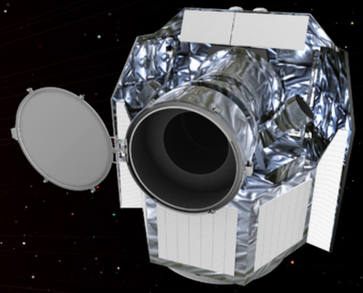
A possible misaligned orbit for the young planet AU Mic c



Z. Garai,
H. Yu, M. Cretignier, Gy. M. Szabó, S. Aigrain, D. Gandolfi, et al.,
including the CHEOPS and NGTS consortia





Institute seminar, Astronomical Institute, Slovak Academy of Sciences,
Tatranská Lomnica, May 21, 2025

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A possible misaligned orbit for the young planet AU Mic c

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H. Rauer [31,57] I. Ribas [58,59] N. C. Santos [26,27] G. Scandariato [51] D. Ségransan [13]
A. E. Simon [20,21] A. M. S. Smith [31] S. G. Sousa [26] R. Southworth,[60] M. Stalport,[40,61]
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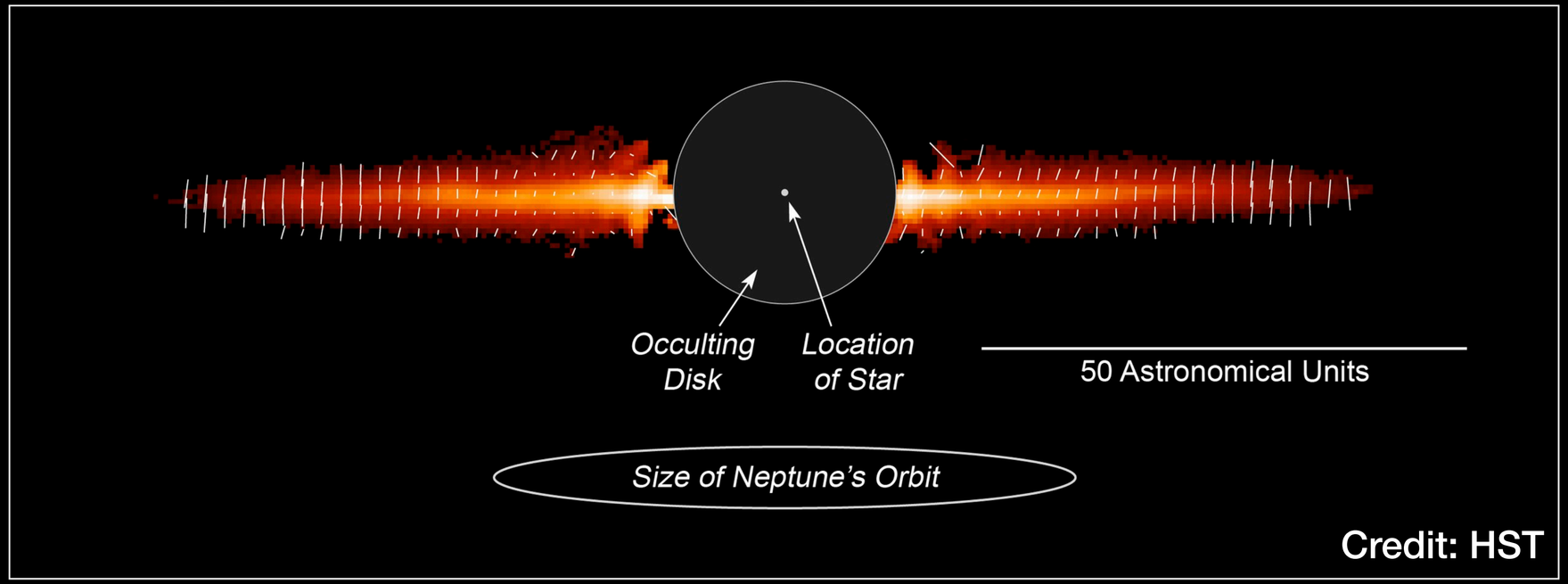
J. Venturini [13] E. Villaver,[22,23] N. A. Walton [62] and P. J. Wheatley [14,15]

Our motivation:

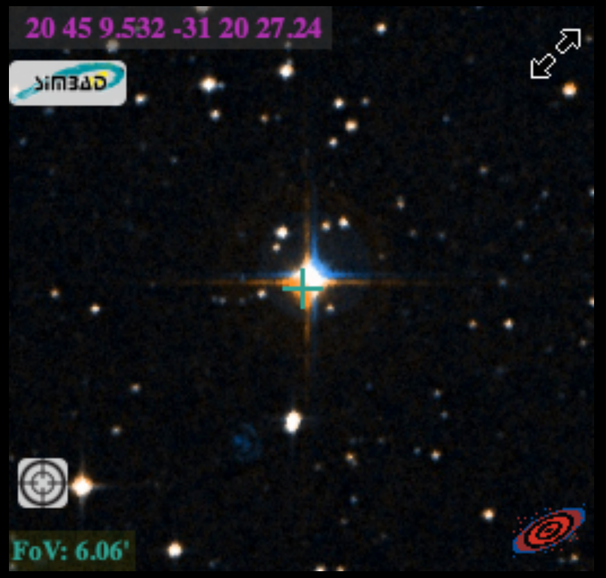
1.) The early dynamical history of planetary systems is encoded in the orientation of the orbits of young planets.
2.) Obliquity measurements for young planets are vital for constraining the key time scales of the dynamical mechanisms.
3.) Only a few such measurements have been published to date.

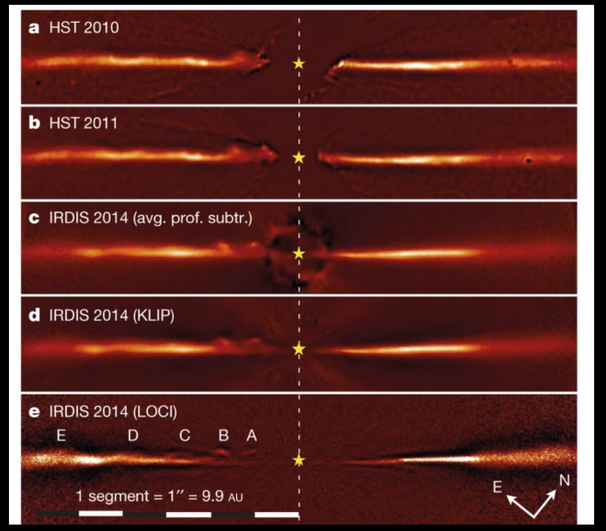
AU Mic (why is it special?):

- A young (Age = 24.3 ± 0.3 Myr) multiplanet system (e.g., Mamajek & Bell 2014),
- located in the Beta Pictoris moving group (Barrado et al. 1999),
- it is only 9.7 pc away (Gaia Collaboration 2018),
- one of the brightest ($V = 8.7$ mag) M-dwarfs (Torres et al. 2006),
- very magnetically active: 0.1-mag photometric fluctuations and frequent flaring (e.g., Torres & Ferraz-Mello 1973),
- edge-on debris disk with fast-moving structures (e.g., Kalas et al. 2004).



Credit: HST





Boccaletti et al. (2015)

The AU Mic planetary system:

- Two confirmed close-in transiting Neptune-sized planets b and c discovered by TESS (Plavchan et al. 2020, Martioli et al. 2021):

- planet b: $P_{\rm b} \sim 8.46\,{\rm d}$, $R_{\rm b} = 3.55 \pm 0.13\,{\rm R}_\oplus$, $M_{\rm b} = 10.2^{+3.9}_{-2.7}\,{\rm M}_\oplus$,

- planet c: $P_{\rm c} \sim 18.86\,{\rm d}$, $R_{\rm c} = 2.56 \pm 0.12\,{\rm R}_\oplus$, $M_{\rm c} = 14.2^{+4.8}_{-3.5}\,{\rm M}_\oplus$

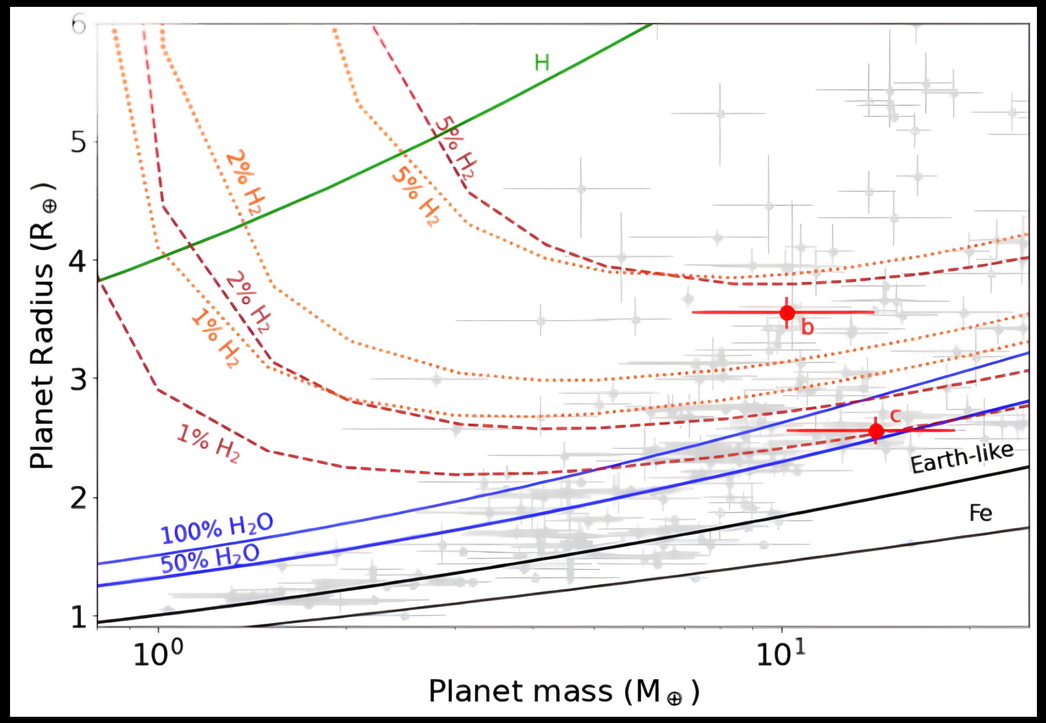
(Donati et al. 2023).

Additional planets:

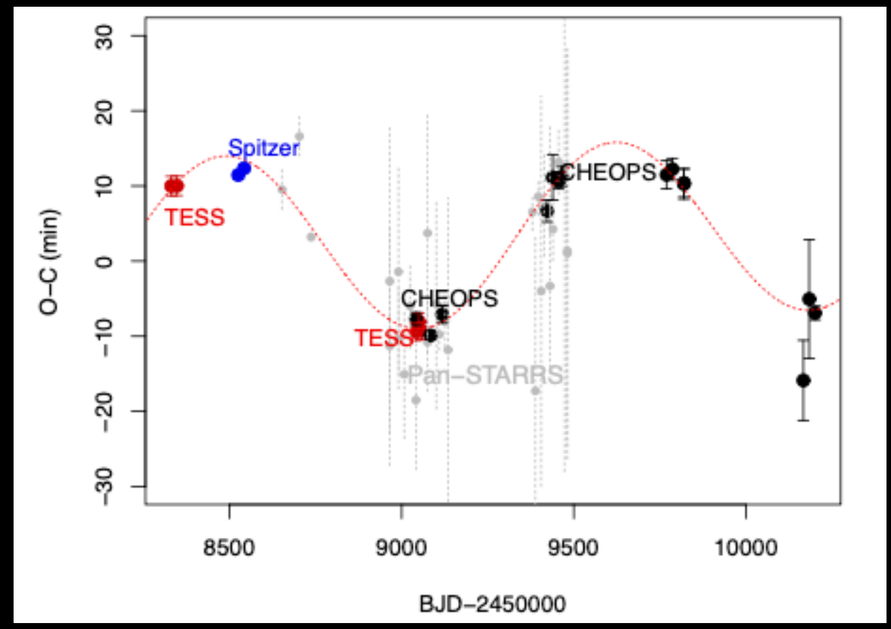
- planet d: a non-transiting Earth-mass planet, based on TTV, $P_{\rm d} \sim 12.73\,{\rm d}$,

- planet e: a non-transiting planet candidate, based on RV and TTV, $P_{\rm e} \sim 34\,{\rm d}$

(Wittrock et al. 2023, Donati et al. 2023, Boldog et al. 2025).



M-R diagram (Donati et al. 2023)



TTVs of planet b (Boldog et al. 2025)

Problems with the structure of planet c:

- planet b: $\rho_{\rm b} = 1.26^{+0.68}_{-0.43}\,{\rm g\,.\,cm^{-3}}$,

- planet c: $\rho_{\rm c} = 4.7^{+2.5}_{-1.6}\,{\rm g\,.\,cm^{-3}}$

(Donati et al. 2023).

- Planet c has a more massive core and a smaller H/He gaseous envelope in tension with the theoretical expectations:

massive core → larger mass of gas.

- Possible explanations:

1.) planet c could be the result of a giant impact,

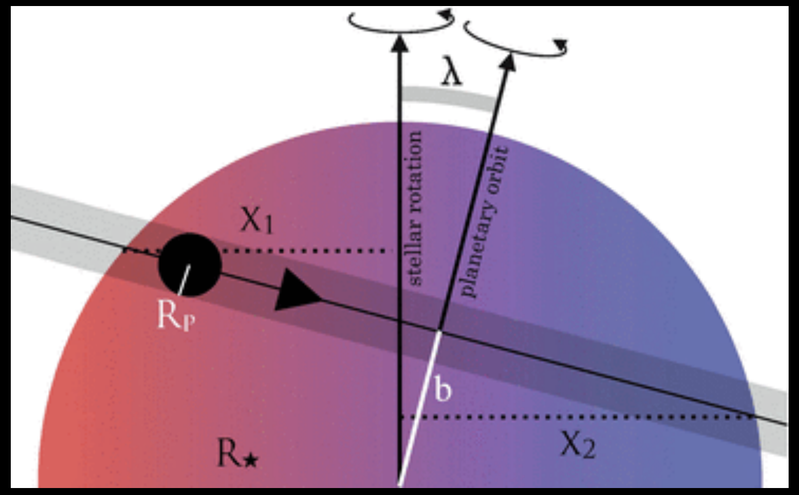
2.) b and c were formed in different conditions.

The main scientific goal:

To measure the orientation of AU Mic c's orbit, which might be helpful to differentiate between these scenarios:
1.) a misaligned orbit of planet c would suggest the giant impact scenario or other types of dynamical disruptions,
2.) an aligned orbit would indicate a more sedate dynamical history.

The Rossiter-McLaughlin (RM) effect:

- A portion of the blueshifted or redshifted starlight is blocked during the transit, this causes an anomalous apparent RV, which reflects the trajectory of the planet.
- The RM effect allows for the measurement of the projected spin-orbit angle λ.



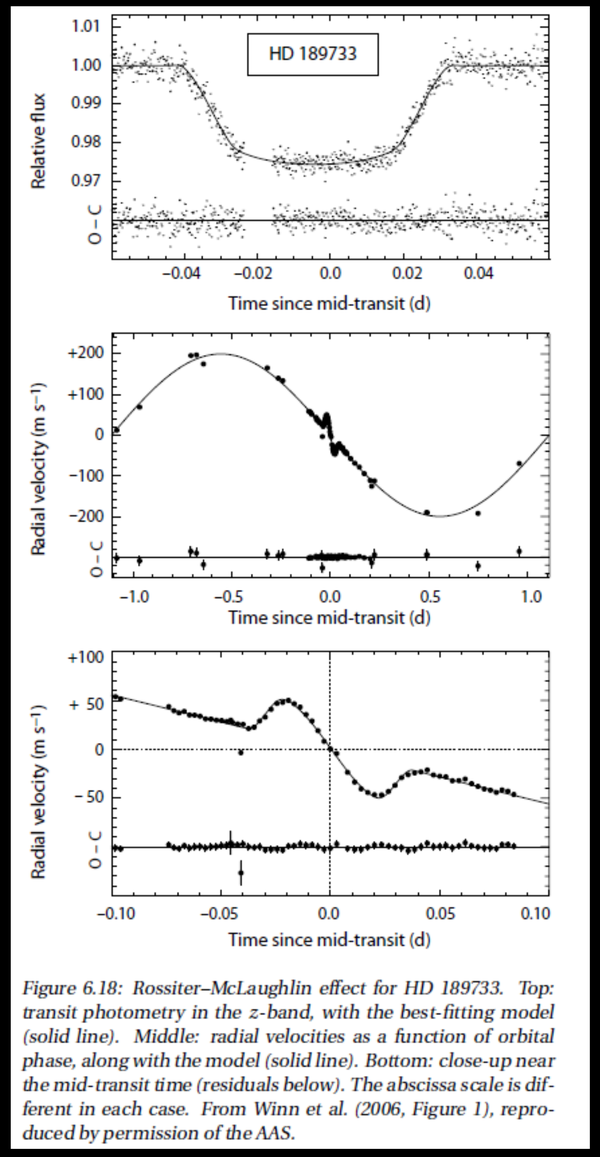
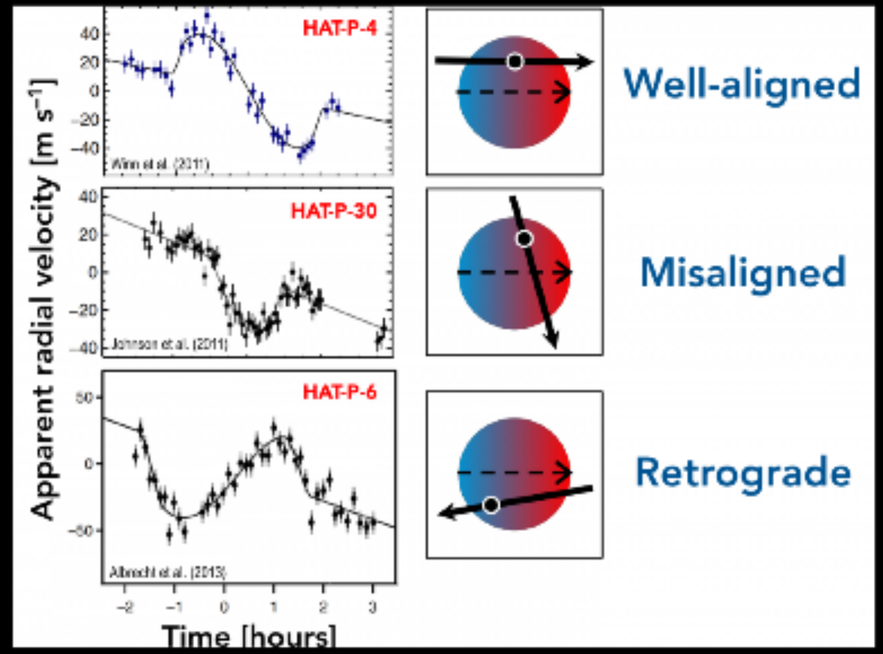
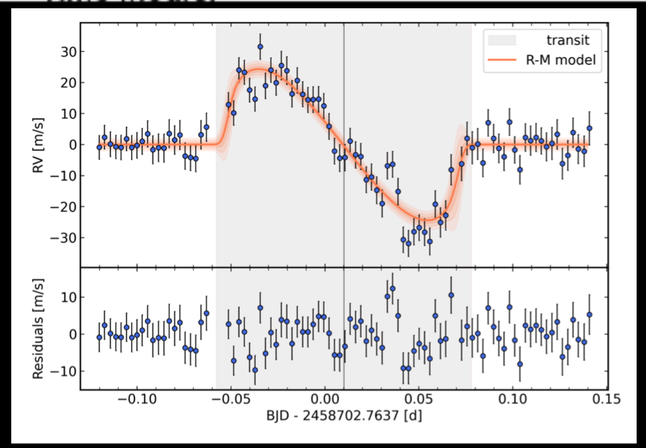


Figure 6.18: Rossiter–McLaughlin effect for HD 189733. Top: transit photometry in the z-band, with the best-fitting model (solid line). Middle: radial velocities as a function of orbital phase, along with the model (solid line). Bottom: close-up near the mid-transit time (residuals below). The abscissa scale is different in each case. From Winn et al. (2006, Figure 1), reproduced by permission of the AAS.



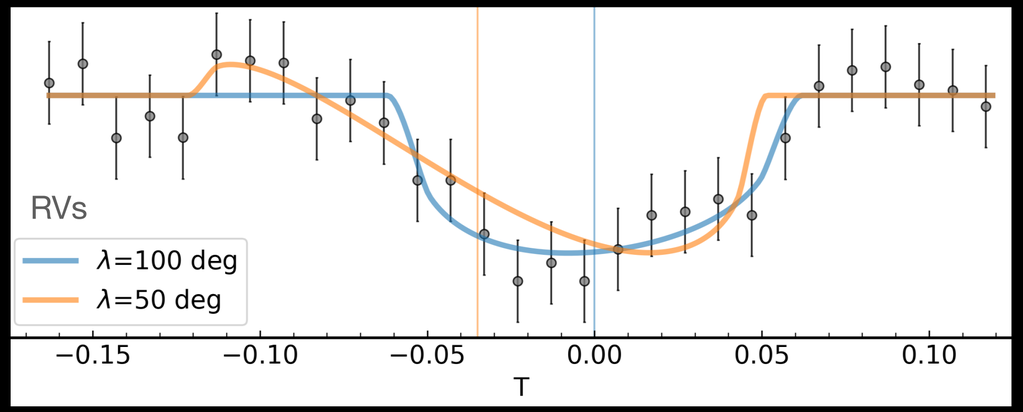


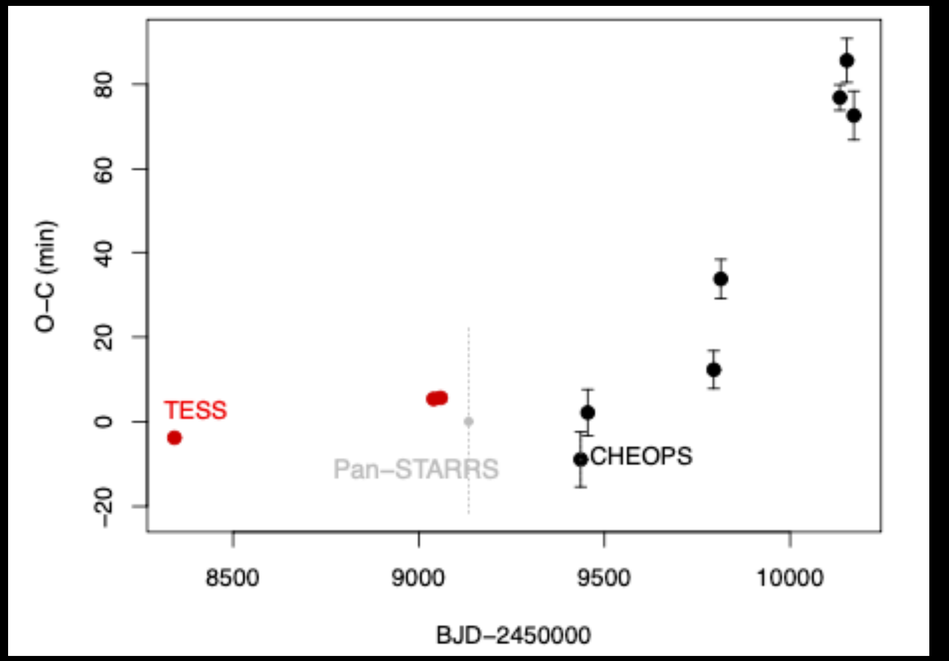
- Planet b is well-aligned (Pallé et al. 2020).

Observations:

1.) Spectroscopy - RVs to measure λ_c: VLT/ESPRESSO spectrograph (two observations, 7 July and 16 July 2023, program 111.24VF - PI: H. Yu).
2.) Photometry - planet c displays TTVs. These TTVs make it challenging to predict the mid-transit times precisely enough to interpret the new spectroscopic observations: CHEOPS, NGTS simultaneous photometry.

- The same RV dataset can be interpreted differently based on the mid-transit time.
- The mid-transit time is important.

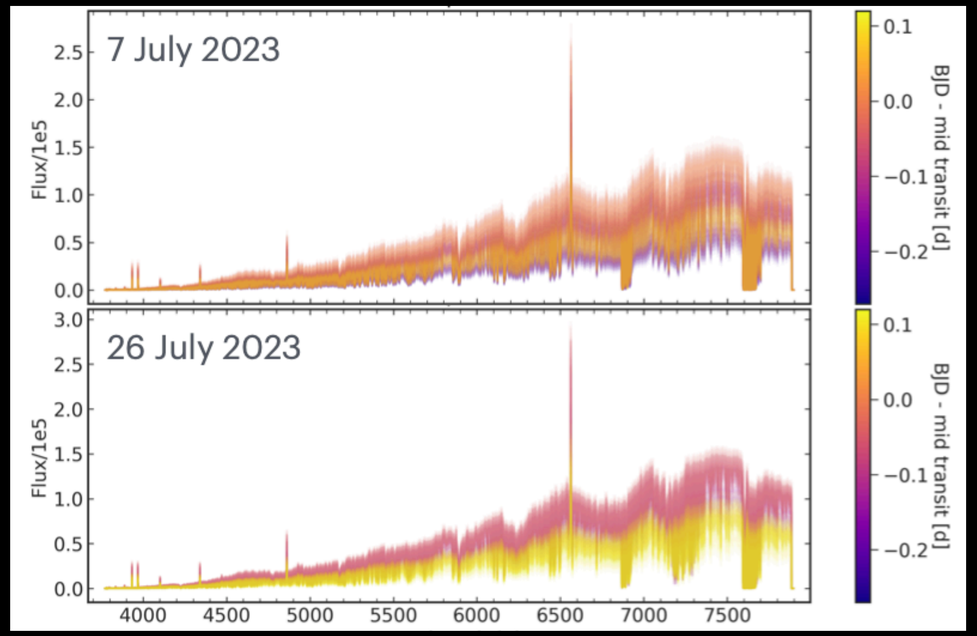


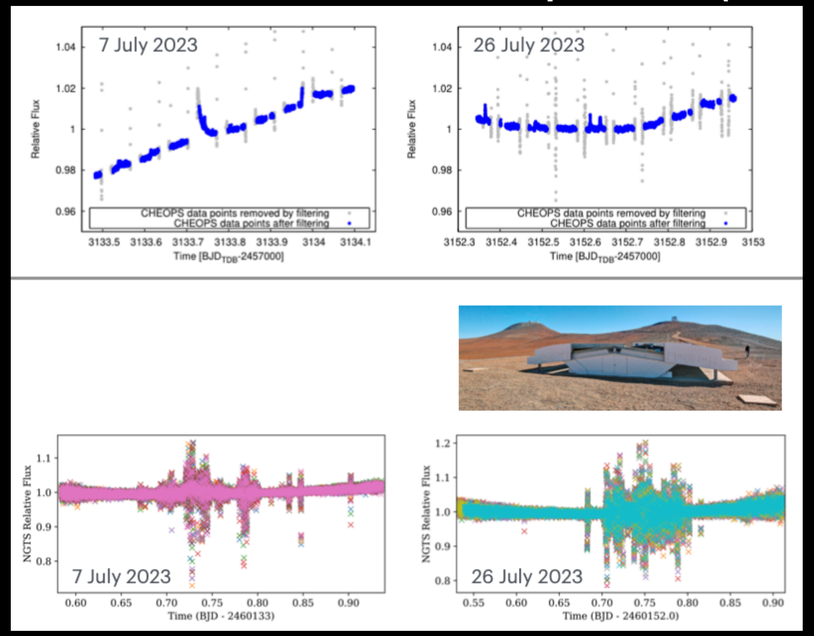


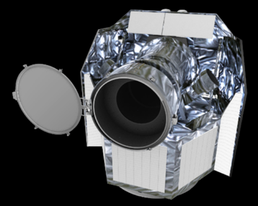
TTVs of planet c (Boldog et al. 2025)



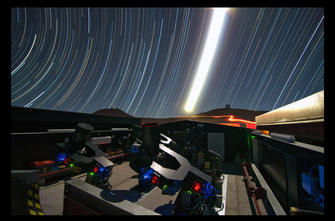
S1D spectra: VLT/ESPRESSO





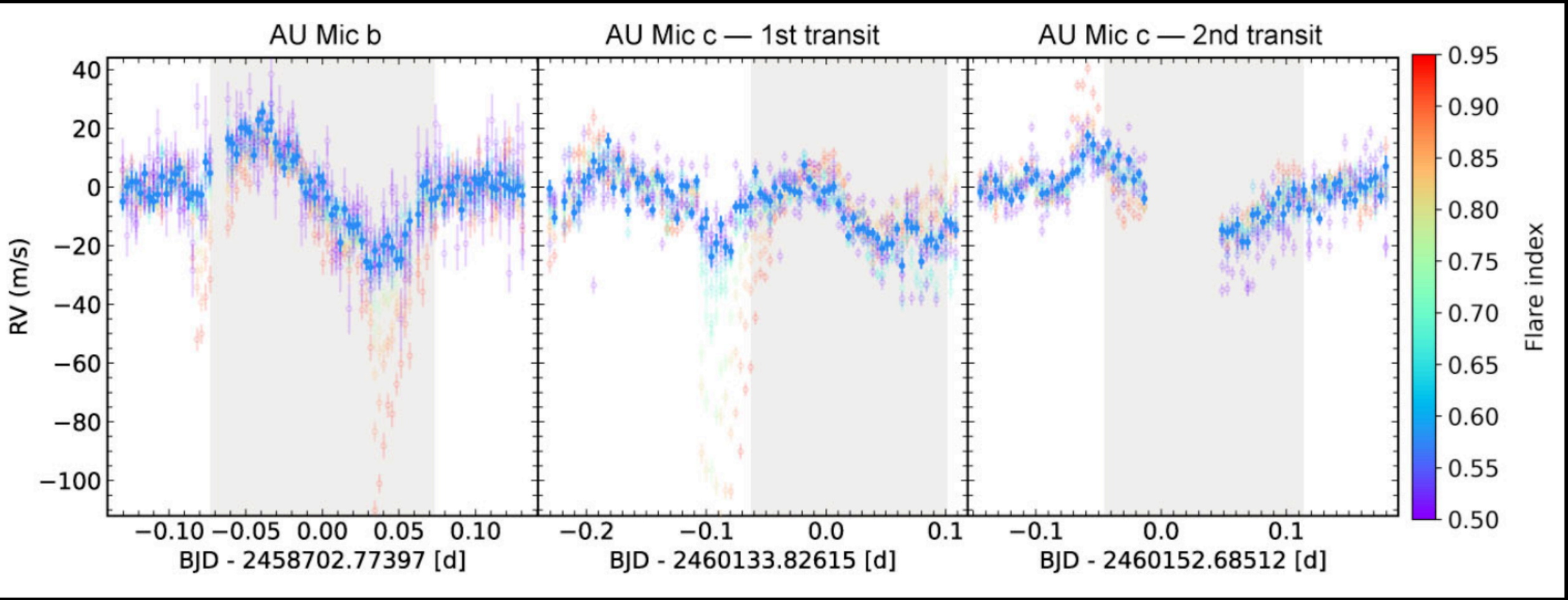


Photometry: CHEOPS, NGTS



Data reduction - spectroscopy:

- The VLT/ESPRESSO data were first reduced using the dedicated data reduction software DRS 3.0.0 (Pepe et al. 2021).
- The RVs were all severely affected by flares → applying our post-processing and RV extraction (Cretignier et al. 2021).
  - We defined a flare index that quantifies the sensitivity of each line to flares (tested on the archive measurement of planet b) to rank the lines in order of flare sensitivity and computed the CCFs and RVs without the flare-sensitive lines.



Final selection: flare index < 0.6 and ~ 2000 lines gave the best trade-off between flare suppression and RV precision.

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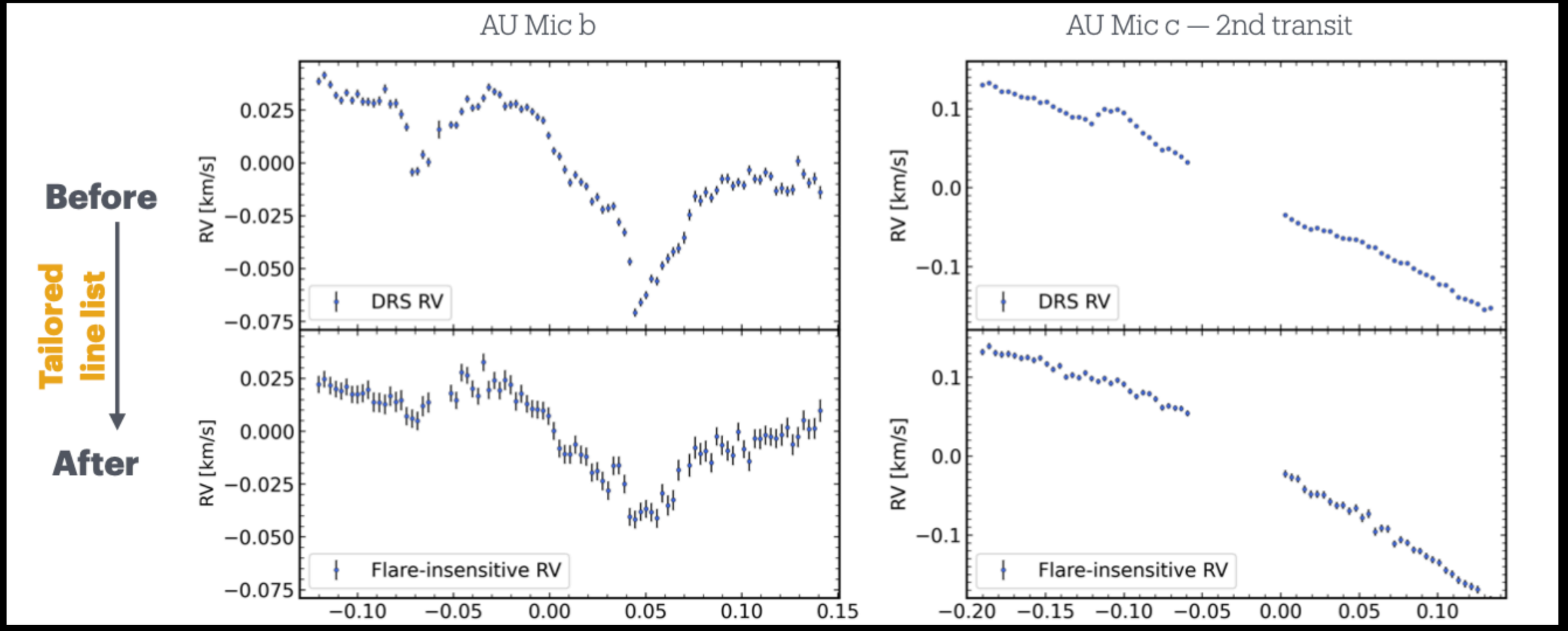
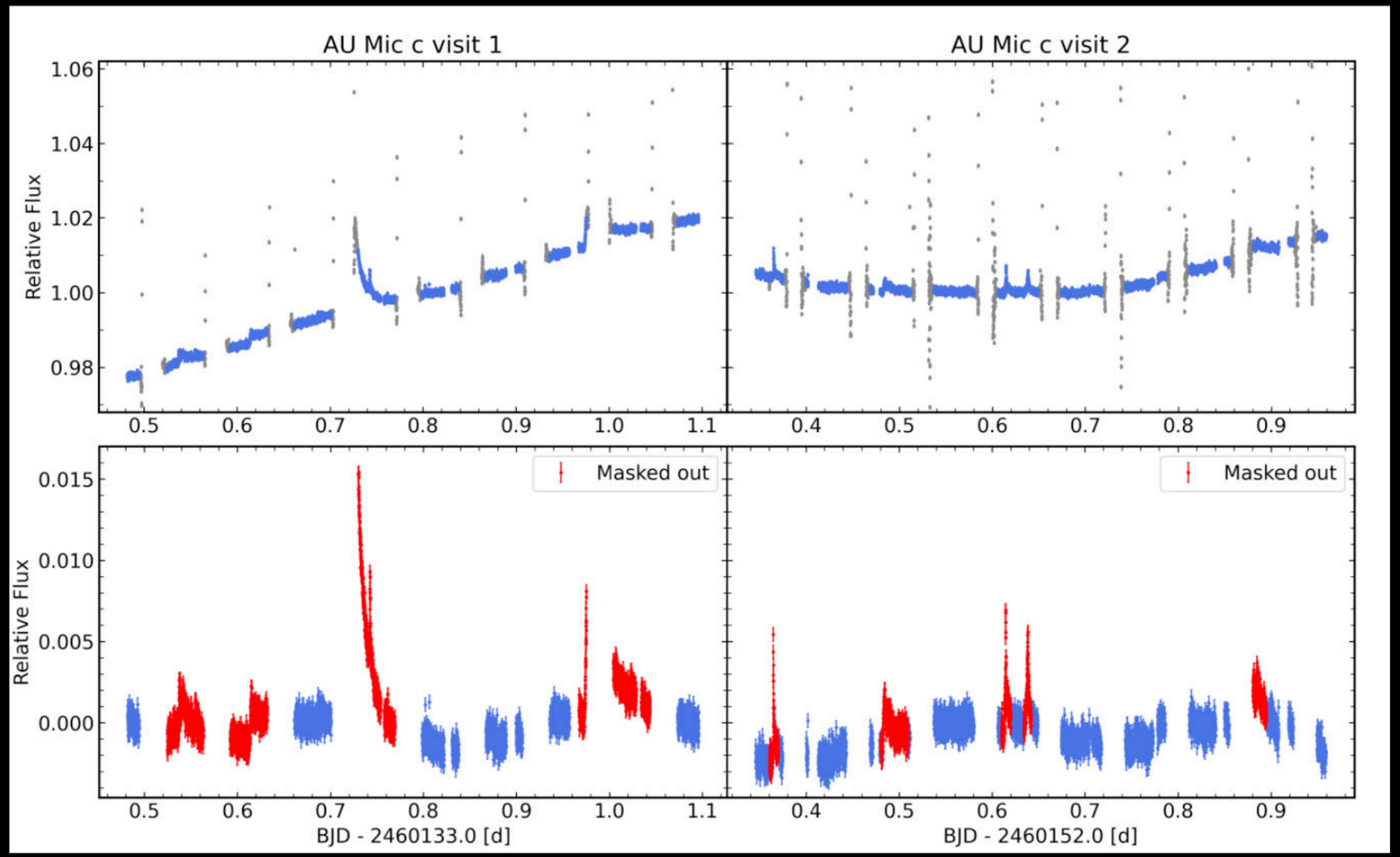


Final selection: flare index < 0.6 and ~ 2000 lines gave the best trade-off between flare suppression and RV precision.

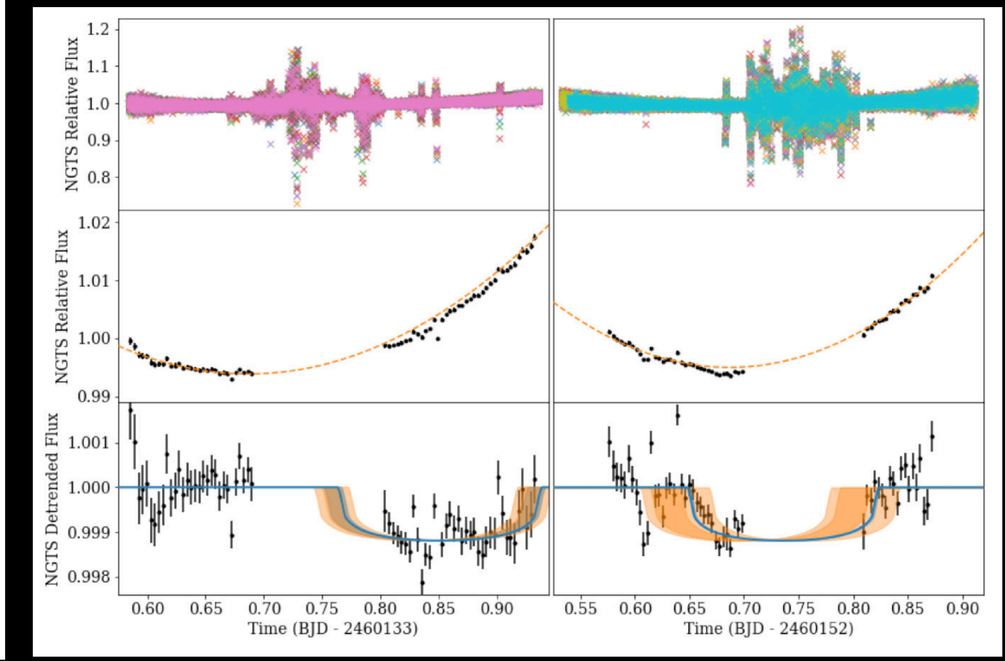
Data reduction - photometry:

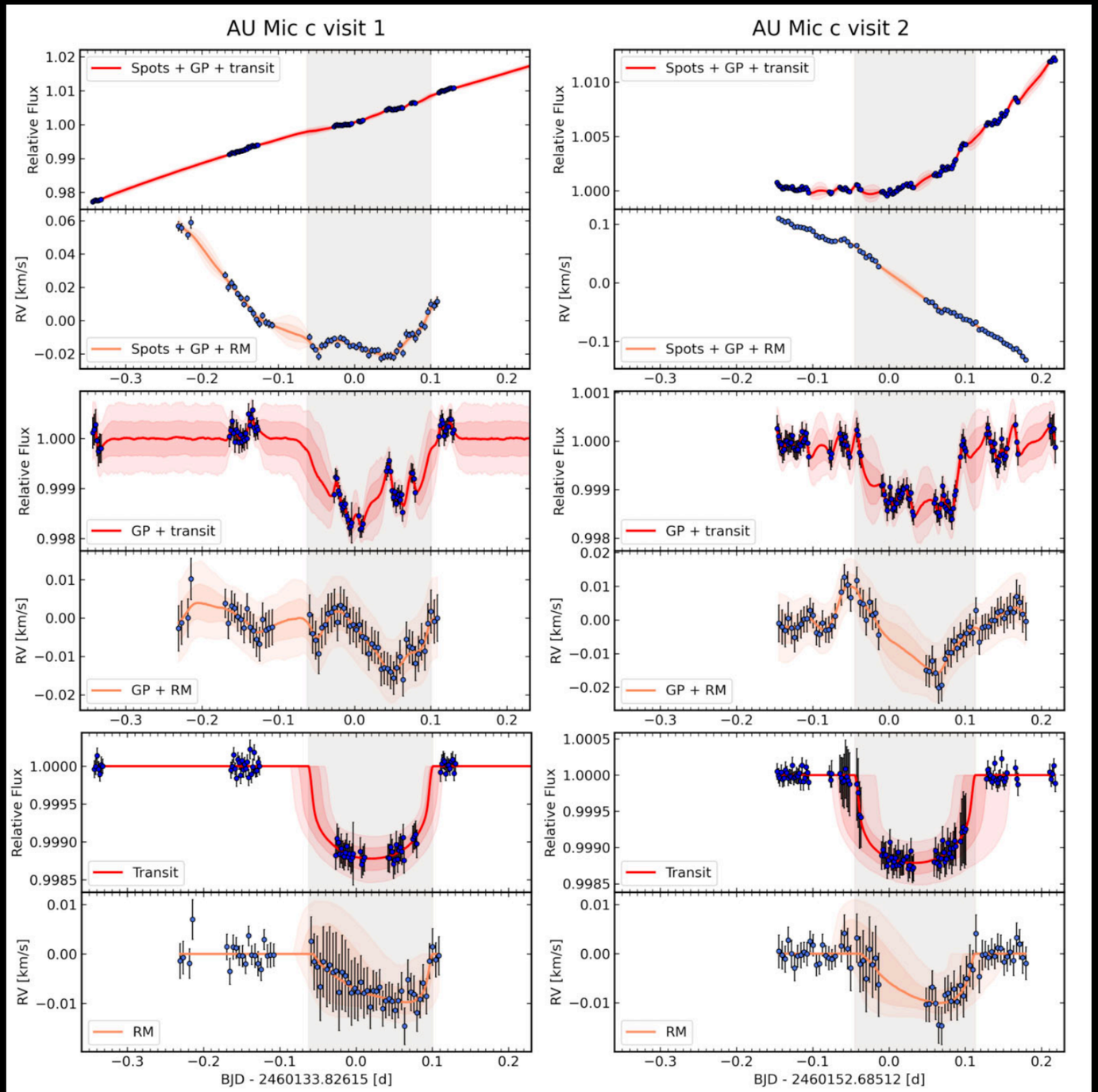
- The CHEOPS data were reduced using PSF fitting on circular imagettes of 30-pixel radius centered on the target using the dedicated PIPE software (Szabó et al. 2021, 2022). Imagettes are not stacked before downloading → better time sampling than the standard CHEOPS DRP, which uses stacked subarrays (200-pixel radius). The outliers and flares were removed from the CHEOPS dataset. Fitting the flares would result in a huge number of free parameters.
- NGTS data were not used during the final analysis: both nights were severely impacted by clouds, which caused large spurious fluctuations in the photometry.



CHEOPS data

NGTS data - not used in our final analysis

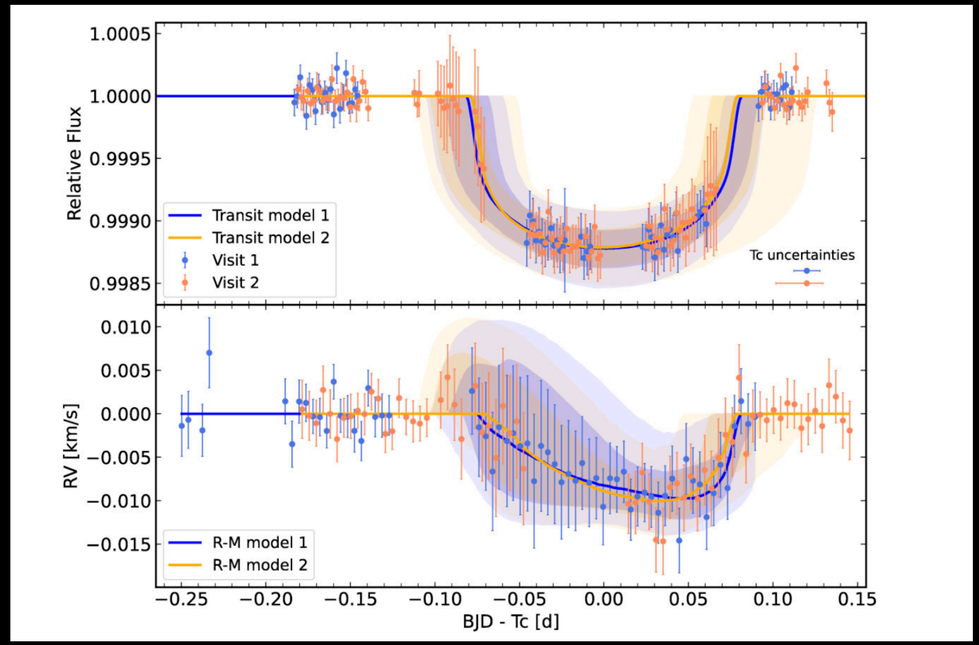




Joint modelling of the photometry and RVs:

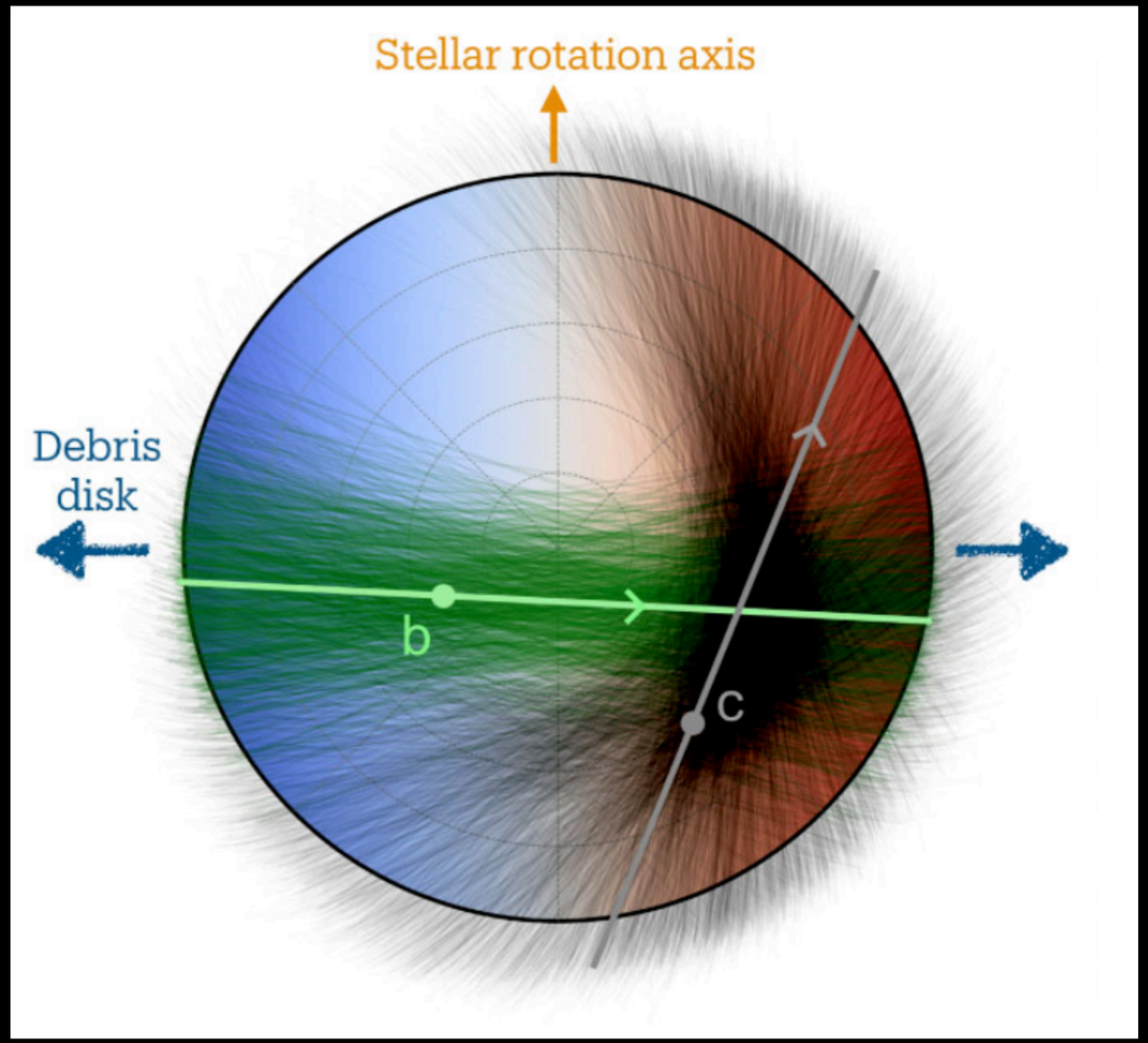
- We jointly (not sequentially) modelled the CHEOPS LCs and the ESPRESSO RVs. In this case, the result is more robust. The sequential approach does not guarantee a self-consistent fit between the LCs and RVs.
- The joint model consists of three components:

1.) the planetary transit in the LCs, as well as in the RVs,
2.) long-term stellar variations (star spots) fitted with a polynomial,
3.) short-term stellar variations (granulation) fitted with a Matérn 5/2 GP.

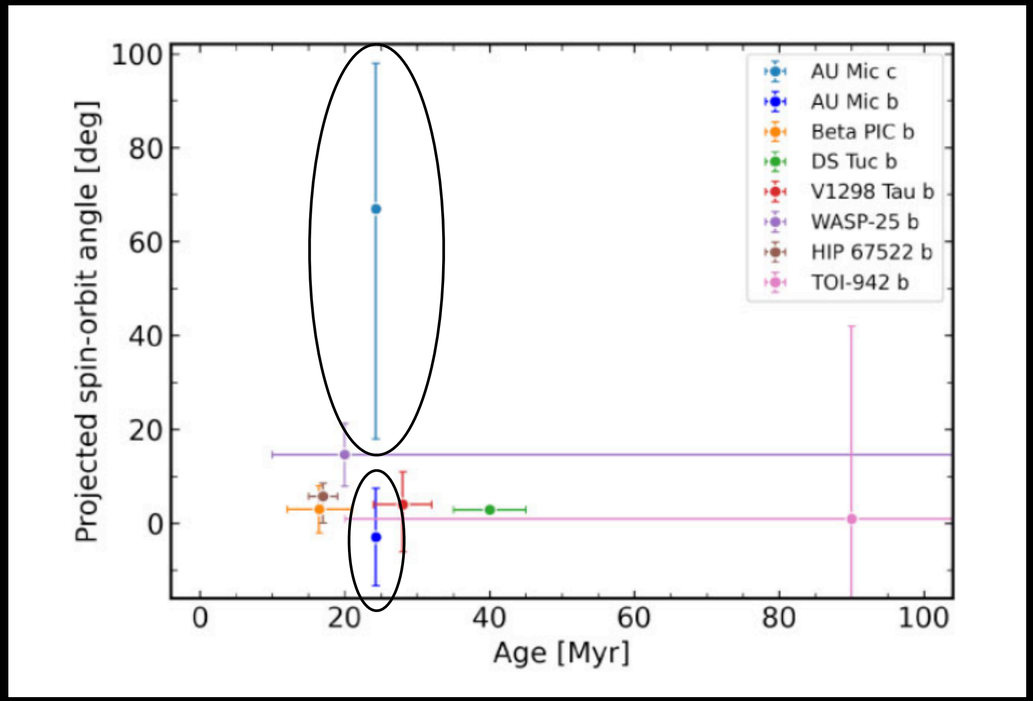


Results:

- Using the joint model, we measure $\lambda_c = 67.8^{+31.7}_{-49.0}$ degrees (planet b has $\lambda_b = -2.96^{+10.44}_{-10.30}$ degrees).
- While inconclusive, our results provide a tentative indication (89% of confidence) that the orbit of planet c is misaligned.



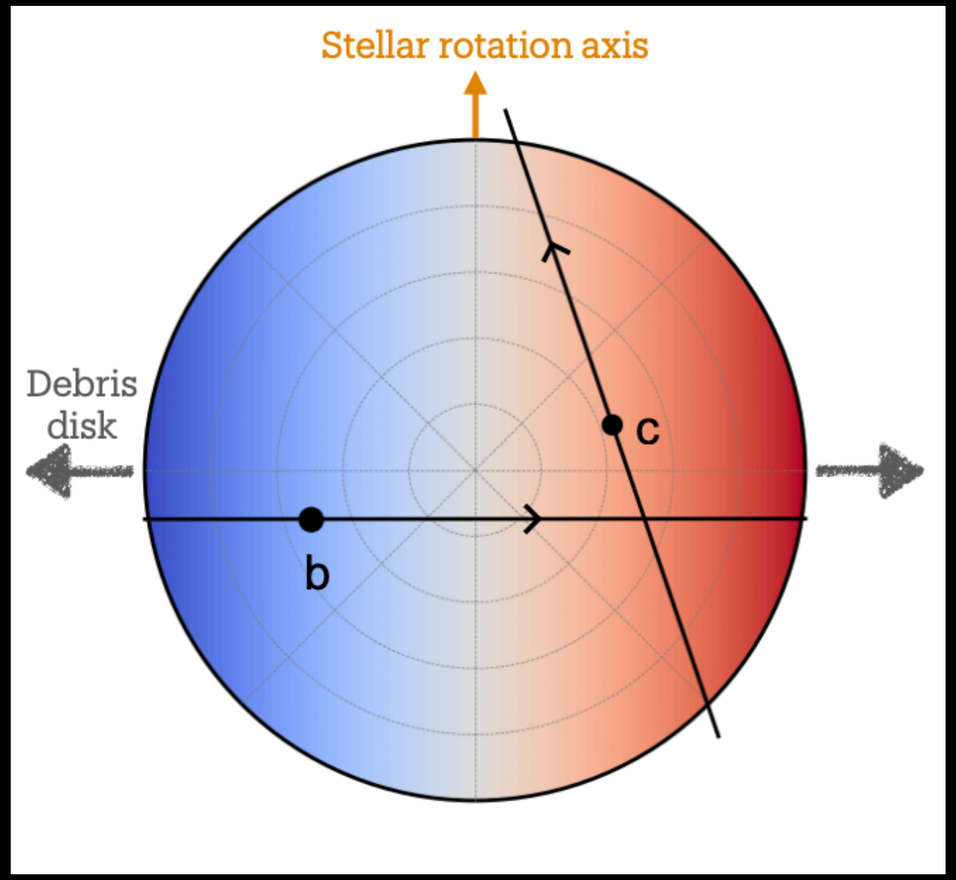
- If confirmed in the future with higher significance, this will be the first observation of a young (< 100 Myr) planet on a misaligned orbit.

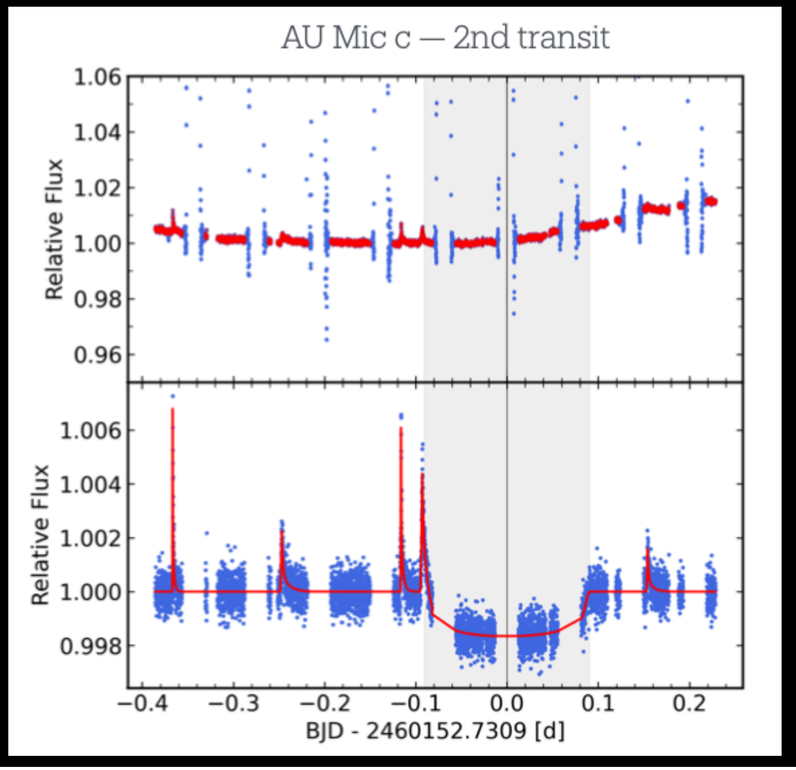


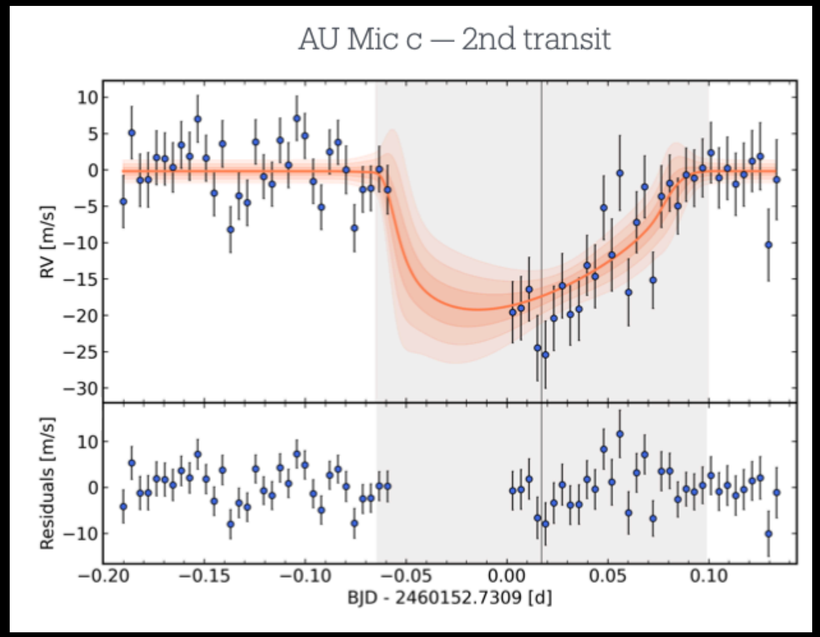
- Very few systems with two transiting planets exhibit large mutual inclinations, irrespective of age. A very similar example is the HD 3167 planetary system (Bourrier et al. 2021).

Results (not adopted as final results):

- The sequential approach enabled us to model the LCs, including flares, resulting in tighter constraints on the mid-transit times T_c.
- The subsequent fit to the RVs was restricted to the second transit, as the lack of a post-transit baseline excluded the use of the first.
- There was a significant 2σ tension between the T_c obtained from the 2nd LC fit and the RV fit (despite the LC prior on T_c).
- This sequential fit yielded $\lambda_c = 108.7 \pm 12.5$ degrees.



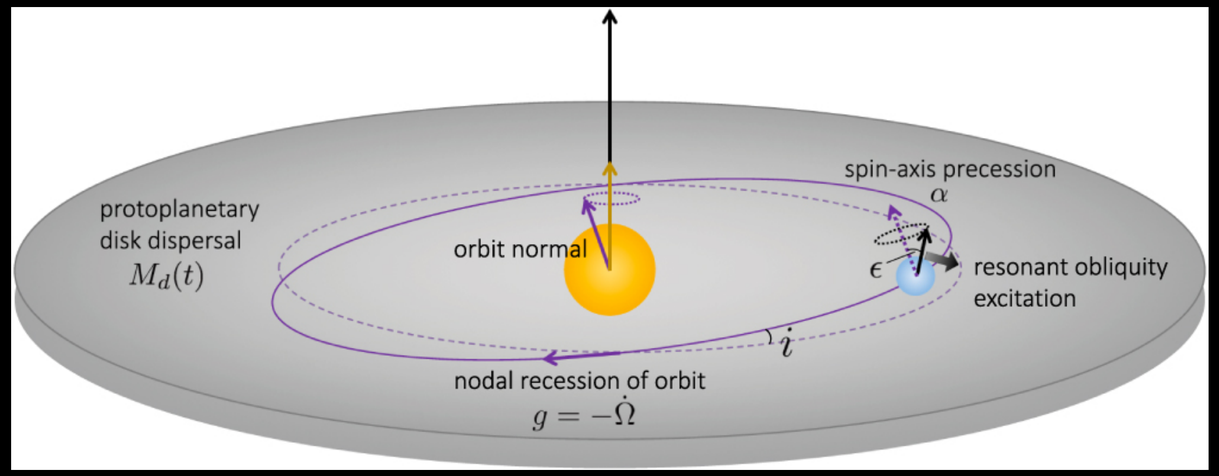




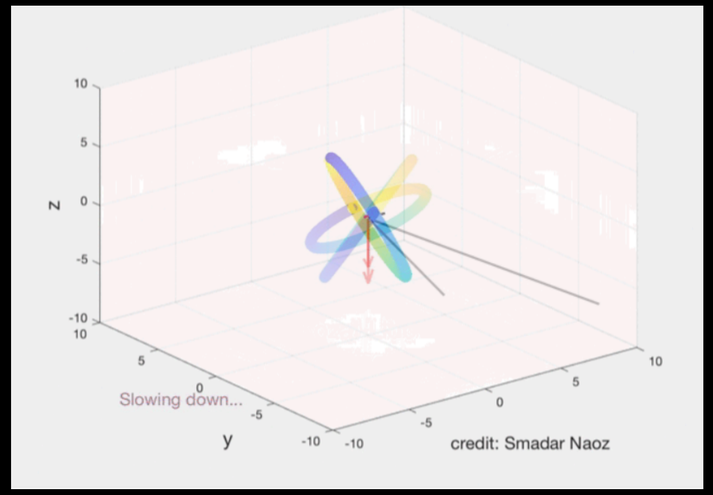
Possible explanations for a misaligned orbit:

1.) Planet-planet scattering - collisions or giant impacts can result in inclination changes. In the event of a collision, such a scenario would likely result in planet c losing its atmosphere. This could explain the abnormal density trend between the planets. Large eccentricity is assumed (e is weekly constrained).





2.) Nodal secular resonance - given the possible presence of an exterior planetary companion, this mechanism is a viable explanation for the planet c's misalignment. This mechanism drives planets towards polar orbits. It does not require a large e.



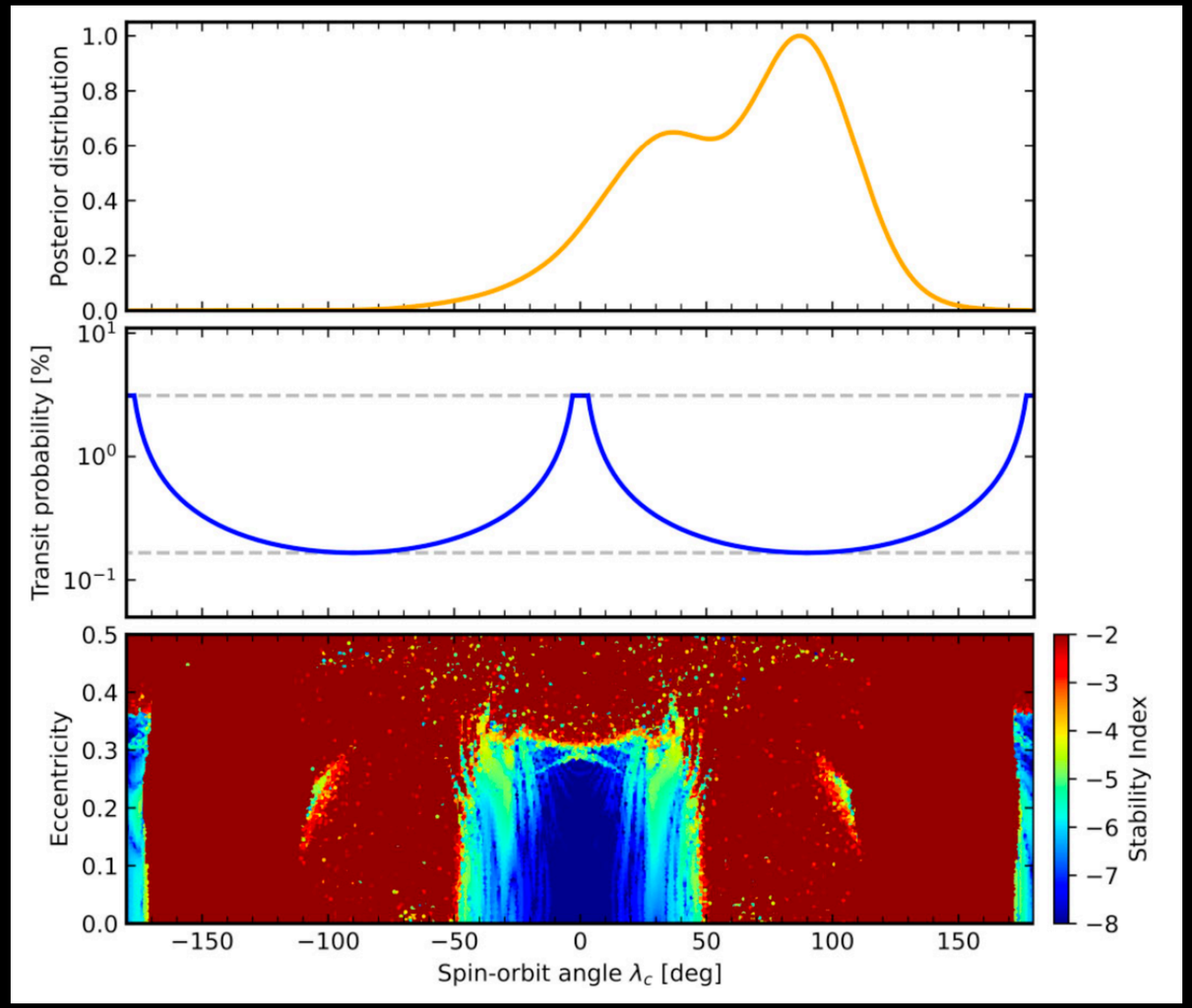
3.) Kozai-type dynamics - causes inclination and eccentricity to oscillate. We might currently be observing AU Mic c in a high inclination and low eccentricity phase.

Concluding remarks:

1.) An independent dynamical analysis confirmed a misaligned/retrograde orbital geometry of planet c with a mean value of $\lambda_c = 171.91$ degrees (Boldog et al. 2025).

2.) A significant misaligned orbit for planet c is in some degree of tension with dynamical stability arguments, and with the fact that we see both planets in transit; however, these arguments alone do not exclude such an orbit.

3.) Further observations would be highly desirable to constrain the spin-orbit angle of planet c more precisely.




Thank you!