Stellar Activity and Ariel Observations

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- **Stellar radiation and its variability, determines and shapes the evolution of planetary atmospheres, during the star lifespan.**
- **Stellar activity is the major source of astrophysical «noise» for planetary observations**

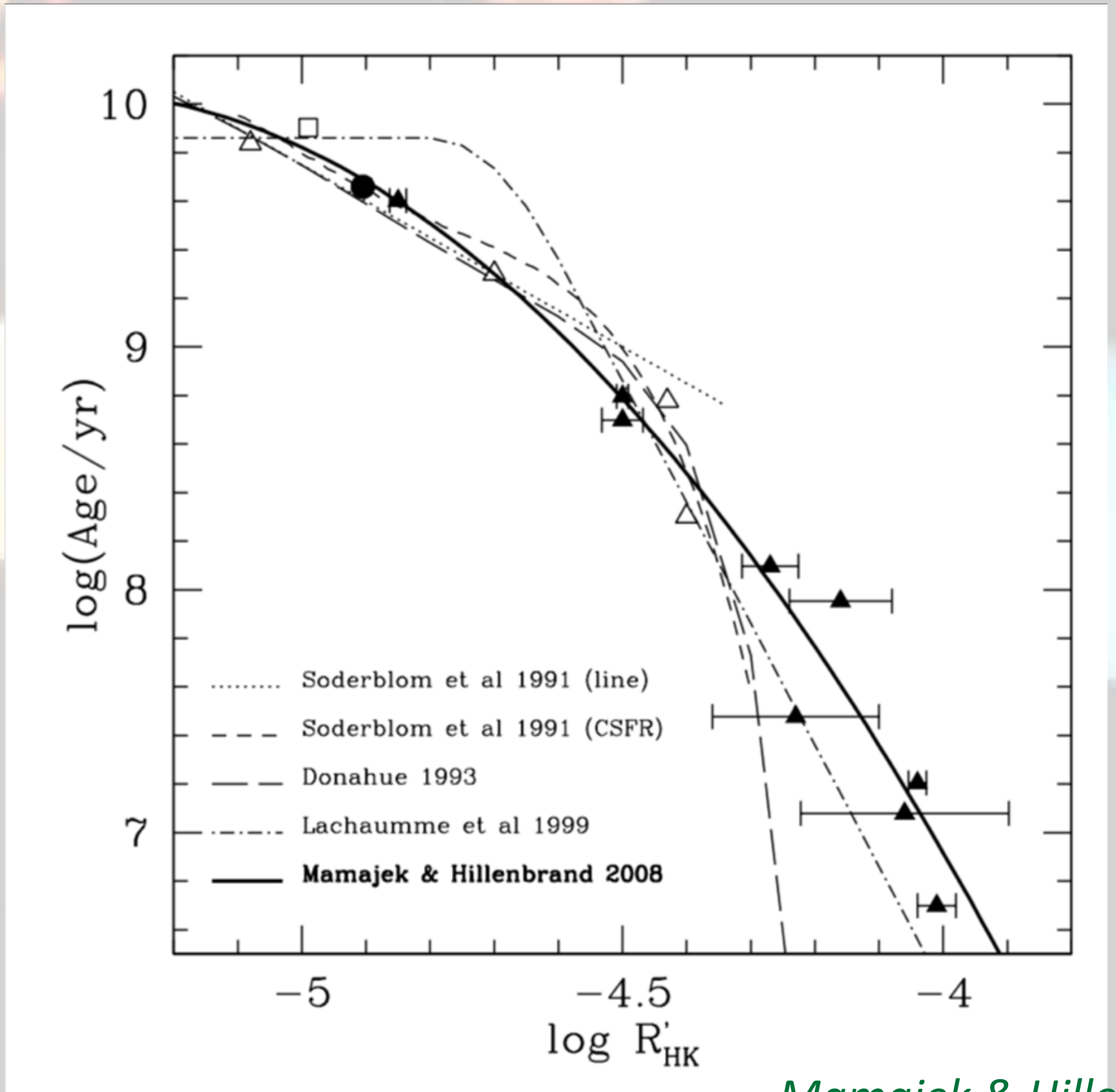
Most exoplanetary science requires tackling stellar activity

ARIEL

- Time - resolved photometric/spectroscopic observations
- Broad-band (covered simultaneously)

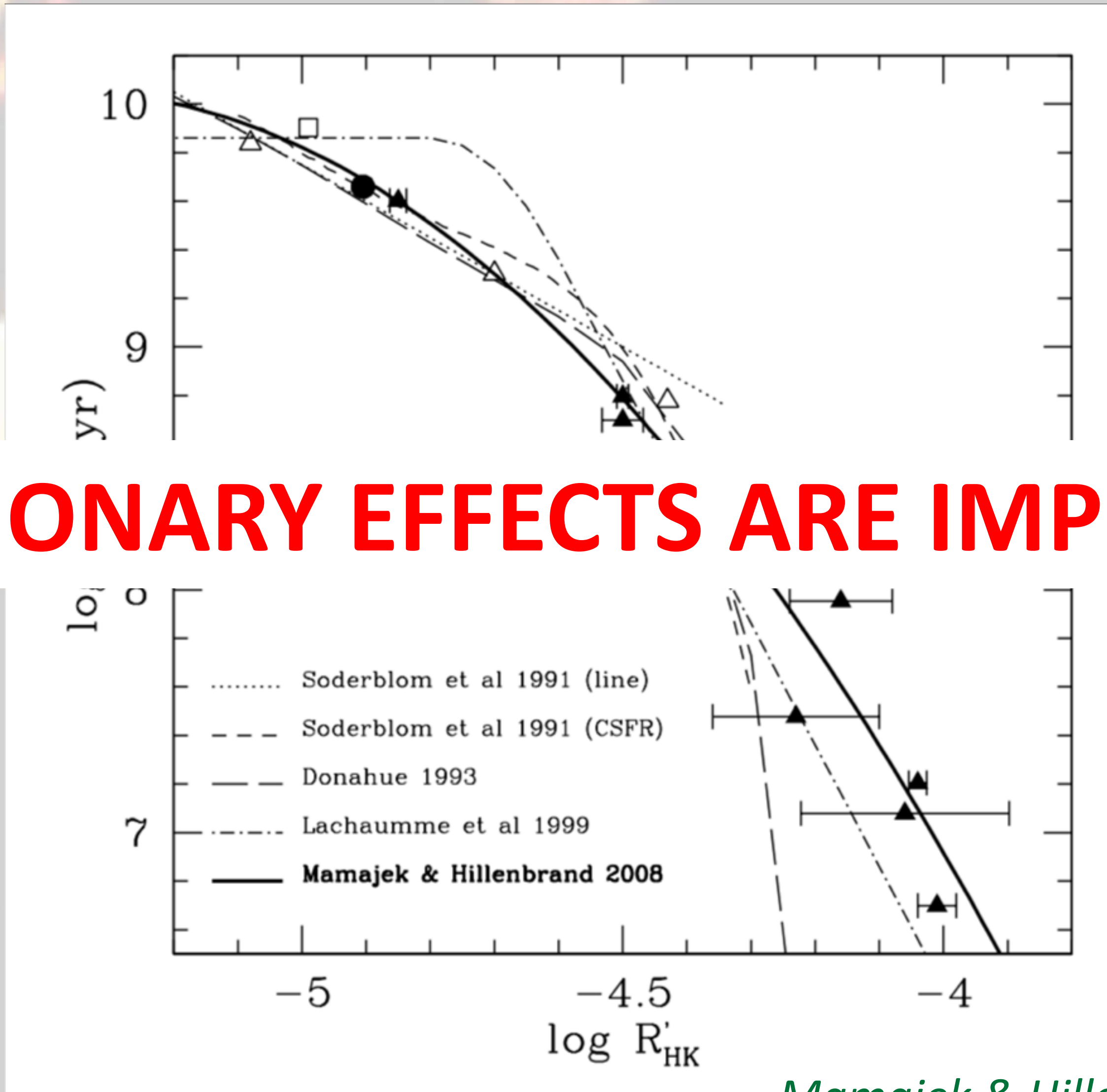
Useful characteristics to study/disentangle the stellar activity

Stellar variability declines with age



Mamajek & Hillebrand 2008

Stellar variability declines with age



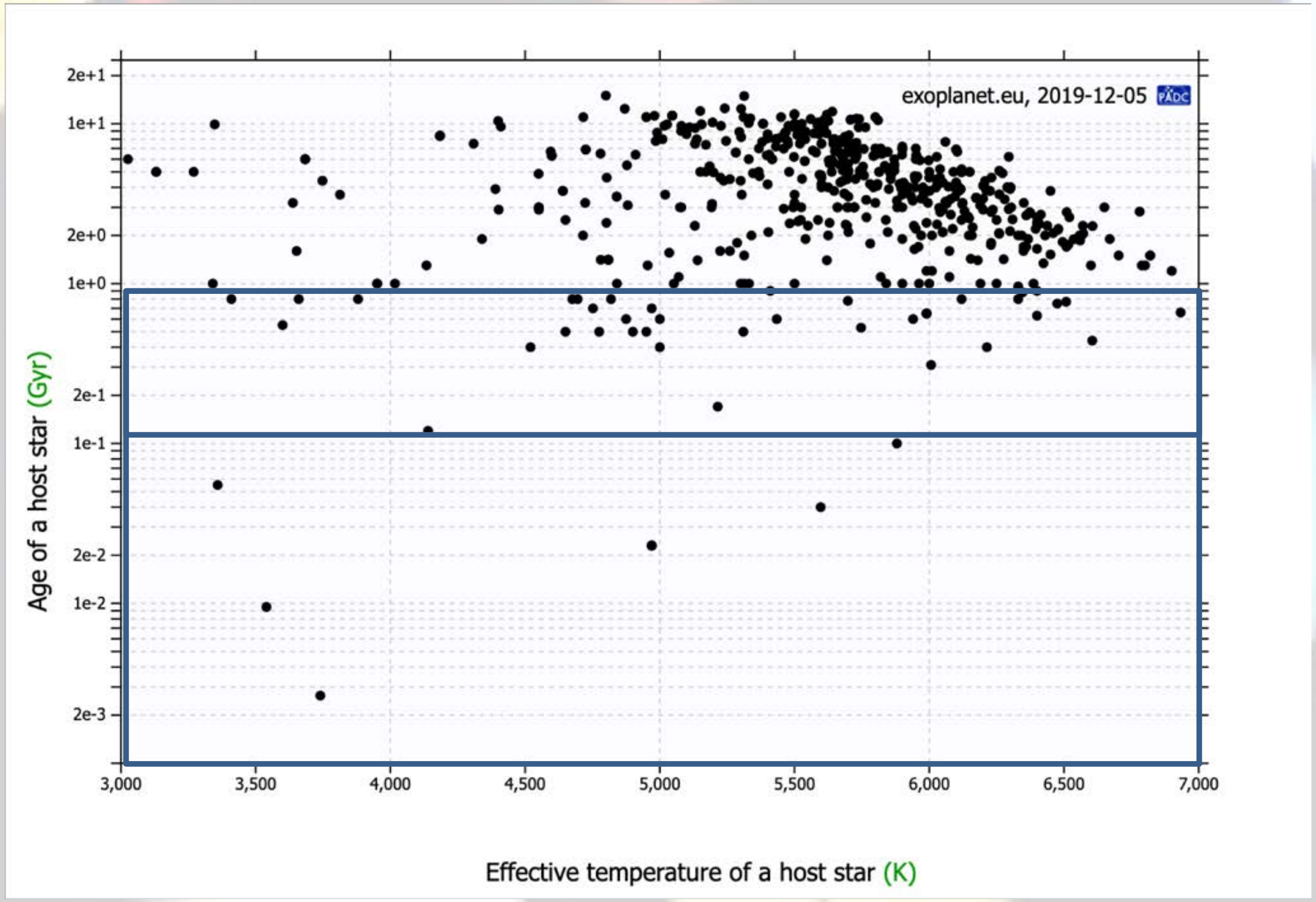
EVOLUTIONARY EFFECTS ARE IMPORTANT

Mamajek & Hillebrand 2008

To avoid observational limitations young/active stars are often missing in most planetary surveys

Intermediate age ⇒

young ⇒

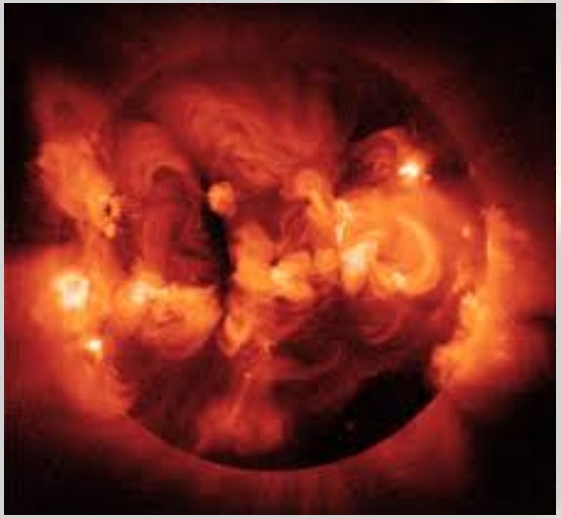


Luckily, things are changing: *Donati et al., 2017a, 2017b; Keppler et al. 2018; Grandjean et al. 2019; Benatti et al. 2019, …*

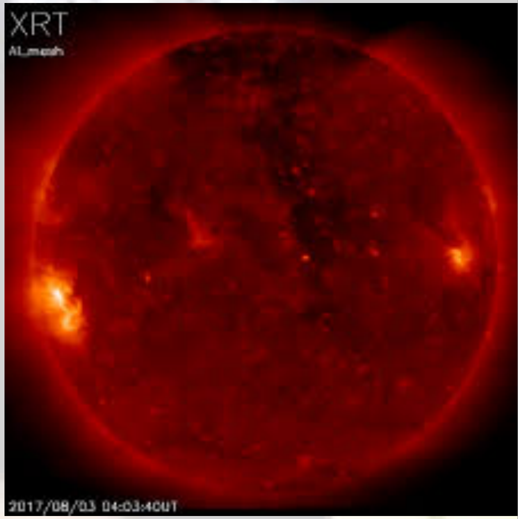
The young (bright) Sun

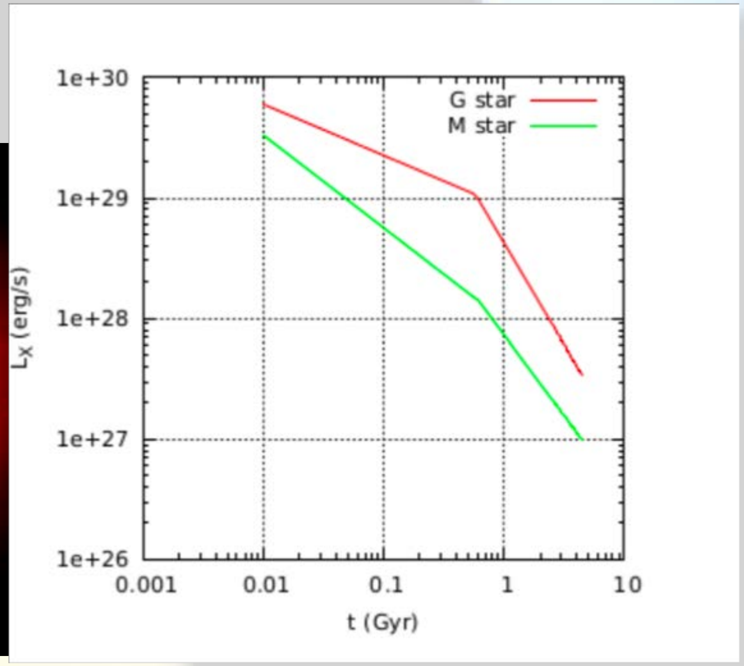
High energy radiation

At < 1Gyr 10^{29}-10^{31} erg/s

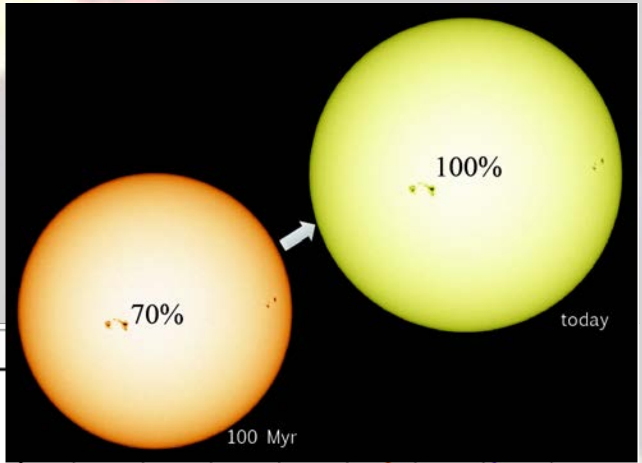


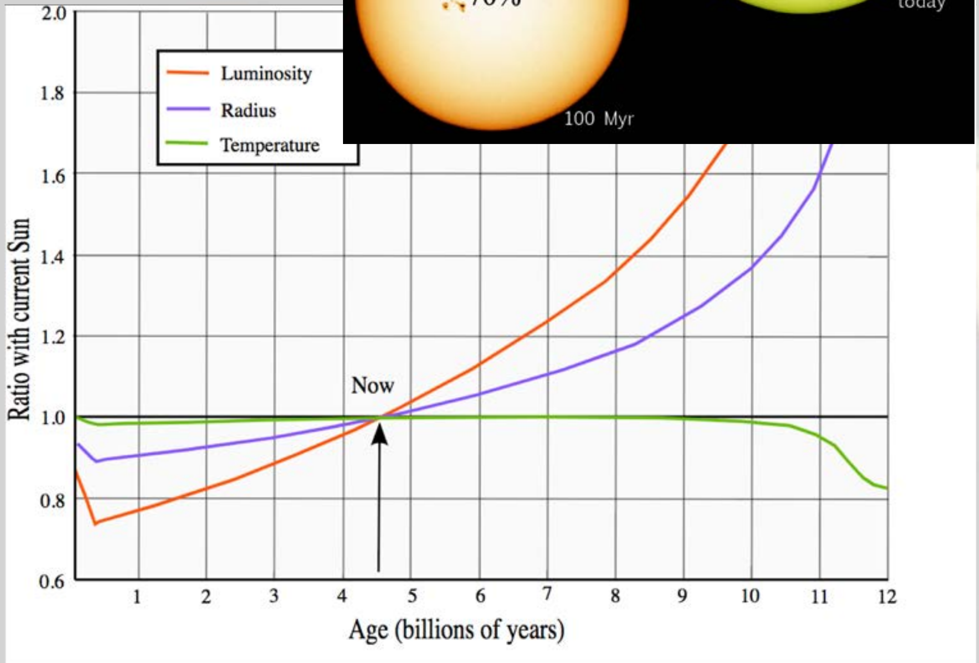
Today $5 \times 10^{26} – 3 \times 10^{27}$ erg/s

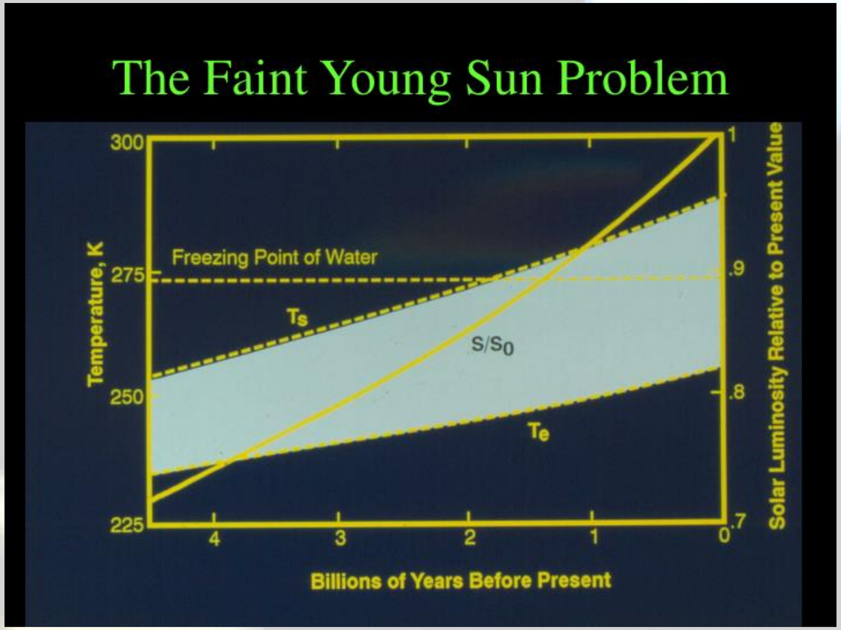




The young (faint) Sun:

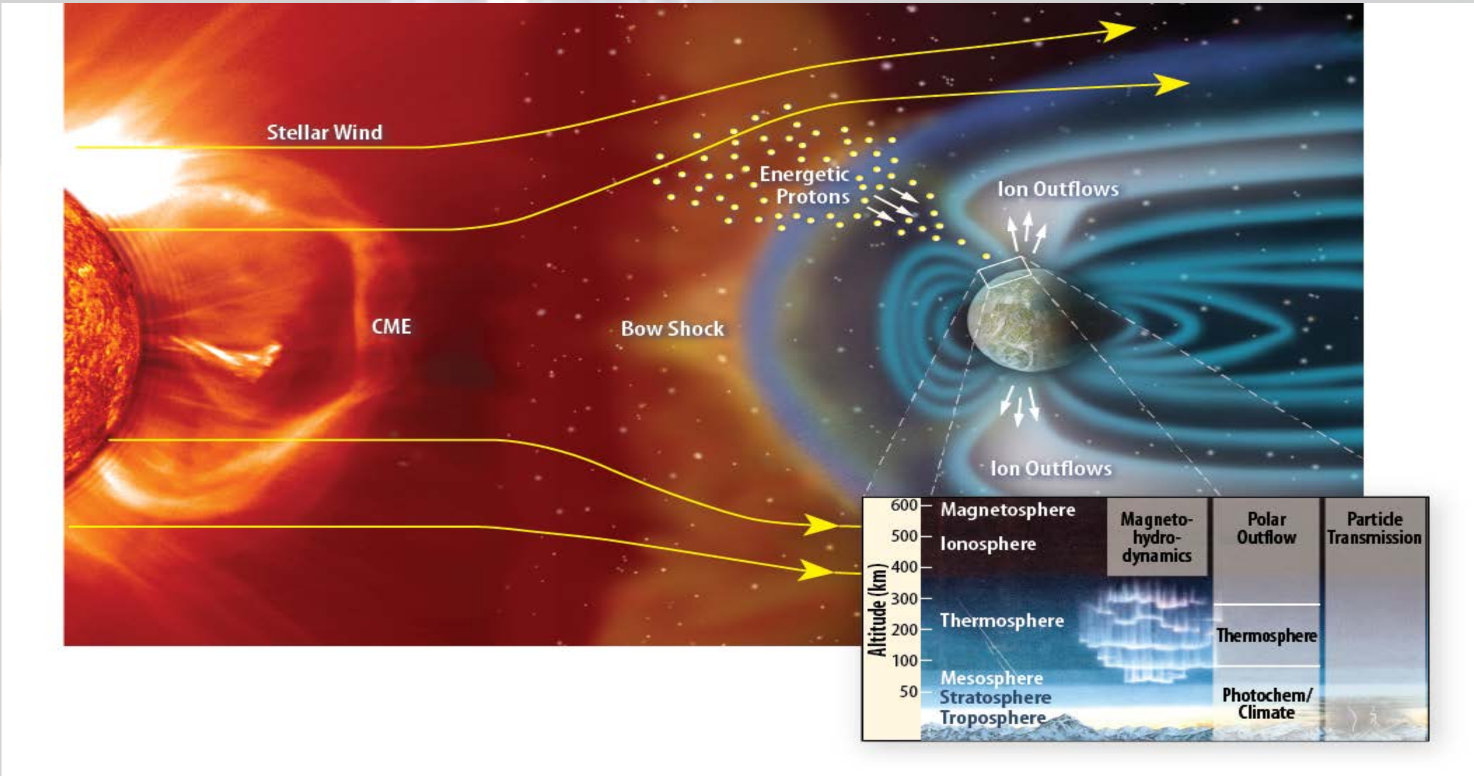






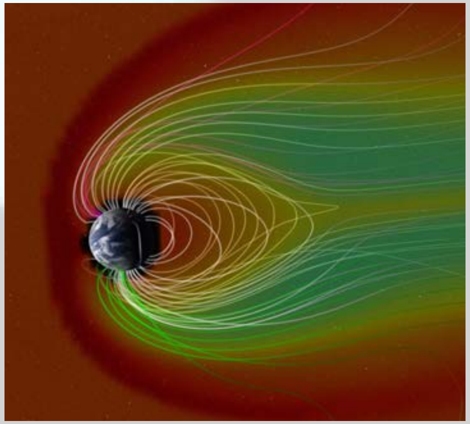
- 30% fainter
- Earth and Mars are icy balls
- Earth and Mars should not be habitable
- Faint Young Sun paradox

Star-Planet Interaction Creates Stellar Space Weather



Star-Planet Interactions
Hot Jupiters

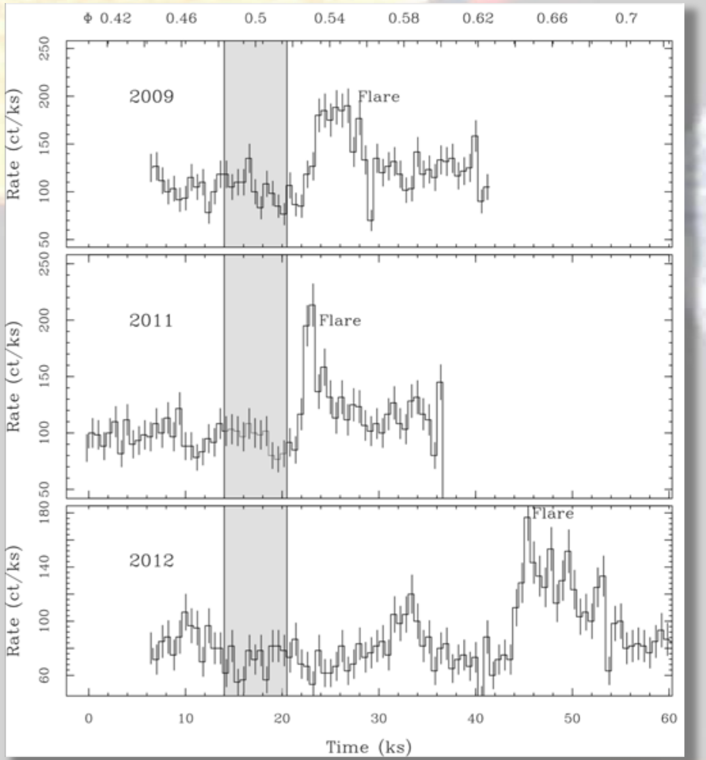
- **Star-Planet Magnetic Interactions ⇒** Stellar (dynamo-generated) magnetic field interact with the magnetospheres of close-in Jupiter-mass planets
- **Magnetic stresses and reconnection events** ⇒ energy release, heating (and evaporation) of planetary atmospheres

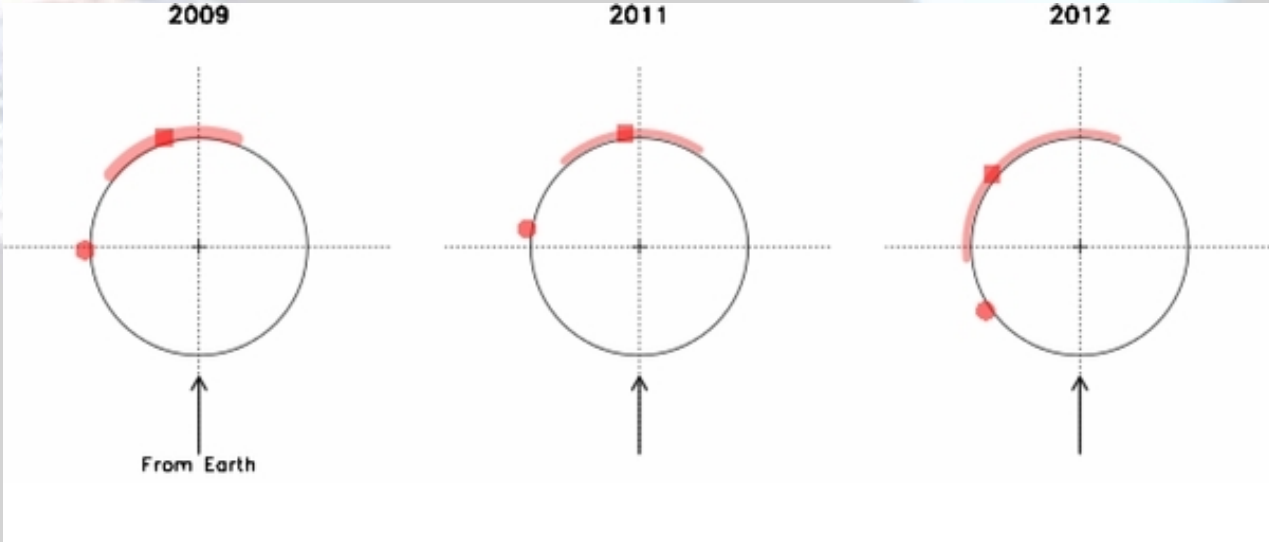


Observations of these effects
characterization of planetary magnetospheres, feedback effects, flares, e.g. diagnostics of heating and evaporation of planetary atmospheres

XMM-Newton X-ray observations of HD 189733

(Pillitteri et al. 2010, 2011, 2014)

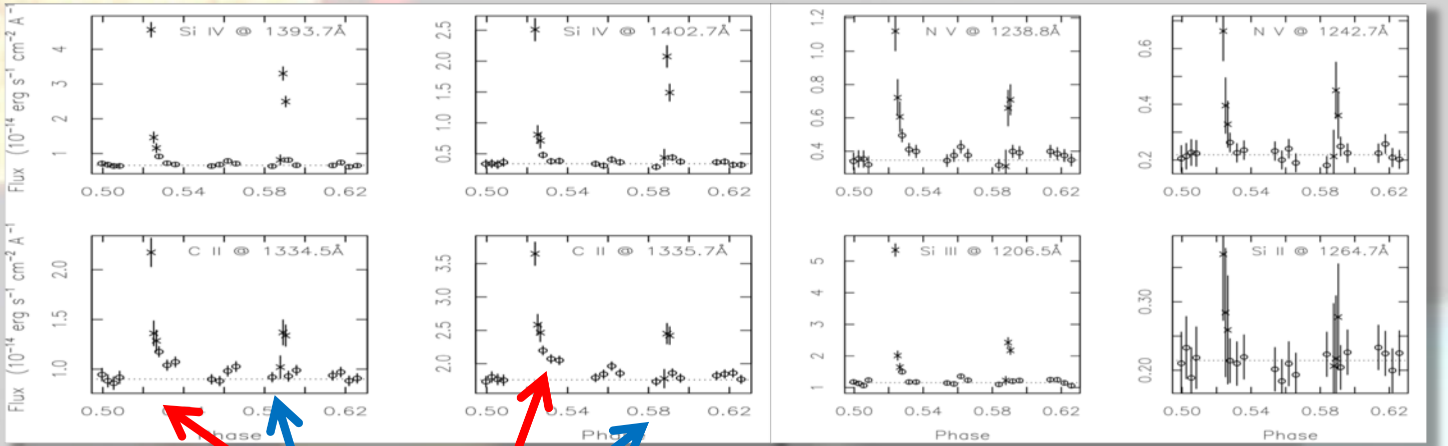


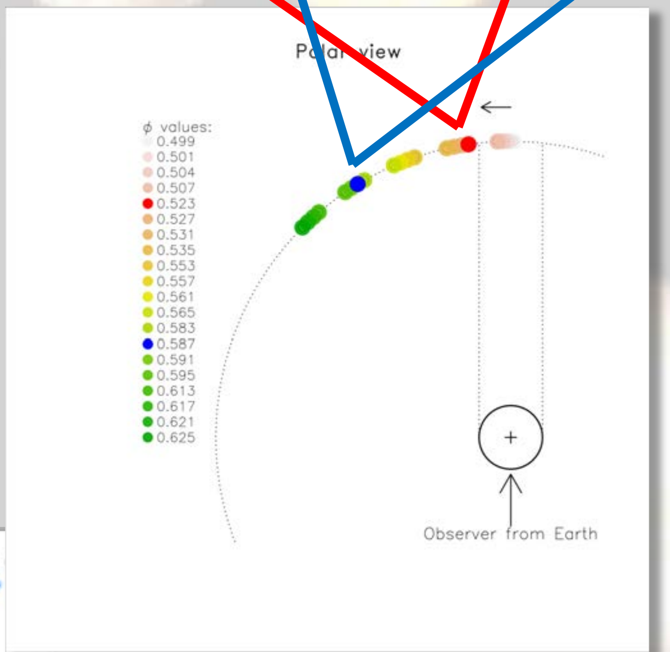


- ❖ Strong variability after the planetary eclipse (phase 0.5)
- ❖ Analysis of 2012 X-ray flare suggests long magnetic structure, 40-100 G magnetic field, and dense plasma

HST/COS FUV observations of HD 189733

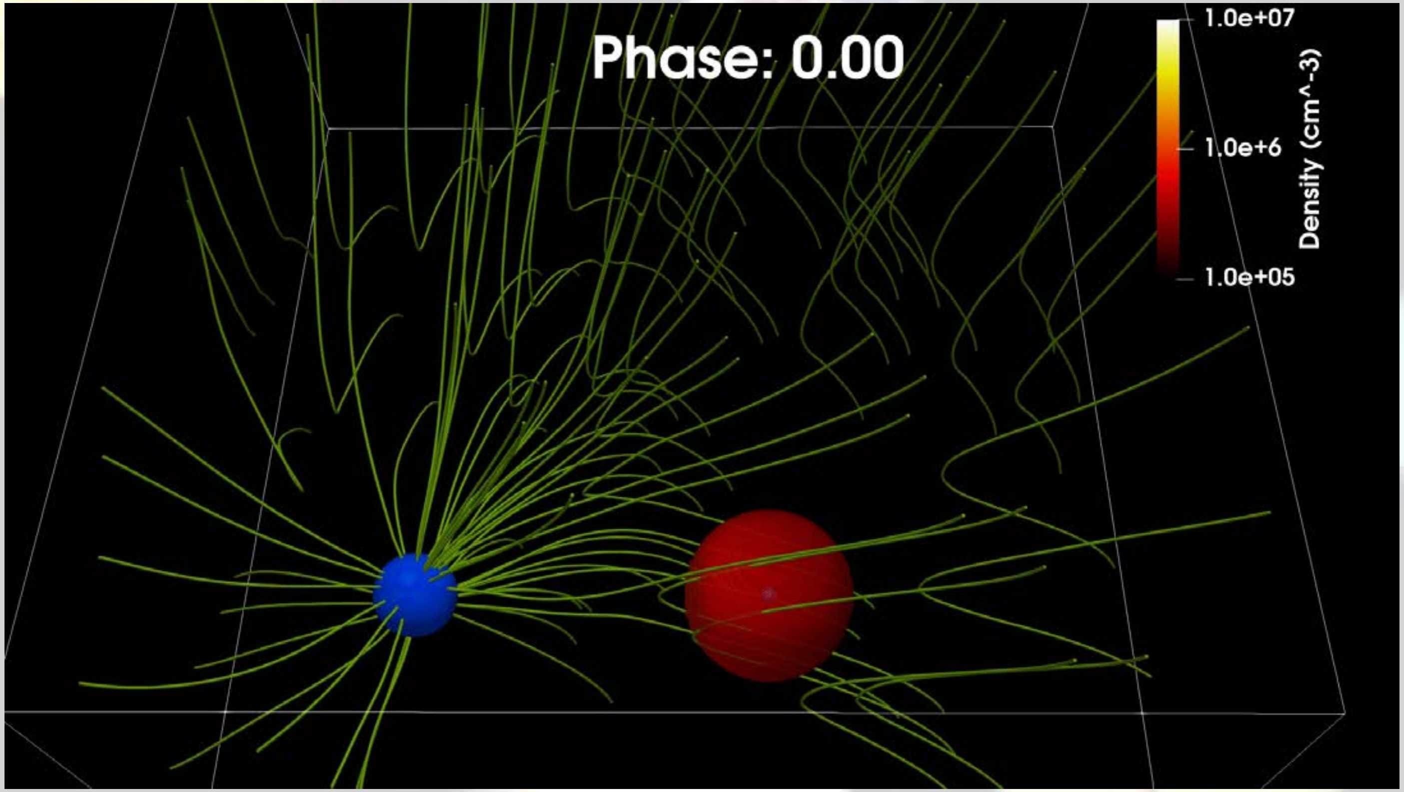
Pillitteri et al., 2015 ApJ





- **5 HST orbits, COS spectra 1150-1450 A**
- **Strong FUV variability after phase 0.5**
- **First event: red-shifted lines, up to +20 ± 5 km/s**
- **Second event: lines blue-shifted of -20 ± 5 km/s**

Strong interaction of Hot Jupiters with the host star *(Colombo et al, in prep.)*



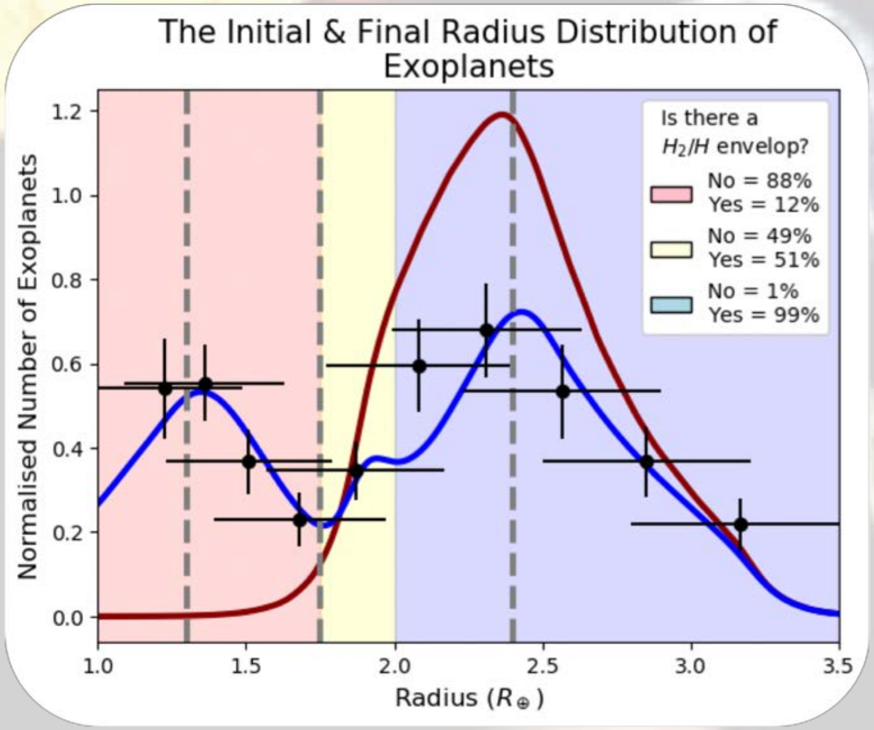
3-D MHD simulations of the HD189733 system.
Evaporation of the planet atmosphere and accretion on the star.

Initial evolution of the system~1. , *work in progress* P_{orb} simulated.

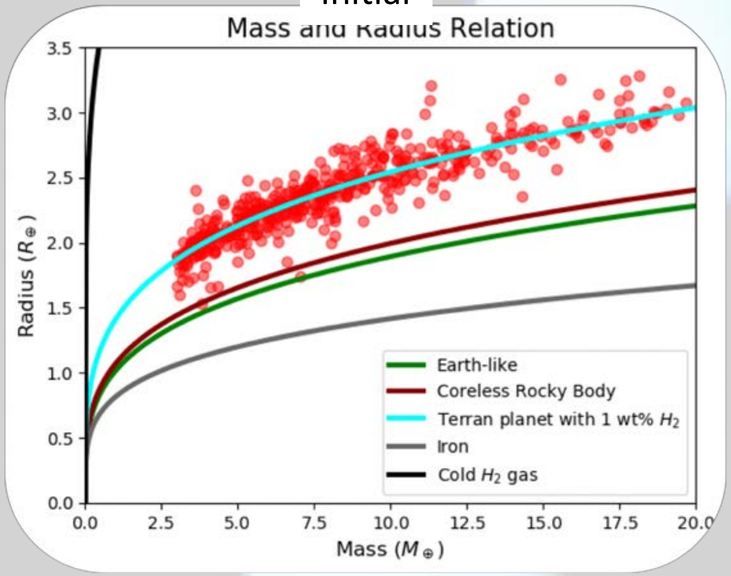
Rotating star-planet reference system

In less extreme environment: XUV-induced atmospheric erosion can explain the 'Fulton Gap'

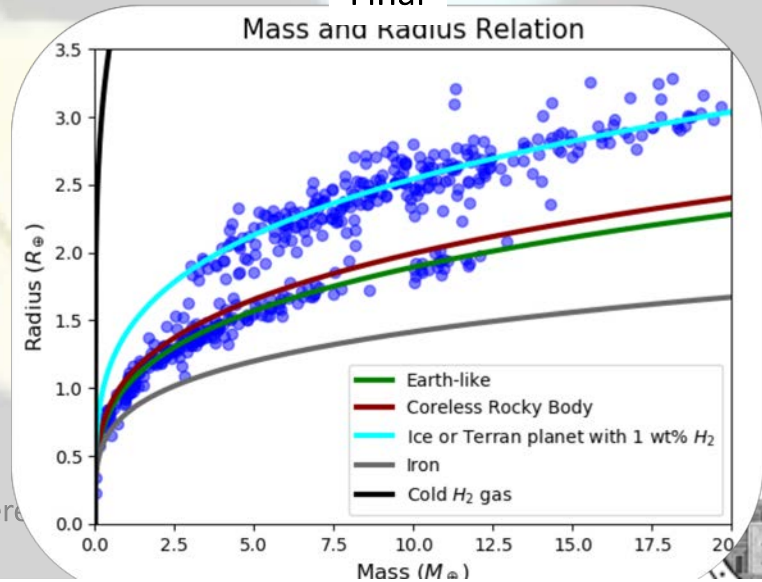
On long-time scale



Initial



Final



Planets with P_{orb} < 100 days

See Poster of Modirrousta-Galian

We need to estimate the stellar activity:

to understand the planetary environment and its evolution

and to correctly extract the planetary signal

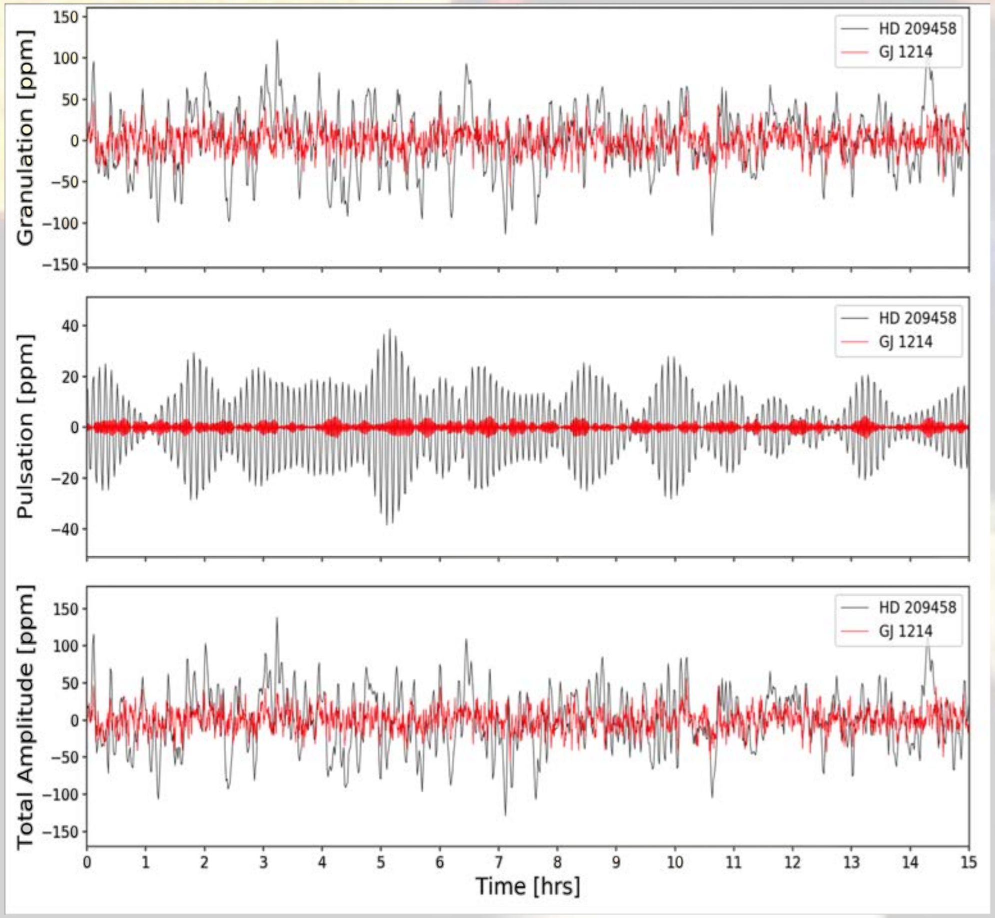
How to deal with active stars

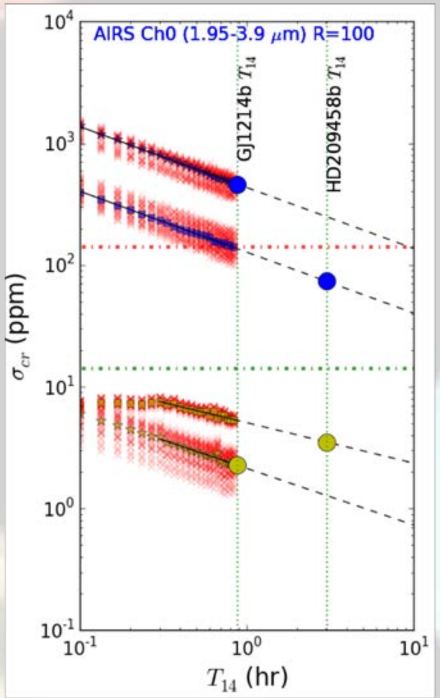
Several phenomena, several time scales

For a solar type star	
Phenomenon	Time scale
Granulation and pulsations	5-20 min
Spots, plages,…	2-50 days ←
Cycles	3-30 yrs

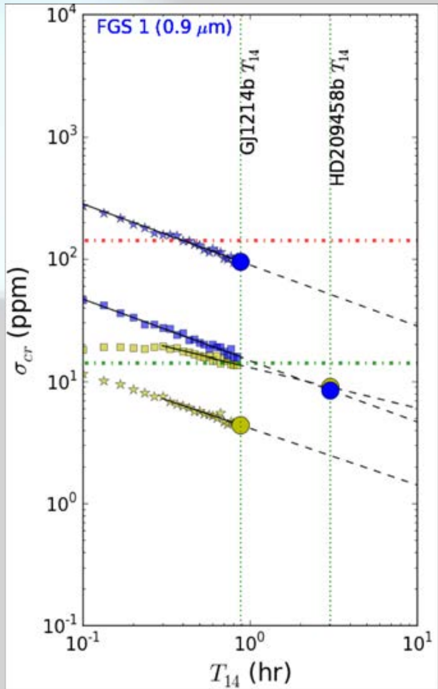
- A problem common to any planetary observations (detection and characterization)

Pulsations and granulation



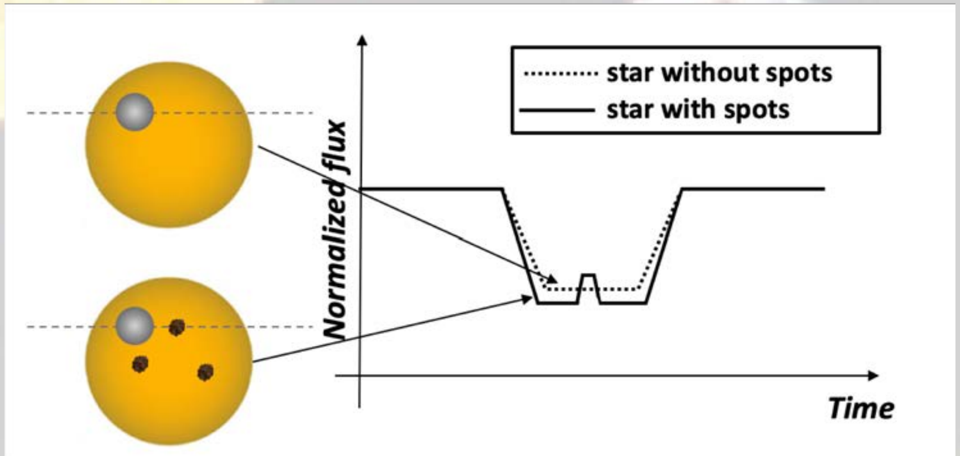


- GJ 1214 (M4.5V)
- HD 209458 (G0V)



Sarkar et al. 2018

We need to analyse in detail the spot (plage)-activity

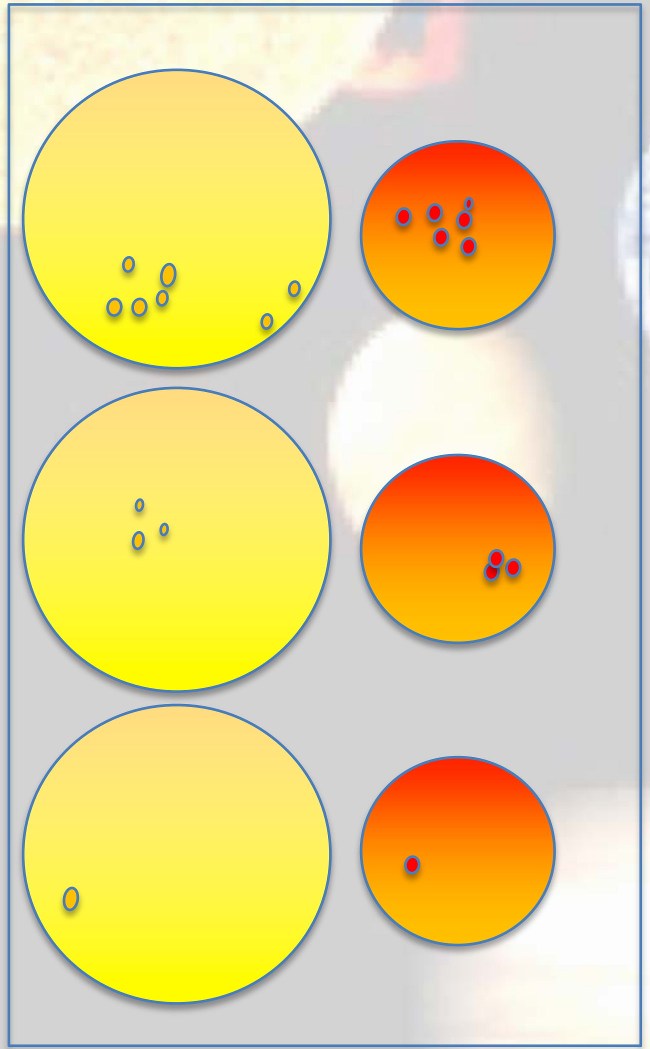


The effect is wavelength dependent
If not properly accounted for, it affects the atmospheric measurements

Several methods have been devised from A0 phase to correct the ARIEL spectra

Simultaneous ground-based observations *(Perger talk)*
Post-processing ARIEL spectra
Gaussian Processes modeling of stellar activity
Decorrelation techniques based on machine learning
…

Post-processing based on ARIEL data



STARS: G0, K0, M0

GRID: ***(f, T_{sp})***

$$F_\lambda' = (1 - f)\times F_\lambda(T_*) + f\times F_\lambda(T_{sp})$$

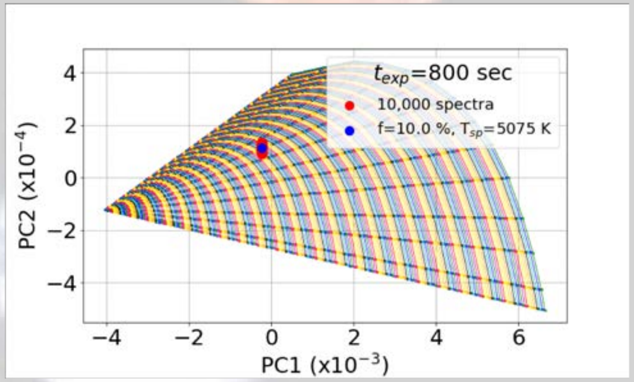
ASSUMPTIONS:

- **Variations in optical band are dominated by stellar activity (here λ < 1.95μ)**
- **The atmospheric signal is concentrated in NIR**

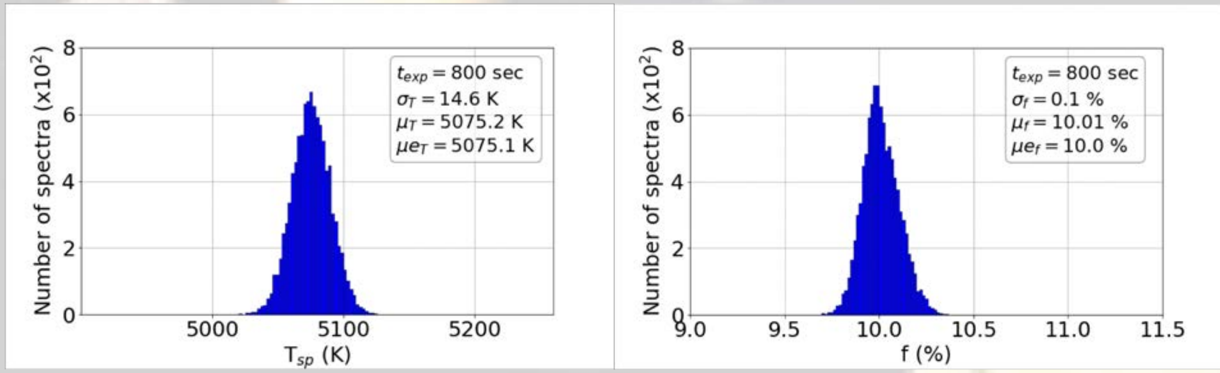
See Poster of Cracchiolo

Post-processing based on ARIEL data

G0 dwarf
Teff=6075
V=9
10000 simulations with ArielRad
(*Mugnai et al.*)

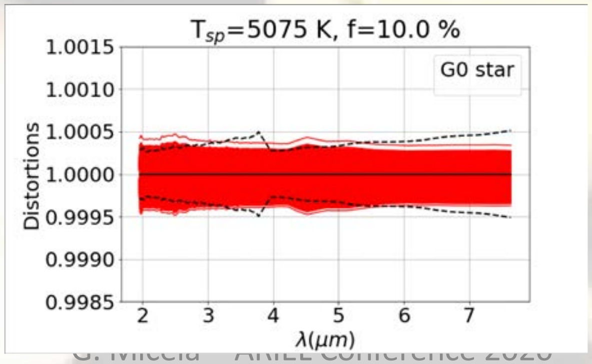


1) Generation of Pr Comp (λ < 1.95μ) and projections of the simulations on the first two component space



2) Derivation of Tspot and filling factor

3) Infrared expected stellar spectrum compared with photon noise



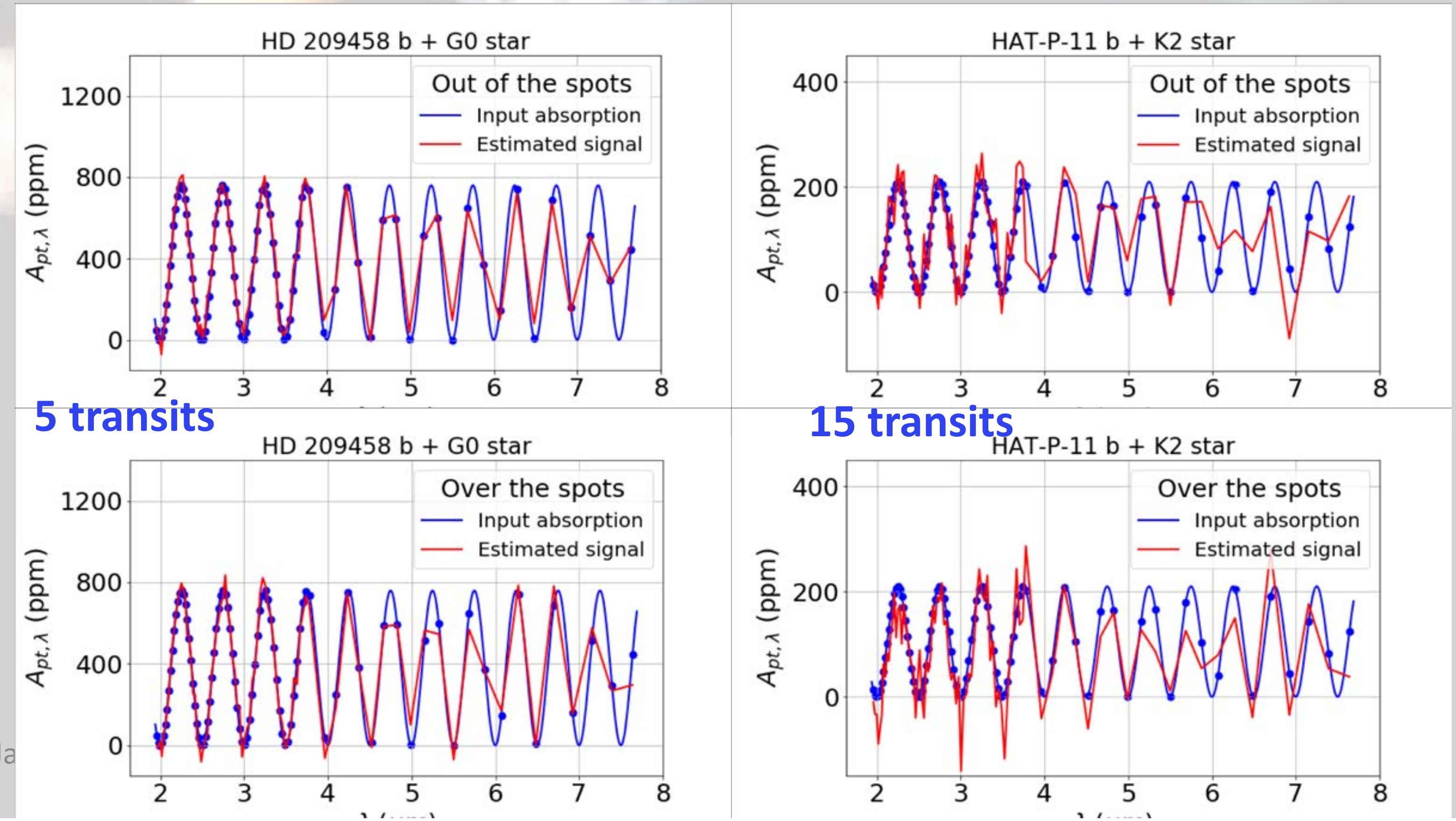
Post-processing based on ARIEL data

Injecting a ***«spectrum»*** of the planetary atmospheres

TRANSIT OUT AND OVER THE SPOTS

Planet	Type Planet	*Rpt*(*RJ*)	*Mpt*(*MJ*)	*d*(*AU*)
HD 209458 b	Hot Jupiter	1.38	0.69	4.75×10^{-2}
HAT-P-11 b	Hot Neptune	0.389	0.074	5.3×10^{-2}

See Poster of Cracchiolo



STARSIM

Herrero et al. (2013), Rosich et al. (in prep.)

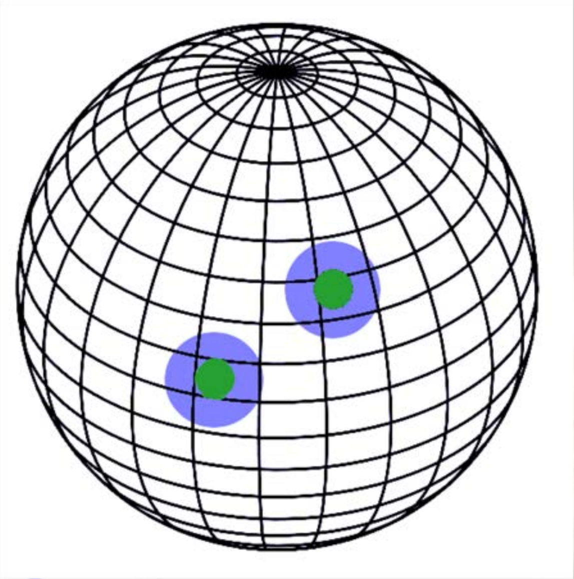
(See Perger talk)

Forward problem

$$\mathbf{X} = \mathsf{F}(\mathcal{S}, \theta) + \epsilon$$

Inverse problem

$$\hat{\mathcal{S}}_\theta = \mathsf{F}^{-1}(\mathbf{X}, \theta)$$



Time-series data X

Activity model F

Set of stellar parameters θ

- Teff, Prot, log(g), [Fe/H], i
- Differential rotation
- facula-to-spot Q

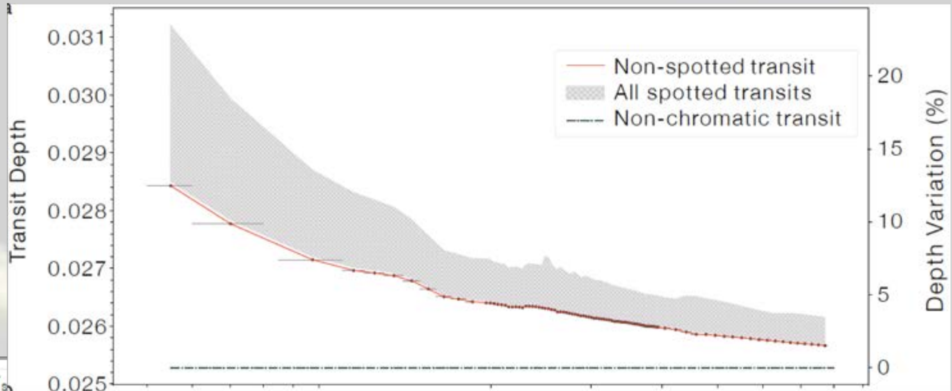
Grid of surface elements **S**

- inmaculate photosphere Tph
- groups of circular **spots** Tsp
- concentric bright **facula** Tfac
- t, dt, r, position
- Doppler shifts
- **convective shifts**
- **limb darkening/brightening**
- **projection effects**

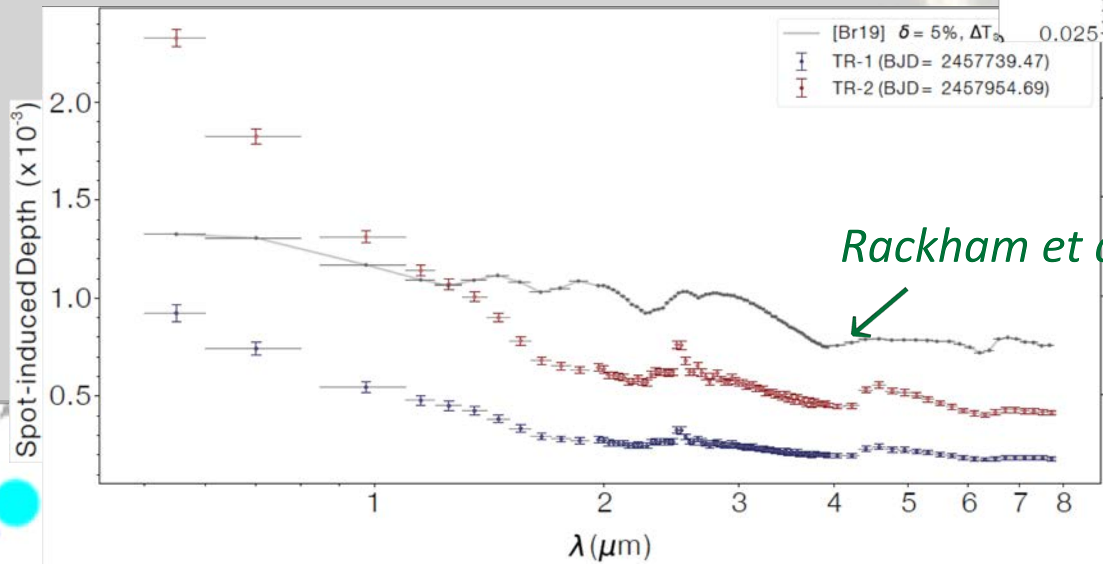
STARSIMs capabilities

<u>**Contemporaneous** multiband photometry + STARSIM</u>

- independend spot filling factor and temperature contrast
- absolute filling factors
- precise stellar activity model
- correct for activity by factor 5 - 30



Rosich et al. (in prep.)



Rackham et al. (2018, 2019)

Summary

- Stellar activity determines the planet environment and is a key element driving the planetary evolution
- Effects evolve with the stellar life
- In extreme cases, feedback on the star is possible
- **We are able of dealing with planets around active stars**
- **We will learn a lot on stellar activity**