High-resolution atmospheres of Exoplanets

The role of SONG in TESS times

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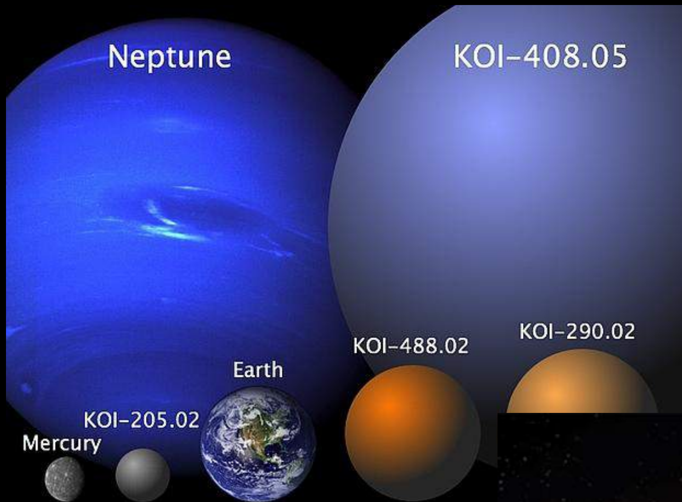
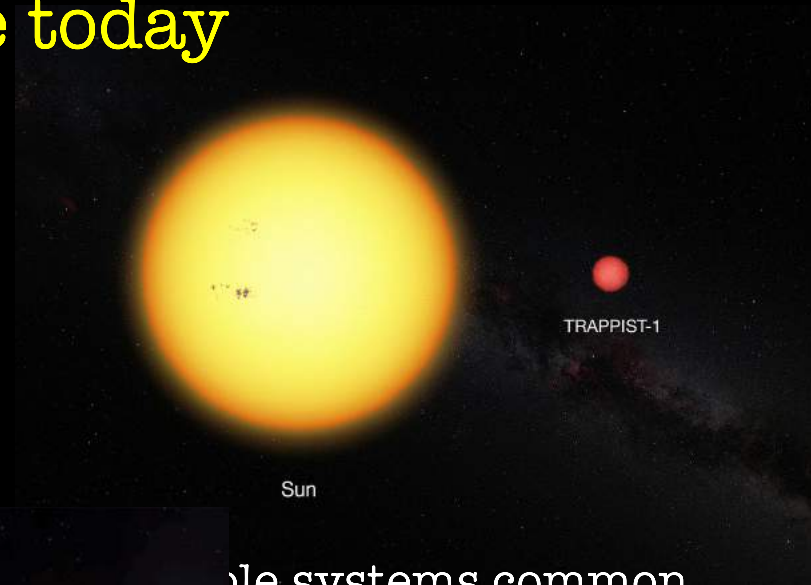
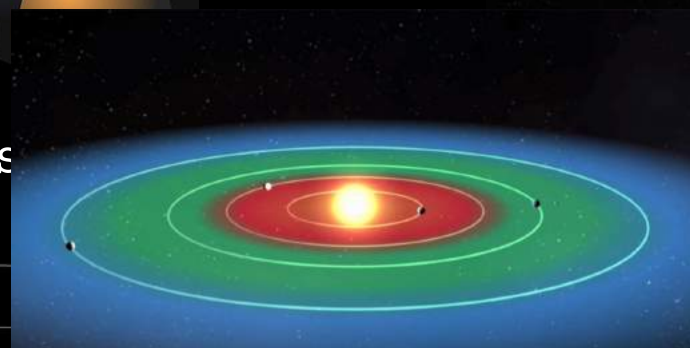
SONG 2018

The Landscape today

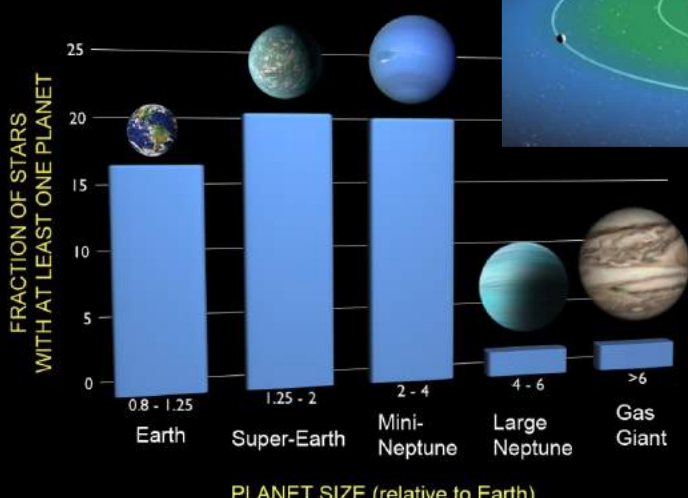


#Planets > #Stars





ple systems common
ecially for M stars

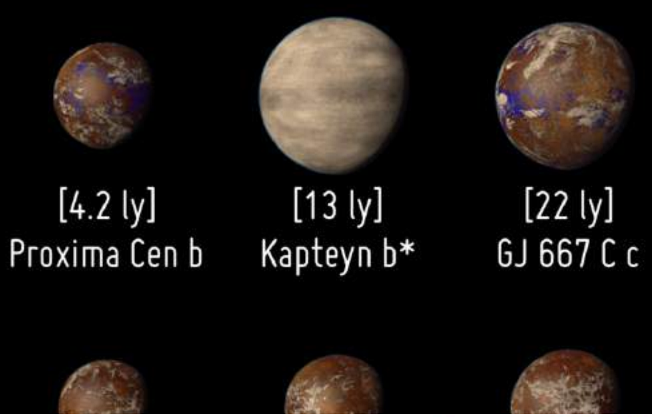


Most common: Super-earths

Even the closest star has a *potentially* habitable planet

Potentially Habitab…

Ranked by Distance from Earth (lig…



Conservative Sample of Potentia…

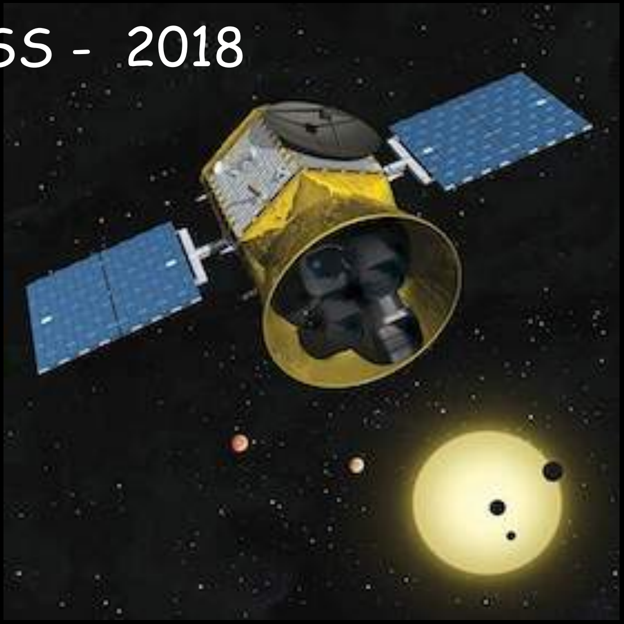
This is a list of the exoplanets that are more likely to have a rocky com… Planet Radius ≤ 1.5 Earth radii or 0.1 < Planet Minimum Mass ≤ 5 Earth… habitable zone). They are represented artistically in the top image.

Name	Type	Mass (M_E)	
001. Proxima Cen b	M-Warm Terran	≥ 1.3	0.…
002. TRAPPIST-1 e	M-Warm Terran	0.6	
003. GJ 667 C c	M-Warm Terran	≥ 3.8	1.…
004. Kepler-442 b	K-Warm Terran	8.2 - 2.3 - 1.0	
005. GJ 667 C f*	M-Warm Terran	≥ 2.7	1.…
006. Kepler-1229 b	M-Warm Terran	9.8 - 2.7 - 1.2	
007. TRAPPIST-1 f	M-Warm Terran	0.7	
008. Kapteyn b*	M-Warm Terran	≥ 4.8	1.…
009. Kepler-62 f	K-Warm Terran	10.2 - 2.8 - 1.2	
010. Kepler-186 f	M-Warm Terran	4.7 - 1.5 - 0.6	
011. GJ 667 C e*	M-Warm Terran	≥ 2.7	1.…
012. TRAPPIST-1 g	M-Warm Terran	1.3	

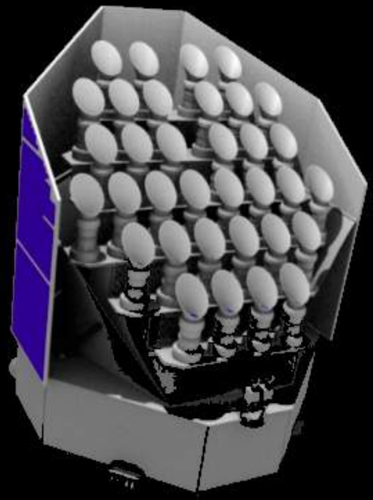
Name	Type	Mass (M_E)	Radius (R_E)	Flux (S_E)	T_{eq} (K)	Period (days)	Distance (ly)	ESI
001. TRAPPIST-1 d	M-Warm Subterran	0.4	0.8	1.15	264	4.0	39	0.90
002. GJ 3323 b (N)	M-Warm Terran	≥ 2.0	0.9 - 1.3 - 1.6	1.21	264	5.4	-	0.89
003. Kepler-438 b	M-Warm Terran	4.0 - 1.3 - 0.6	1.1	1.38	276	35.2	473	0.88
004. GJ 273 b (N)	M-Warm Terran	≥ 2.9	1.0 - 1.4 - 1.8	1.22	267	18.6	12	0.86
005. Kepler-296 e	M-Warm Terran	12.5 - 3.3 - 1.4	1.5	1.22	267	34.1	737	0.85
006. Kepler-62 e	K-Warm Superterran	18.7 - 4.5 - 1.9	1.6	1.10	261	122.4	1200	0.83
007. Kepler-452 b	G-Warm Superterran	19.8 - 4.7 - 1.9	1.6	1.11	261	384.8	1402	0.83
008. K2-72 e	M-Warm Terran	9.8 - 2.7 - 1.2	1.4	1.46	280	24.2	181	0.82
009. GJ 832 c	M-Warm Superterran	≥ 5.4	1.2 - 1.7 - 2.2	1.00	253	35.7	16	0.81
010. K2-3 d	M-Warm Terran	11.1	1.5	1.46	280	44.6	137	0.80
011. Kepler-1544 b	K-Warm Superterran	31.7 - 6.6 - 2.6	1.8	0.90	248	168.8	1138	0.80
012. Kepler-283 c	K-Warm Superterran	35.3 - 7.0 - 2.8	1.8	0.90	248	92.7	1741	0.79
013. tau Cet e*	G-Warm Terran	≥ 4.3	1.1 - 1.6 - 2.0	1.51	282	168.1	12	0.78
014. Kepler-1410 b	K-Warm Superterran	31.7 - 6.6 - 2.6	1.8	1.34	274	60.9	1196	0.78
015. GJ 180 c*	M-Warm Superterran	≥ 6.4	1.3 - 1.8 - 2.3	0.79	239	24.3	38	0.77
016. Kepler-1638 b	G-Warm Superterran	42.7 - 7.9 - 3.1	1.9	1.39	276	259.3	2866	0.76
017. Kepler-440 b	K-Warm Superterran	41.2 - 7.7 - 3.1	1.9	1.43	273	101.1	851	0.75
018. GJ 180 b*	M-Warm Superterran	≥ 8.3	1.3 - 1.9 - 2.4	1.23	268	17.4	38	0.75
019. Kepler-705 b	M-Warm Superterran	? - 12.7 - 4.8	2.1	0.83	243	56.1	818	0.74
020. HD 40307 g*	K-Warm Superterran	≥ 7.1	1.3 - 1.8 - 2.3	0.68	227	197.8	42	0.74
021. GJ 163 c	M-Warm Superterran	≥ 7.3	1.3 - 1.8 - 2.4	0.66	230	25.6	49	0.73
022. Kepler-61 b	K-Warm Superterran	? - 13.8 - 5.2	2.2	1.27	267	59.9	1063	0.73
023. K2-18 b	M-Warm Superterran	? - 16.5 - 6.0	2.2	0.92	250	32.9	111	0.73
024. Kepler-1606 b	G-Warm Superterran	? - 11.9 - 4.5	2.1	1.41	277	196.4	2869	0.73
025. Kepler-1090 b	G-Warm Superterran	? - 16.8 - 6.1	2.3	1.20	267	198.7	2289	0.72
026. Kepler-443 b	K-Warm Superterran	? - 19.5 - 7.0	2.3	0.89	247	177.7	2540	0.71
027. Kepler-22 b	G-Warm Superterran	? - 20.4 - 7.2	2.4	1.11	261	289.9	619	0.71
028. GJ 422 b*	M-Warm Superterran	≥ 9.9	1.4 - 2.0 - 2.6	0.68	231	26.2	41	0.71
029. K2-9 b	M-Warm Superterran	? - 16.8 - 6.1	2.2	1.38	276	18.4	359	0.71
030. Kepler-1552 b	K-Warm Superterran	? - 25.2 - 8.7	2.5	1.11	261	184.8	2015	0.70
031. GJ 3293 c*	M-Warm Superterran	≥ 8.6	1.4 - 1.9 - 2.5	0.60	223	48.1	59	0.70
032. Kepler-1540 b	K-Warm Superterran	? - 26.2 - 9.0	2.5	0.92	250	125.4	854	0.70
033. Kepler-298 d	K-Warm Superterran	? - 26.8 - 9.1	2.5	1.29	271	77.5	1545	0.68
034. KIC-5522786 b	A-Warm Terran	5.8 - 1.8 - 0.8	1.2	2.70	305	757.2	-	0.67
035. Kepler-174 d	K-Warm Superterran	? - 14.8 - 5.5	2.2	0.43	206	247.4	1174	0.61
036. Kepler-296 f	M-Warm Superterran	28.7 - 6.1 - 2.5	1.8	0.34	194	63.3	737	0.60
037. GJ 682 c*	M-Warm Superterran	≥ 8.7	1.4 - 1.9 - 2.5	0.37	198	57.3	17	0.59
038. Wolf 1061 d	M-Warm Superterran	≥ 5.2	1.2 - 1.7 - 2.2	0.28	182	67.3	14	0.56
039. KOI-4427 b*	M-Warm Superterran	38.5 - 7.4 - 3.0	1.8	0.24	179	147.7	782	0.52

Focus of searches: brightest and closest stars

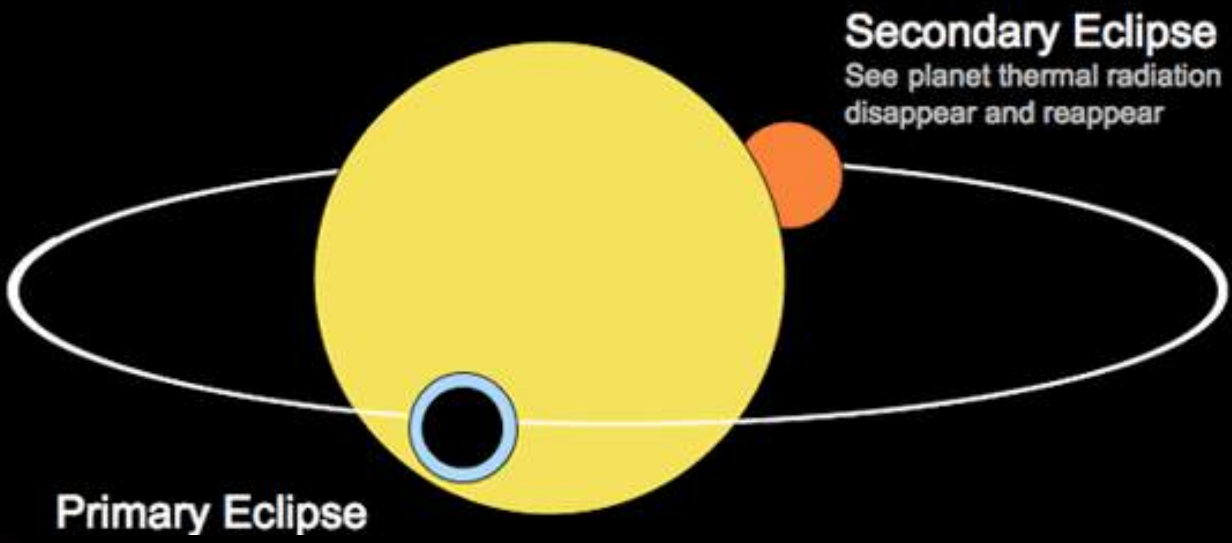
TESS - 2018

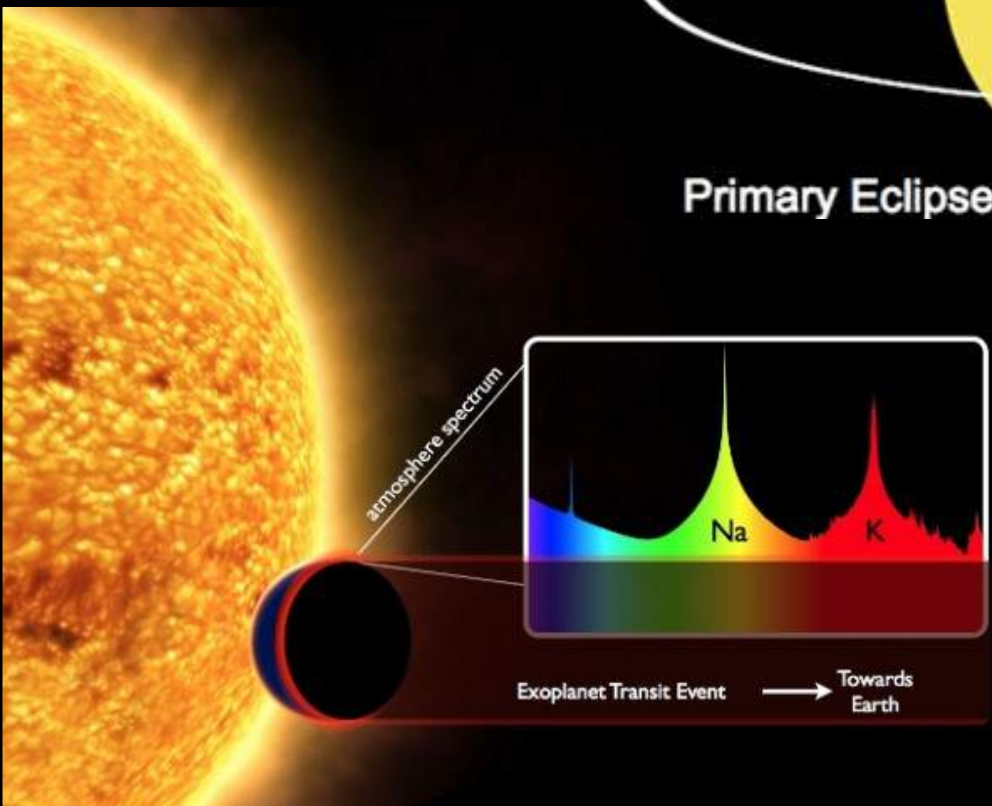


PLATO - 2025



Transiting Planets: first detections of planetary atmospheres

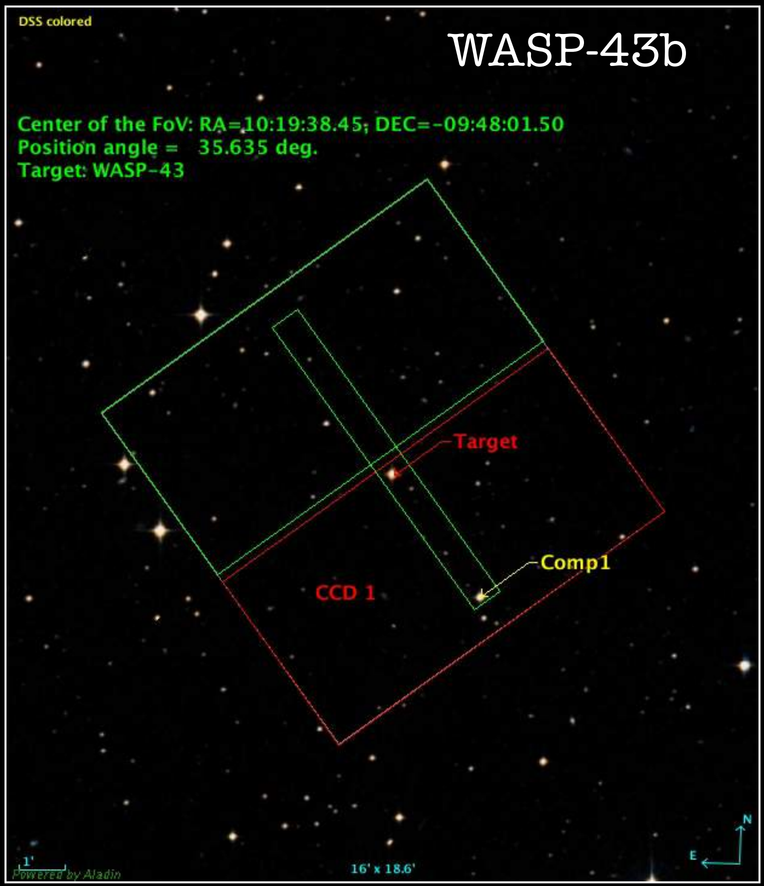


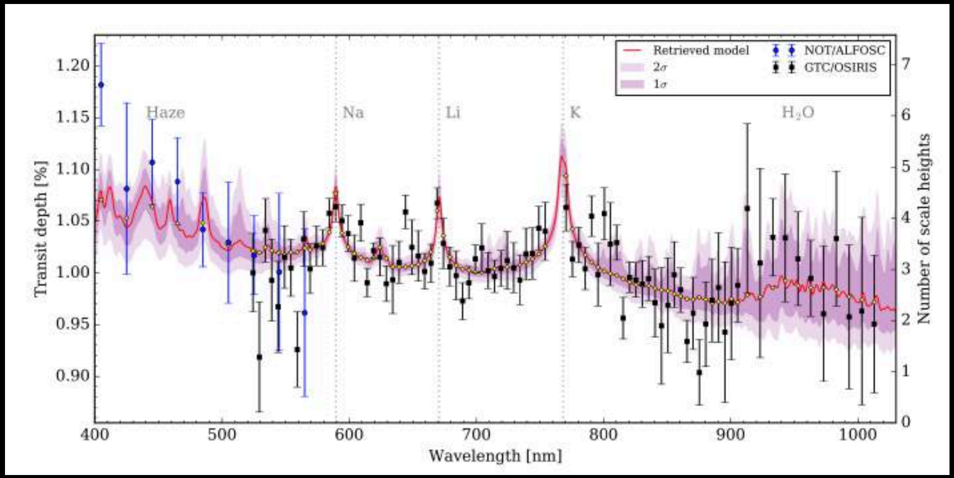


What can be learned:

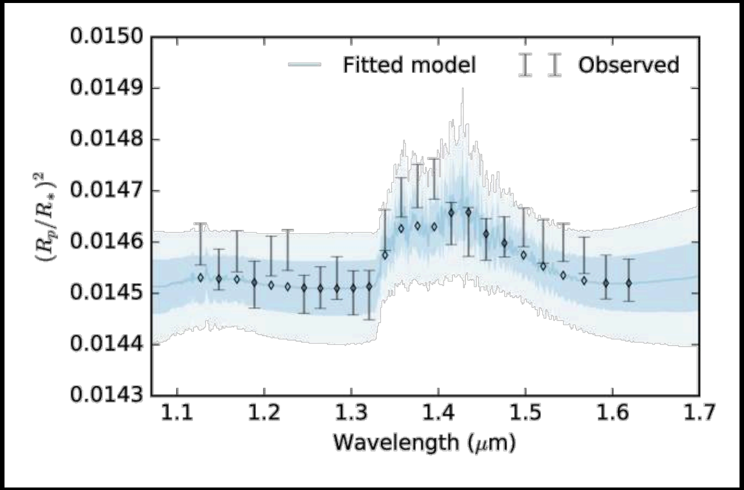
- Chemical composition
- Relative chemical abundancies
- Upper-atmosphereic T-P profiles
- Clouds/hazes

Low resolution Differential spectroscopy from groung absolute from HST





Chen et al, 2018



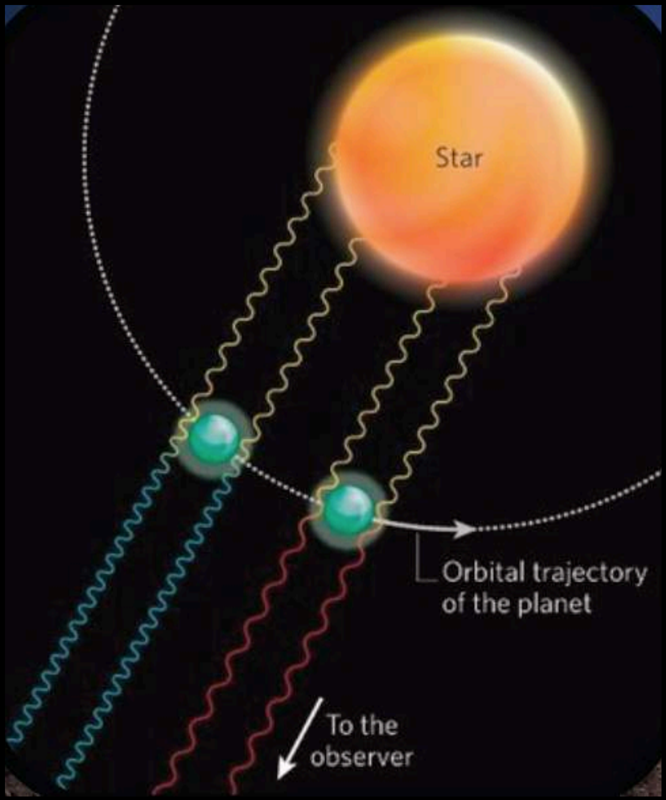
Tsiaras et al, 2015

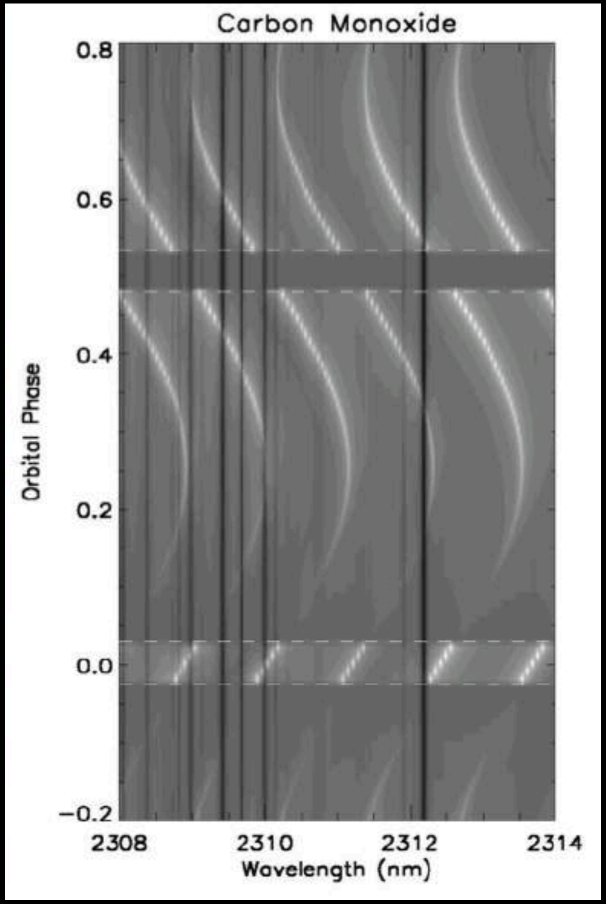
Exoplanet Atmospheres

High spectral resolution

Getting rid of the atmosphere:

The planet moves at different speed than the star





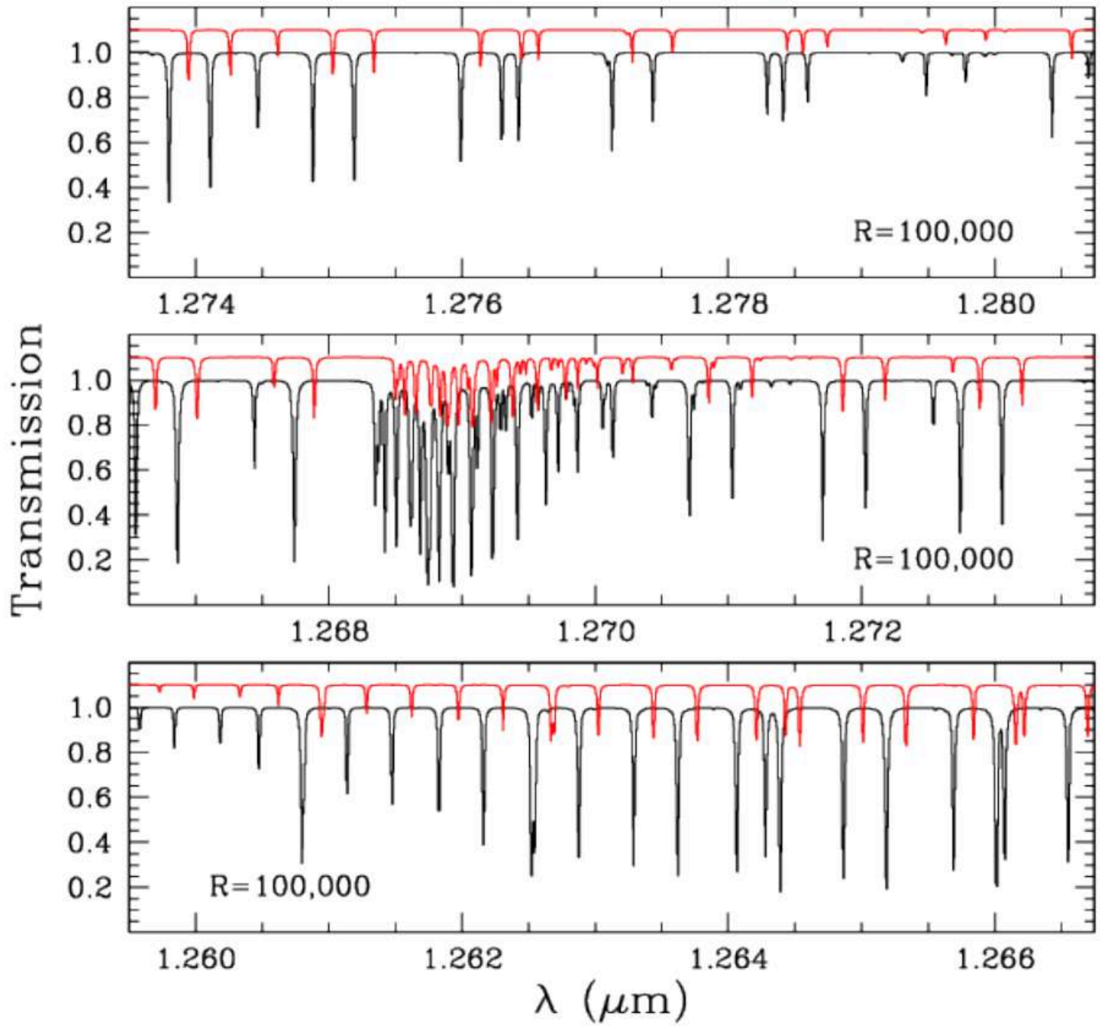
Snellen, 2010

Habitable earths: life tracers

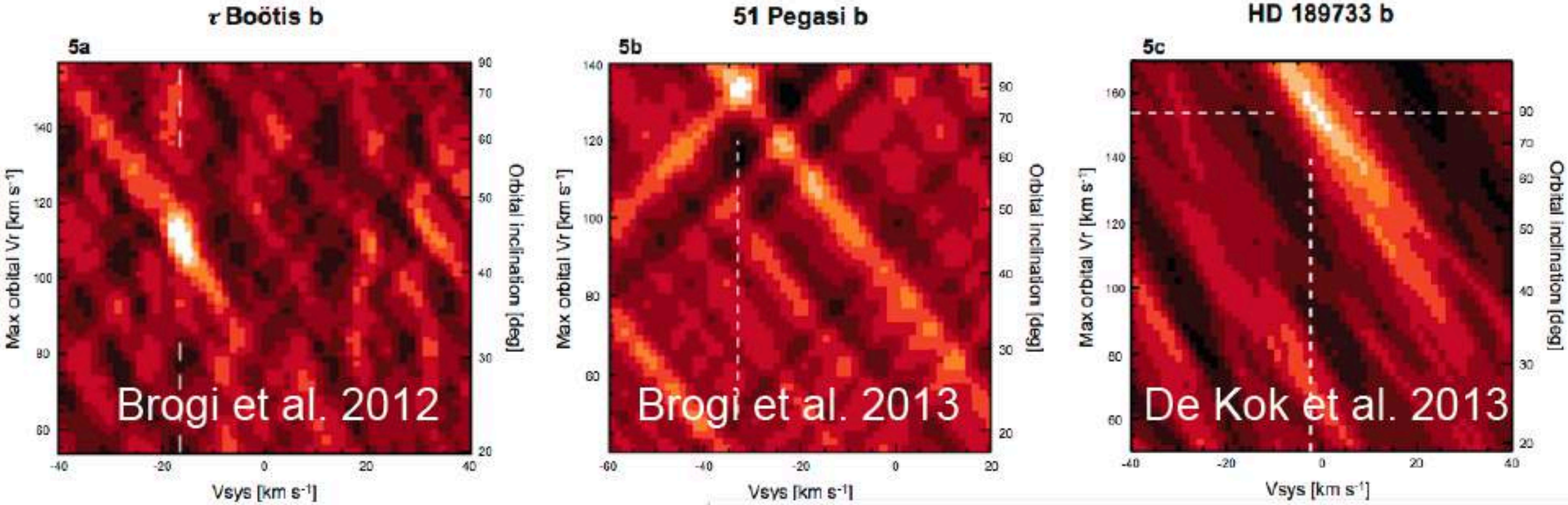
Need HR to disentangle from Earth spectrum

Need ELT to collect enough photons

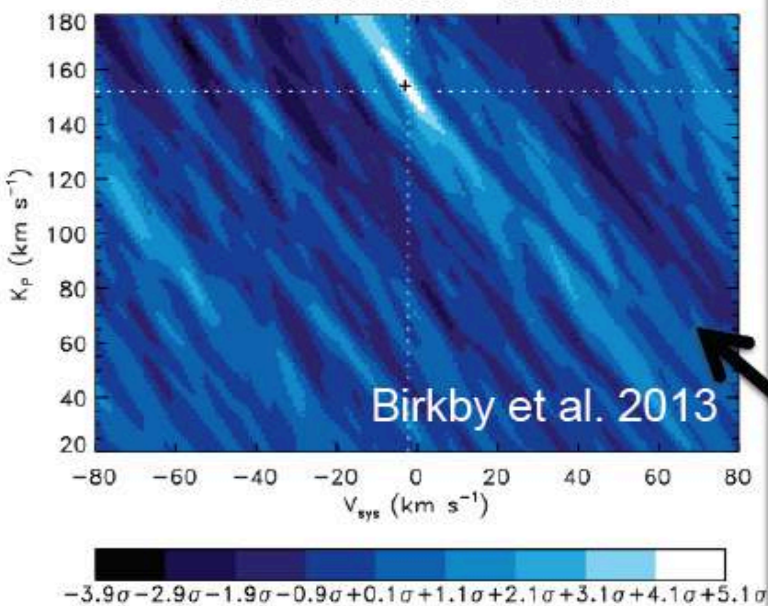
black: Earth atmosphere
red: exo-planet atmosphere



CO in dayside spectra of hot Jupiters



HD189733b - Water!



CRIRES@VLT Upgrade (2015) →
6x larger wavelength coverage
CO, H2O, CH4, NH3, H3+,…..

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

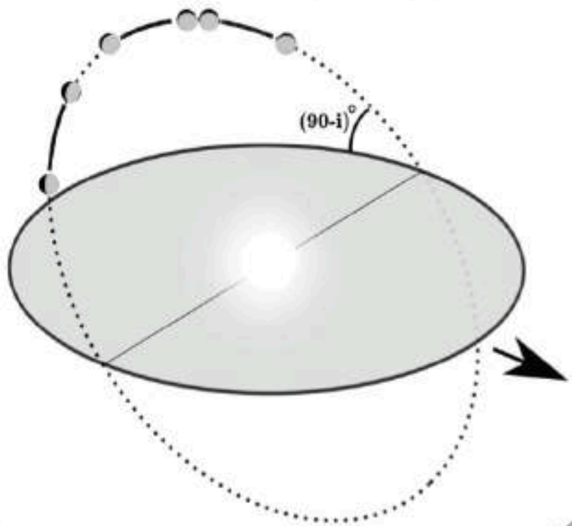
Now also with Keck!
Lockwood et al. 2014

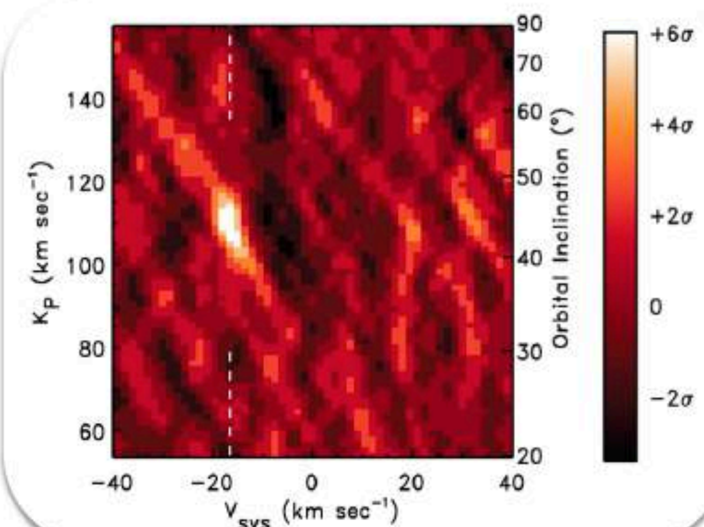
Stepping-stone for the ELTs

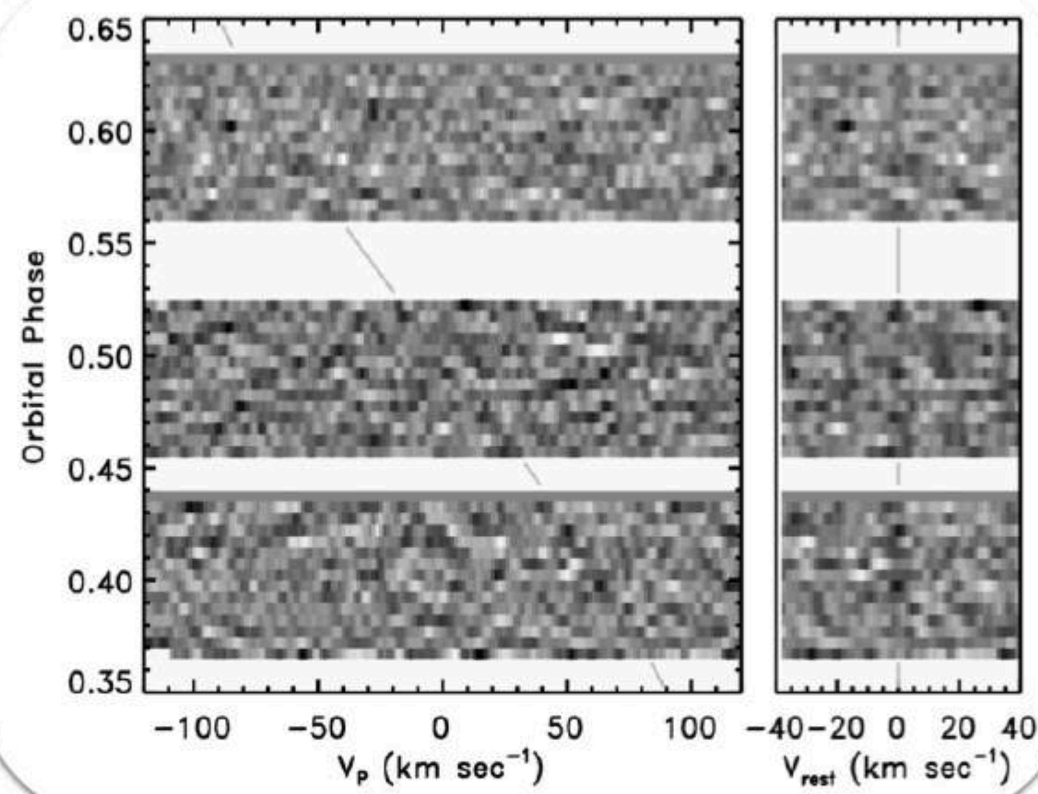
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

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

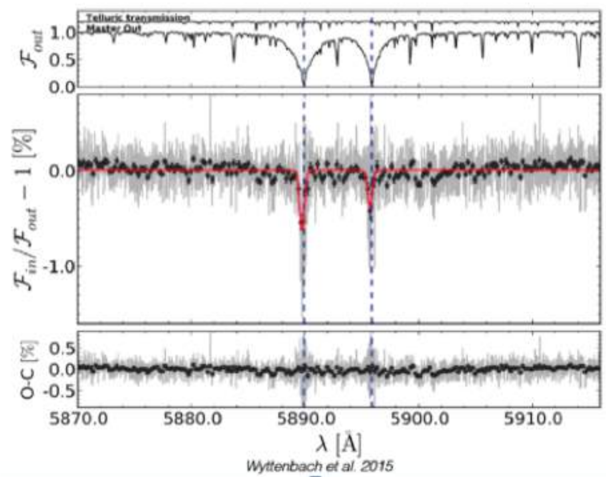
First detection of non-transiting planet→ inclination, mass





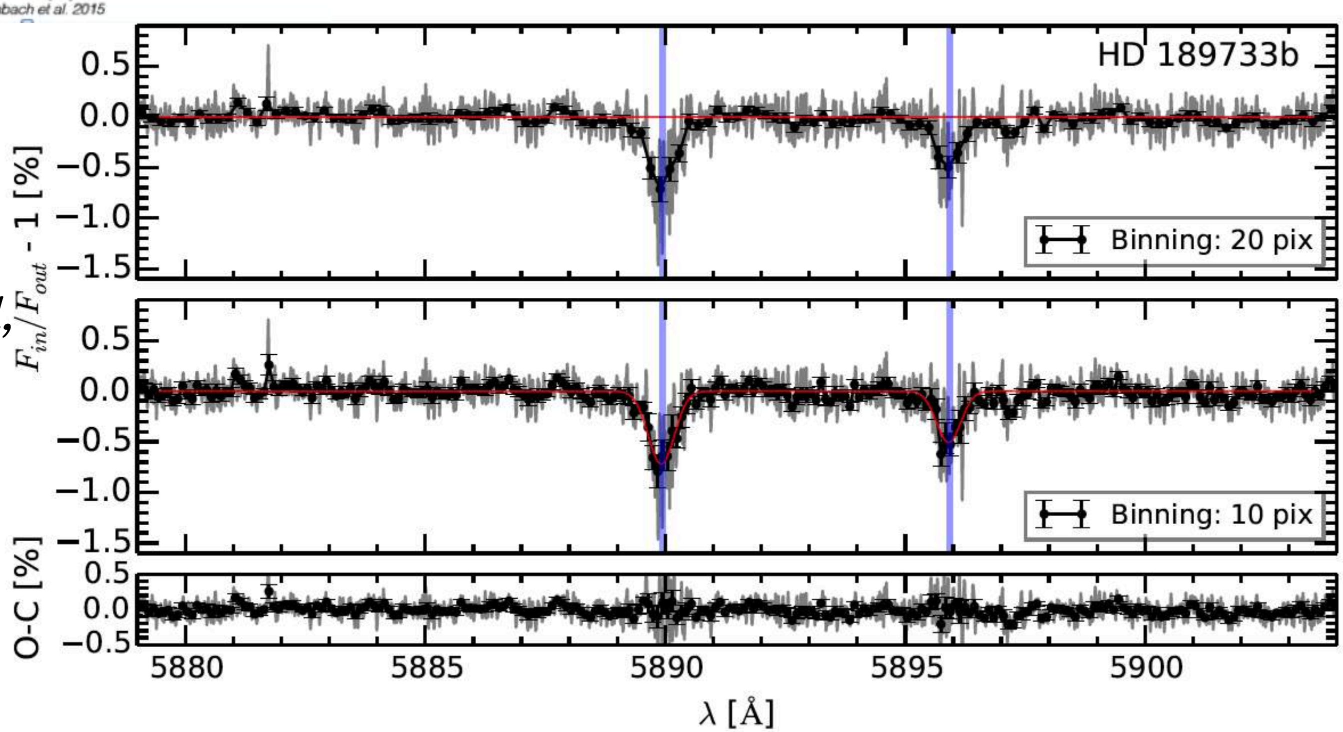


Transmission spectroscopy in the Visible

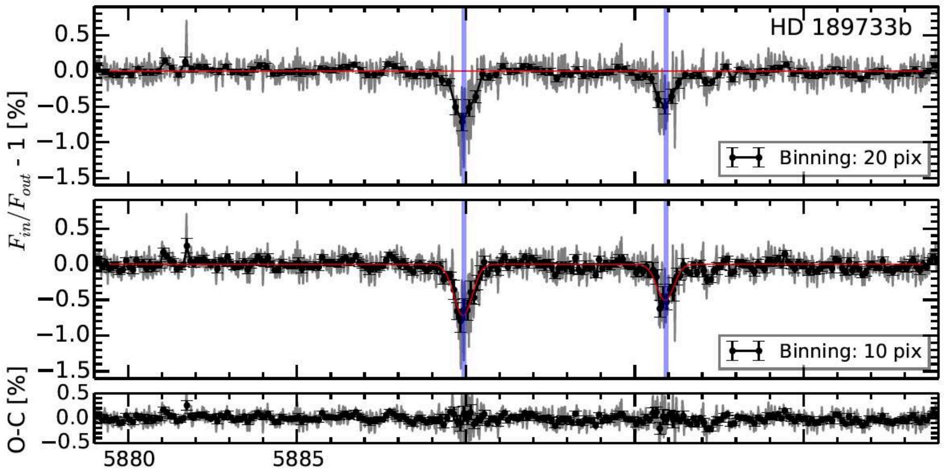


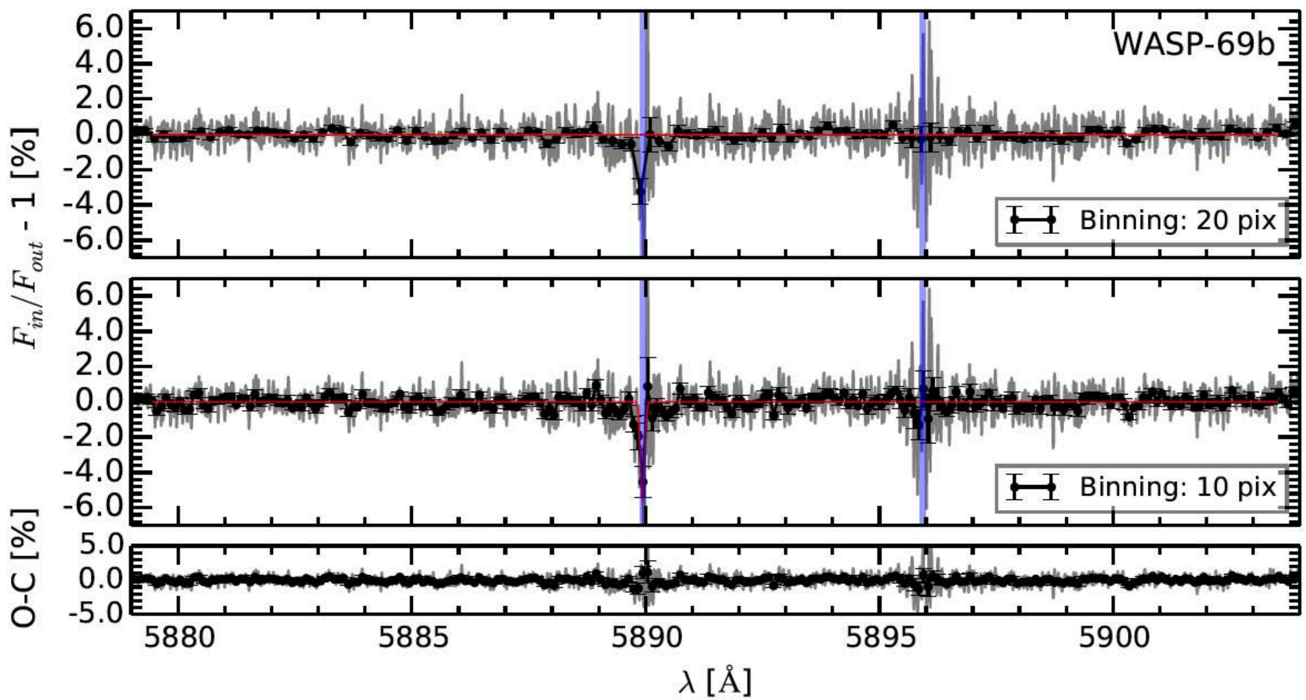
Wyttenbach et al, 2016

Casasayas et al, 2017



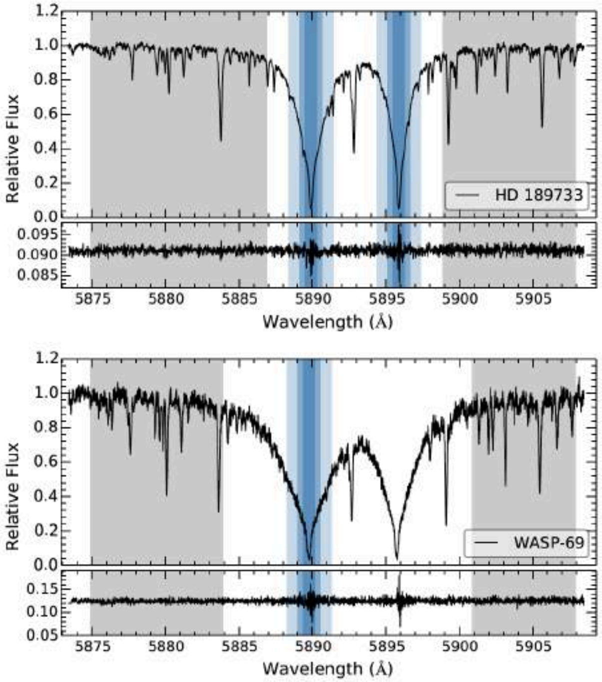
Transmission spectroscopy in the visible

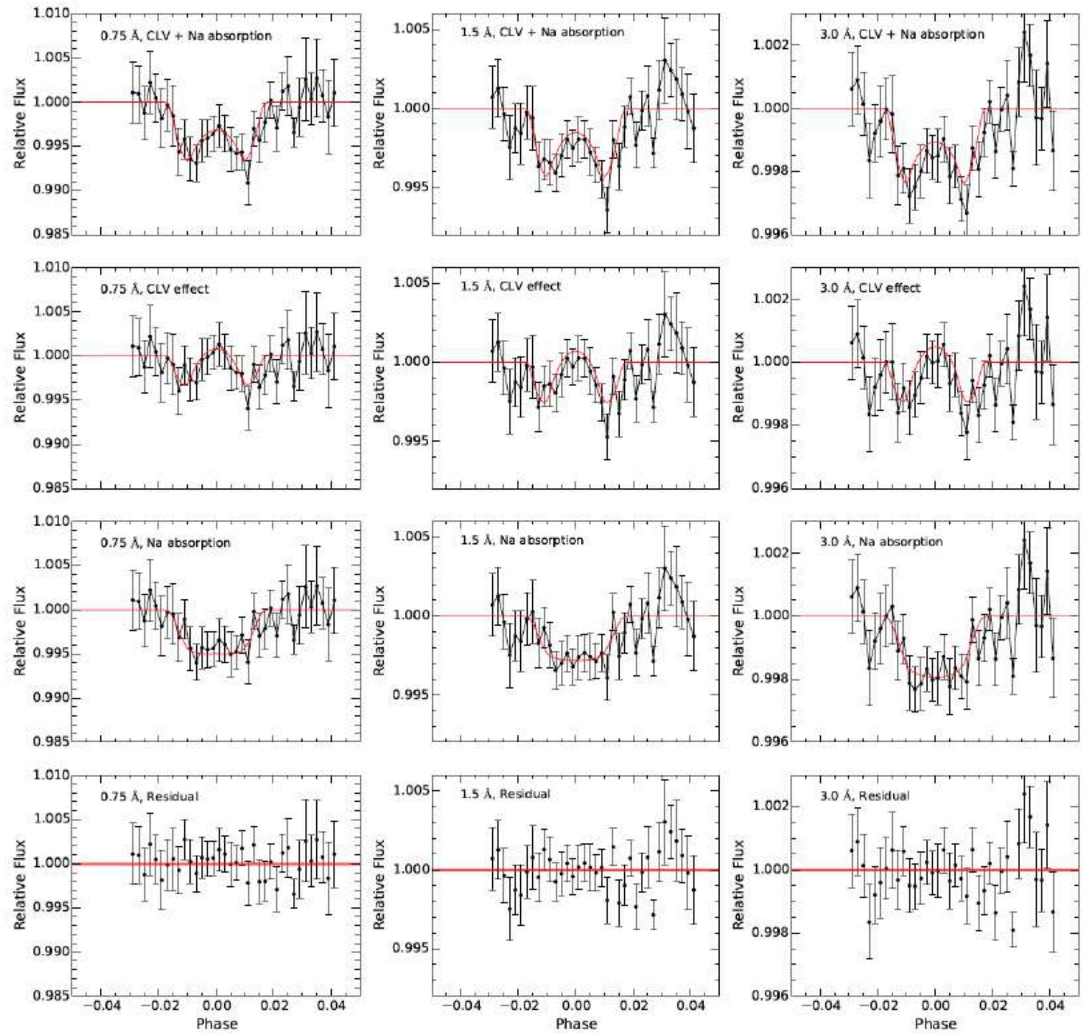




Casasayas et al, 2017

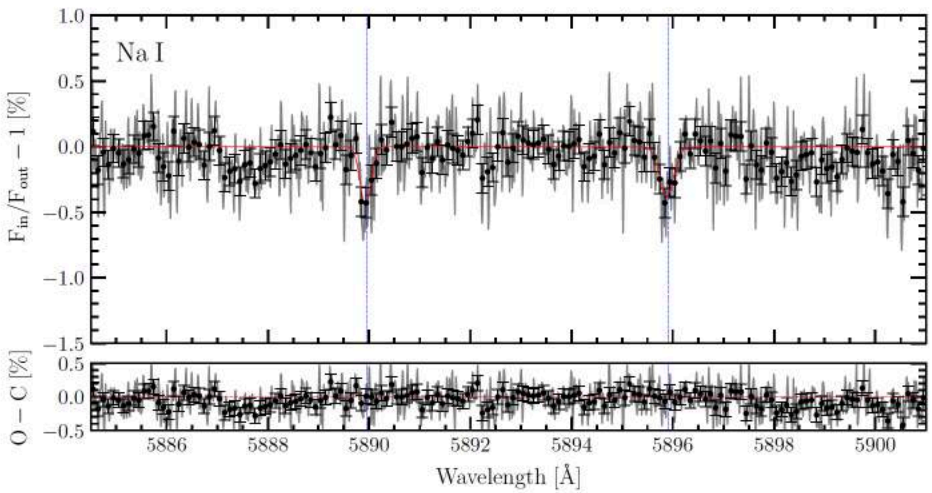
Transmission spectroscopy in the visible



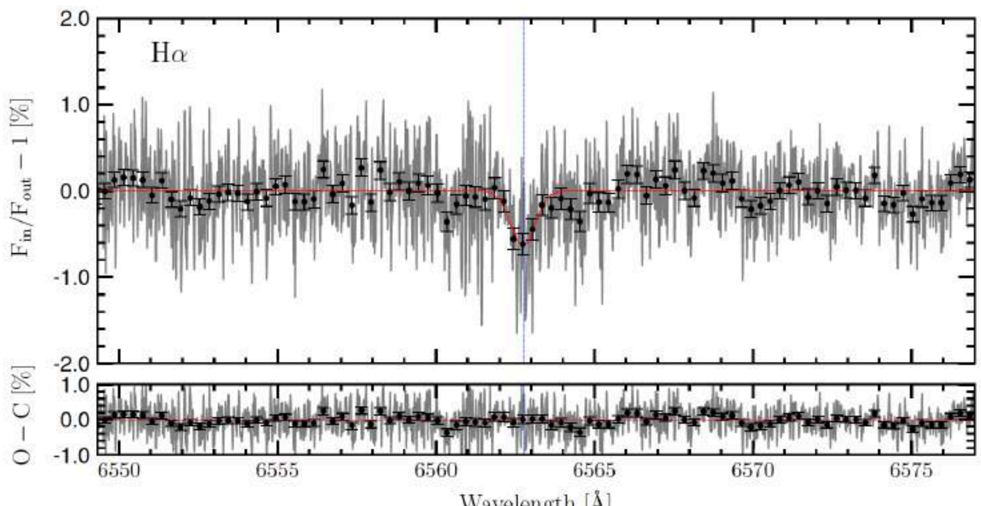


Casasayas et al, 2017

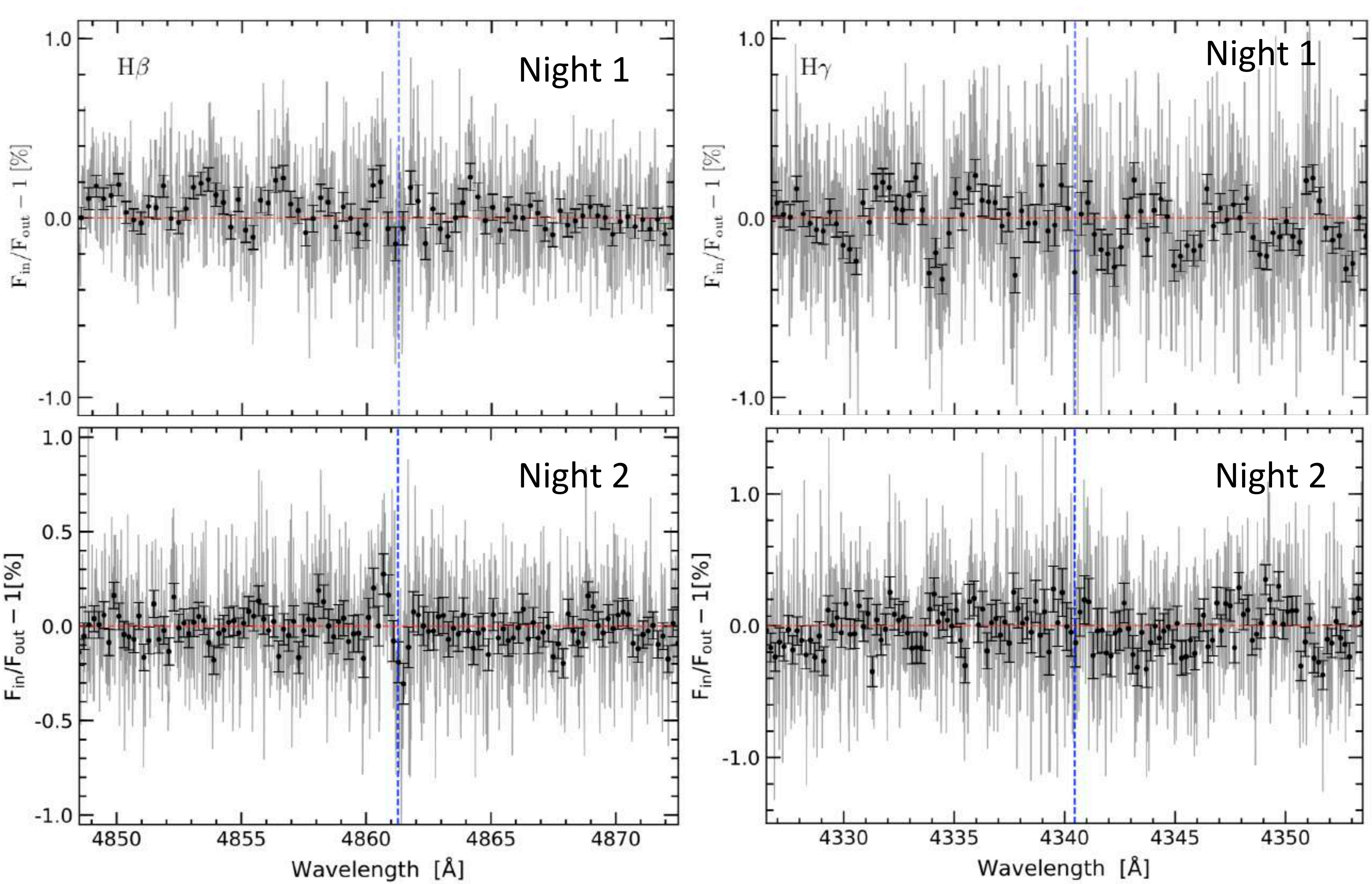
Transmission spectroscopy in the visible
MASCARA2 - 1 transit



Casasayas et al, 2018



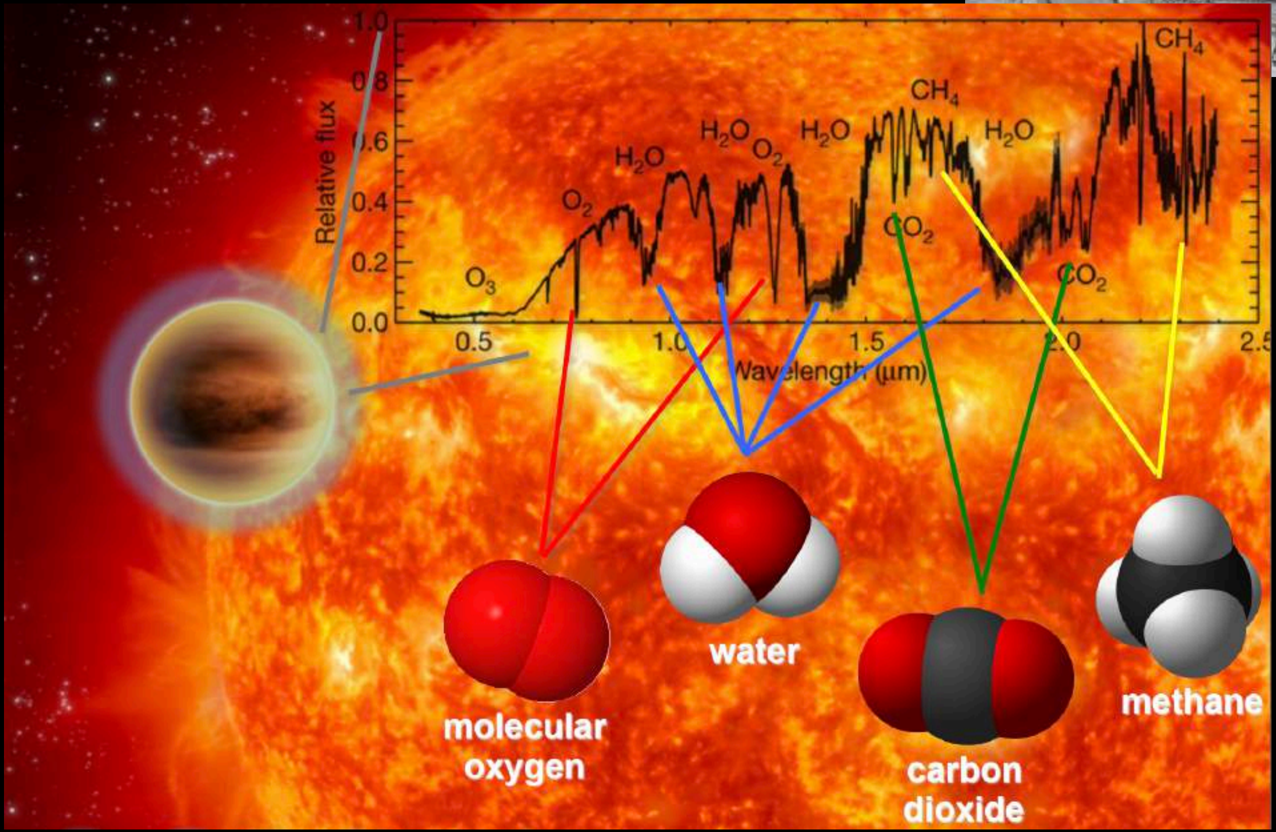
Preliminary results: Detection Balmer series



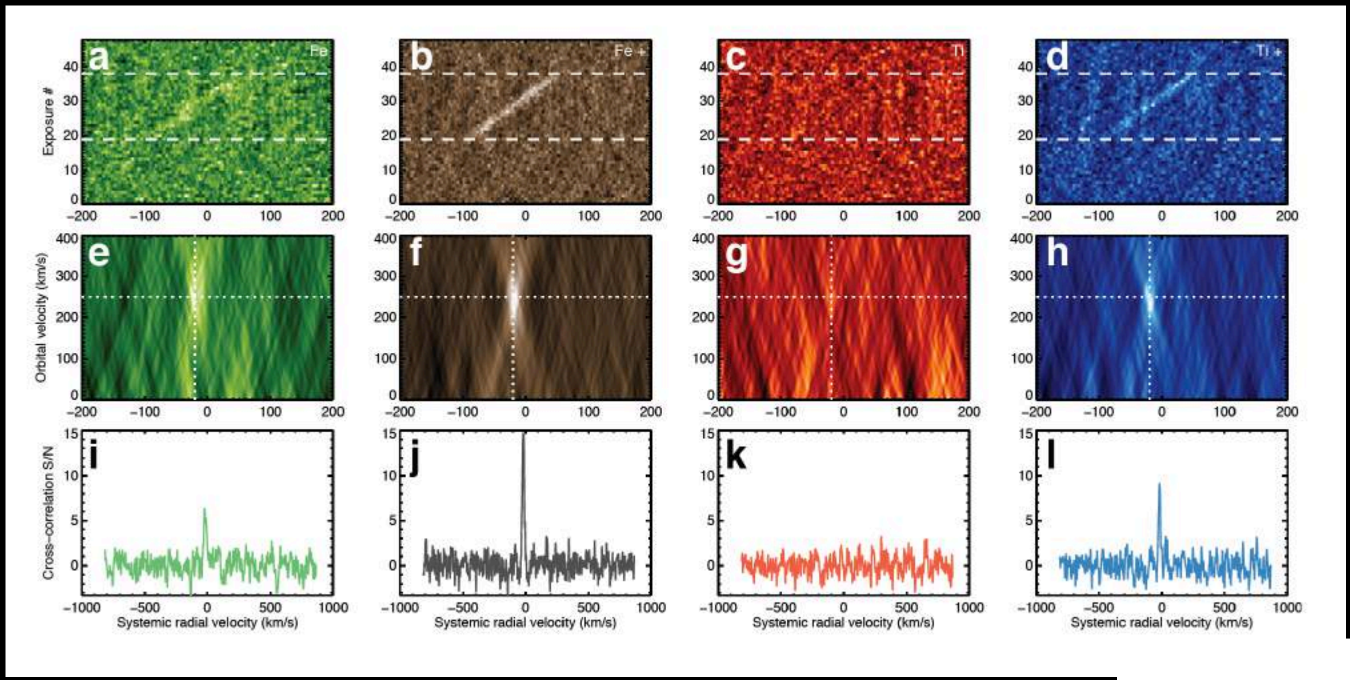
High-resolution with infrared spectrographs

Access to further molecular species

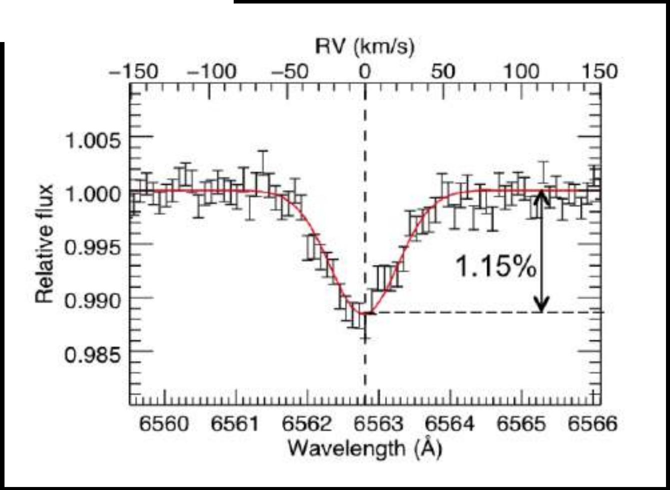
- H_2O
- CO_2
- CH_4



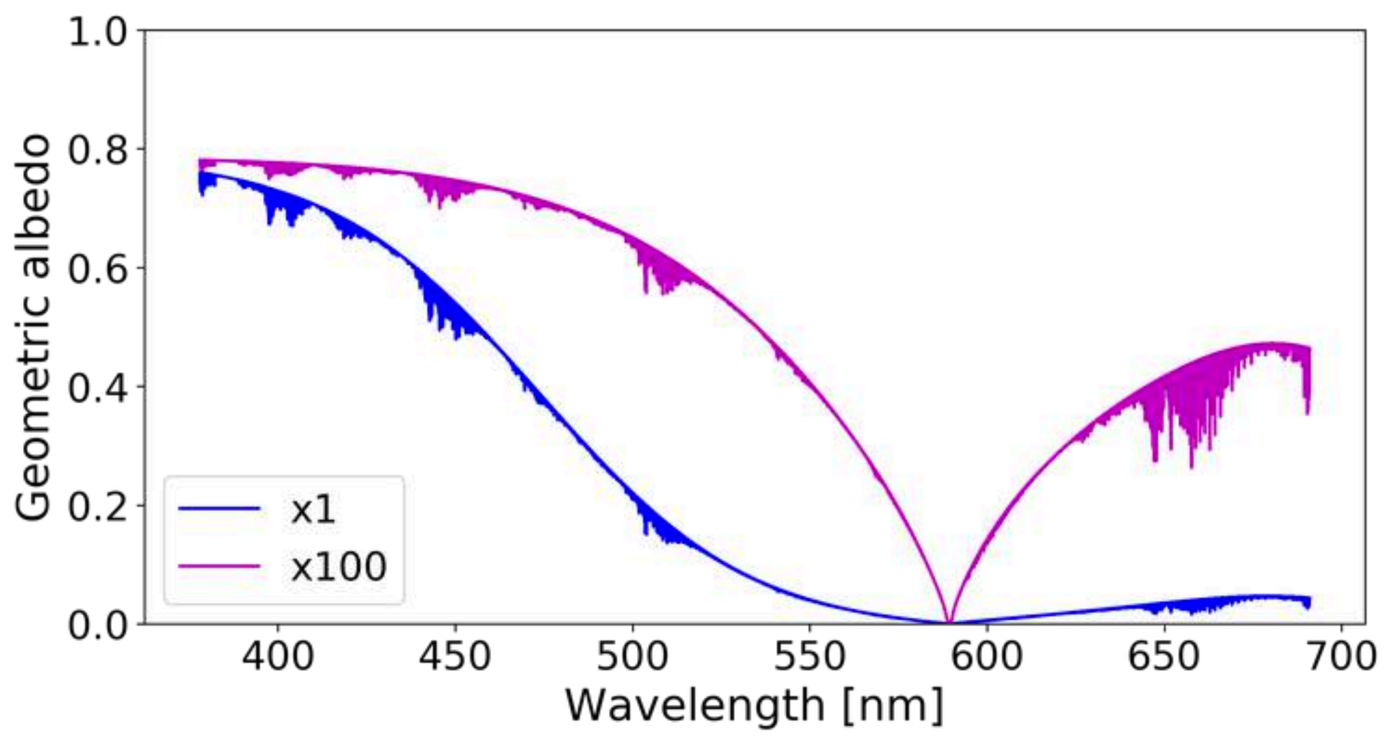
Ultra Hot Jupiters   T ≈ 2000K



Metallicities (formation), *Hoeijmakers, Nature, 2018*
Planetary escape, *Yan,Nature Astronomy, 2018*



Already here: ESPRESSO @ VLT

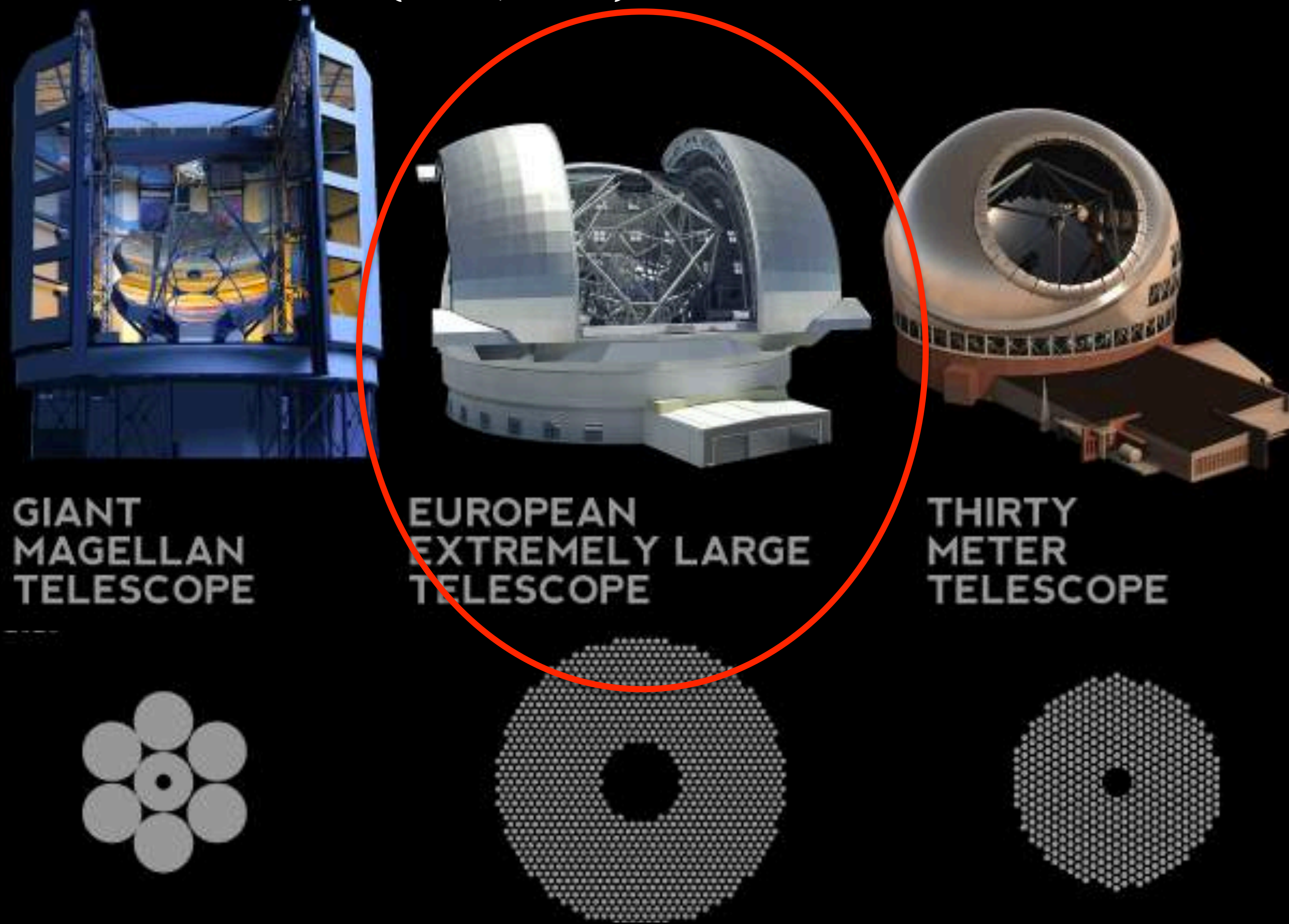


- Reflected light and albedos measures Martins, 2018
- Visible range species Tio, VO, FeH

- Know techniques: More planets, smaller planets

The Future: HIRES

Atmospheric characterization via High-Res Spec (FOV, +AO) 2025-2030



The HIgh-RESolution Spectrograph for ELT
HIRES

Consortium of 12 Countries (Italian PI) to build a high spectral resolution spectrograph:

- R = 100,000
- Spectral range 0.36-2.5 micron
- CODEX + SIMPLE Concept

SCIENCE CASES

- ***Exo-planet atmospheres and signatures of life***
- Planetary debris on the surface of white dwarfs
- Protoplanetary and proto-stellar disks
- Galactic archaeology to the Local Group and beyond
- Evolution of galaxies
- Stellar and AGN
- Chemical signatures during the epoch of re-ionization
- Fundamental physics
- …

Exoplanet Atmospheres with ELTs

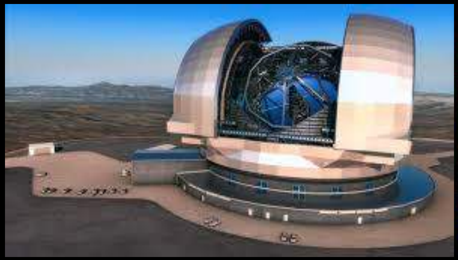
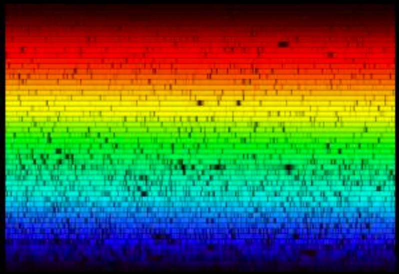
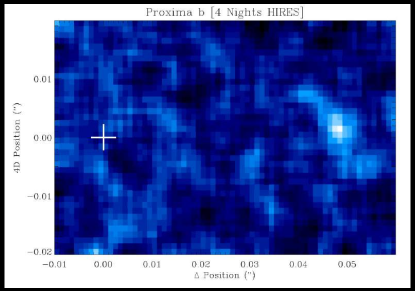
This science case involves ***two separate techniques***:

a) Transmission spectroscopy

b) Direct detection of the planet's reflected light.

The TRLs defined for instruments such as HIRES enable both simultaneously, but it must be distinguished here than *only the former relies on the need of an AO system*.

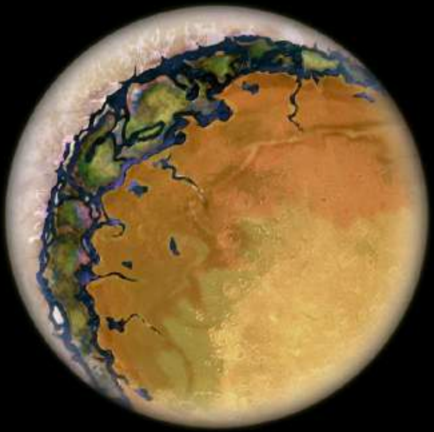
Both cases involve high-resolution spectrographs (R>100,000) in the visible and near-IR

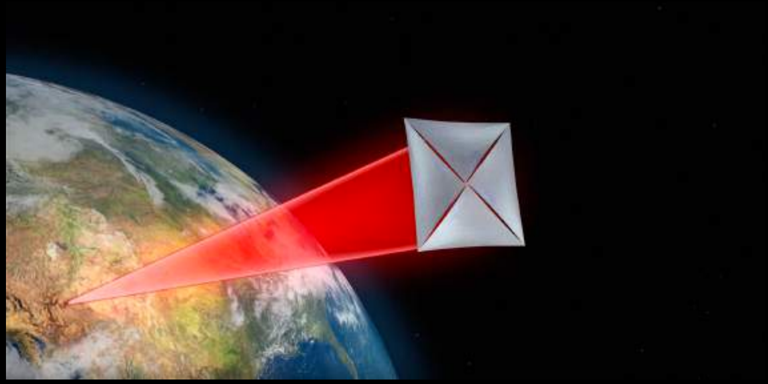




What about biomarkers?

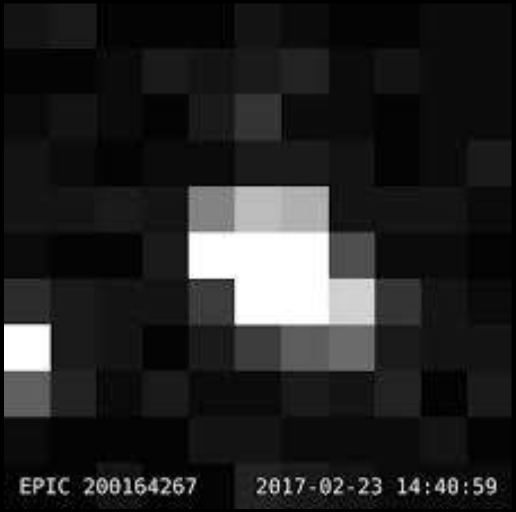
HIRES Phase A just finished. During this time

Proxima-b





Trappist-1b, c, d, e, f, g ..

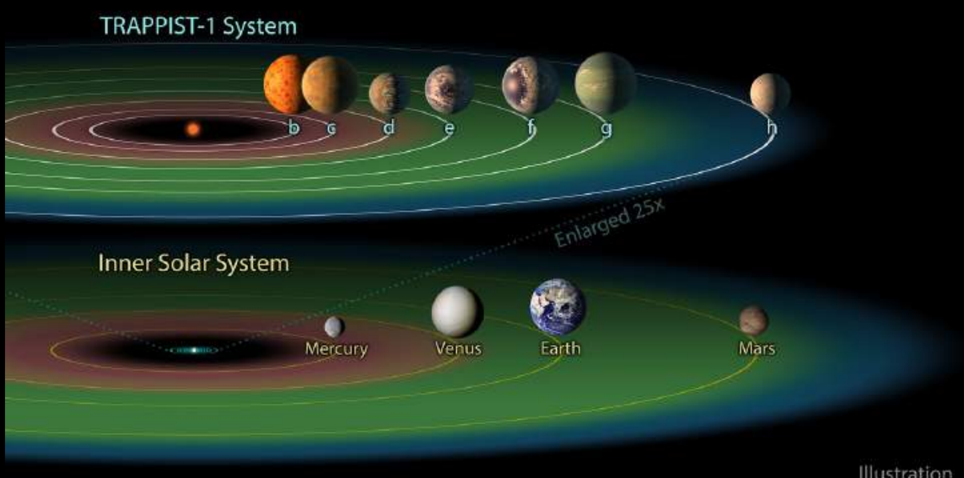


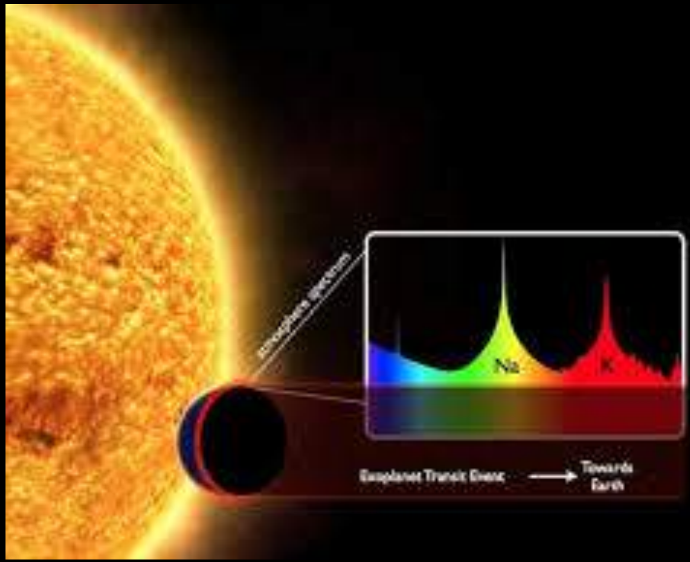
Exoplanet Atmospheres : transmission spectroscopy

M dwarf Trappist 1 b & c:

- 1.3-1.7 um H_2O band at an SNR of 6 in two transits
- 0.9-1.1 um H_2O band in 4 transits
- CO_2 in 4 transits.
- molecular oxygen detected in 25 transits.

For these planets, the transit duration is less than 1 hour.





Exoplanet Atmospheres : transmission vs direct light

Probability of transits of Earth - Sun 0.5%
Probability of transit of Earth – M star 1-2%

- We will only be able to explore in transmission 1/200 of the closest Sun-Earth twins
- We will only be able to explore in transmission 1/50 of the closest Earth-like planets around Mstars
- Probabilities and distances **= photons**

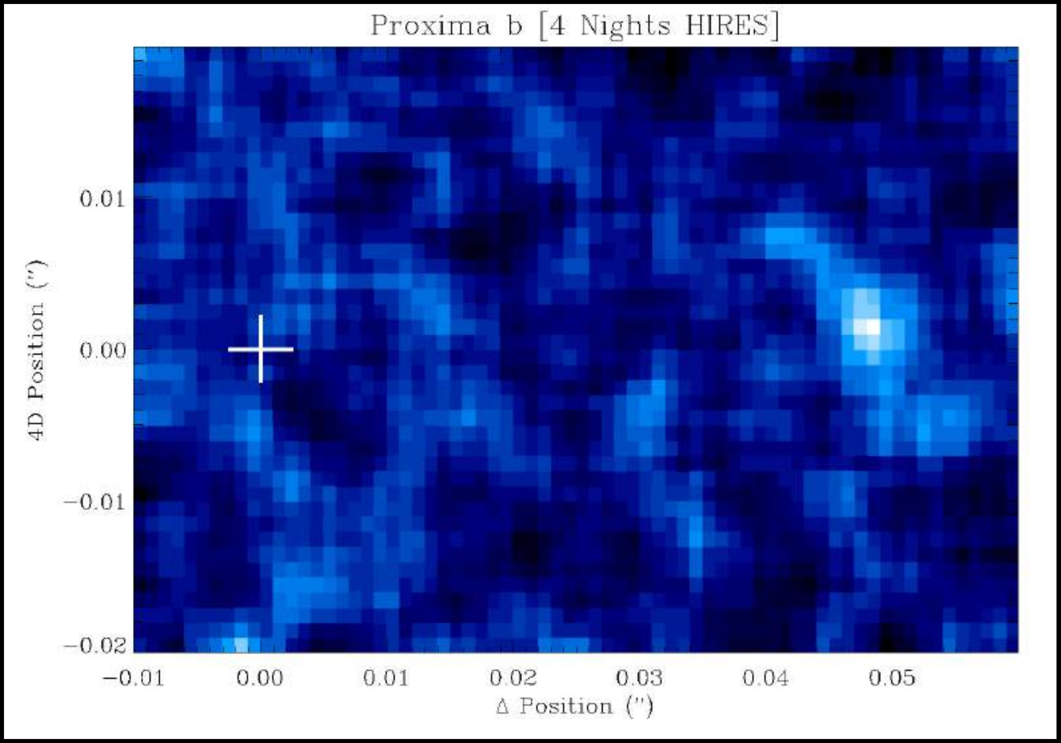
Transmission spectroscopy probes the (upper) atmosphere of the planet

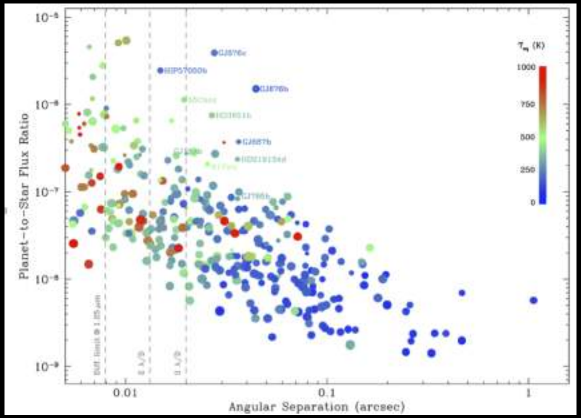
Reflected light from telluric planets probes down to the surface, including surface features (biomarkers)

Exoplanet Atmospheres: Reflected light

HIRES: AO+ IFU

Simulated reflected light cross-correlation signal of the direct surroundings of Proxima, showing Proxima b at 48 mas in 7 nights, at the 6 sigma level





Not clear if possible in the optical

Near-IR might require EAO

What about SONG ?

Will TESS provide targets?

CONS

In total 3.2M targets will be observed by TESS, of which 214,000 are observed at 2-minute cadence.

But, SONG is a 1-meter telescope

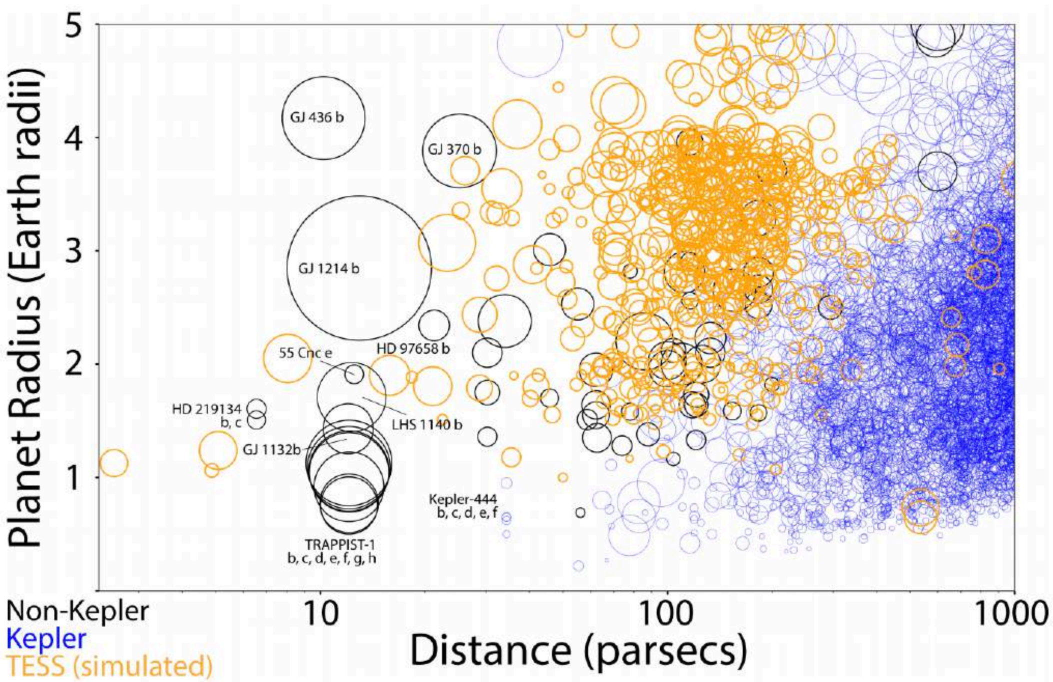


Figure 14. Orbital distance versus planet radii. This plot updates a widely shared figure created by Z. Berta-Thompson, to now include our new simulation results. Kepler planet candidates from Thompson et al. (2018) are shown in blue, our simulated 2-minute cadence detections in orange, and planets detected using other telescopes in black. The size of the circle is proportional to the transit depth. A subset of nearby planets are marked. Data was extracted from the Exoplanet Archive (Akeson et al. 2013). Three planets in our simulation orbit stars closer than the nearest known transiting planet system HD 219134.

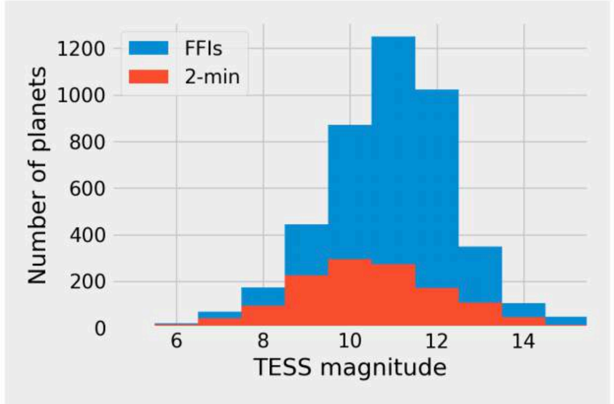


Figure 8. Brightness of the planet host stars in the TESS bandpass magnitude. The median brightness of stars with planets found in 2-minute cadence data was 10.4, with a maximum range of 3.5–15.3. For planets found only in FFI data, the median brightness was 11.3, and a maximum range of 6.1–16.4.

Barclay et al, 2018

CONS

V< 7 : 50 stars meaning 25 Northern Hemisphere
V< 8 100 targets for SONG

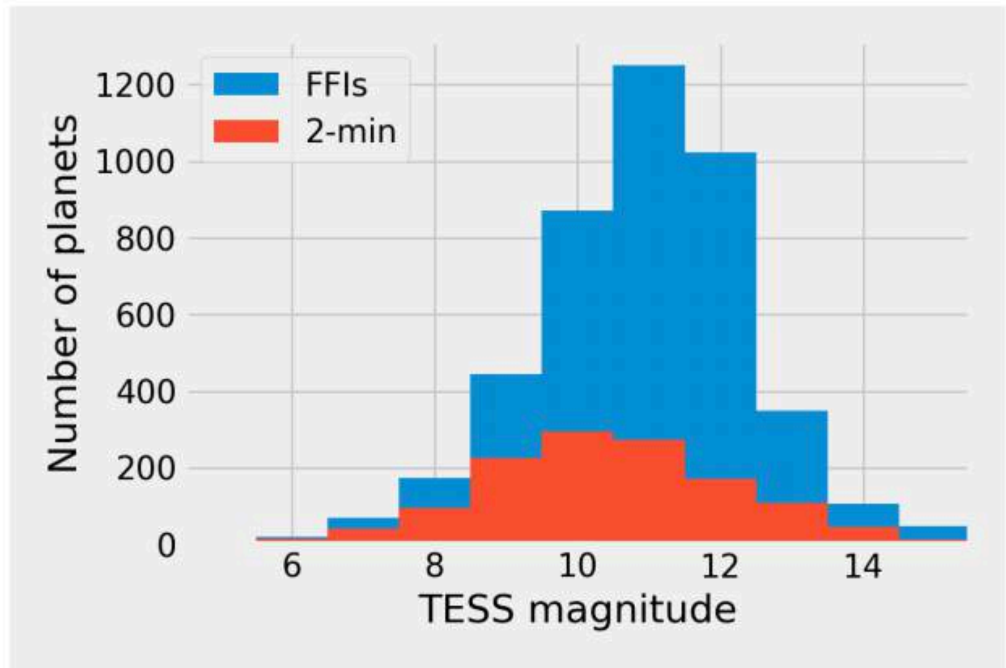
Spectral type !!

Tess magnitude !!

V< 7 ≈15
V< 8 ≈ 50

Planet type !!

Barclay et al, 2018



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Best Test: real data, TESS Sector 1 alerts

Tmag	Rp	Period	Duration	Transit Depth	
5.10	1.86	6.27	3.09	249	3 (1.5) m/s
7.14	12.2	11.5	8.56	2.39e+3	15 m/s
7.36	1.97	1.01	1.53	220	2-3 m/s
7.43	2.36	14.3	4.65	411	
7.90	2.77	4.94	2.20	399	
8.14	2.84	4.14	1.82	1.15e+3	
8.70	2.28	17.7	2.76	883	
8.80	7.72	3.31	5.63	3.18e+3	
8.87	9.58	14.2	7.94	3.96e+3	

tic_id
261136679
394137592
403224672
263003176
391949880
207141131
425997655
290131778
270341214

PROS SONG and TESS

1) Sampling capability (network) USP planets

2) Availability and Flexibility

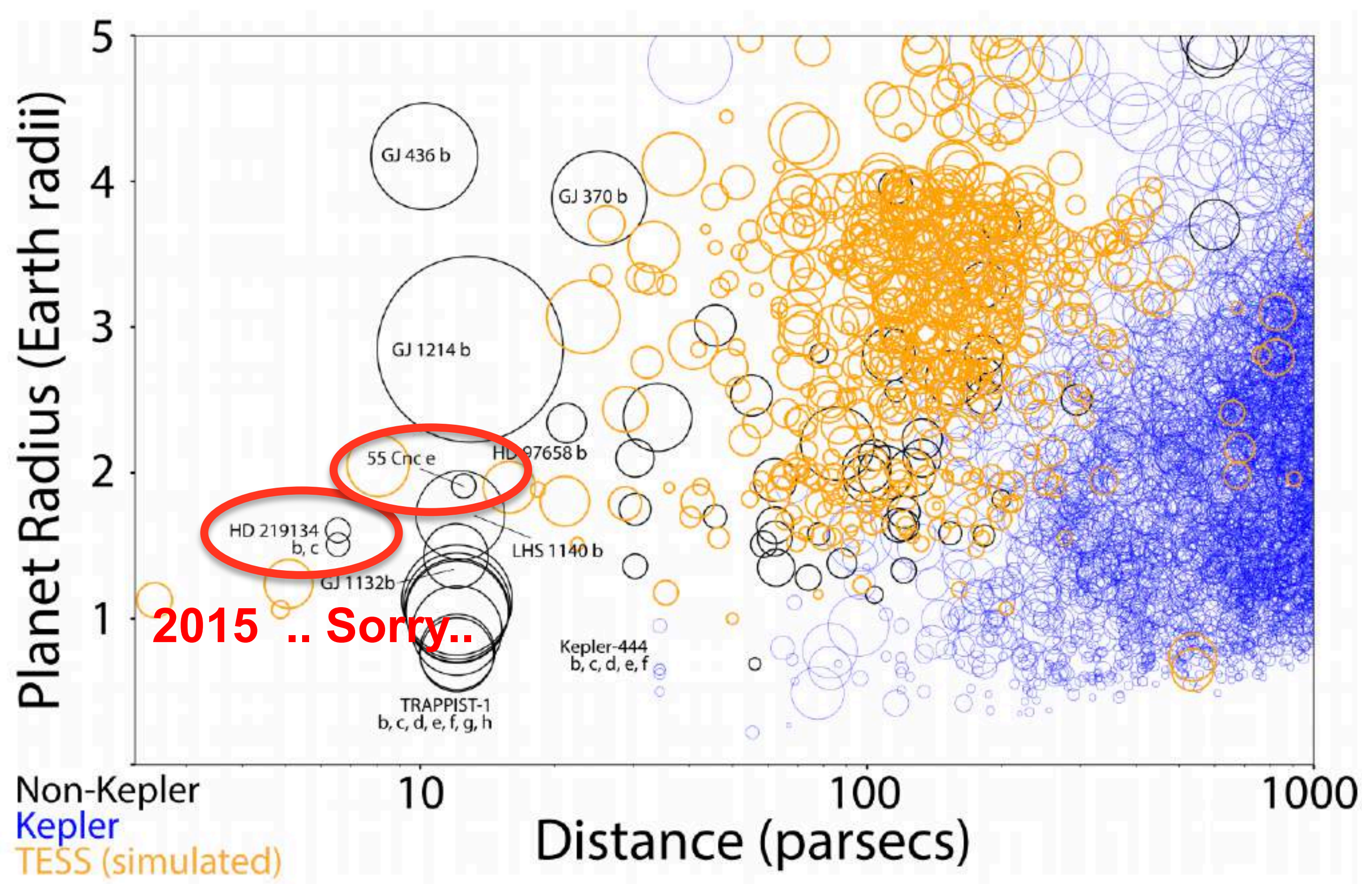
Proposal: Approved ToO program ready to jump to opportunities on the same day they are alerted/published.

SONG TESS Program:

- Recons Spectroscopy TESSSONG? Upload to TFOP!
- RV follow-up V=7/8 (Mia's talk)
- RM/Tomography some candidates V=7/8? (Maria's talk)
- Atmospheric Characterization 5/6

Pilot studies?

Data in hand



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Tangential stuff…

A red/near-IR spectrograph for GTC

We will be proposing a 0.8-1.7 nm high-resolution spectrograph (R>70,000) for the 10-m GTC

Science cases:

1) Exploration volume-limited sample of stars
2) Atmospheres of exoplanets

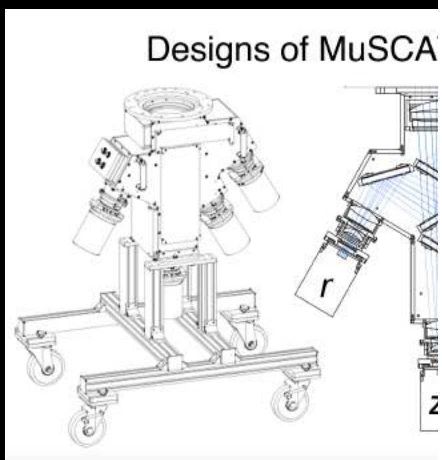
Design is very preliminary (0) at the moment but will move forward in the coming months

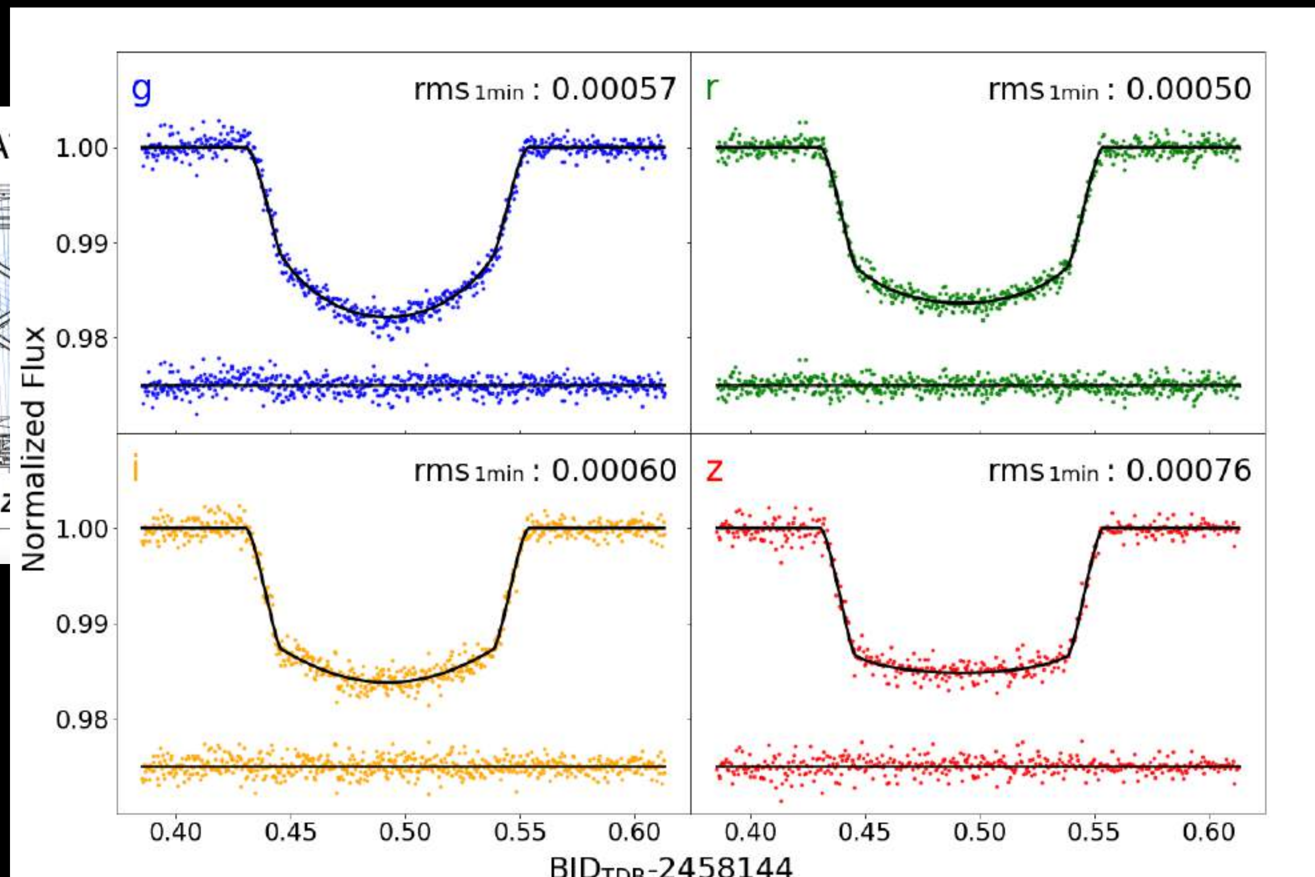
We welcome input, institutional collaborations and enthusiastic colleagues to join

Meet your neighbor: MUSCAT2 @ TCS

1.6-m telescope
4 channel simultaneous imager g, r, I , z
2019: equipped with diffusers
300 nights/year

Open to collaboration projects and simultaneous observations






Thanks !!