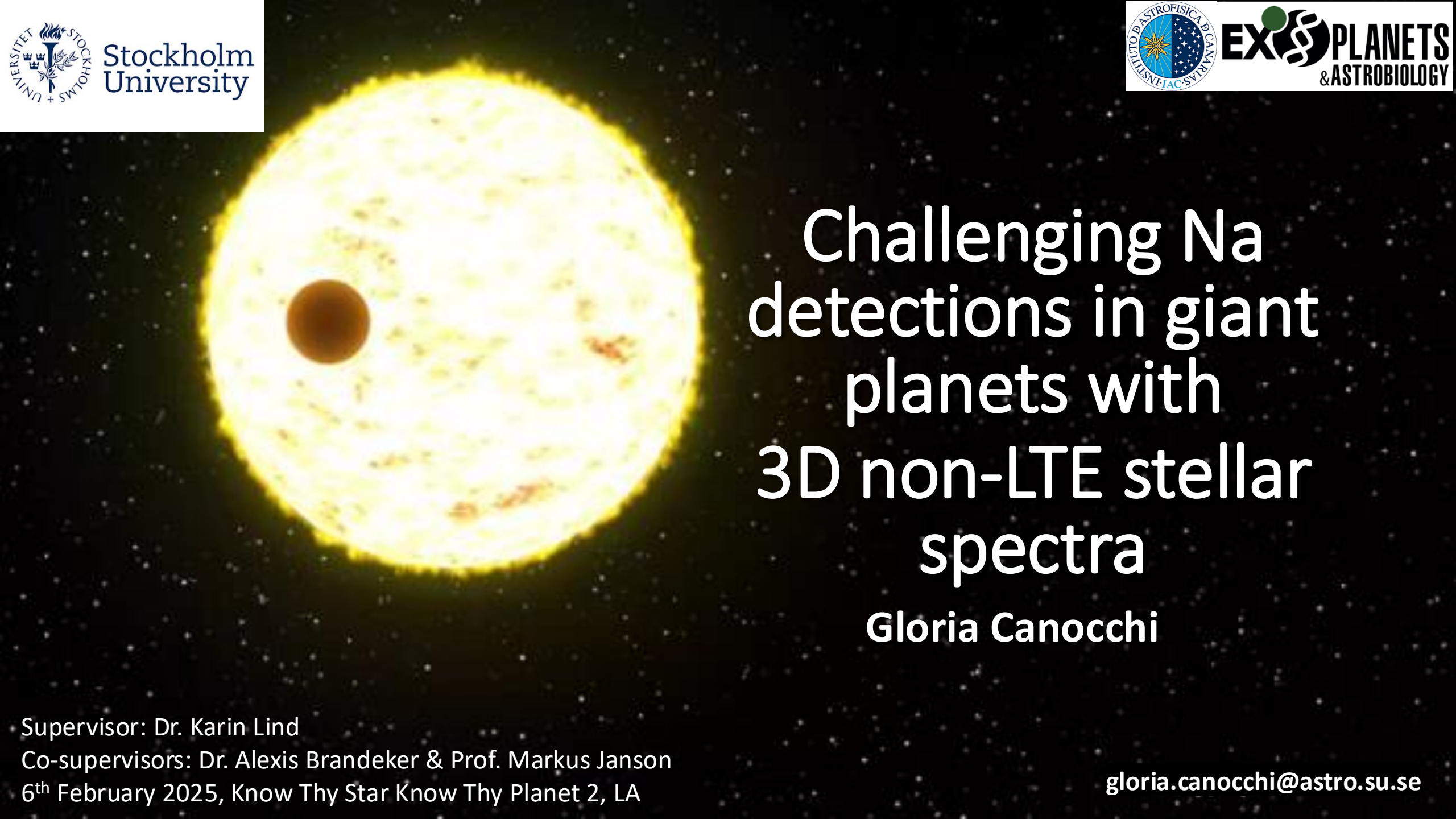


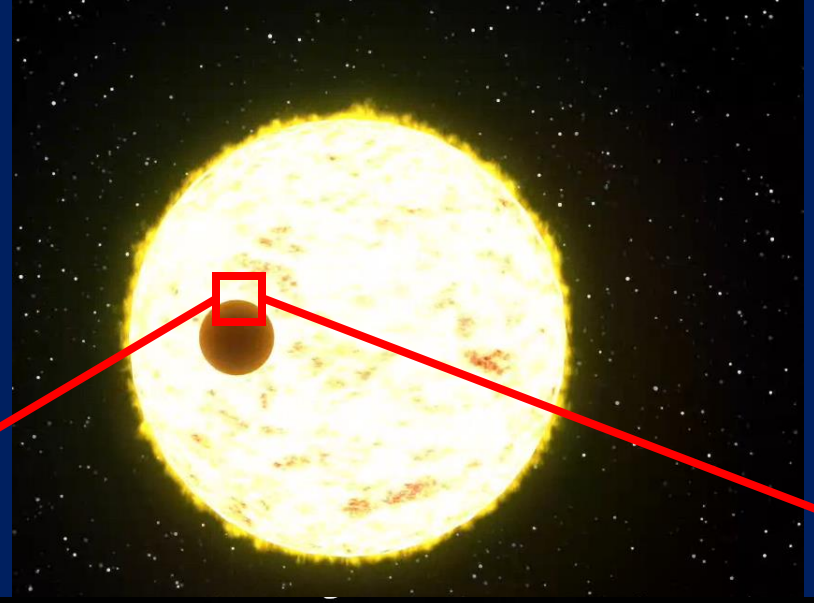
Challenging Na detections in giant planets with 3D non-LTE stellar spectra

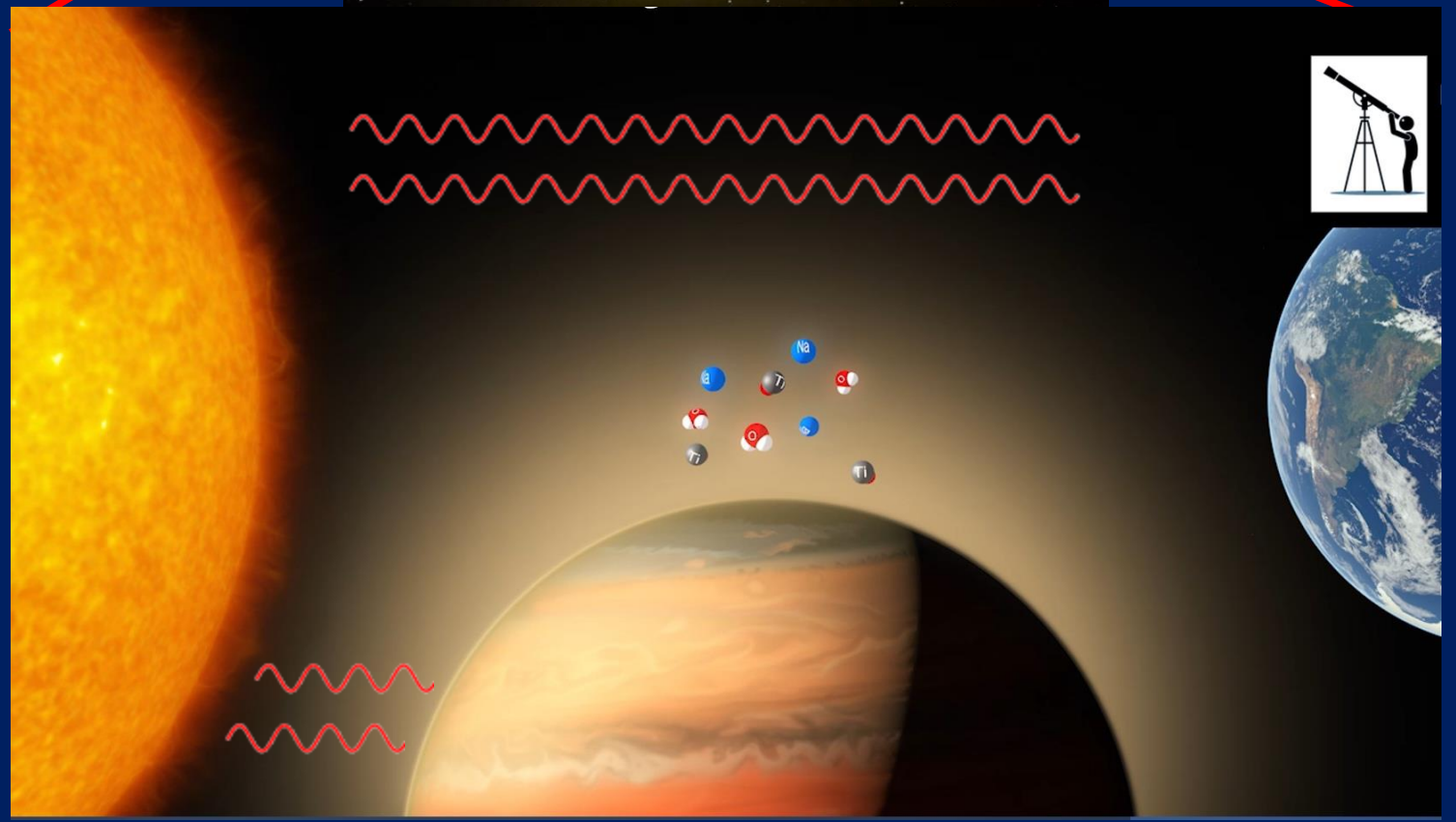
Gloria Canocchi

Supervisor: Dr. Karin Lind
Co-supervisors: Dr. Alexis Brandeker & Prof. Markus Janson
6th February 2025, Know Thy Star Know Thy Planet 2, LA

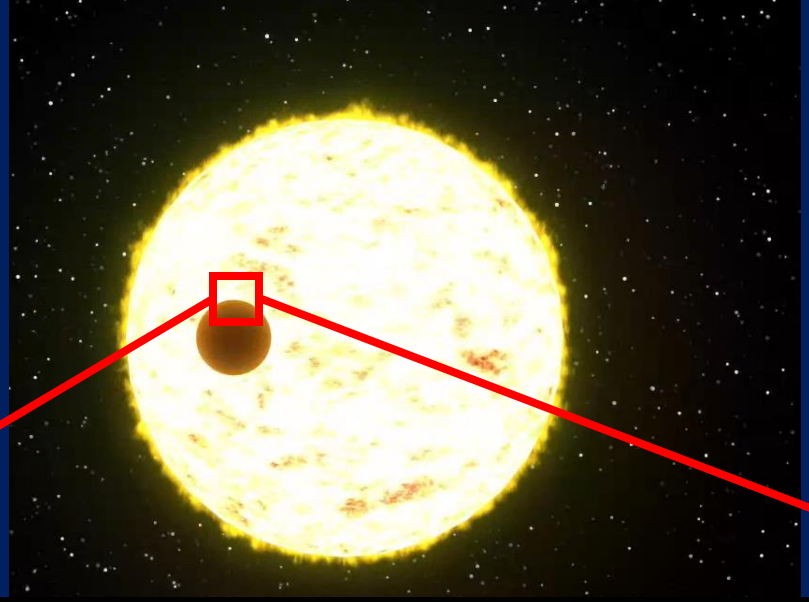
gloria.canocchi@astro.su.se

TRANSMISSION SPECTROSCOPY:





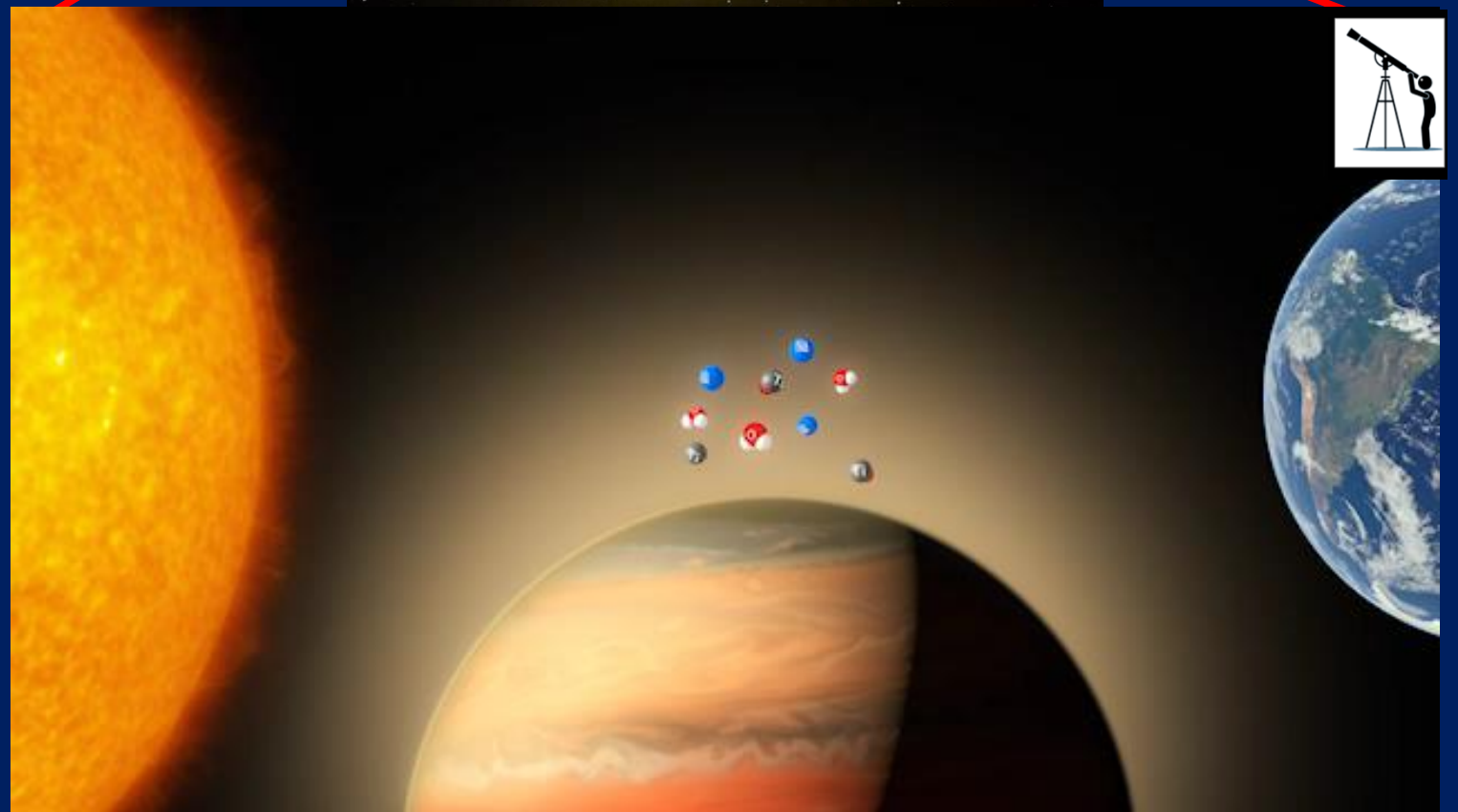
TRANSMISSION SPECTROSCOPY:



Some light filters through the **upper layers** of the planet's atmosphere.

Out-of-transit (F_{out}) → ★

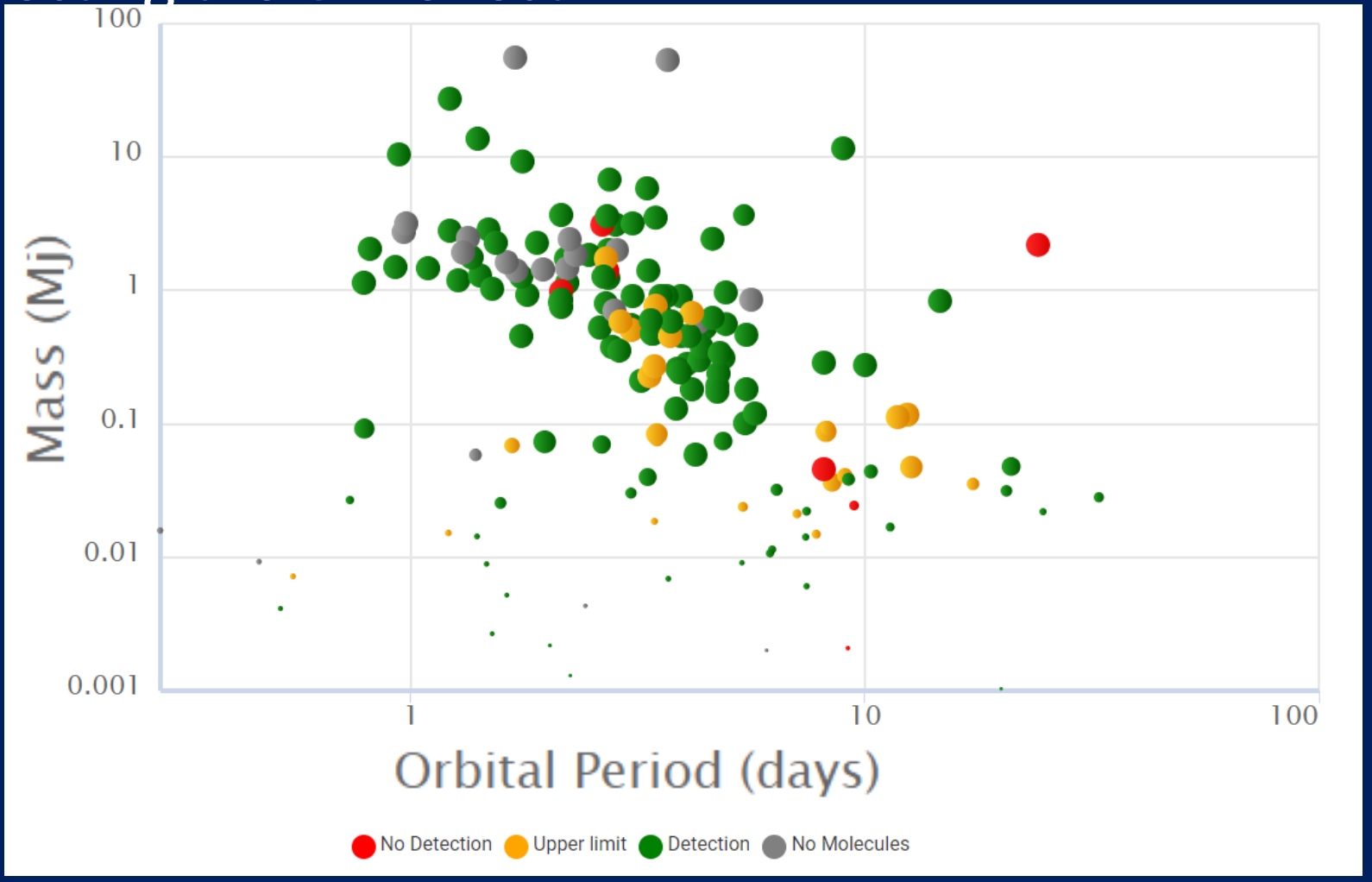
In-transit (F_{in}) → ★ + 🪐



Video credits to:
ESO/M. Kornmesser

>50 species detected in >100 exoplanets!

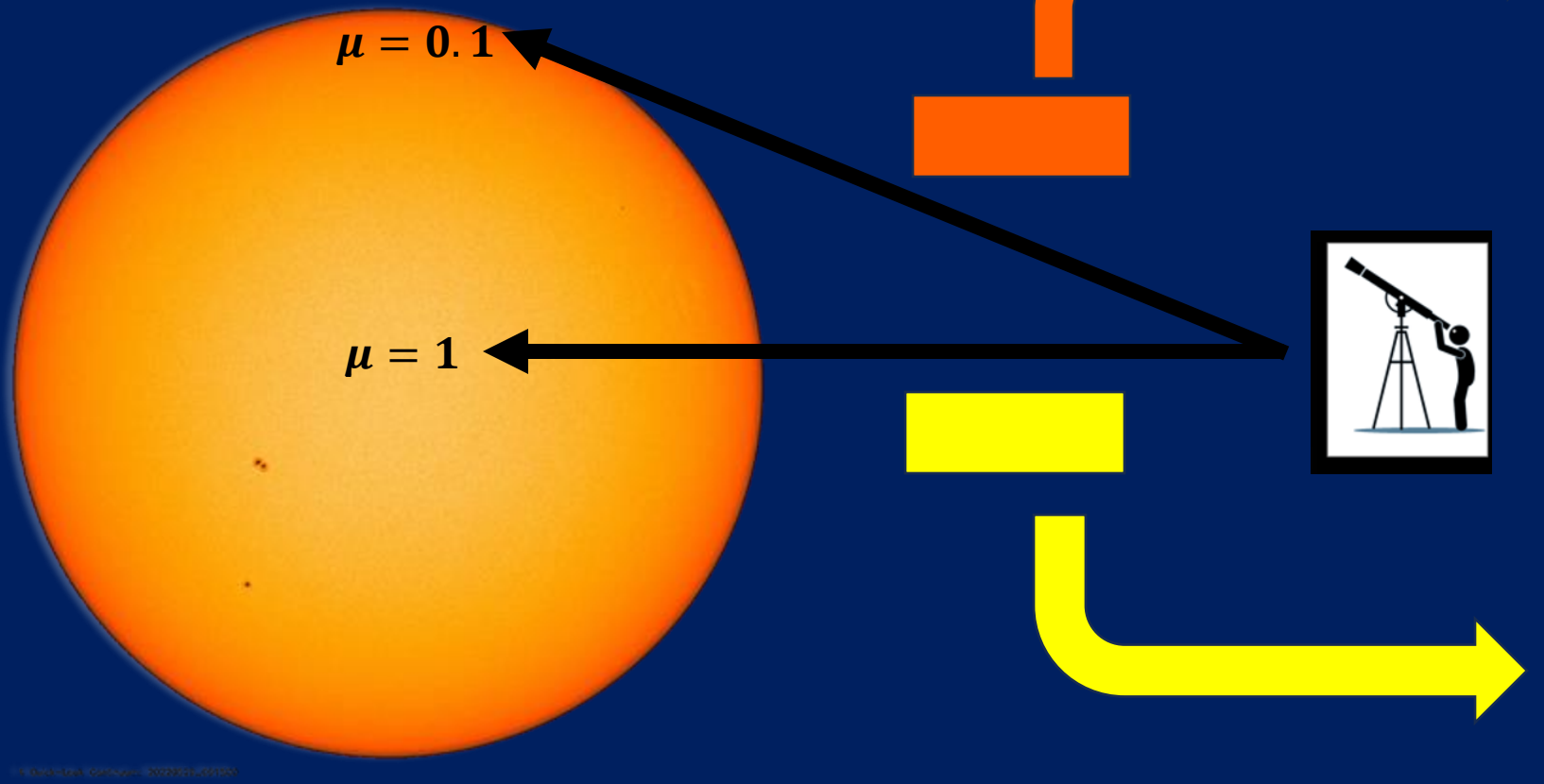
Na is the most successful!! But only 1D stellar models used so far for correcting the CLV effect….

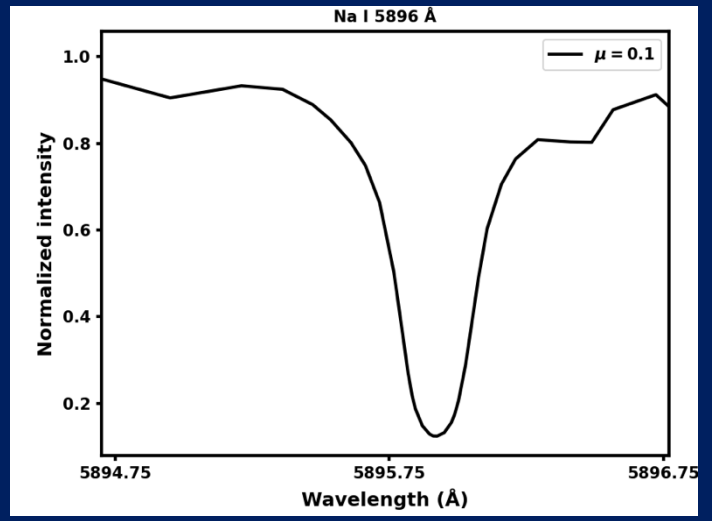


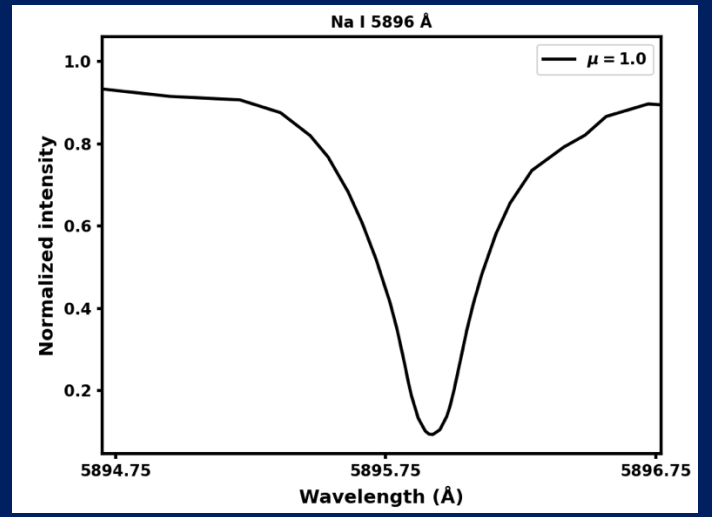
https://research.iac.es/proyecto/exoatmospheres/plot.php

The center-to-limb variation (CLV) of spectral lines in the stellar disk: line forming in increasingly higher layers towards the limb.

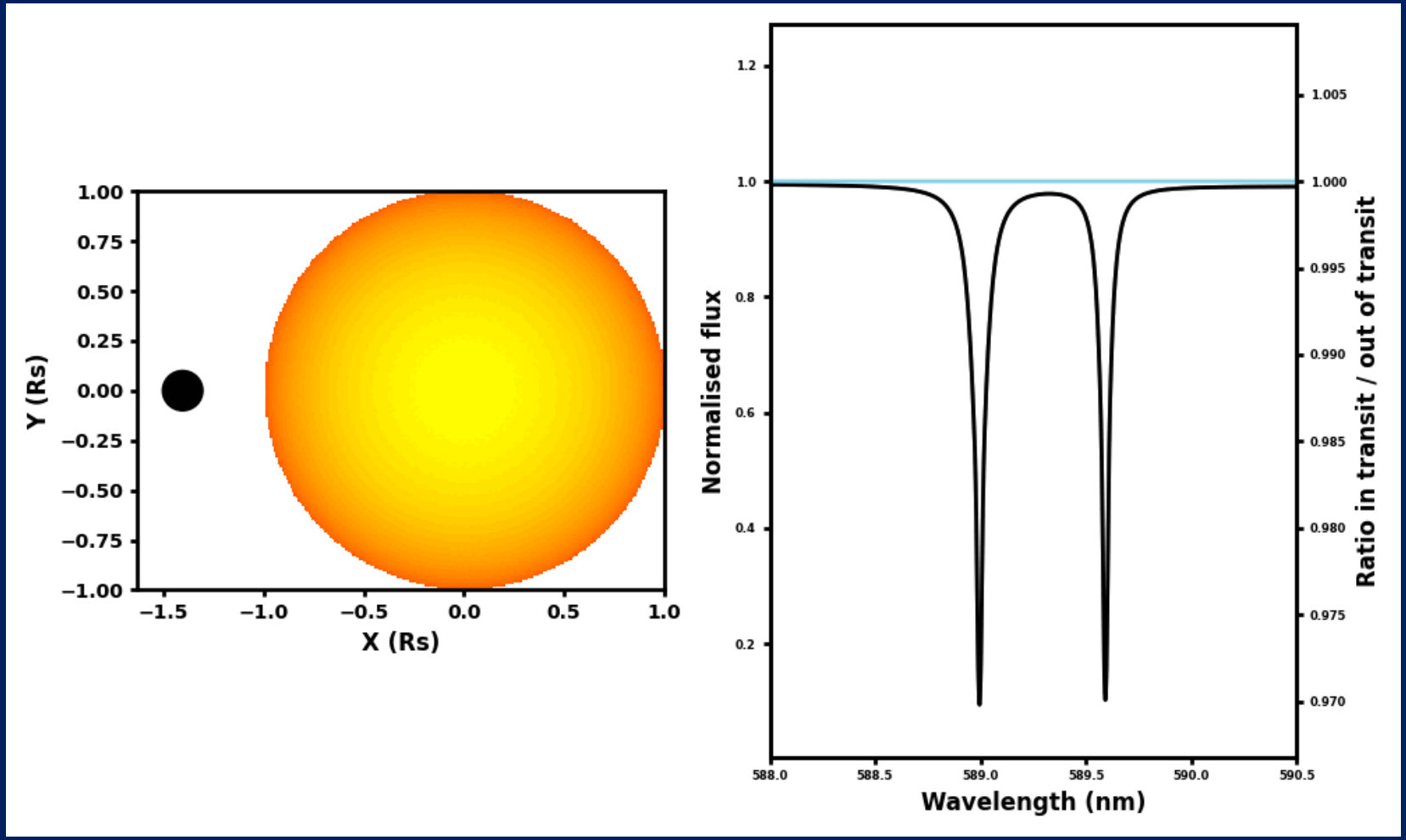
$$\mu = viewing\ angle = \cos(\theta)$$



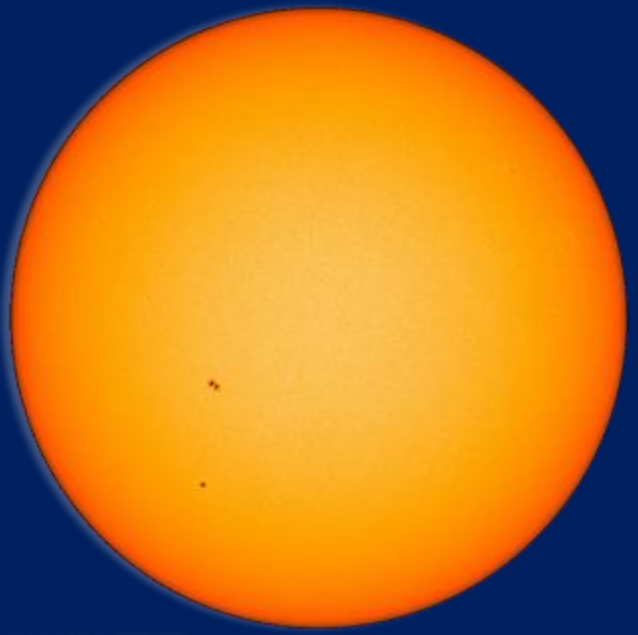




Why is CLV important in transmission spectroscopy?



The Sun → observations of the CLV!



Other stars → synthetic spectra for the CLV!

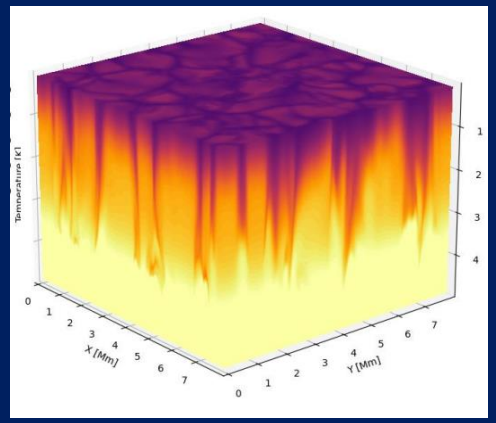
Credits to: JWST collaboration

Stellar Synthetic Spectra

Model atmosphere

1D (Marcs)

3D (Stagger)

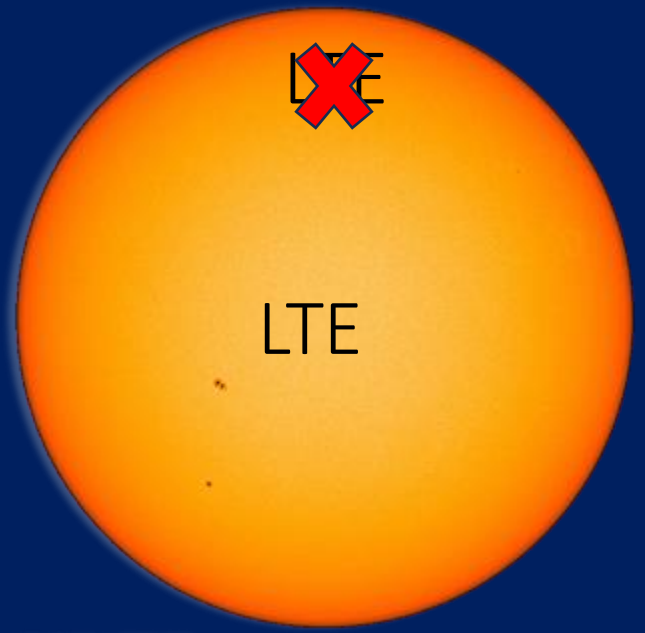


Credits to: C. Lagae

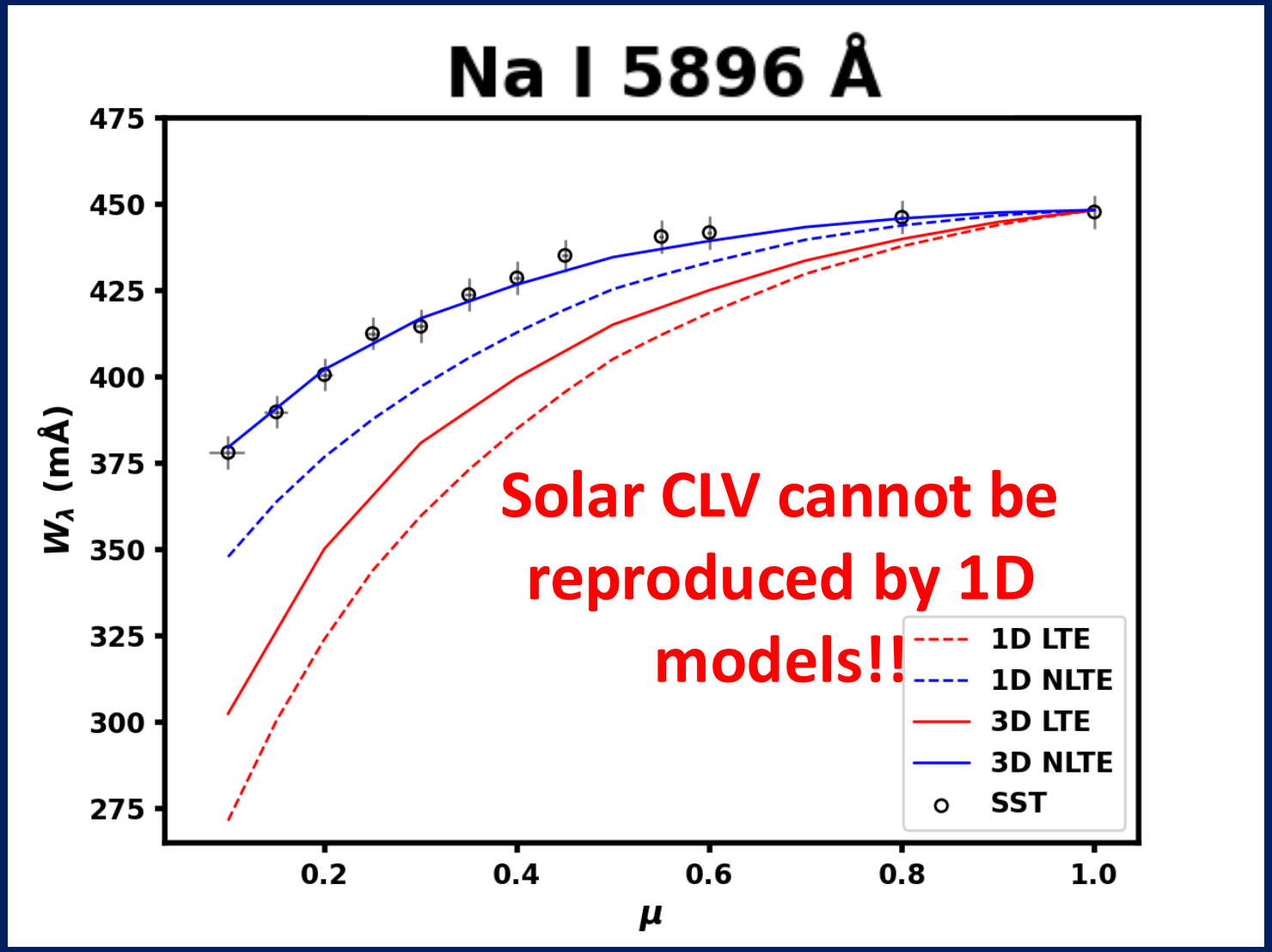
Radiative Transfer

LTE

non-LTE



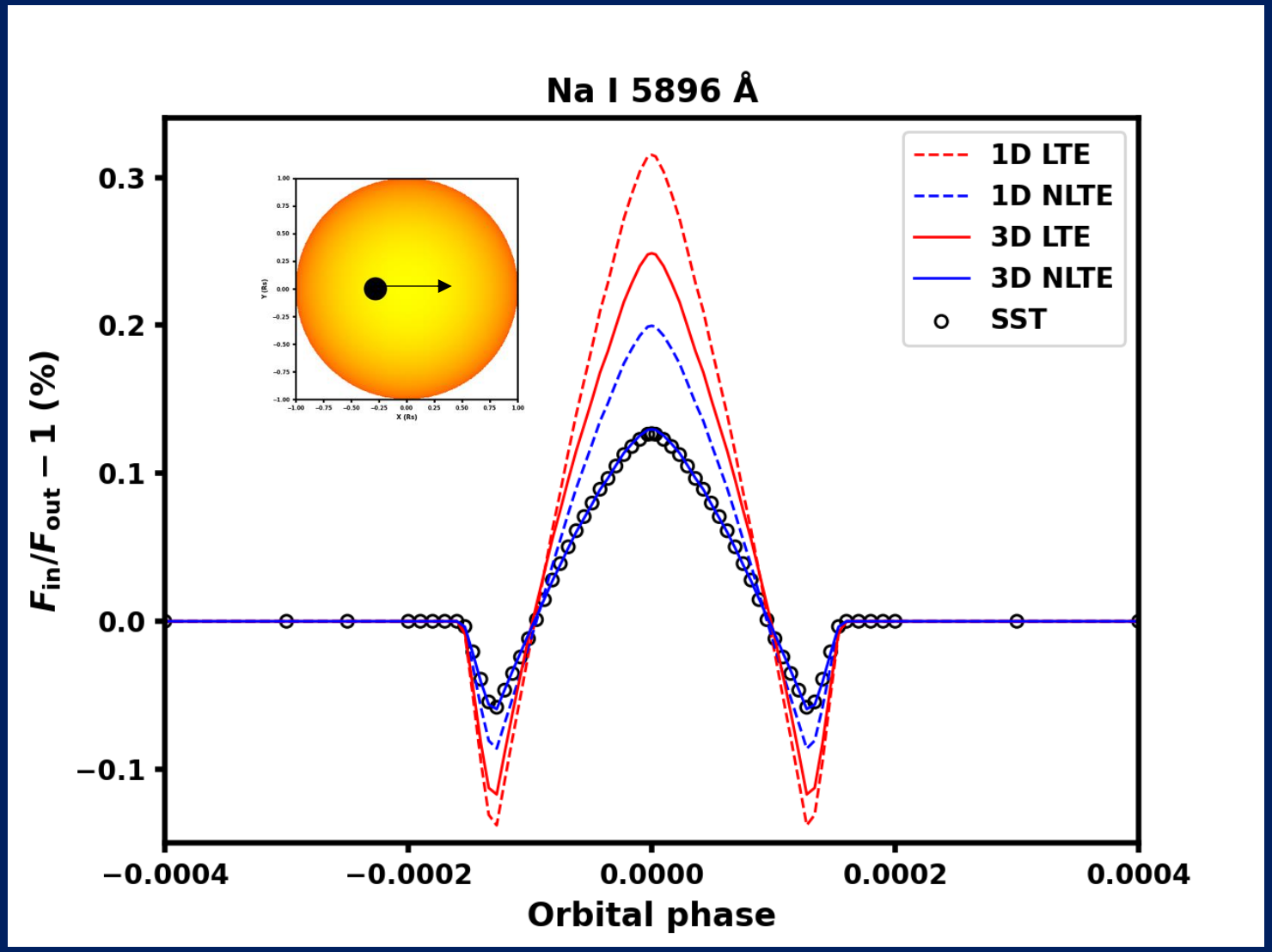
CLV is observed in the Sun (SST/CRISP data):



Canocchi et al. 2024a
A&A, 683, A242

Simulated transmission light curve of a **Sun-Jupiter** system:

The shape of the CLV+RM model is strongly dependent on the stellar synthetic spectra:



Canocchi et al. 2024a
A&A, 683, A242

Simulations performed with the **StarRotator** code by J. Hoeijmakers

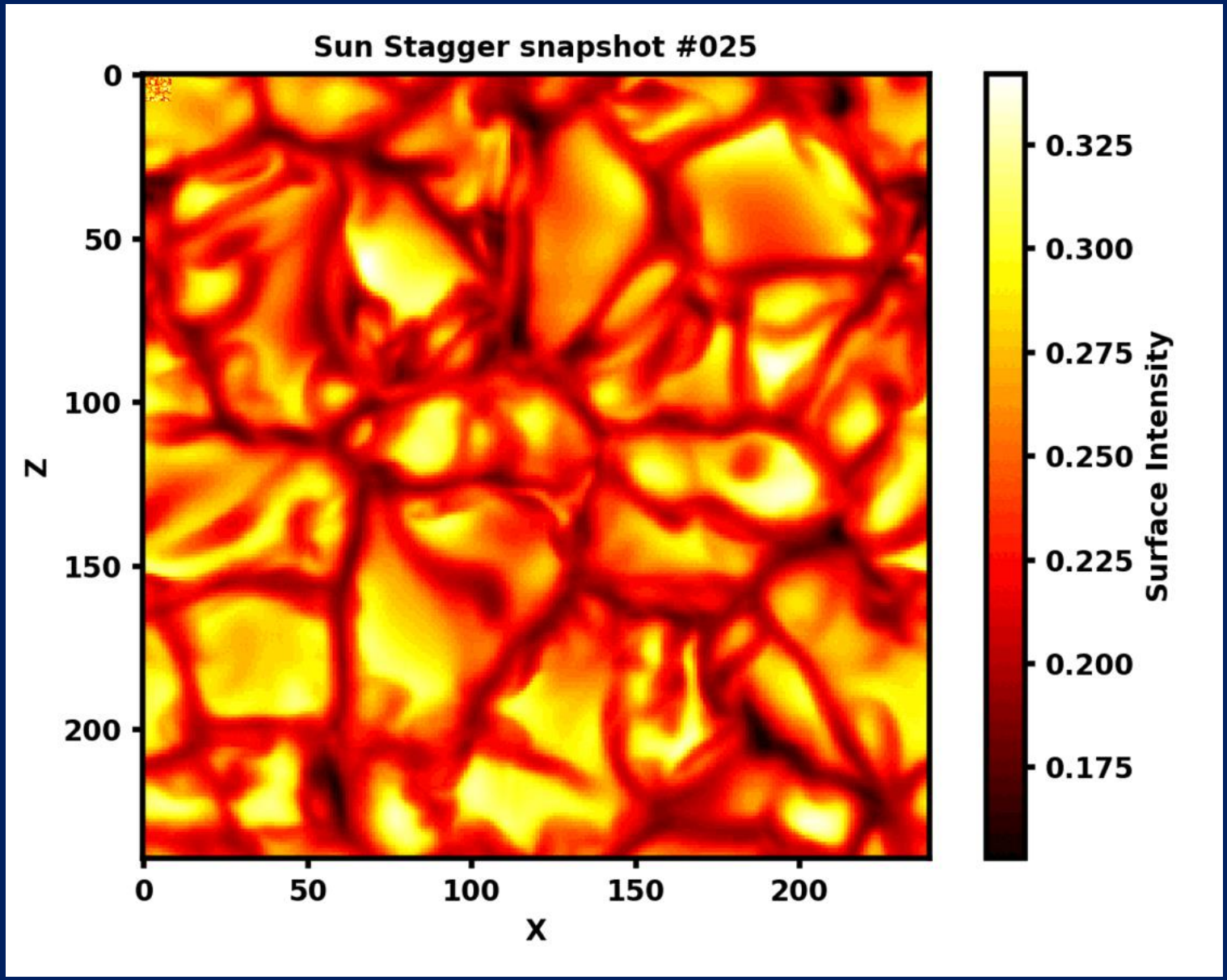
Modeling in 3D non-LTE

- Why? Required to correctly reproduce Solar observations;

- How?
3D **STAGGER** stellar atmospheres (Rodriguez-Diaz et al. 2024)

+

non-LTE radiative transfer with **BALDER** (Amarsi et al. 2018) ;



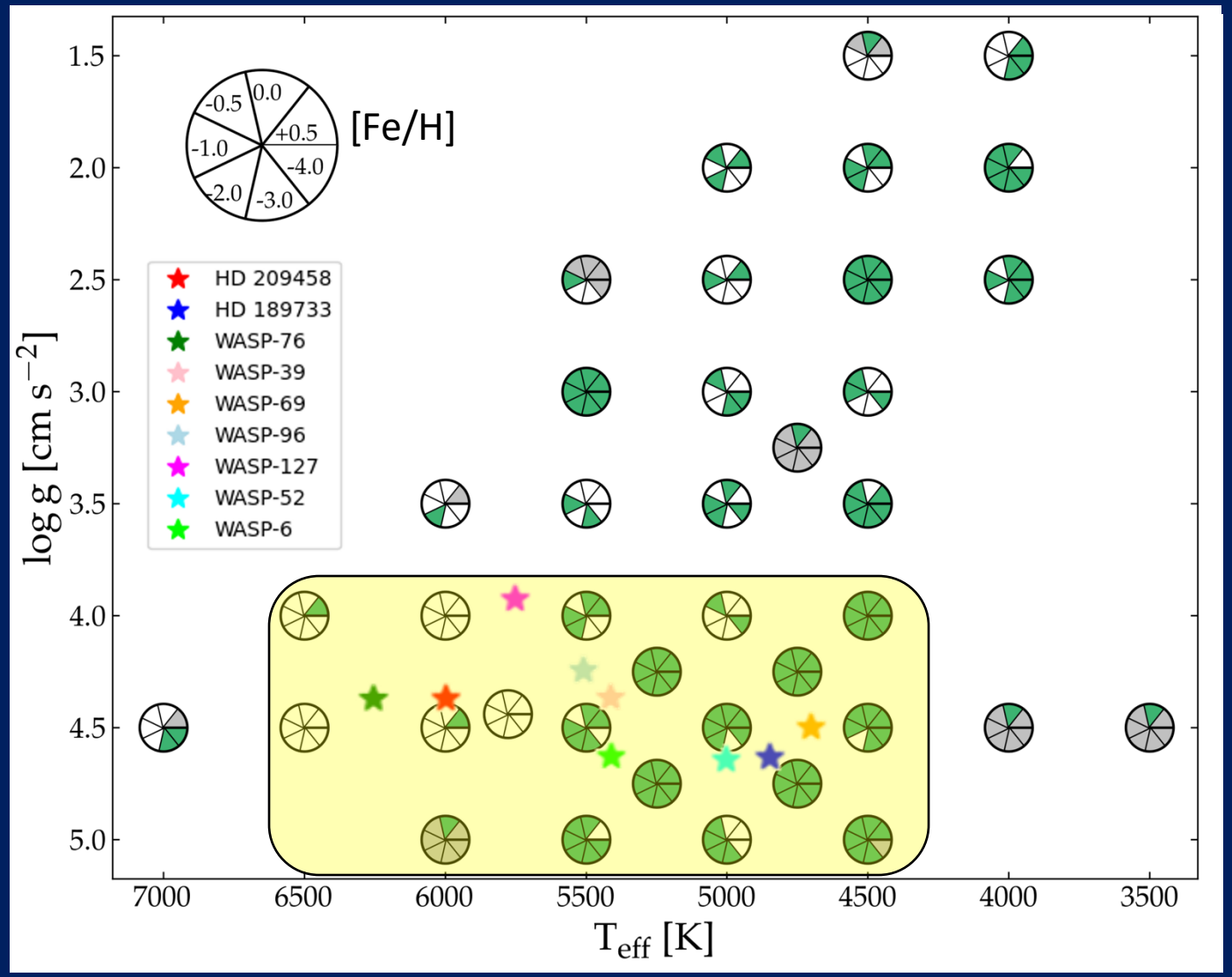
Computation of 3D non-LTE stellar spectra for Na lines in the new Stagger-grid:

- Where?

$T_{eff} \in [4500 - 6500]K$
$logg \in [4.0 - 5.0]\ dex$
[Fe/H]$\in [-0.5, +0.5]$

- What now?

Application on benchmark Hot Jupiters observed with ESPRESSO!

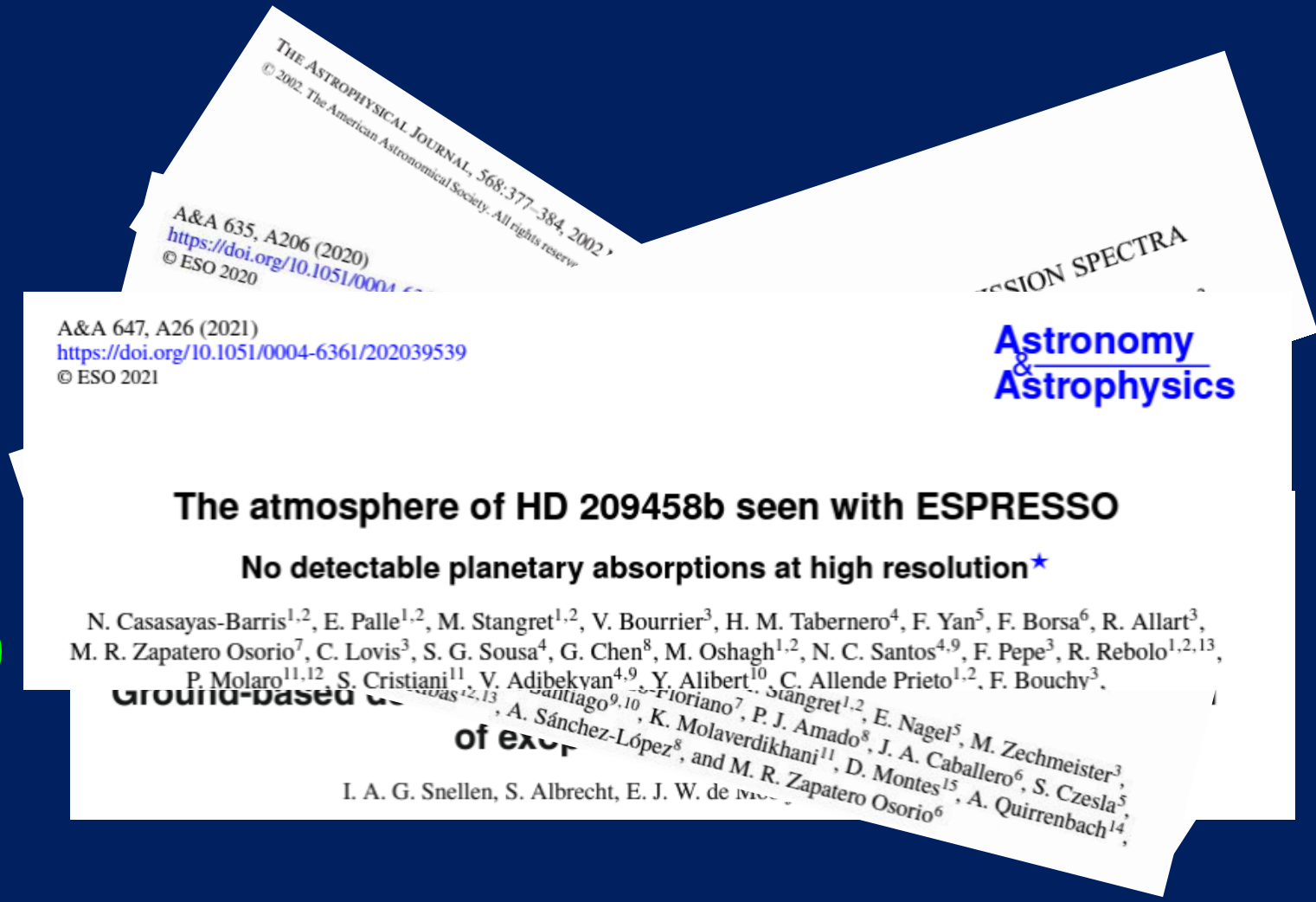


Credits to: C. Lagae

HD 209458b: a giant planet with a troubled history of Na (non-)detections!

Is there Na in the atmosphere of HD 209458b??

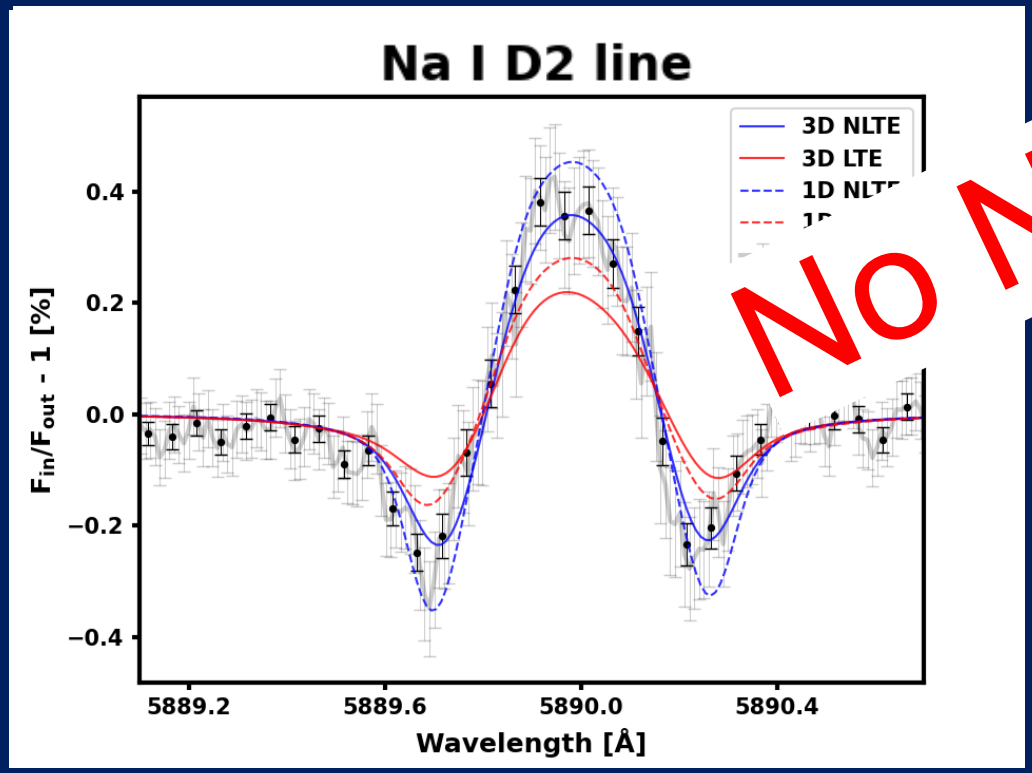
Charbonneau et al. (2002)
Narita et al. (2005)
Sing et al. (2008)
Snellen et al. (2008)
Albrecht et al. (2009)
Langland-Shula et al. (2009)
Jensen et al. (2011)
Astudillo-Defru & Rojo (2013)
Santos et al. (2020)
and many others…
Casasayas-Barris et al. (2020)
Casasayas-Barris et al. (2021)

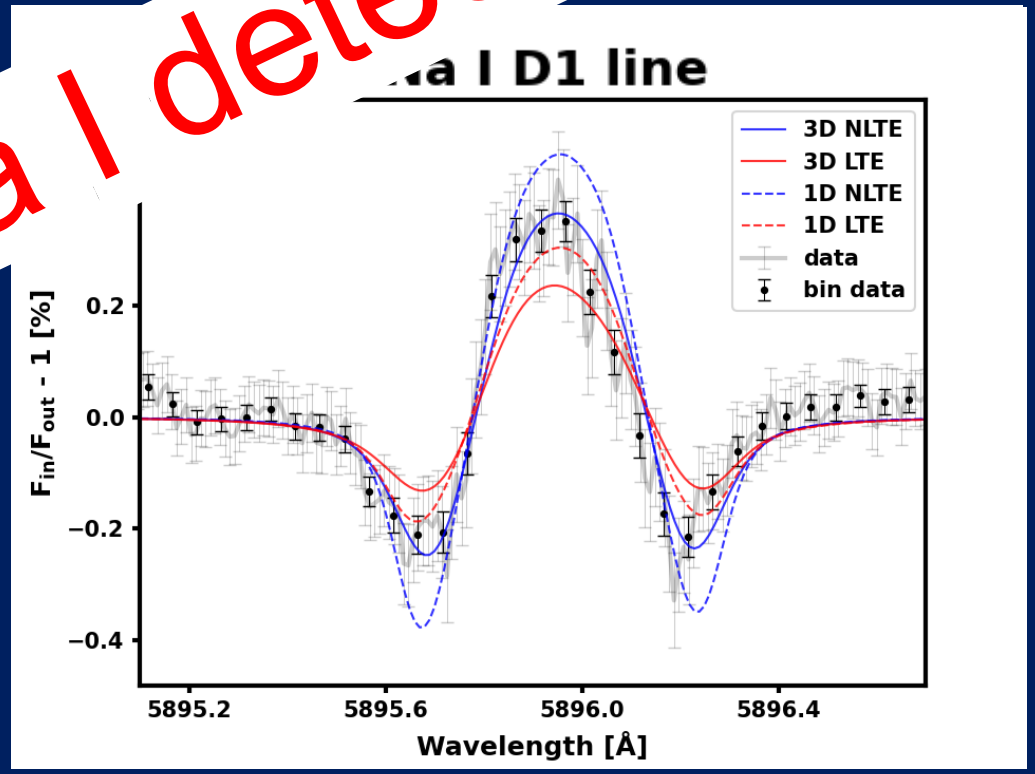


"To see Na or not to see Na, that is the question."

- G-type bright star (Teff= 6000 K; logg= 4.237; [Fe/H]=−0.306)
- 2 nights from ESPRESSO (R=140000)

No Na I detected!!!





Canocchi et al. 2024b
A&A, 692, A43

Main takeaways:

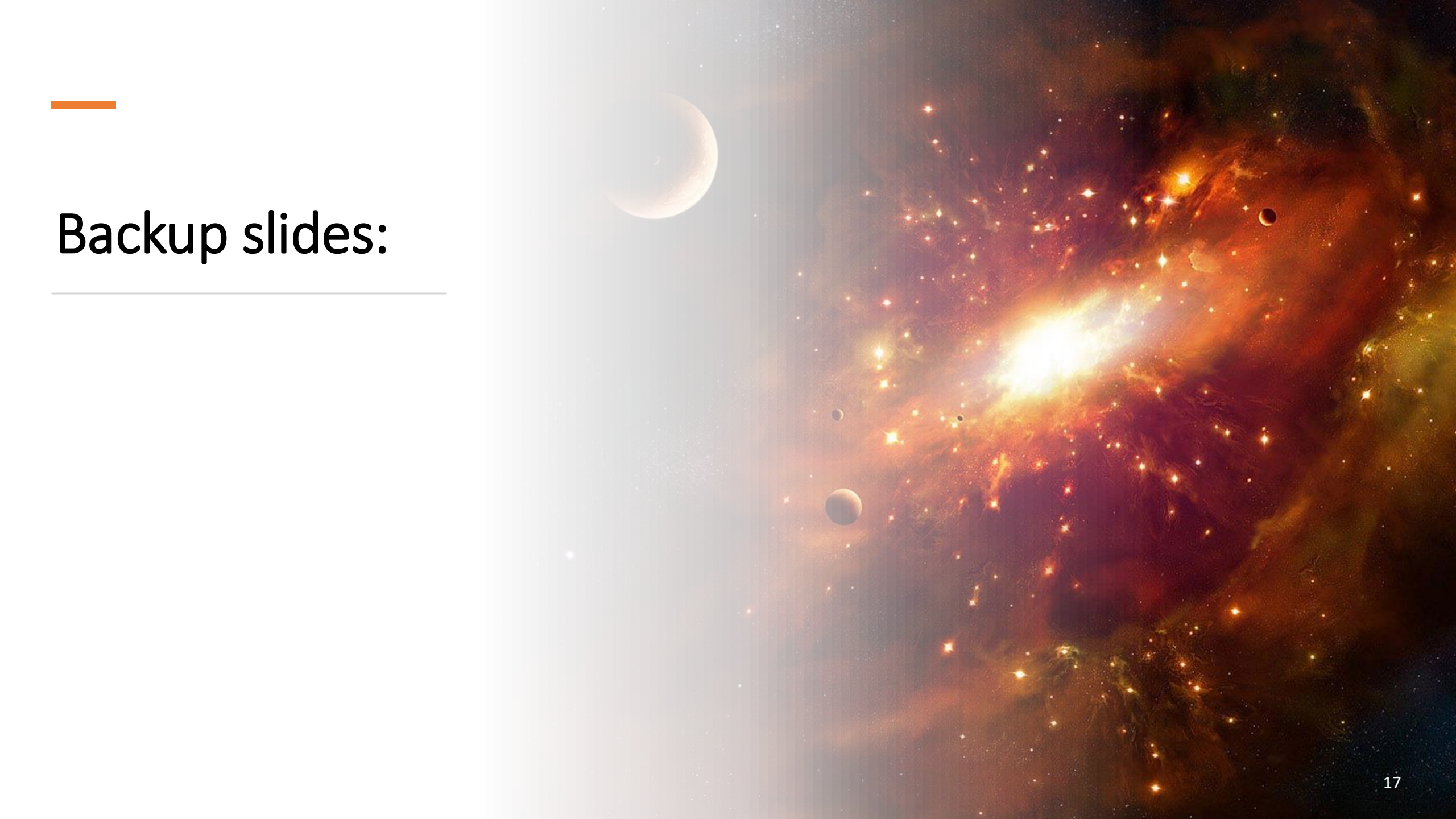
- The stellar CLV affects transmission spectra and should be corrected for accurate measurements!
- Only 3D non-LTE models can reproduce the observed CLV of Na D lines in the Sun
- 3D non-LTE stellar spectra of Na for planet-host stars ARE NOW AVAILABLE and ready to use!

THANK YOU FOR THE ATTENTION!

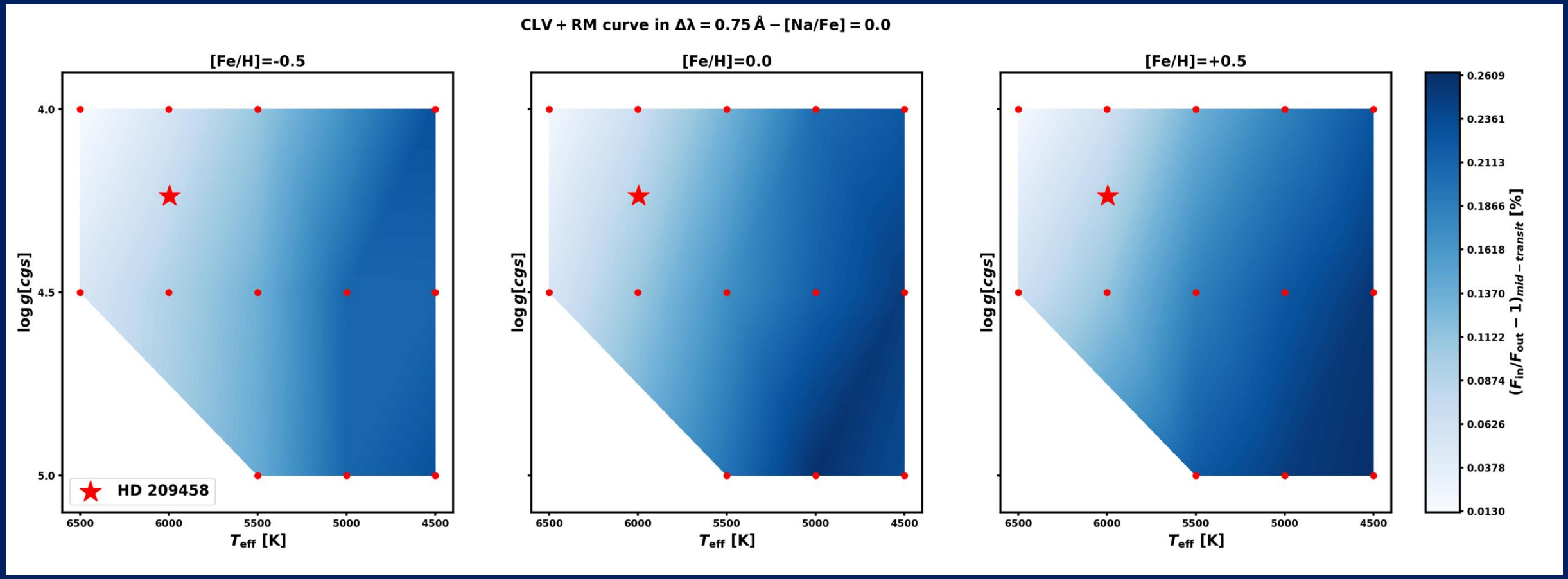
gloria.canocchi@astro.su.se

Credits: ESO/M. Kornmesser

Backup slides:

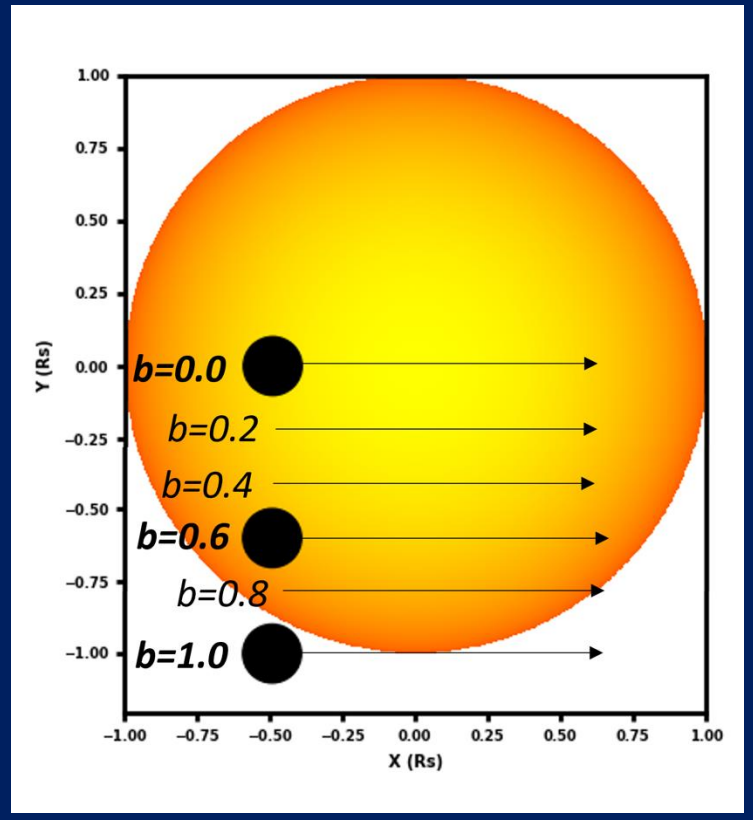


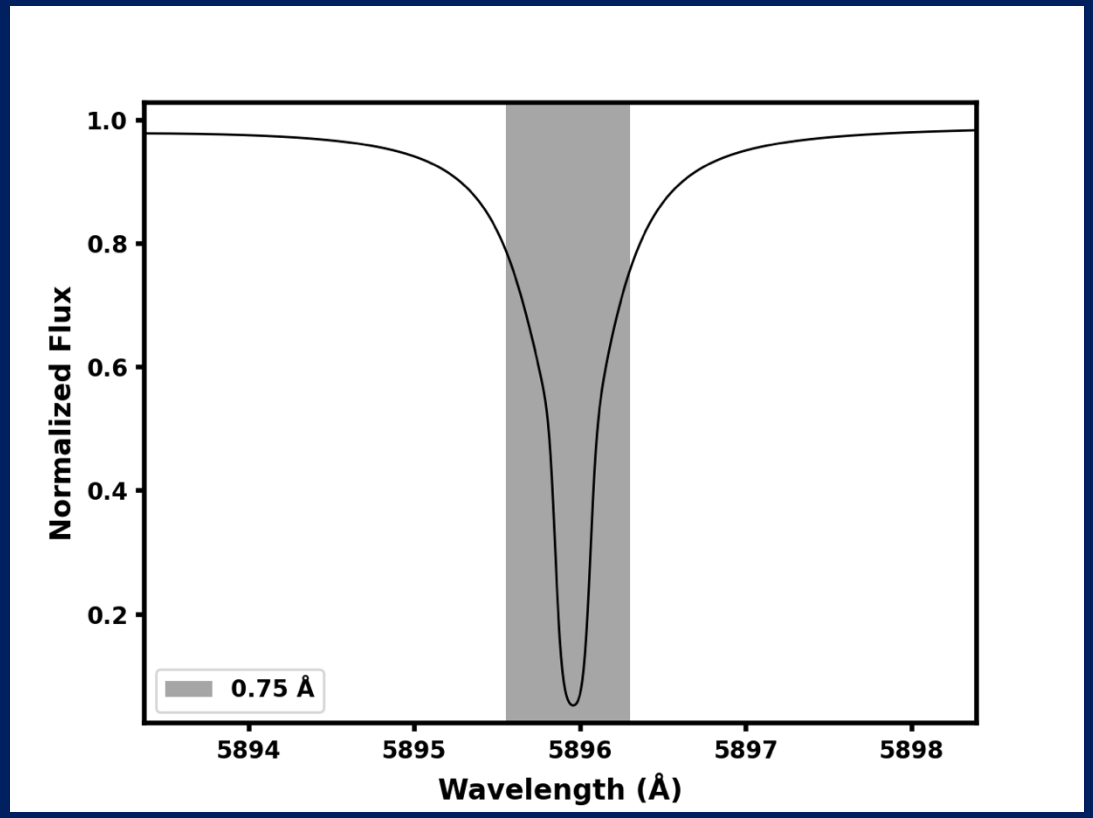
CLV+RM effect in the stellar grid



Simulating Jupiter as an exoplanet: Na D1 during a transit event

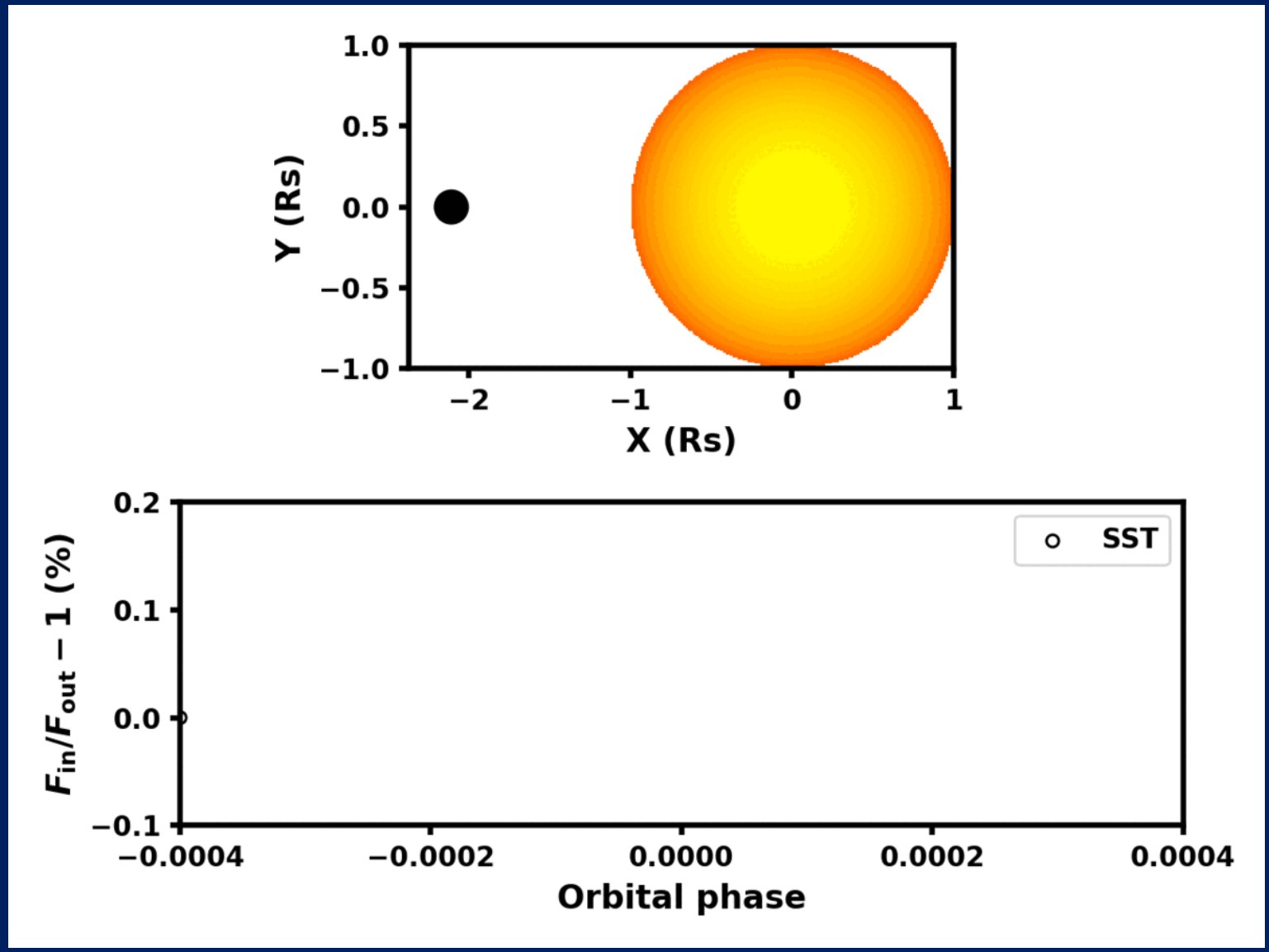
CLV curve for different orbits:



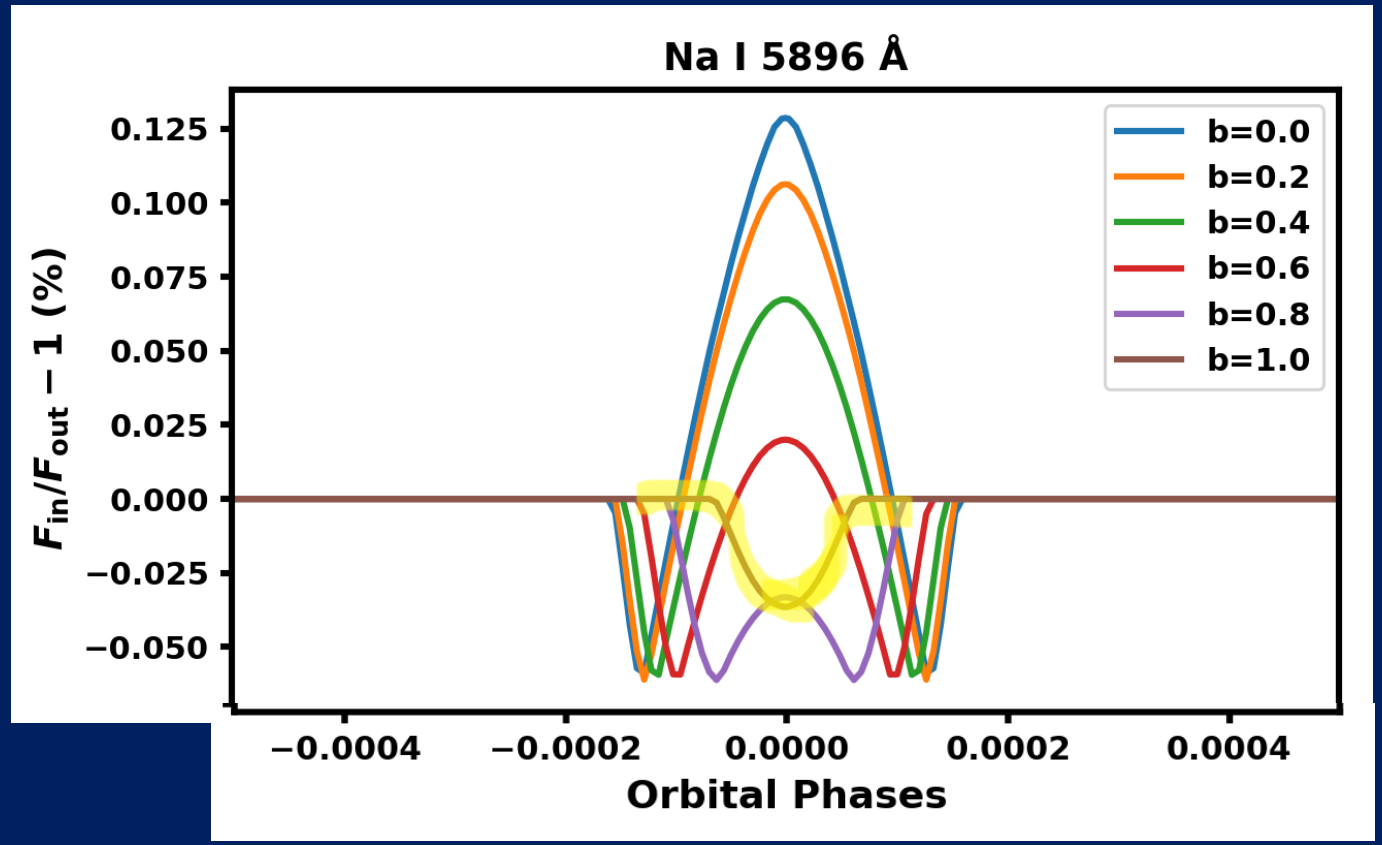


Simulation performed with the **StarRotator** code (by J. Hoeijmakers).

CLV curve for an edge-on transit (b=0):



CLV curve with different orbits (in 3D NLTE):



Local Thermodynamic Equilibrium (LTE) vs Non-LTE

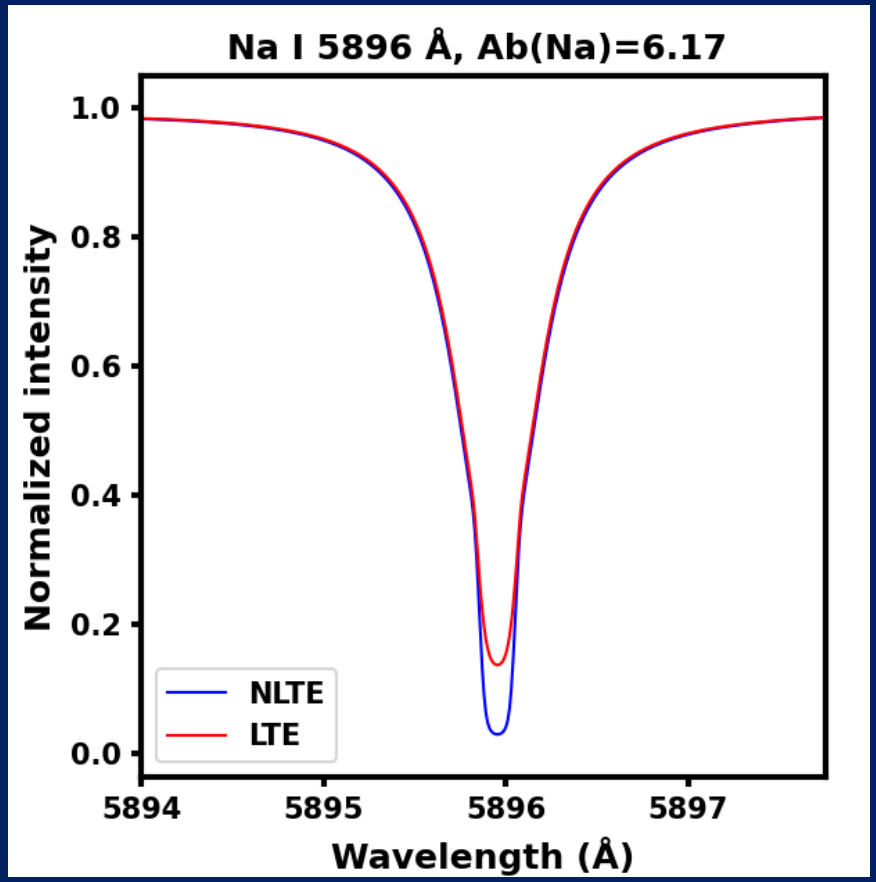
Radiative Transfer

LTE (cheap):

1) Level population set by the **Boltzmann and Saha** (depends on local conditions);

2) Collisional rates dominate radiative;

3) Line source function is Planckian;



Non-LTE (expensive):

1) Level population set by **the statistical equilibrium**;

2) Radiative rates dominate/equal collisional;

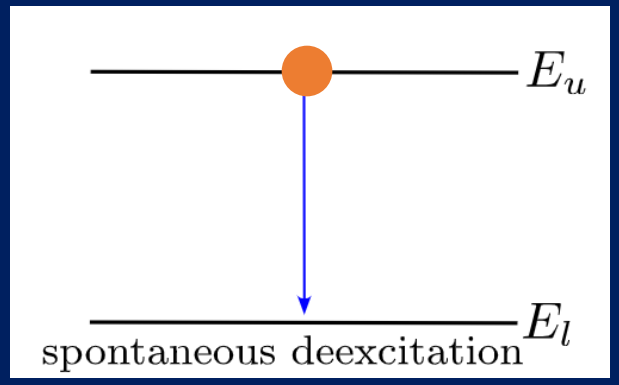
3) Line source function is not Planckian;

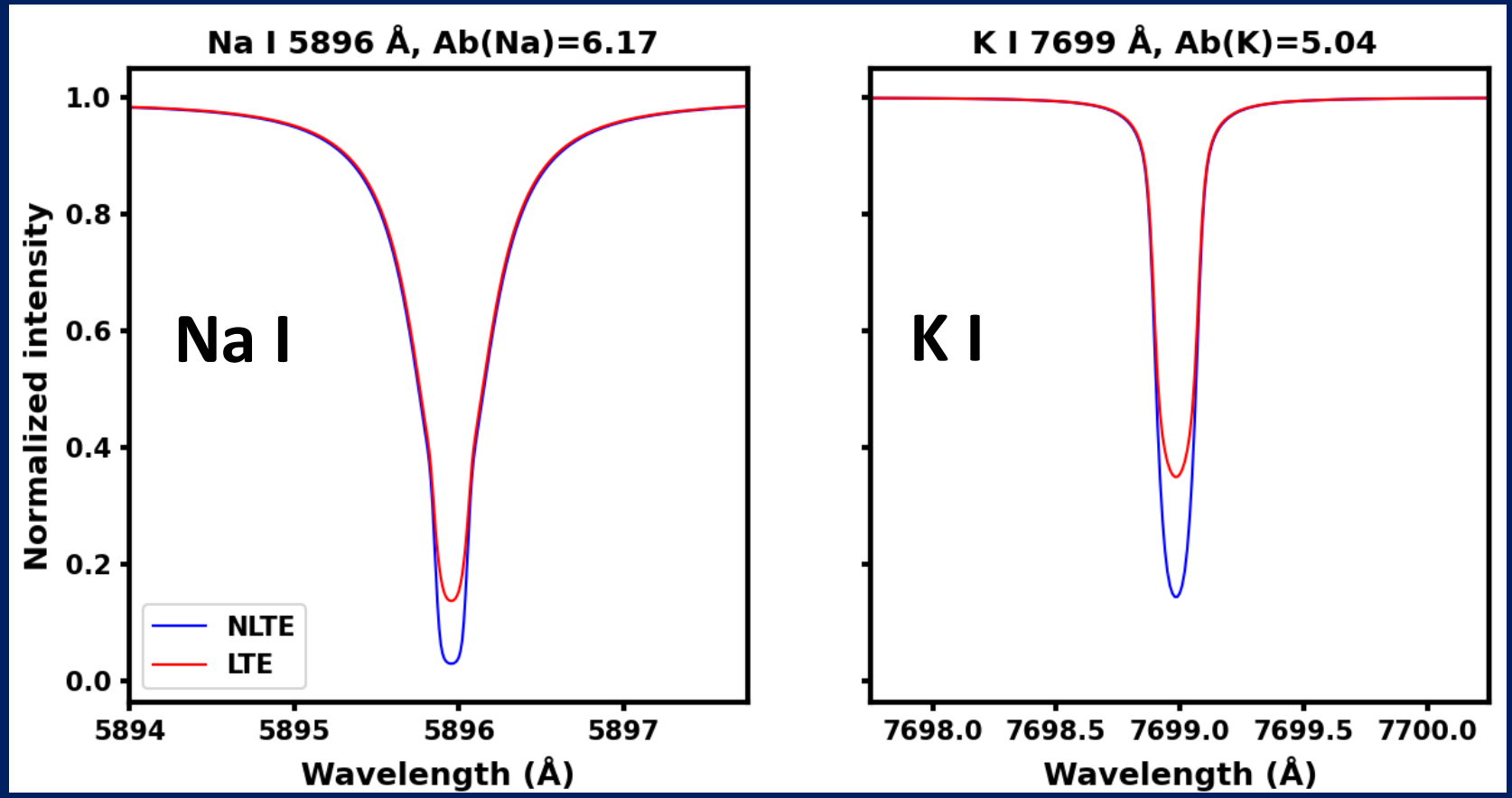
Non-LTE effects arise because of differences between the mean radiation field and the Planck function:

Radiative Transfer

$$S_\nu = J_\nu < B_\nu$$

- over-deexcitation of the upper levels;
- $n_l > n_{l,LTE}$

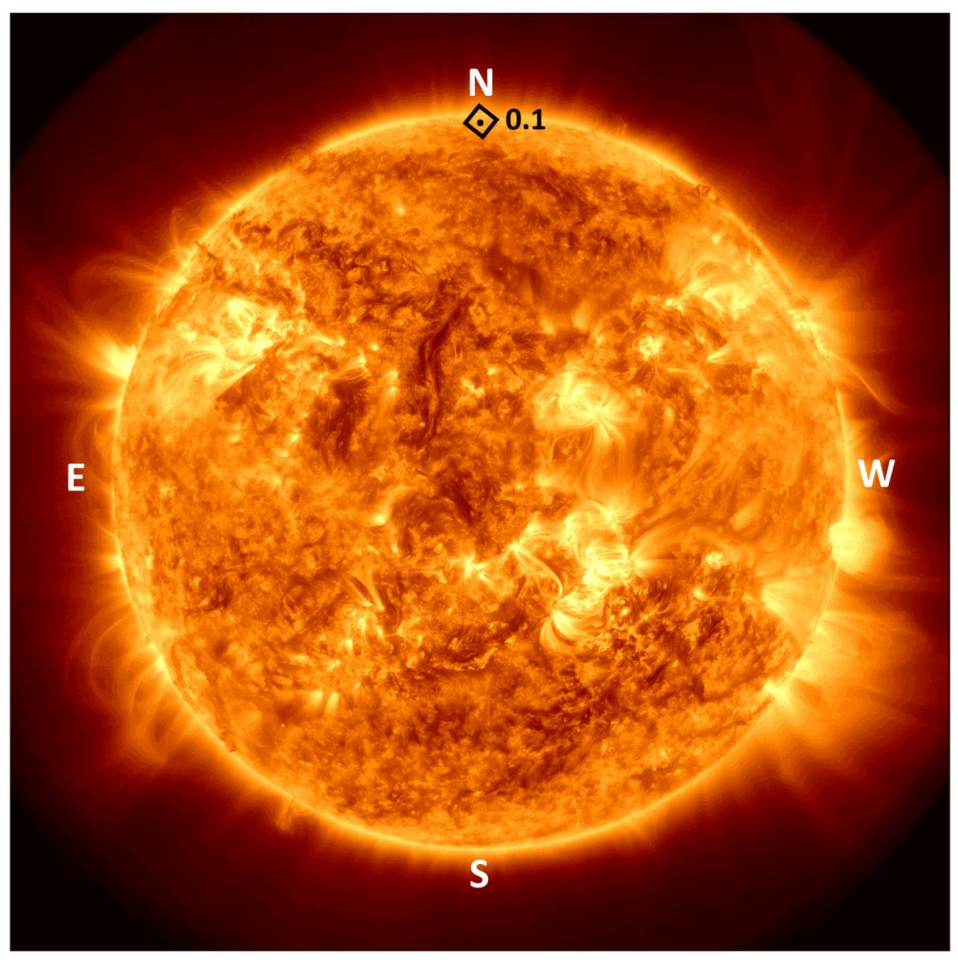


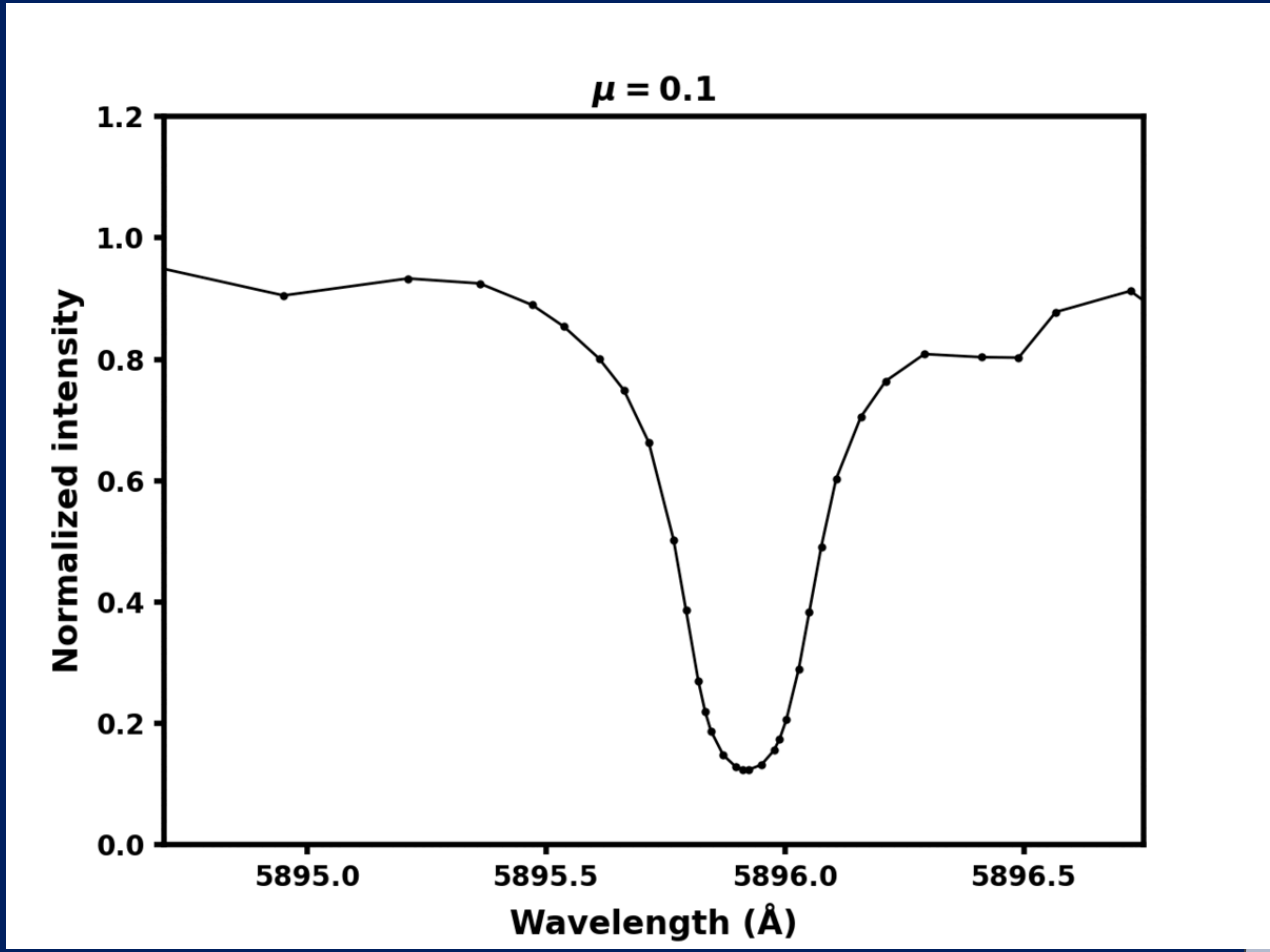


The center-to-limb variation (CLV) effect

Variation of spectral lines across the stellar disk can affect the determination of planetary abundances.

$\mu = \cos(\theta)$ θ =heliocentric angle





From NASA's SDO: https://sdo.gsfc.nasa.gov/data/