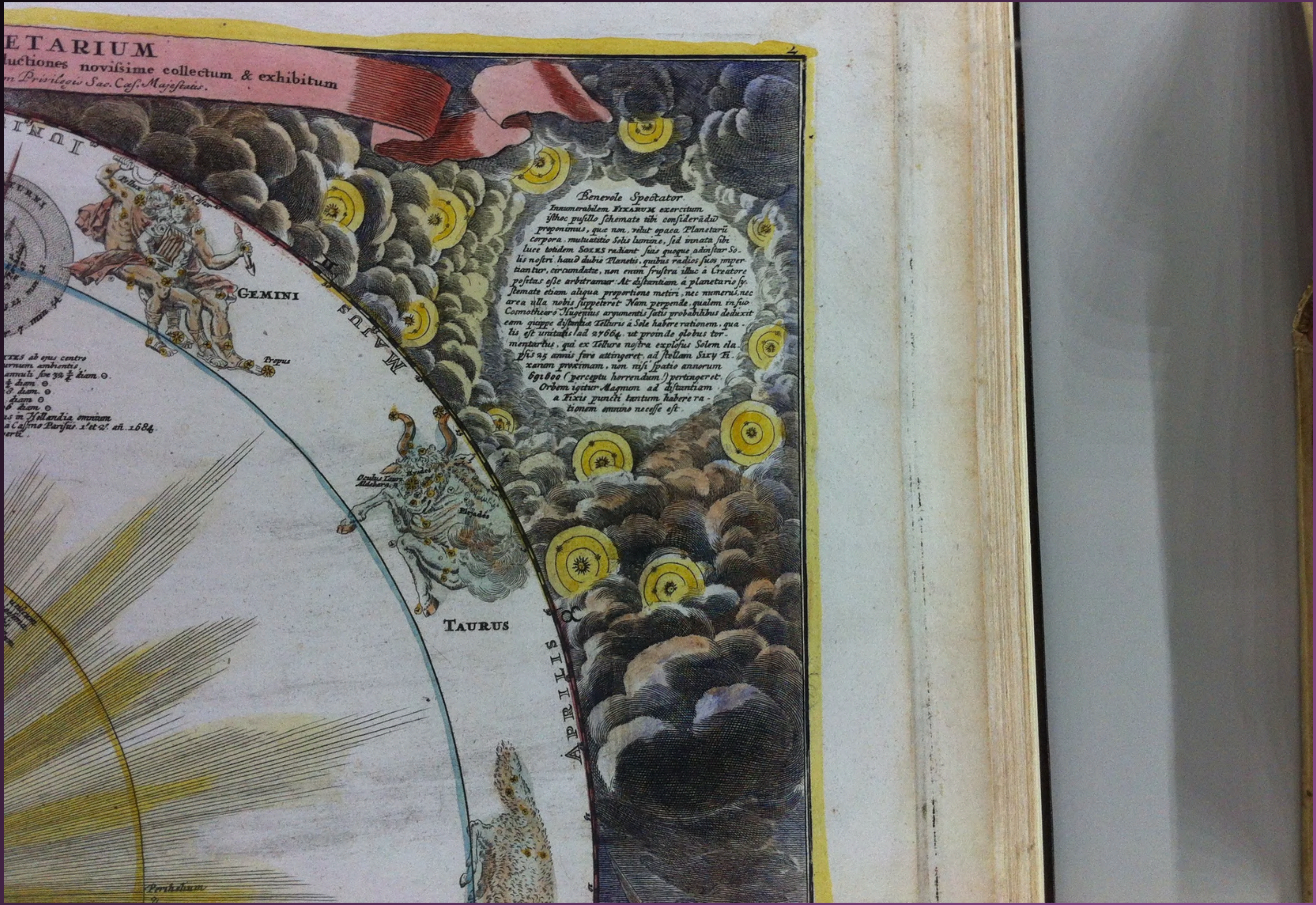
*** A change of paradigm during the 20th century

*** Searching for planets hosted by low mass stars ….
and maybe suitable for the life chemistry !

- 1952 How many planetary systems in the Milky Way..

… a complete change of paradigm

Atlas Doppelmayr 1742



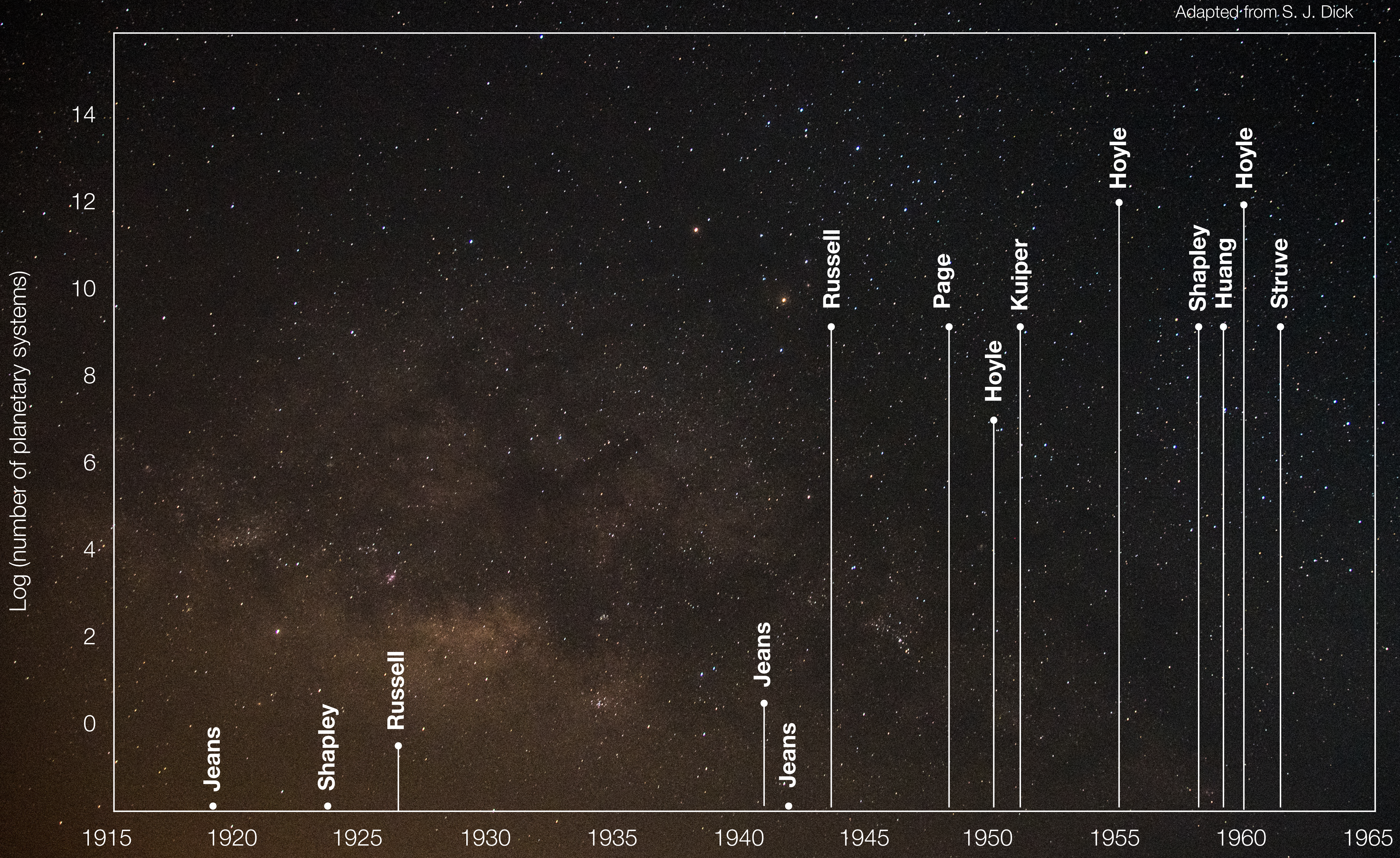
ETARIUM
ductiones novissime collectum & exhibitum
Benevole Spectator
Innumerabilem FIXARUM exercitum
isthoc pusillo schemate tibi considerãdũ
proponimus, quæ non, velut opaca Planetarũ
corpora mutuatitio Solis lumine, sed innata sibi
luce totidem SOLES radiant suas quoque adinstar So-
lis nostri haud dubie Planetis, quibus radios suos imper
tiantur, circumdatæ, non enim frustra illuc à Creatore
positas esse arbitramur. At distantiam à planetario sy-
stemate etiam aliqua proportione metiri, nec numerus nec
area ulla nobis suppeteret Nam perpende, qualem in suo
Cosmotheoro Hugenius argumentis satis probabilibus deduxit
eam quippe distantiæ Telluris à Sole habere rationem, qua-
lis est unitatis ad 27664. ut proinde globus tor-
mentarius, qui ex Tellure nostra explosus Solem ela-
psis 25 annis fere attingeret, ad stellam Sixy Fi-
xarum proximam, non nisi spatio annorum
691600 (perceptu horrendum!) pertingeret.
Orbem igitur Magnum ad distantiam
a Fixis puncti tantum habere ra-
tionem omnino necesse est.
GEMINI
TAURUS
MAIUS
APRILIS

"Illustration of exoplanets"

Currently in the Clementinum cloister (Prague).
1752, By an Italian artist who was informed of the suggestion made by Giordano Bruno (1600)

Estimated number of planetary systems

in the Milky Way



Observatory (1952) 72,199

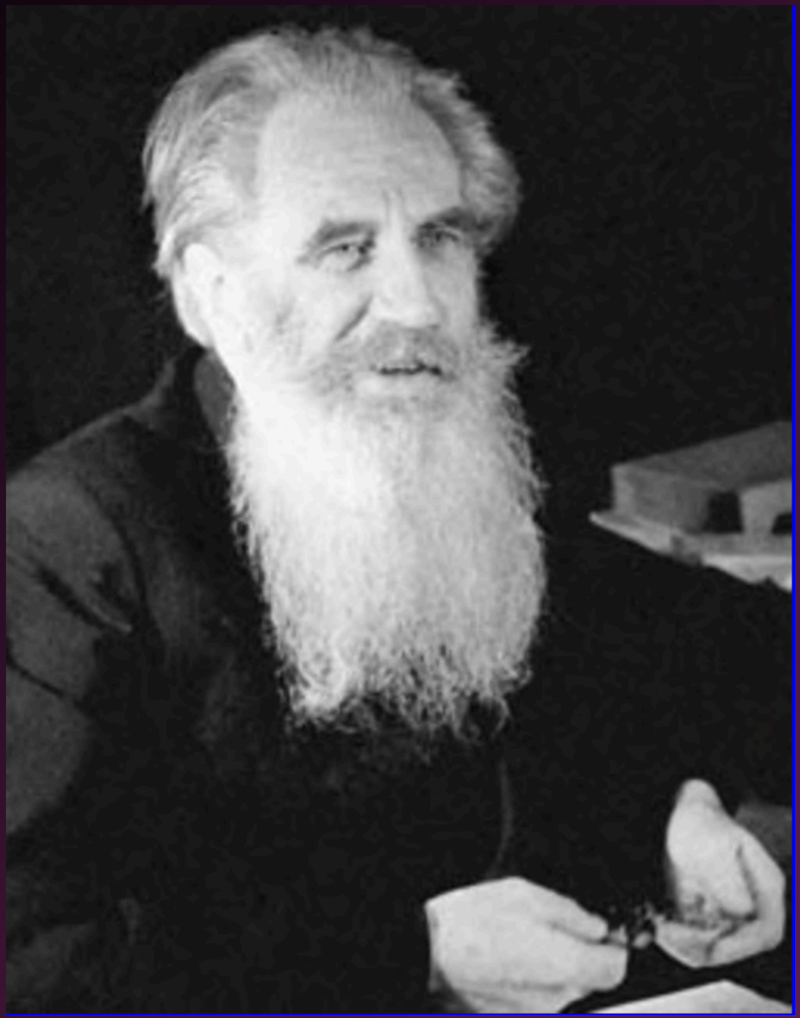
PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR RADIAL VELOCITY WORK

By Otto Struve

"I have suggested elsewhere that the lack of rapid axial rotation of normal solar-type stars ... suggests that these stars have converted their angular momentum from axial rotation to angular momentum from the orbital motion of the planets. Therefore there can be many planet-like objects in the galaxy. "

The accretion scenario for the planetary formation

Otto Yulyevitch Schmidt and Viktor Safronov



1891- 1956

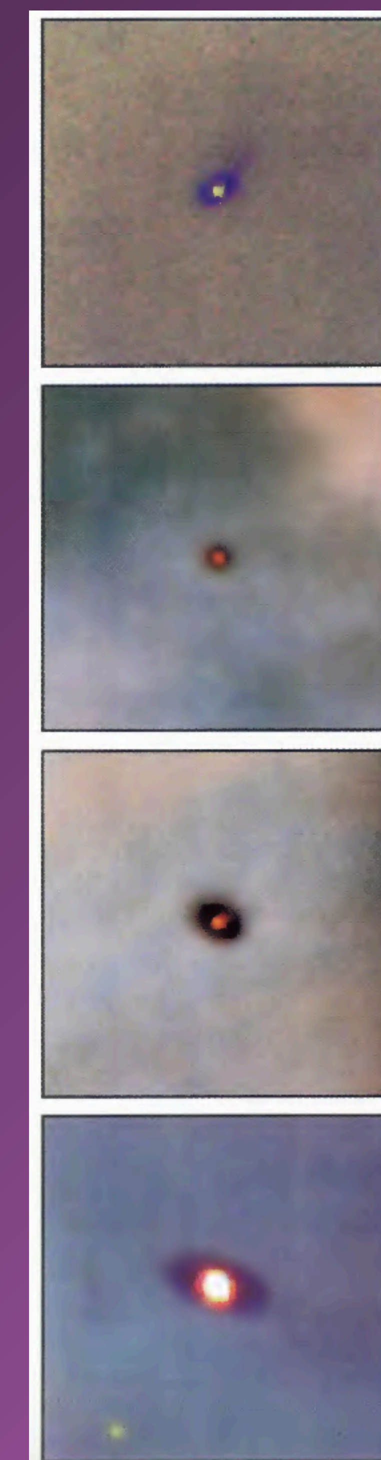
1917- 1999

Propose the scenario to explain the formation of planetary systems by agglomeration of planetesimals from dust grains to planets.

Safronov,V.S. 1969 Evolution of the protoplanetary cloud and the formation of the Earth and planets

Protoplanetary discs

Images from the HST , 1995



Increasing the precision

Radial velocity via cross-correlation spectroscopy:
A path to the detection of Earth-type planets

SPECTRO	year	precision	Telescope	
CORAVEL	1977	300 m/s	1 m	OHP
ELODIE	1994	13 m/s	1.9 m	OHP
CORALIE	1998	6 m/s	1 m	ESO Chile
HARPS	2003	1 m/s	3.6 m	ESO Chile
HARPS-N	2013	1 m/s	3.5 m	IAC La Palma
ESPRESSO	2018	0.1 m/s	8.2 m (x4)	ESO Chile

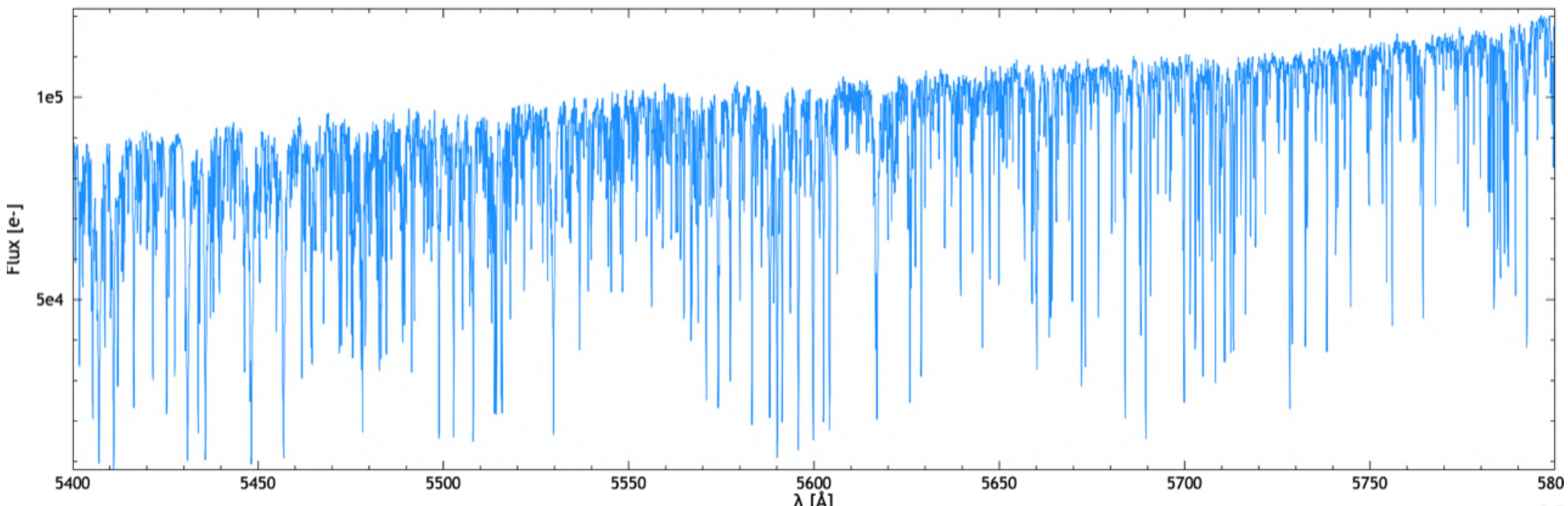
An increase of the sensibility by a factor 3000 during the last 40 years

The variation in the stellar radial velocity induced by the gravitational influence of a planet analogous to our Earth.

Below: 1/10 of the spectral range used for the determination of the radial velocity using the Doppler effect.
This ESPRESSO spectrum has a spectral resolution of 130’000.
The variation of the radial velocity of a solar star due to an Earth-like planet (P = 1 year) is (8 cm/s) and corresponds to about 0.001 of the width of one absorption line!

>>>>>> **the cross-correlation technique makes it possible to concentrate the Doppler information of several thousand spectral lines to achieve this precision.**

The concentration of the Doppler information (distributed on several thousand lines) was the key factor having allowed the discovery of 51 Pegasi b.



THE ASTROPHYSICAL JOURNAL, **241**:425–441, 1980 October 1

DISK-SATELLITE INTERACTIONS

PETER GOLDREICH
California Institute of Technology

AND

SCOTT TREMAINE
Institute for Advanced Study, Princeton, New Jersey
Received 1980 January 7; accepted 1980 April 9

ABSTRACT

We calculate the rate at which angular momentum and energy are transferred between a disk and a satellite which orbit the same central mass. A satellite which moves on a circular orbit exerts a torque on the disk only in the immediate vicinity of its Lindblad resonances. The direction of angular momentum transport is outward, from disk material inside the satellite's orbit to the satellite and from the satellite to disk material outside its orbit. A satellite with an eccentric orbit exerts a torque on the disk at corotation resonances as well as at Lindblad resonances. The angular momentum and energy transfer at Lindblad resonances tends to increase the satellite's orbit eccentricity whereas the transfer at corotation resonances tends to decrease it. In a Keplerian disk, to lowest order in eccentricity and in the absence of nonlinear effects, the corotation resonances dominate by a slight margin and the eccentricity damps. However, if the strongest corotation resonances saturate due to particle trapping, then the eccentricity grows.

We present an illustrative application of our results to the interaction between Jupiter and the protoplanetary disk. The angular momentum transfer is shown to be so rapid that substantial changes in both the structure of the disk and the orbit of Jupiter must have taken place on a time scale of a few thousand years.

Subject headings: hydrodynamics — planets: Jupiter — planets: satellites — solar system: general

The orbital migration of exoplanets was studied by several authors before the discovery of 51 Pegasi b

but not considered in any searches for exoplanets .

Before the discovery of 51 Pegasi b

Goldreich,P., Tremaine,S., 1980, Disk-satellite interactions, ApJ 241,425

Papaloizou, J., Lin,D.N.C. 1984, On the tidal interaction between protoplanets and the primordial solar nebula. I. Linear calculation of the role of angular momentum exchange. ApJ,285,818

Lin,D.N.C., Papaloizou, J. 1986, On the tidal interaction between protoplanets and the protoplanetary disk. III -Orbital migration of protoplanets ApJ 309,846

Ward,W.R., 1986, Density waves in the solar nebula - Differential Lindblad torque. Icarus 67, 164

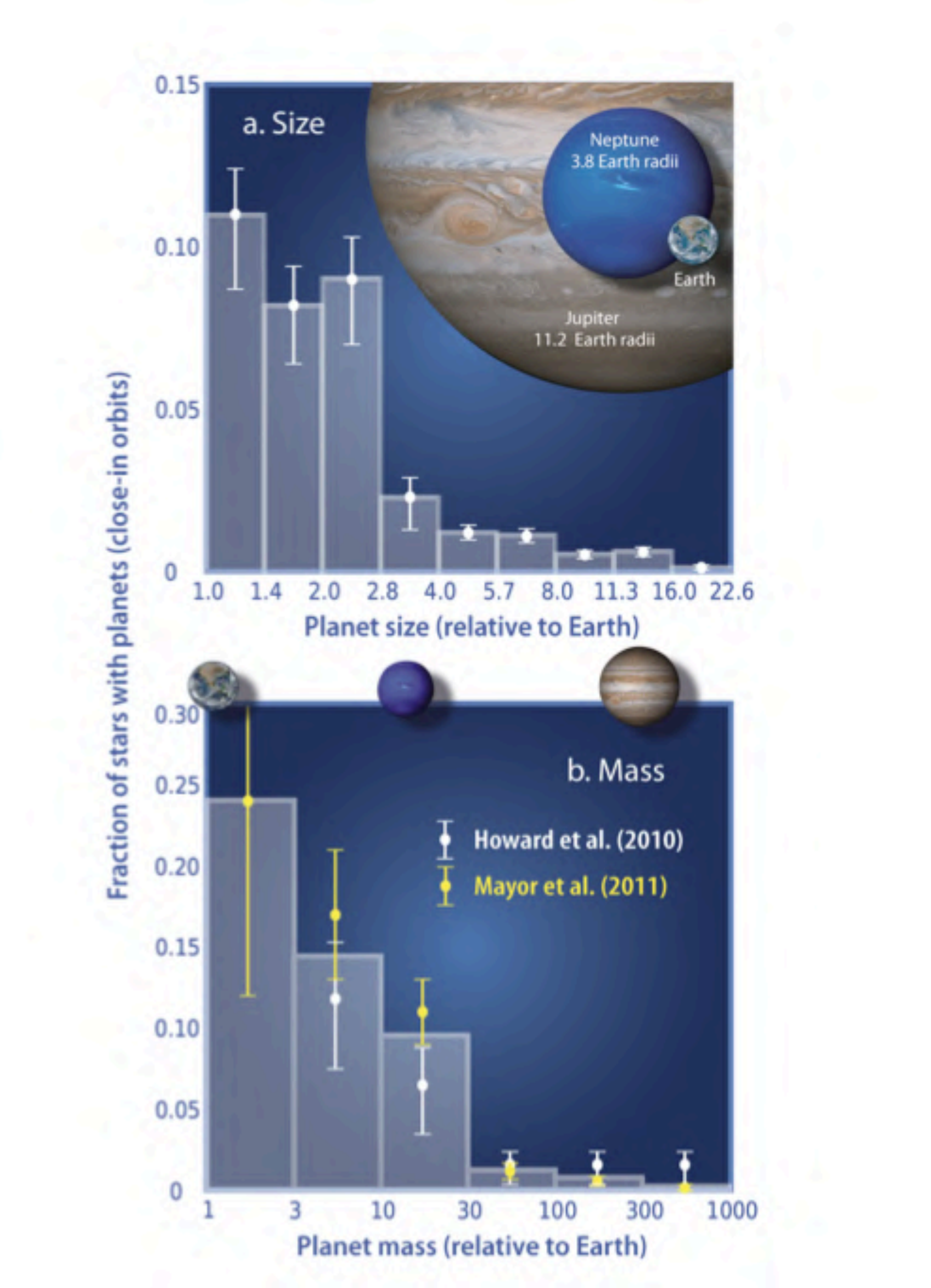
After 51 Pegasi b

Lin,D.N.C, Bodenheimer, P., Richardson,D.C. 1996, Orbital migration of the planetary companion of 51 Pegasi to its present location. Nature 380,606

And now orbital migration is part of all formation scenarii of planetary formation

Planets with masses
from 1 to 10 Earth-mass
are the most frequent ones

(at least with our current
level of detection !)

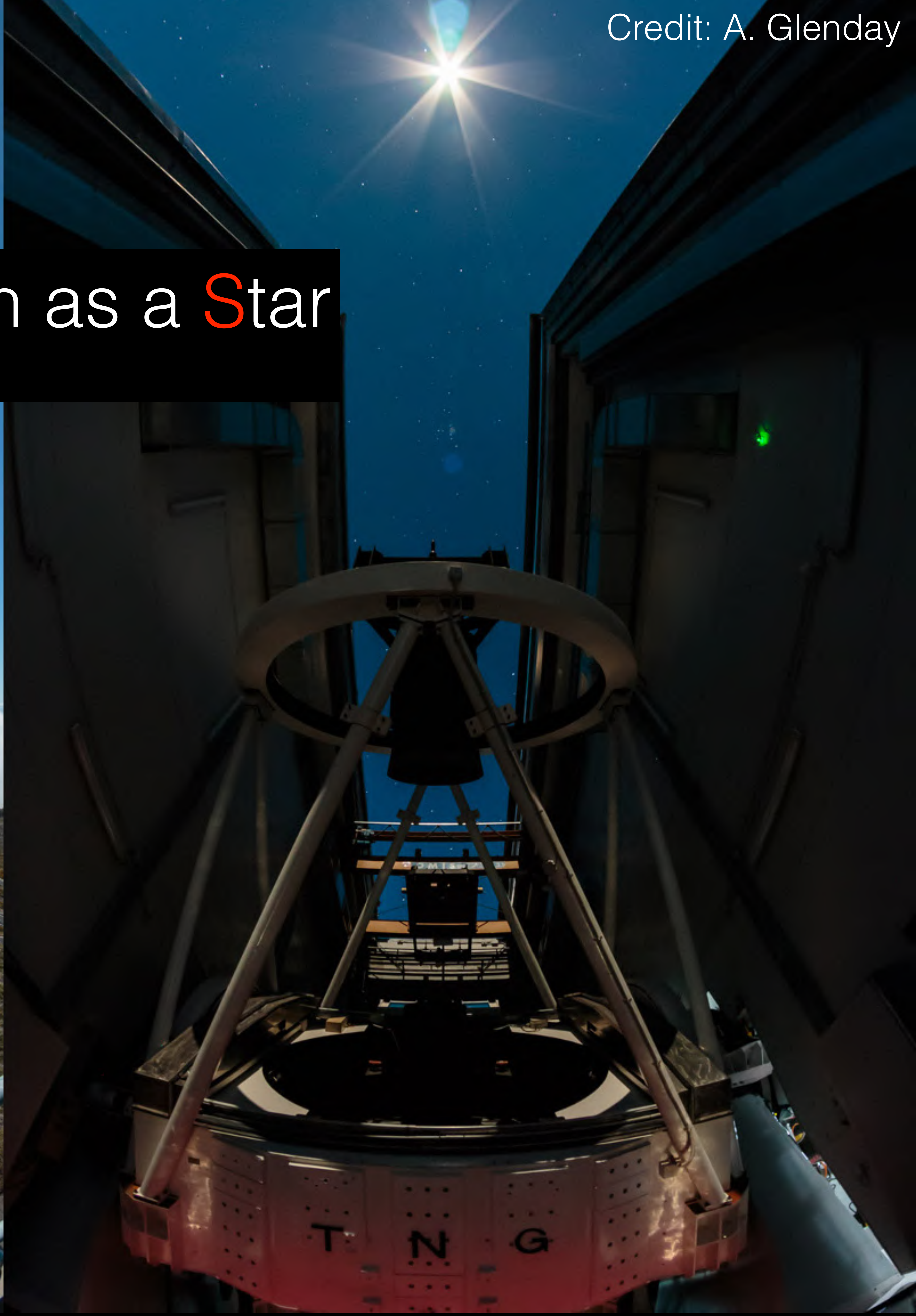


From 1 m/s to 0.1 m/s
The search for rocky planets

But… intrinsic variability of stellar atmospheres !!!!!

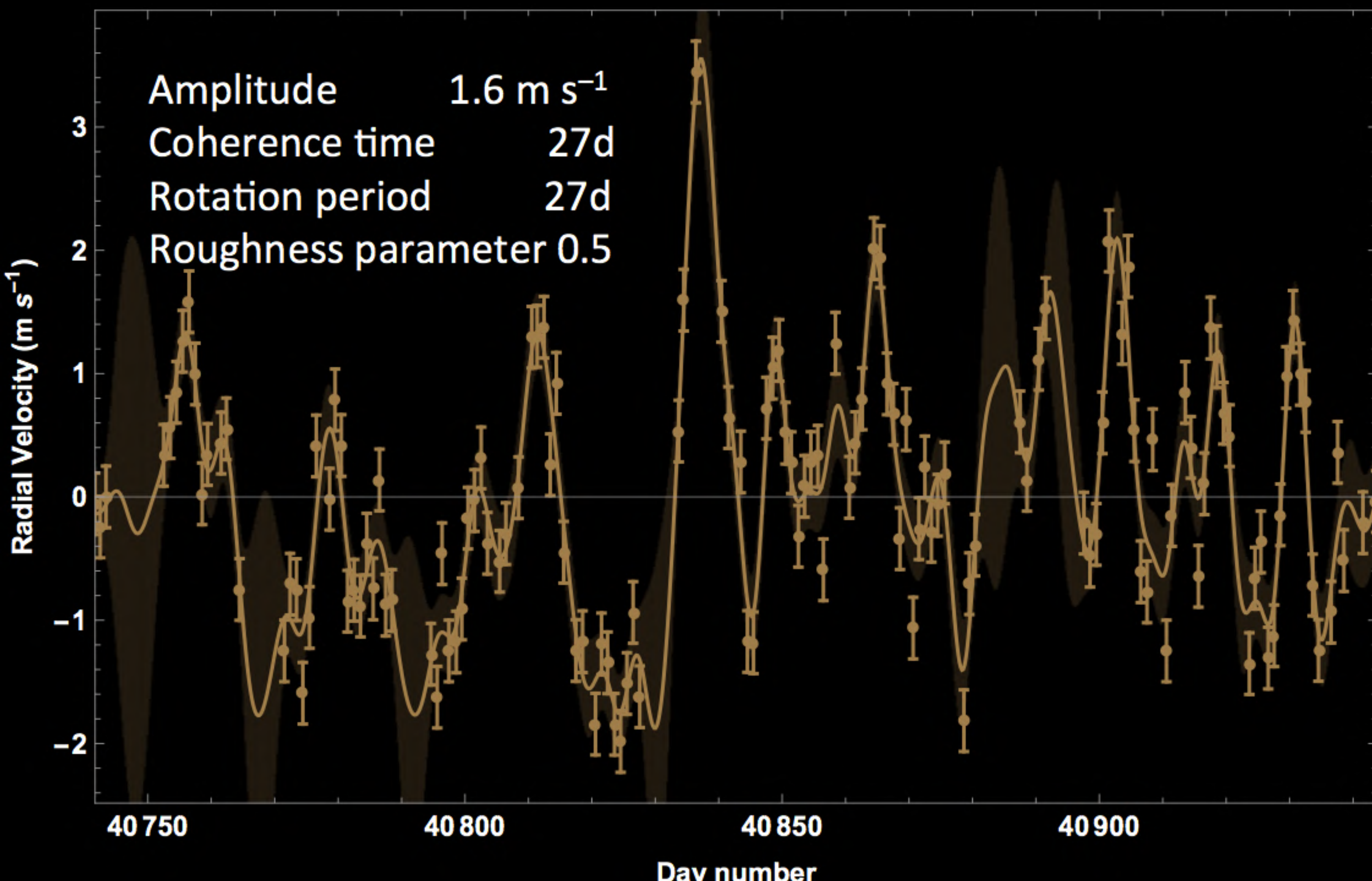
HARPS-N Observes the Sun as a Star

X. Dumusque et al. 2017



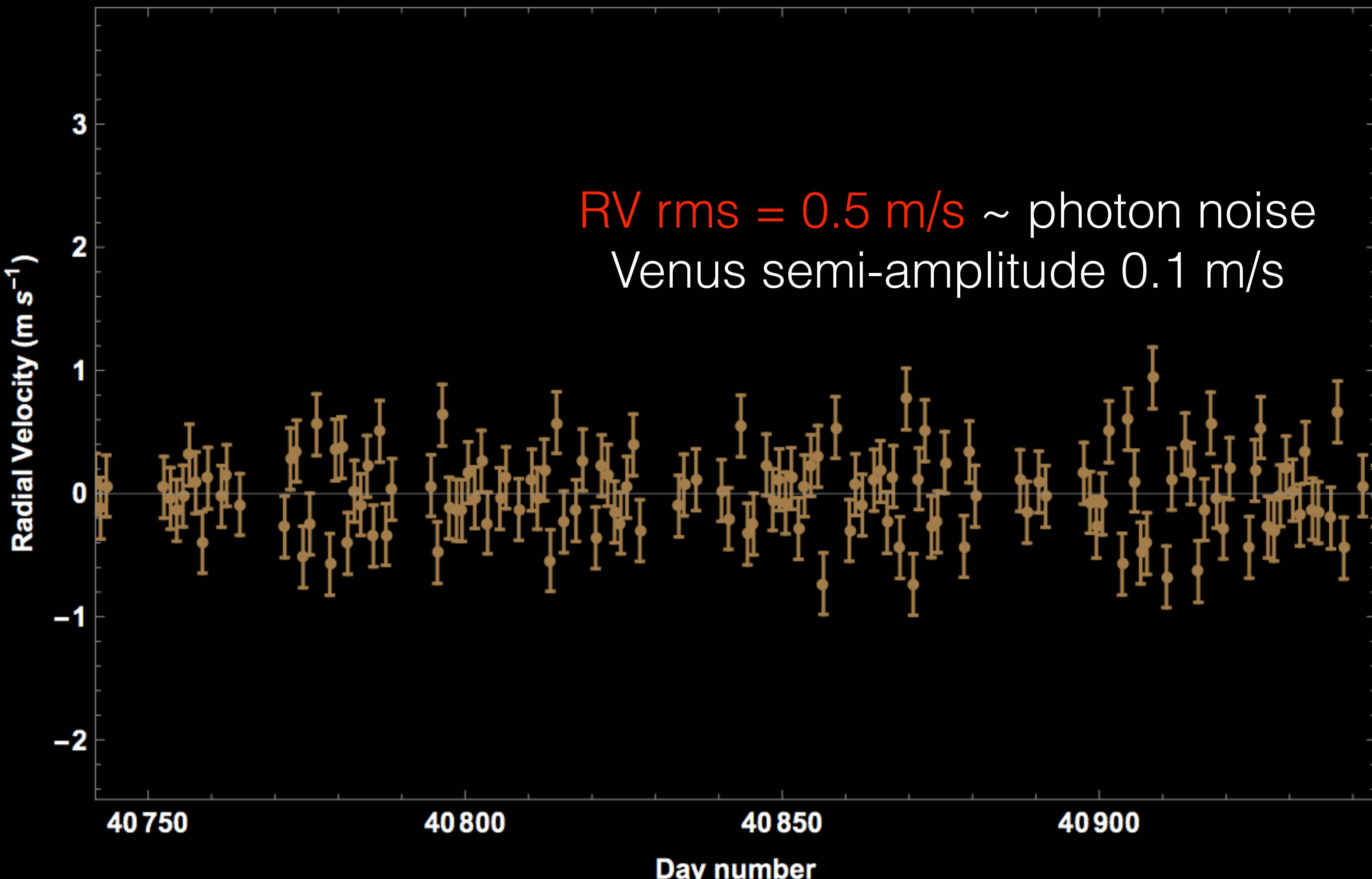
Credit: A. Glenday

Gaussian Process Regression



A. Collier Cameron

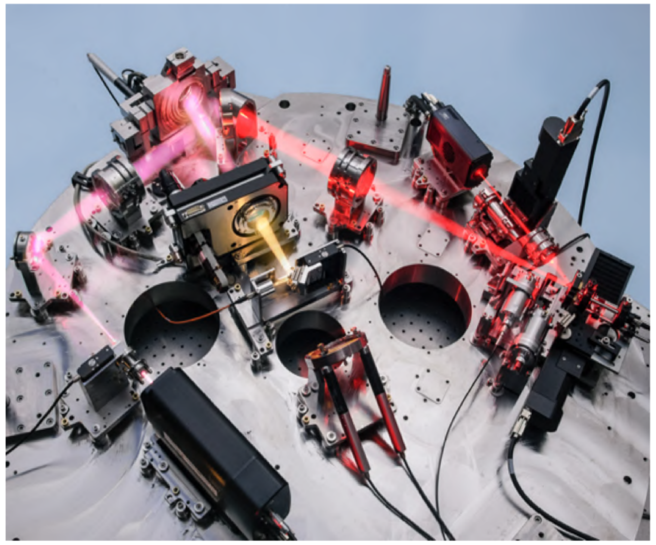
Residuals after Gaussian Process Regression

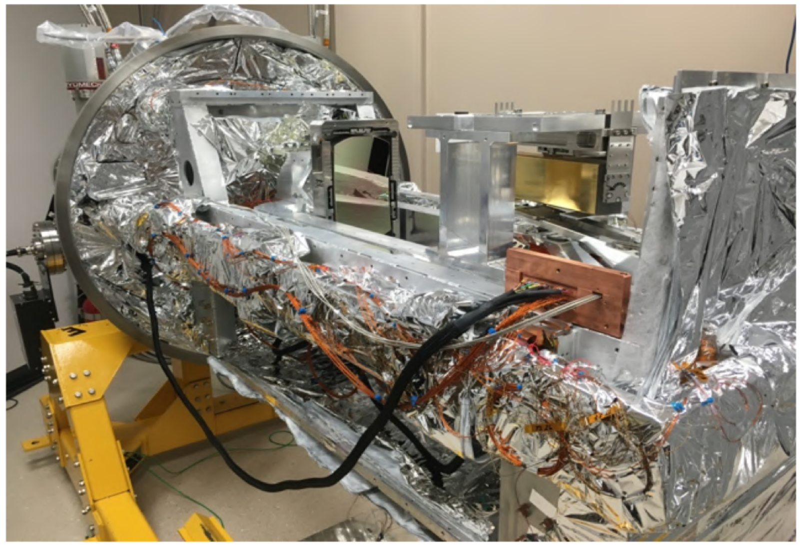


A. Collier Cameron

NIRPS joining HARPS for further characterization of planetary systems

François Bouchy and the NIRPS consortium
Astronomy department of Geneva University





https://www.eso.org/sci/facilities/develop/instruments/NIRPS.html

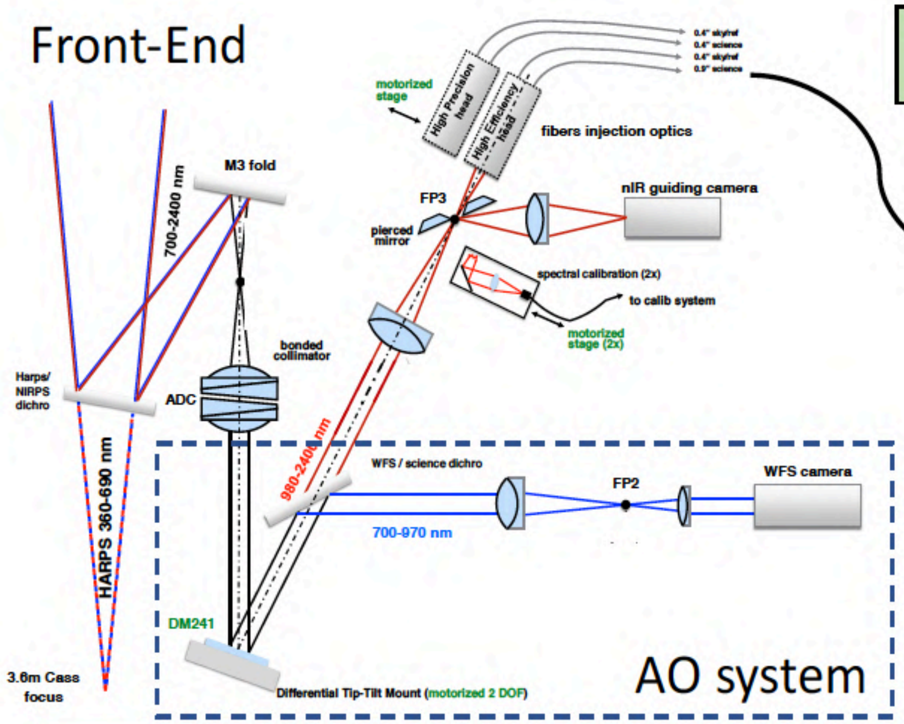
http://www.astro.umontreal.ca/nirps

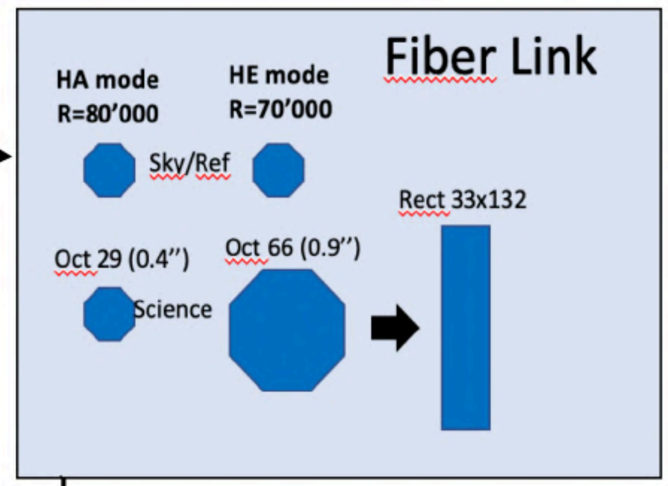
Near-InfraRed Planet Searcher to Join HARPS on the ESO 3.6-metre Telescope

The Near-InfraRed Planet Searcher (NIRPS) is a new ultra-stable infrared (*YJH*) spectrograph that will be installed on ESO's 3.6-metre Telescope in La Silla, Chile. Aiming to achieve a precision of 1 m s^{-1}, NIRPS is designed to find rocky planets orbiting M dwarfs, and will operate together with the High Accuracy Radial velocity Planet Searcher (HARPS), also on the 3.6-metre

NIRPS Sub-systems

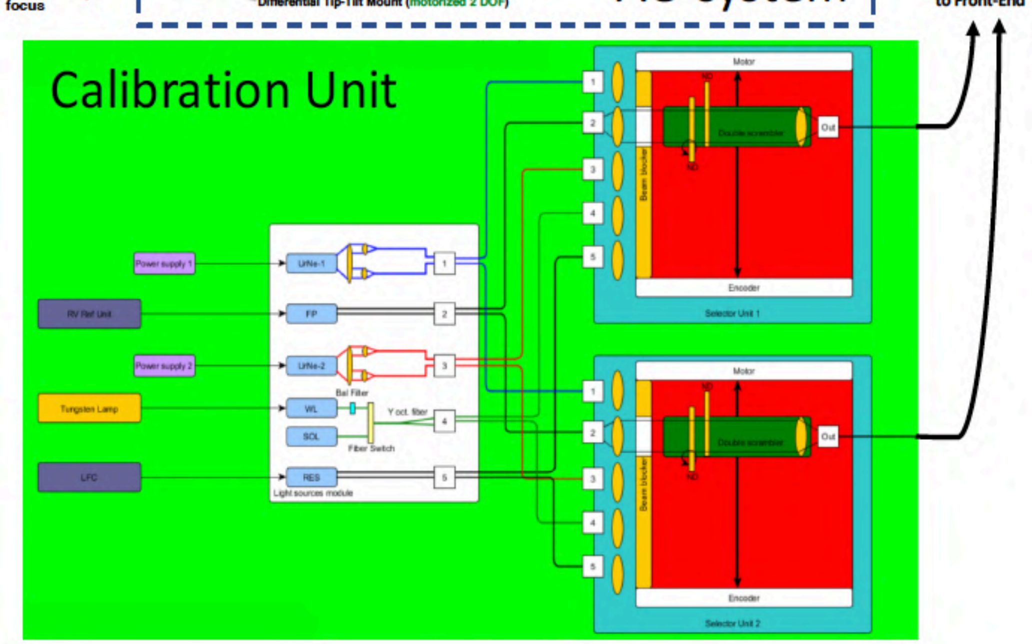
Front-End



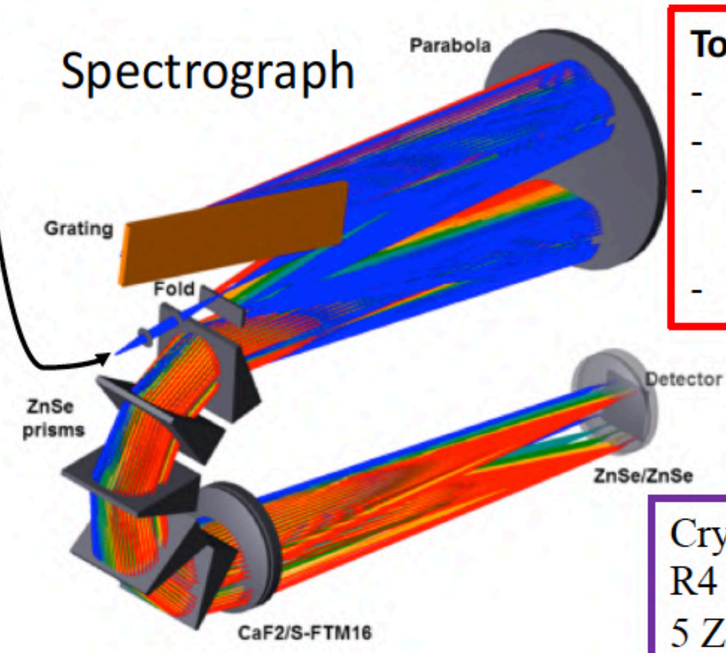


- Co-PIs : Doyon (UdM) + Bouchy (Geneva)
- Co-Is : Pepe, Santos, Rebolo, Delfosse, De Medeiros, Wade
- Proj. Scientist : Artigau (UdM)
- Proj. Manager : Malo (UdM)
- System Engineer : Wildi (Geneva)

Calibration Unit



Spectrograph



Top Level Requirements
- Y, J, H bands
- R ≥ 80'000
- High RV precision (1 m/s) and high spectral fidelity
- Simultaneous operation with HARPS

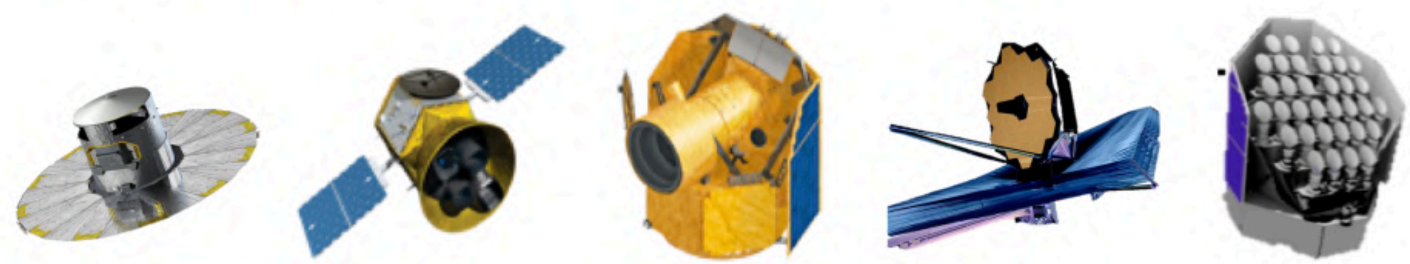
Cryogenic white pupil spectrograph
R4 echelle grating (73x73 mm pupil, 13.3 l/mm)
5 ZnSe prisms train for cross-dispersion
H4RG-15 detector 4k x 4k

Milestones and schedule

Kickoff Jan 2016
PDR Oct 2016
FDR May 2017
PAE Fiber Link May 2019
PAE Front End Sept 2019
Front-End Comm1 Nov 2019
Front-End Comm2 June 2021
Front-End Comm3 Sept 2021
PAE Spectrograph Oct 2021
Front-End Comm4 Dec 2021
First Light Q1 2022
Open to the community P111

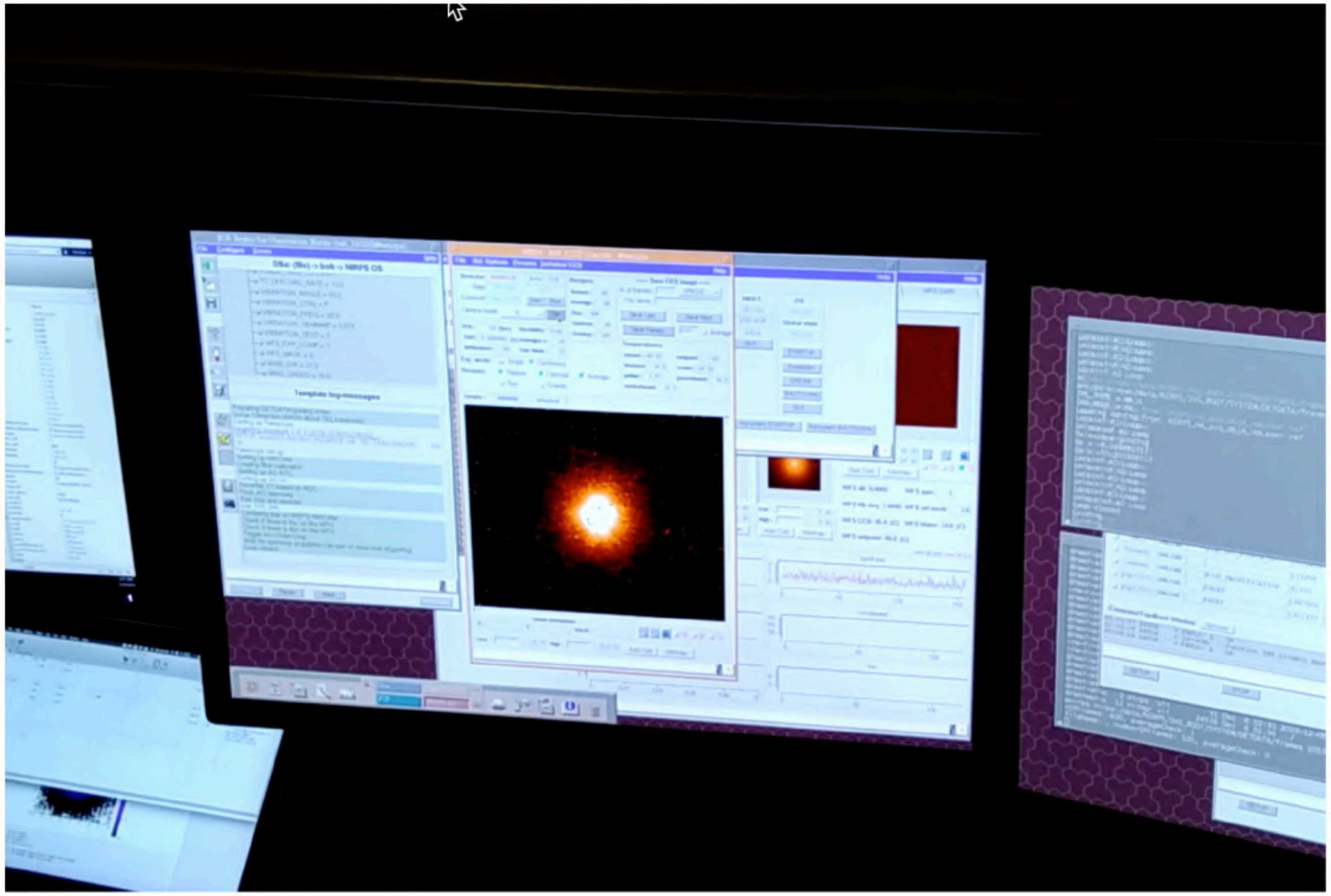
NIRPS GTO 725 nights over 5 years

3 main programs
- M-dwarfs RV survey
- Transit Follow-up of M targets → mainly TESS
- Exoplanet atmosphere characterization

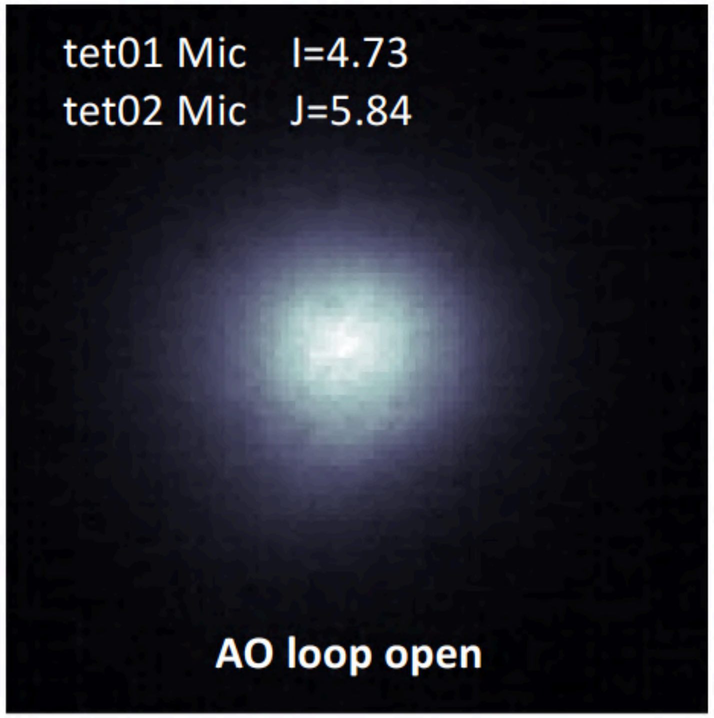


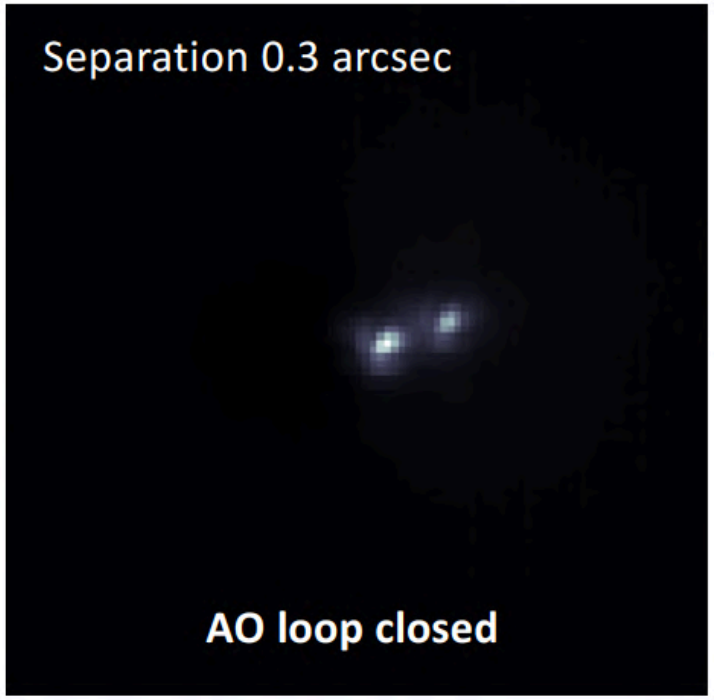
Bouchy et al. 2017, The Messenger, 169, 21

NIRPS AO imaging capability

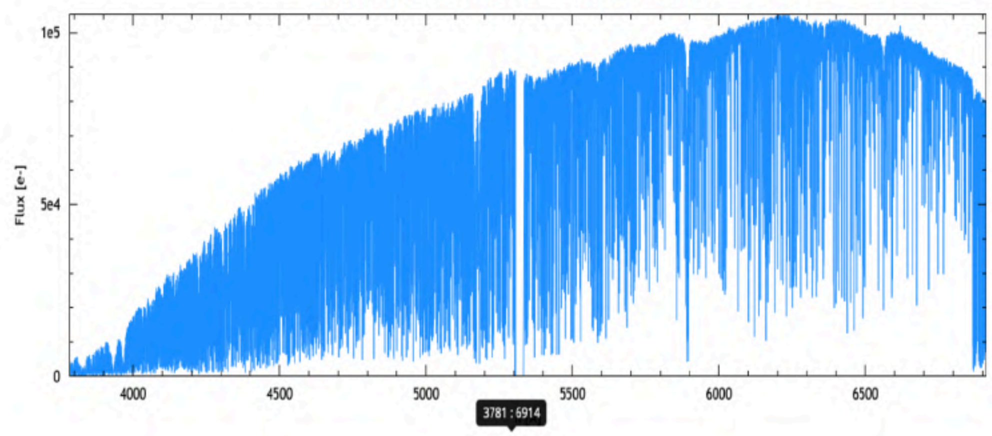


35 mas / pixel

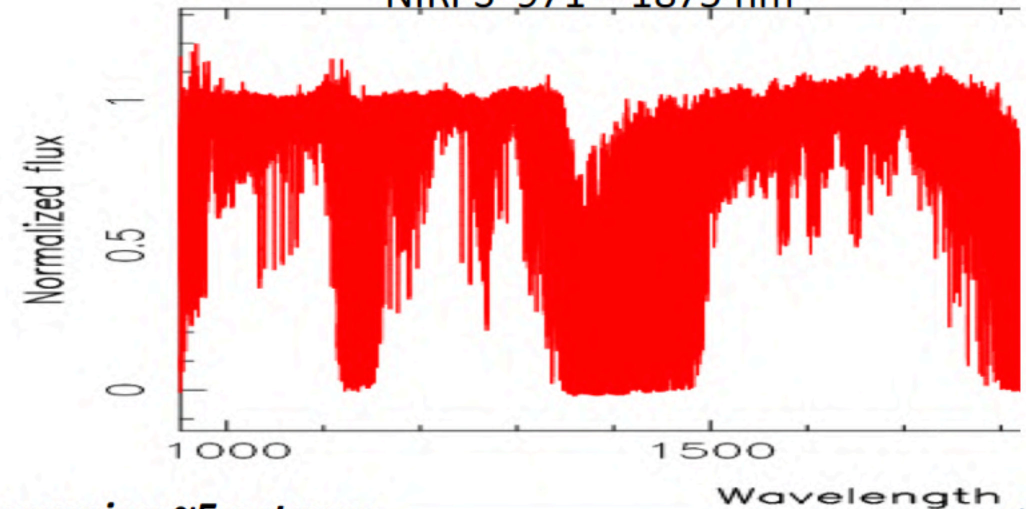




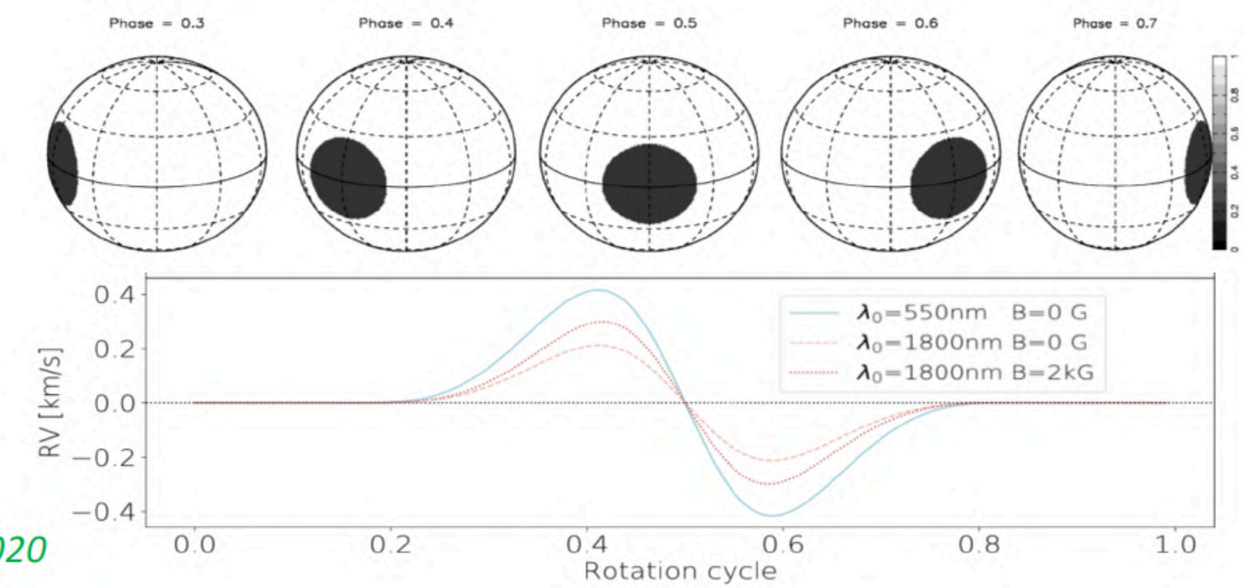
HARPS 378 – 691 nm



NIRPS 971 – 1875 nm



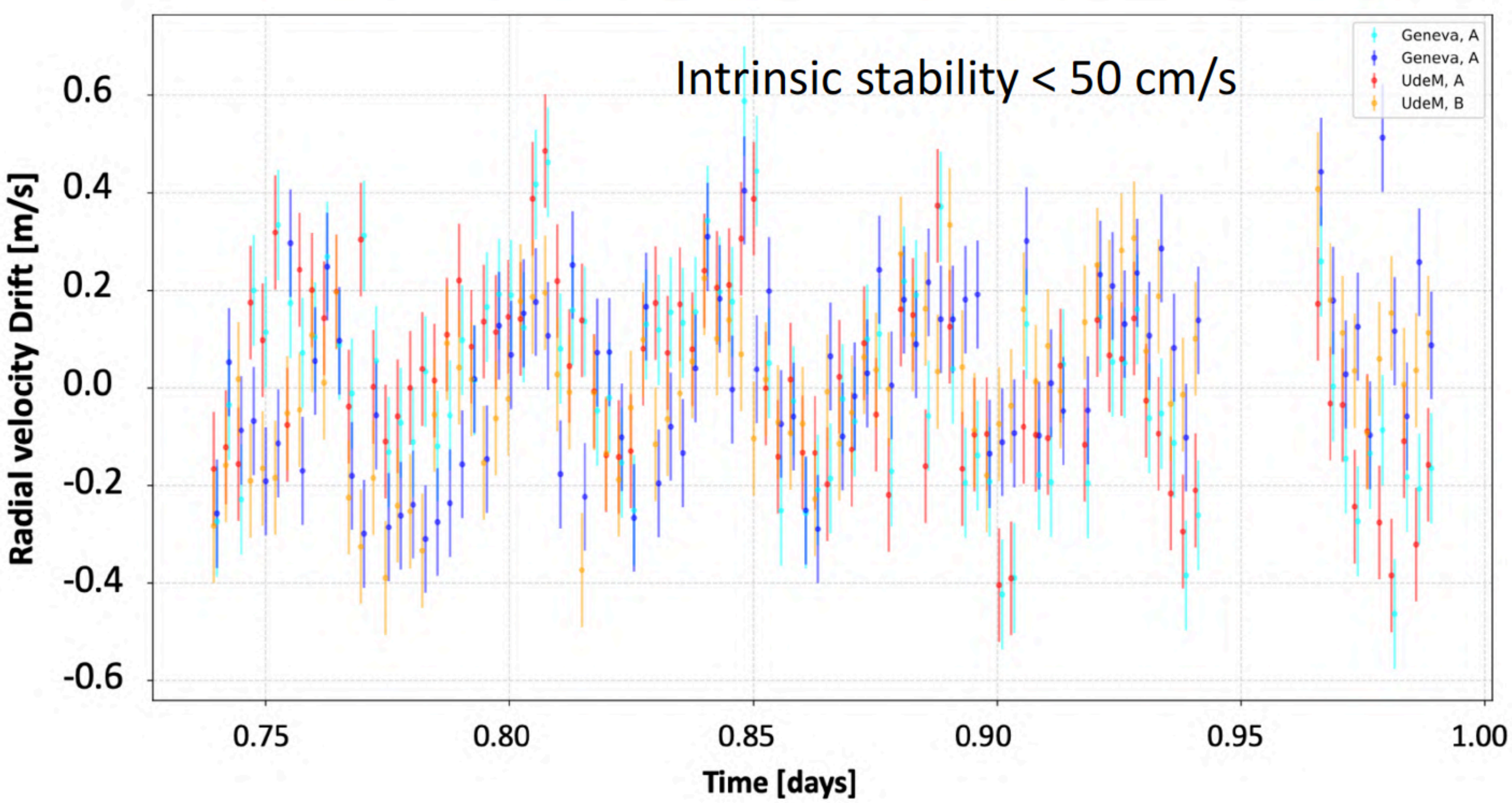
HARPS+NIRPS are covering ~5 octaves

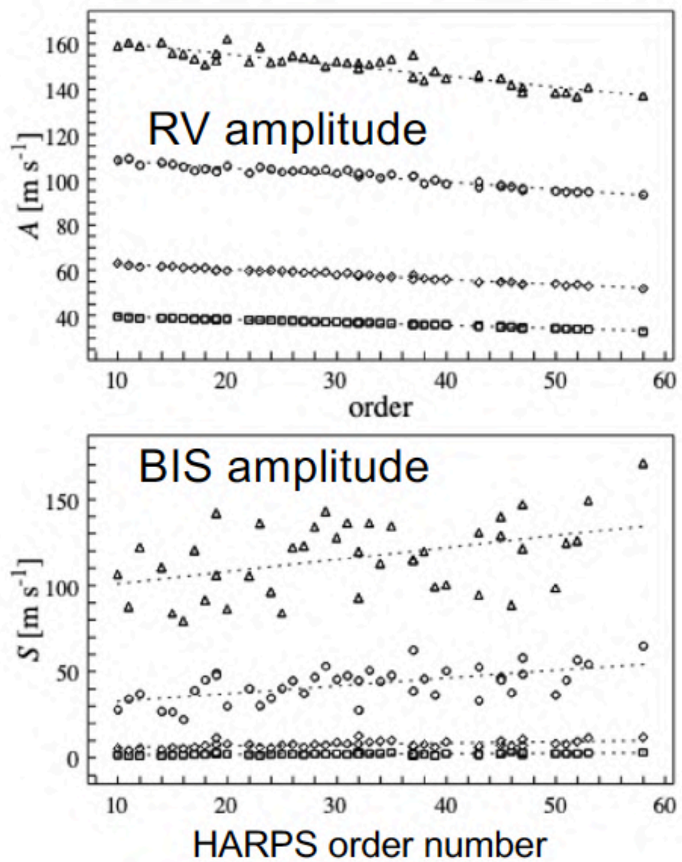


Klein PhD 2020

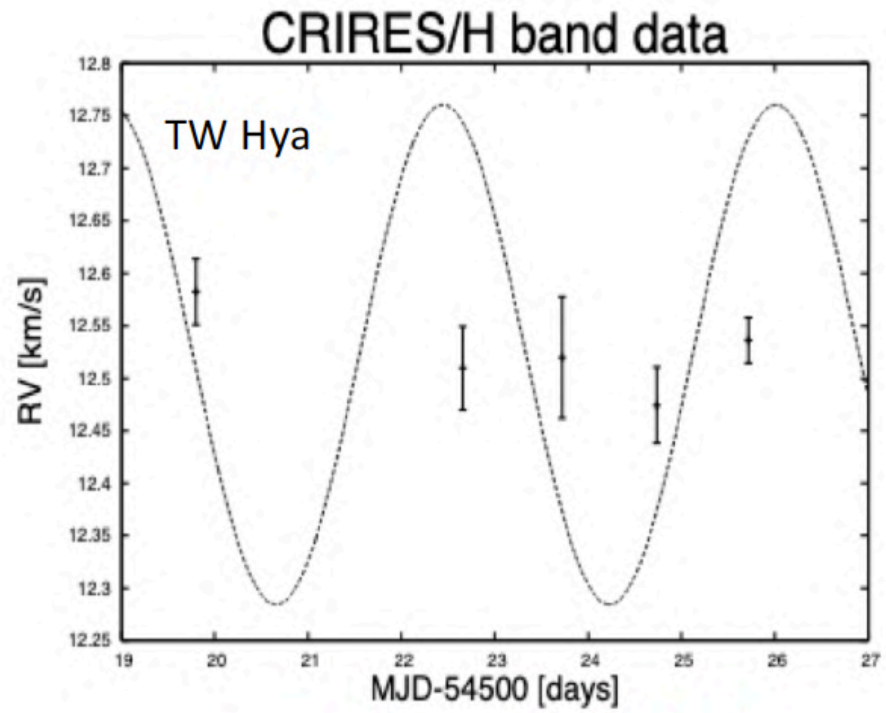
Stellar-spot induced RVs are highly chromatic

Data Reduction Software based on ESPRESSO pipeline (Geneva)



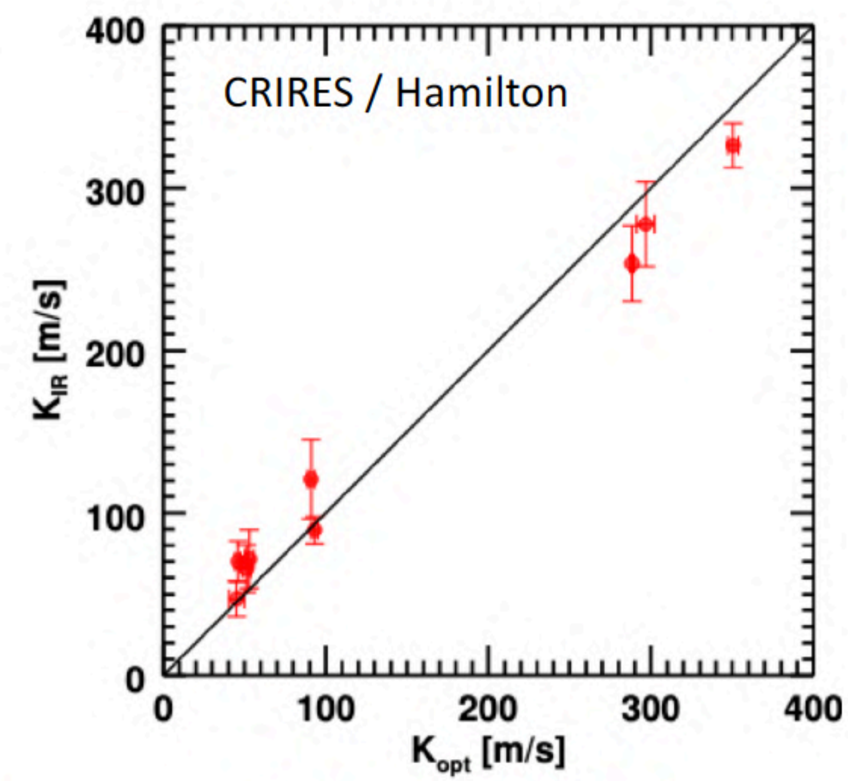


Desort et al. 2007



Huélamo et al. 2008

~~10 M_{Jup} exoplanet~~ → *Spot on ~7% surface*



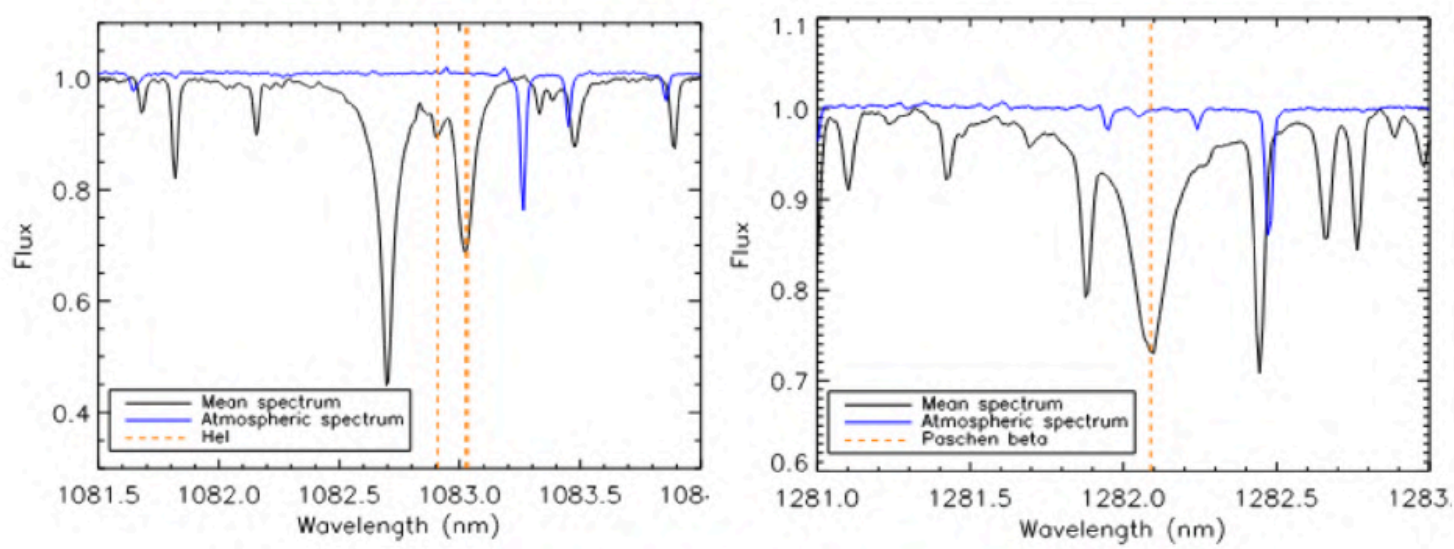
Trifonov et al. 2015

Equatorial spot of 1% size on a G2V-type star seen edge-on and with vsini = 2, 3, 5, and 7 km.s^{-1}

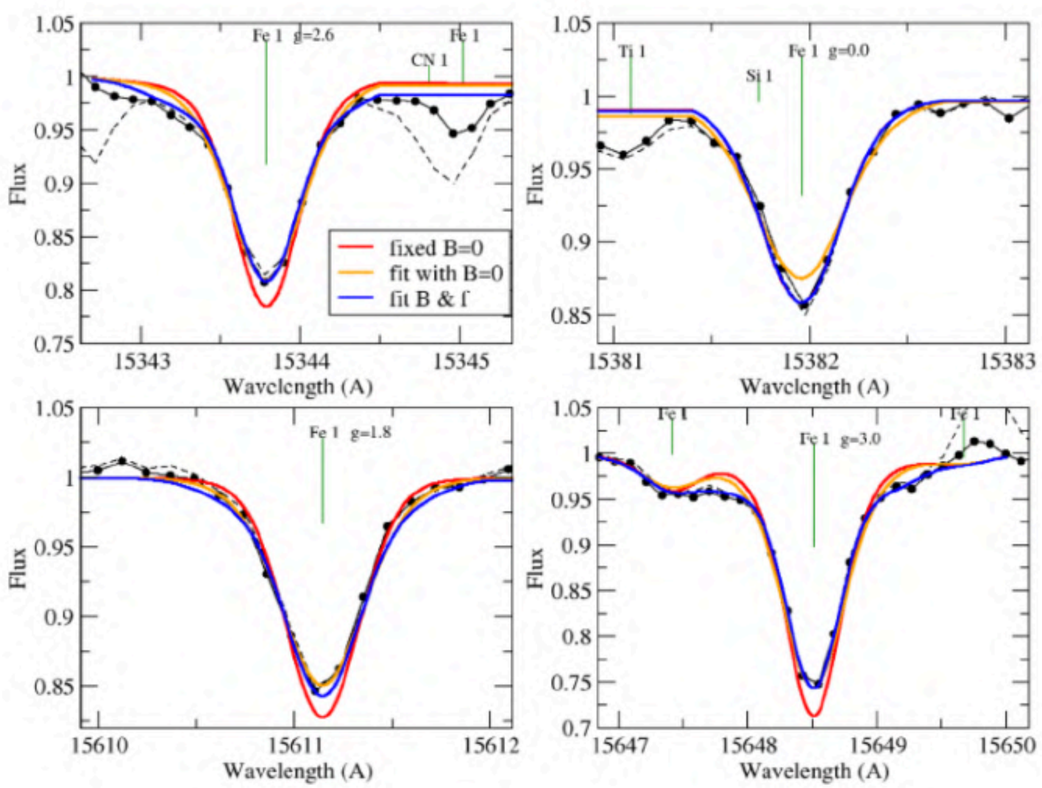
Optical and nIR RVs of giant stars are consistent

Several resonant spectral lines are widely used to monitor and to model the activity jitter

Ca II H & K (393.4 and 396.8 nm)
He I D3 (587.6 nm)
Na I D1 & D2 (589.5 and 589.0 nm)
Hα (656.9 nm)
He I triplet (1083 nm)
Pa β (1281.8 nm)



From SPIROU - Moutou et al. 2020



Magnetic field measurements from the Zeeman broadening of unpolarized spectral lines which scales with λ^2
Fe I lines at 1534.38, 1538.20, 1561.11, and 1564.85 nm with a wide range of effective Landé factors
Reiners & Basri, 2006, 2007, 2008
Moutou et al. 2020

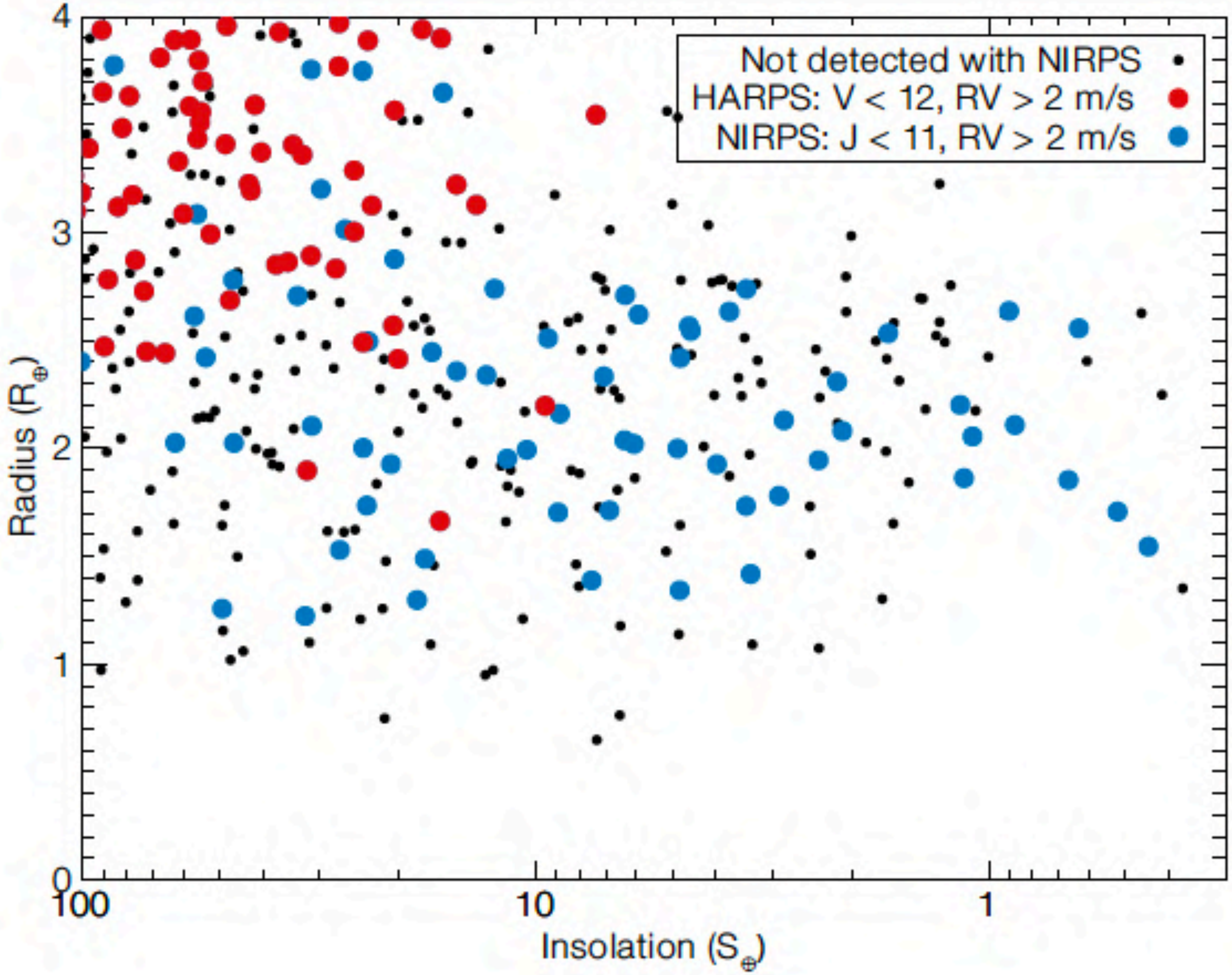


Figure 1. Simulated TESS sample of southern (declination < 20°) planets in an insolation versus radius diagram. Planets amenable to HARPS follow-up are shown in red while those, much more numerous, amenable to NIRPS follow-up are shown in blue. NIRPS will allow the follow-up of numerous planets that are only slightly larger than Earth (1–2.5 $R_\oplus$) and that receive a comparable insolation (0.3–10 $S_\oplus$). Radius, insolation and photometric values are drawn from the simulated set (Sullivan et al., 2015). These planets will be the prime targets for atmospheric characterisation studies with the JWST.

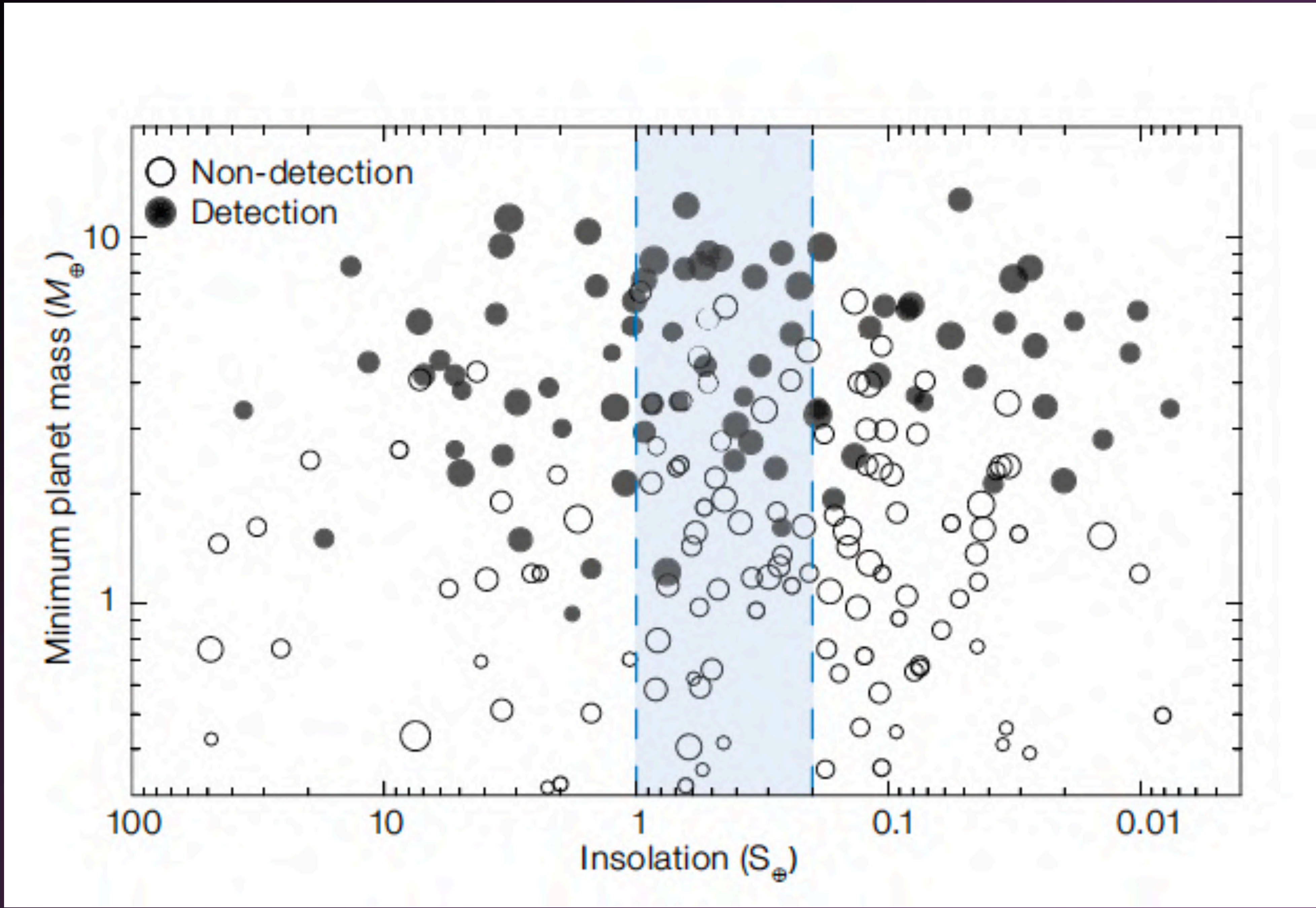


Figure 2. Simulated NIRPS planet survey results in the insolation/minimum planet mass plane. With the predicted NIRPS performances and realistic stellar properties we recovered 79 planets around 100 stars in 150 to 200 visits per star. The detection framework is described in Cloutier et al. (2017). The size of each marker is proportional to the planet's radius. The approximate "maximum greenhouse" and "water-loss" limits of the habitable zone are highlighted in blue ($0.2 \leq S/S_\oplus \leq 1$); (Kopparapu et al., 2013).

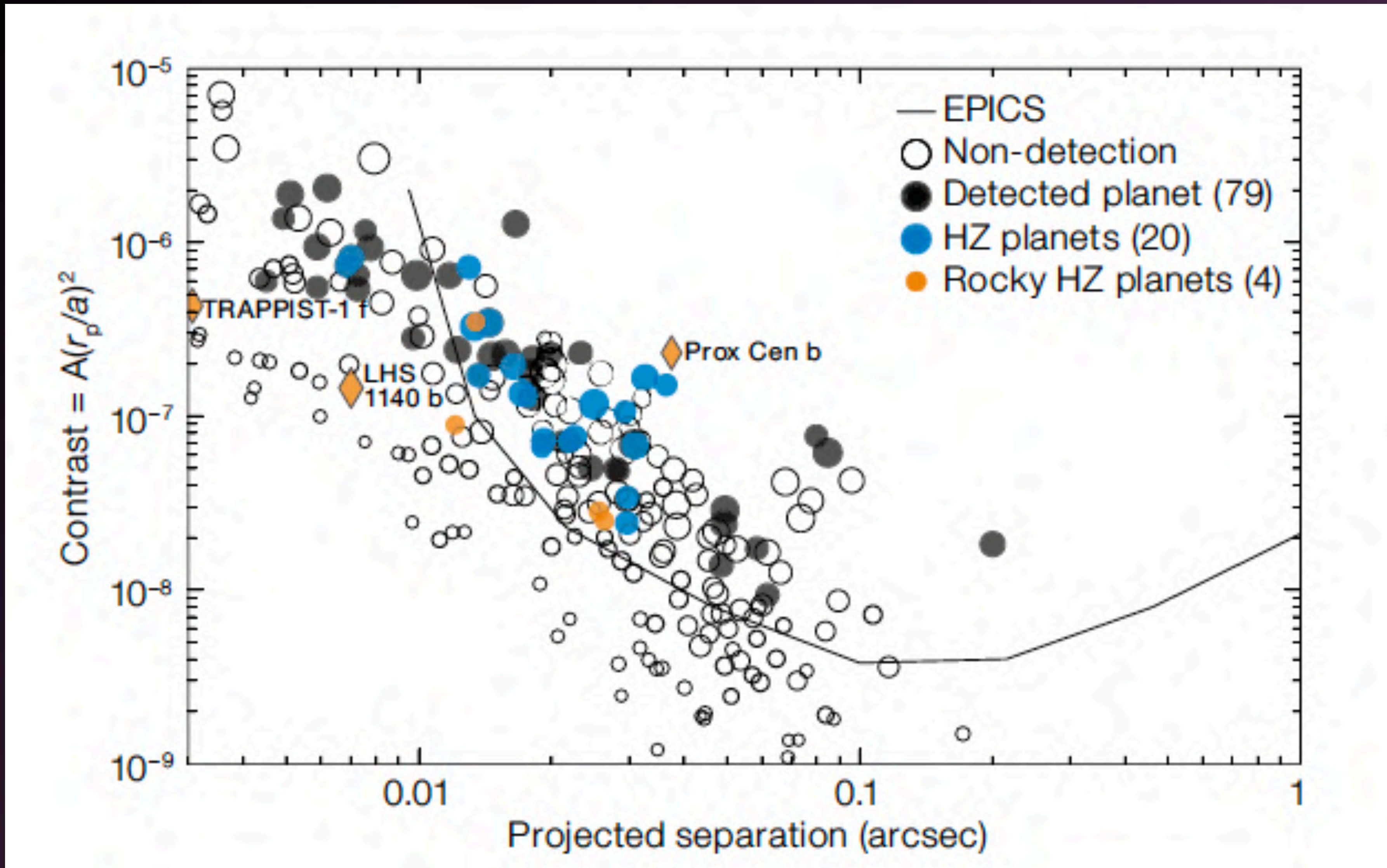


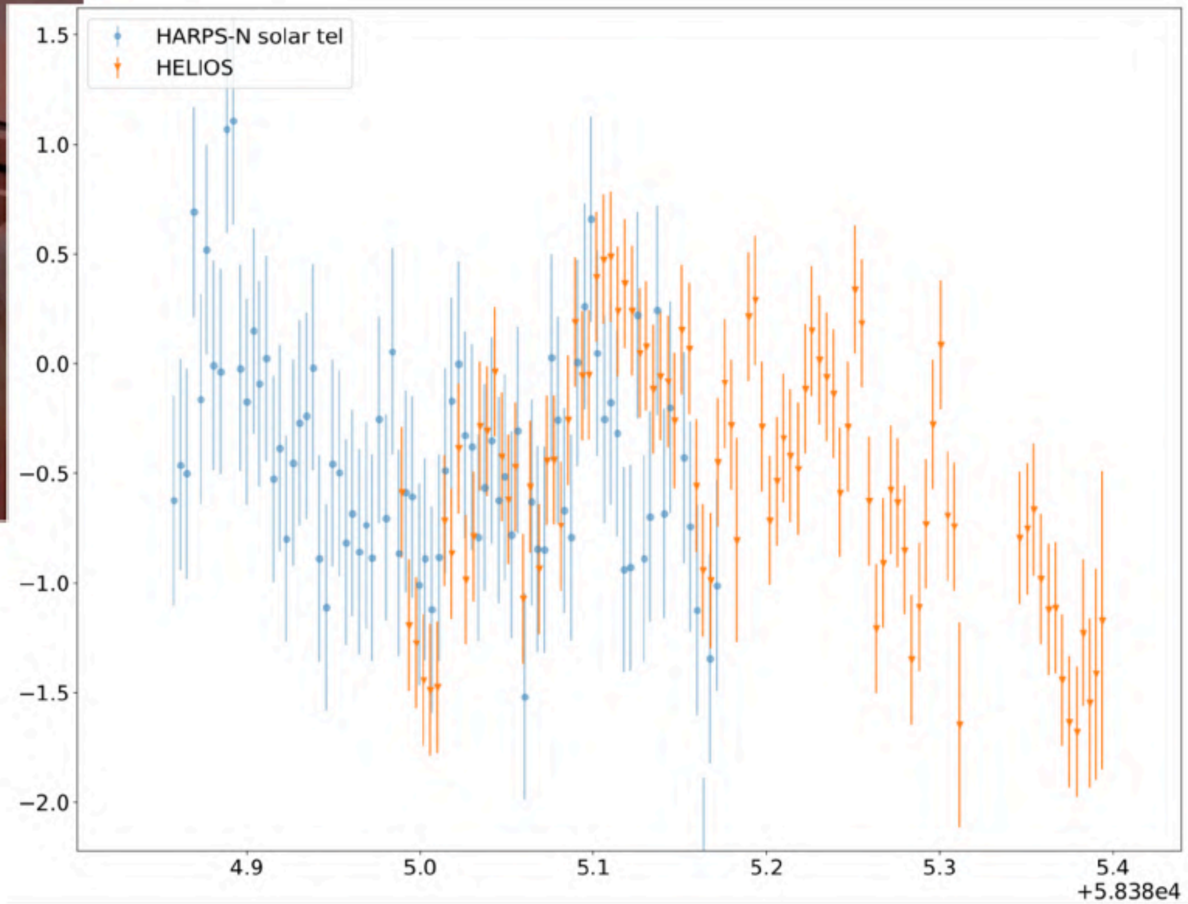
Figure 3. The same simulated NIRPS planet population as shown in Figure 2 in the projected separation/contrast plane. The contrast in reflected light depends on the planet radius (r_p), separation (a) and geometric albedo (A; we have assumed a value of A = 0.3 for all planets). Shaded circles represent planets that would be detected with NIRPS; detected habitable-zone planets are highlighted in blue and detected rocky ($r_p < 1.5\ R_\oplus$) habitable-zone planets are highlighted in red. The planet population is compared to the contrast curve expected to be achieved by the third generation of near-infrared imagers (using the ELT). Orange diamonds show the estimated location of nearby habitable-zone planets around M dwarfs (Anglada-Escudé et al., 2016; Gillon et al., 2016; Dittmann et al., 2017).

Table 1. Summary of NIRPS characteristics

Subsystem	Parameters
HAM-mode	Spectral resolution: $\lambda/\Delta\lambda$ = 100 000 0.4 arcsecond object fibre, AO-assisted feed 0.4 arcsecond simultaneous reference fibre
HEM-mode	Spectral resolution: $\lambda/\Delta\lambda$ = 75 000 0.9 arcsecond double slicing in the pupil plane 0.4 arcsecond simultaneous reference fibre
Environment	Vacuum: < 10^{-5} mbar Cryogenic: 80 K with 1 mK stability
Spectral domain	0.97–1.81 μm (*YJH* photometric bandpasses)
Calibration sources	Hollow cathode lamp, Stabilised Fabry-Perot, Laser Frequency Comb
Detector and format	Hawaii-4RG, 4 k x 4 k, 15 μm pixels
Limiting magnitude	1 m s^{-1} in 30 min for an M3 star with $H = 9$
Stability	< 1 m s^{-1} intrinsic stability over one night Calibration down to < 1 m s^{-1} over the lifetime of the instrument
Sampling	1 km s^{-1} per pixel, 3 pixels per FWHM
Operation	Simultaneous operation with HARPS without degrading HARPS's performance

HELIOS will also be connected to NIRPS

to observe the Sun as a star
with HARPS and NIRPS
every possible day



Courtesy : X. Dumusque

NIRPS joining HARPS for further characterization of planetary systems

Detection of exoplanets around M dwarfs, active stars and young stars
RV search for planets around M dwarf to image with ELT
Mass and density characterization of transiting exoplanets
Exoplanet atmosphere characterization through transmission spectroscopy at high resolution
Mitigation of stellar activity using chromatic effect + sensitive spectral lines + Zeeman broadening
NIRPS AO guiding camera to identify nearby stellar component and/or rule out blended EBs
Long term monitoring of Sun observed as a star in both visible + nIR

RISTRETTO
Pi: Prof. Christophe Lovis

Primary science goal

RISTRETTO primary science goal is the detection of the reflected light of exoplanets in the visible. It focuses on exoplanets orbiting very nearby stars, most of which do not transit.

Doing so also requires to locate the planet around its star, and this will be achieved using an integral-field unit with 7 hexagonal spaxels covering the full annulus at 2 λ/d

The design driver is to be able to detect the reflected light from Proxima b, at a contrast of about 10^{-7}

Courtesy : Ch.Lovis

The instrument could also detect the signature of different gases in the atmospheres of exoplanets such as H_2O and O_2

Bibliography

Paper directly linked to the project

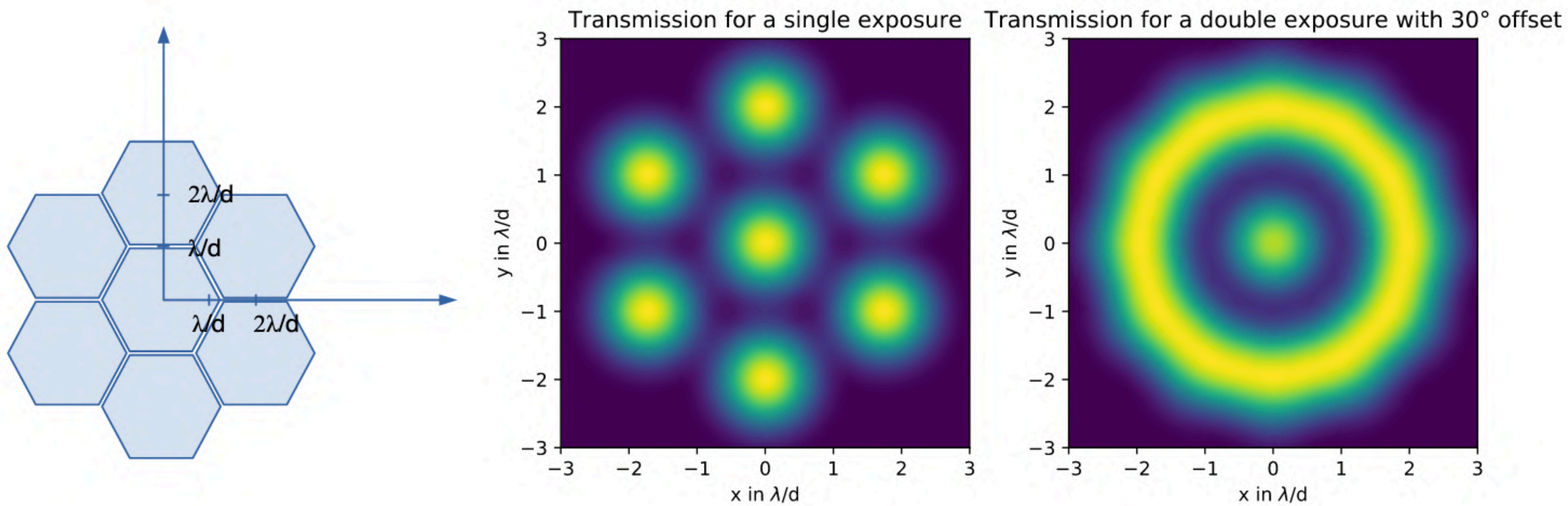
- (Chazelas et al 2020); RISTRETTO: a pathfinder instrument for exoplanet atmosphere characterization, 2020.
- (Lovis 2019), Reflected-light spectroscopy of nearby expoplanets with RISTRETTO at the VLT, The Very Large Telescope in 2030.
- (Lovis, C. et al 2017); Atmospheric characterization of Proxima b by coupling the SPHERE high-contrast imager to the ESPRESSO spectrograph

Courtesy : Ch.Lovis

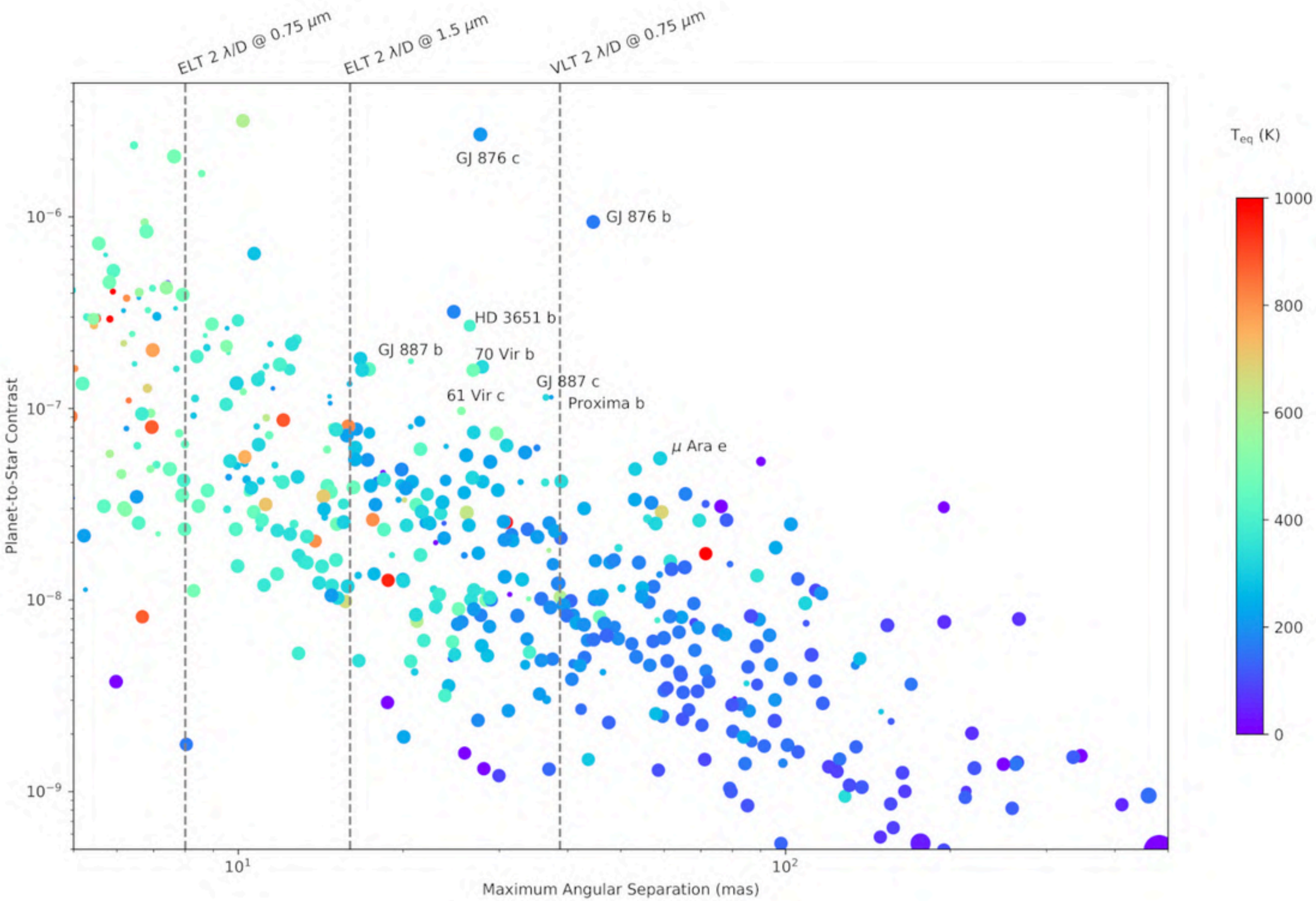
IFU

The position angle of the planet is a priori unknown, thus there is the need for an IFU covering the whole area around the star.

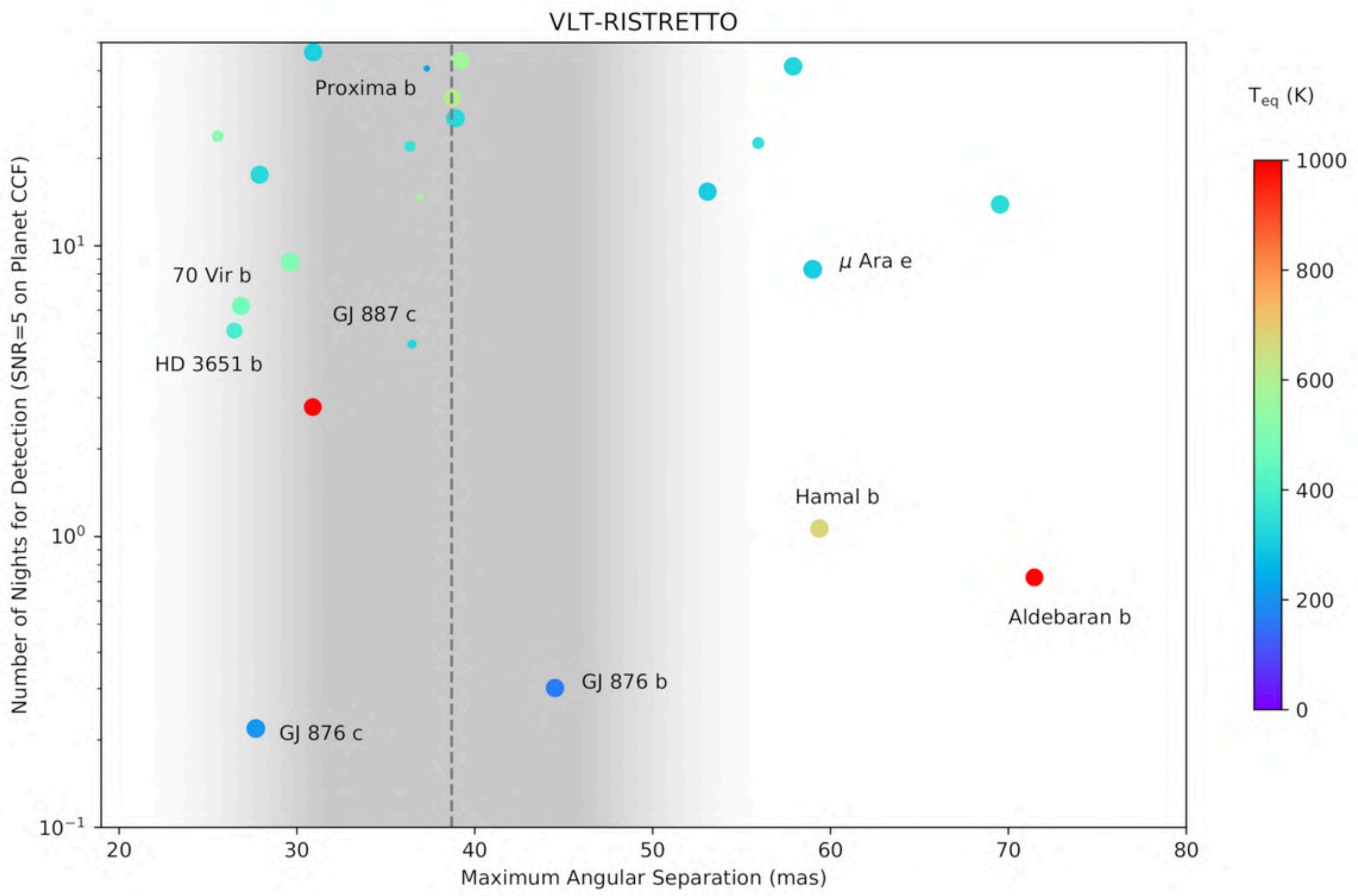
The IFU is paved in an hexagonal fashion as shown in the following figure



The focal plane is paved hexagonally. The lateral spaxels are centered at 2λ/d. At once one cannot cover the full ring around the star. One need a second exposure at 30° offset



Contrast Vs Separation of the nearest known exoplanet



Exposure time Vs Separation of the nearest known exoplanet: there are a handful of easy targets, and Proxima b is hard but highly rewarding

Thank you