Hints of atmosphere around the 1.6 $R_\oplus$ Super-Earth L98-59 d with one JWST NIRSpec G395H transit observation [Gressier at al. 2024 submitted]

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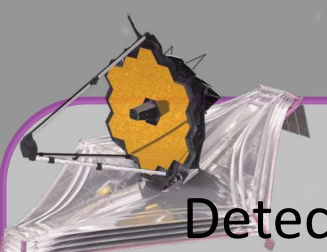


Detecting atmospheres around rocky planets (< 1.6 $R_\oplus$) orbiting M-dwarf stars is an ongoing key focus in exoplanet research with the JWST allowing for meaningful constraints for the first time over an extended wavelength range. We observed a transit of the **Super-Earth L98-59 d (1.58 $R_\oplus$, 2.31 $M_\oplus$)** using **JWST NIRSpec G395H**, covering 2.8 to 5.1µm. (GTO 1224 PI: S.Birkmann). The transit spectrum shows significant deviations from a flat line, revealing absorption features between 3.3 and 4.8 µm best fitted by sulfur-bearing absorption features.

The planet [1,2]

- ➔ R_p= 1.58 $R_\oplus$
- ➔ M_p= 2.31 $M_\oplus$
- ➔ Rho = 3.17 g/cm3
- ➔ T_{eq} = 416 K
- ➔ Period = 7.4507245 days
- ➔ b = 0.922±0.059

Multi-planetary system : b, c, d and e

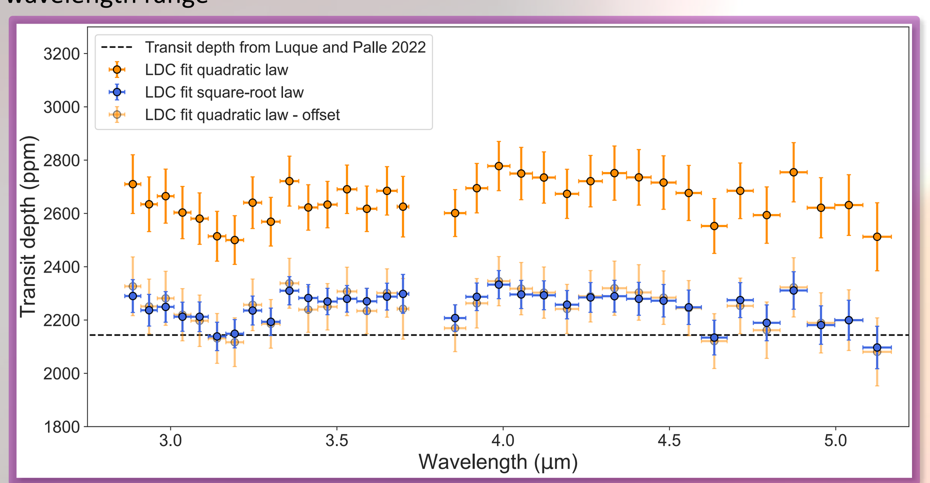
The star M3 V [1]

- ➔ Rs = 0.303
- ➔ Teff = 3415 K
- ➔ Log g =4.86
- ➔ Fe/H =-0.46

A note on Limb-darkening coefficients

The planet has a very high impact parameter, making it difficult to constrain the limb-darkening coefficients during the white and spectral light curve fits. To test the sensitivity of the transmission spectrum to the choice of limb-darkening coefficients, we adopted several approaches. The shape is unchanged but a general offset is seen between tests.

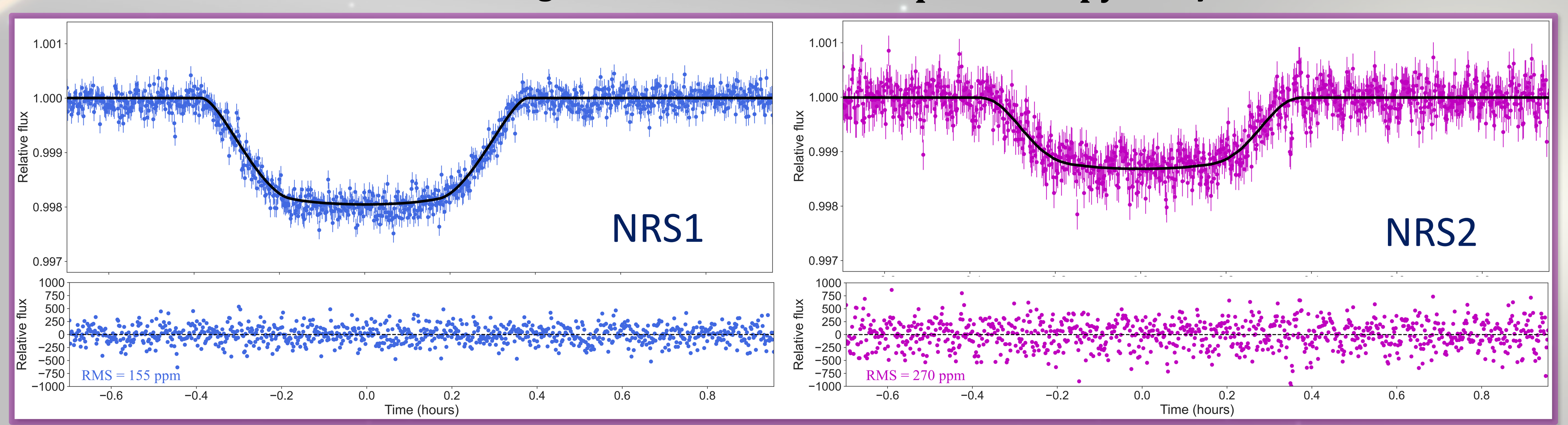
- ➔ **Square-root law truncated:** Fit the coefficients using a truncated normal prior between 0 and 1, with the mean set to an estimate from the ExoTIC package[7] and PHOENIX model, and a standard deviation of 0.1.
- ➔ **Square-root law uniform:** Fit the coefficients using a uniform prior between 0 and 1.
- ➔ **Quadratic law uniform**: Fit the coefficients using a uniform prior between 0 and 1.
- ➔ **Quadratic law fix** : The coefficients are fixed to the same value for the entire wavelength range



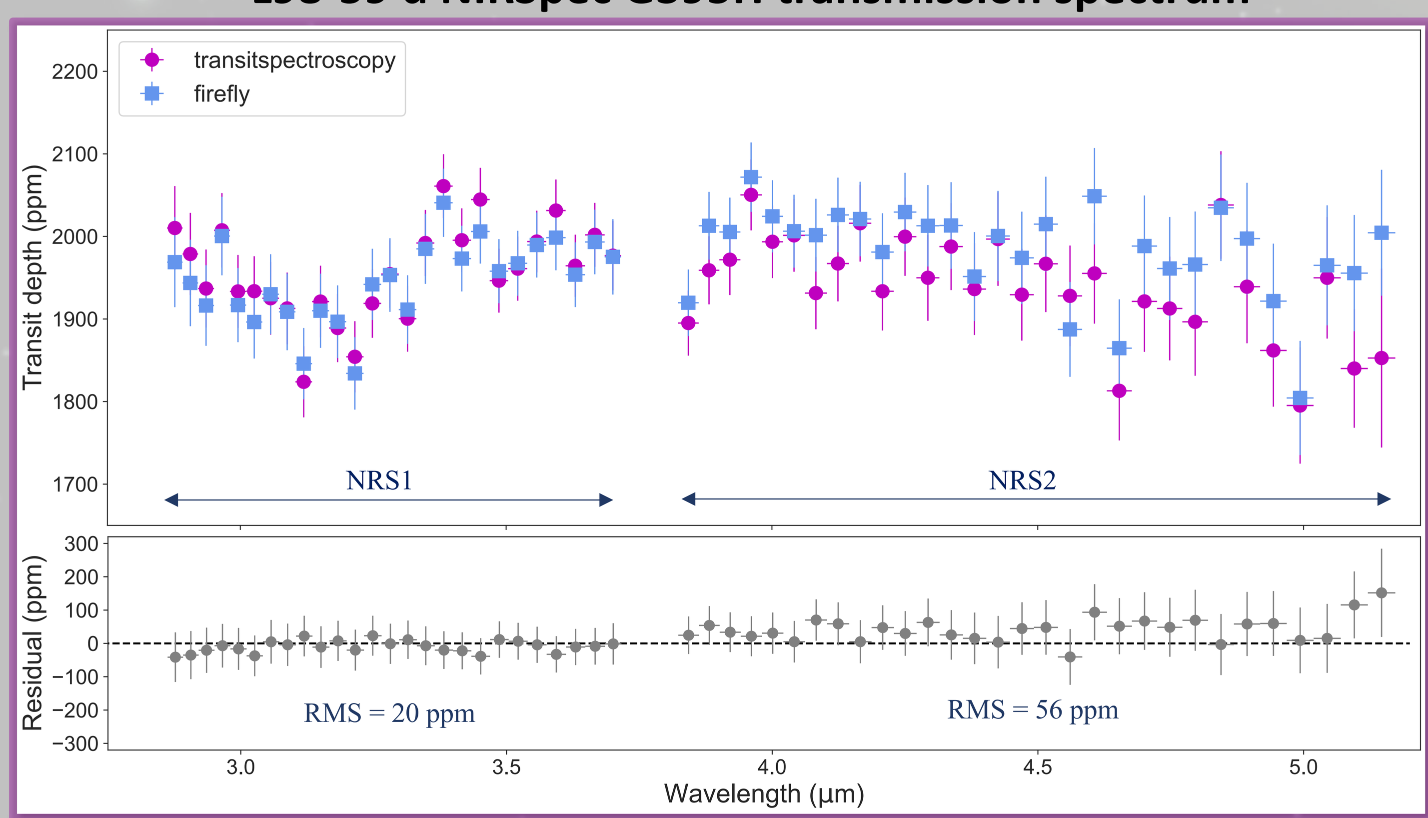
Data reductions

We performed two independent data reductions on one **JWST NIRSpec G395H transit observation** from June 25th using **transitspectroscopy[3] and FIREFLy [4,5]**. We followed standard jwst pipeline steps but incorporated a custom jump detection algorithm for the transitspectroscopy reduction. White light curves and pixel-level light curves were generated from the time series of 1D stellar spectra for both detectors. The spectral light curve fits were performed using juliet[6] at pixel-level resolution with fixed T0, a/rs, and b, based on combined best-fit results from the white light curve analysis. The noise was detrended using GP processes with time and FWHM as regressors. The limb-darkening coefficients were fitted between 0 and 1 using a square-root law and a truncated normal prior.

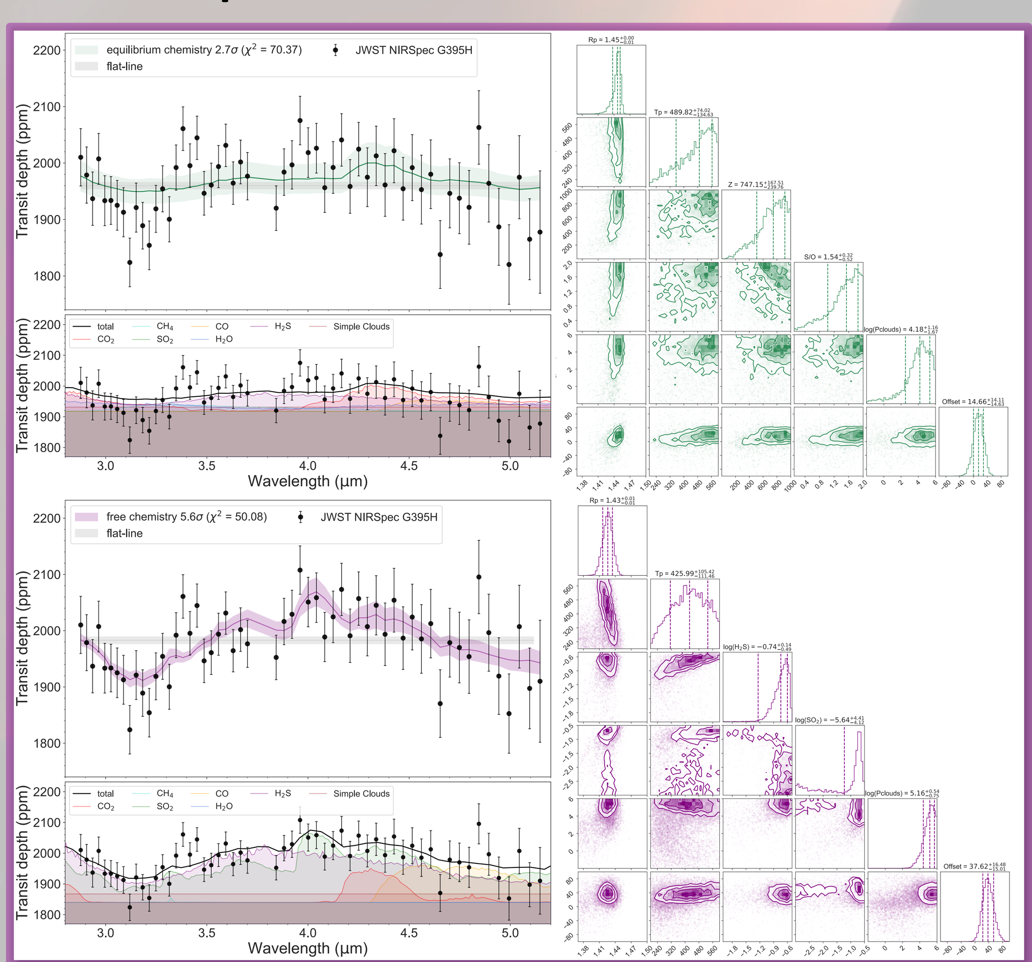
White light curves from transitspectroscopy analysis



L98-59 d NIRSpec G395H transmission spectrum



Atmospheric retrieval results



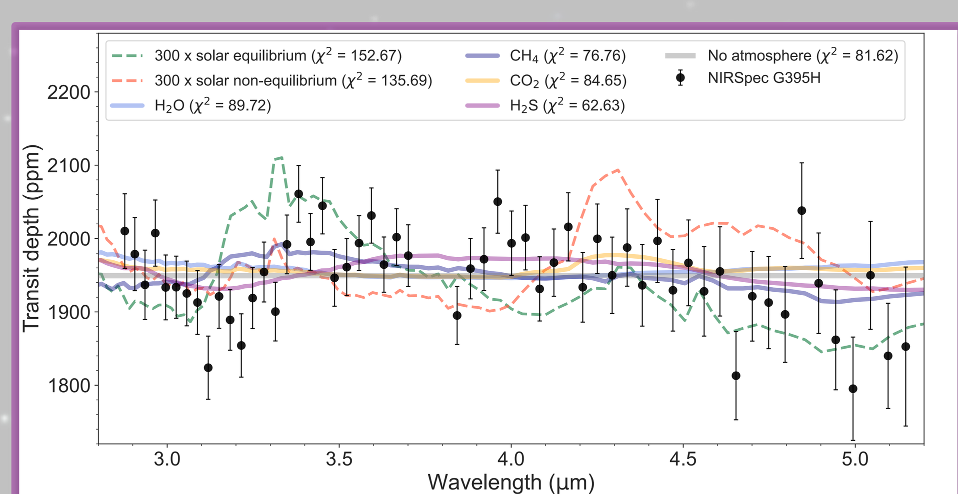
We performed atmospheric retrievals on the L98-59 d transmission spectrum using the Bayesian code TauRex[8] and the transitspectroscopy reduction. We run free retrieval analysis varying the inactive gas H_2 He and N_2 and equilibrium chemistry retrieval using ggchem [9].

The primary result is the detection of an atmosphere around L98-59 d, with a 5.6σ significance from the free chemistry retrieval and a 2.7σ significance from the equilibrium chemistry retrieval. We report a constraint on H_2S from both types of retrievals, with an extremely large abundance.

Both the free and equilibrium models suggest a contribution from H_2S opacity. CO_2 contributes in the equilibrium model, while SO_2 contributes in the free chemistry model. The free chemistry retrieval is a significantly better fit than the equilibrium chemistry by 3.8σ. The retrieval suggest a water-poor atmosphere with an upper constraint on its abundance found < 10^{-5}.

We use the Bayes factor to compare models and evaluate **the detection significance of sulfur-bearing compounds in the atmosphere of L98-59 d at 4.5σ.**

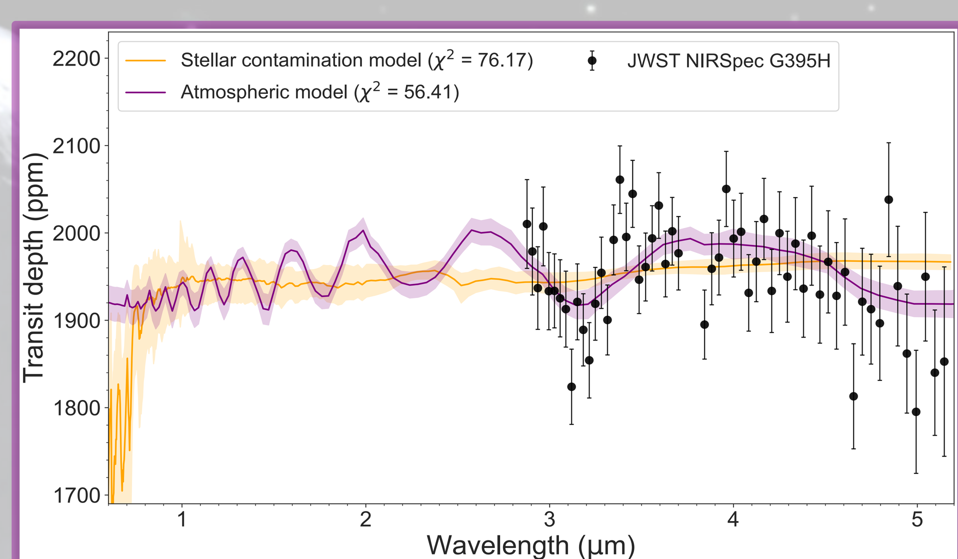
Hints of an atmosphere from 1D forward modelling



We used **Exo-REM[10, 11, 12] a 1D self-consistent radiative-convective code** for exoplanets and brown dwarfs atmospheric modelling. We create a grid of transmission spectra for L98-59 d, simulating a 300× solar atmosphere with both equilibrium and out-of-equilibrium chemistry.

The pure H_2S model provided the best fit to the observed spectrum. The spectrum is not flat at more than 4σ. Cloud-free models with H_2O CH_4, CO, and CO_2 did not match the observed features. The results suggest the presence of sulfur-bearing species.

No evidence of stellar inhomogeneities



Contamination from hot and cold spots on the star's photosphere can introduce false features into the spectrum. To test for stellar contamination, we used exoretrievals[13, 14] to model the spectrum considering various spot scenarios. **None of the stellar contamination models explained the observed spectral features.**

The best-fit atmospheric retrieval, favoring an H_2S/SO_2-rich atmosphere, suggests that the features between 3.3 and 4.8 µm likely originate from the planet's atmosphere rather than stellar contamination.

References
[1] Demangeon et al. 2021
[2] Luque and Palle 2022
[3] Espinoza et al 2019a
[4] Rustamkulov et al. 2022
[5] Rustamkulov et al 2023
[6] Espinoza et al. 2018
[7] Grant et al. 2022
[8] Al. Refaie et al. 2021
[9] Woitke et al. 2018
[10] Baudino et al. 2015
[11] Charnay et al. 2018
[12] Blain et al. 2021
[13] Espinoza et al. 2019b
[14] Rackham et al. 2018

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Want to know more about detecting atmospheres around rocky planets orbiting M-dwarfs using MIRI photometry ? Check out the Hot-Rocks survey (PI: H. Diamond-Lowe)