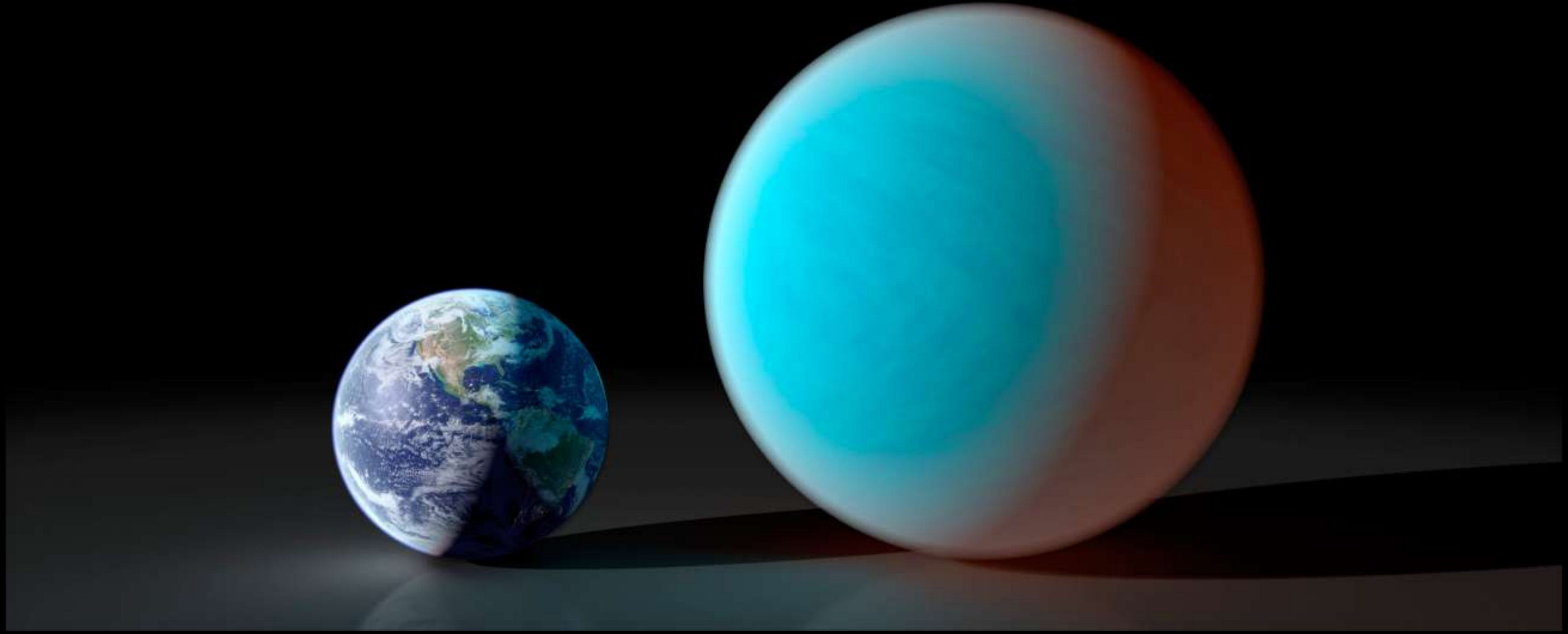
# Atmospheric characterization of sub-Neptunes with ELT-HIRES



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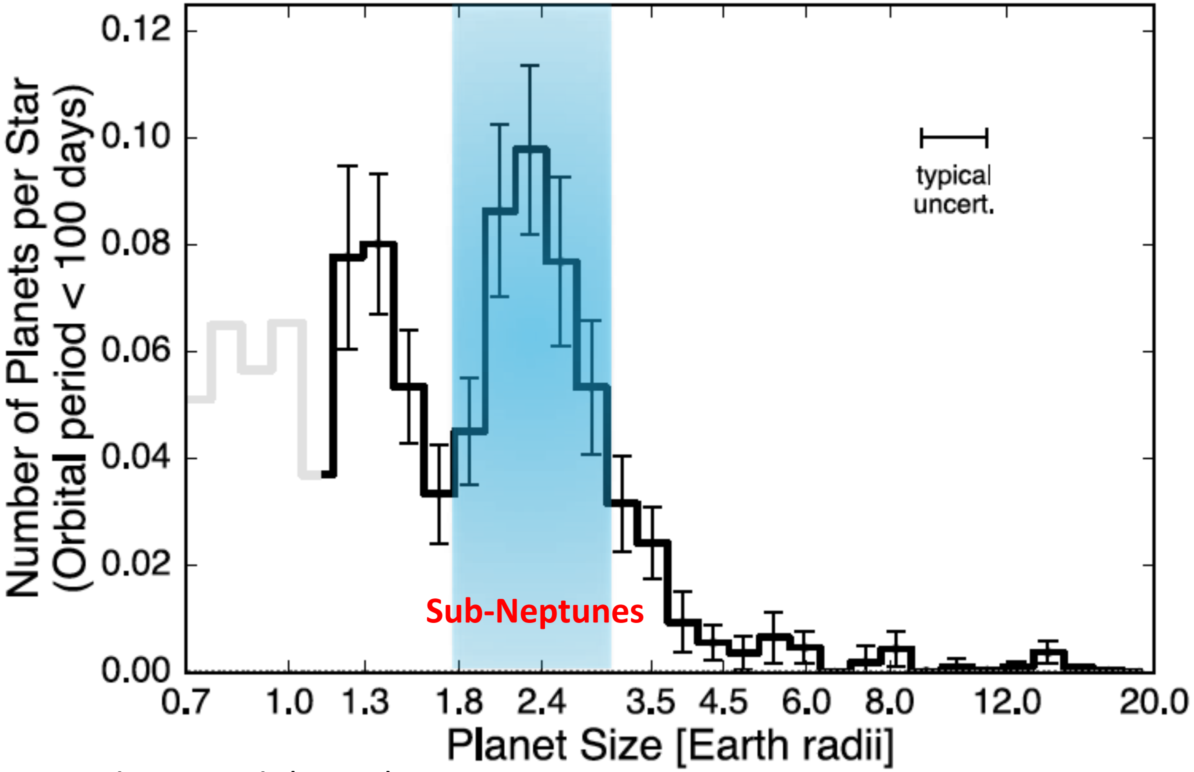
e-PYTHEAS
exo-PlanetarY high-Temperature Hydrocarbons by Emission and Absorption Spectroscopy

# Atmospheric composition of sub-Neptunes
## *What is the nature of sub-Neptunes?*

Frequency of exoplanets




*Fulton et al.* (2018)

Degenerated internal structure

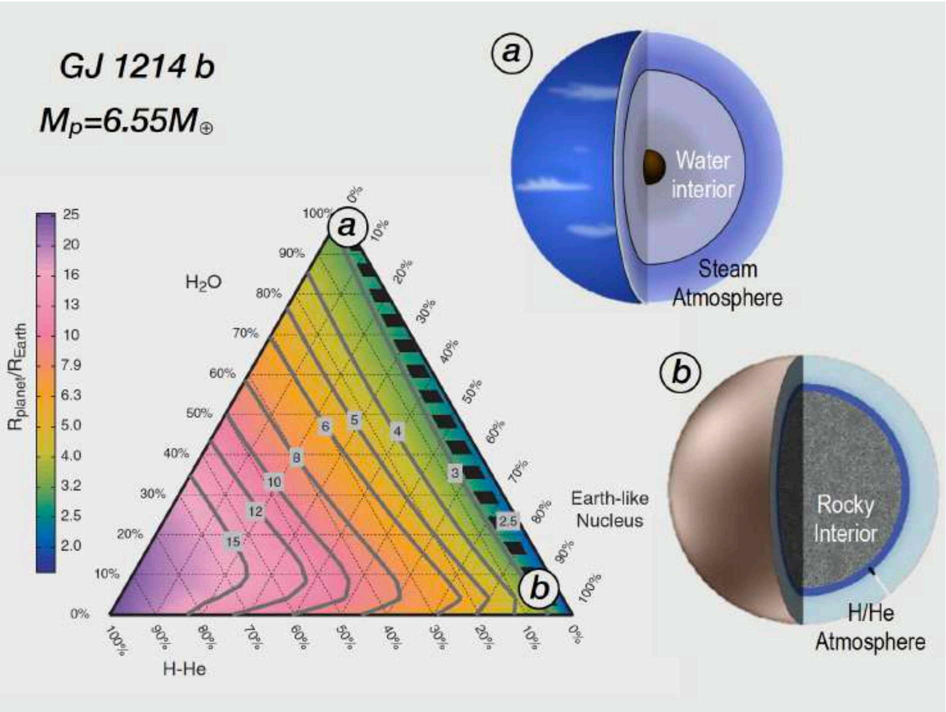
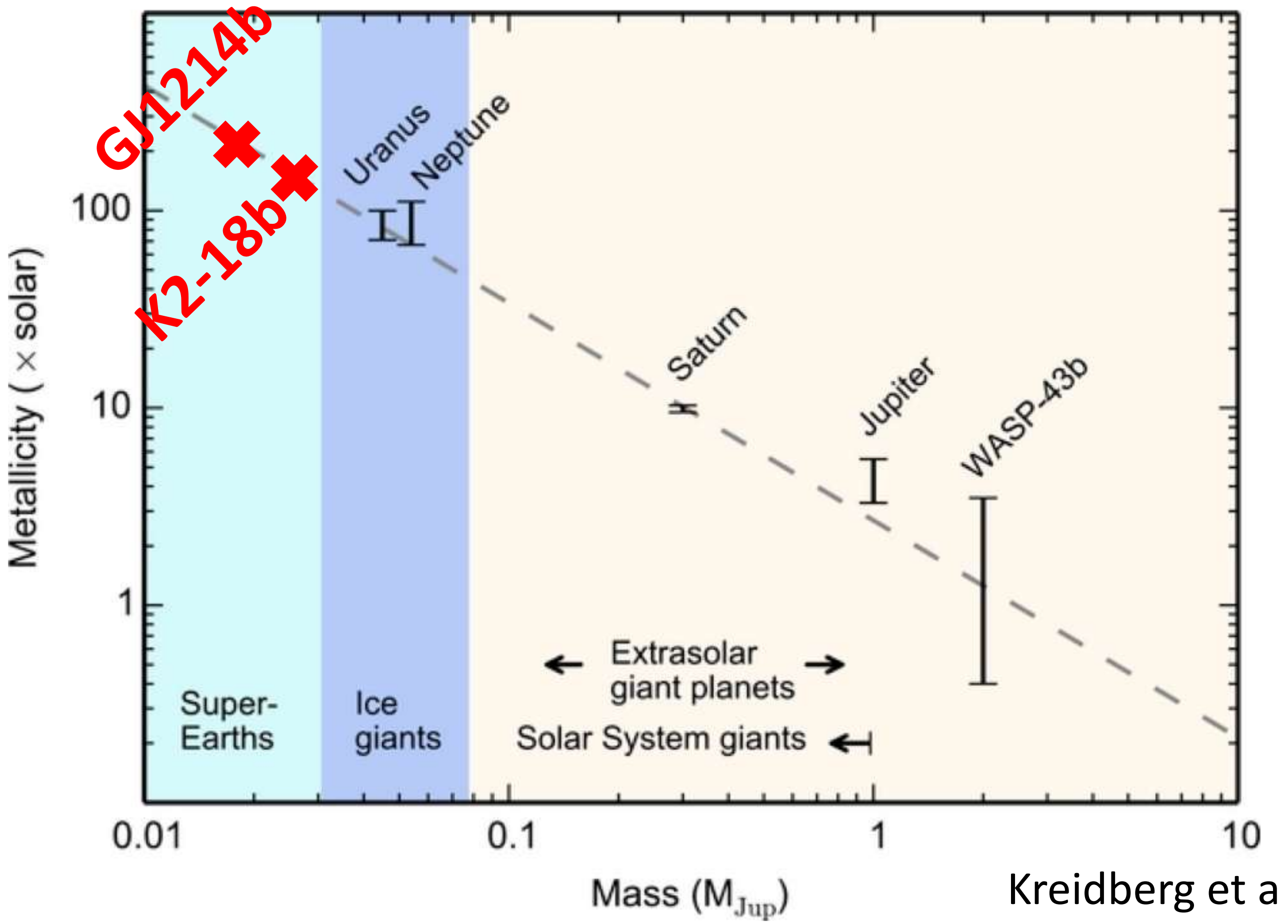



Figure adapted from *Valencia et al.* (2013)

**Atmospheric characterisation is required to constraint the nature of sub-Neptunes**

# Atmospheric composition of sub-Neptunes
## *Metallicity*



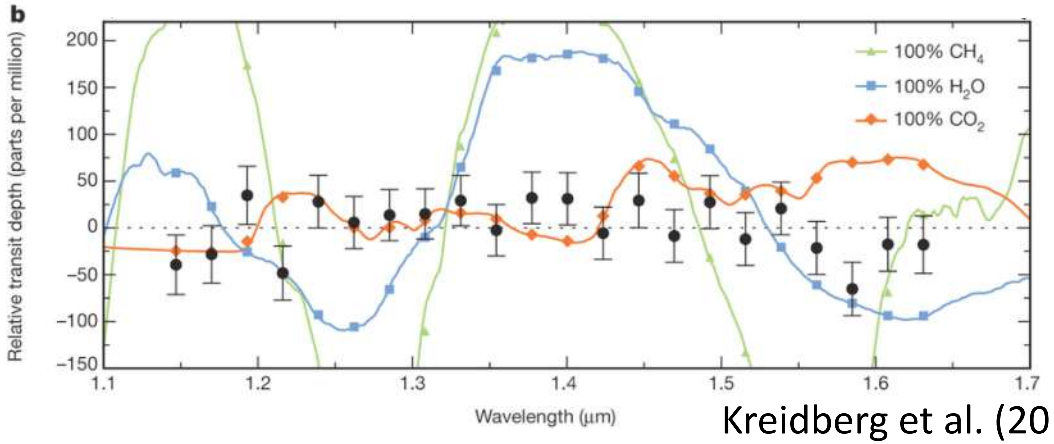

Kreidberg et al. (2015)

High metallicity expected for sub-Neptunes (≈100-400xsolar)

# Lesson from transit observations

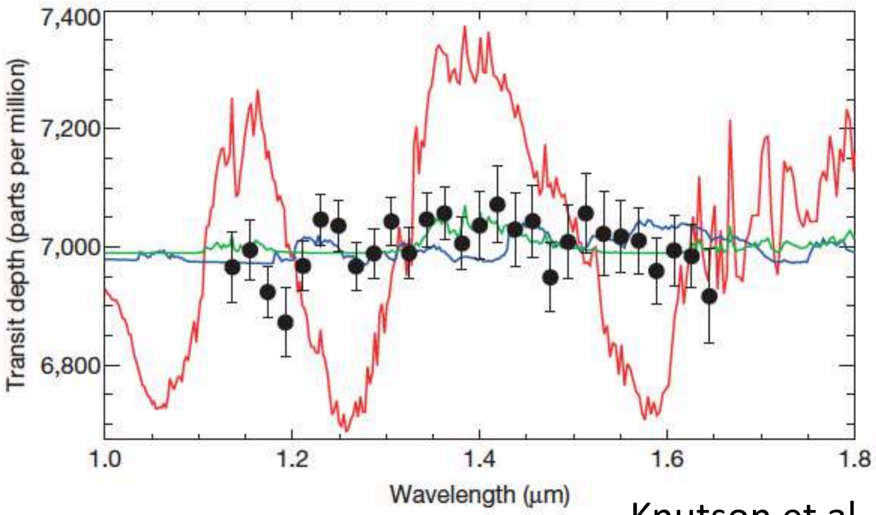
## Low-mass planets have relatively flat transit spectra

**GJ 1214b**



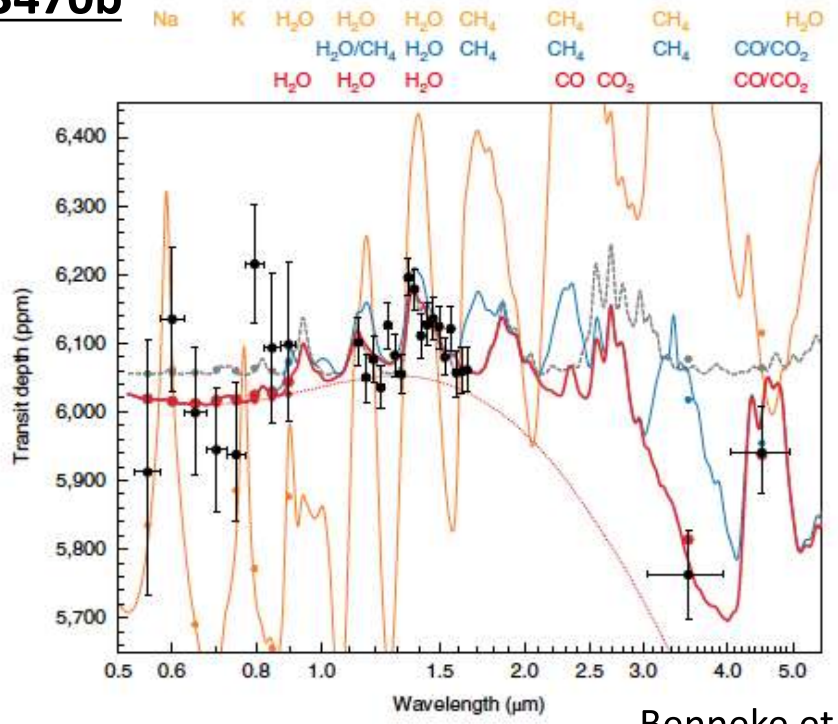

Kreidberg et al. (2014)

**GJ 436b**




Knutson et al. 2014

**GJ 3470b**




Benneke et al. 2019

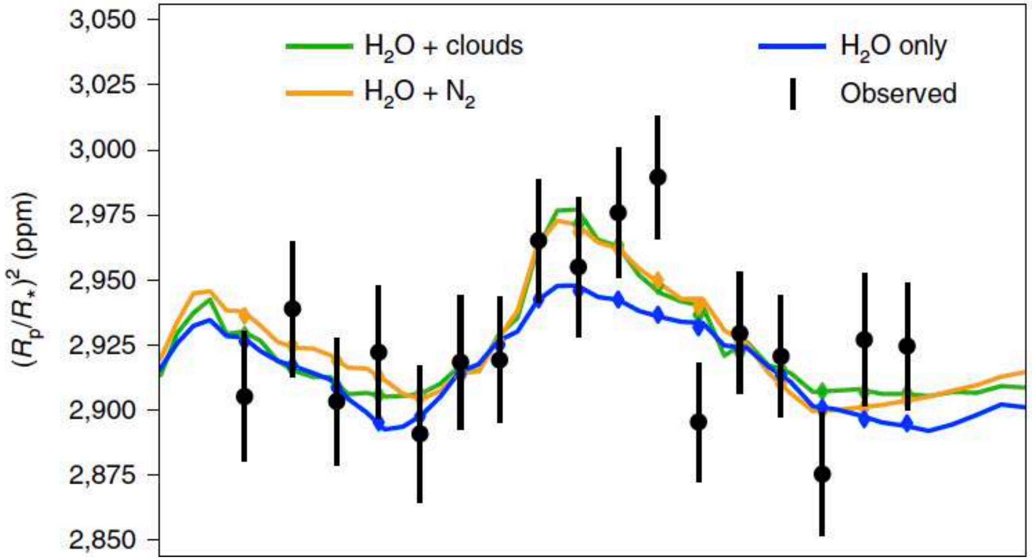
**Flat transit spectrum:**
→ high mean molecular weight (i.e. high metallicity)
+ clouds/hazes

# Discovery of water vapour on K2-18b

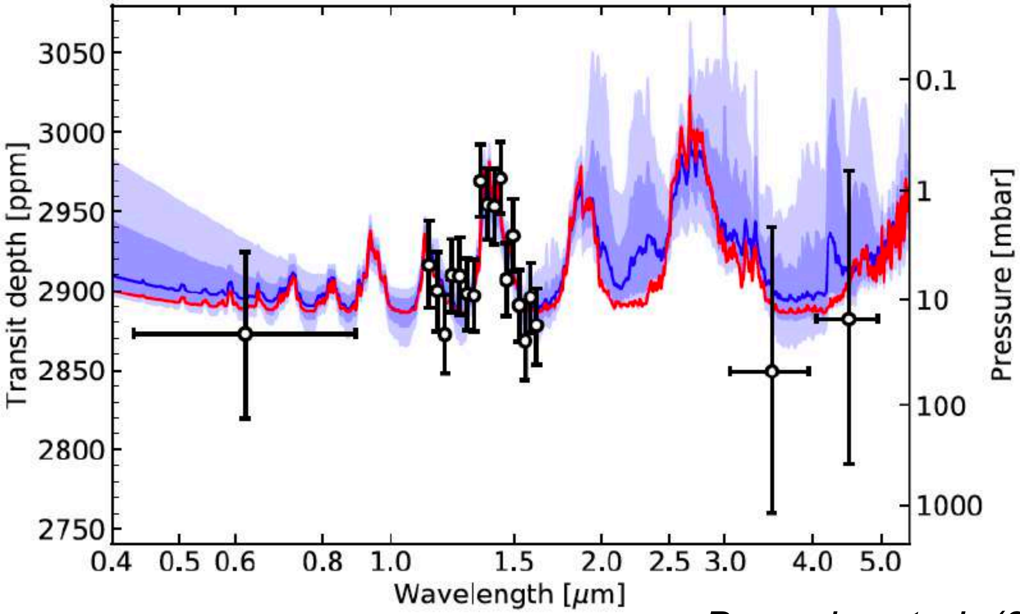
**K2-18b:**
Mass = 8.63 $M_\oplus$
Radius = 2.6 $R_\oplus$
Irradiation = 1368 $W/m^2$
(1361 $W/m^2$ for the Earth)
Orbital period = 33 days

**A temperate sub-Neptune, with water vapour and potentially water clouds**

## HST transit spectrum




*Tsiaras et al. (2019)*

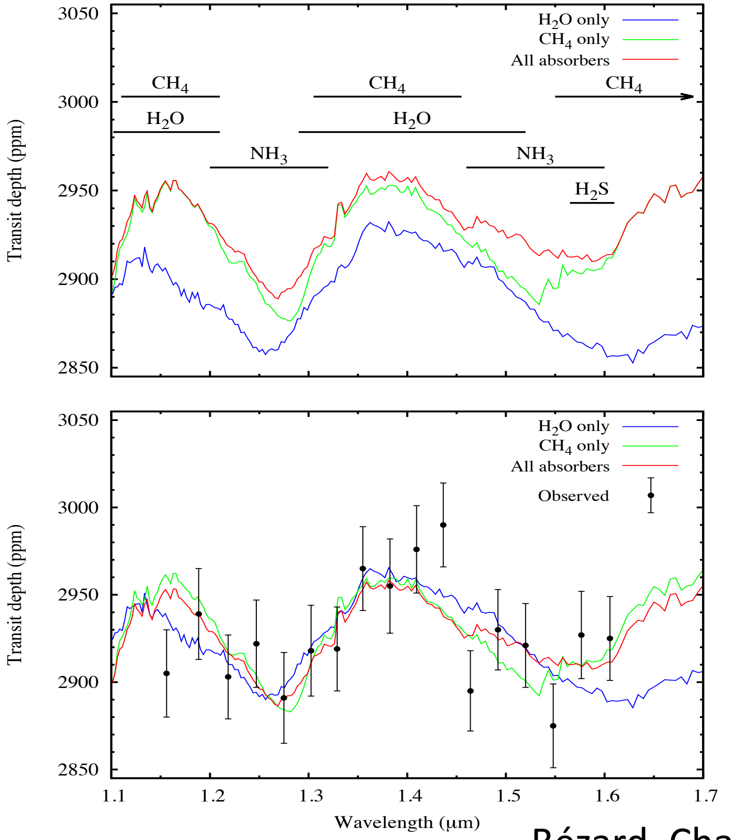


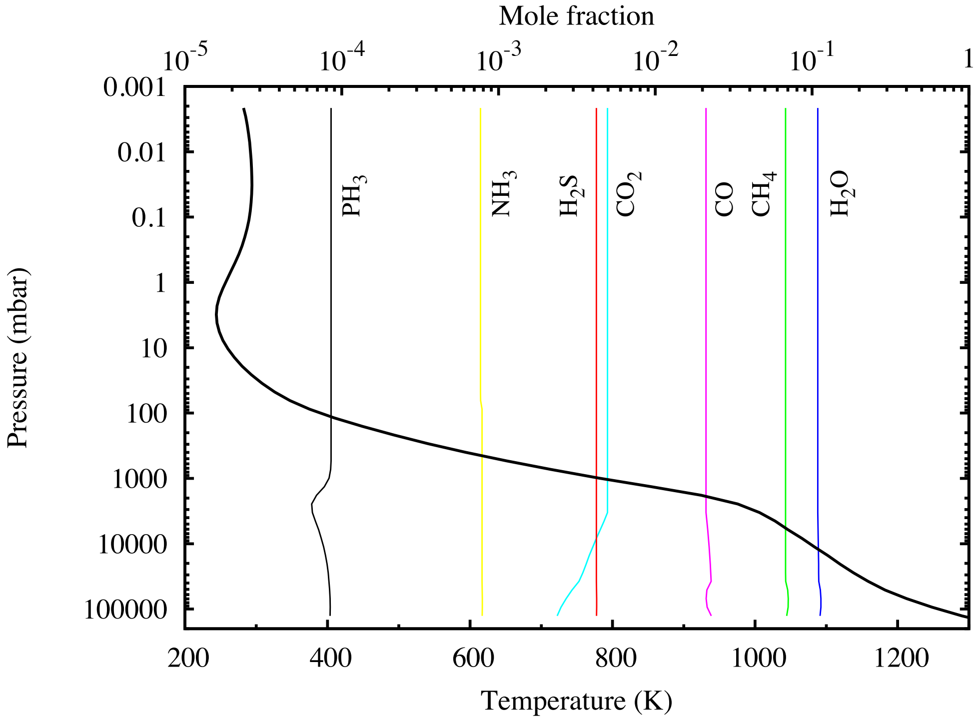

*Benneke et al. (2019)*

# 1D modelling of K2-18b

***Atmospheric composition***

**Exo-REM:** 1D self-consistent model with non-equilibrium chemistry and clouds
(Baudino et al. 2017, 2017, Charnay et al. 2018, Blain et al. 2020)



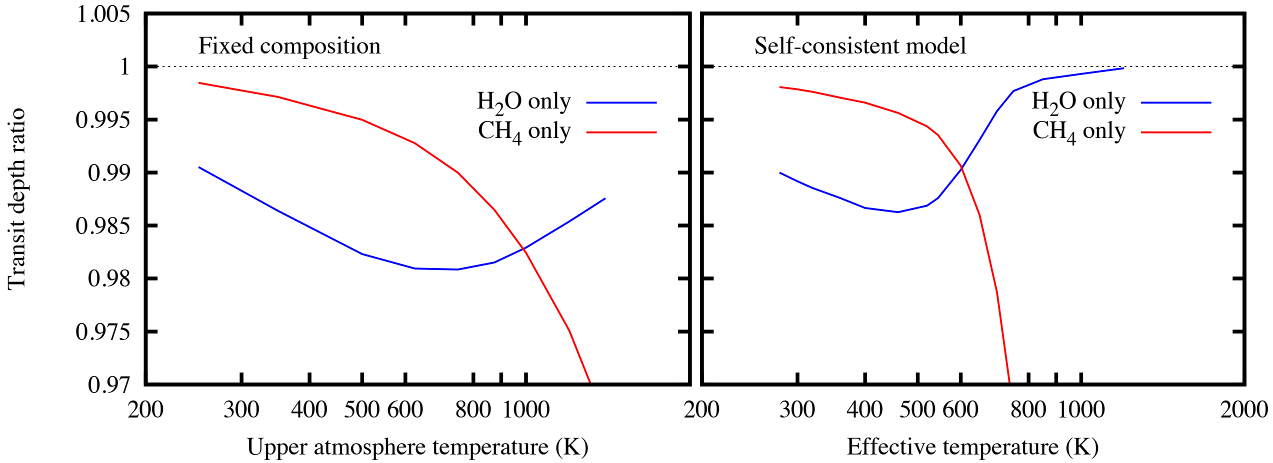

Bézard, Charnay & Blain, *in rev.*

**$CH_4$ should be the dominant absorbant due to its numerous weak lines**
**A larger spectral range or HR spectroscopy is required to distinguish CH4 from H2O**

# 1D modelling of K2-18b

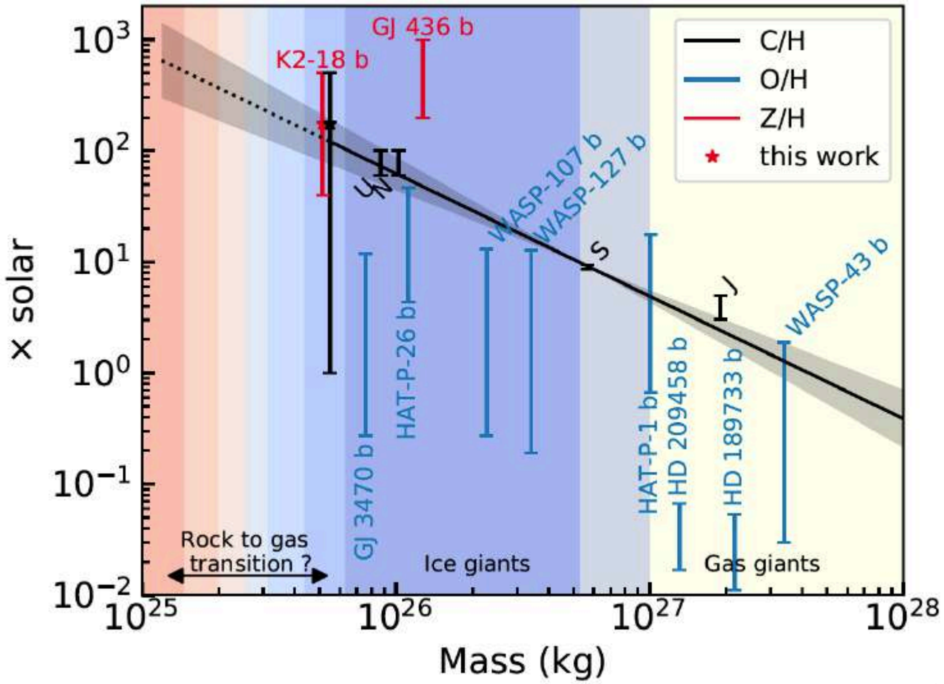
## *Atmospheric composition*

**<u>Exo-REM:</u>** 1D self-consistent model with non-equilibrium chemistry and clouds (Baudino et al. 2017, 2017, Charnay et al. 2018, Blain et al. 2020)




Bézard, Charnay & Blain, *in rev.*

**Metallicity=fraction of heavy elements**



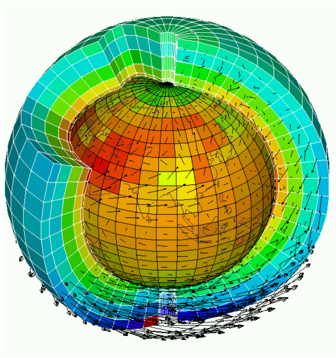

Blain, Charnay & Bézard, *in press*

**<u>1D self-consistent modelling suggests:</u>**

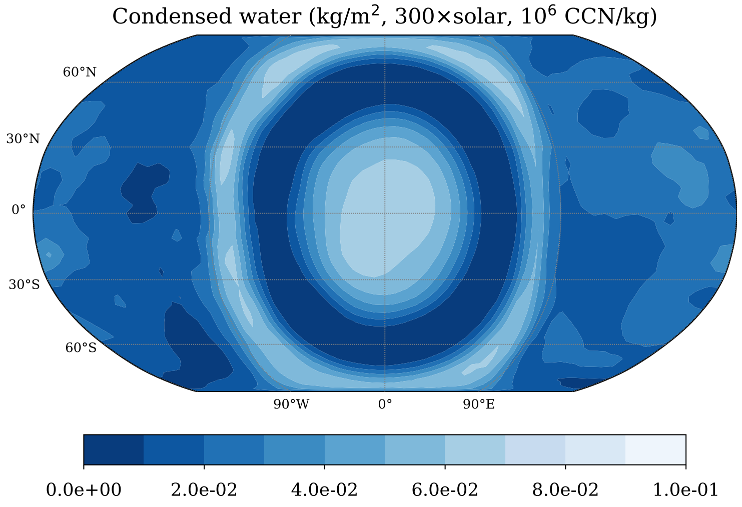
- **HST transit spectrum dominated by $CH_4$ for $T_{eff}$ < 600 K**
- **50-400×solar metallicity compatible with the Solar System trend**

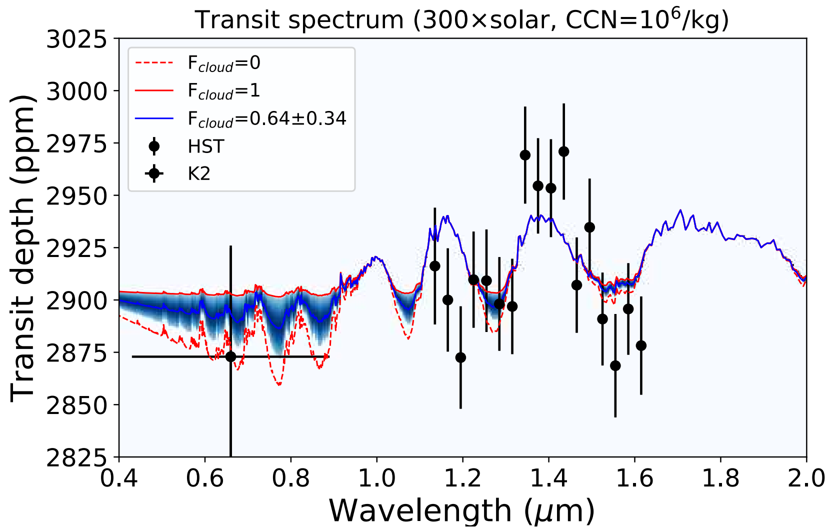
# 3D modelling of K2-18b

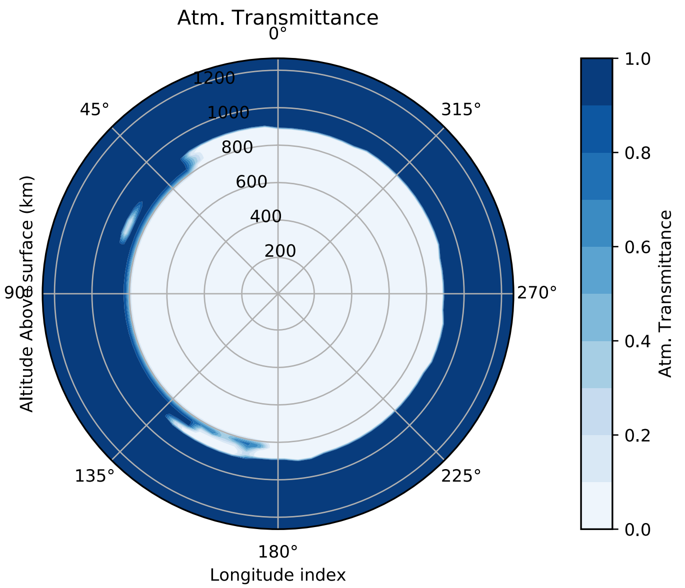
## *Cloud distribution*



### Simulations of water clouds on K2-18b with the 3D LMD Generic GCM (Charnay et al. *in rev*)




**3D cloud modelling suggests:**

- Day to night-side circulation (upper winds ~100 m/s)
- Inhomogenous cloud distribution
- Possible asymmetric limb cloudiness
- Variability of transit spectra in spectral windows (i.e. in visible spectral range)

# The golden age of sub-Neptunes

<u>Variation of transit depth:</u>

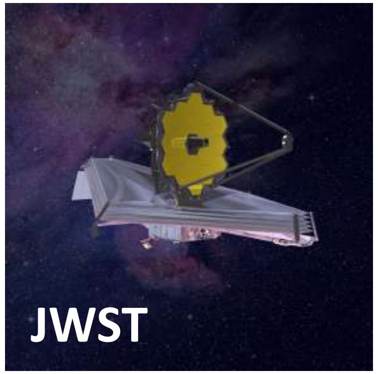
$\Delta\delta_{tra} \approx 2N_H \frac{R_p H}{{R_\star}^2}$; $H = \frac{RT}{Mg}$; Number of scale heights: $N_H \approx 5 - 7$

→ **The SNR is ∼10 higher for a sub-Neptune ($R_p$=2.5$R_\oplus$, met=100×sol) than for a rocky planet ($R_p$=1$R_\oplus$, compo: $N_2/CO_2/H_2O$)**

**<u>Scientific questions:</u>**

- Nature of sub-Neptunes ($H_2$-dominated or $H_2O$-dominated)
- Atmospheric composition (metallicity and C/O ratio) and chemistry
- Atmospheric circulation
- Upper atmosphere and atmospheric escape
- Photochemical hazes or clouds
- Water clouds on temperate sub-Neptunes (implication for the climate of rocky planets)

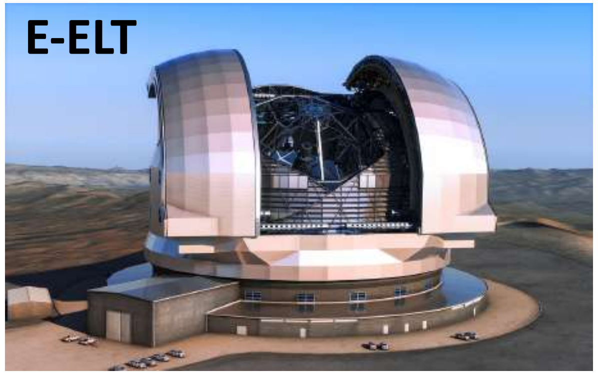
Large spectral range





- Covering multiple molecular bands
- Clouds optically thinner in infrared

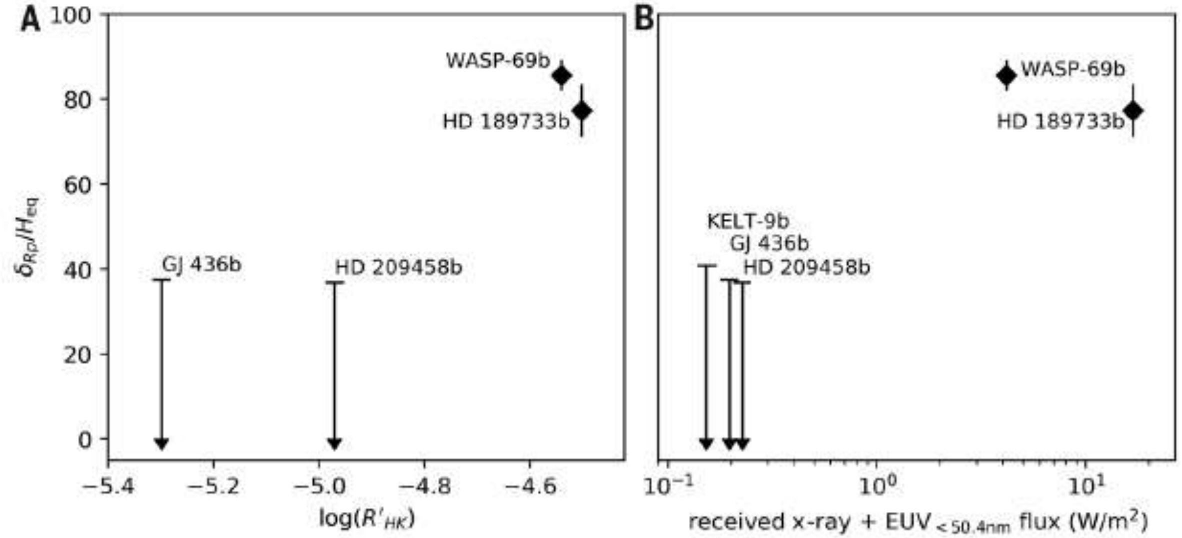
High spectral resolution




- Detecting/resolving individual lines
- HR spectroscopy can probe above clouds

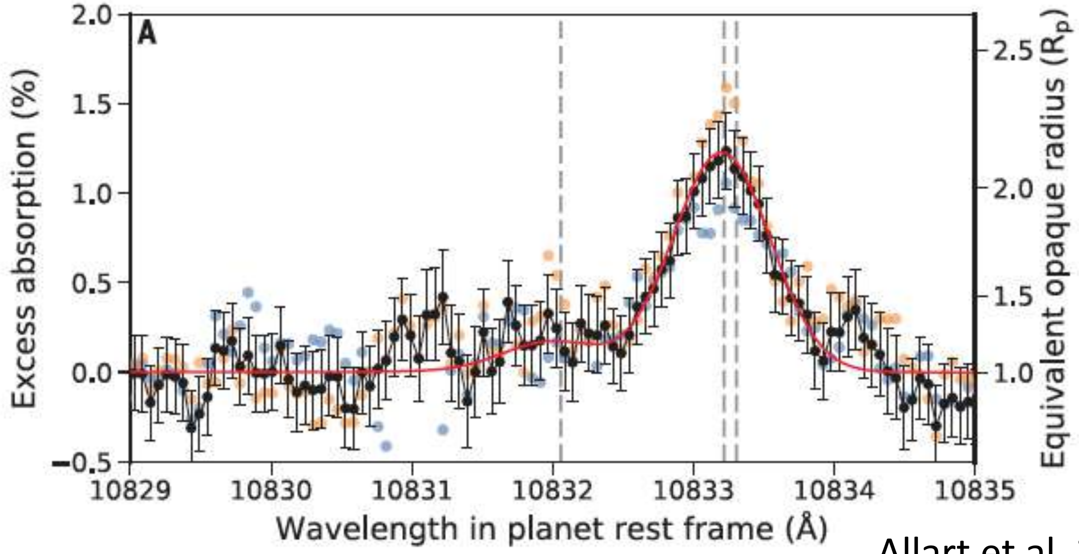
# The golden age of sub-Neptunes

**Detection of extended atmospheres and atmospheric escape from He I triplet (1.0834 micron) with HR spectroscopy**



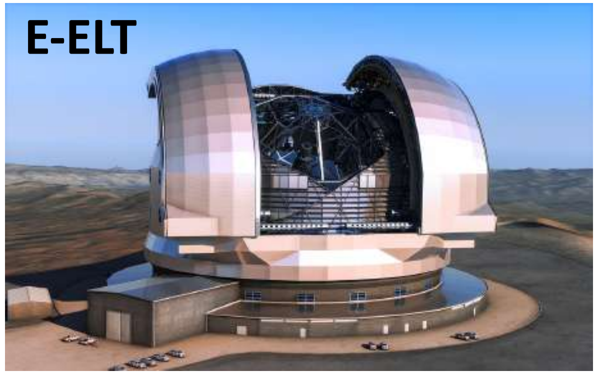

Nortmann et al. 2018

Ttransmission spectrum of  HAT-P-11b (He I triplet)




Allart et al. 2018

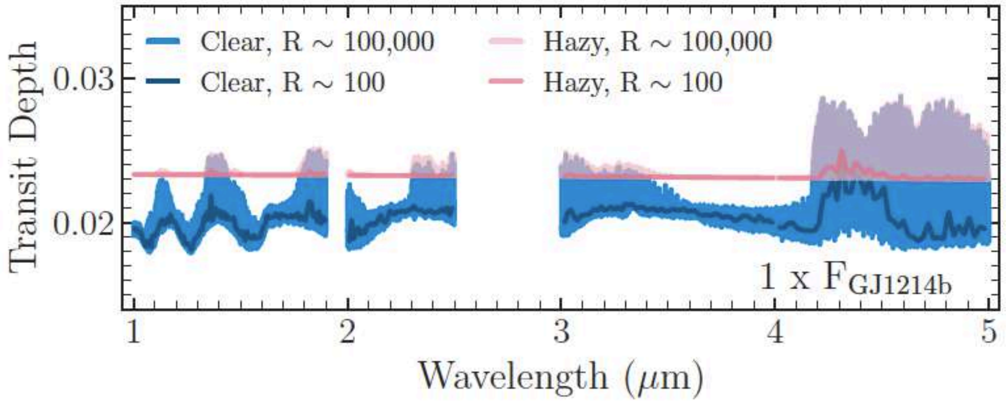
High spectral resolution

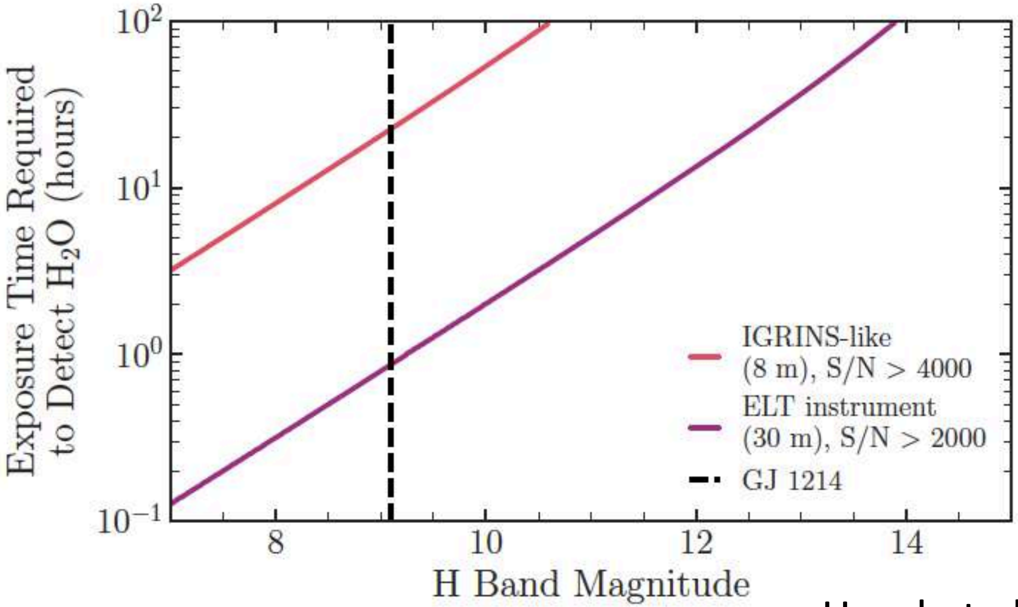



- **Dectecting/resolving individual lines**
- HR spectroscopy can probe above clouds

# The golden age of sub-Neptunes

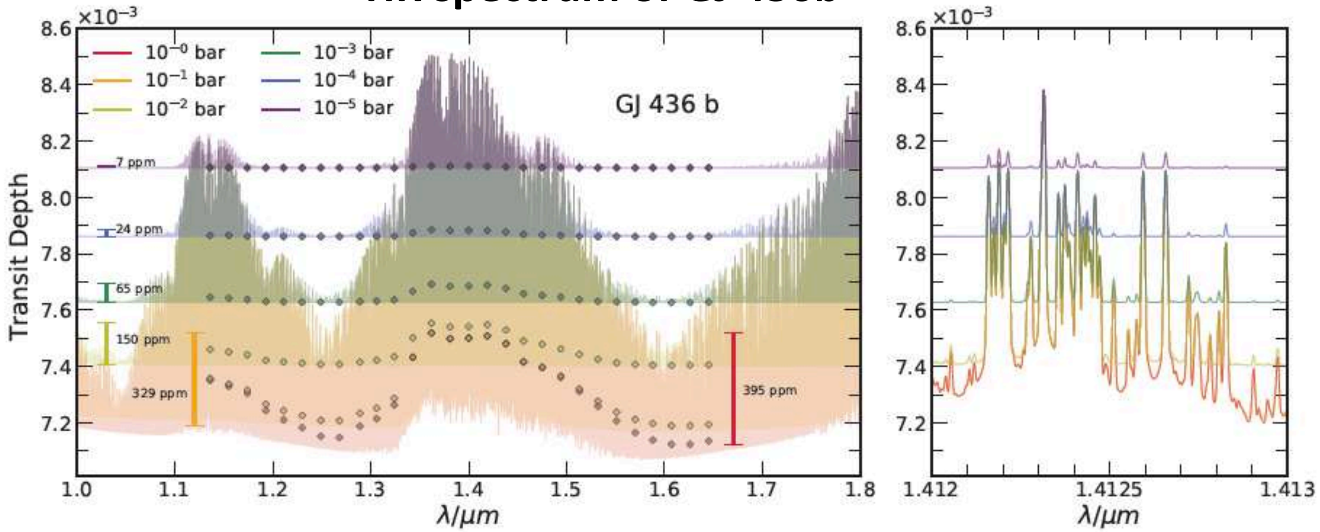
**HR spectrum of GJ 1214b**



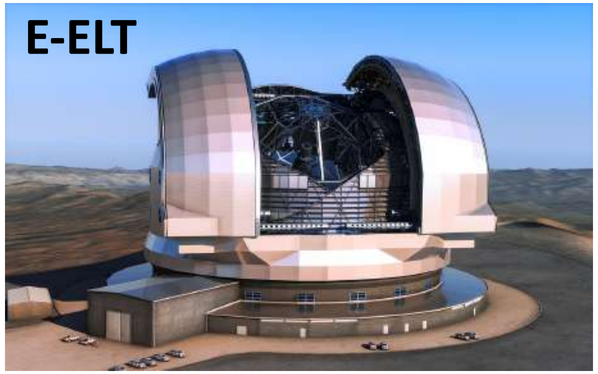

Hood et al. 2020

**HR spectrum of GJ 436b**




Gandhi et al. 2020

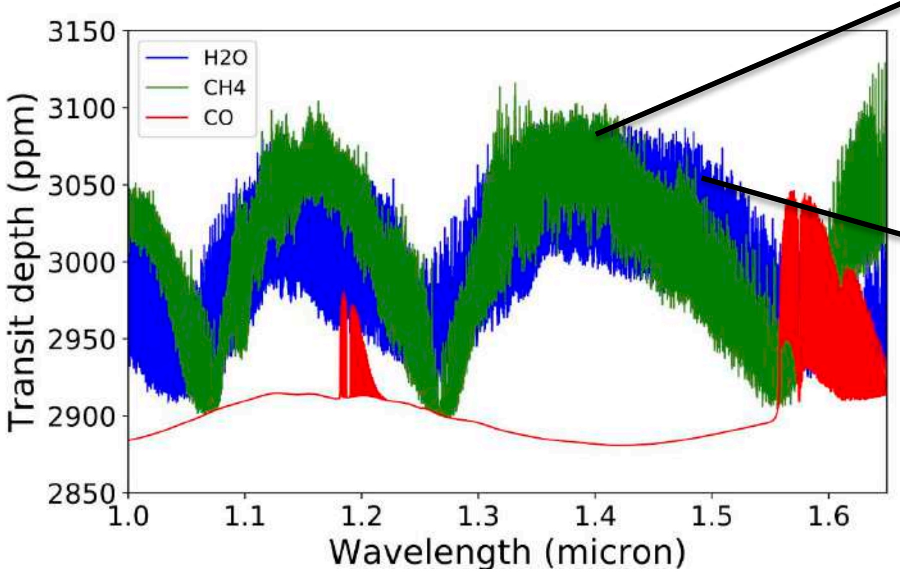
High spectral resolution

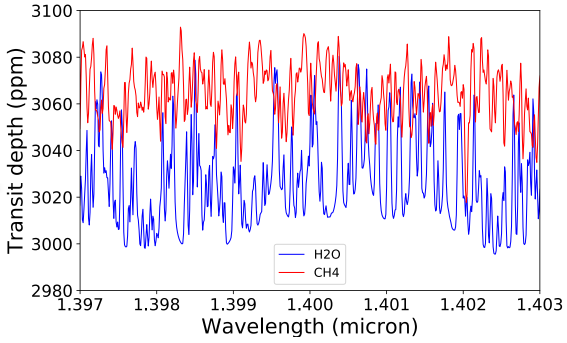


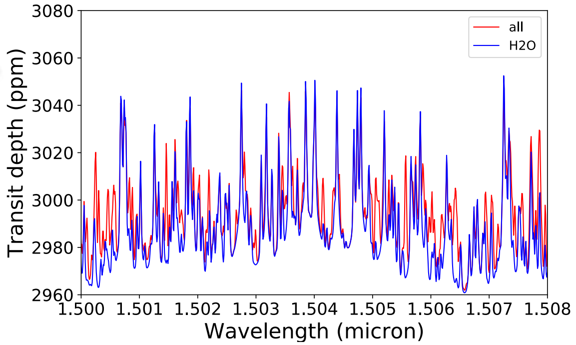

- ➢ Detecting/resolving individual lines
- ➢ **HR spectroscopy can probe above clouds**

# 1D modelling of K2-18b

***Line-by-line calculations***



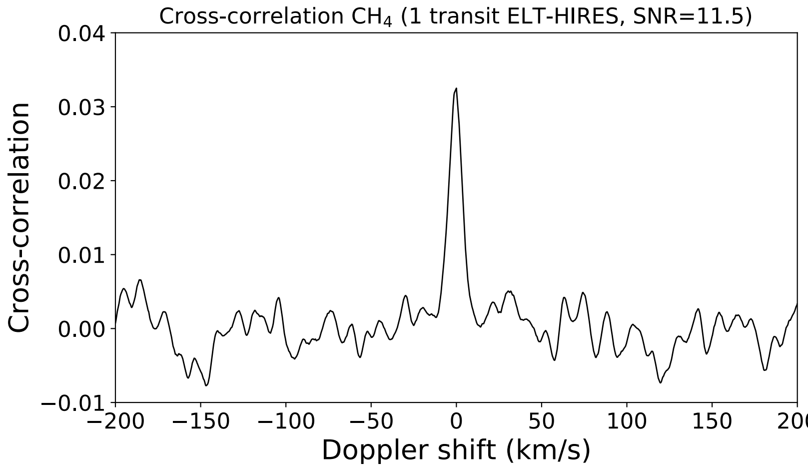



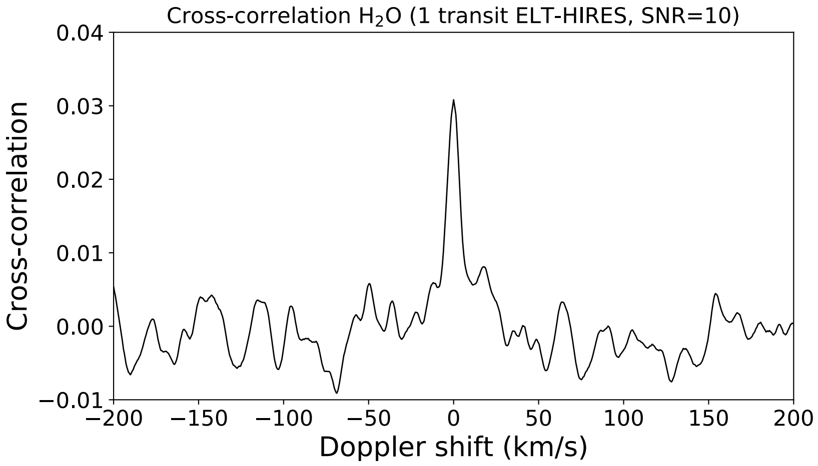



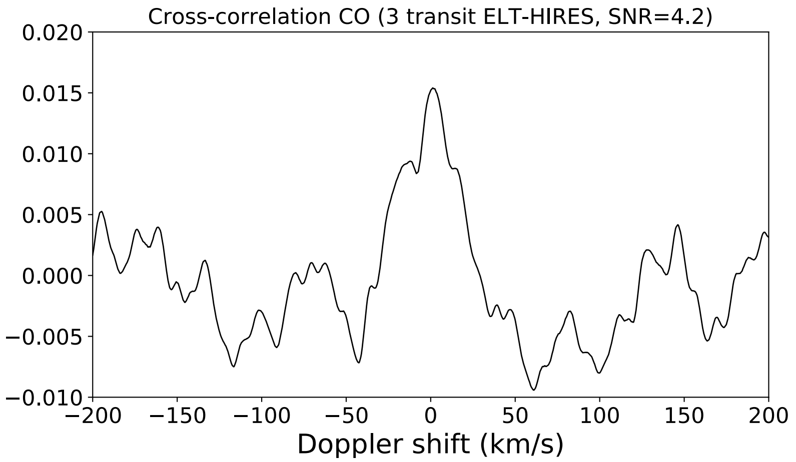

**<u>HR spectroscopy requires accurate line lists:</u>**

- ANR e-Pytheas for hydrocarbon line list (PI: A. Coustenis)
- TheoReTS instead of ExoMol for $CH_4$

Estimations of cross-correlation for K2-18b with ELT-HIRES assuming photon-noise limit and 30% instrumental throughput



# Take-home messages

- With future telescopes (JWST, ELTs, ARIEL) **the next decade will be the golden age of sub-Neptunes**
- Sub-Neptunes are **a fundamental step before habitable rocky planets**
- Atmospheric modelling of K2-18b suggests that **$CH_4$ is the dominant absorber** with important implications for other temperate sub-Neptunes
- 3D modelling of K2-18b suggests a circulation from day to night-side with **inhomogeneous clouds and transit spectral variability**
- A large spectral range or **a high spectral resolution is required** to characterize sub-Neptunes (i.e. $CH_4$ VS $H_2O$)
- **ELT-HIRES could constrain their atmospheric composition, escape, photochemistry and clouds/hazes**