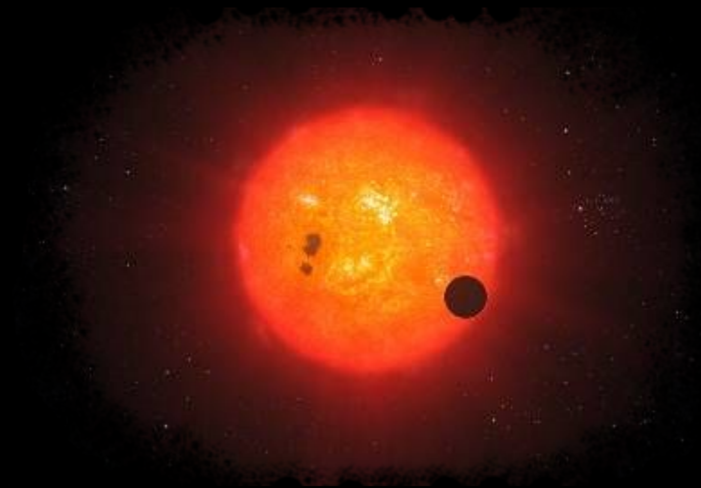

Exoplanet atmosphere challenges
Understanding stellar activity

Juan Carlos Morales

Collaborators: Ignasi Ribas, Manuel Perger, Guillem Anglada, Enrique Herrero, David Baroch, Jordi Blanco, Òscar Porqueres, and the stars & planets ICE-IEEC group

Institut d'Estudis Espacials de Catalunya (IEEC) and Institute of Space Sciences (ICE, CSIC)
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CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Institute of Space Sciences

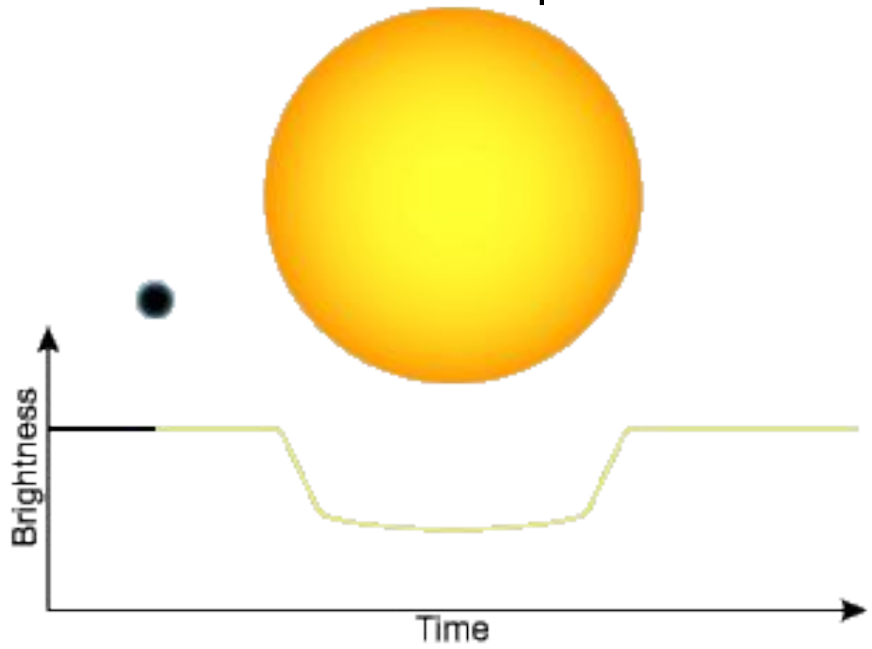
EXCELENCIA MARÍA DE MAEZTU

IEEC

Studying exoplanet atmospheres

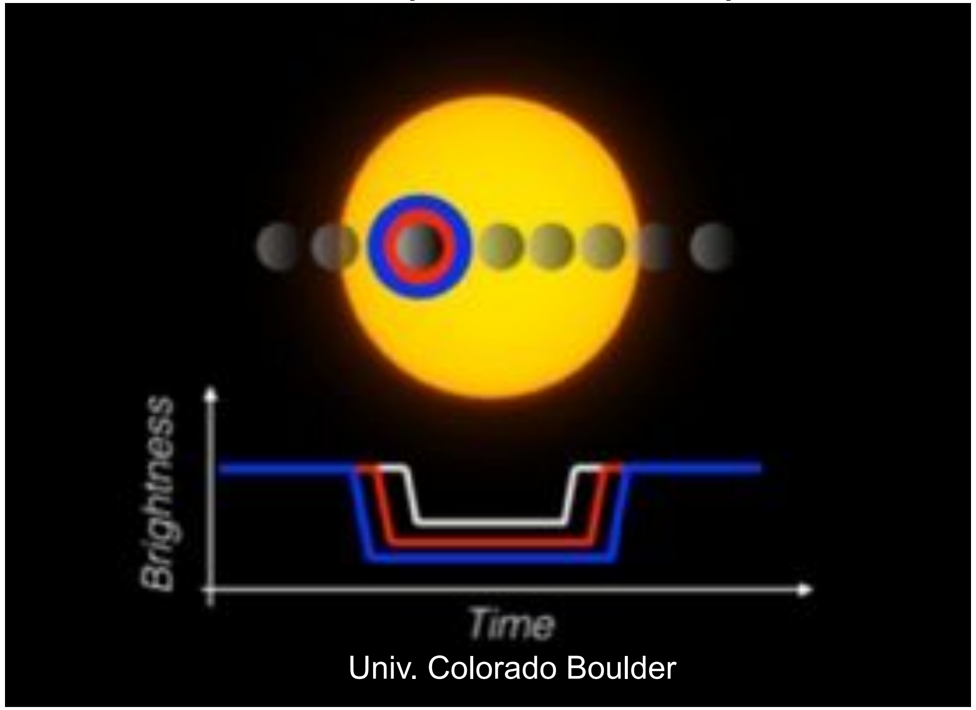
- <u>Transiting exoplanets</u>

Detection and bulk properties
White light or broadband filter:
radius of the planet



Univ. Hertfordshire

Transmission spectroscopy
Narrow band filter/spectra:
radius of the planet + atmosphere



Univ. Colorado Boulder

Studying exoplanet atmospheres

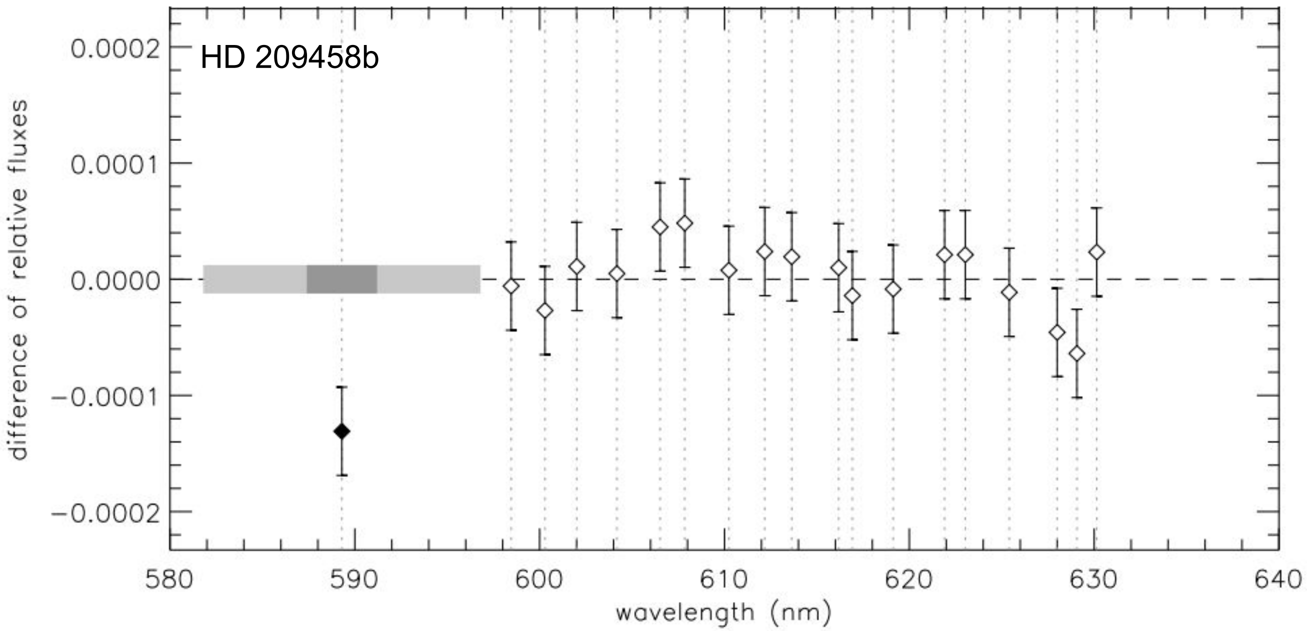
- <u>First exoatmospheres detections</u>

2002 - Na in the atmosphere of a hot Jupiter planet (Charbonneau et al. 2001)

DETECTION OF AN EXTRASOLAR PLANET ATMOSPHERE[1]

DAVID CHARBONNEAU,[2,3] TIMOTHY M. BROWN,[4] ROBERT W. NOYES,[3] AND RONALD L. GILLILAND[5]

THE ASTROPHYSICAL JOURNAL, 568:377–384, 2002 March 20

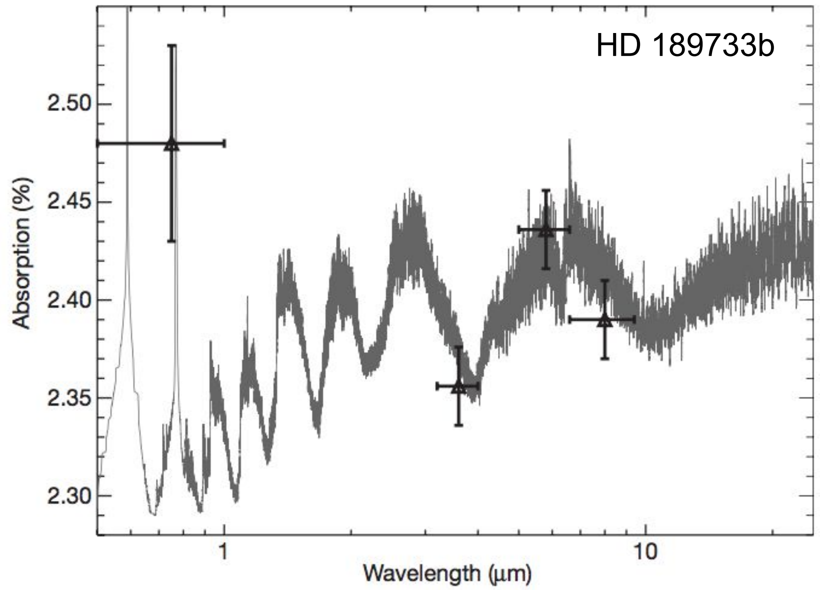


2007 - Water in the atmosphere of a hot Jupiter (Tinetti et al. 2007)

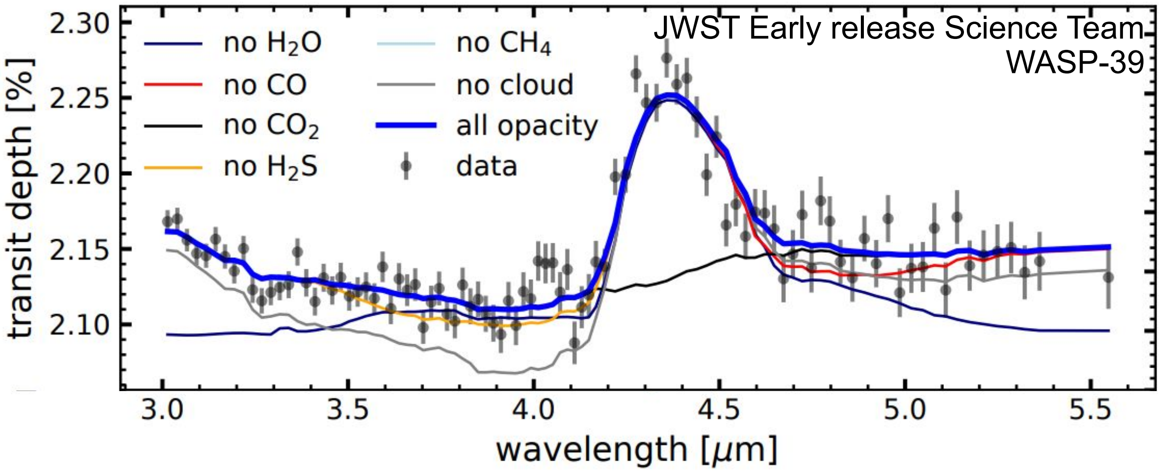
Water vapour in the atmosphere of a transiting extrasolar planet

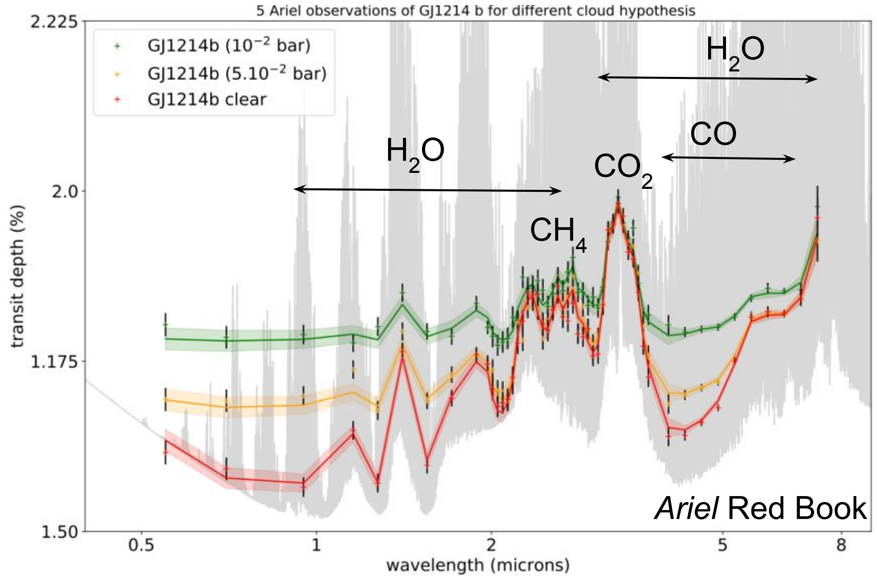
Giovanna Tinetti, Alfred Vidal-Madjar, Mao-Chang Liang, Jean-Philippe Beaulieu, Yuk Yung, Sean Carey, Robert J. Barber, Jonathan Tennyson, Ignasi Ribas, Nicole Allard, Gilda E. Ballester, David K. Sing & Franck Selsis

Nature **448**, 169–171 (2007) | Cite this article



Studying exoplanet atmospheres





- Exploding in the coming years with JWST
- Future dedicated space missions such as *Ariel* (expected launch 2029)

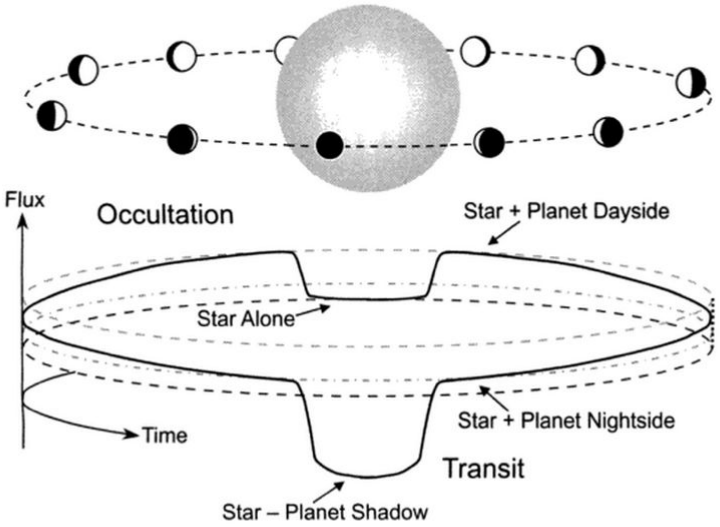
  → large survey of exoplanets (~1000)
  → wide spectral coverage

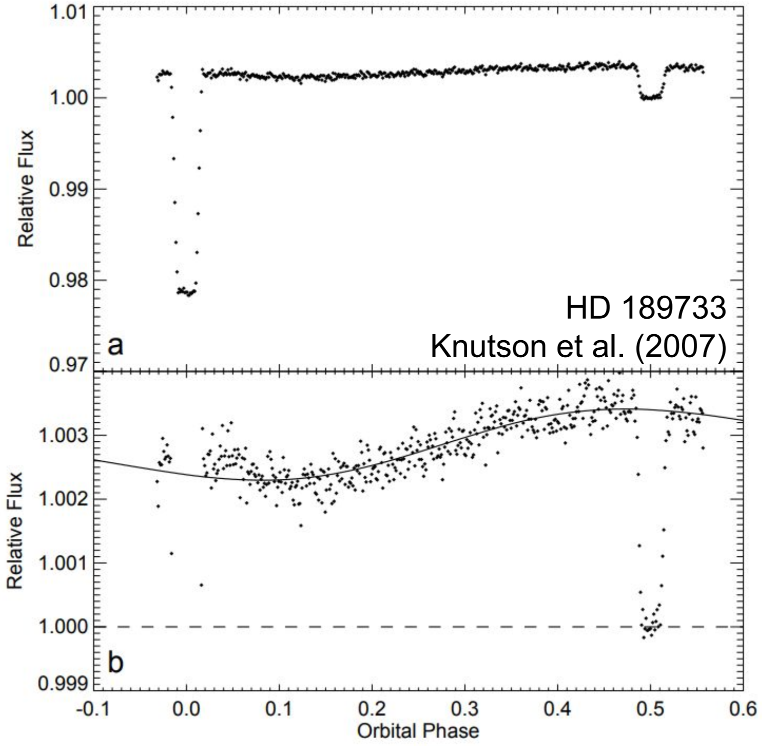
Studying exoplanet atmospheres

- <u>Transmission spectroscopy</u>
  Light of the star passing through the atmosphere terminator
  → Composition
  → Temperature profile
  → Clouds/hazes
  → Line profiles

- <u>Emission spectroscopy</u>
  Reflection and thermal emission from the dayside
  → Dayside temperature profile
  → Albedo
  → Chemical composition

- <u>Phase curves</u>
  Reflection/emission from the exoplanet at different phases
  → Day/nightside differences
  → Albedo
  → Temperature map
  → Atmosphere circulation





Studying exoplanet atmospheres

- <u>Exoplanet atmospheres</u>

  Already a lot of progress!
  181 planets studied, 56 molecules detected

  → Mainly ultrahot (> 2000 K) and hot Jupiters (> 800 K)

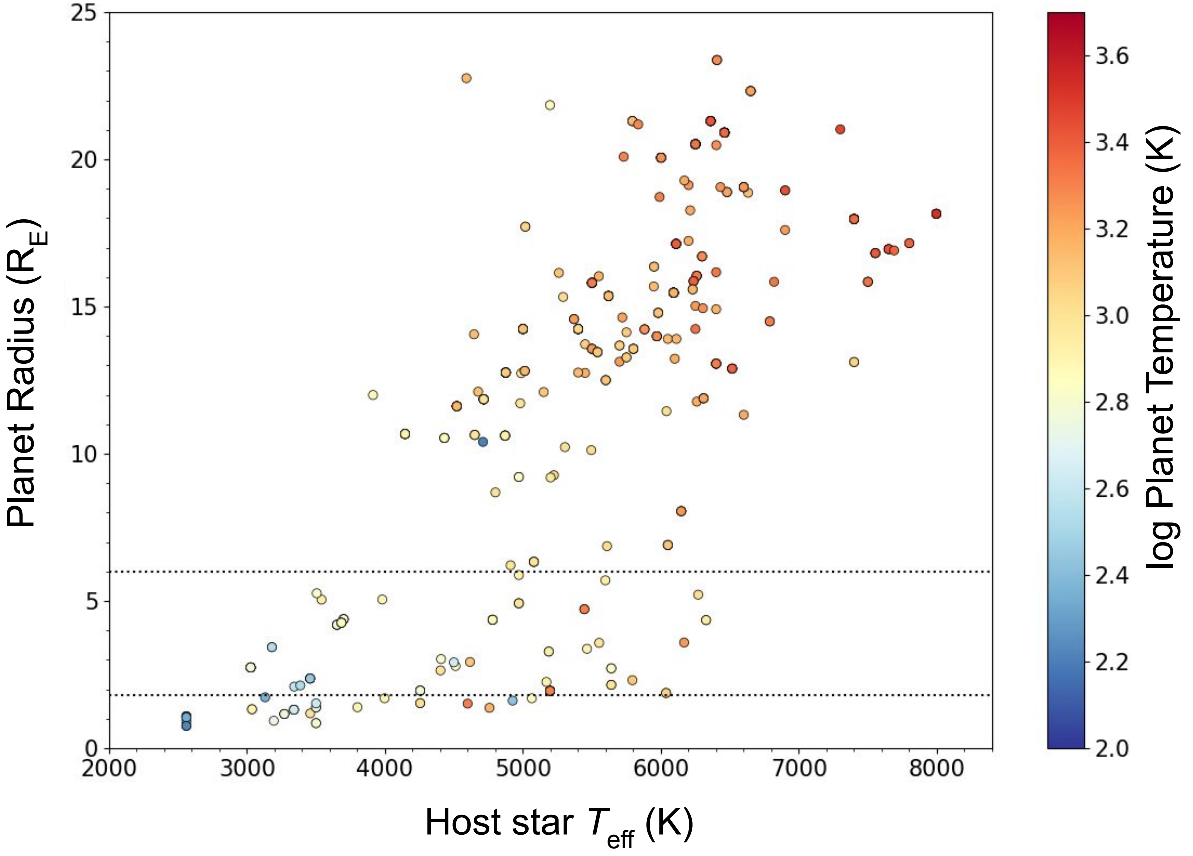
  → Several hot and warm Neptunes and sub-Neptunes

  → Few Earth and SuperEarths

  Different species detected:
  H, He, H_2O, CO, CO_2, Ca, Na, Fe…

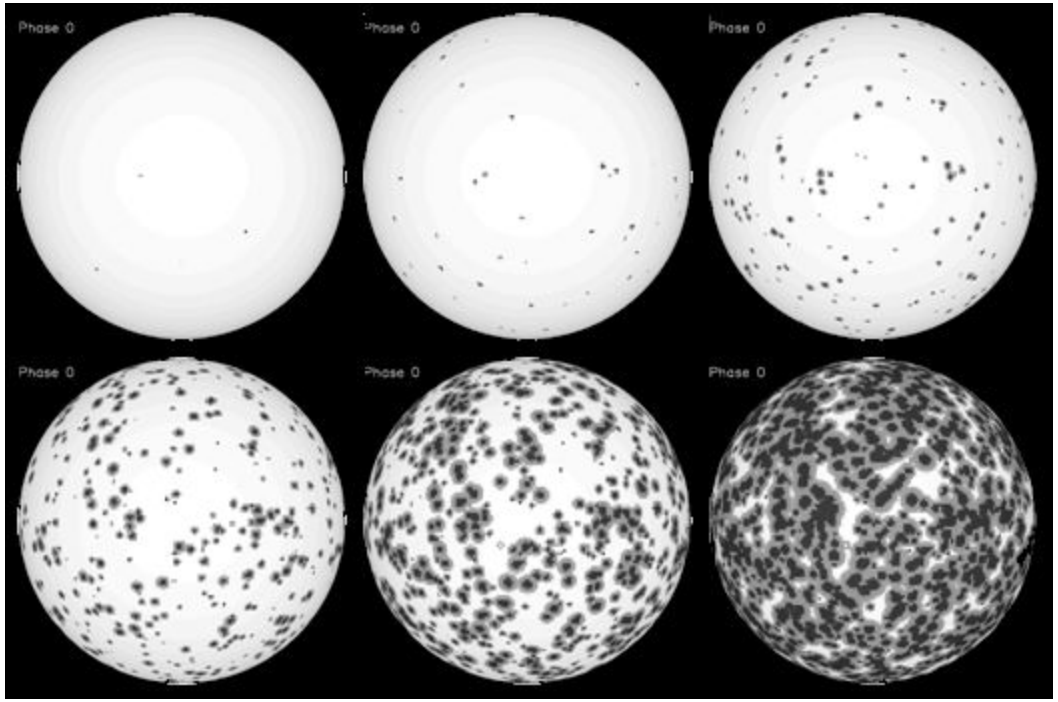
  Atmosphere signal ≲ 10^{-3}!

Data from ExoAtmospheres:
http://research.iac.es/proyecto/exoatmospheres/

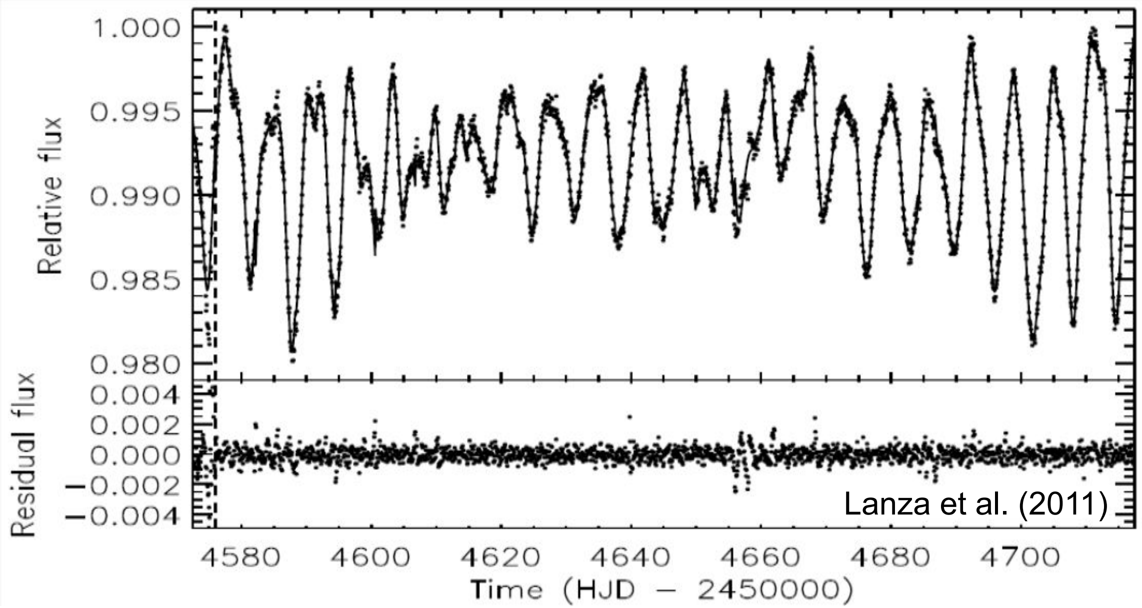


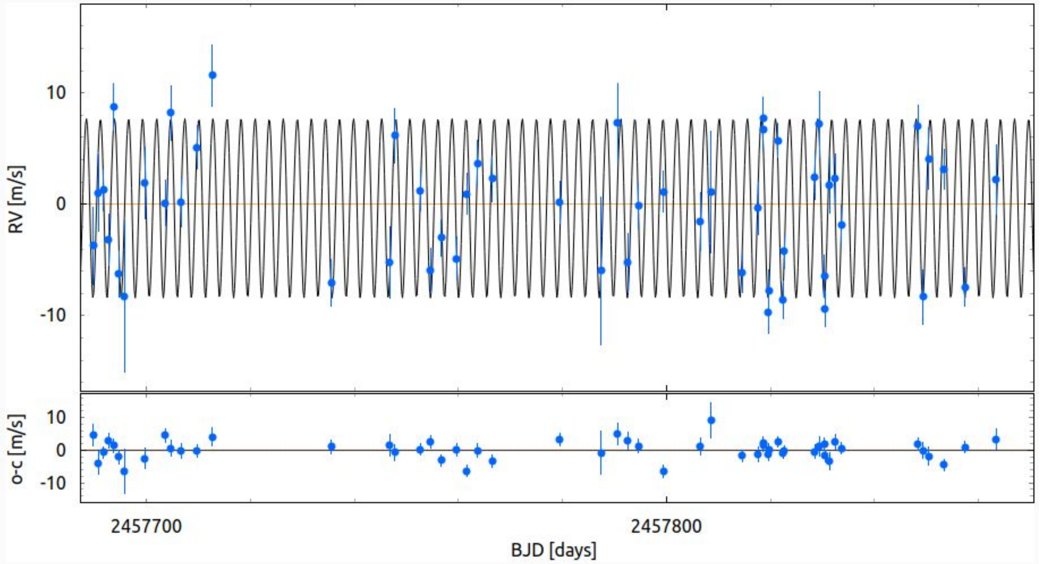
Stellar activity, a challenge!

- Stellar spots → photometric variability
  → transit depth variations
  → spectroscopic variability



Barnes et al. (2011)

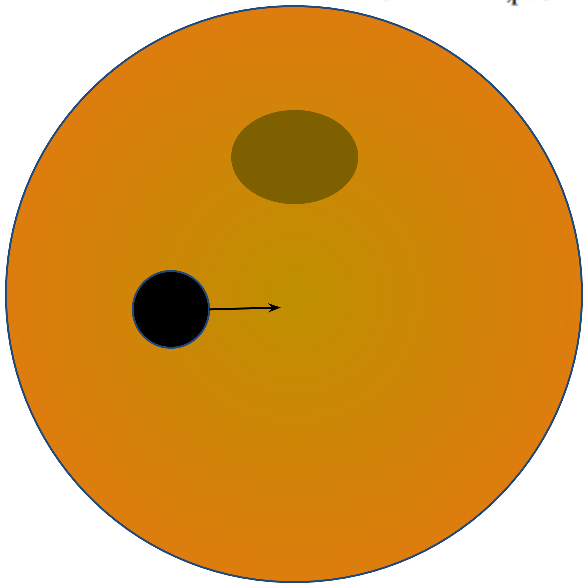


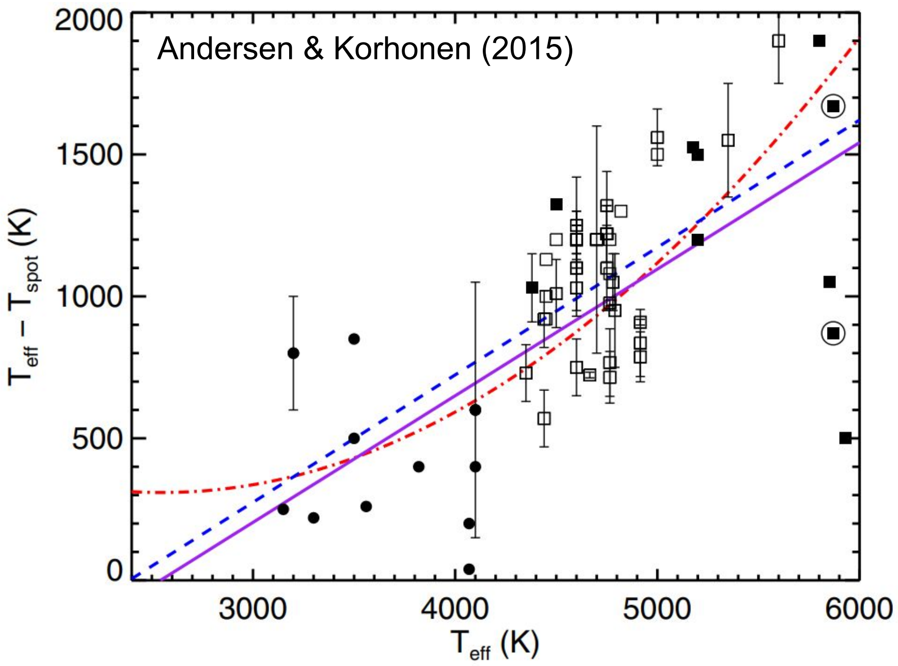


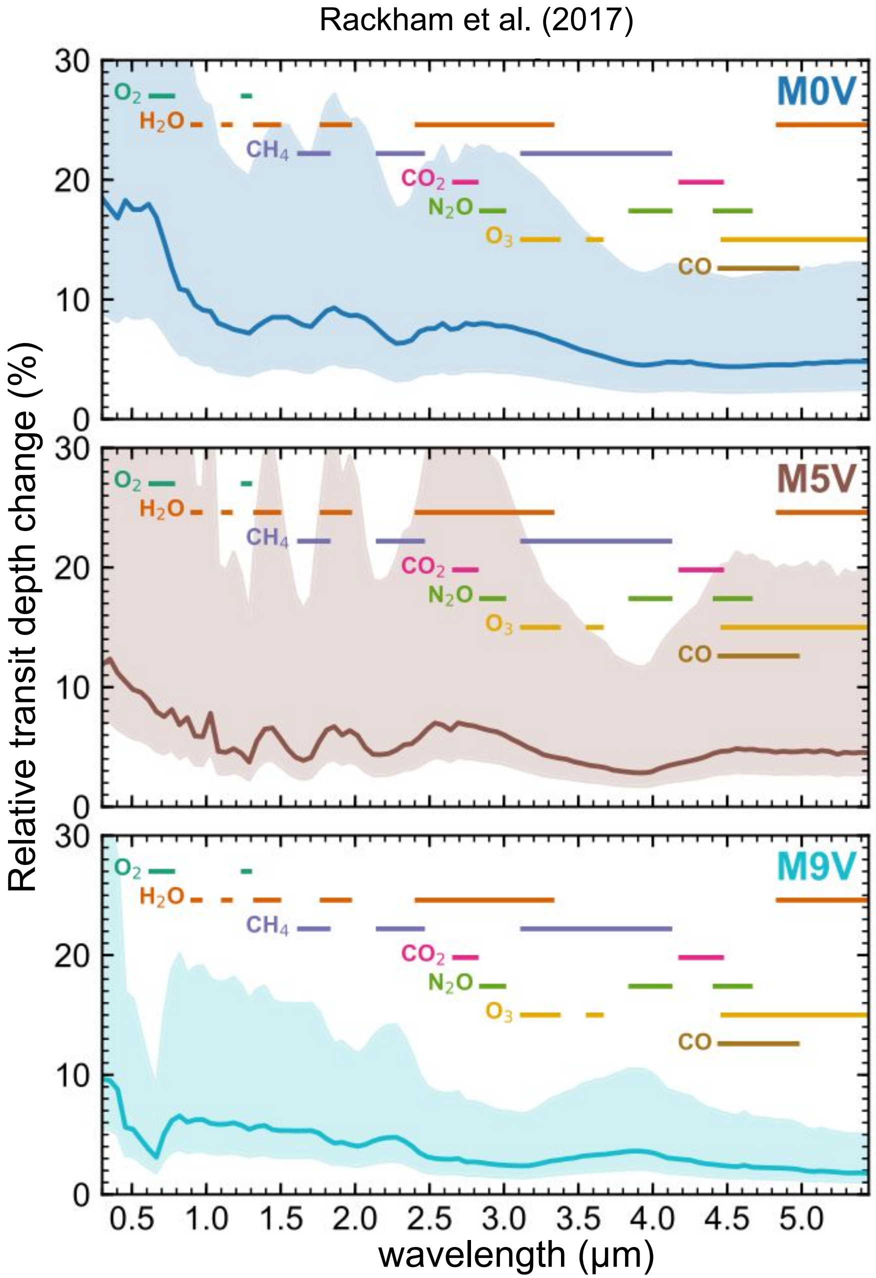
Stellar activity, a challenge!

- Spot effects on transmission spectroscopy:
  - Chromatic → wavelength dependence
  - Spots size/temperature → large differences
  - Spots evolution → variability
- Particularly relevant for M-dwarf stars!

$$\mathcal{D}'(\lambda) = \frac{\mathcal{D}_0}{1 - \delta_{\rm sp}\left(1 - \frac{F_{\lambda,\rm sp}}{F_{\lambda,\rm ph}}\right)}$$

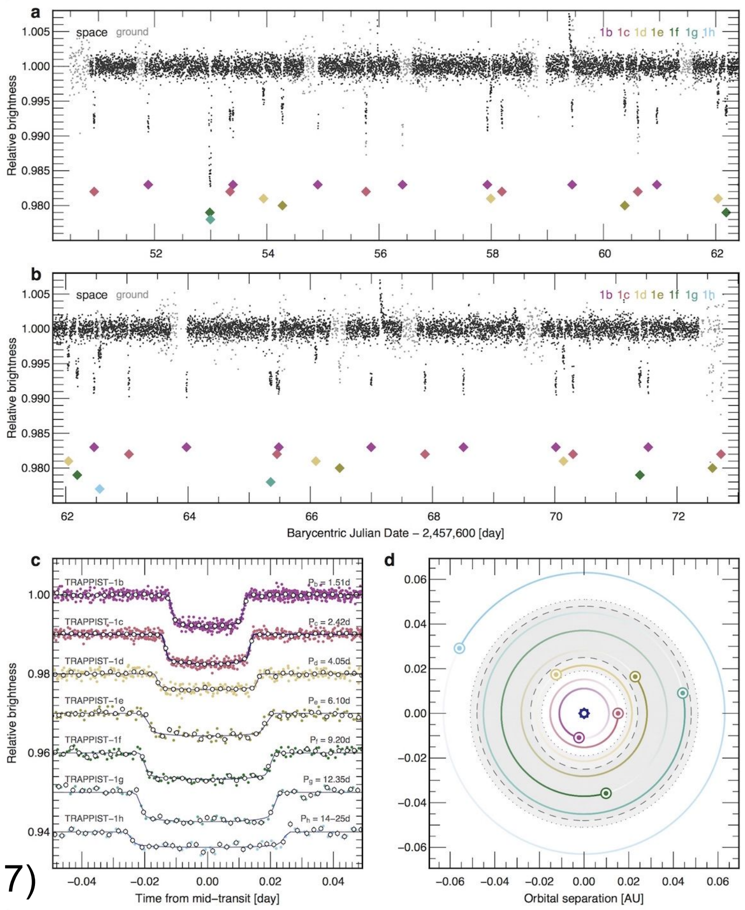






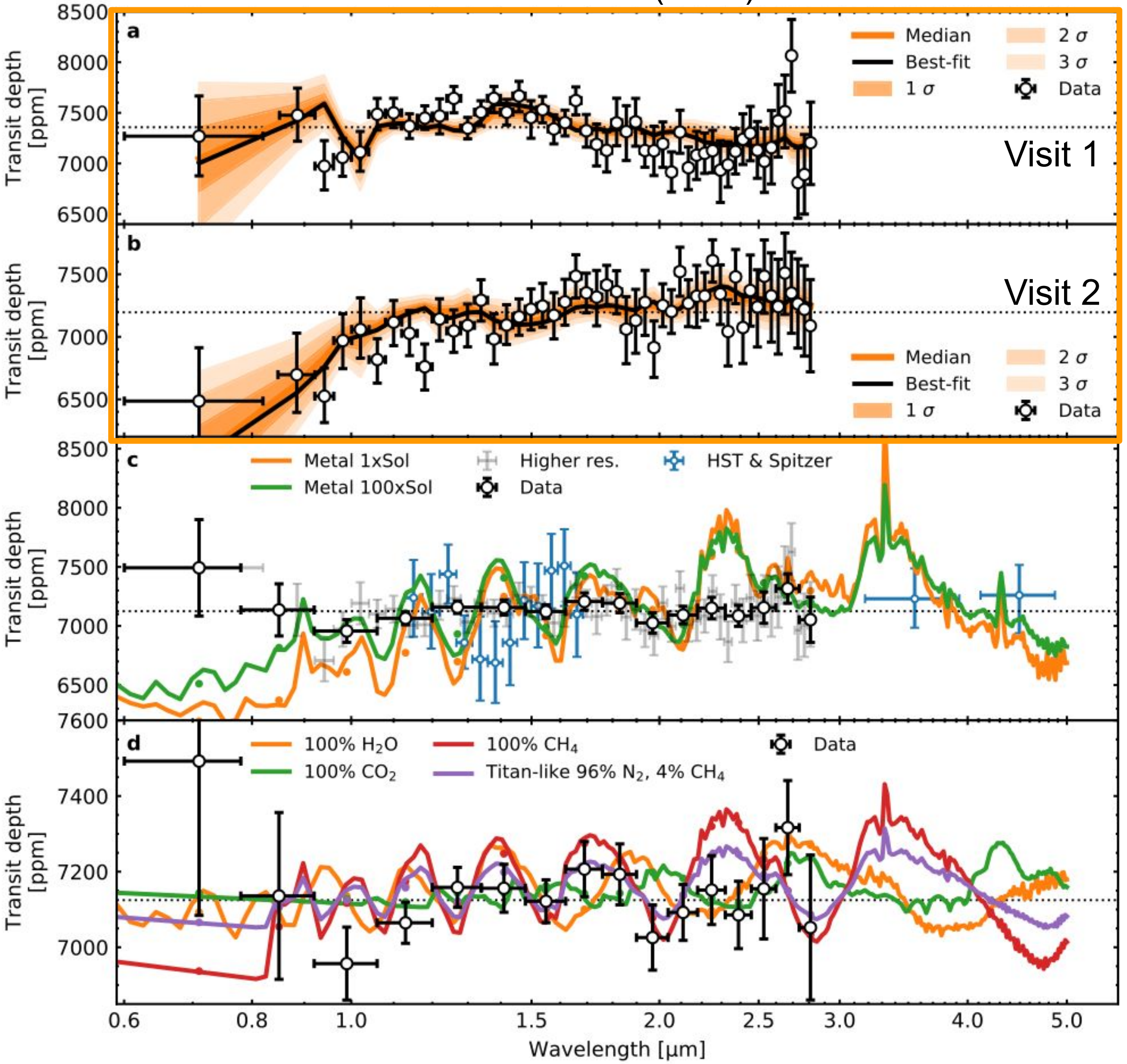
Stellar activity, a challenge!

- JWST transmission spectra of TRAPPIST-1b:
  - Contamination from spots
  - Different on each visit



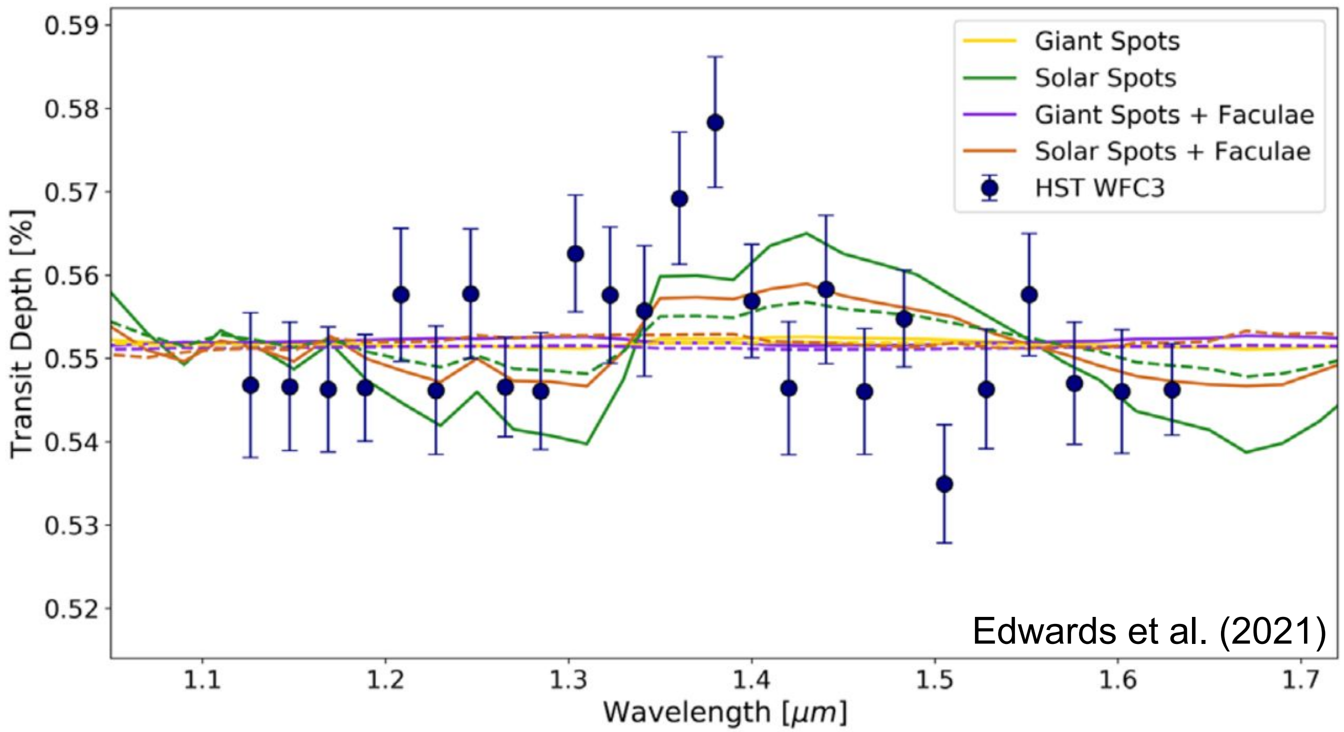
Gillon et al. (2017)

Lim et al. (2023)



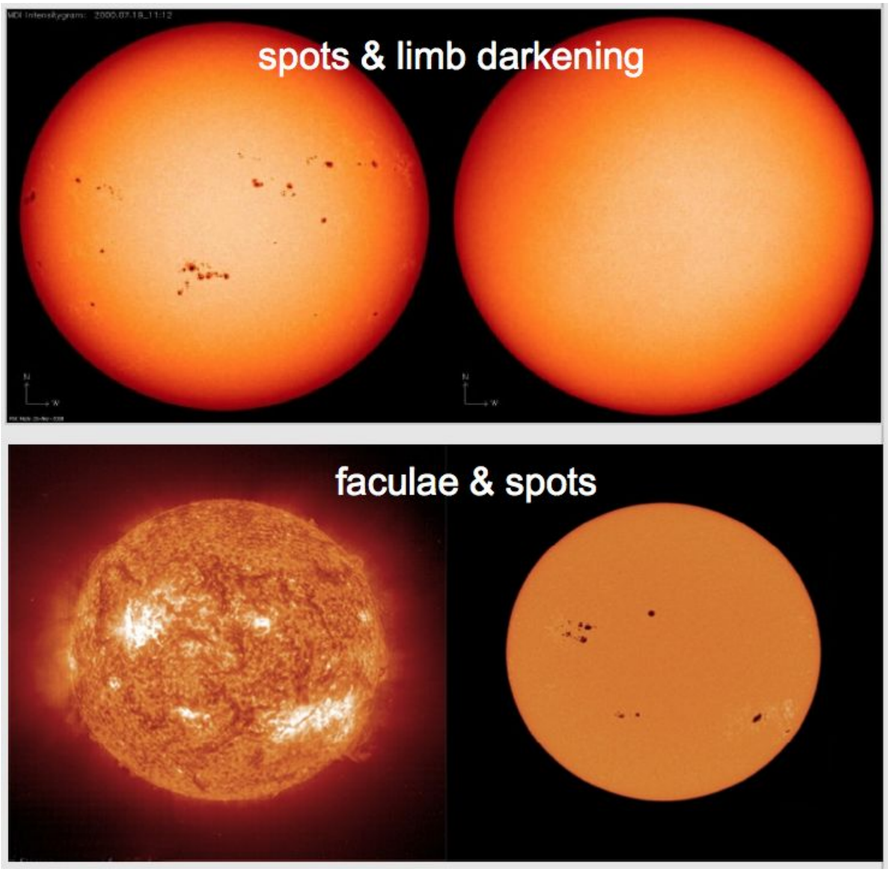
Stellar activity, a challenge!

- HST transmission spectra of LHS 1140b:
  - Contamination from spots reduce the detection significance



StarSim, the solution!

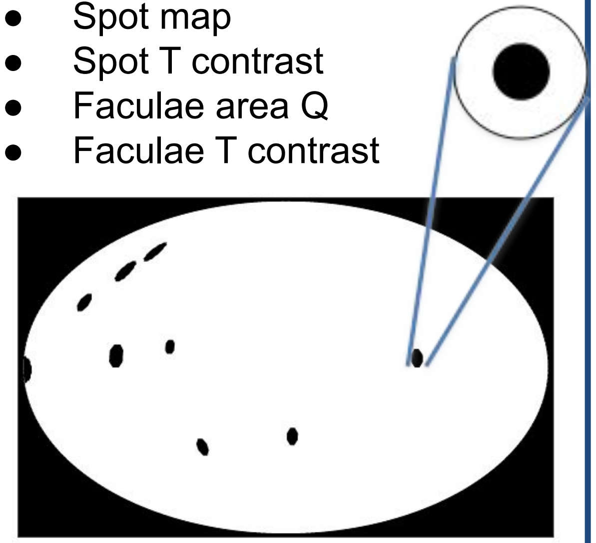
- Modeling the effects stellar activity.
(Herrero et al. 2016, Rosich et al. 2020)



Input

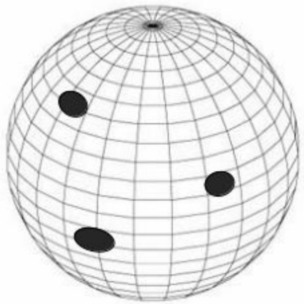
Stellar parameters
- T_{eff}
- $\log(g)$
- Metallicity
- Rotation period
- Differential rotation
- Axis inclination

Active regions
- Spot map
- Spot T contrast
- Faculae area Q
- Faculae T contrast

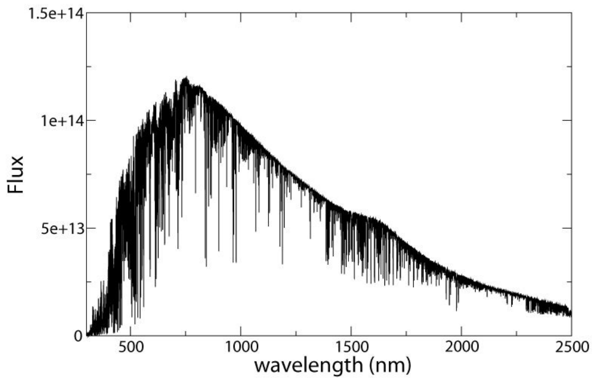


Methodology

Spectrum of the spotted photosphere
Σ (spectrum of each surface element):
- Individual Teff (photosphe or spot)
- Individual limb darkening
- Individual rad. vel. (Doppler shift)



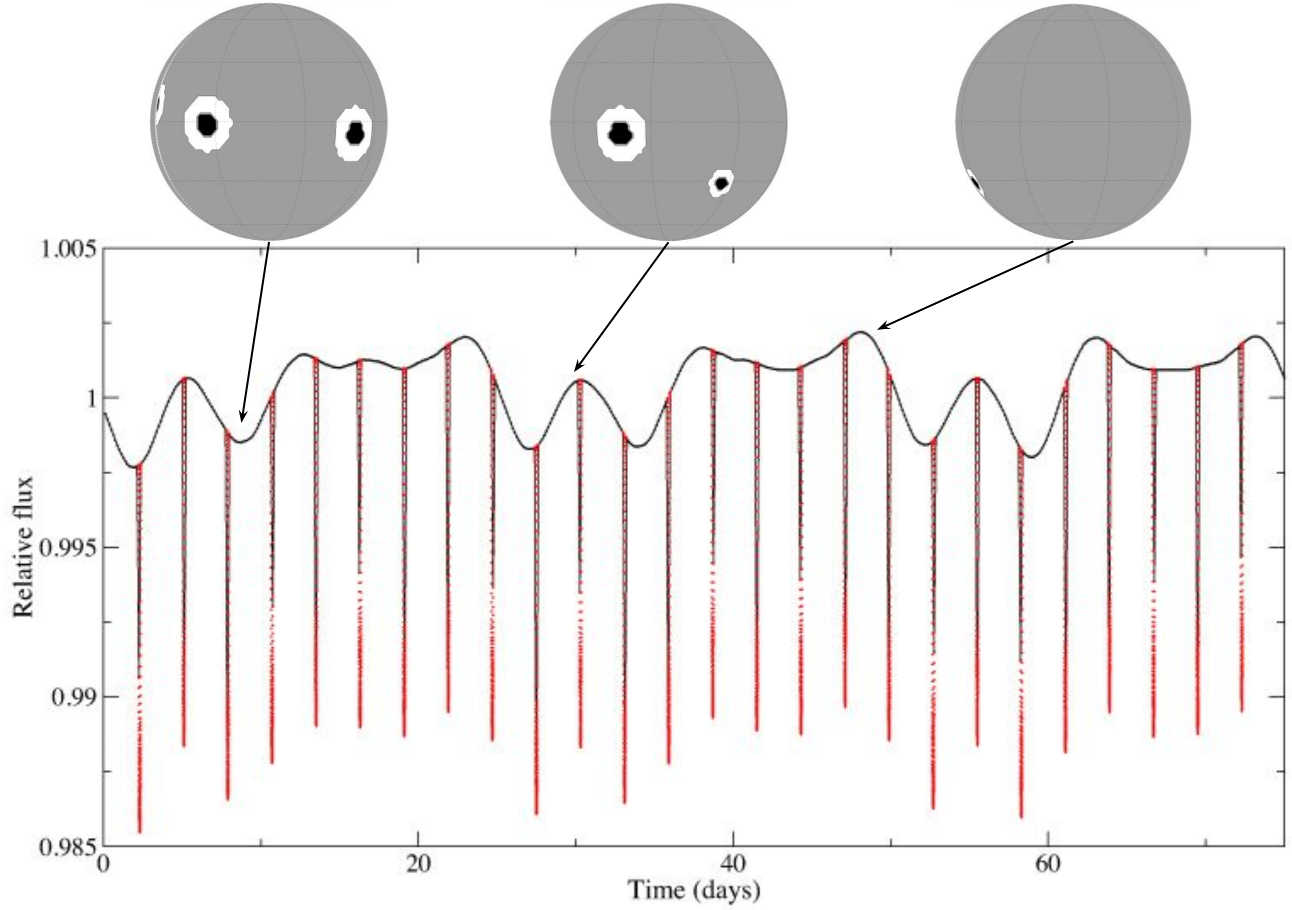
BT-Settl models (Phoenix)
- Teff = 3500-10000 K
- λ range: 10-5000 nm
- Low resolution (R~5000)



StarSim, the solution!

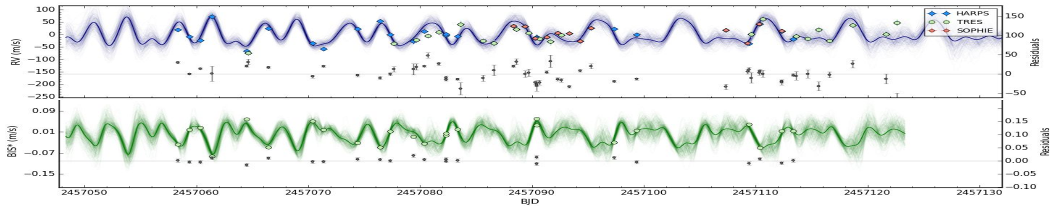
Output

Photometric variability



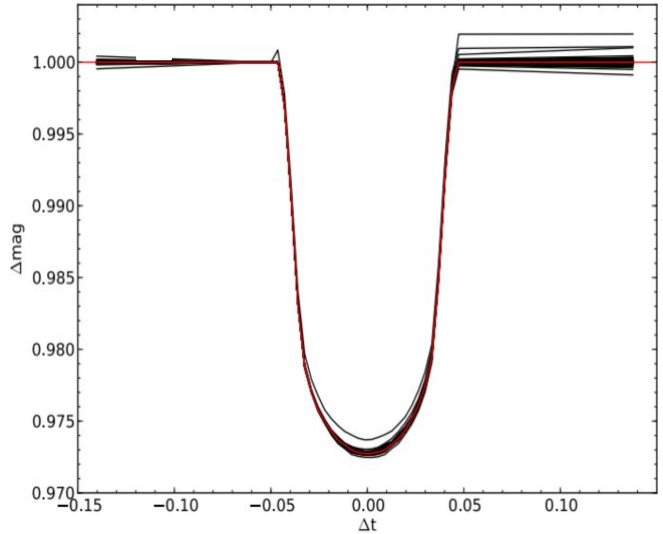
Output

Radial velocity variability and spectroscopic indices
(Baroch et al. 2020, Perger et al. 2023)
J. Blanco-Pozo talk



Transit depth variation

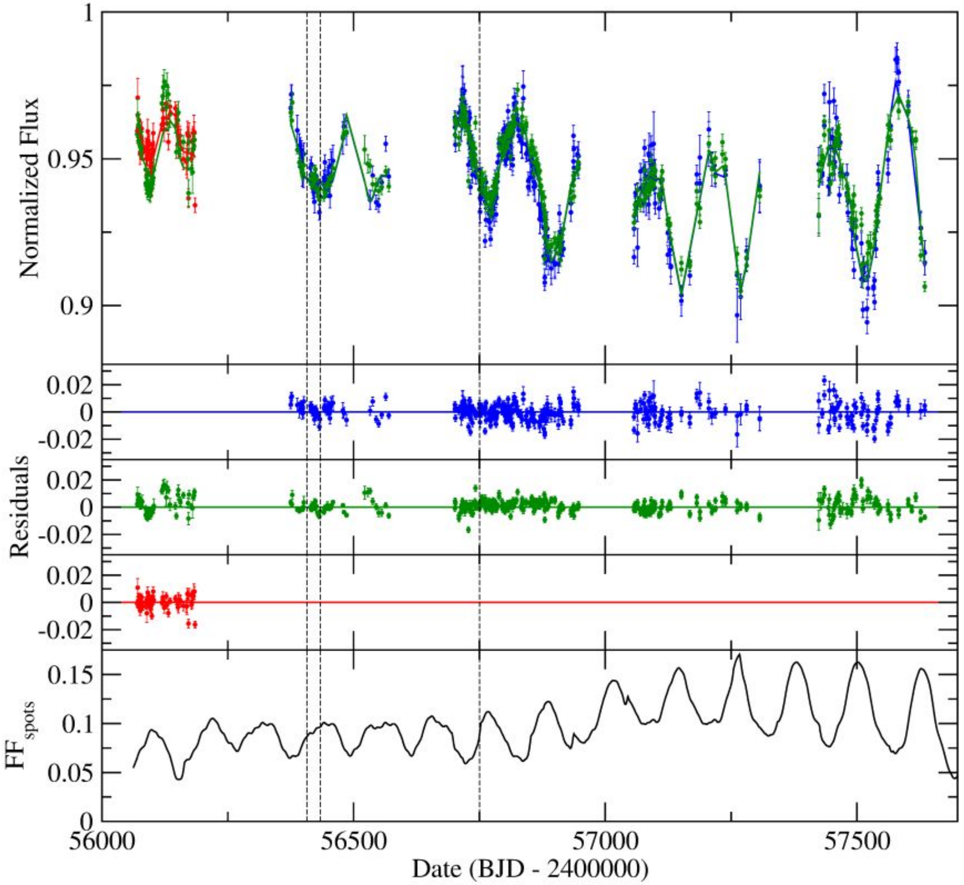
$$\mathcal{D}'(\lambda) = \frac{\mathcal{D}_0}{1 - \delta_{\rm sp}\left(1 - \frac{F_{\lambda,\rm sp}}{F_{\lambda,\rm ph}}\right)}$$



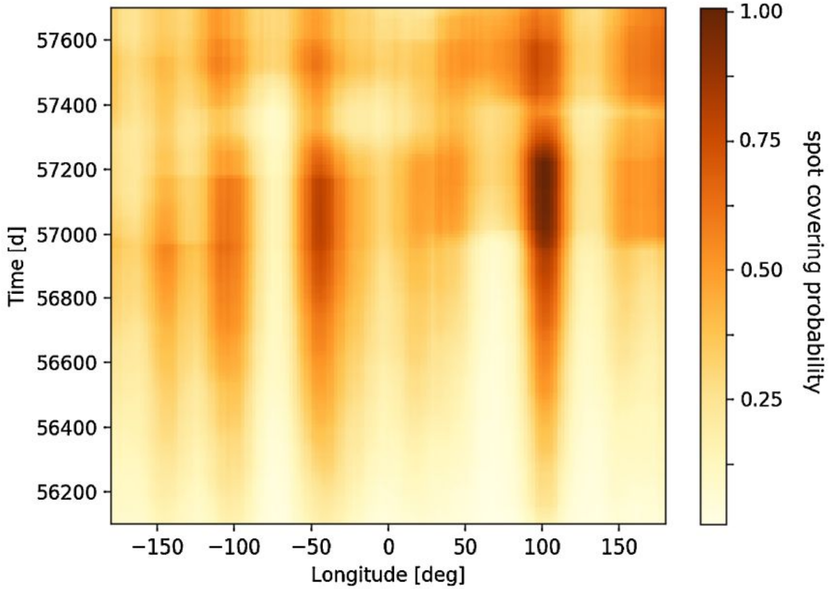
StarSim, the solution!

- Multiwavelength photometry: 2 bands
  → Disentangle spot filling factor and spot temperature
  → Spot distribution

Mallonn et al. (2018)
GJ 1214



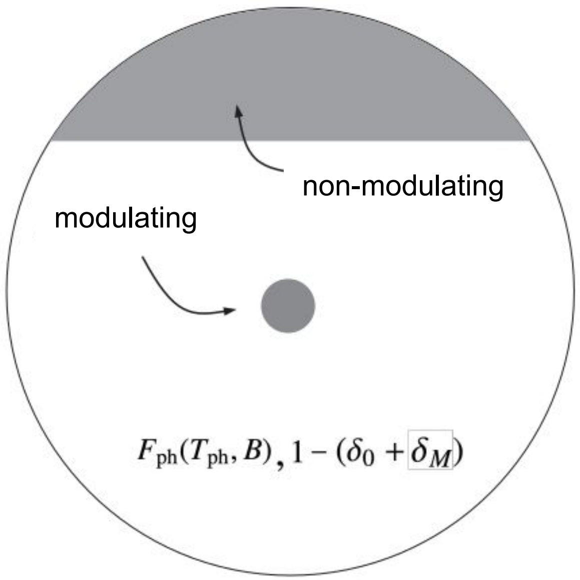
ΔT_{spot} = 370 ± 150 K

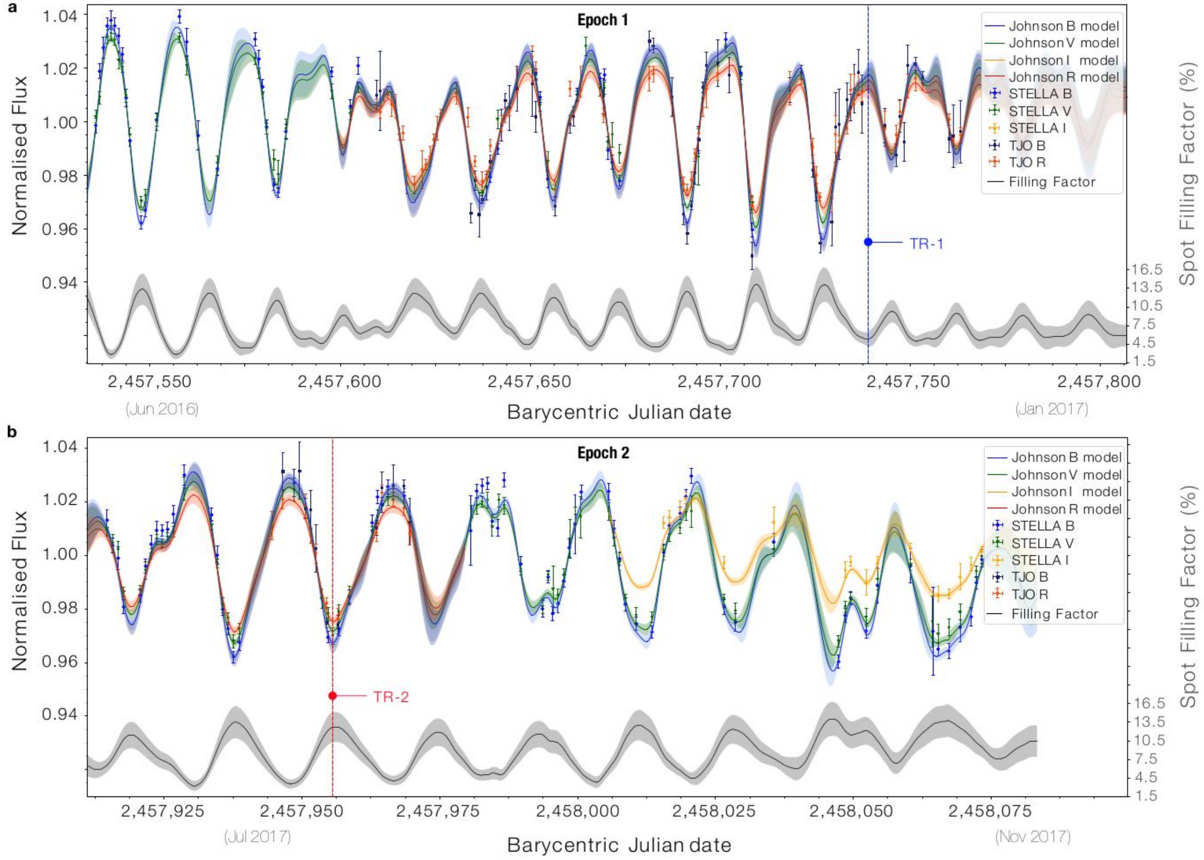


StarSim, the solution!

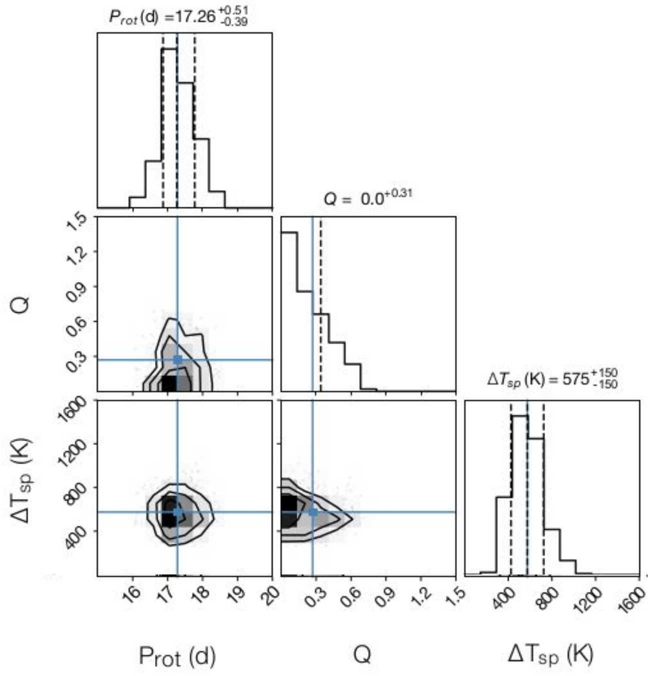
- Contemporaneous multiwavelength photometry: >2 bands
  → Disentangle spot filling factor and spot temperature
  → Spot distribution
  → Non-modulating spot component (amplitude changes)

Rosich et al. (2020)
WASP-52





ΔT_{spot} = 575 ± 150 K

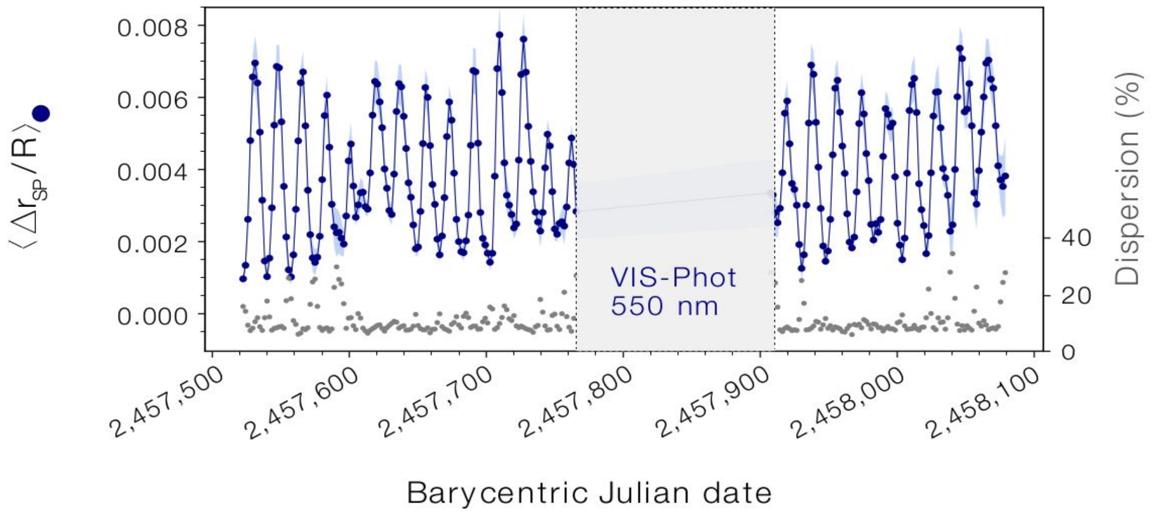


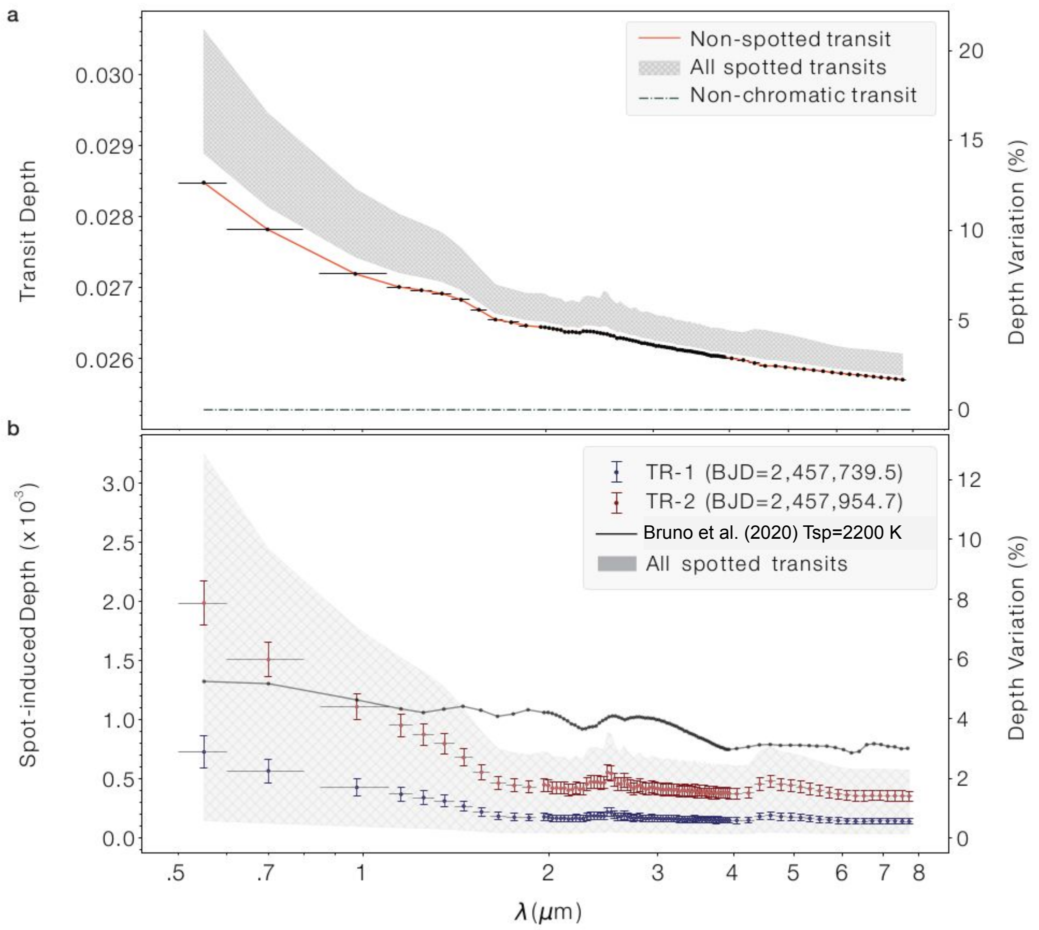
StarSim, the solution!

- Contemporaneous multiwavelength photometry:
  → Evaluate rotation phase at the time of transit
  → Infer transit depth variations from light curve variability
  → Estimate values for longer wavelengths

Rosich et al. (2020)
WASP-52

Instrument	λ_{eff} (μm)	$(\langle SP(\lambda)\rangle \pm \sigma) \times 10^{-3}$ low-activity TR-1	high-activity TR-2
VIS-Phot	0.55	0.73 ± 0.13	1.99 ± 0.18
FGS-1	0.7	0.57 ± 0.10	1.51 ± 0.15
FGS-2	0.975	0.43 ± 0.07	1.11 ± 0.11
NIR-Spec	1.525	0.22 ± 0.04	0.56 ± 0.06
AIRS-Ch0	2.95	0.17 ± 0.03	0.43 ± 0.05
AIRS-Ch1	5.875	0.15 ± 0.02	0.37 ± 0.04





Summary

- Features caused by stellar activity complicates the interpretation of the transmission spectra of exoplanets
- Multiband photometry helps to overcome this problem:
  → independent filling factor and spot temperature
  → absolute filling factor
  → spot distribution at the time of transit
  → correction factors on other bands
- Key for JWST observations of exoplanets around active stars, and for future missions such as *Ariel*:
  → ground-based support observations
  → space-based contemporaneous surveys (e.g. PhotSat)
- New methodologies: training Neural Networks with StarSim
  → Already applied for radial velocity data (J. Blanco-Poxo next talk)
  → Plan to develop similar tools for transmission spectroscopy

Thank you!

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