Pettinare la luce per scoprire nuove terre

G. Micela

INAF – Osservatorio Astronomico di Palermo

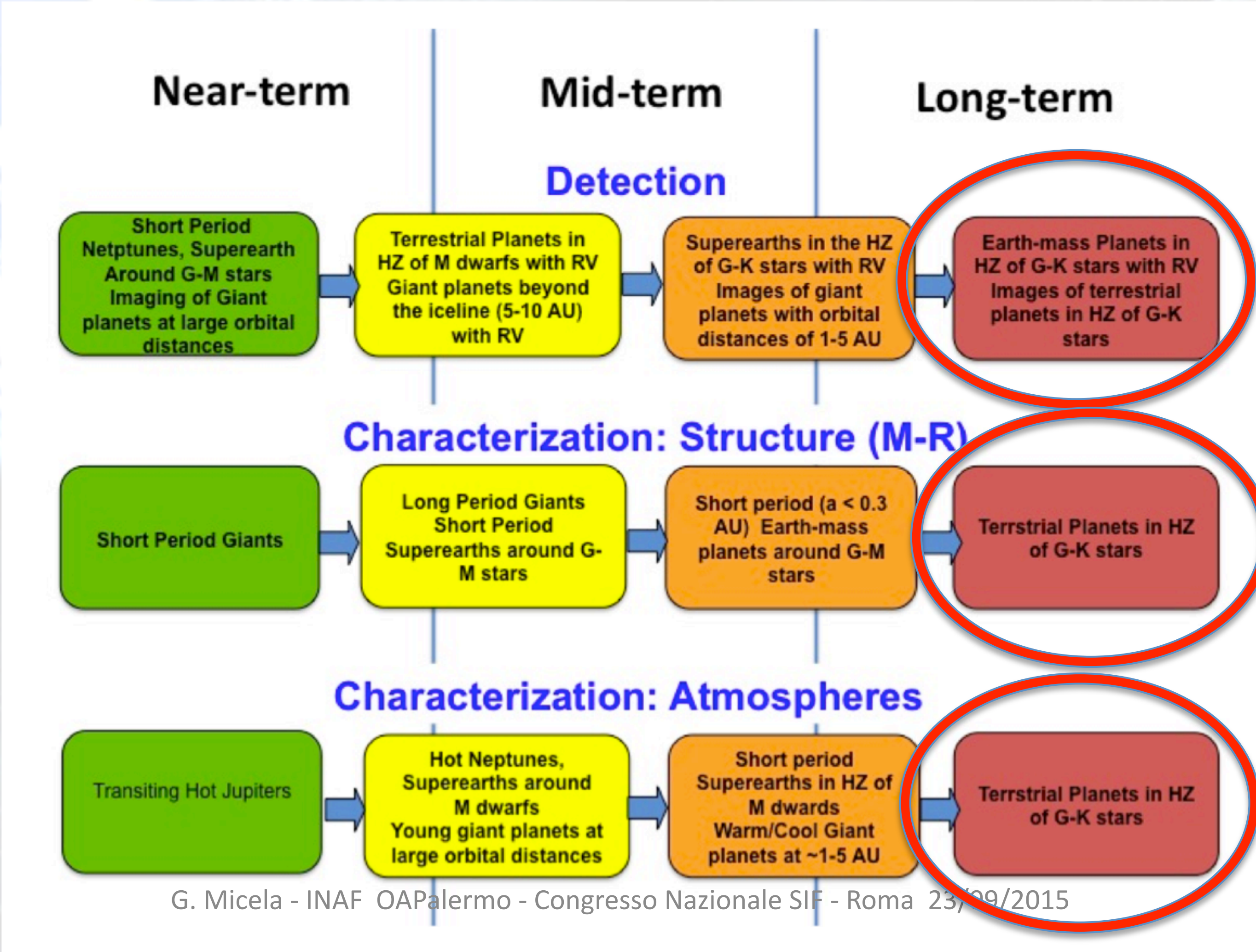
In the last years an effort (by NASA, ESO, ESA, …) has been done to to identify the necessary preconditions and technologies to address the exo-planetary science for the next years

1) Detections

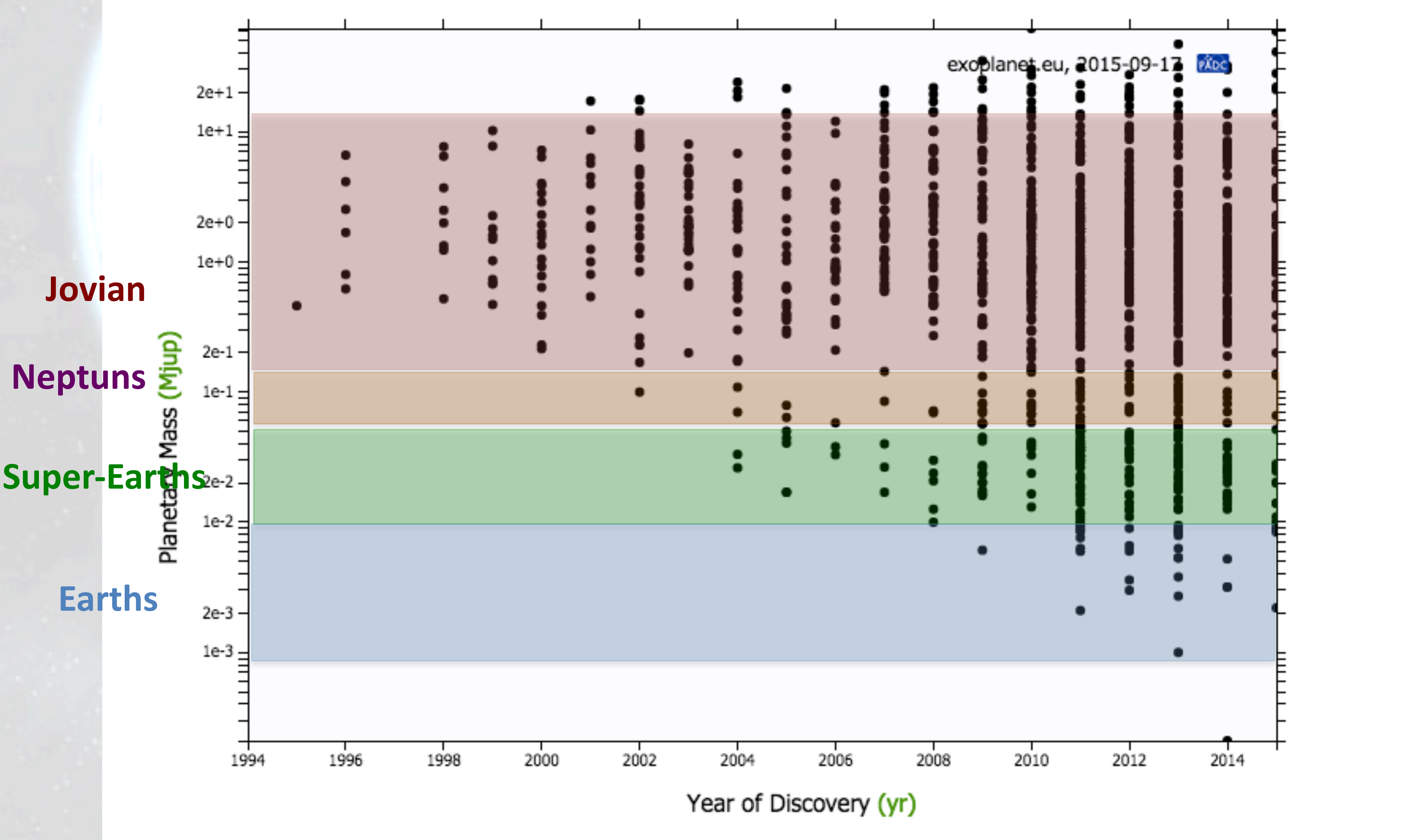
2) Characterization of the internal structure

3) Characterization of the exoplanetary atmospheres

ESA
EXOPLANET ROADMAP ADVISORY TEAM (2010) *still valid*

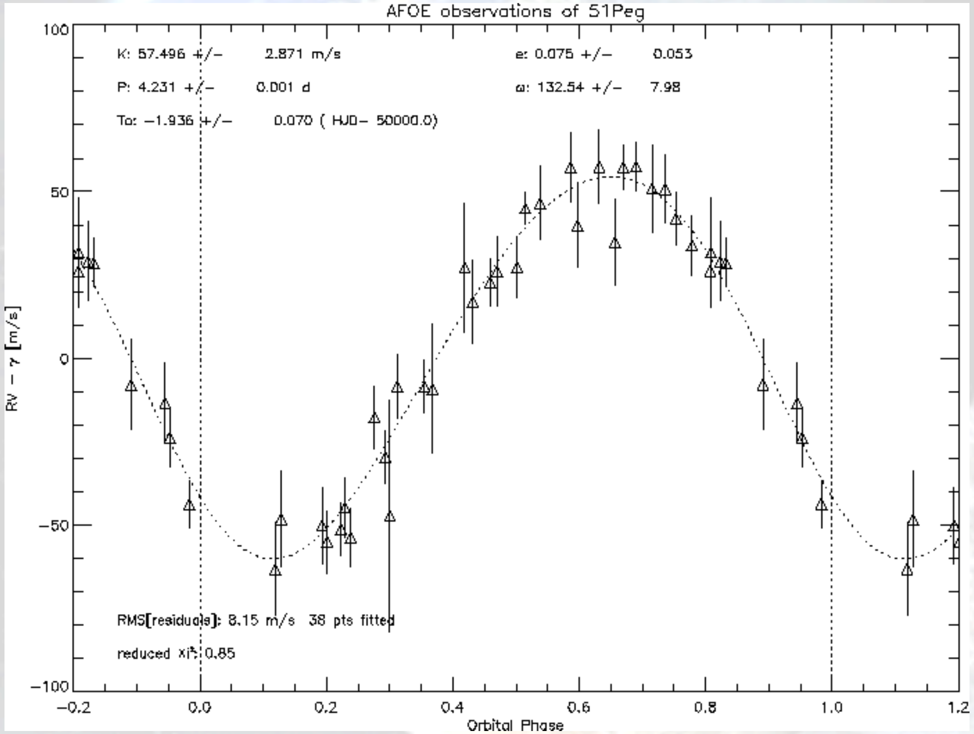


From Jupiters to Earths



51 Peg b- the first exoplanet–

Mayor & Queloz, Nature, 1995



The star: G2, V=5.5, dist=14.7pc

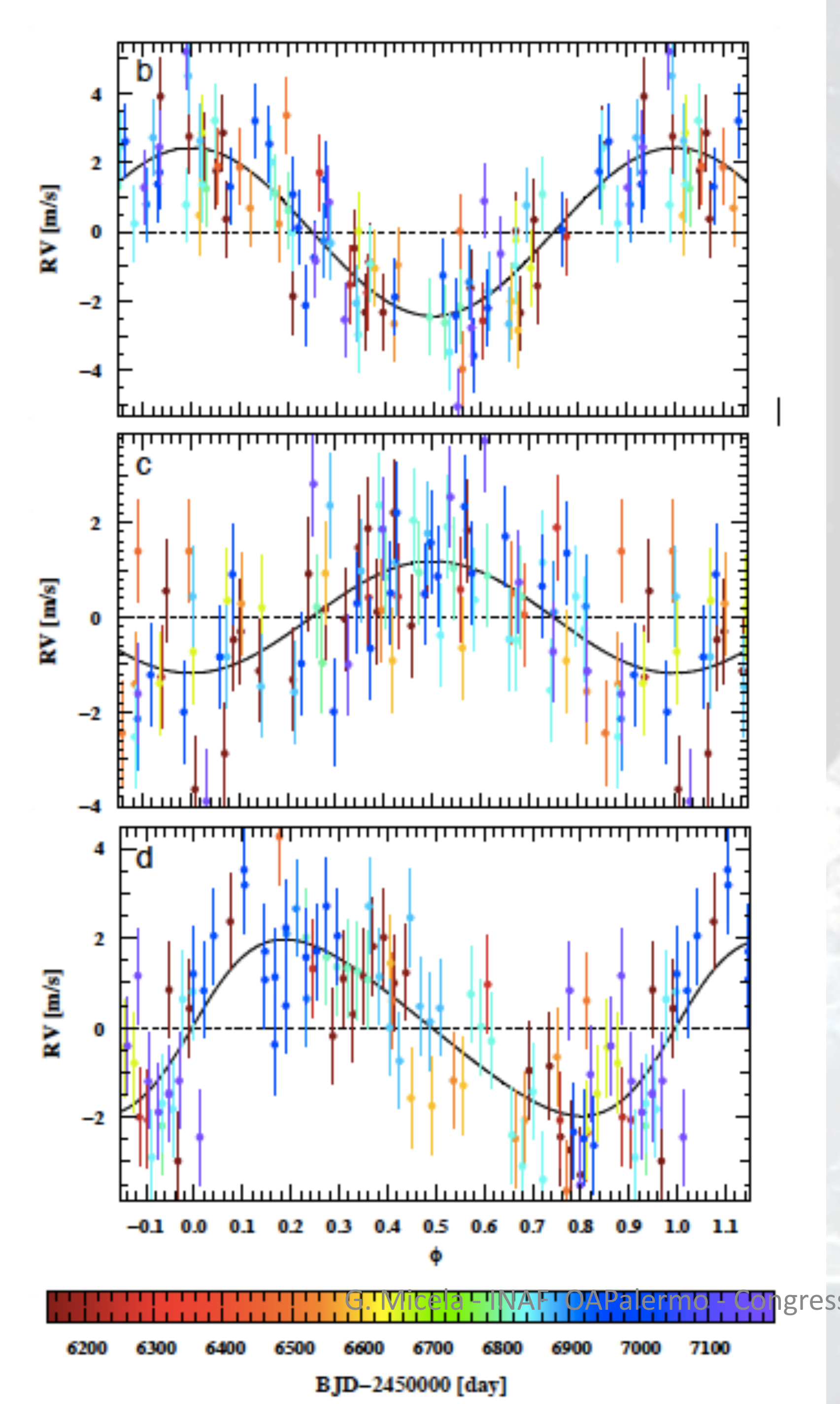
Phase-folded radial-velocity measurements with the Keplerian model (solid line)

0.46Mj, 0.052 AU

- fiberr-fed spectrograph with simultaneous thorium lamp in a parallel fibre calibration - *Mayor & Queloz 1995*
- spectrographs with absorption cells (iodine cell) *Marcy et al. 1995*

Both methods gave precision ~15 m s−1.

Double-fiber spectrograph was more efficient in terms of photon noise



HD219134:

a planetary system with 3-super-Earth and 1 sub-Saturn

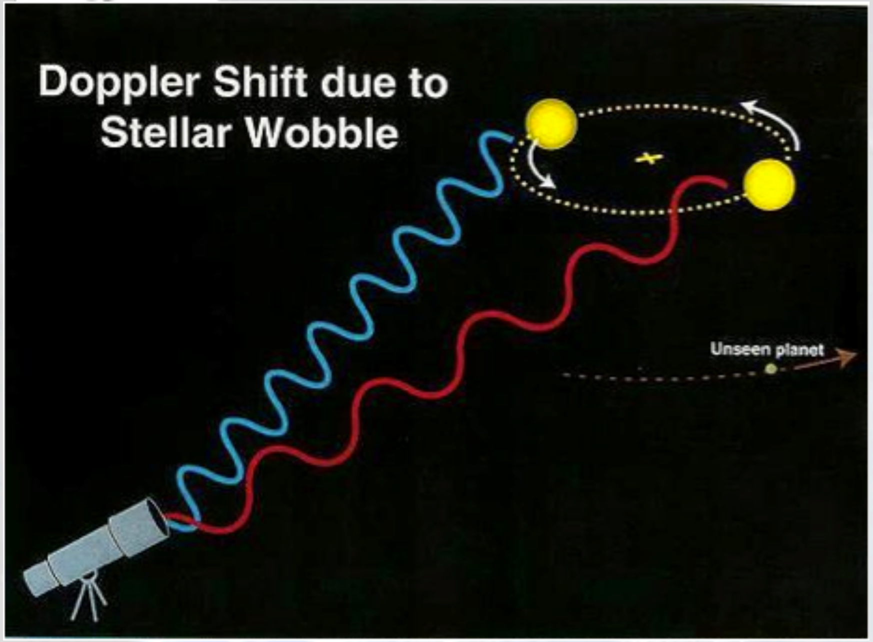
The star: K3, V=5.6, dist=6.5pc

Phase-folded radial-velocity measurements with the Keplerian model (solid line) for each of **the 3 inner super-Earths**, after removing the contribution of all the other planets in the system *(Motalebi et al. 2015 in press)*

From top to bottom:

Planet	Semi-axis(AU)	Mass (M_E)
b	0.038	4.46
c	0.064	2.67
d	0.234	8.67
e	2.14	62.

Effetto Doppler



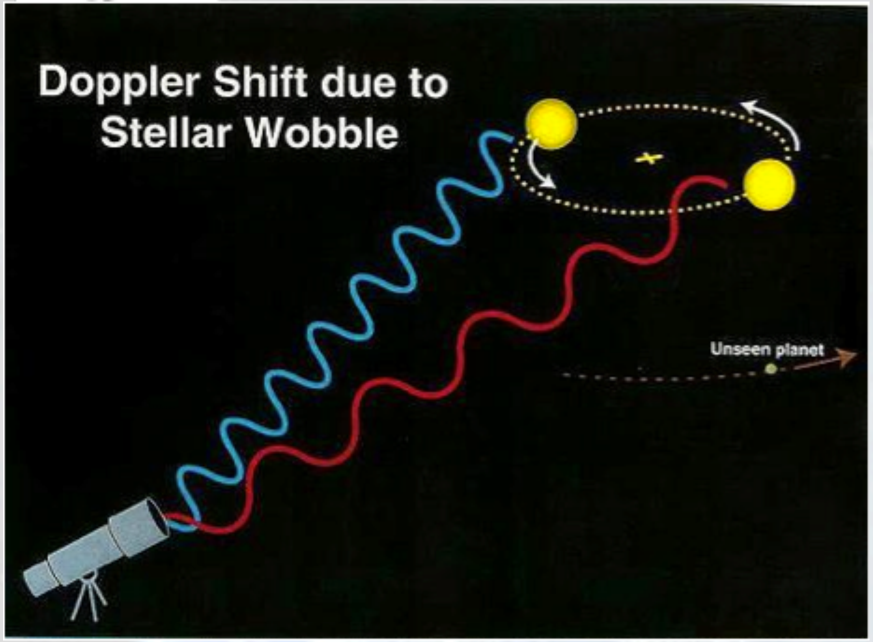
$$V_{star} = (M_{pl}/M_{star})\,(G\,M_{star}/Dist)^{1/2}$$

Planet Mass	Distance AU	Radial velocity
Jupiter	1	28.4 m/s
Jupiter	5	12.7 m/s
Neptune	0.1	4.8 m/s
Neptune	1	1.5 m/s
Super-Earth (5 M⊕)	0.1	1.4 m/s
Super-Earth (5 M⊕)	1	0.45 m/s
Earth	1	9 cm/s

For MK-type stars with planets in the habitable zone

Stellar Mass (M☉)	Planet Mass (M⊕)	Lum. (L0)	Type	RHAB. (AU)	RV (cm/s)	Period (days)
0.10	1.0	8e-4	M8	0.028	168	6
0.21	1.0	7.9e-3	M5	0.089	65	21
0.47	1.0	6.3e-2	M0	0.25	26	67
0.65	1.0	1.6e-1	K5	0.40	18	115
0.78	2.0	4.0e-1	K0	0.63	25	209

Effetto Doppler



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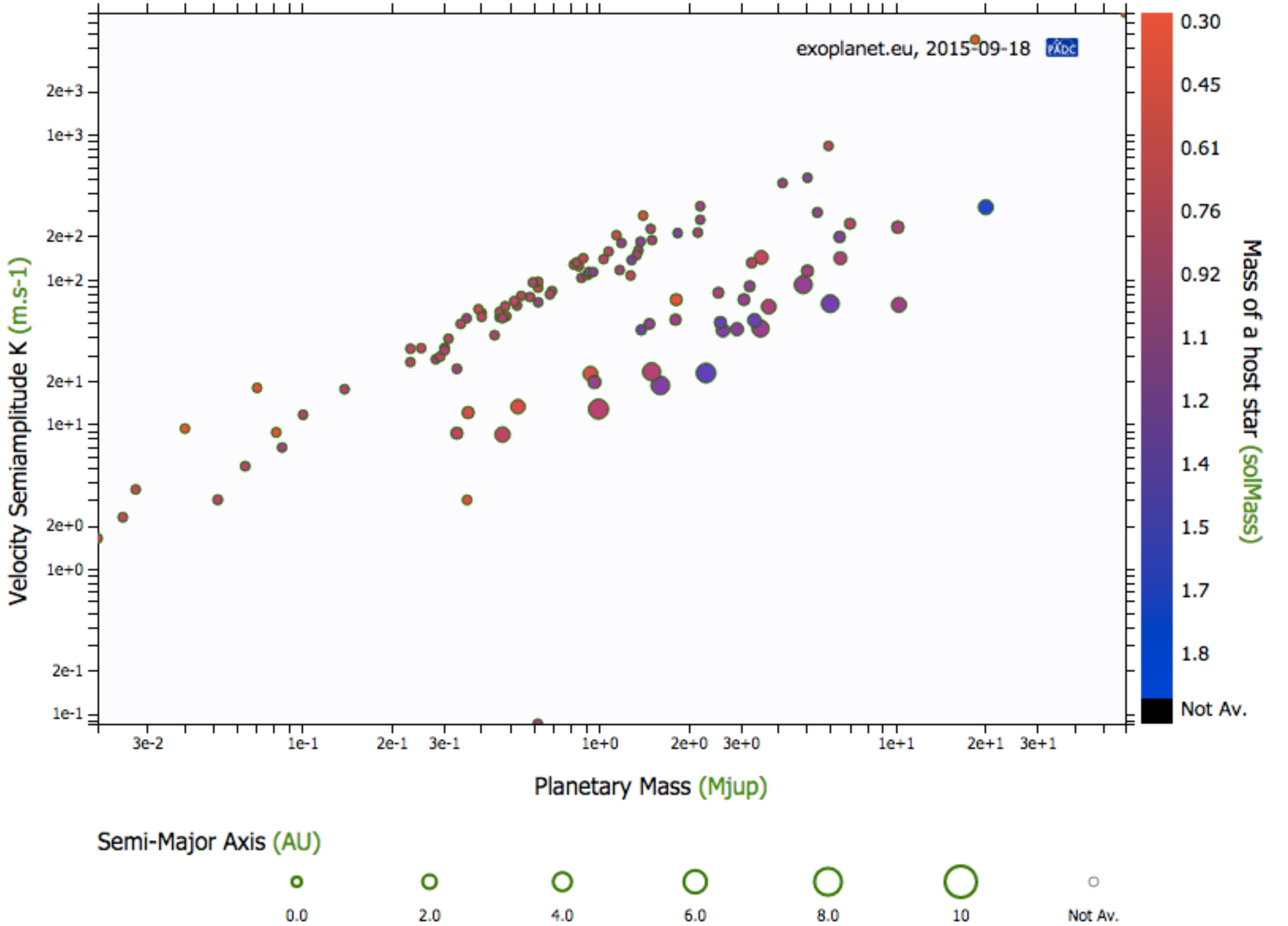
@1 m/s → $v/c \approx \Delta\lambda/\lambda \approx 3 \cdot 10^{-8}$

$R = \lambda/\Delta\lambda = 10^5$ + thousands of lines


exoplanet.eu, 2015-09-18
Velocity Semiamplitude K (m.s-1)
2e+3
1e+3
2e+2
1e+2
2e+1
1e+1
2e+0
1e+0
2e-1
1e-1
3e-2
1e-1
2e-1
3e-1
1e+0
2e+0
3e+0
1e+1
2e+1
3e+1
Planetary Mass (Mjup)
0.30
0.45
0.61
0.76
0.92
1.1
1.2
1.4
1.5
1.7
1.8
Not Av.
Mass of a host star (solMass)
Semi-Major Axis (AU)
0.0
2.0
4.0
6.0
8.0
10
Not Av.

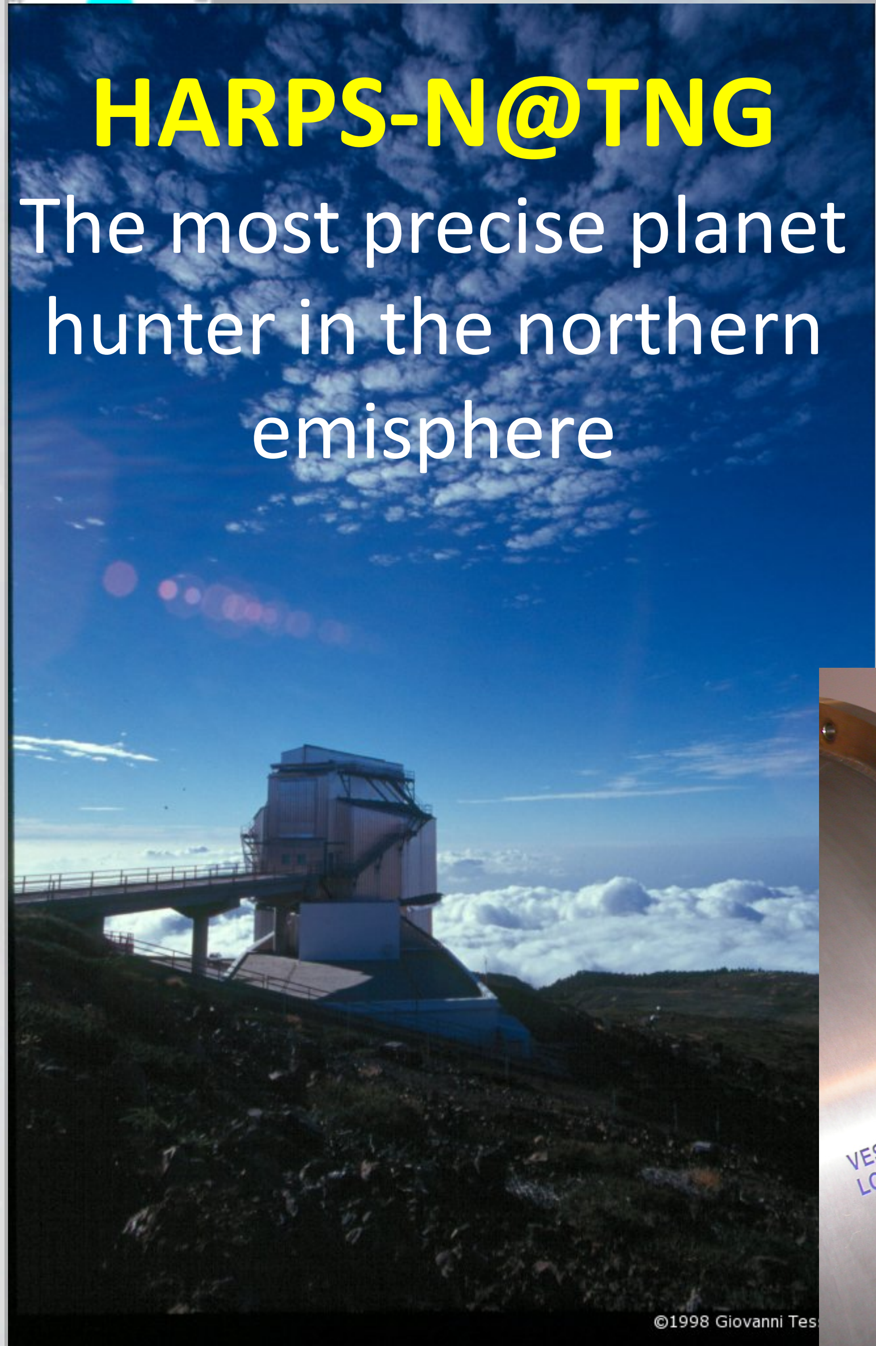
HARPS-N@TNG

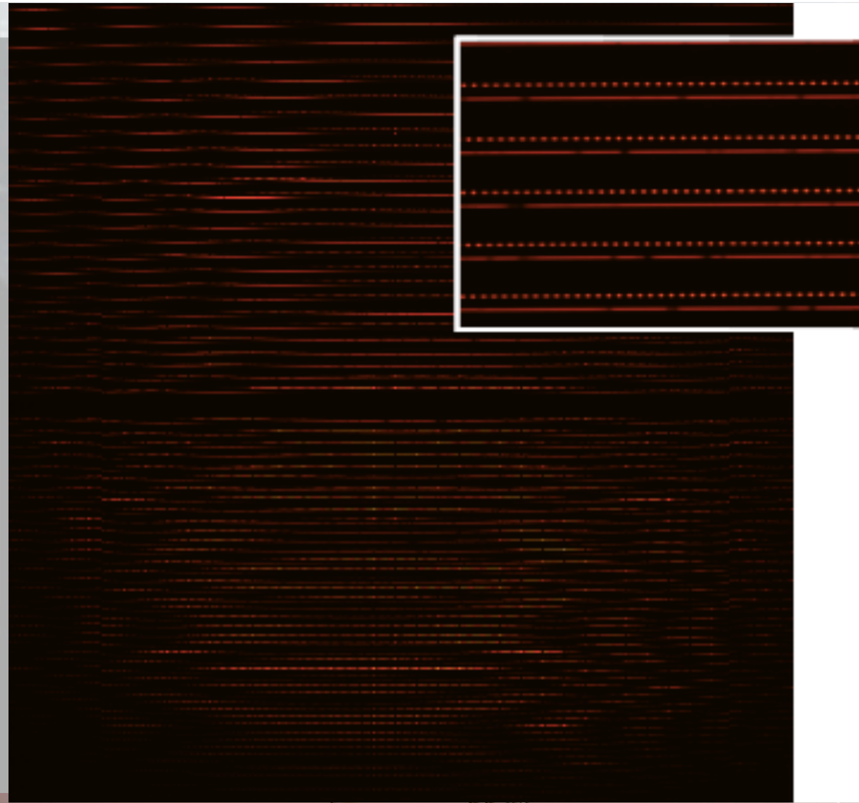
Italy, Swiss, US, UK

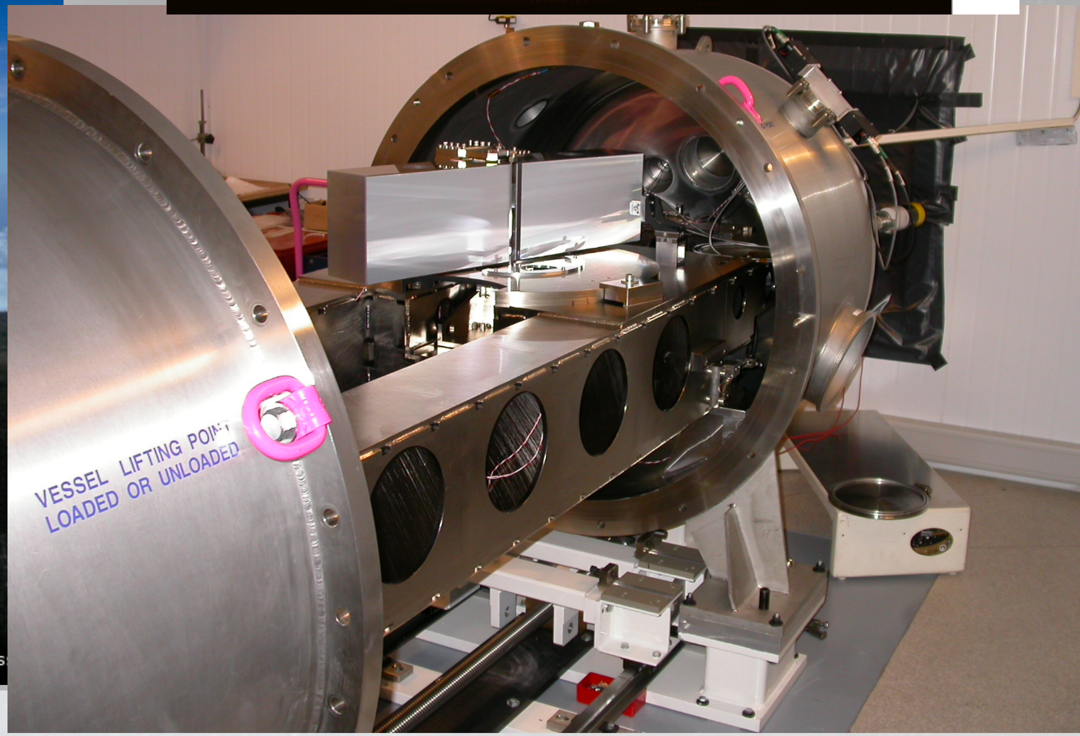
- Spectrograph type Fiber fed, *cross-dispersed echelle spectrograph*
- R = 115’000
- Wavelength range 383 nm - 690 nm
- Calibration ThAr
- Vacuum operation - 0.001 K temperature stability
- Observational efficiency SNR = 50 per extracted pixel on a Mv=8, Texp = 60 sec

HARPS-N@TNG

The most precise planet hunter in the northern emisphere

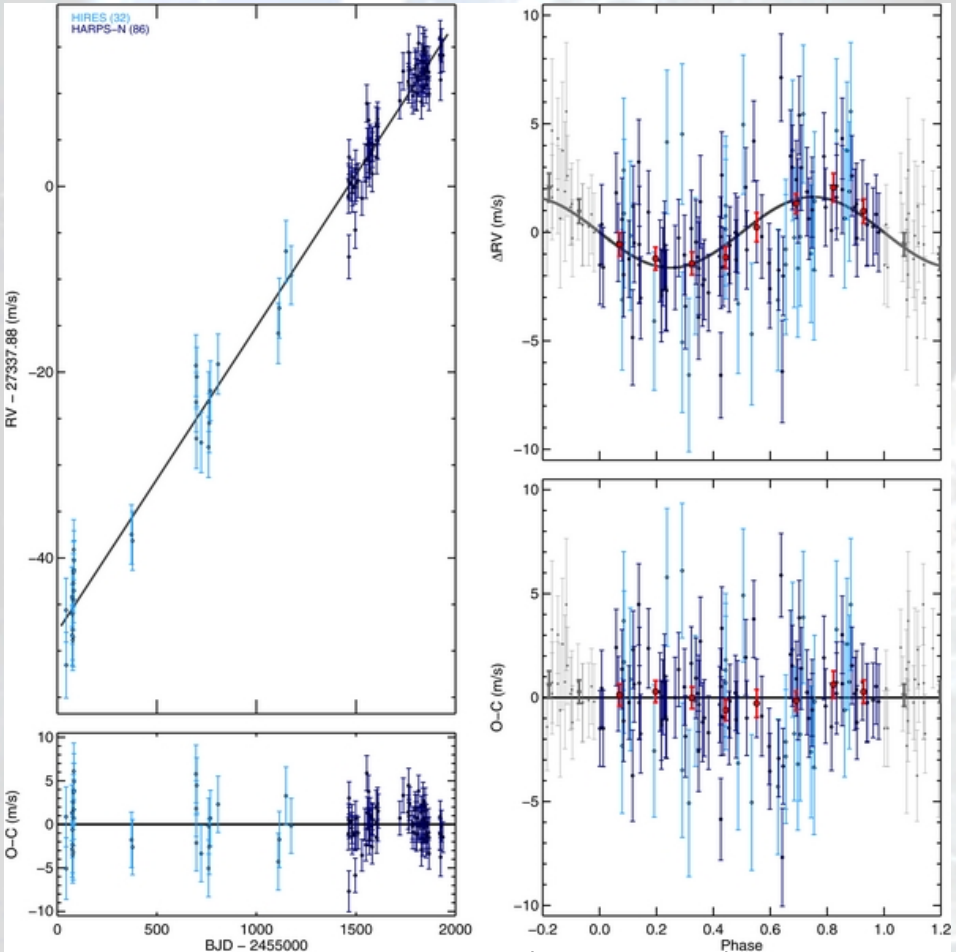






Some results: Kepler 93

A long period + transiting planet: mass determination



- Best-fit and HIRES (light blue) and HARPS-N (dark blue) RVs .
- Long period + short period planets *(Dressing et al. 2015)*

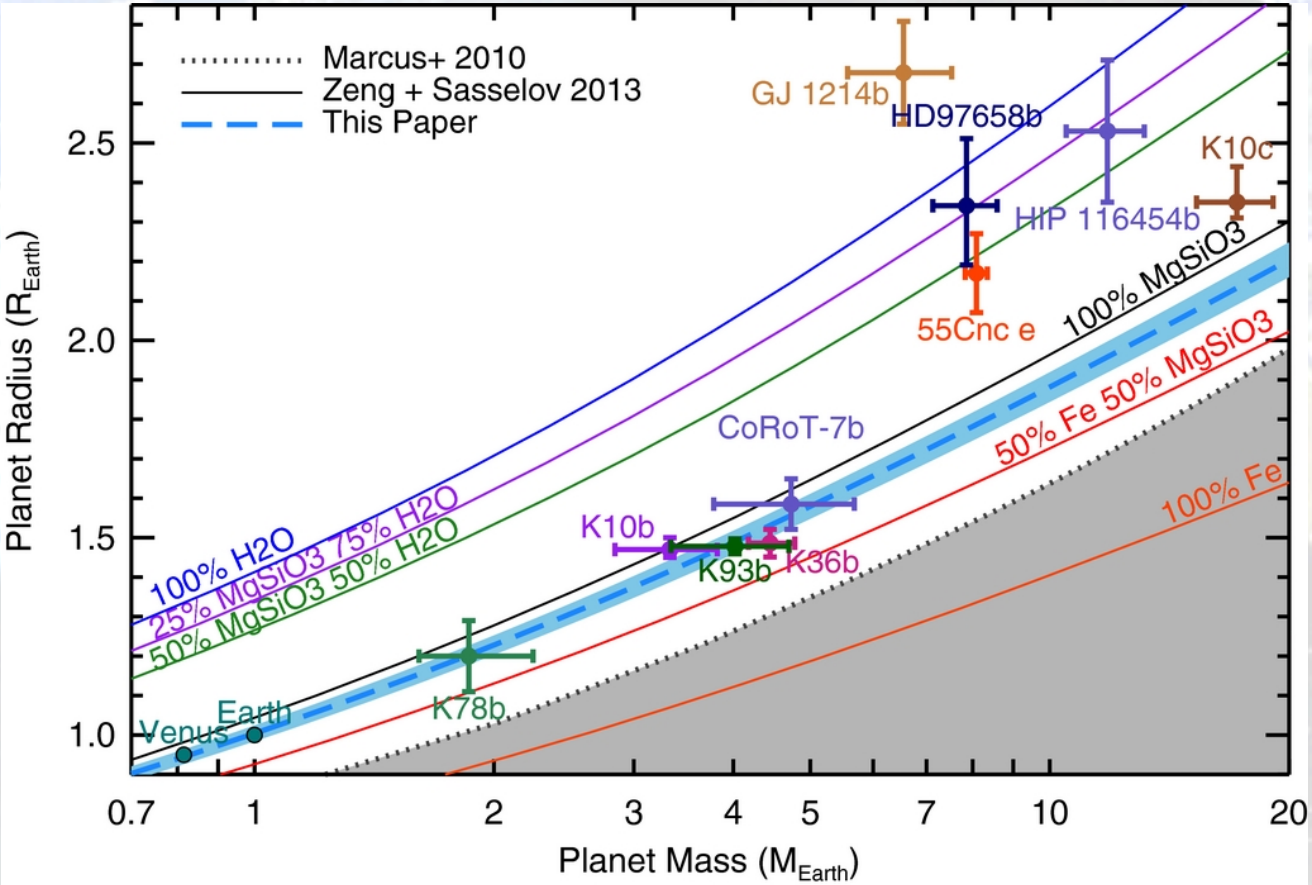
Kepler-93 G bright star

Planetary parameters

Rp($R_\oplus$)	1.478 ± 0.019
Mp($M_\oplus$)	4.02 ± 0.68
ρ(g cm^{-3})	6.88 ± 1.18
a (AU)	0.053 ± 0.002
Teq (K)	1037 ± 134

Some results: Kepler 93b

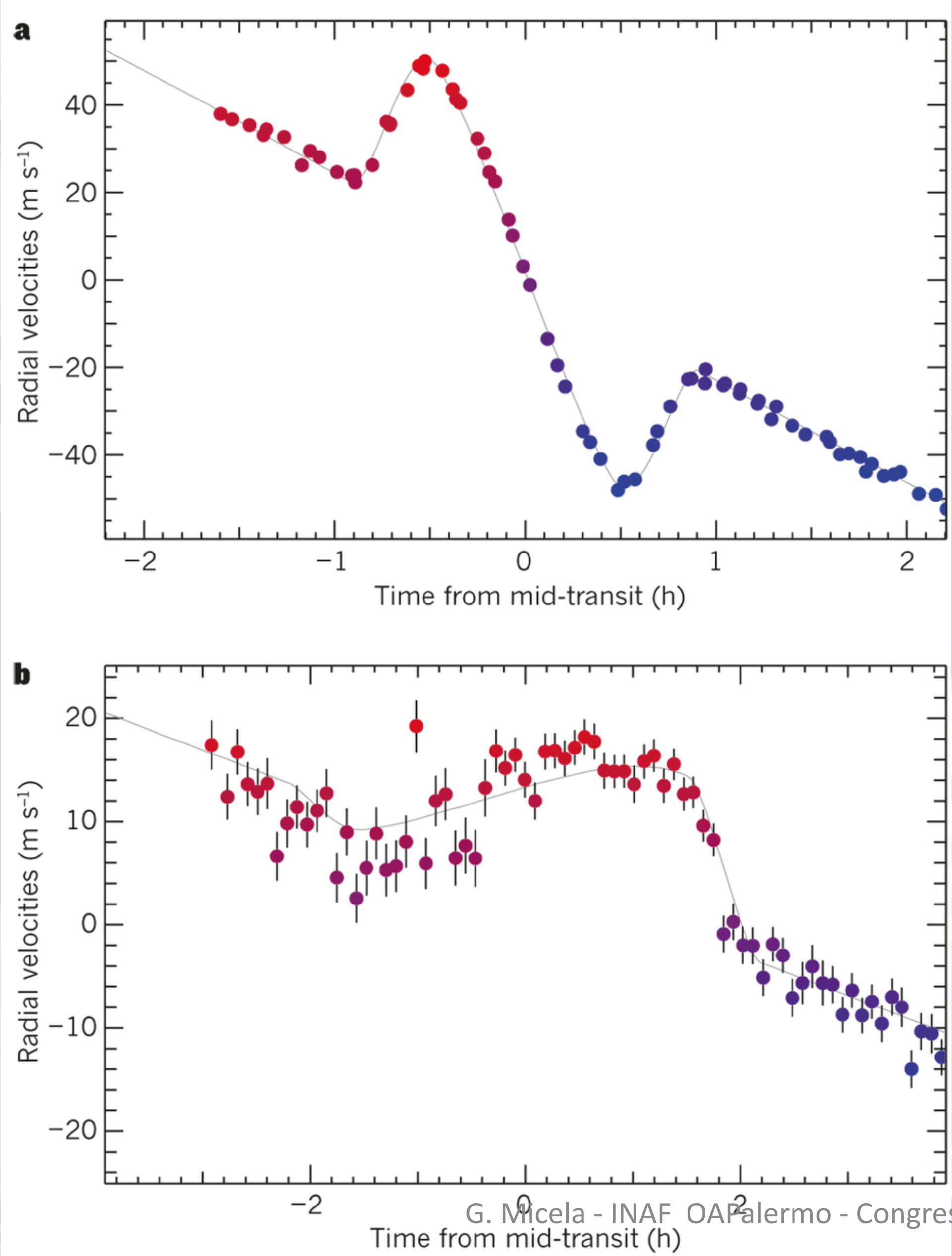
a rocky hot superEarth



Dressing et al. 2015

Rossiter effect

(mis)alignement spin-orbit



Selective occultation of approaching and receeding parts of the rotating stellar disk by the planet during transit

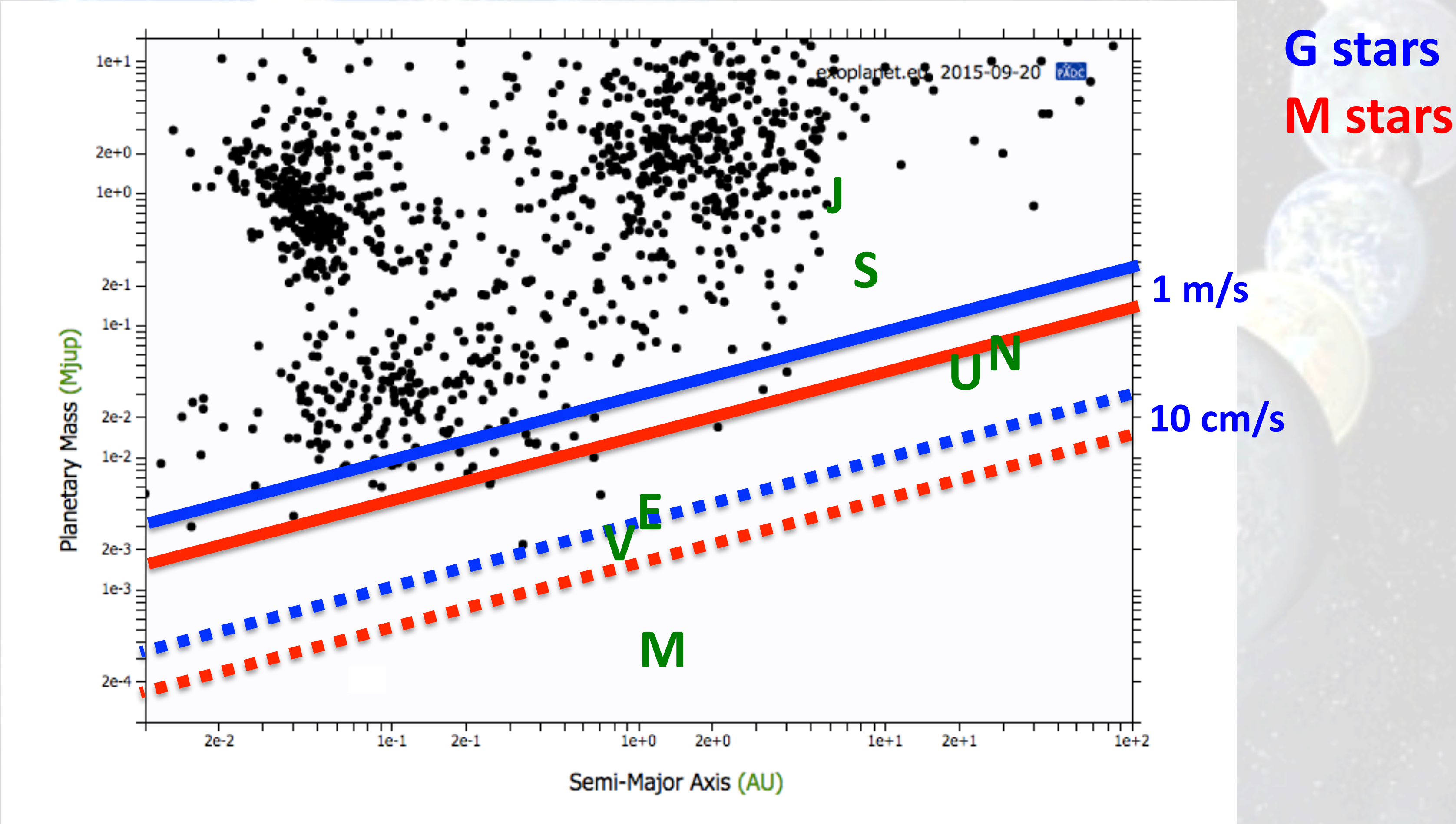
Top: HD 189733A b

a symmetric RM effect, signature of an aligned and prograde star–planet system. *Triaud et al. 2009*

Bottom: WASP-8A

a clearly asymmetric RM effect caused by a planet on a retrograde and strongly misaligned orbit with respect to the stellar rotation axis. *Queloz et al. 2010*

Planetary mass sensitivity



Limiting factors

Two main factors – two different solutions

- **Stability → More accurate wavelength calibration**
- **Photons → Larger telescopes**

Stability

- A single line of the **Th-Ar calibration lamps**, normally used, has an intrinsic precision of tens of m/s.
- with ~10,000 lines we may achieve 1 m/s

A **Laser comb (astrocombs)** improves

- the precision of the position of single lines
- the number of lines
- the omogeneity of lines in the spectral orders

→ precision of **few cm/s** - important for bright stars

Astrocomb for HARPS-N@TNG

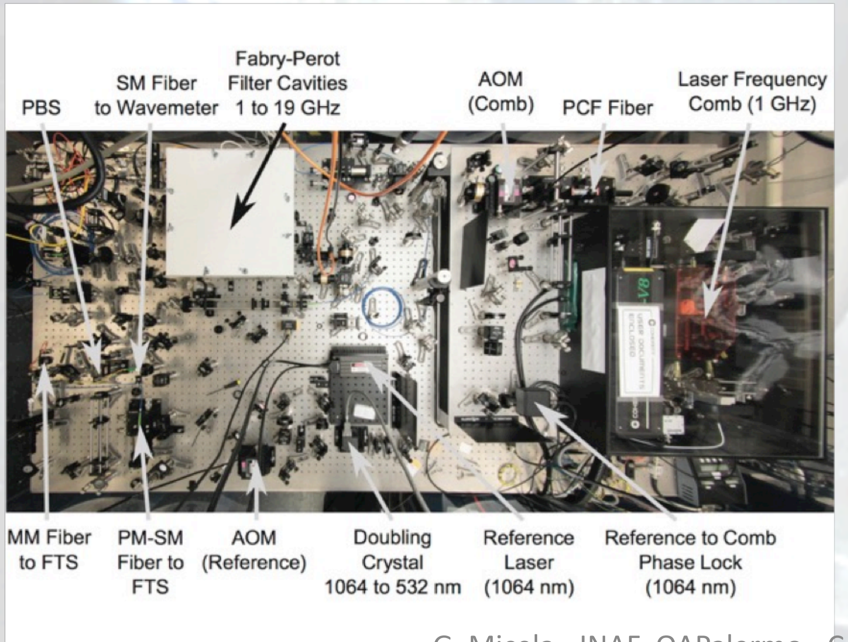
in collaboration with Center for Astrophysics (CFA), funded by NSF (USA) and WOW (progetto premiale MIUR)

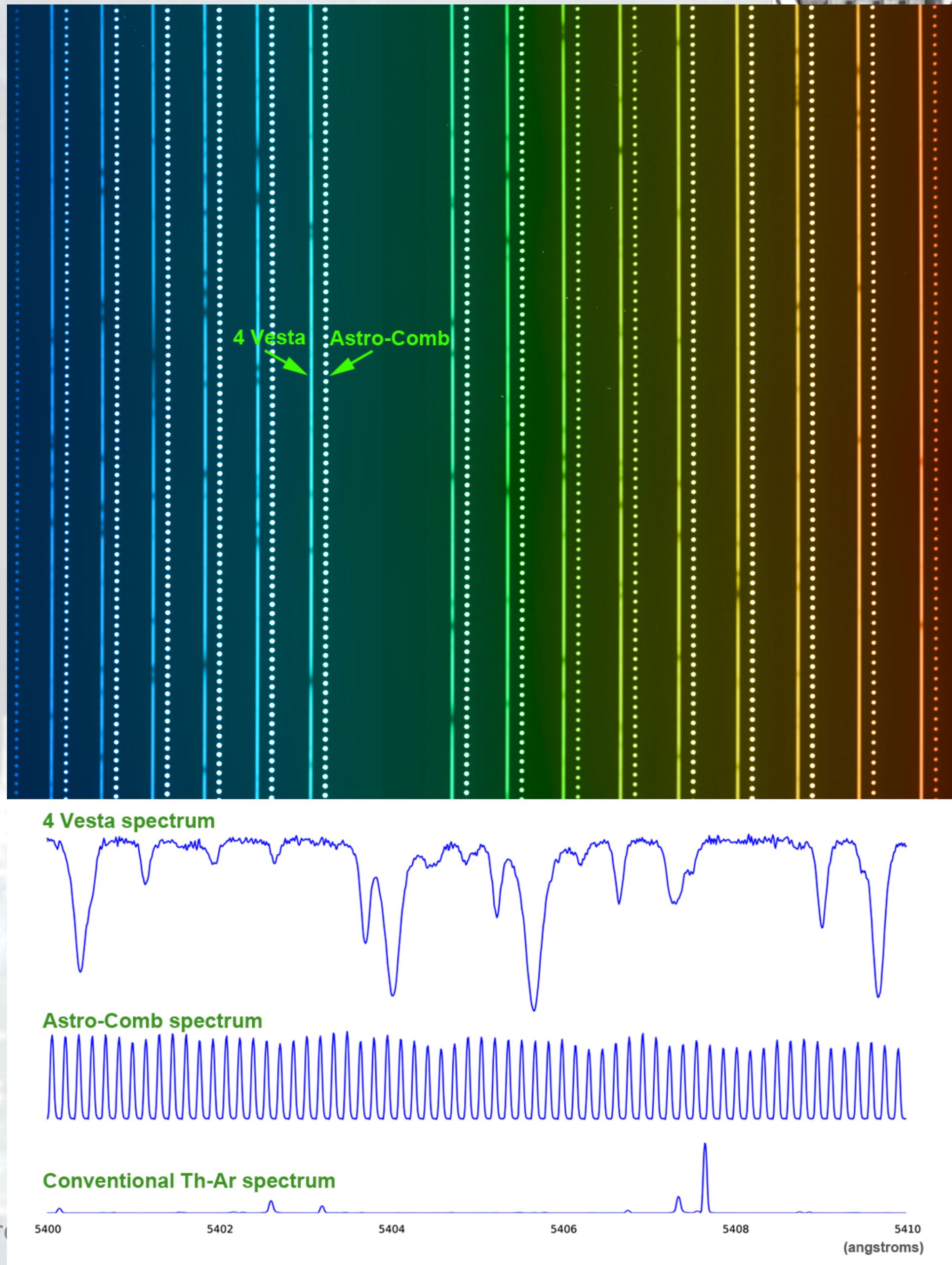
- Frequency laser (LFC) to produce a "comb" full of lines, with delta function shape, evenly distributed in frequency, with a standard atomic frequency as reference
- A highly non-linear photon crystal fibre to shift the radiation from NIR to the band of interest
- A Fabry-Perot cavity to make compatible the Laser comb and the spectrograph resolutions

Astrocomb HARPS-N@TNG

Solar spectrum reflected by Vesta

Below: an order compared with the lines of the Astrocomb and of Lamp





Astrocomb for HARPS-N@TNG

still to do

- **Automation**

  in order to use the Astrocomb as a routine calibrator

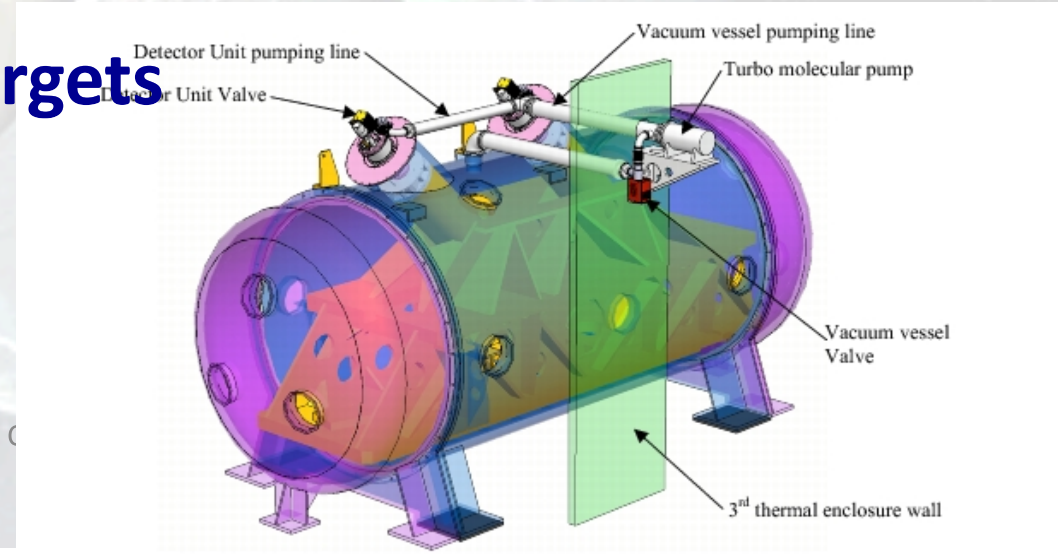
- **Extension of the wavelength band**

  From the today ~100 nm, to the entire HARPS-N spectrum: 383 to 693 nm

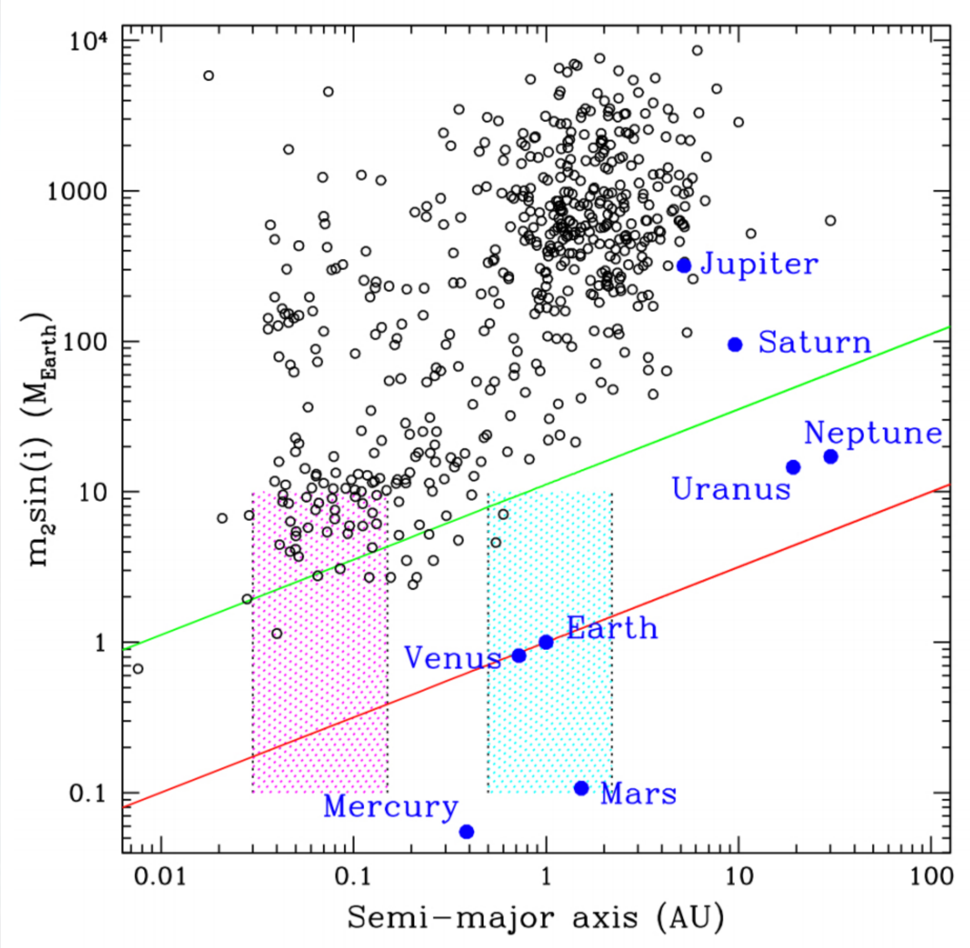
Increase photons

ESPRESSO@VLT: an ESO project

- A fiber-fed, cross-dispersed, high resolution echelle spectrograph (R=120,000) – INAF contribution
- @VLT First light on telescope **2016**
- Few cm/sec → rocky planets around solar type stars
- **Few well selected targets**



ESPRESSO@VLT



- Red line: 10 cm/s curve for planets orbiting a 0.8 $M_\odot$ star (ESPRESSO limit)
- Green line: 1m/s curve for planets orbiting a 1 $M_\odot$ star
- Blue and pink areas: habitable zones of stars of 0.8-1.2 $M_\odot$, and 0.2-0.3$M_\odot$, respectively.

Pepe et al. 2014

Not only detections!

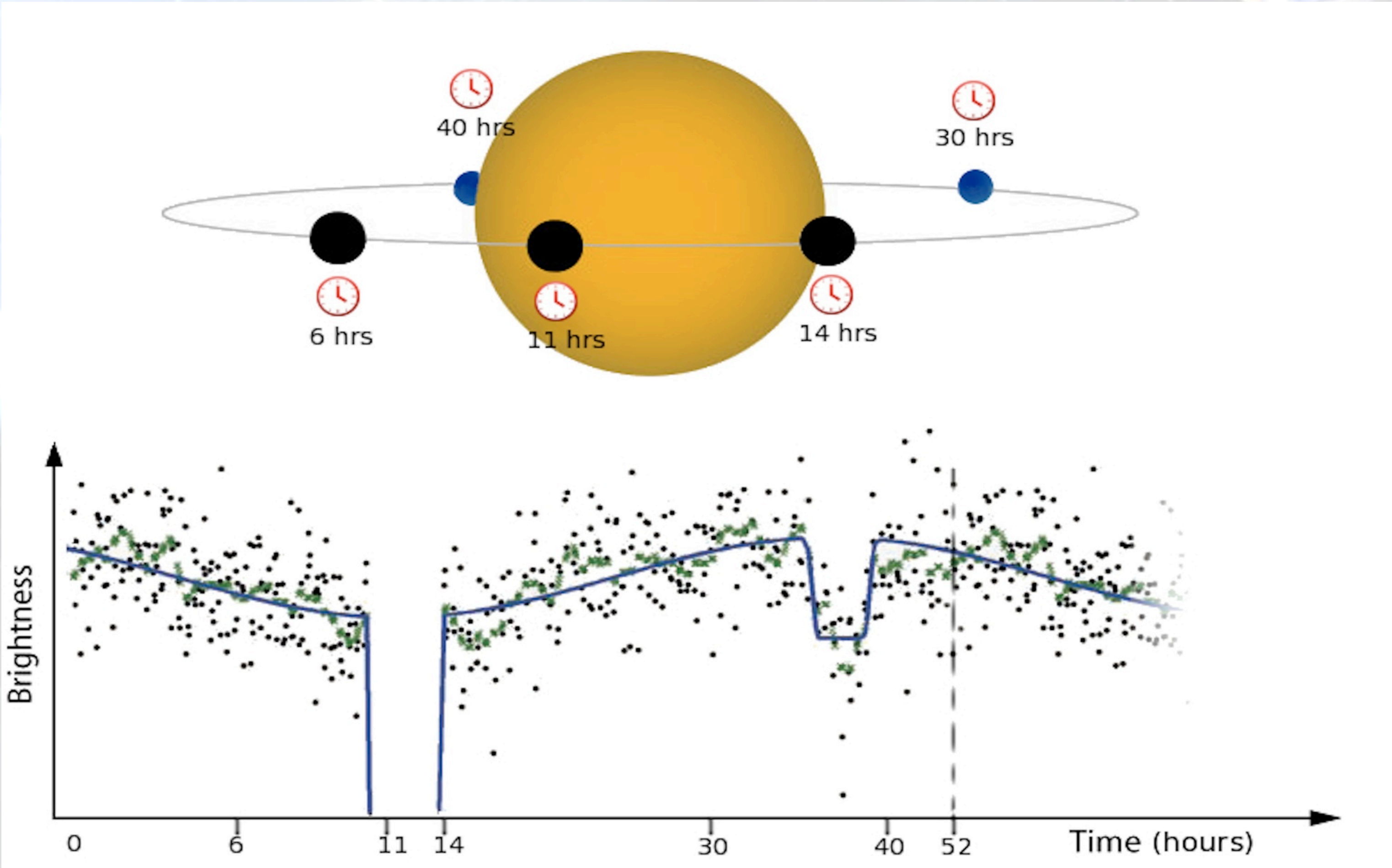
Exo-planetary atmospheres

understanding the effective temperature, composition, and presence of possible biosignatures in the atmospheres of exoplanets.

- Mass and density do not determine the atmosphere properties
- Atmospheres evolve

Transit & eclipse spectroscopy

Aiming at ~10^{-4} stellar flux at multiple wavelengths
through stable instrument, external calibration & postprocessing analysis

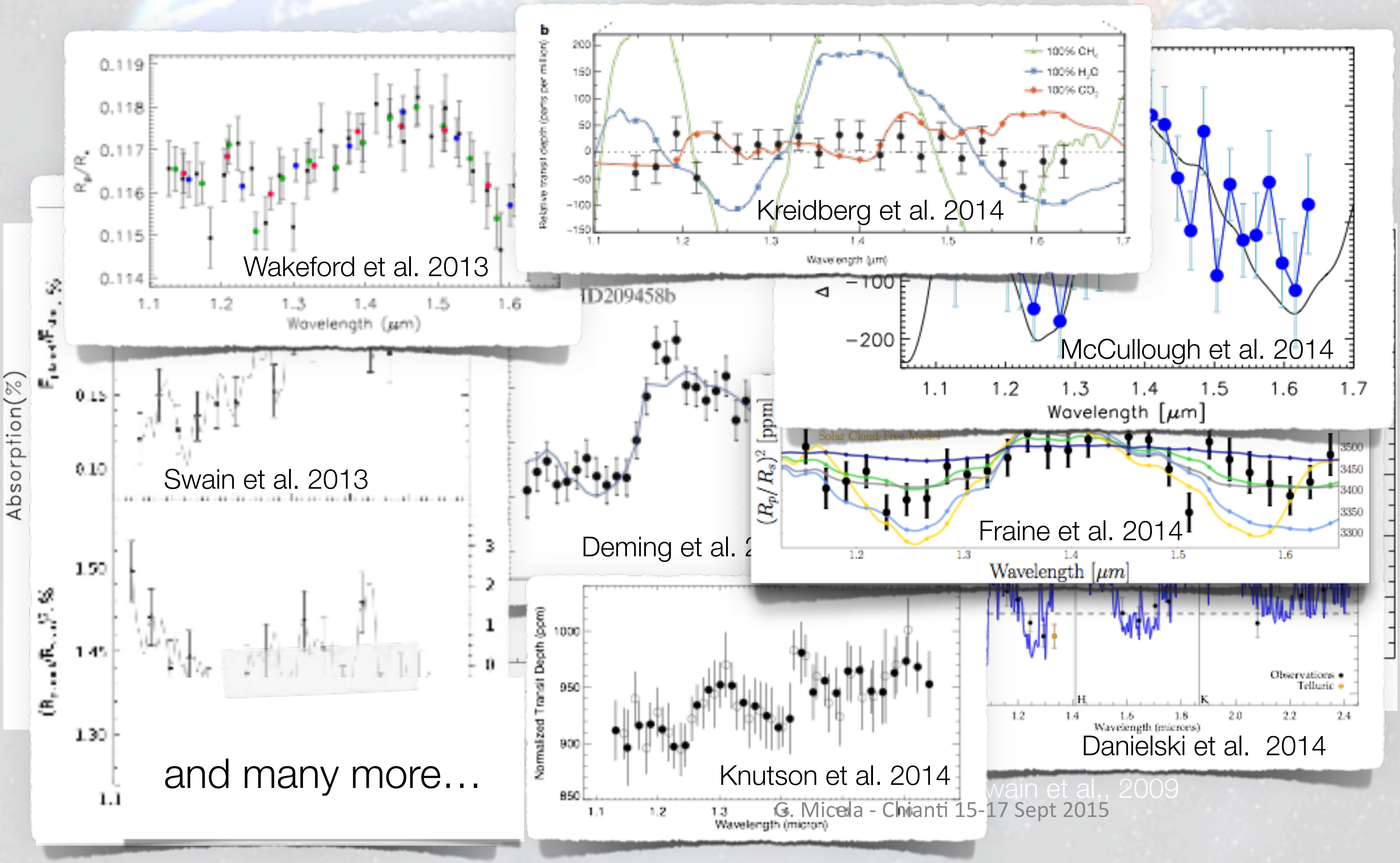


- Day side spectra - eclipse
  - Reflected radiaton - ~ Visible -NIR
  - Thermal emission - IR

  T < 1200K – Reflected emission > Thermal emission
    1. Albedo
    2. T-p profile
    3. Chemistry

- Night side spectra – primary transit
  - Transmitted spectrum - IR
    1. ~Upper atmosphere
    2. Chemical composition
    3. ~Temperature

Exo-atmospheres
with current telescopes



Diversity is the rule:

difficult to derive univocally physical parameters

- Planetary spectra are still too poor – low signal – low resolution
- Signal dominated by the star
- Instrument systematics
- Problems with our atmosphere

- **Space** – no atmosphere, no night-days, entire IR band observable → low spectral resolution, large simultaneous band
- **Ground** – high stability, large mirrors → high spectral resolution

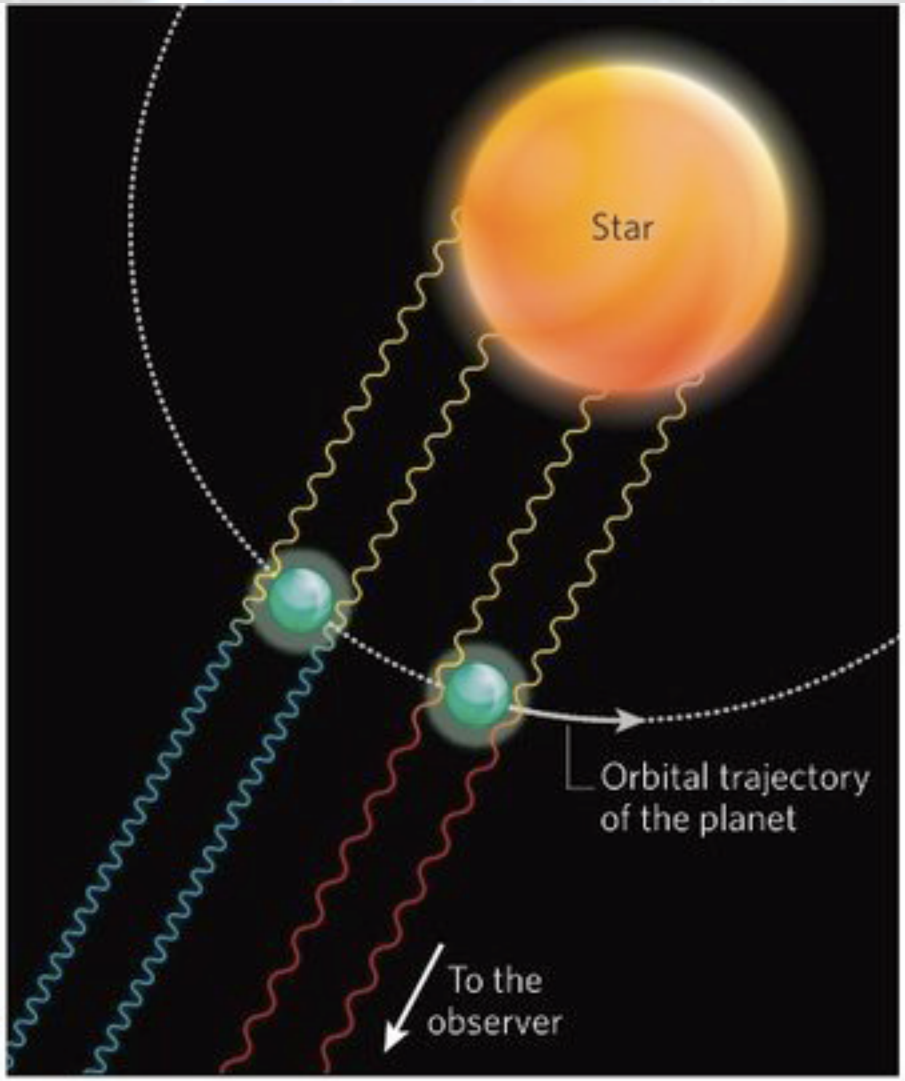
Challenges for ground-based observations of planetary atmospheres

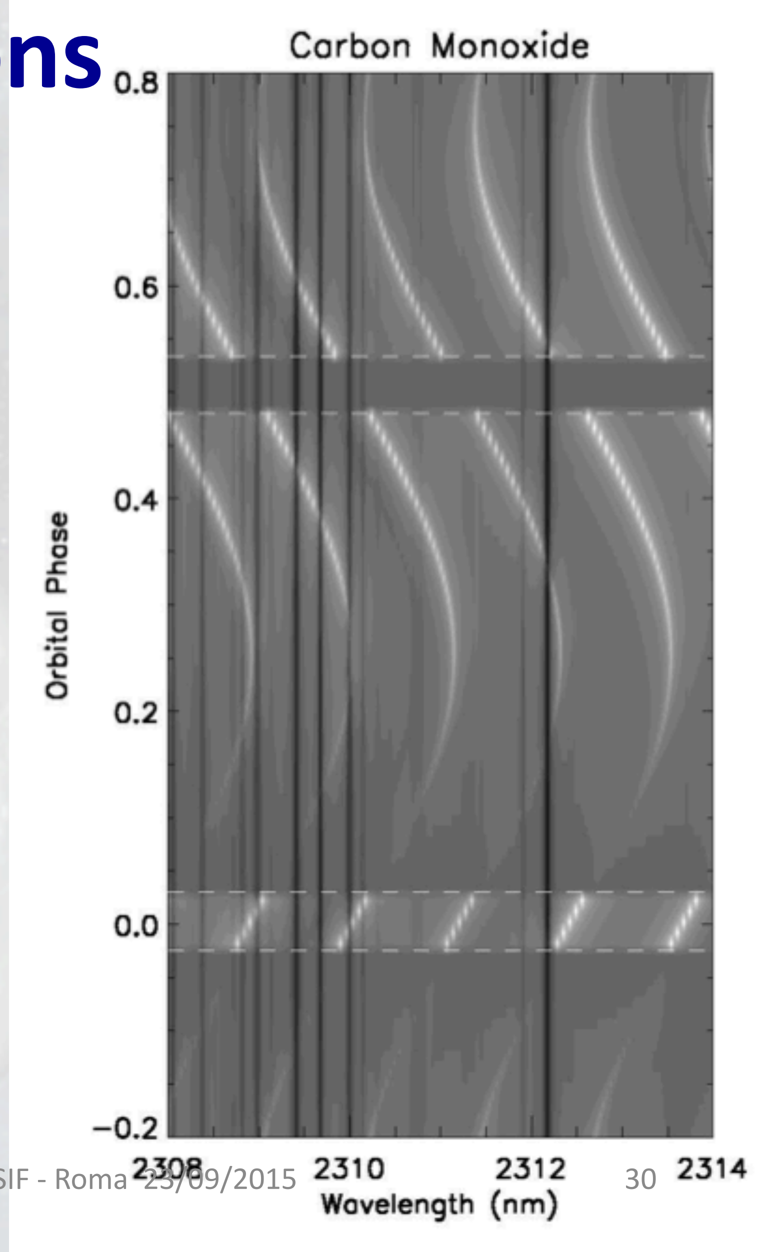
- Measure <10^{-3-4} variations in flux as function of λ over 1-5 hour time scales
- **Earth Atmosphere:**
  - Variations in turbulence / seeing
  - Variations in absorption & scattering
  - Variations in thermal sky emission
- **Instrumental:**
  - Variations in gravity vector or field rotation
  - Variations in thermal behaviour

Strategy for Ground-based Observations

- **High-Dispersion Spectroscopy** ($\lambda/\Delta\lambda \geq 100{,}000$)
  - Molecular Bands are resolved in tens of individual lines
  - Strong Doppler effects due to orbital motion of the planet (up to >150 km/sec)
  - Moving planet lines can be distinguished from stationary telluric & stellar lines

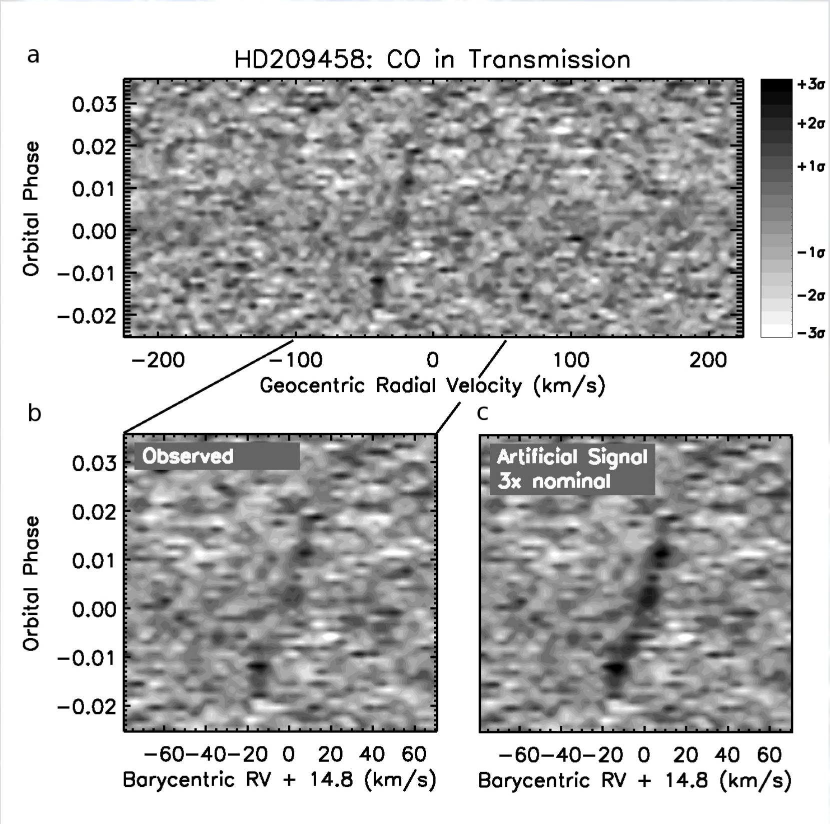
Strategy for Ground-based Observations





Some pilot experiments: CRIRES@VLT

- CO in transmission in HD209458b (CRIRES@VLT) *(Snellen et al. Nature 2010)*

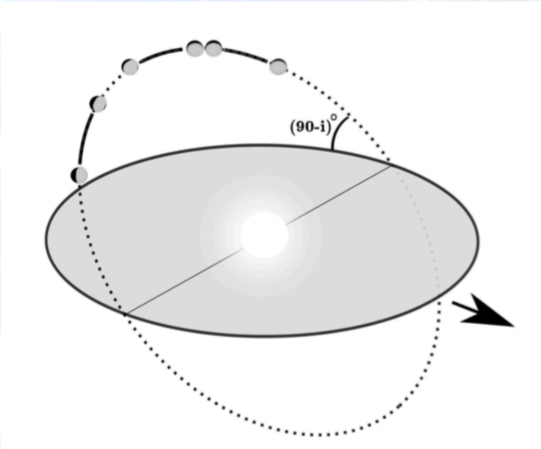


- Reveals planet orbital velocity
- Solves for masses of both planet and star (model independent)
- Evidence for blueshift - high altitude winds? - marginal 2σ suggestion

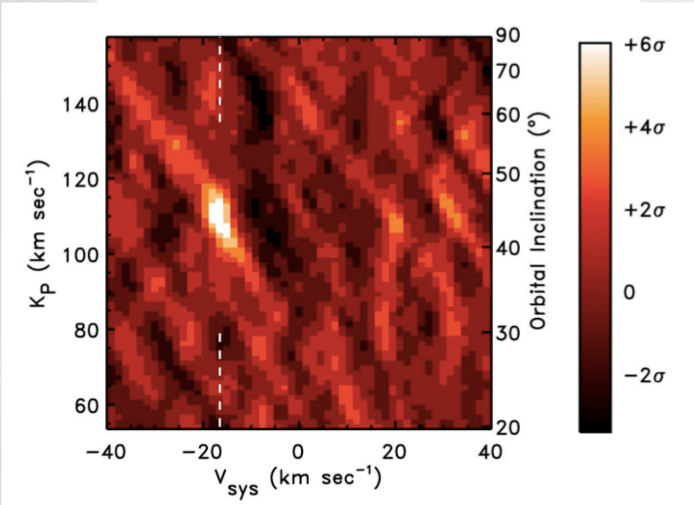
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

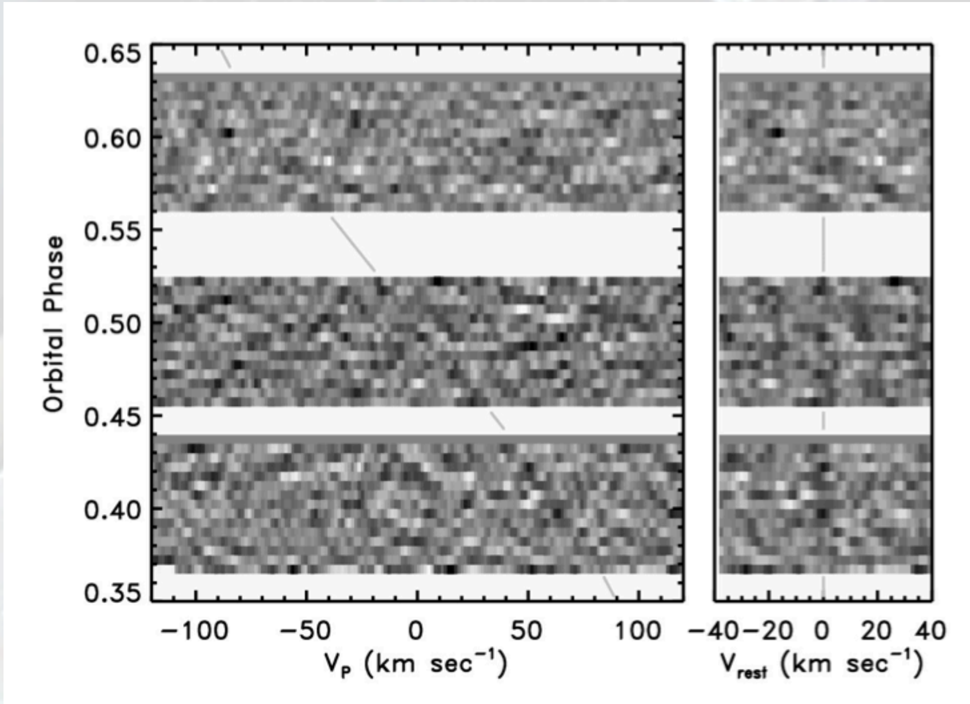
(Brogi et al. Nature 2012 – see also Rodler et al. 2012)

•

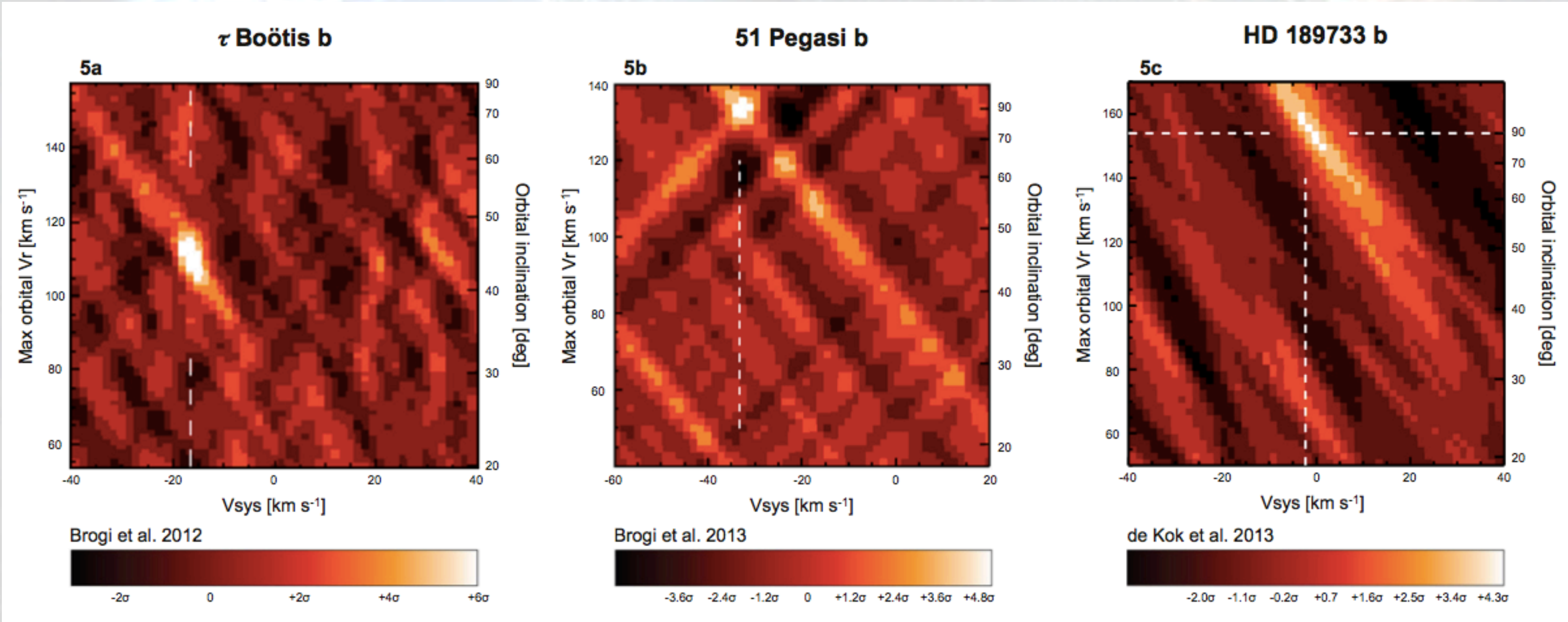


First detection of non-transiting planet! inclination, mass





CO in dayside spectra of hot Jupiters



CRIRES@VLT Upgrade! 6x larger wavelength coverage

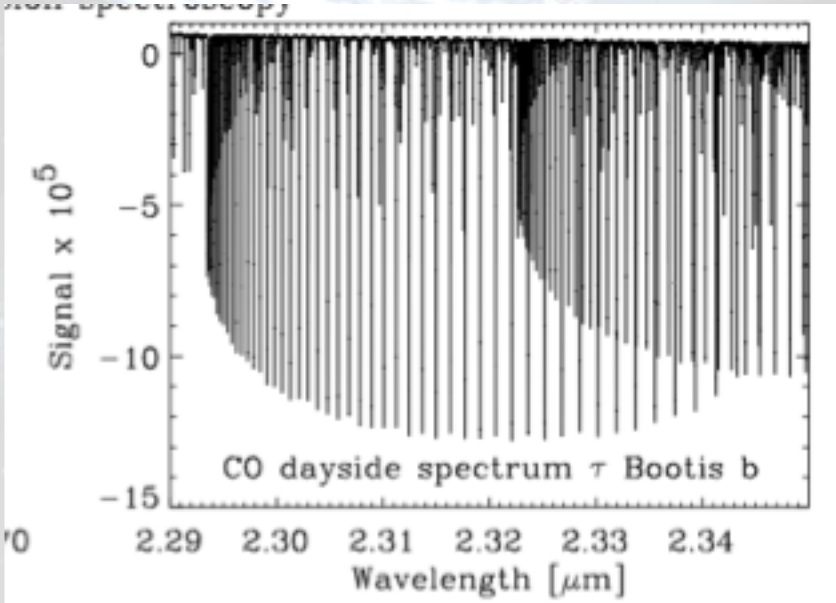
CO, H_2O, CH_4, NH_3, H_3+,…..

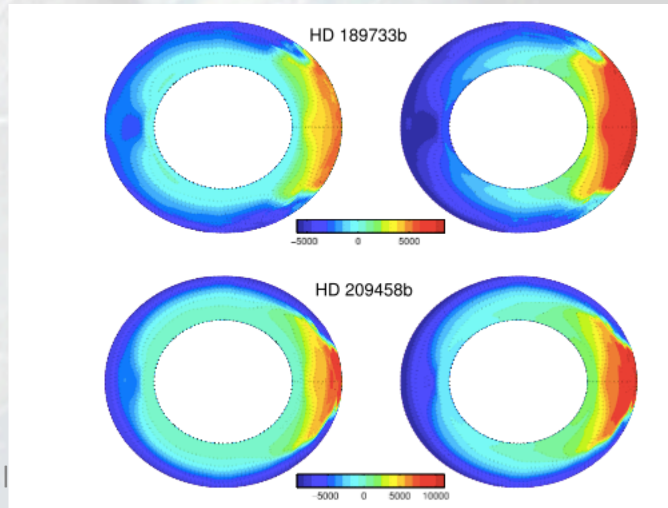
VLT ESPRESSO (Optical ! TiO, VO, FeH...)

HIRES@E-ELT : *High resolution spectroscopy (PI: A. Marconi)*

ELT: 39 m Large Area!

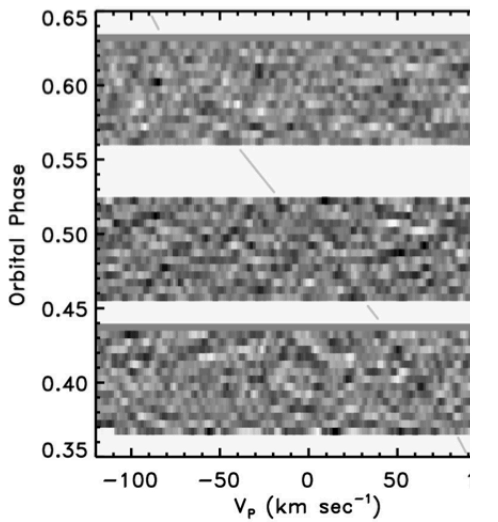
- Orbital inclinations and masses of >100 non-transiting planets
- Detection of the individual lines (instead of cross-correlation)
- T/P profile; unambigous detections of inversion layers
- Line broadening ! planet rotation and circulation

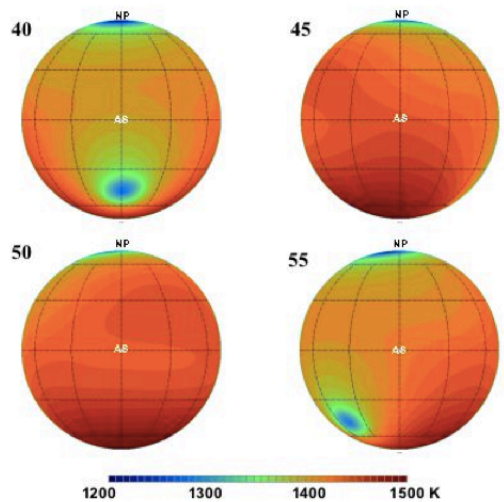


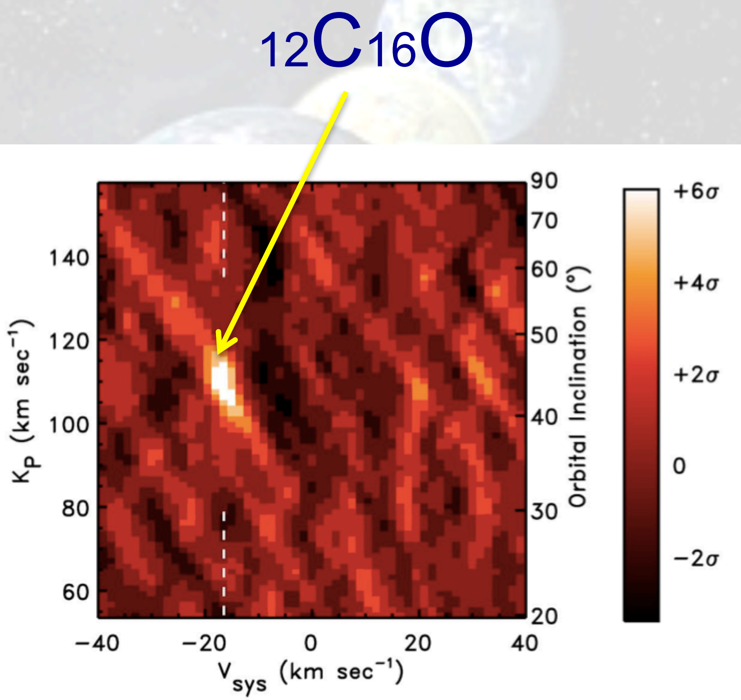


HIRES@E-ELT : *High resolution spectroscopy (PI: A. Marconi)*

- Molecular spectra (CO, CO_2, H_2O, CH_4) as function of orbital phase → photochemistry, T/P vs. longitude
- Evolution of planetary atmospheres

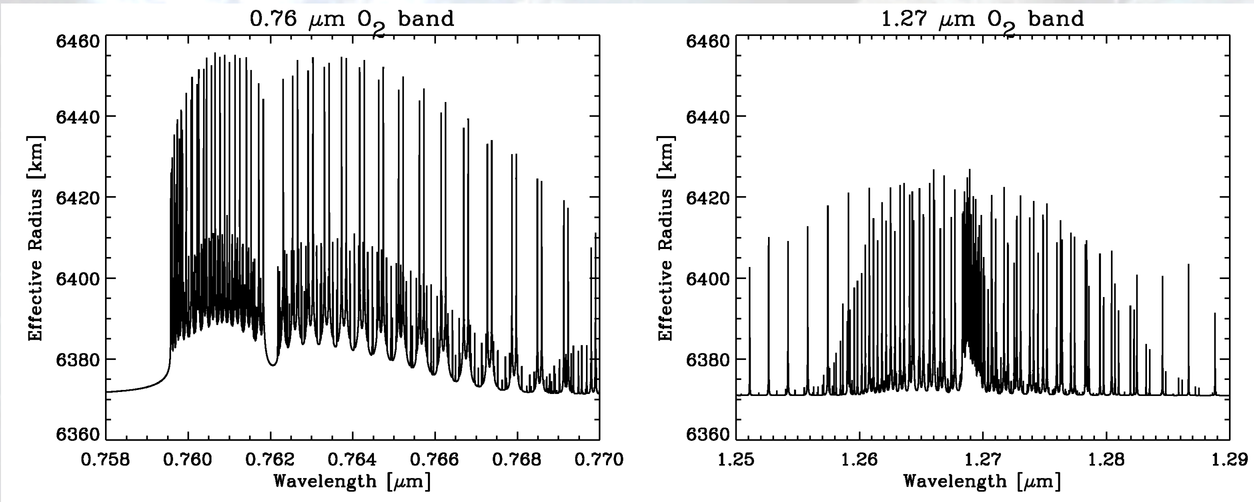




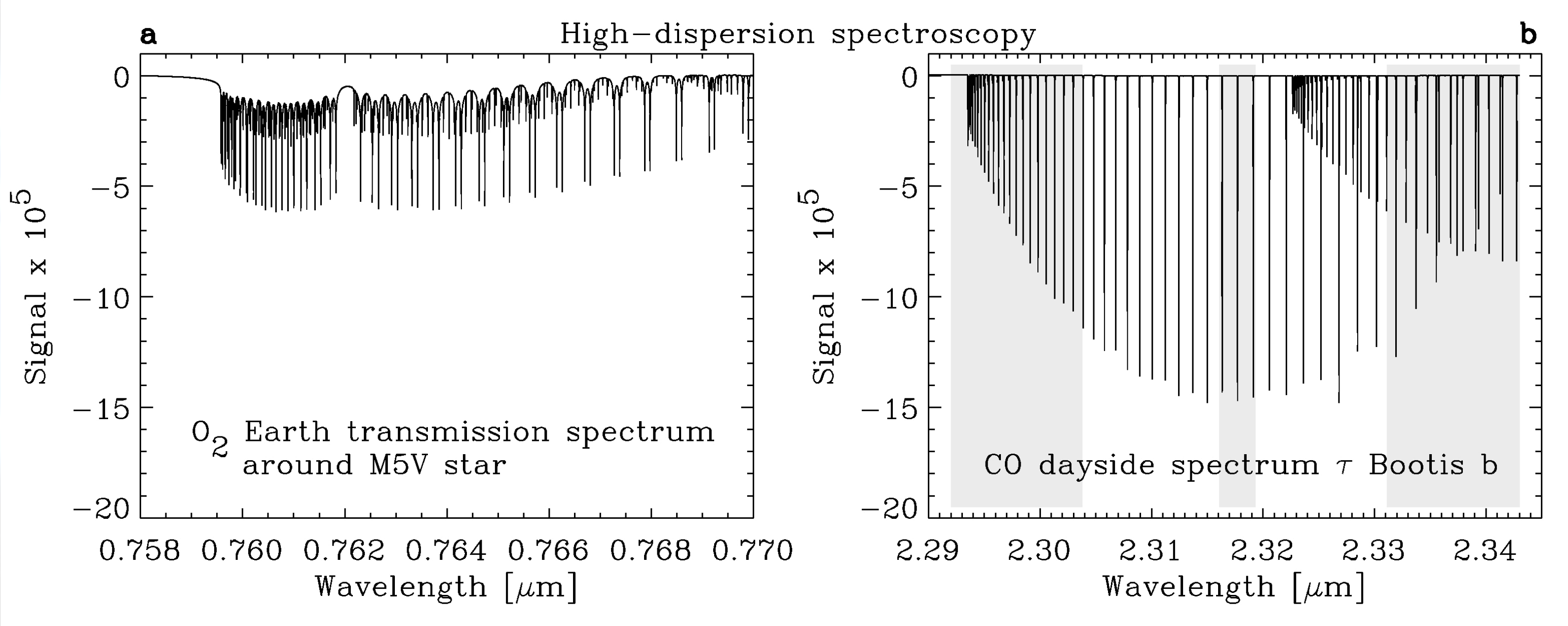


HIRES@E-ELT : *High resolution spectroscopy (PI: A. Marconi)*

- The most ambitious ELT Science Case:
- Characterizing twin-Earths
  - O_2 in transmission is possible!



Extremely Large Telescopes



Stellar type	R_* [R_{sun}]	M_* [M_{sun}]	a_{HZ} [au]	Prob [%]	P_{HZ} [days]	Dur. [hrs]	I (η_e=1) [mag]	Line Contrast	SNR σ
G0-G5	1.00	1.00	1.000	0.47	365.3	13	4.4 - 6.1	2×10^{-6}	1.1-2.5
M0-M2	0.49	0.49	0.203	1.12	47.7	4.1	7.3 - 9.1	8×10^{-6}	0.7-1.5
M4-M6	0.19	0.19	0.058	1.52	11.8	1.4	10.0-11.8	5×10^{-5}	0.7-1.7

Snellen et al. 2013

The expected outcome from atmospheric studies

- We have already identified key molecules in few planets (water vapour, methane, CO, CO_2)
- Today we have already a significant numbers of targets suitable for atmospheric observations
- Detailed physical analysis of exoplanetary atmosphere will be possible
- Detection of oxygen in Earth twin in the HZ zone around mid-M star will be possible
- Significant synergy between space low resolution spectra and ground high resolution spectra

A very promising future for high resolution exoplanetary spectroscopy