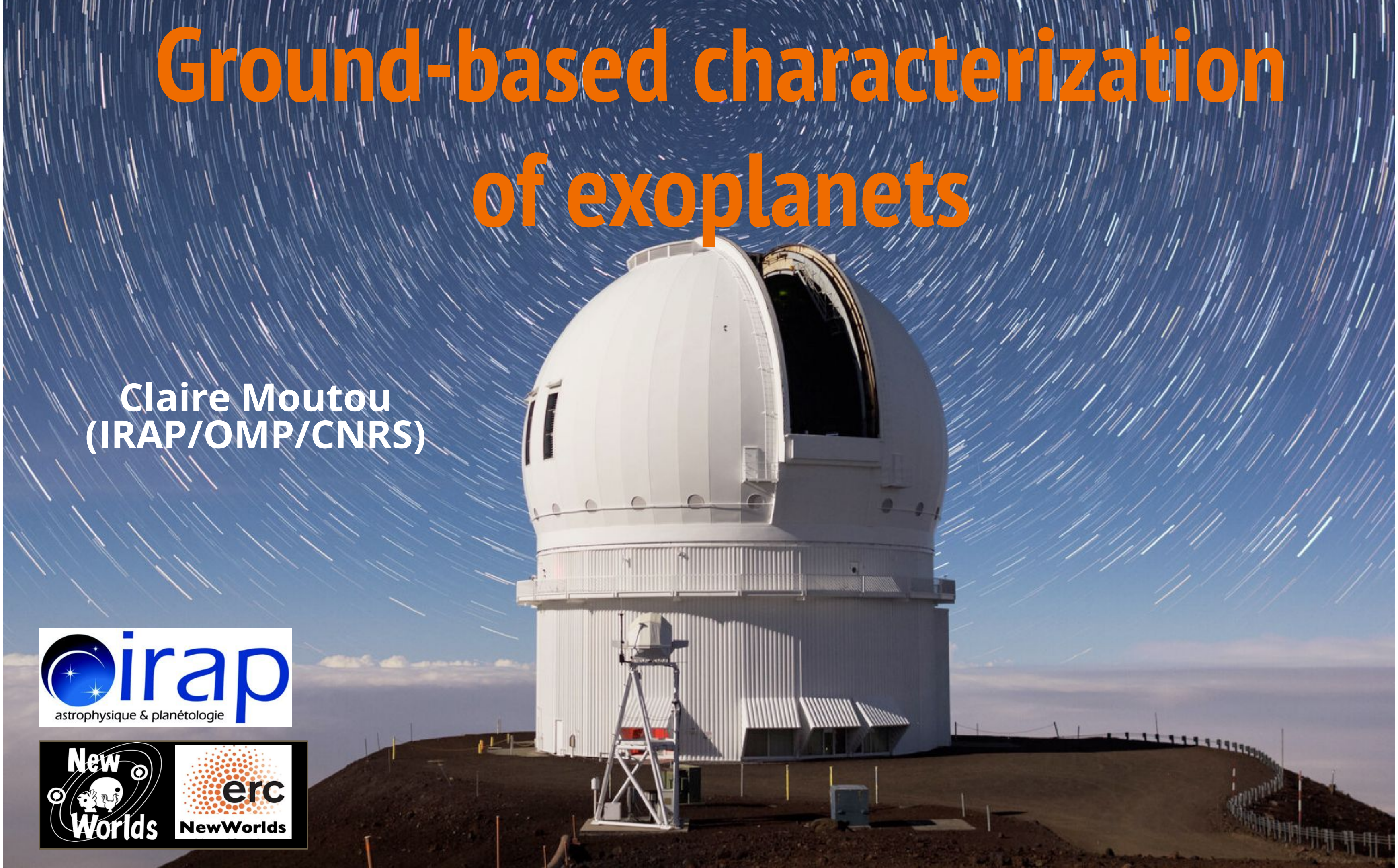
Ground-based characterization of exoplanets

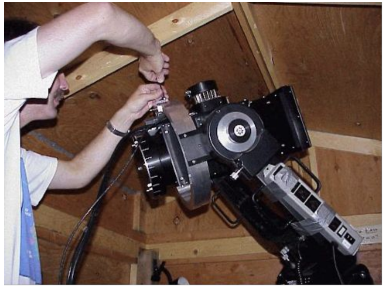


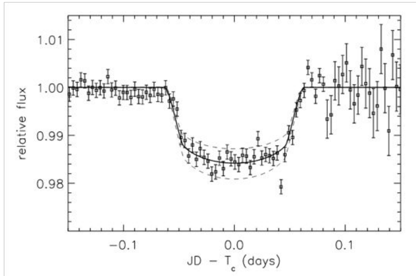
Claire Moutou
(IRAP/OMP/CNRS)

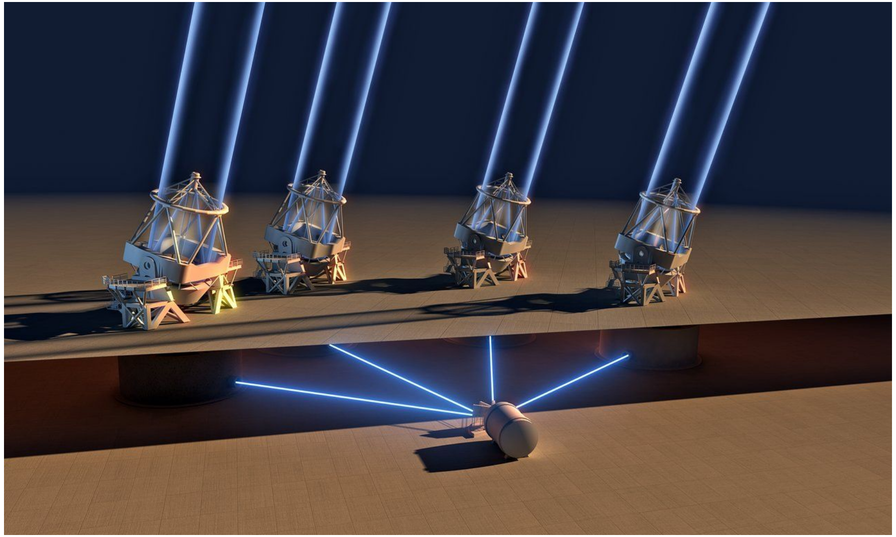
What kind of gb observatory for exoplanets?

Both small telescopes with easy access (dedicated) and niche instruments

… and large telescopes with amazing collecting area and instruments

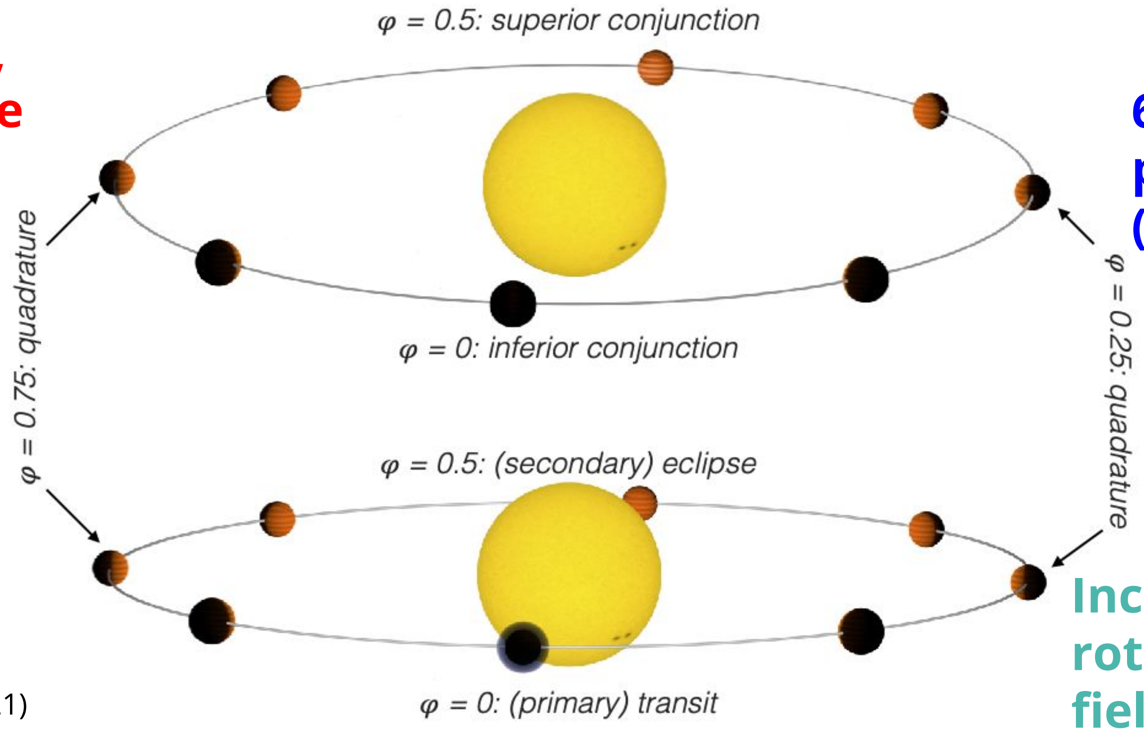






What do we call characterization?

Mass, radius, (gravity, scale height), composition



6 orbital parameters (P, e, ephem)

Inclination, rotation, magnetic field, atm physics…

Courtesy M. Brogi (2021)

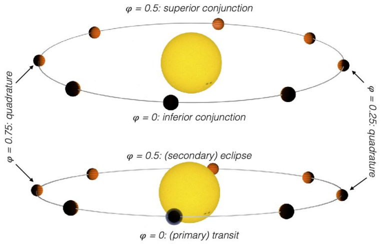
Fundamental parameter characterization

	Measured parameter	Biases
Transits	Radius, orbit inclination, period	Close-in, large, only aligned
RV	Minimum mass, eccentricity, period, obliquities when transit	Close-in, massive, quiet stars
Astrometry / interferometry	Mass, inclination, separation	Outer, closeby systems
Direct imaging	Luminosity (age, mass), astrom	Young, massive, hot planets

Various techniques give different constraints and have different biases

There is a growing overlap between these various technics: more complete

Atmospheres characterization



Method	Access to…	For…
Transmission spectroscopy	Composition Temperature-Pressure profile	Close-in planets in transit
Eclipses/phase curves	Thermal/reflection spectrum of day side	Close-in planets
Direct imaging	Mean thermal spectrum	Distant planets

Optical	Na, K, Fe, Ca, H, HeI, TiO, VO, FeH,Rayleigh scattering H_2
nir	H_2O, CO, CO_2, HCN, NH_3, C_2H_2, HeI, CH_4

Exoplanet searches started from the ground

- First radial-velocity discoveries of exoplanets (mid 1990s)
- First transit of a hot Jupiter (1999)
- First ground-based transit surveys (2000s)
- First ground-based transmission spectra (2010s)
- First ground-based direct-imaging exoplanet (2010s)
- First ground-based astrometric exoplanet results (2020s)

Radial velocities

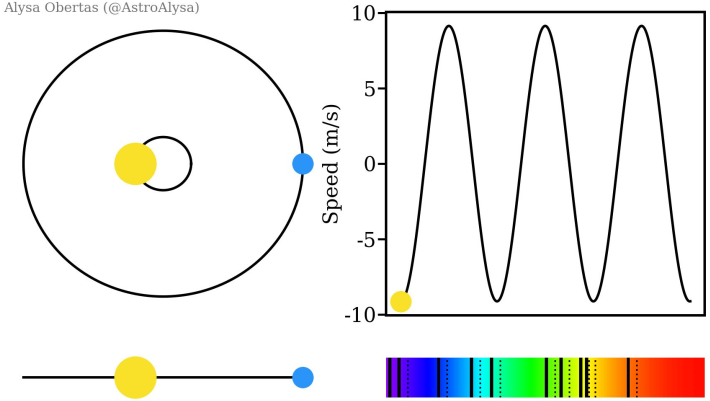
Instruments: HARPS, SOPHIE, ESPRESSO, SPIRou, EXPRES…

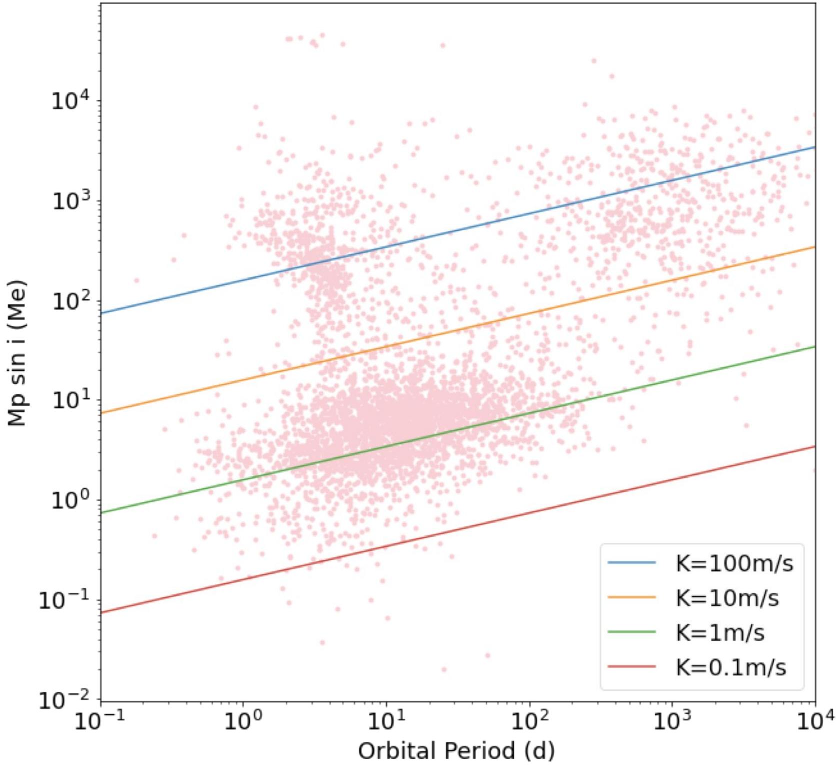
6 parameters to adjust per planet:

$$V_{rad} = V_0 + K \cdot [\cos(\nu(t) + \omega) + e\,\cos\omega],$$

$$K = \frac{m\,\sin i}{(M_* + m)^{2/3}} \cdot \frac{(2\pi\,G)^{1/3}}{P^{1/3}\sqrt{1-e^2}}$$

Alysa Obertas (@AstroAlysa)





Astrometry

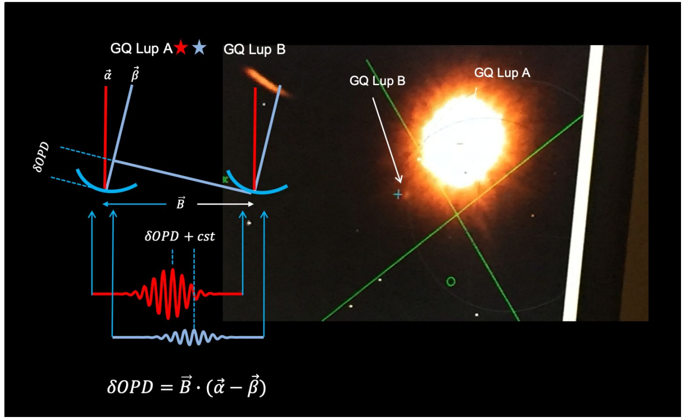
Instruments: Gaia, SPHERE, GPI, VLTI/Gravity...

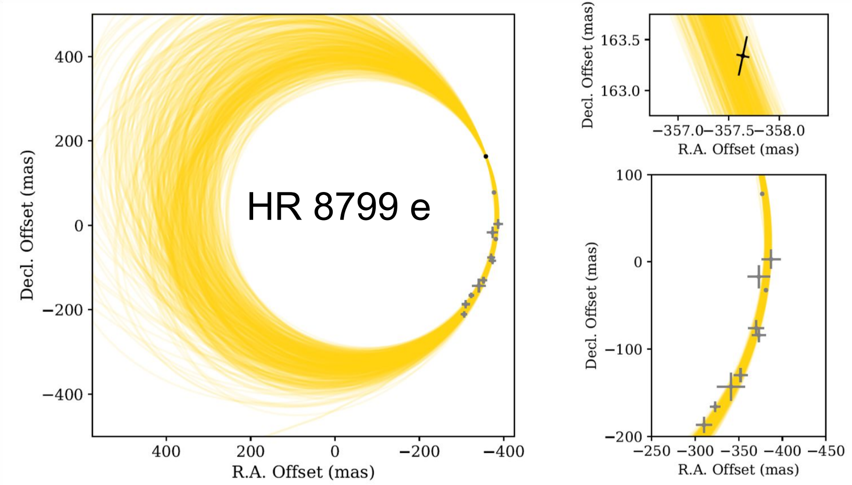
$$\theta = \frac{m_p}{M_s}\frac{a_p}{D} = \left(\frac{G}{4\pi^2}\right)^{\frac{1}{3}} \frac{m_p}{M_s^{\frac{2}{3}}}\frac{p^{\frac{2}{3}}}{D},$$

Measuring actual masses

More efficient for outer planets (a_p)

Depends on stellar distance (D)





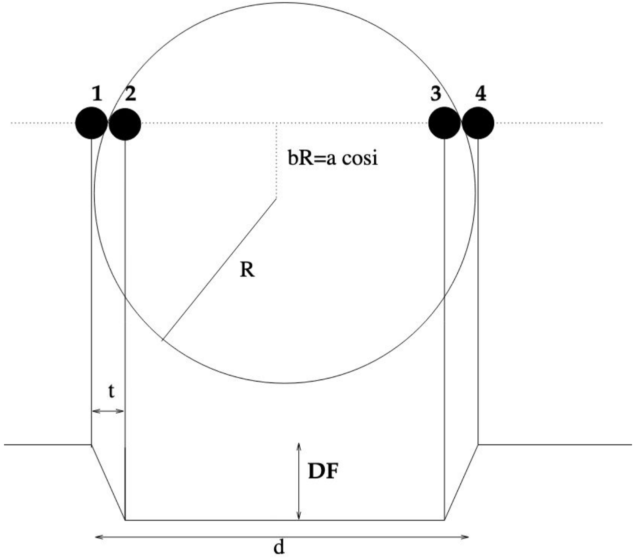
ExoGravity project, 50-100 microarcsec precision

Lacour+ 2019

Transit: radius, period, inclination

Dimming of starlight: radius of planet relative to the star

$$\Delta F = \frac{F_{off} - F_{on}}{F_{off}} = (r/R)^2$$



Jupiter-Sun~1% Earth-Sun~0.008% with a probability:

$$p = \frac{R_*}{r_p},$$

Instruments: Corot, Kepler, TESS, PLATO, and gb surveys!

Ground based transit surveys

Surveys like SuperWASP, HAT, NGTS, Mearth, SPECULOOS...

Small telescopes monitoring the sky for years

~400 exoplanets altogether (10 times more from space)

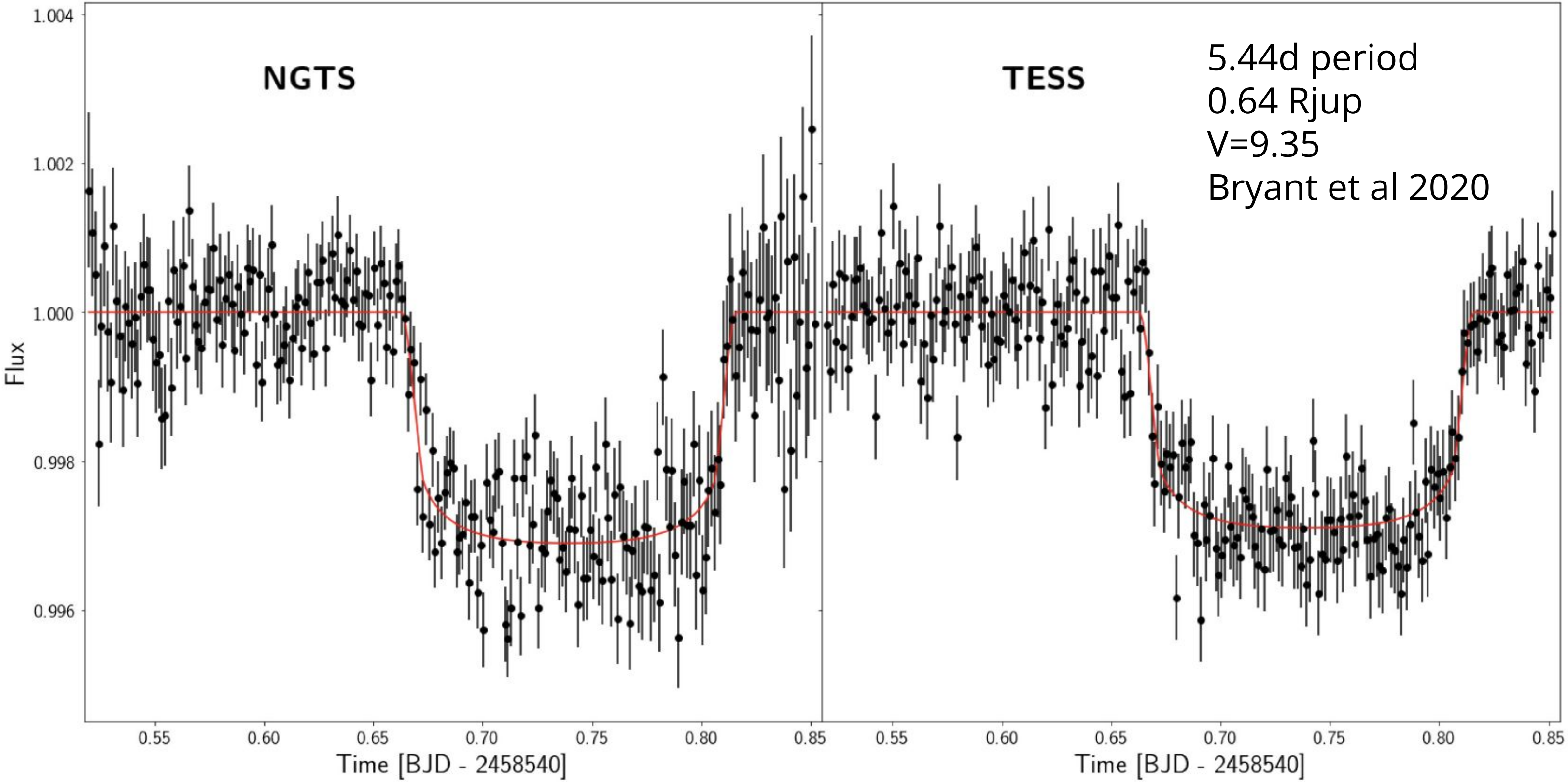
Mostly giant planets, or super-earths/earths around M stars

Bright stars: RV follow-up easier than for space-based candidates

Atmosphere characterization easier on WASP## than most Kepler##

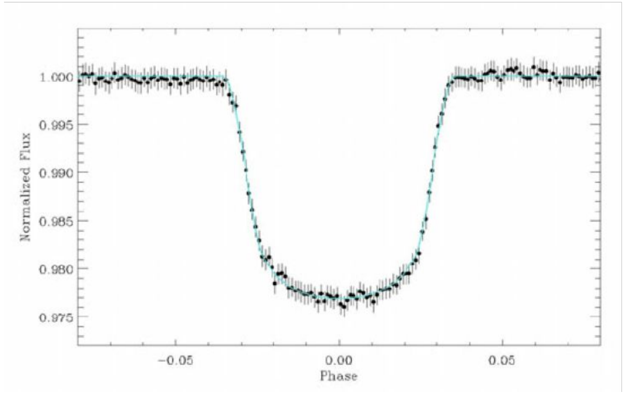
Still useful w/ TESS, especially for monotransits

WASP-166b transit, NGTS and TESS



5.44d period
0.64 Rjup
V=9.35
Bryant et al 2020

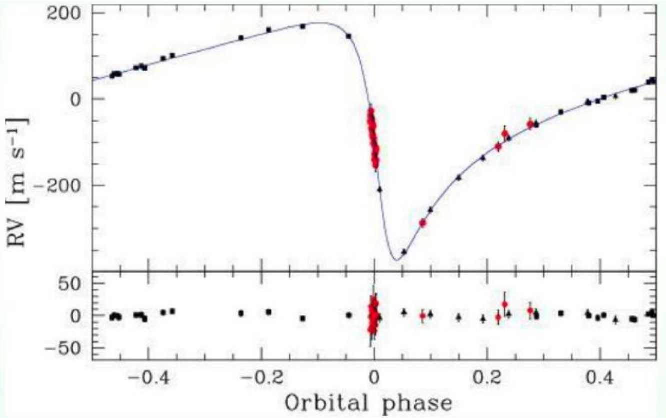
Transits and radial-velocities: a win-win



Precise orbital period and phase

Planetary radius

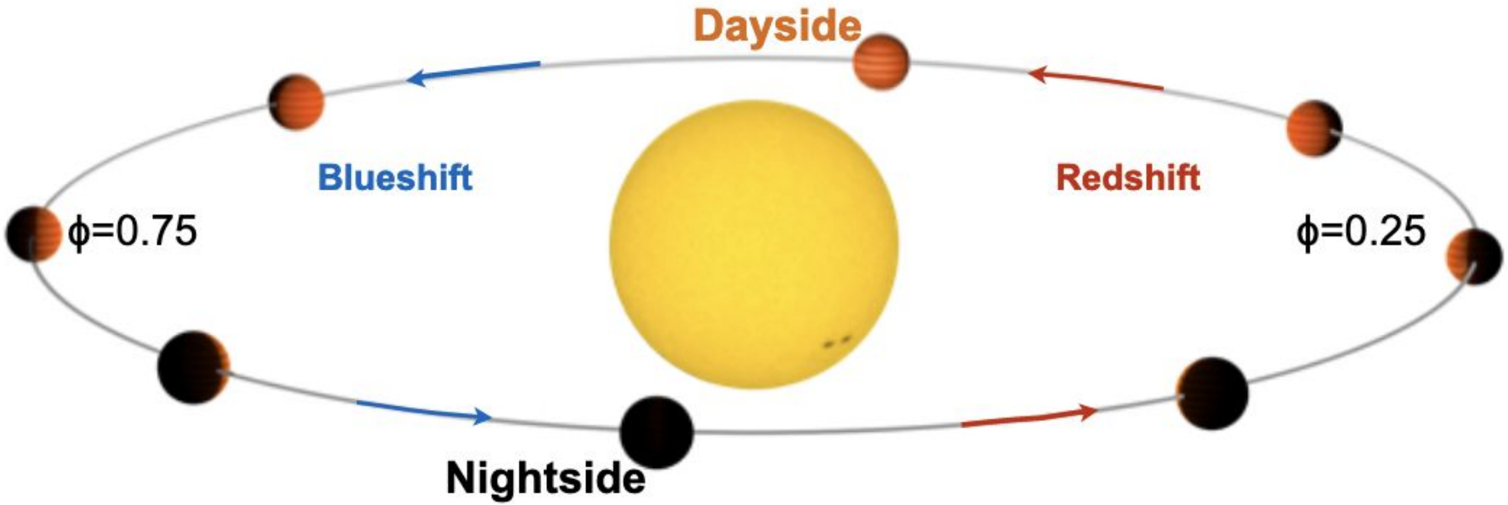
Orbital inclination



Orbital eccentricity

Actual planetary mass

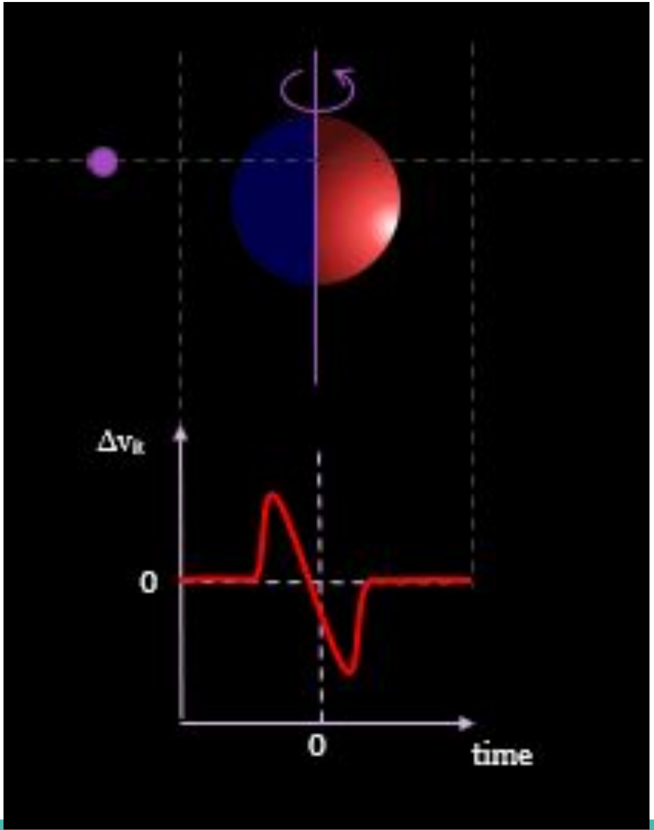
Planet bulk density / nature

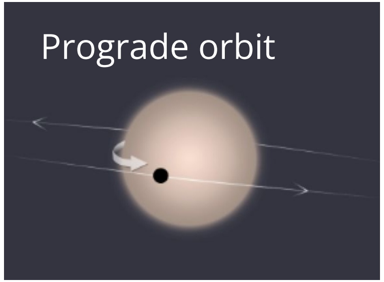


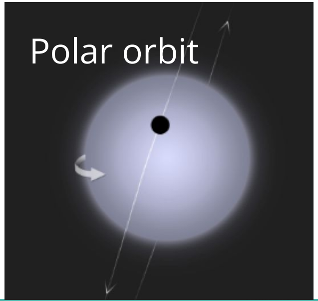
Mass	✓
Radius, when transiting	✓
Orbital parameters	✓

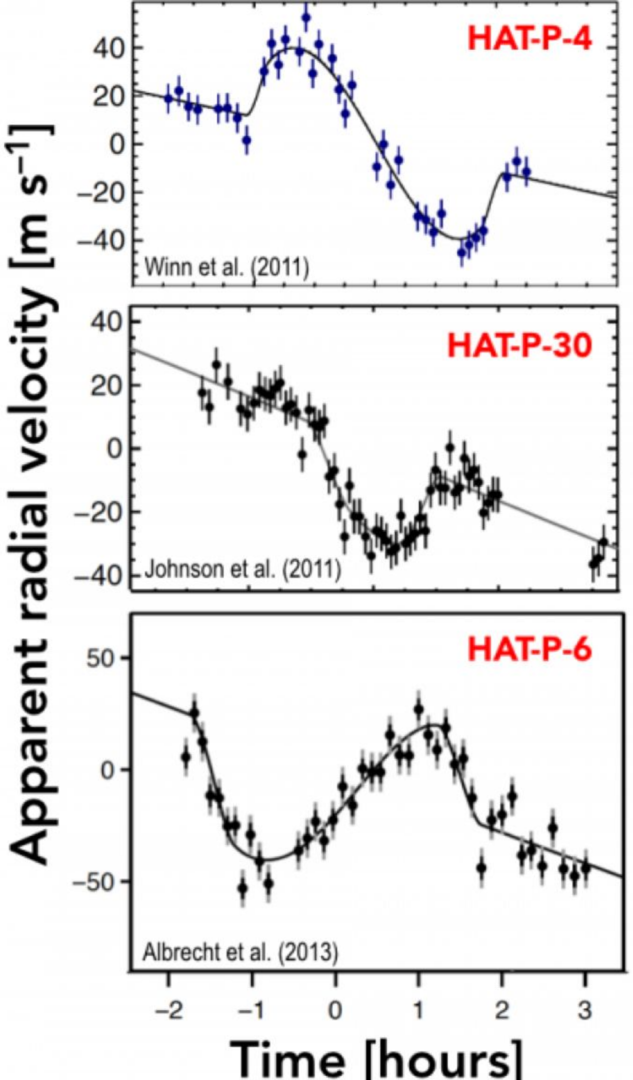
Obliquities : the Rossiter-McLaughlin effect

- The star rotates during the transit
- The planet crosses the blue half first, then the red half
- It results in a small RV anomaly
- The shape of that anomaly measures the relative angle between the rotation axis of the star and the planet's orbital plane





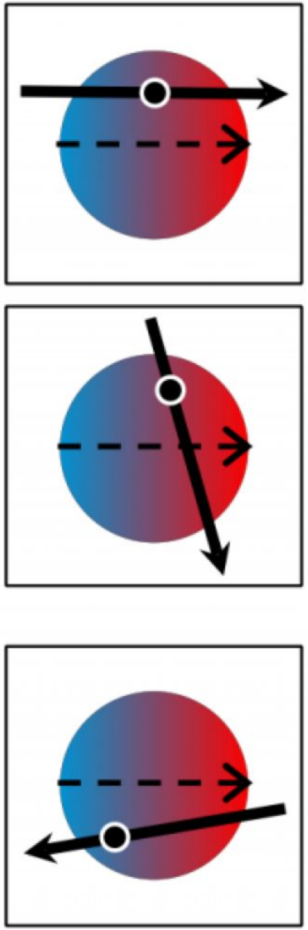




Winn et al. (2011)

Johnson et al. (2011)

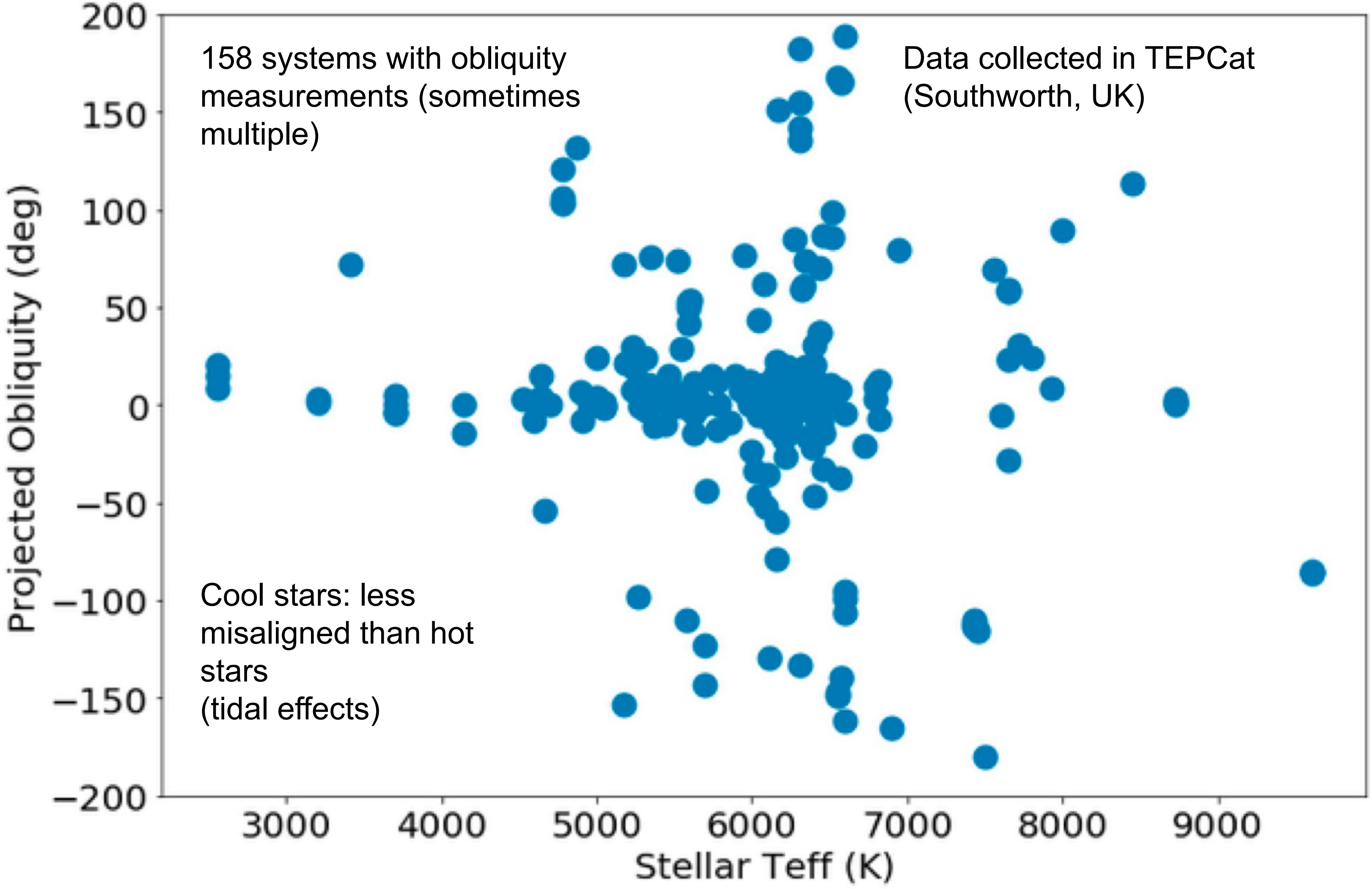
Albrecht et al. (2013)



Well-aligned

Misaligned

Retrograde



158 systems with obliquity measurements (sometimes multiple)

Data collected in TEPCat (Southworth, UK)

Cool stars: less misaligned than hot stars
(tidal effects)

Direct imaging: luminosity, orbit

Planets discovered by the direct imaging: giant, outer, young, self luminous

Hot start or cold start? Formation history

- Luminosity as a function of mass and age
- Teff and log(g)
- Chemical composition (Molecular content, C/O, [M/H])
- age, mass, radius with evolution models

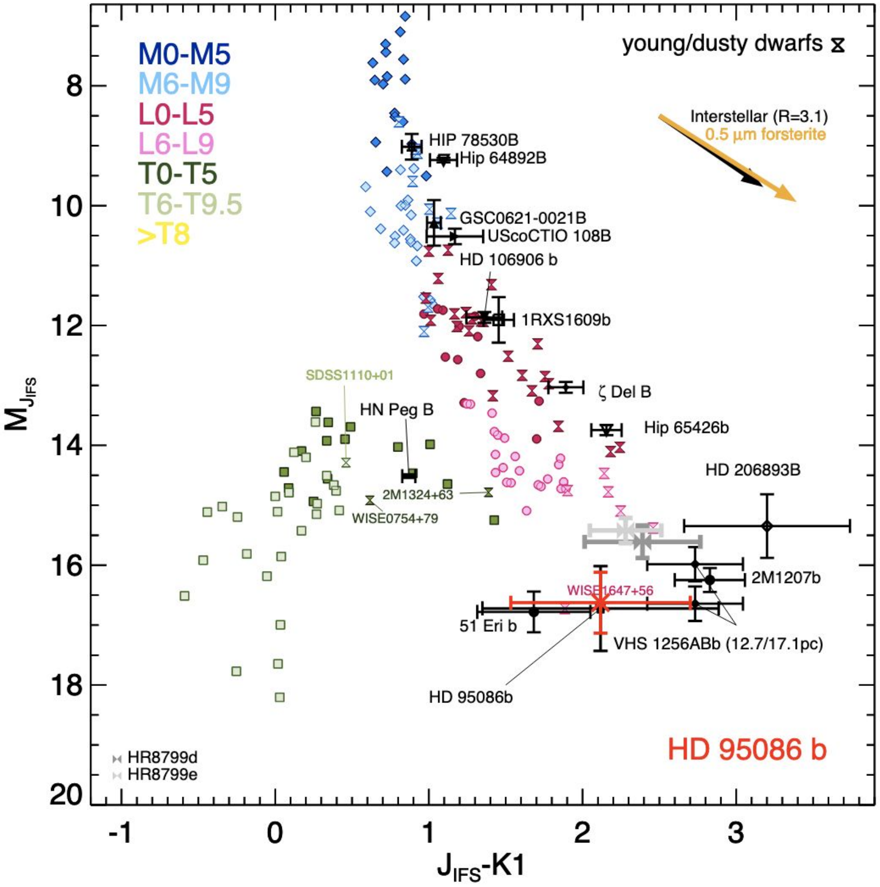
GB photometry of EGP

Multiple wide-band photometry JHKLM

First way of identifying low-mass young companions (spectral type , spectral indices)

Young, low-gravity objects : red sequence wrt older, higher-gravity field objects (stars)

Desgrange+ 2022



GB direct LR spectroscopy

Instruments: VLT/SPHERE, Gemini/GPI, P1640, SCExAO-CHARIS

R ~ 100

Chemistry: CH_4 bands, H_2O bands

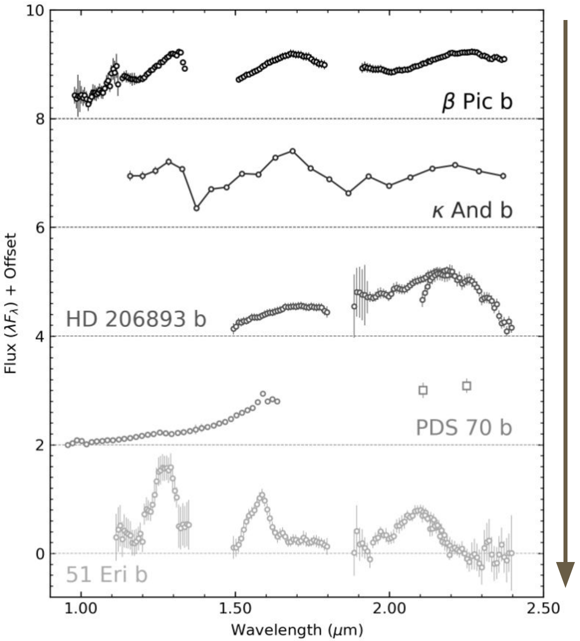
Gravity: lower when collisionally-induced absorption of H_2 is weak => H-band peaks and redder K-band slopes

Presence of atmospheric dust (flat, BB like spectra)

Presence of clouds

Degeneracies exist between all these parameters

Compiled by Currie+ 2022



GB direct MR spectroscopy

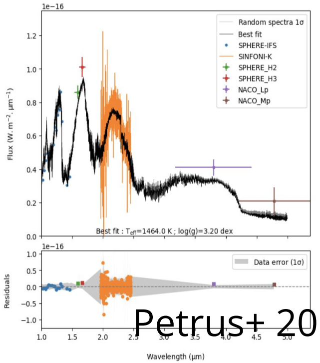
Instruments: Keck/OSIRIS, VLT/SINFONI, XSHOOTER, MUSE, Gemini/NIFS, GRAVITY…

R ~ 500-5000, smaller spectral range

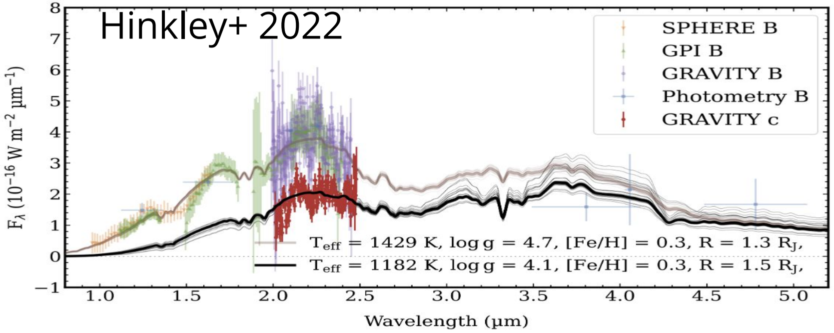
FeH, CO, H20, CH4, NaI, KI, more accurate abundances than LR

Characterizing gravity , accretion, composition, C/O, orbital velocity

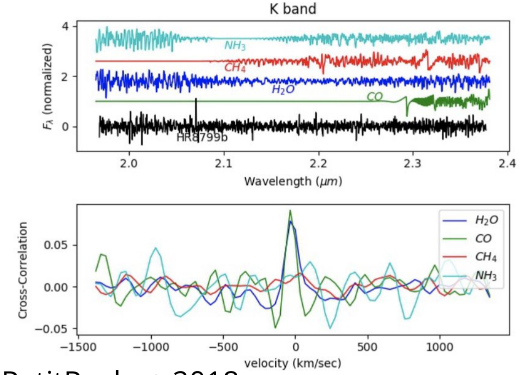
Main limitation comes from noise in the stellar halo @planet location



Petrus+ 2021



Hinkley+ 2022



PetitRoche+ 2018

Atmospheric Transmission Spec from the ground, early work

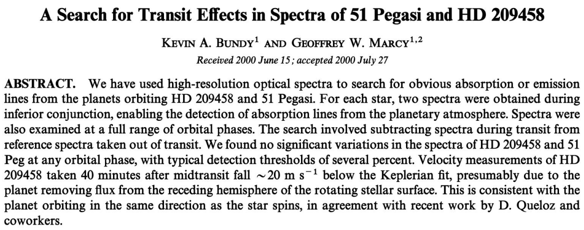
Seeking the Atmospheric Transmission Spectrum of HD209458b

Show affiliations

Brown, T. M. ; Butler, R. P. ; Charbonneau, D. ; Noyes, R. W. ; Sasselov, D. ; Libbrecht, K. G. ; Marcy, G. W. ; Seager, S. ; Vogt, S. S.

Transiting extrasolar giant planets such as HD209458b should impress a spectroscopic signature on the light that is transmitted through the outer parts of their atmospheres. Theory suggests that the depths of absorption features resulting from this effect may be as large as about 10^{-3} of the parent star's continuum intensity. Such spectral features could provide important diagnostics concerning the composition and physical state of the planetary atmosphere. Accordingly, we have obtained low-noise spectra of HD209458 during two transits of its planet, once in visible light using the HIRES spectrograph at the Keck I telescope, and once in the near infrared using the NIRSPEC spectrograph at Keck II. We describe the methods employed and the results of searches for spectral signatures of neutral atomic sodium, carbon monoxide, and other atomic and molecular species.

Publication: American Astronomical Society, 197th AAS Meeting, id.11.05; Bulletin of the American Astronomical Society, Vol. 32, p.1417

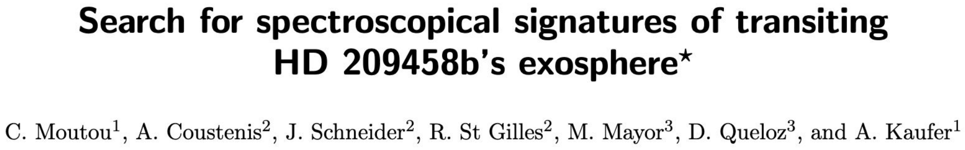


A Search for Transit Effects in Spectra of 51 Pegasi and HD 209458

Kevin A. Bundy[1] and Geoffrey W. Marcy[1,2]

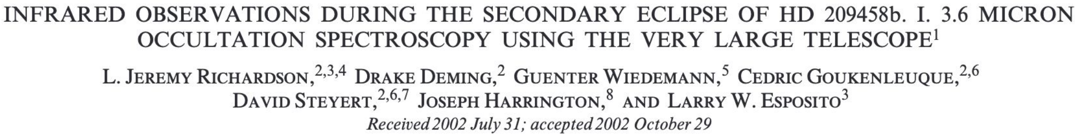
Received 2000 June 15; accepted 2000 July 27

ABSTRACT. We have used high-resolution optical spectra to search for obvious absorption or emission lines from the planets orbiting HD 209458 and 51 Pegasi. For each star, two spectra were obtained during inferior conjunction, enabling the detection of absorption lines from the planetary atmosphere. Spectra were also examined at a full range of orbital phases. The search involved subtracting spectra during transit from reference spectra taken out of transit. We found no significant variations in the spectra of HD 209458 and 51 Peg at any orbital phase, with typical detection thresholds of several percent. Velocity measurements of HD 209458 taken 40 minutes after midtransit fall ~ 20 m s^{-1} below the Keplerian fit, presumably due to the planet removing flux from the receding hemisphere of the rotating stellar surface. This is consistent with the planet orbiting in the same direction as the star spins, in agreement with recent work by D. Queloz and coworkers.



Search for spectroscopical signatures of transiting HD 209458b's exosphere★

C. Moutou[1], A. Coustenis[2], J. Schneider[2], R. St Gilles[2], M. Mayor[3], D. Queloz[3], and A. Kaufer[1]



INFRARED OBSERVATIONS DURING THE SECONDARY ECLIPSE OF HD 209458b. I. 3.6 MICRON OCCULTATION SPECTROSCOPY USING THE VERY LARGE TELESCOPE[1]

L. Jeremy Richardson,[2,3,4] Drake Deming,[2] Guenter Wiedemann,[5] Cedric Goukenleuque,[2,6] David Steyert,[2,6,7] Joseph Harrington,[8] and Larry W. Esposito[3]

Received 2002 July 31; accepted 2002 October 29

Searching for helium in the exosphere of HD 209458b★

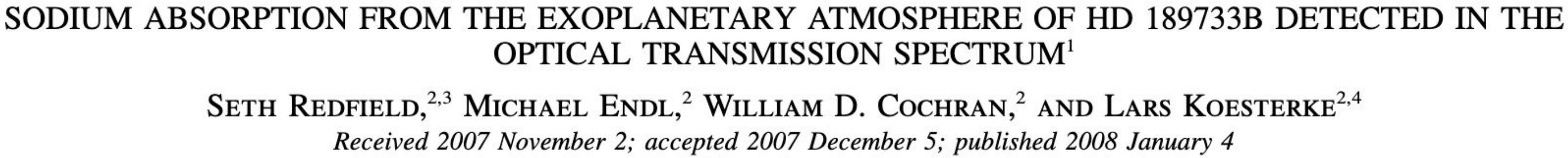
C. Moutou[1], A. Coustenis[2], J. Schneider[3], D. Queloz[4], and M. Mayor[4]

A new method for probing the atmospheres of transiting exoplanets

I. A. G. Snellen★

Searching, not finding (2000-2004) 0.1-1% upper limits

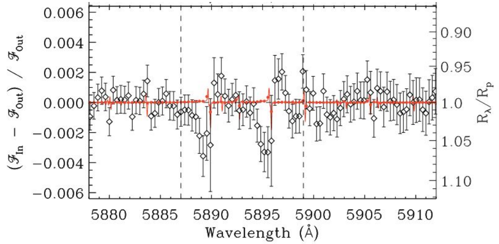
Atmospheres from the ground: first detections (2008)



SODIUM ABSORPTION FROM THE EXOPLANETARY ATMOSPHERE OF HD 189733B DETECTED IN THE OPTICAL TRANSMISSION SPECTRUM[1]

SETH REDFIELD,[2,3] MICHAEL ENDL,[2] WILLIAM D. COCHRAN,[2] AND LARS KOESTERKE[2,4]

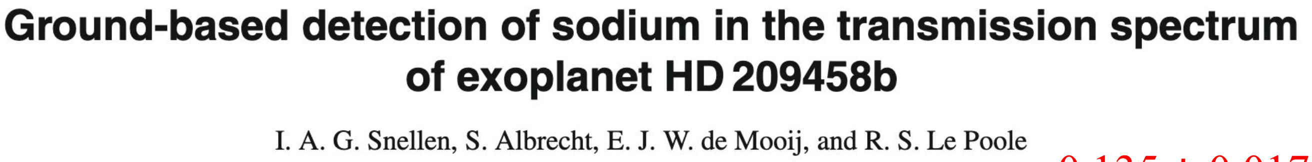
Received 2007 November 2; accepted 2007 December 5; published 2008 January 4



11 HRS transits combined

0.067 ± 0.02%

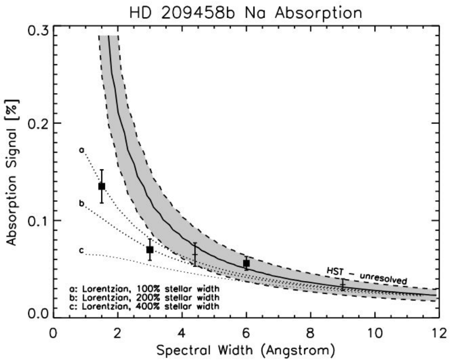
-38km/s blueshift!



Ground-based detection of sodium in the transmission spectrum of exoplanet HD 209458b

I. A. G. Snellen, S. Albrecht, E. J. W. de Mooij, and R. S. Le Poole

0.135 ± 0.017%



Spectral resolution is key

Instruments: CRIRES, CARMENES, HARPS, ESPRESSO, SPIRou...

LR: confusion btw planet/star/Earth lines

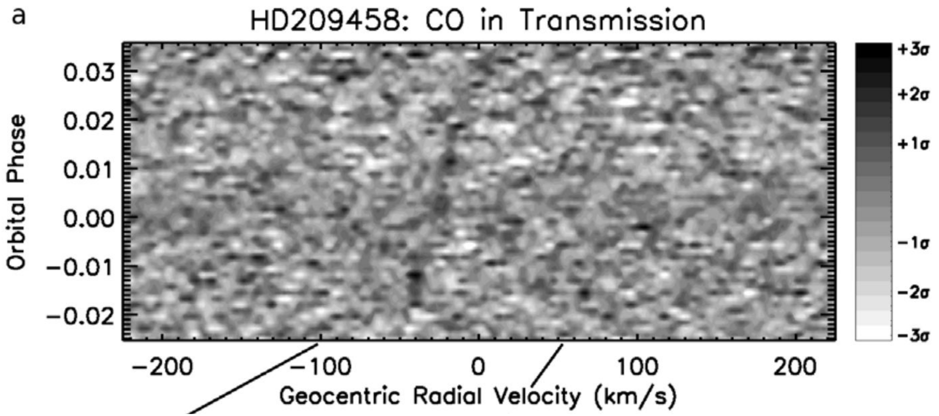
Nir and optical spectrographs R = 40 to 100k

Use the orbital motion of the plane separate its spectrum from the ste spectrum

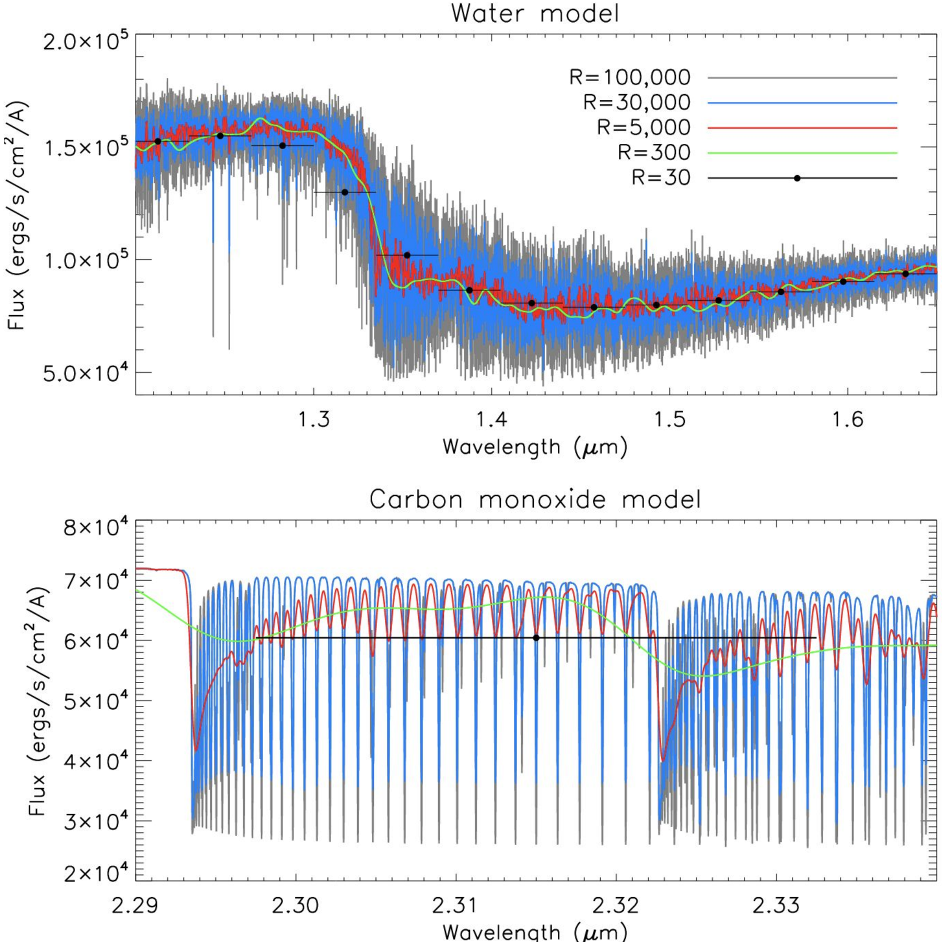
Planet spectrum moves by several pixels during a few obs hours

Detection of atm winds

Snellen et al 2010, CRIRES



Planet detection increases as $\sqrt{n_{\text{lines}}}$



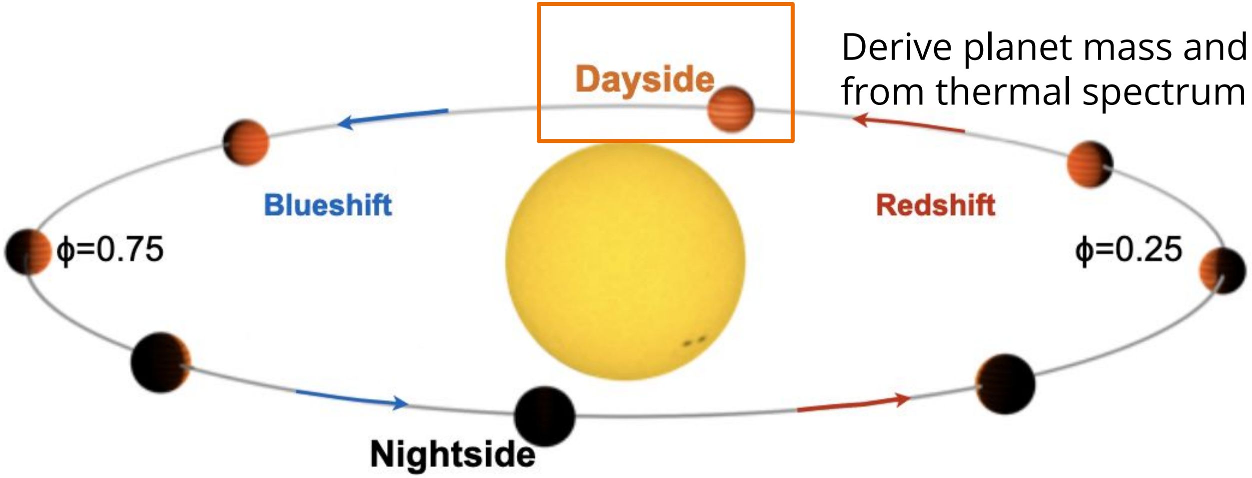
Birkby 2018

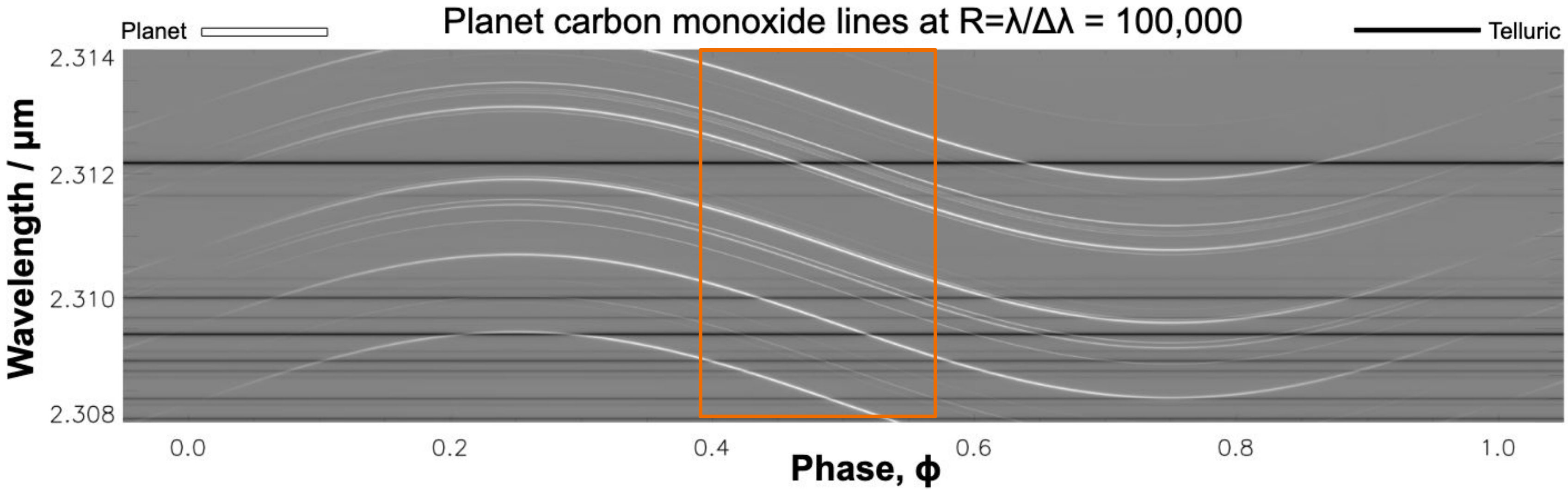
Birkby 2018

Derive planet mass and composition from thermal spectrum and Ks

$$v_{\mathrm{orb}} = \frac{2\pi a}{P}$$

$$K_{\mathrm{P}} = v_{\mathrm{orb}} \sin(i)$$





Birkby 2018

Derive planet mass and composition

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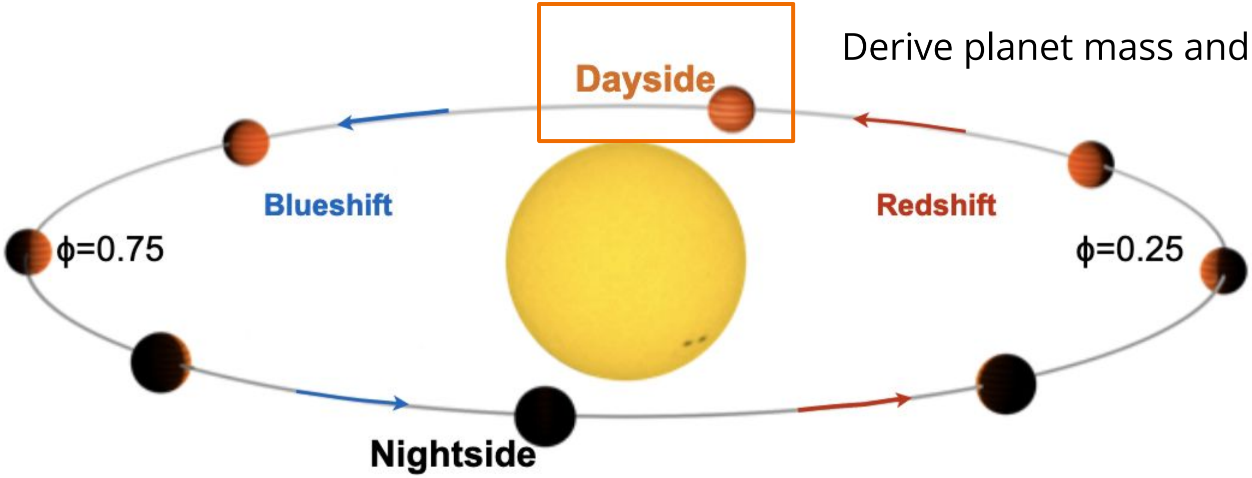
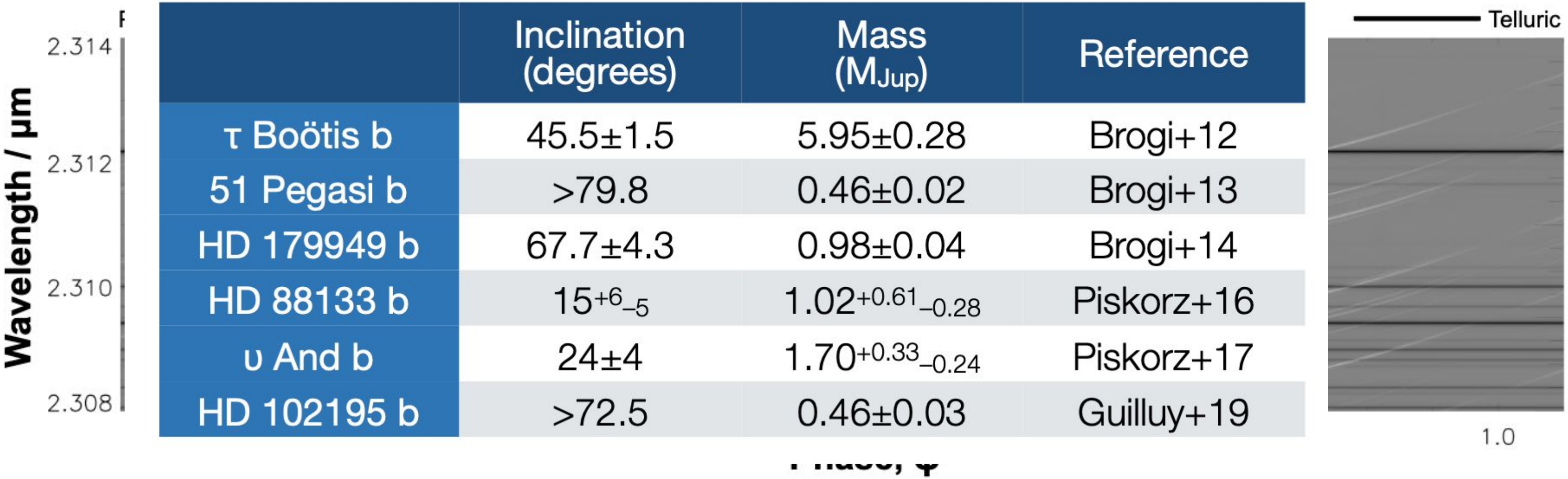
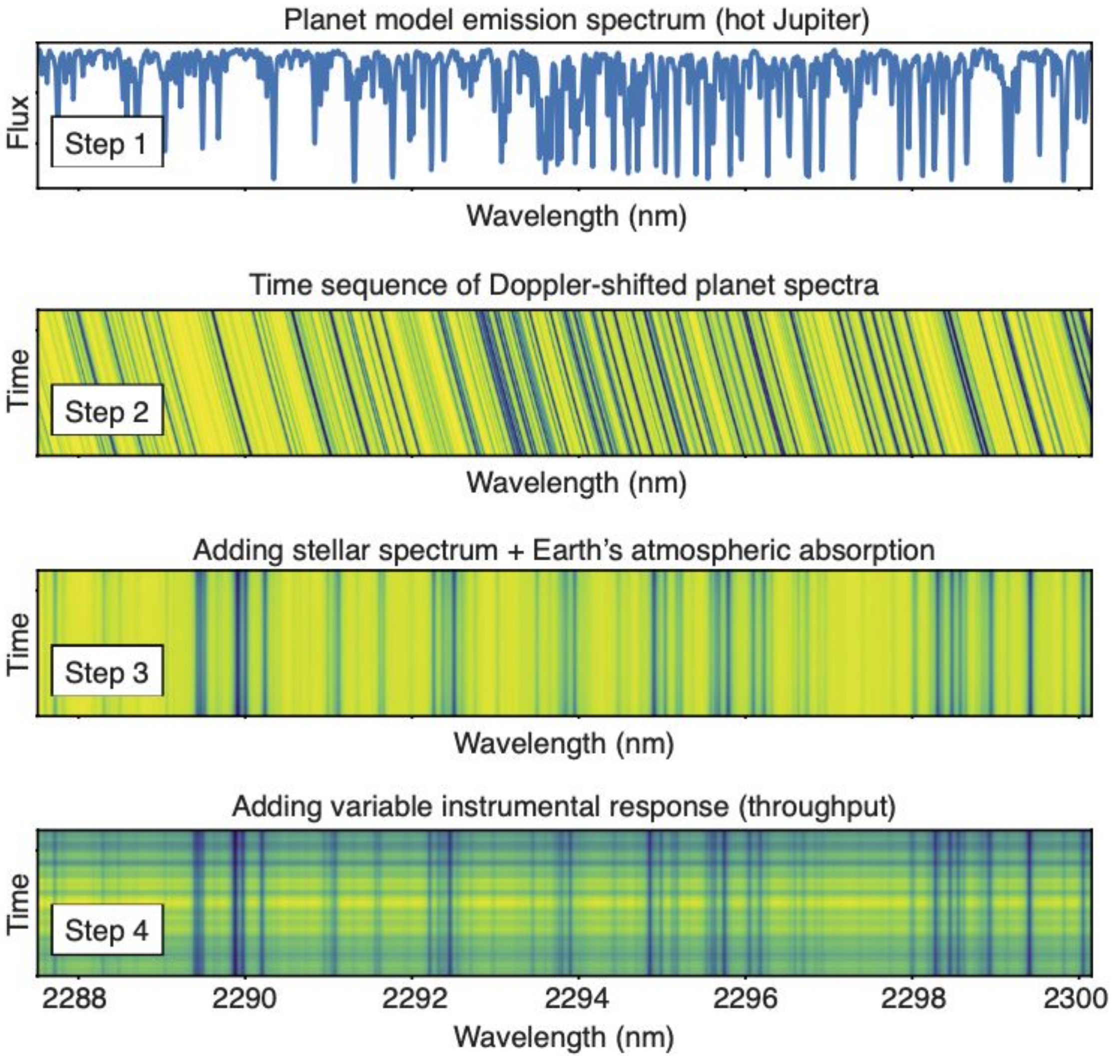




	Inclination (degrees)	Mass (M_{Jup})	Reference
τ Boötis b	45.5±1.5	5.95±0.28	Brogi+12
51 Pegasi b	>79.8	0.46±0.02	Brogi+13
HD 179949 b	67.7±4.3	0.98±0.04	Brogi+14
HD 88133 b	15^{+6}_{-5}	$1.02^{+0.61}_{-0.28}$	Piskorz+16
υ And b	24±4	$1.70^{+0.33}_{-0.24}$	Piskorz+17
HD 102195 b	>72.5	0.46±0.03	Guilluy+19



Planet model emission spectrum (hot Jupiter)

Planet spectral lines
~10^{-4} of stellar continuum

Time sequence of Doppler-shifted planet spectra

Radial component of planet
orbital motion changes by
~10 km / s per hour of
observation

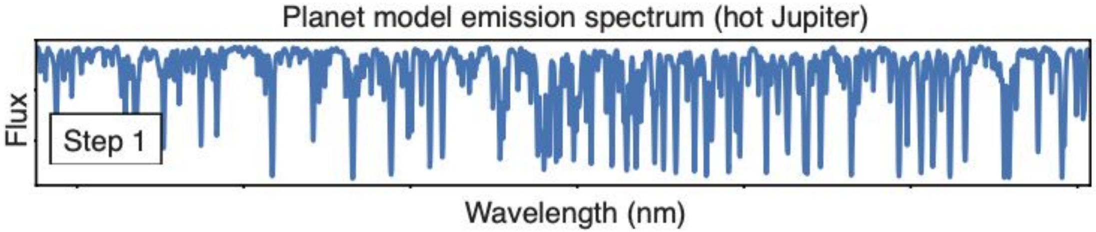
Adding stellar spectrum + Earth's atmospheric absorption

Dominant by orders of magnitude
over the planet signal
(up to 50-60% depth)

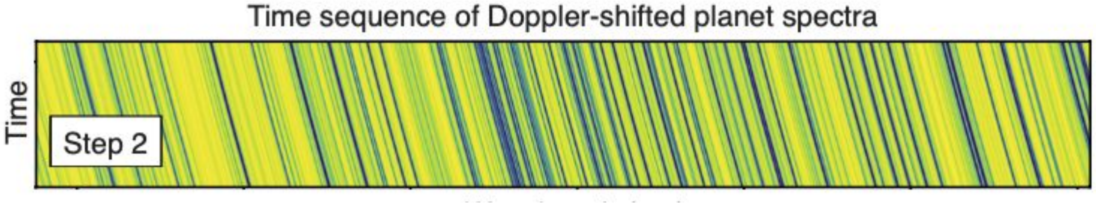
Adding variable instrumental response (throughput)

20-30% variation
in overall measured flux
(telescope pointing,
atmospheric transparency, etc.)

Brogi & Lin
2019



Planet spectral lines
~10^{-4} of stellar continuum



Radial component of planet
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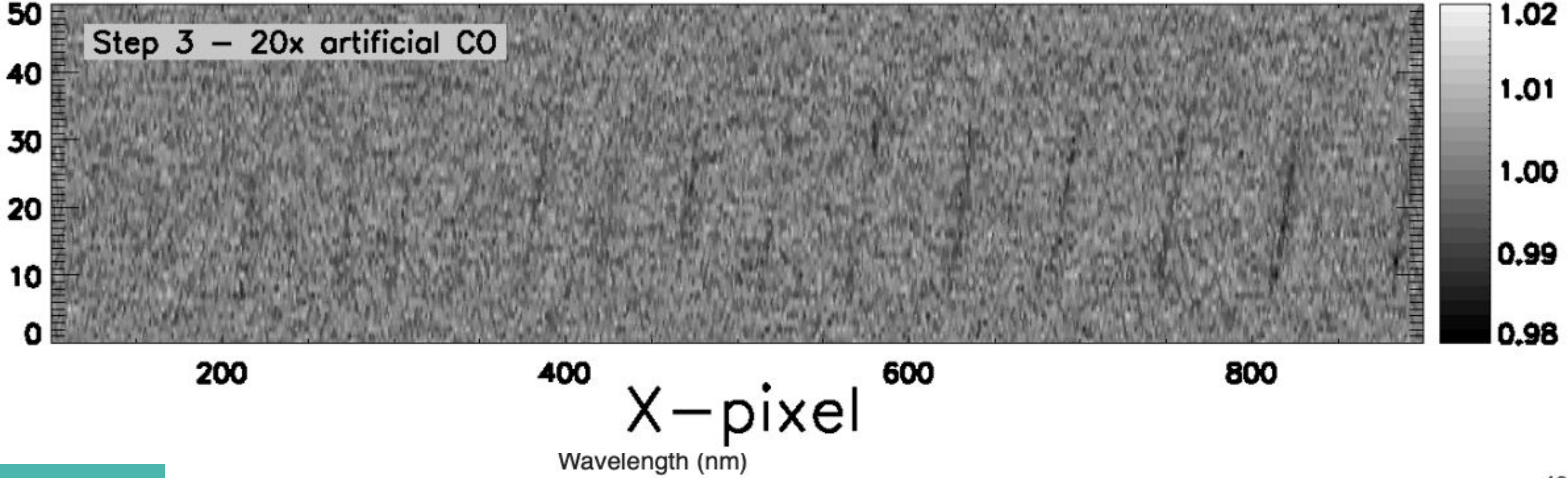
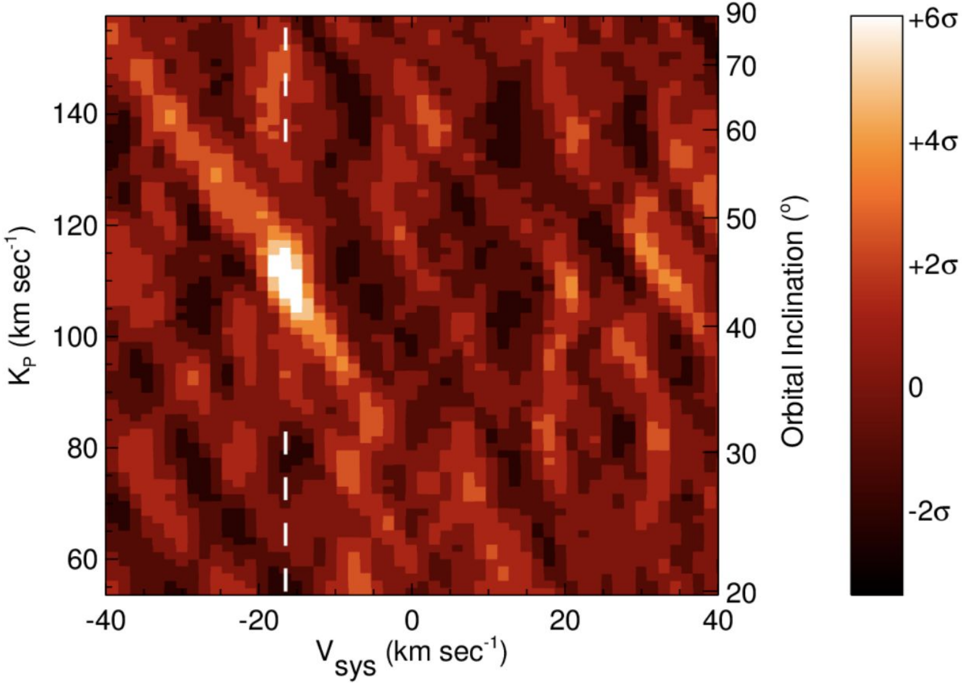


HRS characterizing (non) transiting planets



Clean data
Forward modeling
Cross-correlation map
Systemic velocity/Kp

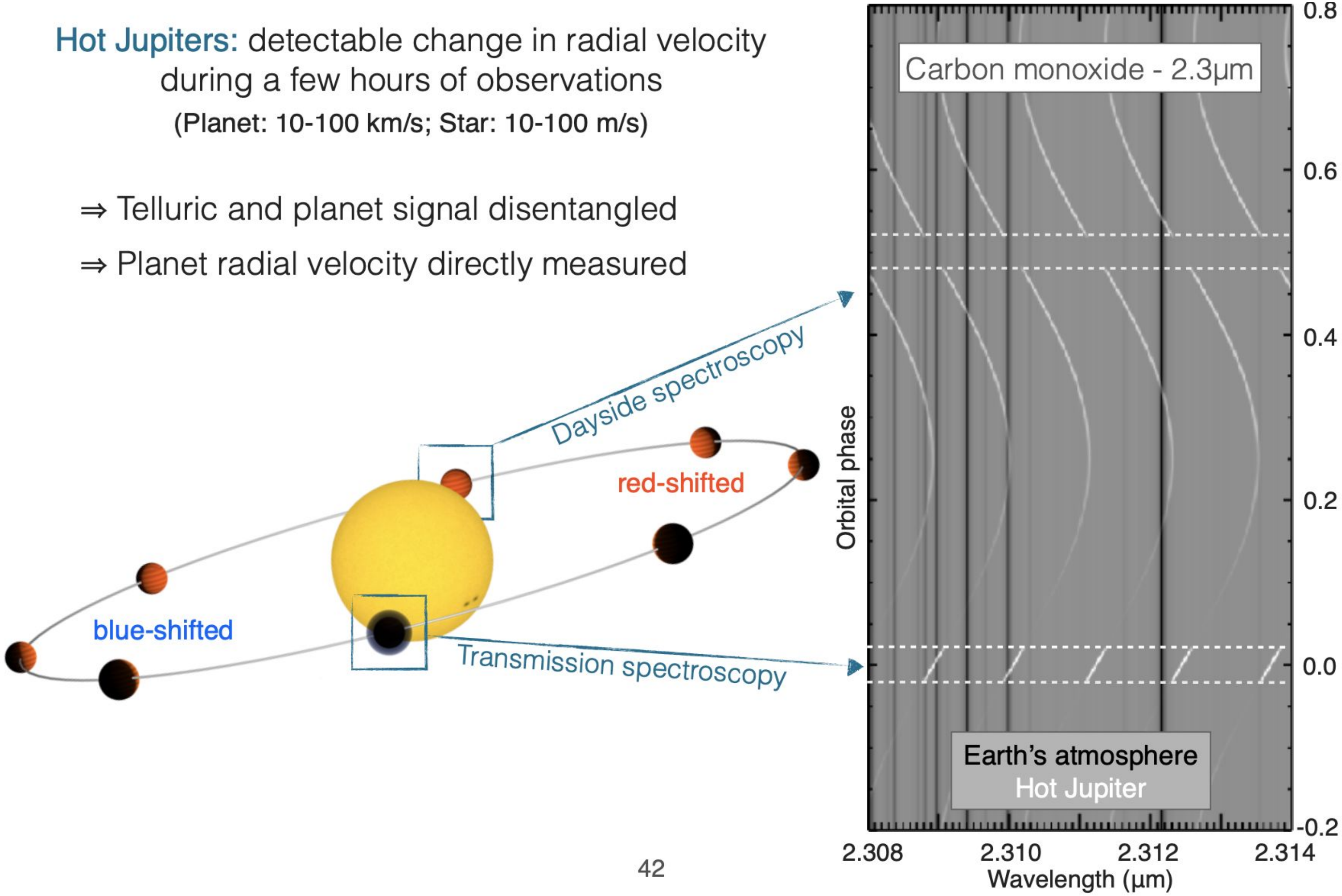
CO signal in the dayside spectrum of tau Boo b (Brogi et al 2013)

HRS : dayside and nightside for transiting systems

Hot Jupiters: detectable change in radial velocity during a few hours of observations
(Planet: 10-100 km/s; Star: 10-100 m/s)

⇒ Telluric and planet signal disentangled

⇒ Planet radial velocity directly measured



Courtesy
M. Brogi (2021)

High spectral resolution of non-transiting planets

The **thermal spectrum**
of the planet is targeted directly

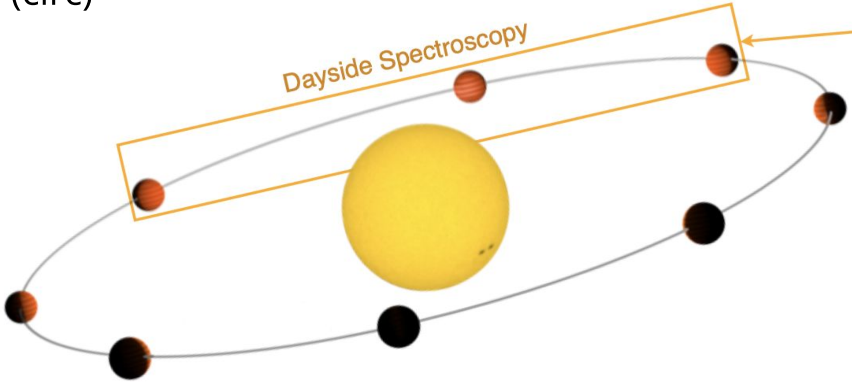
Dayside spectroscopy
applicable to **non-transiting planets**!

Planet orbital velocity (circ)

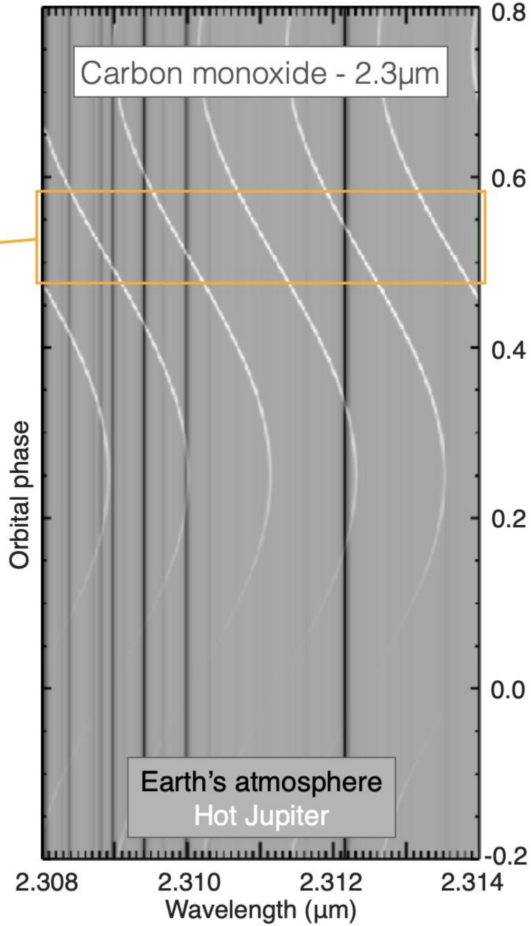
$$v_{\rm orb} = \frac{2\pi a}{P}$$

Max planet RV

$$K_{\rm P} = v_{\rm orb} \sin(i)$$



	Inclination (degrees)	Mass ($M_{\rm Jup}$)	Reference
τ Boötis b	45.5±1.5	5.95±0.28	Brogi+12
51 Pegasi b	>79.8	0.46±0.02	Brogi+13
HD 179949 b	67.7±4.3	0.98±0.04	Brogi+14
HD 88133 b	15^{+6}_{-5}	$1.02^{+0.61}_{-0.28}$	Piskorz+16
υ And b	24±4	$1.70^{+0.33}_{-0.24}$	Piskorz+17
HD 102195 b	>72.5	0.46±0.03	Guilluy+19

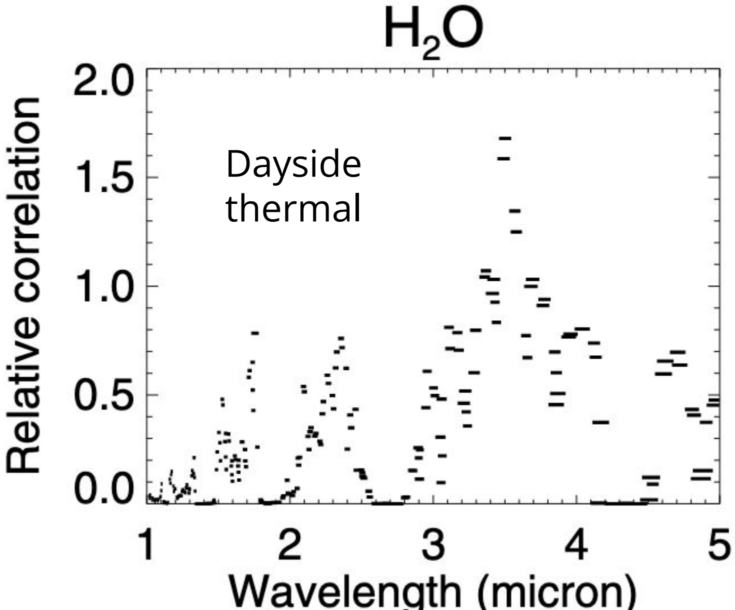


Courtesy
M. Brogi (2021)

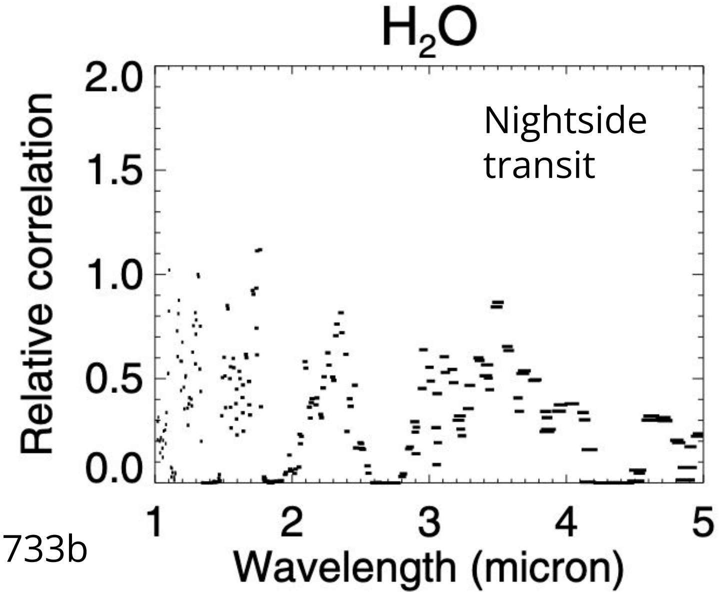
Dayside versus nightside detection limits & wavelength

De Kok+ (2014) for HD 189733 b: H2O, CO, CO2, CH4, HCN, C2H2

Relative sensitivities btw day/night depends on thermal profile



HD 189733b



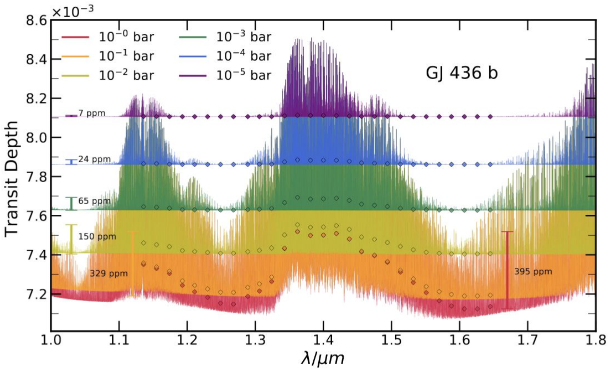
Power of echelle spectroscopy

All molecular species simultaneously

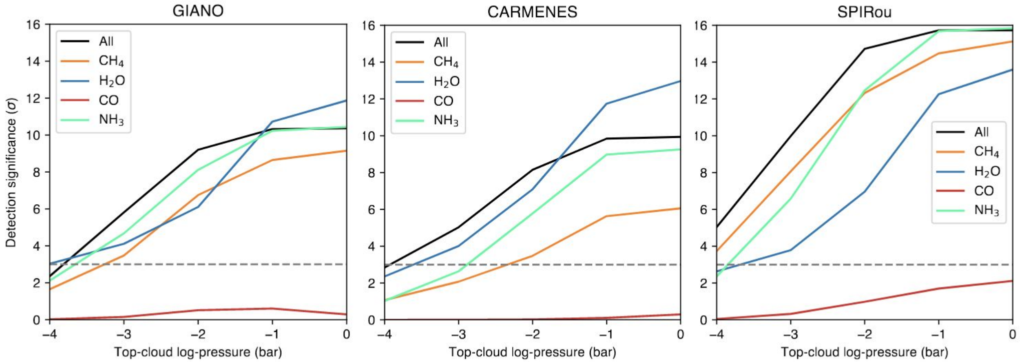
Seeing above the cloud deck at high resolution

HRS breaks degeneracy between H2O abundance and cloud top pressure

High potential to characterize super-Earth/sub-Neptune planet atm



Gandhi+ 2020

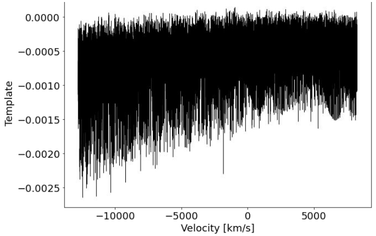


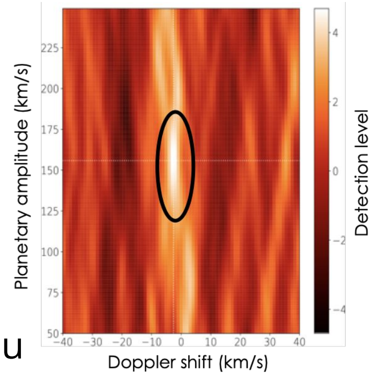
Atmospherix (SPIRou looking at exoplanet atmospheres)

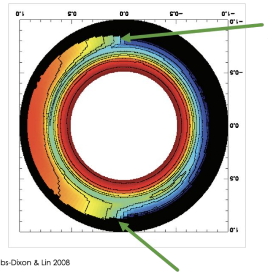
Wavelength range: 980-2500 nm at 70k resolution, in one shot

Goals:

1. Detecting molecules in the atmospheres of hot Jupiters and warm Neptunes
2. Estimating the PT profile and the amplitude of atmospheric winds
3. Characterizing the extended atmosphere through helium Doppler spectroscopy







Redshifted morning limb - Cold
Small absorption depth

Blueshifted evening limb - Hot
Large absorption depth

Dobbs-Dixon & Lin 2008

florian.debras@irap.omp.eu

Sometimes there’s no water

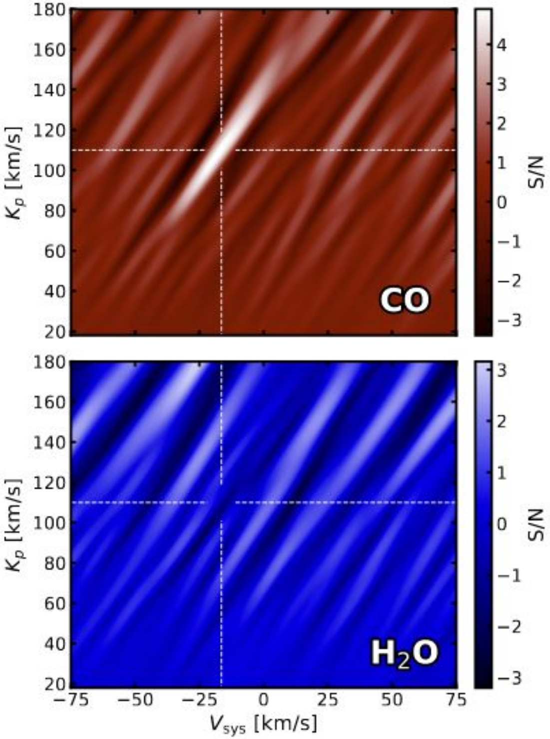
Thermal emission observations of **τ** Boo b with CFHT/SPIRou

volume mixing ratio of log(CO) = −2.46± 0.29

a highly depleted water abundance < 0.0072 times the value expected for a solar composition envelope

gas-phase C/H ratio of 5.8 × solar ~ the value of Jupiter

support a formation scenario beyond the water snowline in a disk enriched in CO due to pebble drift



Pelletier et al, 2021

Power of echelle spectroscopy (cont'd)

All molecular species simultaneously observed with GIANO/TNG

Significant detection: H2O, CH4, CO, HCN, C2H2, NH3

C / O > 1

HD 209458 b formed far in system

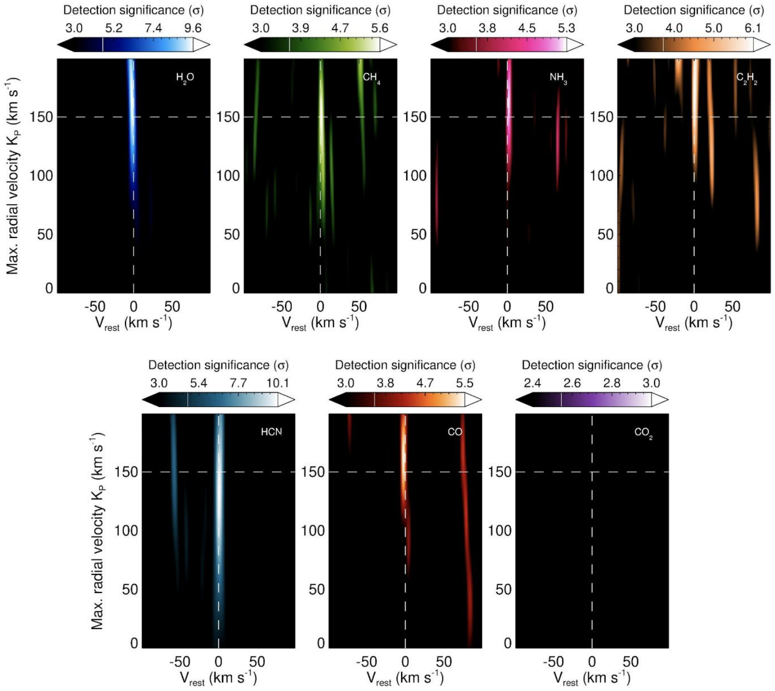


Fig. 1 | Detection significance for H_2O, CH_4, NH_3, C_2H_2, HCN, CO and CO_2. Each panel

Giacobbe+ 2021

Weather patterns on EGP!

Ultra-hot giant exoplanet

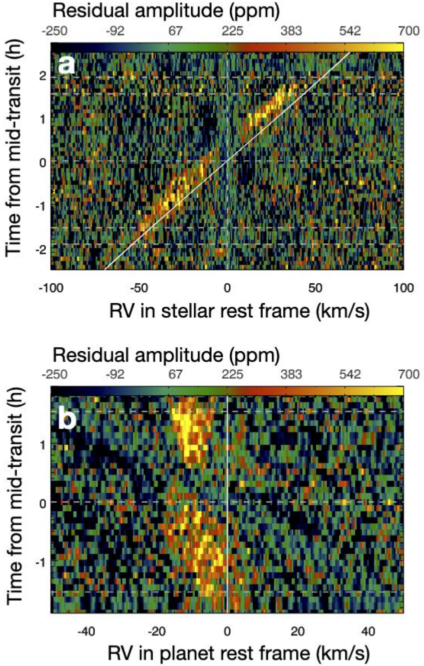
Spectral and **temporal** variations w/ VLT/ESPRESSO

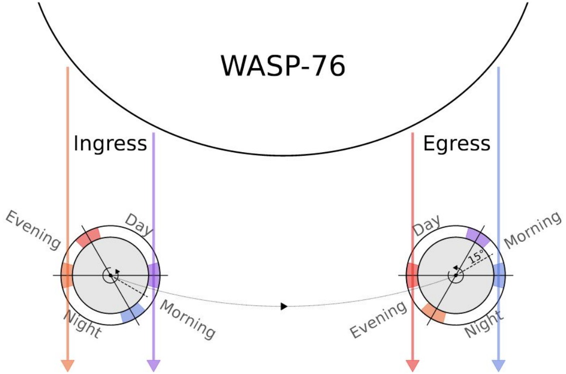
Differentiating day/night sides of evening and morning limbs

Day-to-night wind profiles

T-P profiles and Fe abundance

Ehrenreich+ 2021





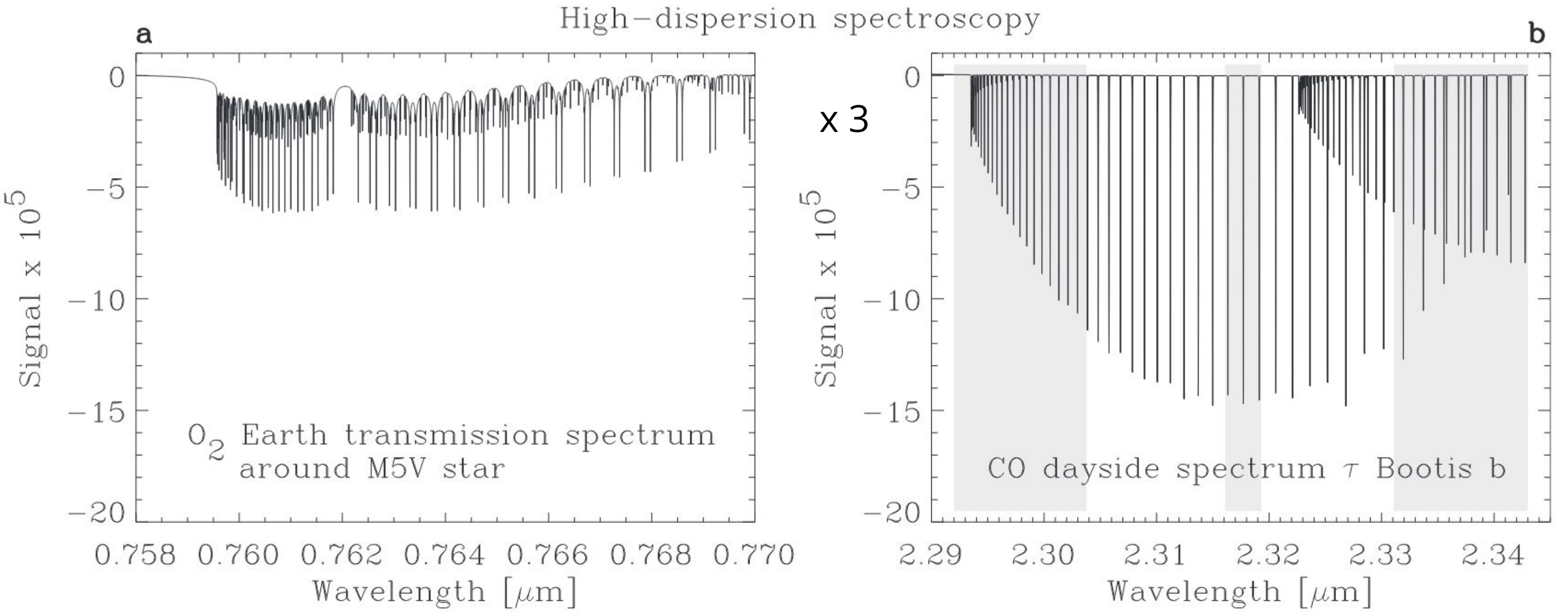
Gandhi+ 2022

Prospects extend to searching for biosignatures (ELTs)

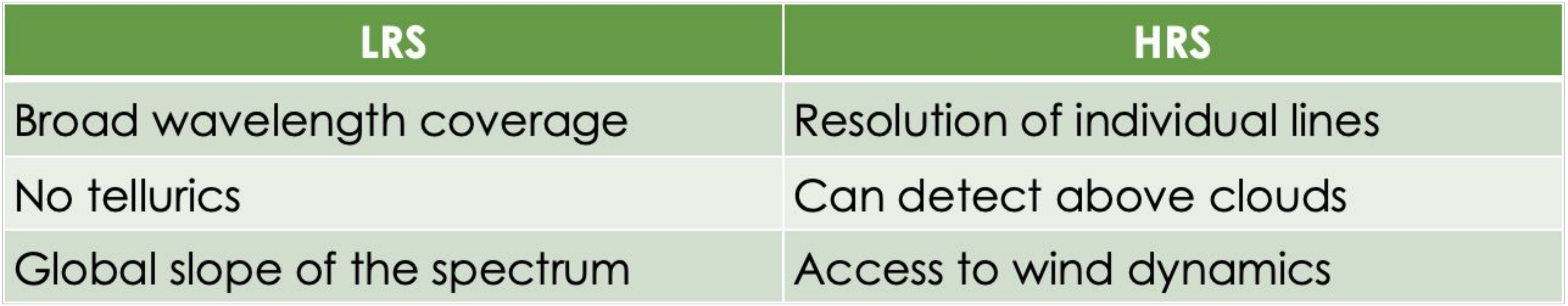
O2 on an Earth-like planet around a nearby M star vs CO/tau Boob

Snellen + (2013) ; see also Hood+ (2020)

This method relies on good line lists



Pros of both LRS and HRS



LRS	HRS
Broad wavelength coverage	Resolution of individual lines
No tellurics	Can detect above clouds
Global slope of the spectrum	Access to wind dynamics

Extended atmospheres

Metastable HeI , very large signatures expected

EUV/X flux, planet density

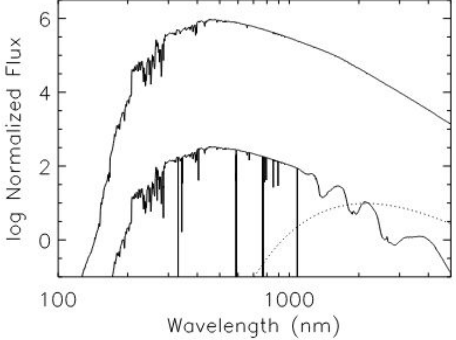
Similar evaporation rate btw GJ3470b (hNep, cold extended atm) and HD189733b (hJup, hot compressed atm)

low mean molec mass for both

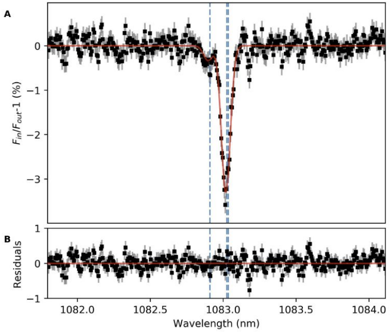
Planet magnetic field possibly plays a role

Allart+17, Salz+18, Palle+20, Lampon+21, Zhang+21, etc.

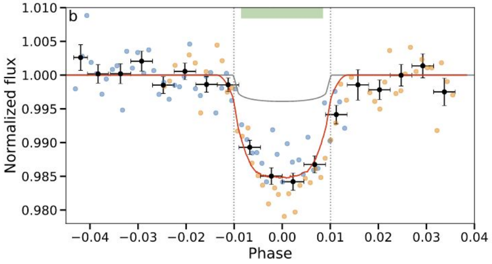
Seager & Sasselov 2000

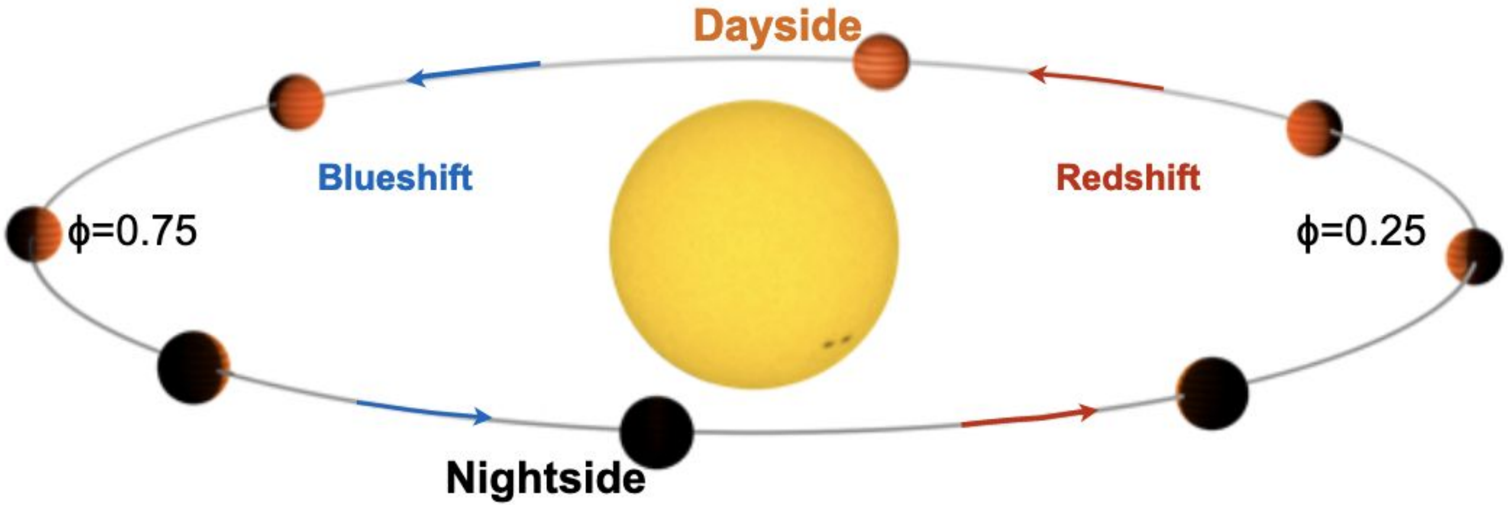


Nortmann+ 18,
in WASP-69,
CARMENES



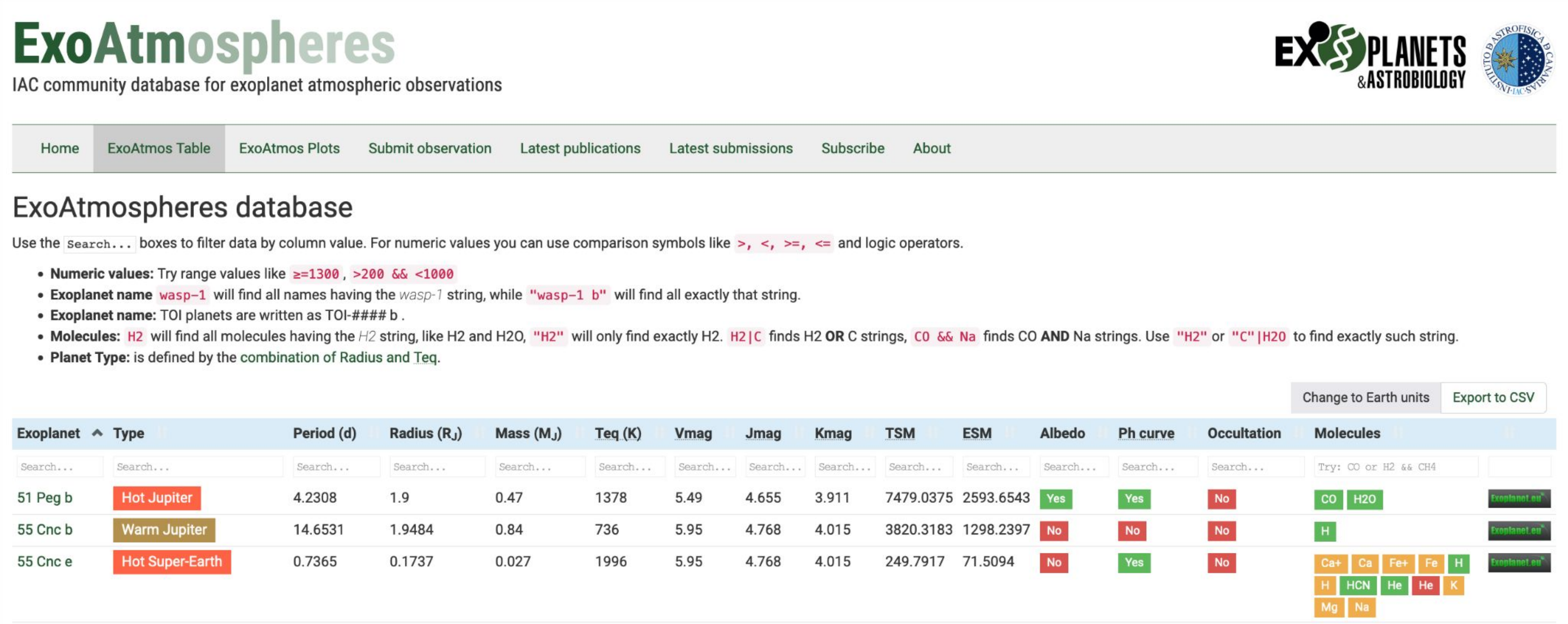
Allart+18
HAT-P-11
1%





Mass ✓
Radius ✓
Orbital parameters ✓

Composition ✓
Temperature-pressure profile ✓
Wind dynamics ✓
Interactions with stellar wind ✓
…



ExoAtmospheres

IAC community database for exoplanet atmospheric observations

ExoAtmospheres database

Use the `Search...` boxes to filter data by column value. For numeric values you can use comparison symbols like `>, <, >=, <=` and logic operators.

- **Numeric values:** Try range values like `≥=1300`, `>200 && <1000`
- **Exoplanet name** `wasp-1` will find all names having the *wasp-1* string, while `"wasp-1 b"` will find all exactly that string.
- **Exoplanet name:** TOI planets are written as TOI-#### b .
- **Molecules:** `H2` will find all molecules having the *H2* string, like H2 and H2O, `"H2"` will only find exactly H2. `H2|C` finds H2 **OR** C strings, `CO && Na` finds CO **AND** Na strings. Use `"H2"` or `"C"|H2O` to find exactly such string.
- **Planet Type:** is defined by the combination of Radius and Teq.

Exoplanet	Type	Period (d)	Radius (R_J)	Mass (M_J)	Teq (K)	Vmag	Jmag	Kmag	TSM	ESM	Albedo	Ph curve	Occultation	Molecules	
Search...	Search...	Search...	Search...	Search...	Search...	Search...	Search...	Search...	Search...	Search...	Search...	Search...	Search...	Try: CO or H2 && CH4	
51 Peg b	Hot Jupiter	4.2308	1.9	0.47	1378	5.49	4.655	3.911	7479.0375	2593.6543	Yes	Yes	No	CO H2O	Exoplanet.eu
55 Cnc b	Warm Jupiter	14.6531	1.9484	0.84	736	5.95	4.768	4.015	3820.3183	1298.2397	No	No	No	H	Exoplanet.eu
55 Cnc e	Hot Super-Earth	0.7365	0.1737	0.027	1996	5.95	4.768	4.015	249.7917	71.5094	No	Yes	No	Ca+ Ca Fe+ Fe H H HCN He He K Mg Na	Exoplanet.eu

118 different planets have been analyzed and **45** different molecules have been detected

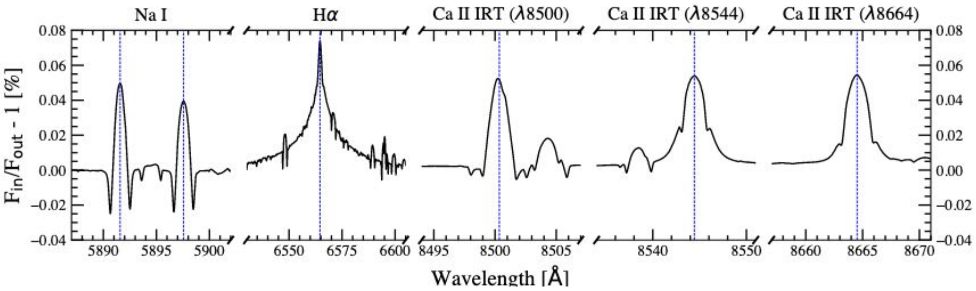
When lines are also in the stellar spectrum

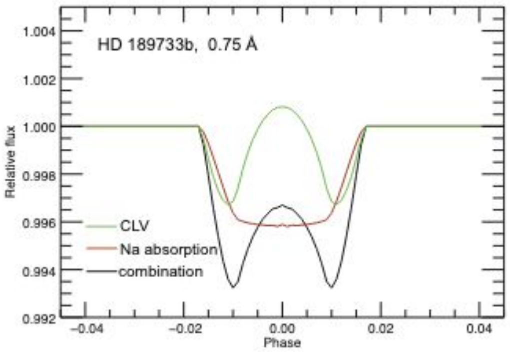
Spurious signature when exoplanet lines also in the star spectrum

Take into account/correct Rossiter effect and center-to-limb variations

Deformation of stellar line cores due to occulting planet

These effects are small when signal in low res (wings, continuum)





E.g. Yan+2017, Casasayas-Barris+2021

Planetary parameters come as function of stellar ones

Radial velocities ⇒ $M_p \sin i / M_s$

Transits ⇒ R_p / R_s

Atmospheres $R_p(\lambda) / R_s(\lambda)$, K_p from K_s

Planetary and stellar metalicities are interesting to compare

So it is critical to have accurate and precise stellar parameters

Spectroscopic: Teff, logg, M/H
Fundamental (models): mass, radius, age

Stars have their own character

Stellar surfaces are not quiet

Stellar activity is wavelength dependent

Stellar surfaces vary at many timescales, from minutes to years

Impact on indirect measurements

There are usually weak correlations between various activity tracers (photosphere, chromosphere and corona)

Characterising rotation period, activity amplitude, flaring level

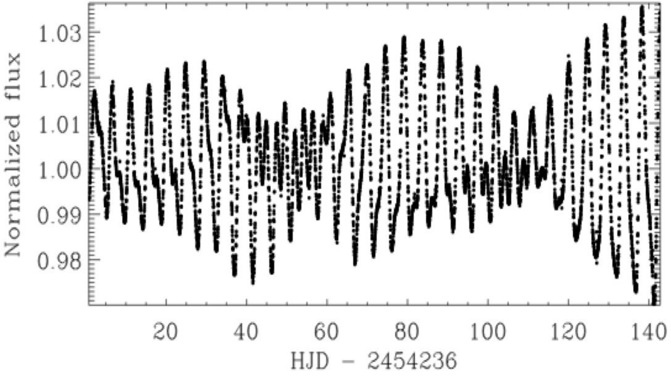
Oscillations (min) **flares (hours)** **rotation (days)** **cycles (years)**

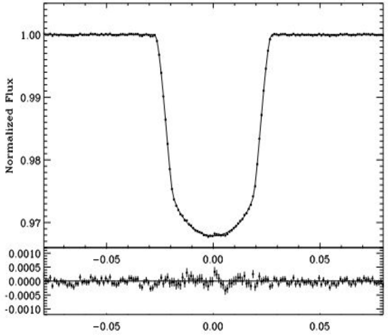
Transits and activity

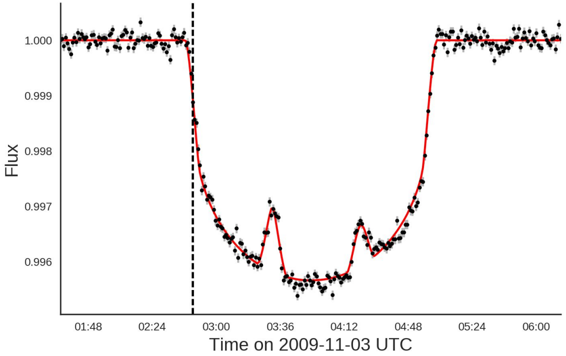
A very active light curve does not prevent the detection and precise characterisation of ~ large planets

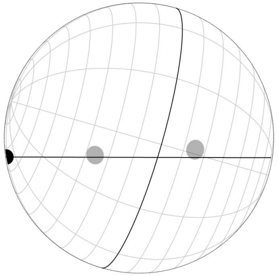
Spot activity and dynamo cycles can be observed through planet-spot crossings

Modification of transit curve by spot crossing is chromatic (temperature contrast)









Alonso+ 2008, Morris+ 2017

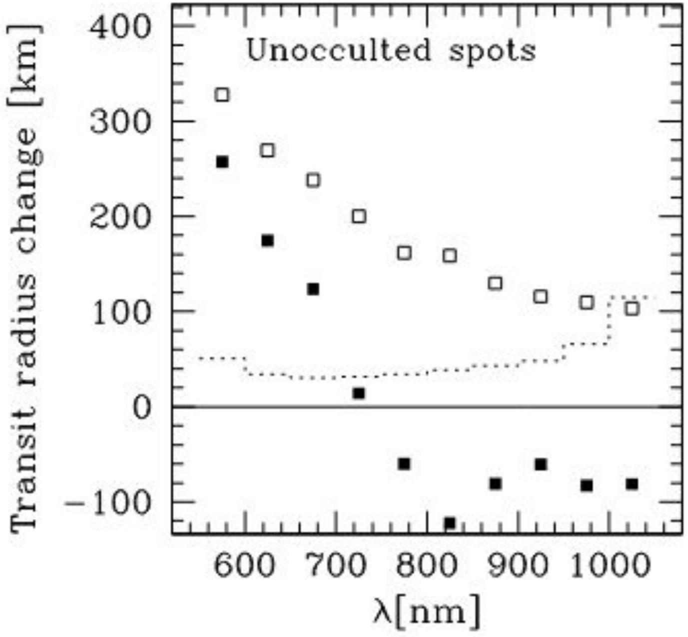
Unocculted structured are worse

Spots not occulted by the planet diminish the star brightness: increase the transit depth

In some cases, faculae can dominate the effect and inverse the impact (decrease transit depth)

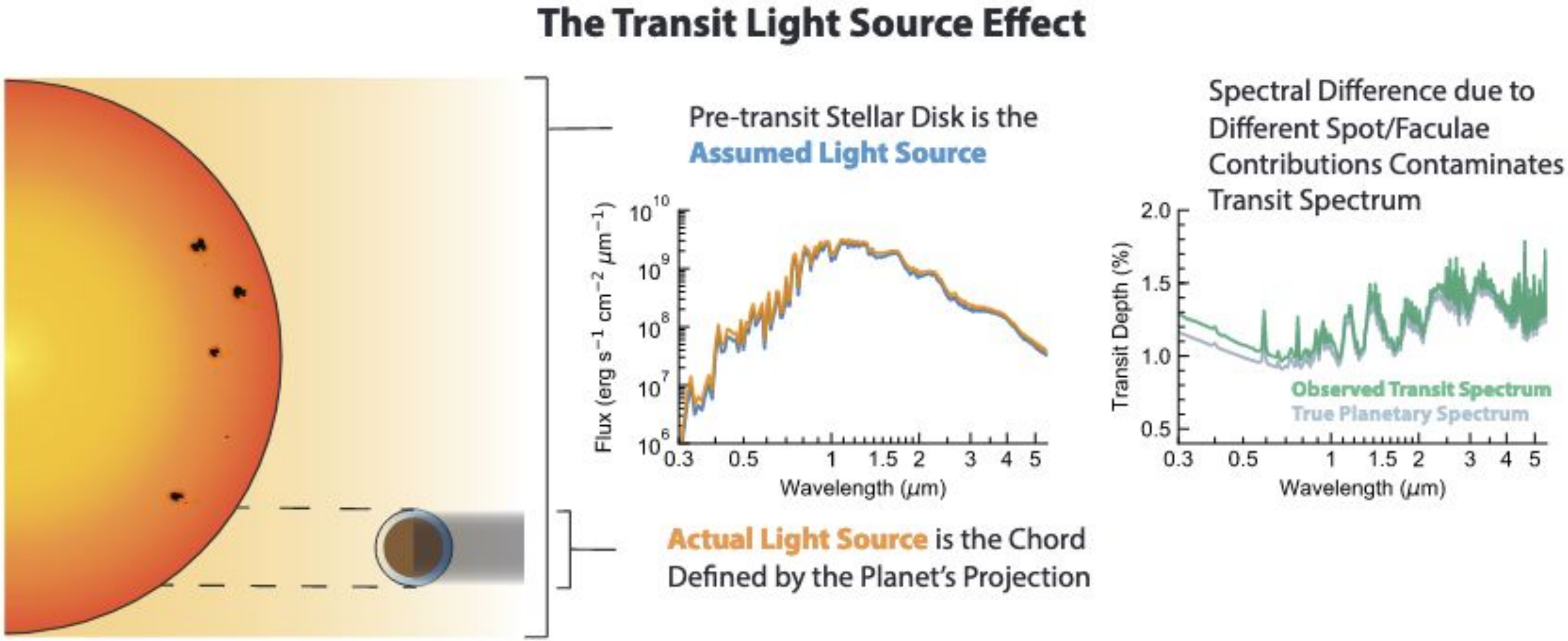
The effect is chromatic

Amplitude of 0.1-1% depending on star's activity level and wavelength



Pont et al 2008 : effect of adding unocculted spots absorbing 1% of the stellar flux (open squares), and of changing the mean temperature of the spots from 4000 K to 3500 K (solid squares).

Not assuming the star is homogeneous



Rackham et al 2018, 2019

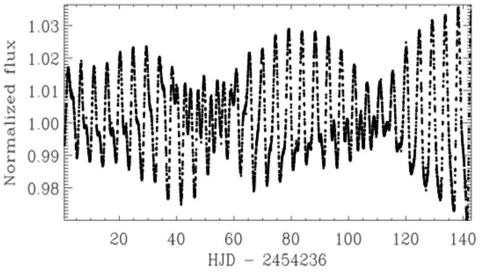
How to characterize stellar activity?

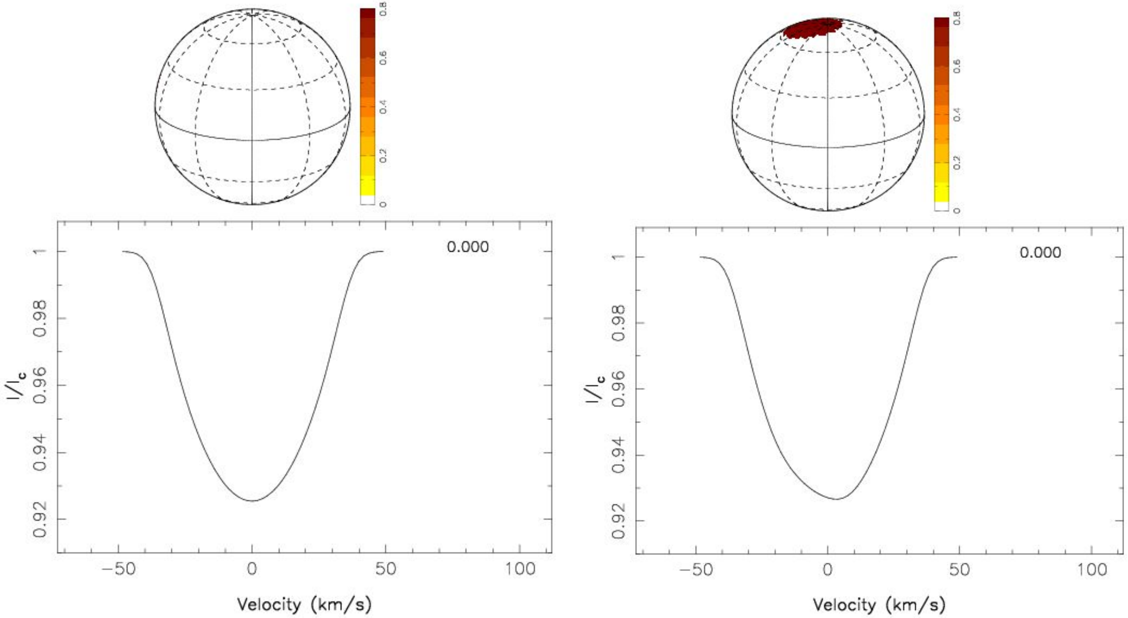
Photometry (space)

Xrays (space)

RV/spect indices (ground)

Warning: degeneracies

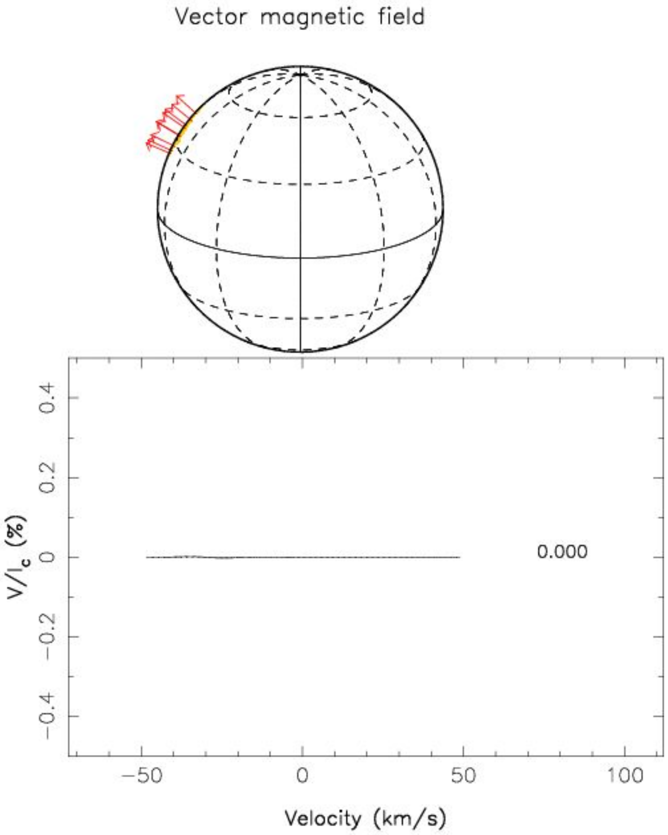




Stellar magnetic field: spectropolarimetry

Stellar magnetic fields are at origin of activity

They can be traced with circular polarization in lines at HRS (Spirou, Espadons, HARPS-POL, PEPSI)



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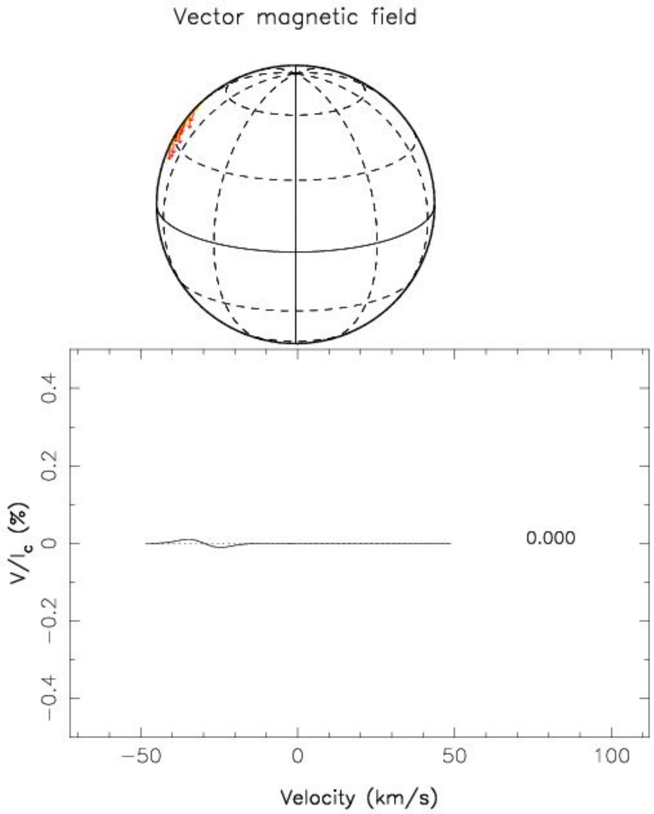


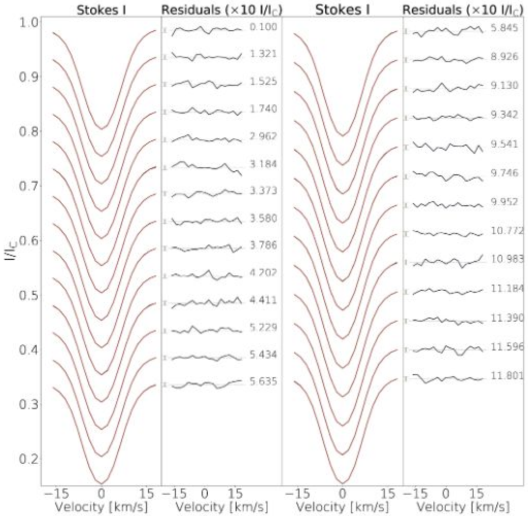
From mean intensity profiles to brightness map

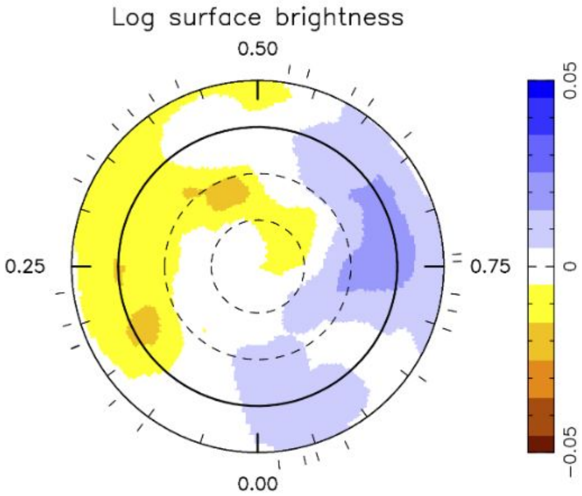
From collections of intensity profiles, find out the distribution of spots and plages

Slow stellar host rotators are more difficult to characterize

AU Mic, SPIRou, HARPS

(Klein+ 2021, 2022)

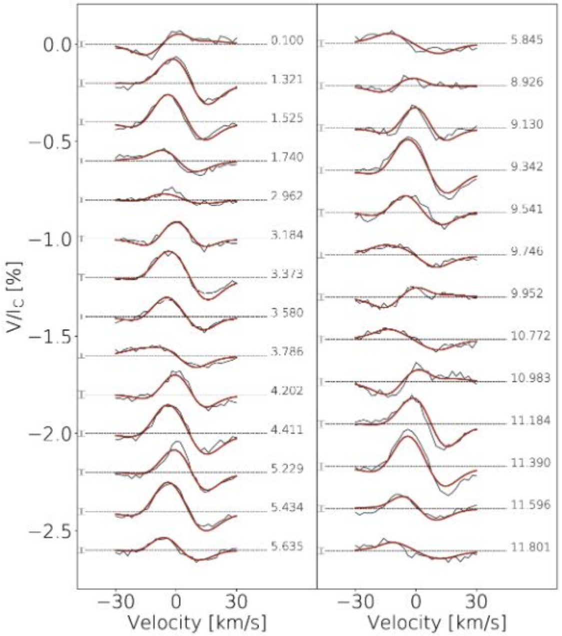


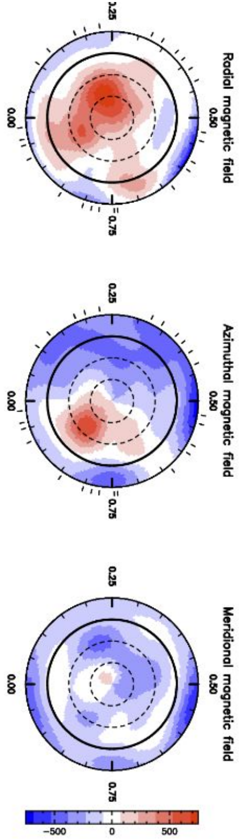


From circular polarisation profiles to magnetic map

From collections of circular polarisation profiles, find out the topology and strength of the stellar magnetic field

Field measurements show a robust measurement of the stellar rotational period

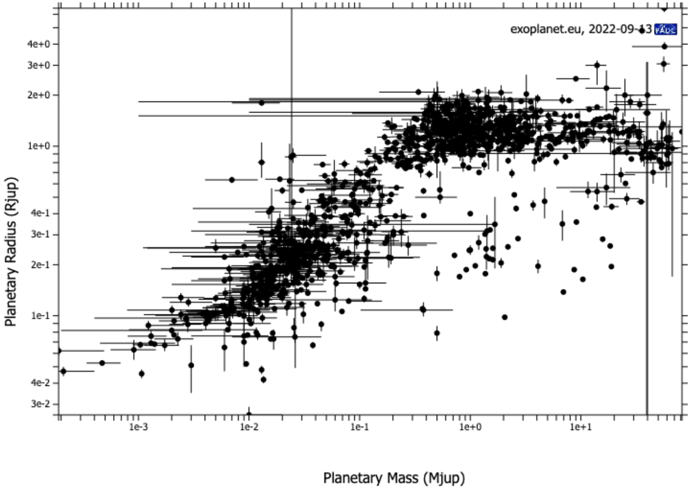




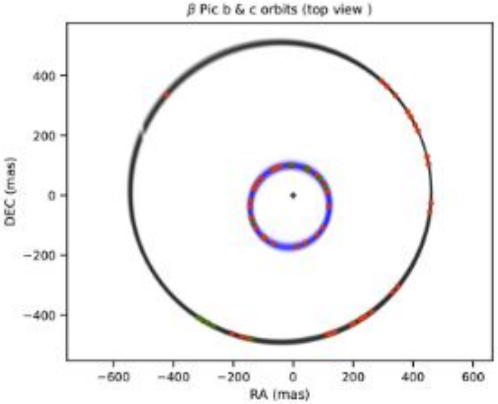
AU Mic, SPIRou (Klein+ 2021)

Exoplanet characterization: complementarities

Planets' radii measurements from space, mass measurements from the ground



Lagrange+ 2020



UV and mid-IR from space, optical and nIR from ground/space

Complementarities

Recent attempts to combine LR and HR nIR observations

Combine space sensitivity and velocity resolution

Make any detection more robust

Underlying model is unique (chemistry, T-P profile, winds...)

Computationally intensive

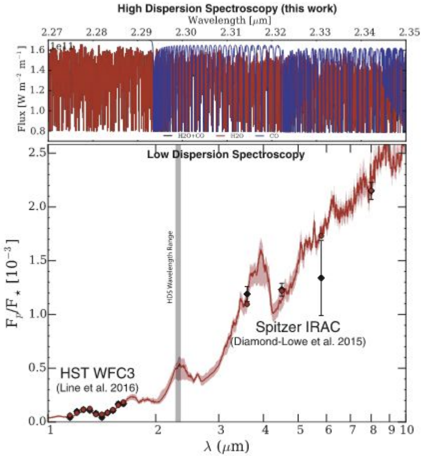


Figure 1. Dayside spectrum of HD 209458 b. Bottom: LDS data (WFC3+*Spitzer*, black diamonds), with the best-fitting low-resolution model spectrum and its 1σ uncertainty overplotted in red. Top: best-fitting HDS model from this analysis, matching the range of CRIRES 2.3 μm data.

Brogi+ 2017

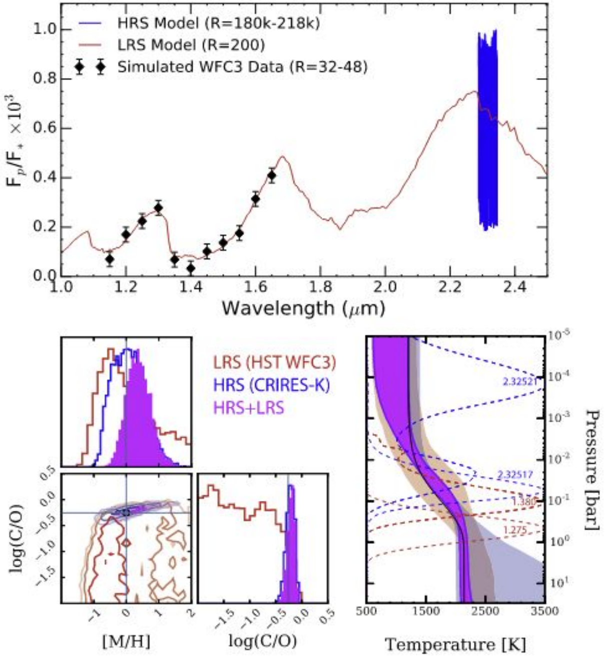


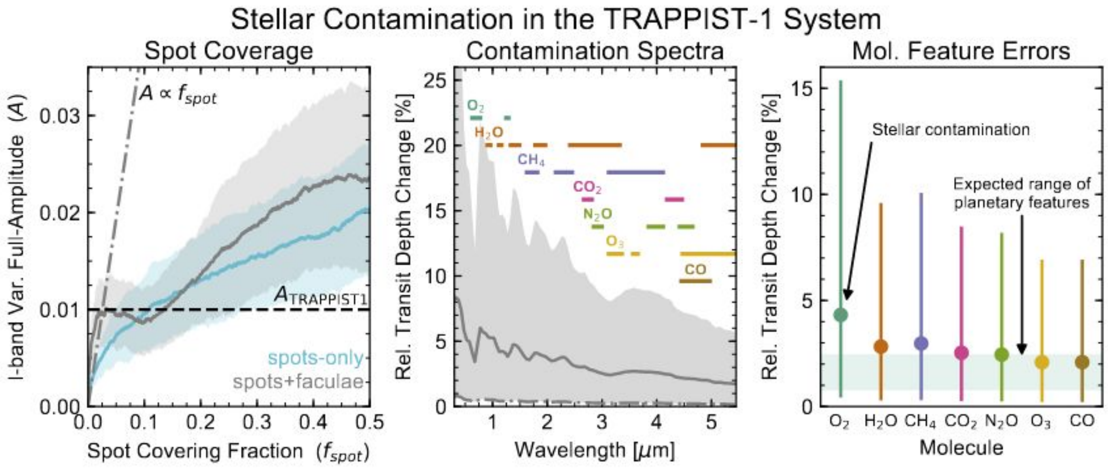
Figure 8. Simulated combined observations with *HST*/WFC3 (black dots, top panel) and VLT/CRIRES around 2.3 μm (blue lines, top panel). The bottom panels show the posterior distributions for planet metallicity ([M/H]), carbon-to-oxygen ratio (C/O), and *T–p* profile (bottom-right panel; summarized with the 68% confidence intervals) obtained by running our framework on the *HST* data alone (red curves), VLT data alone (blue curves), and on the combined data set (magenta curves). The dashed curves (blue = CRIRES, red = WFC3) are the temperature Jacobians at the indicated wavelengths (on and off band/line). In general *HST* WFC3 probes a relatively deep and narrow region. In contrast, the high dynamic range in the CRIRES spectrum permits broad altitude coverage. Combining low- and high-resolution spectra leads to a substantial improvement in the precision of these measurements.

Brogi & Lin 2019

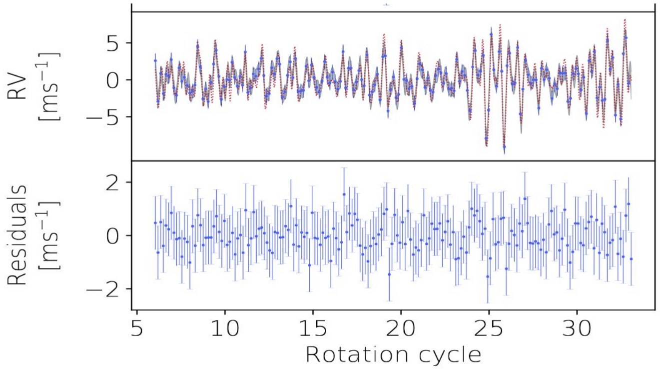
Complementarities

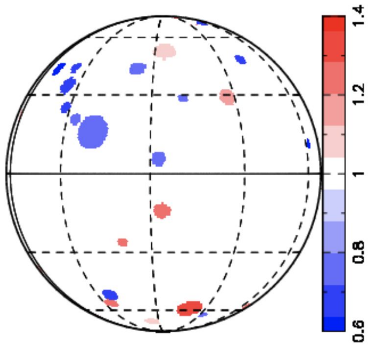
how planetary atmosphere characterization can be hampered by stellar contamination:

need for complementary stellar characterization



Rackham+ 2019: impact of stellar activity on retrieved atm
Klein+ 2019: forward modeling on photometry and RV time series





Perspectives

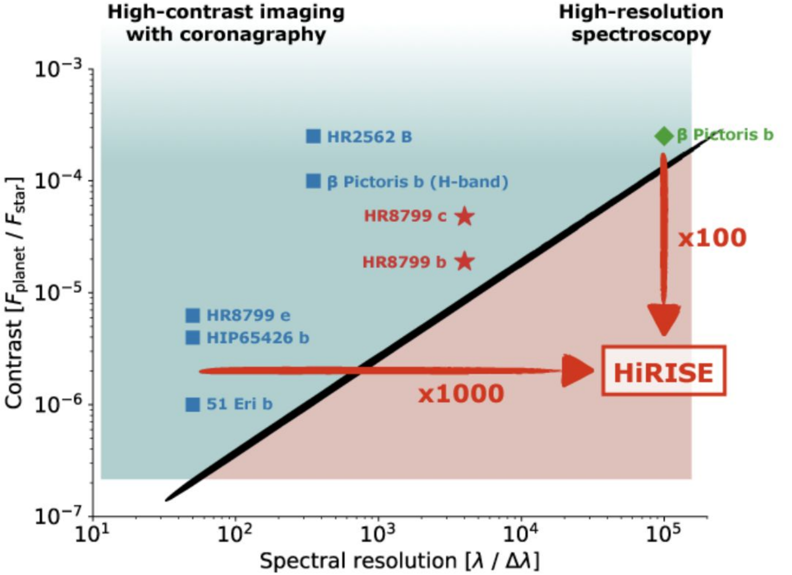
Instrumental innovations from GB telescopes, a bright future

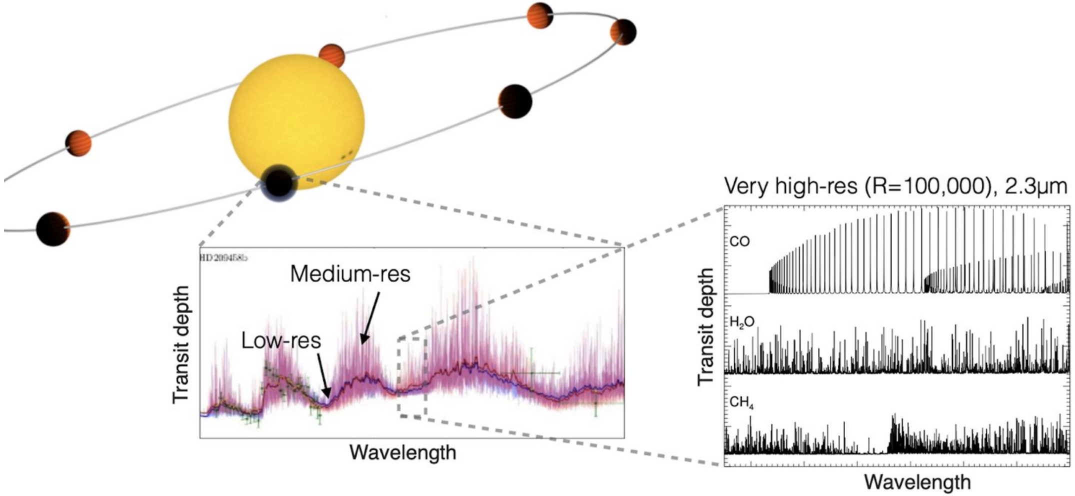
GRAVITY+
SPHERE+
HIRISE (SPHERE+CRIRES+) demonstrator
ESPRESSO+CRIRES+
ELT instrumentation: ANDES, HARMONI, METIS

More combined campaigns would help: one system, night/day sides, simultaneous stellar analyses, combined planet retrieval

Combine high-contrast imaging w/ high-resolution spectroscopy

Combine space low-res wide-band and ground high-res spectroscopies





Take home

- Ground-based instruments have a role to play!
    - Mass measurements (RV & astrometry, indirectly with atm characterization)
    - Orbital param and transit ephemeris (RV, astrom, photometry)
    - Obliquities (RV)
    - Atmospheres in direct spectroscopy (AO+medium resolution IFS)
    - Atmospheres in transmission (HRS)
    - Atmospheres in eclipses (HRS)
    - Atmospheres, planet mass, at superior conjunction (HRS)
- Keep an eye on the host star
- Play the complementarity between methods and instruments

Atmospheres characterization

	Low R, space	High R, ground	
Sensitivity	🟩	🟧	small planets or faint stars
Continuum (low frequencies)	🟩	🟥	Rayleigh scattering, clouds
Telluric contamination	🟩	🟥	nIR, time dependent, wave range
Stellar contamination	🟩🟥	🟥🟩	Rossiter-McLaughling, Activity
Telescope access/instr upgrades	🟧	🟩	Resolution, stability
Degeneracy in atm retrieval	🟥	🟩	Resolving indiv lines, wind dynamics
Length of sequences	🟩	🟧	6h max from the ground/multiT