The impact of stellar activity and winds on the evolution of exoplanets

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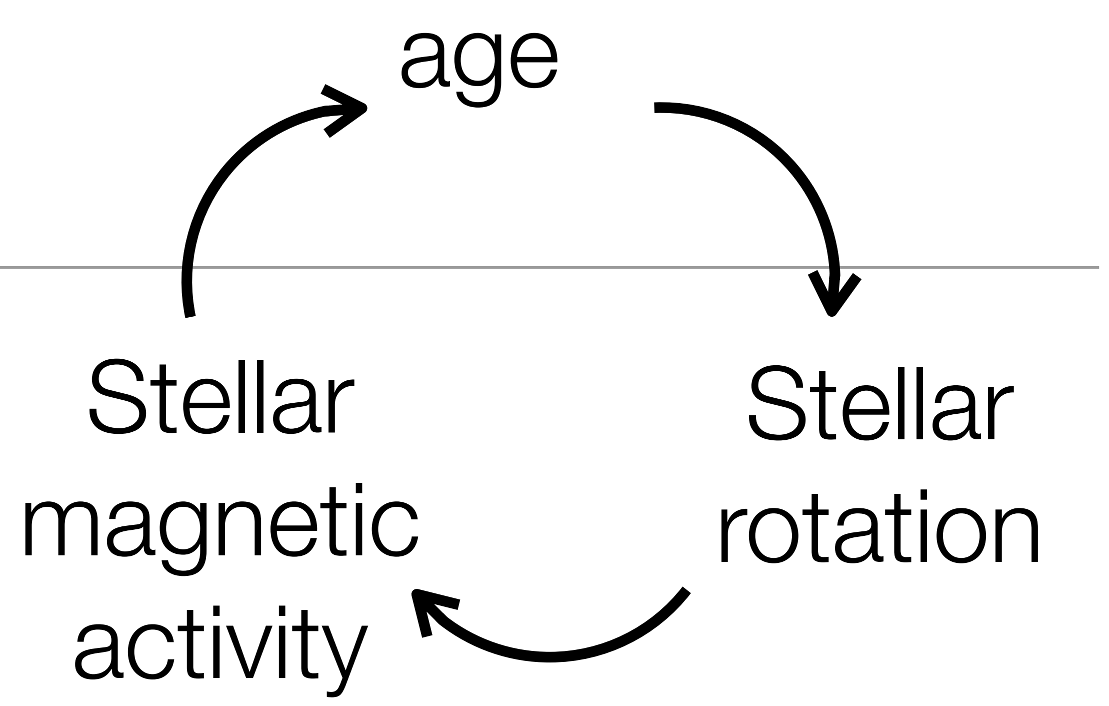
erc

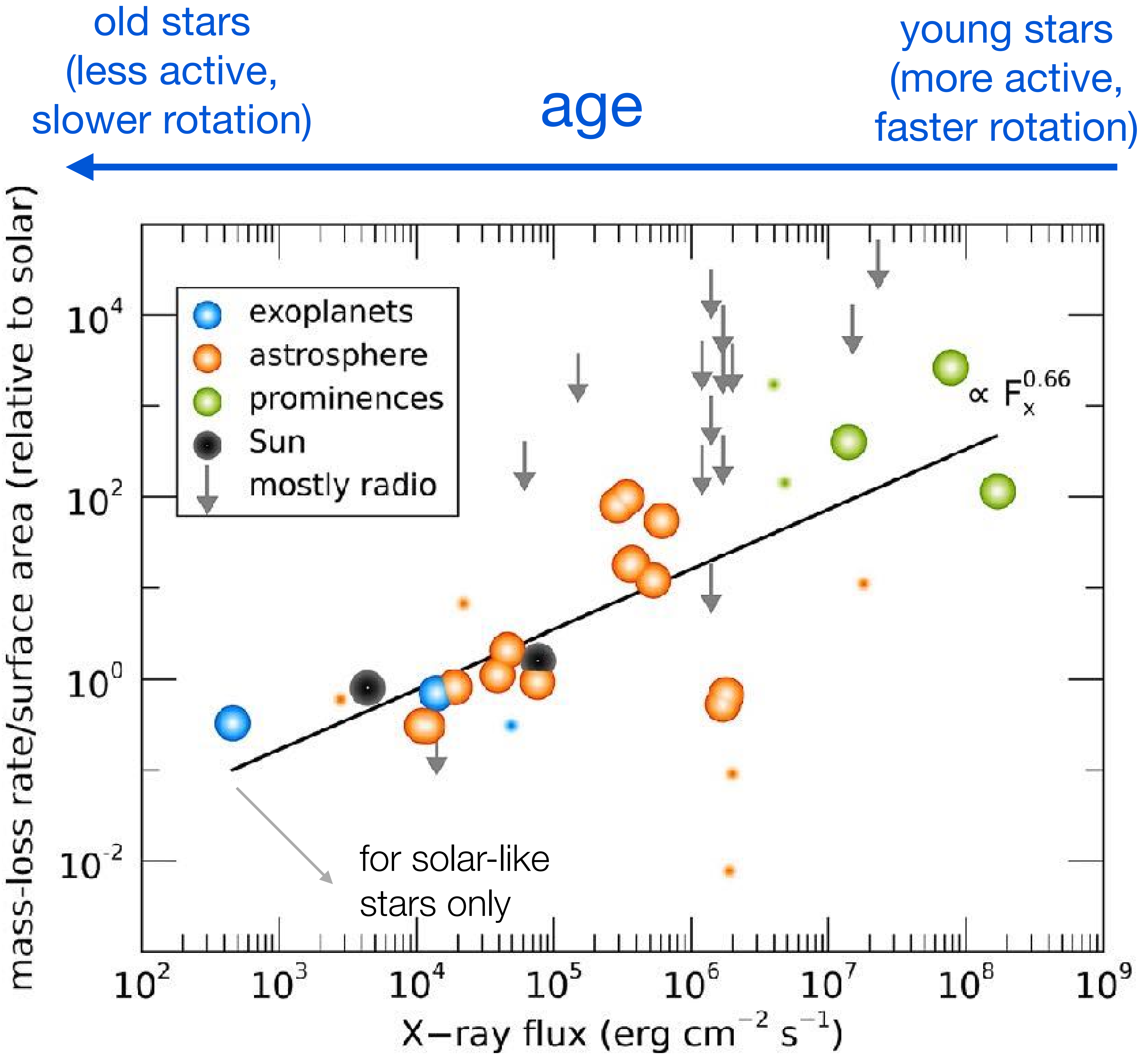
SCOSTEP
Scientific Committee on Solar-Terrestrial Physics

PRESTO


particles: coronal mass ejections, stellar winds, etc
radiation: flares, coronal emission, etc
Stellar activity shapes environment around planets
©KISS report on exoplanetary magnetism

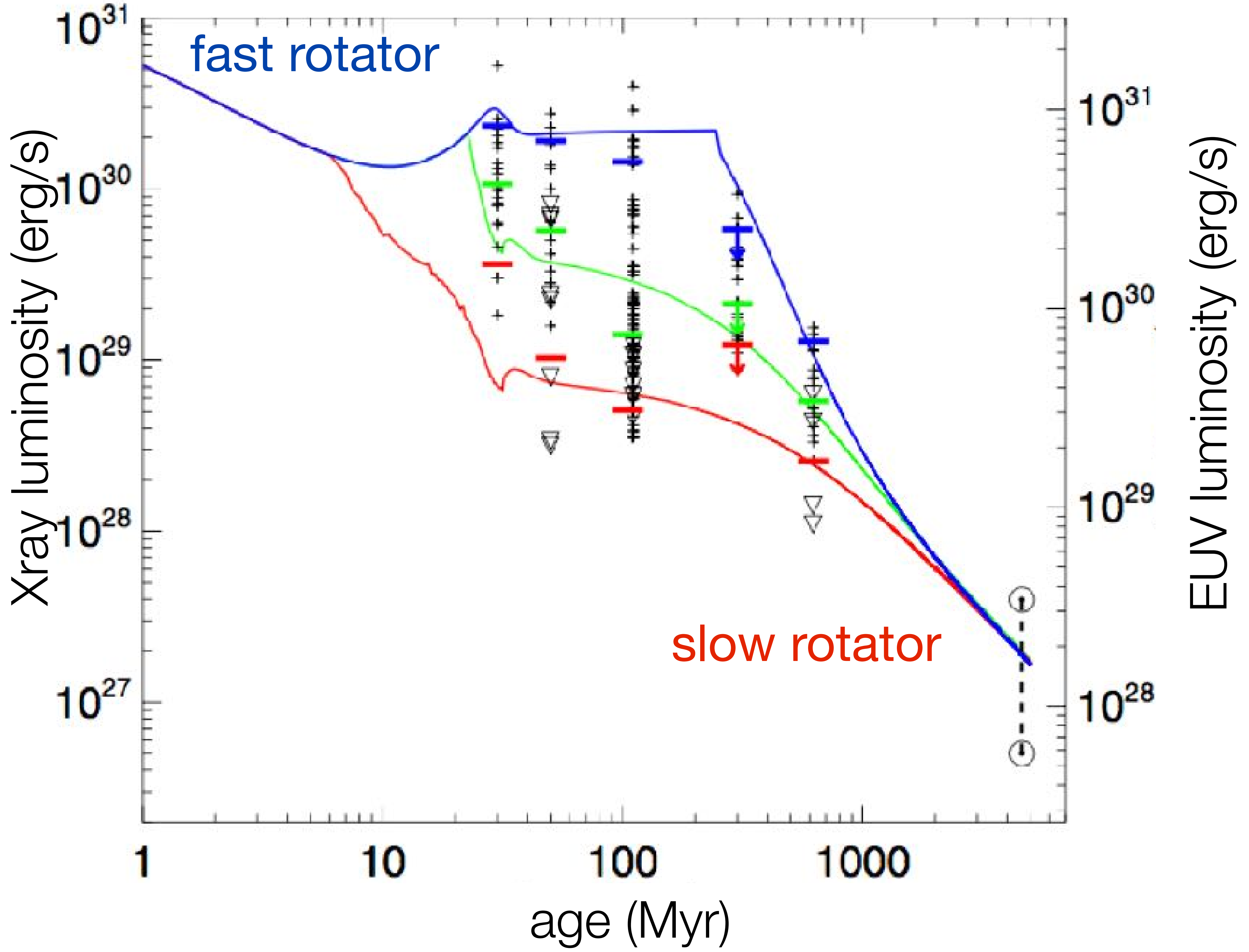
How do winds and high-E radiation evolve?





Vidotto 2021, Living Reviews in Solar Physics

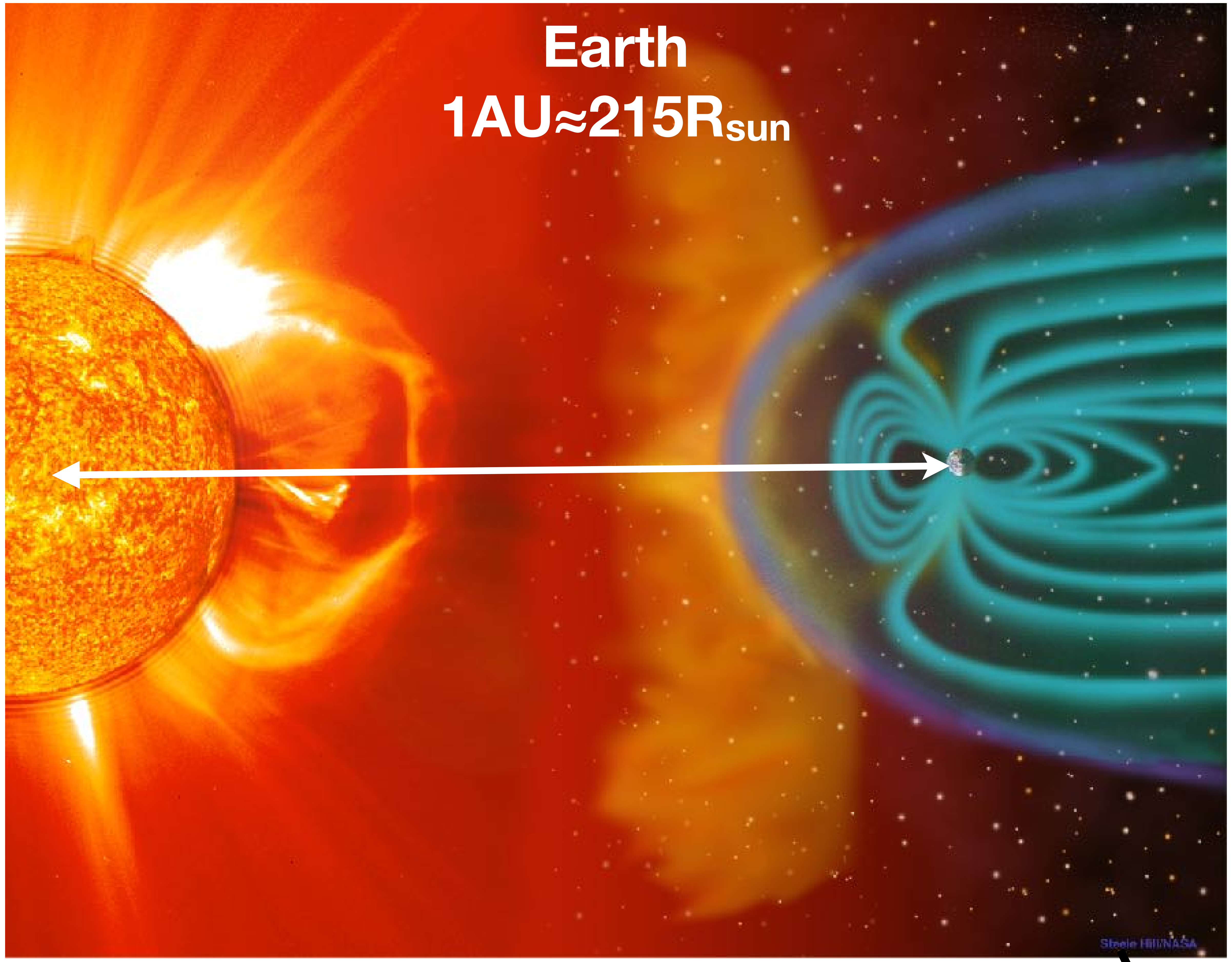
Tu et al 2015

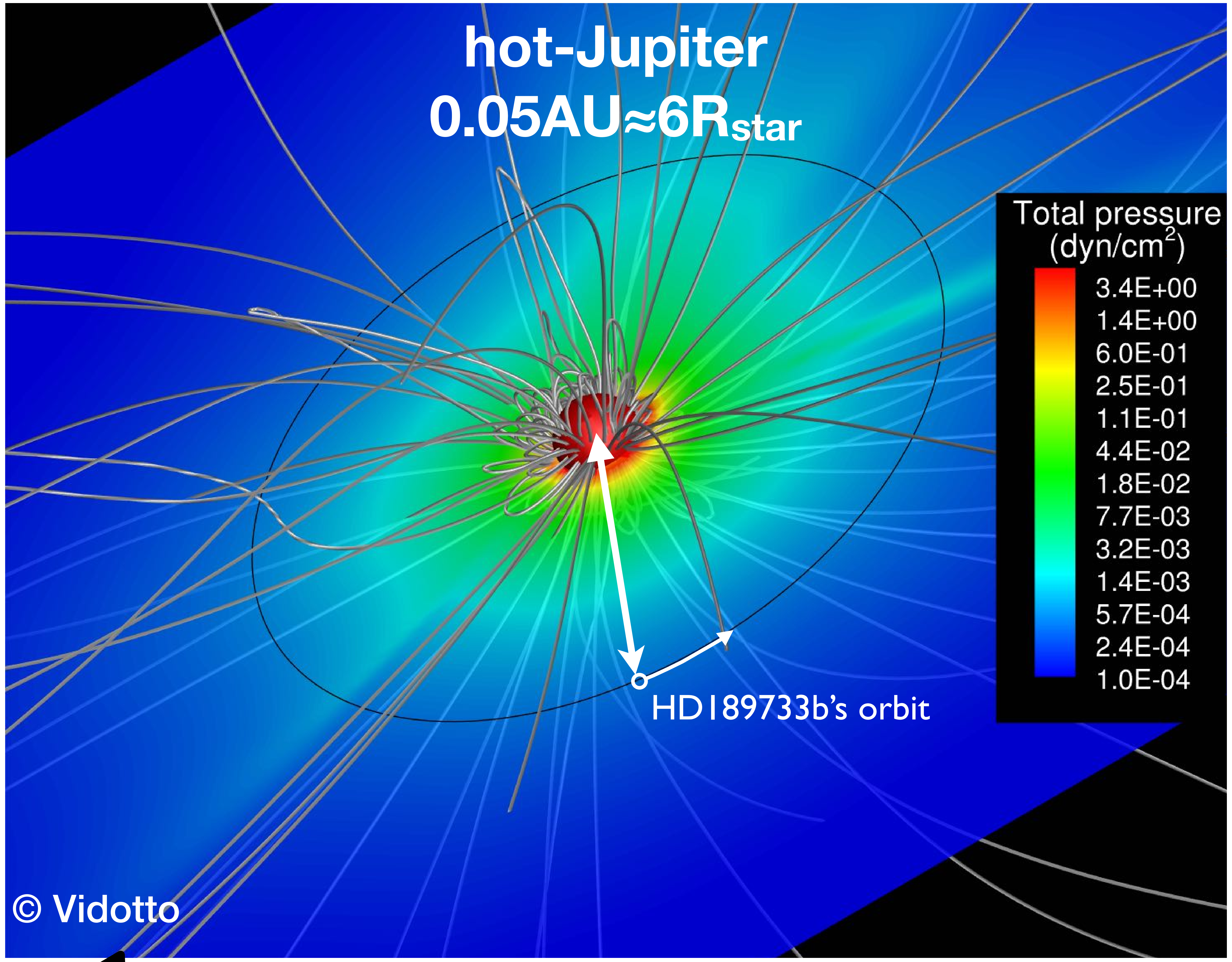


also: Ribas et al 2005, Sanz Forcada et al 2011

Lesson #1: the younger the star is, in general, the higher its rotation rate and activity (e.g., high-E radiation)

Interplanetary medium: stellar wind particles + magnetic fields





Close-in planets experience overall

- higher density external environment
- higher ambient magnetic fields
- higher radiative flux

Lesson #2: the closer the planet is from the star, in general, the stronger the interaction with particles and radiation

Outline

1 Stellar high-E effects on evolution of planetary atmospheres

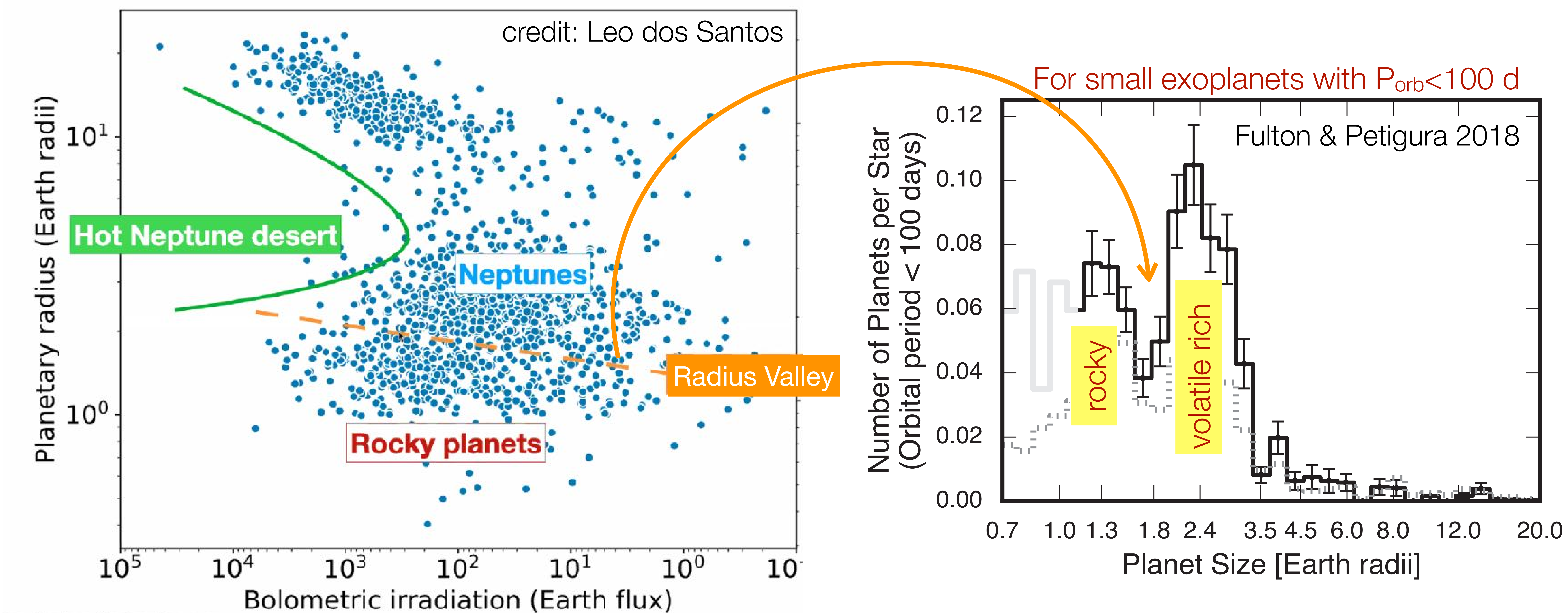
2 Stellar wind and high-E (counter)effects on planetary atmospheres

©Garlick/U.of Warwick

1 Stellar high-E effects on evolution of planetary atmospheres

Very dense outflows:
hydrodynamic escape
(*EUV flux is also important for non-thermal escape)

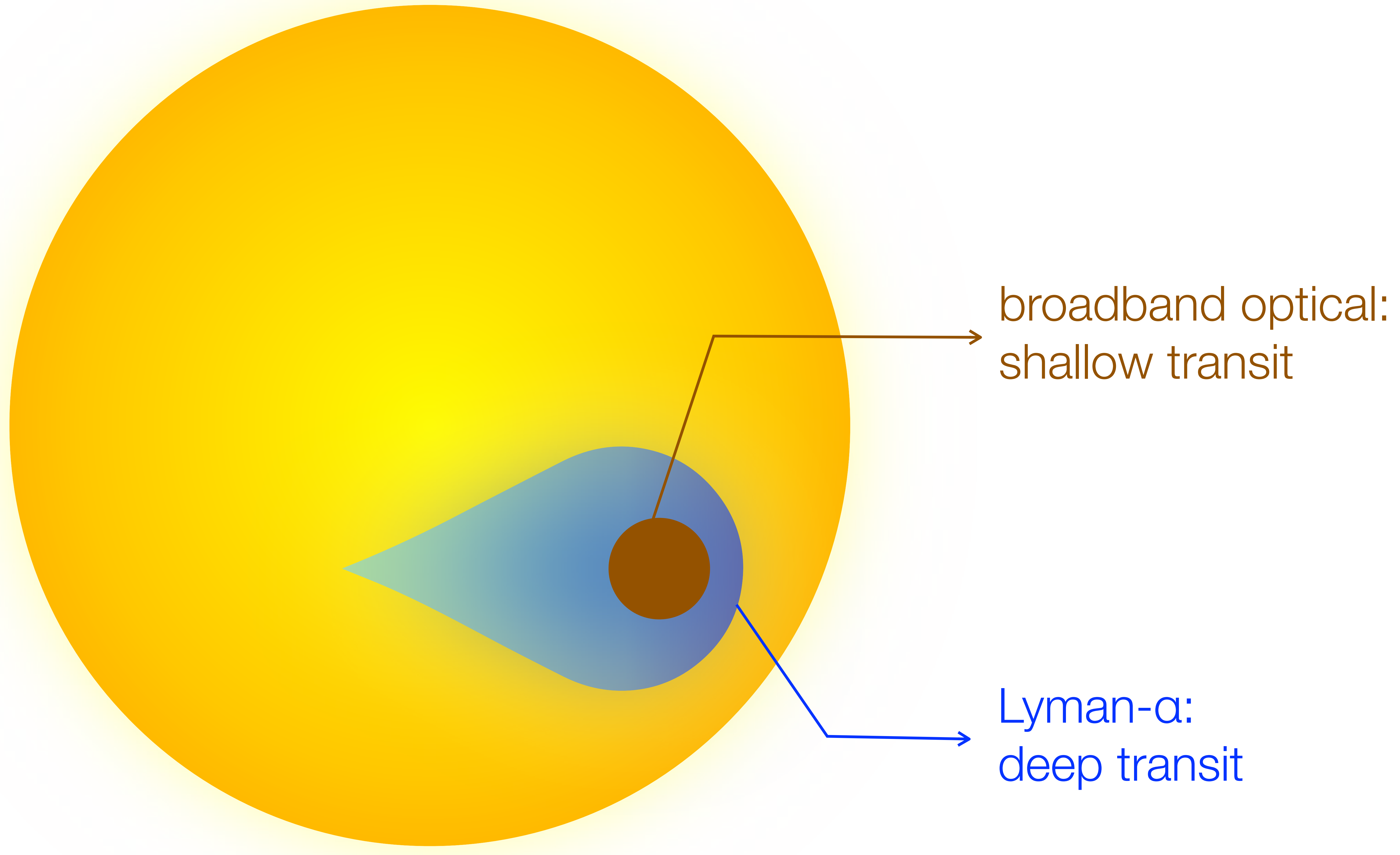
Indirect detection of evaporation through exoplanet population studies



<u>Possible interpretation:</u>

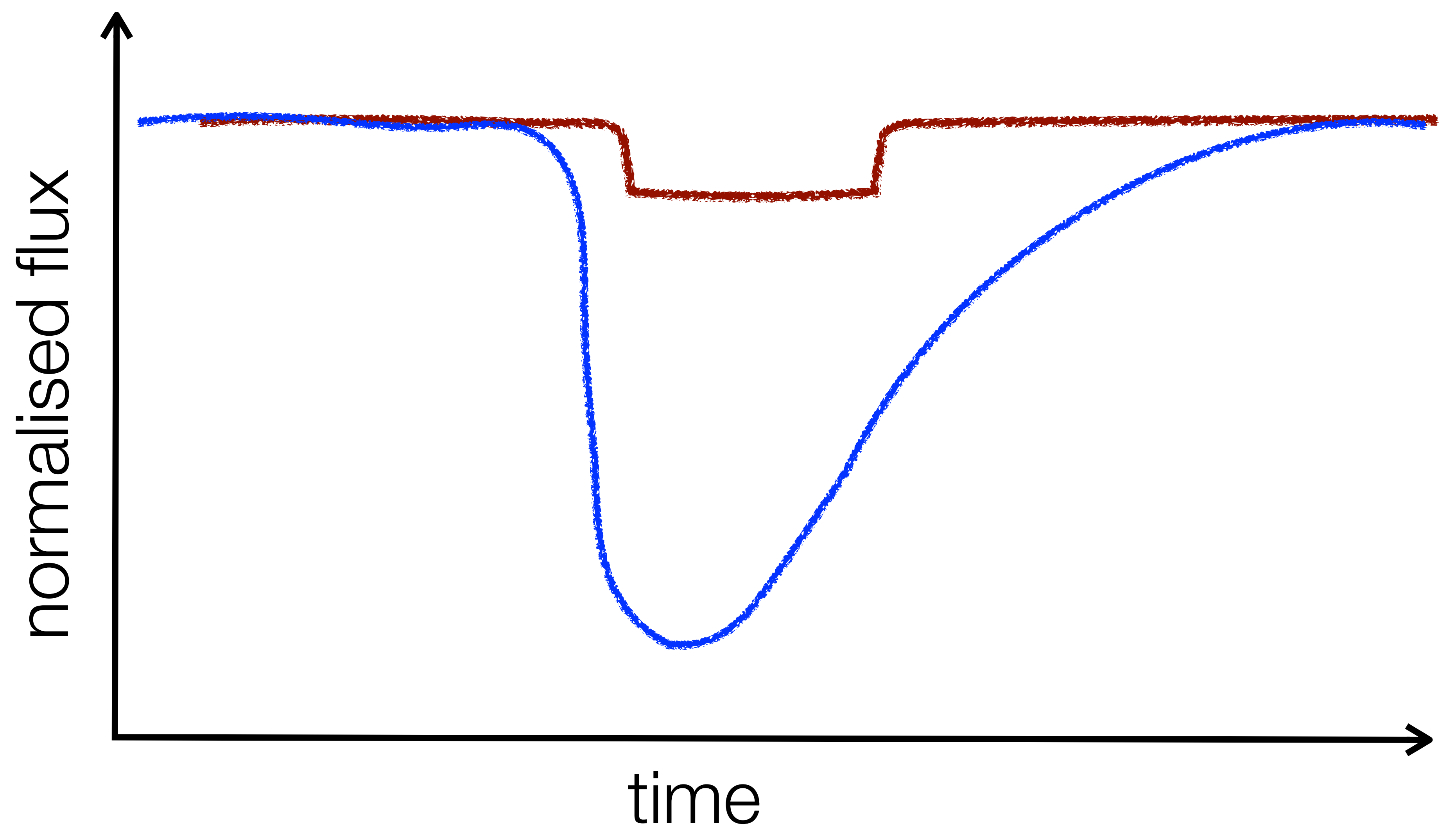
- Planets born as big, volatile rich planets
- Too much evaporation → atmosphere is lost very quickly: Big planets become small rocky cores

Directly detecting (evaporating) atmospheres of exoplanets



Transmission spectroscopy

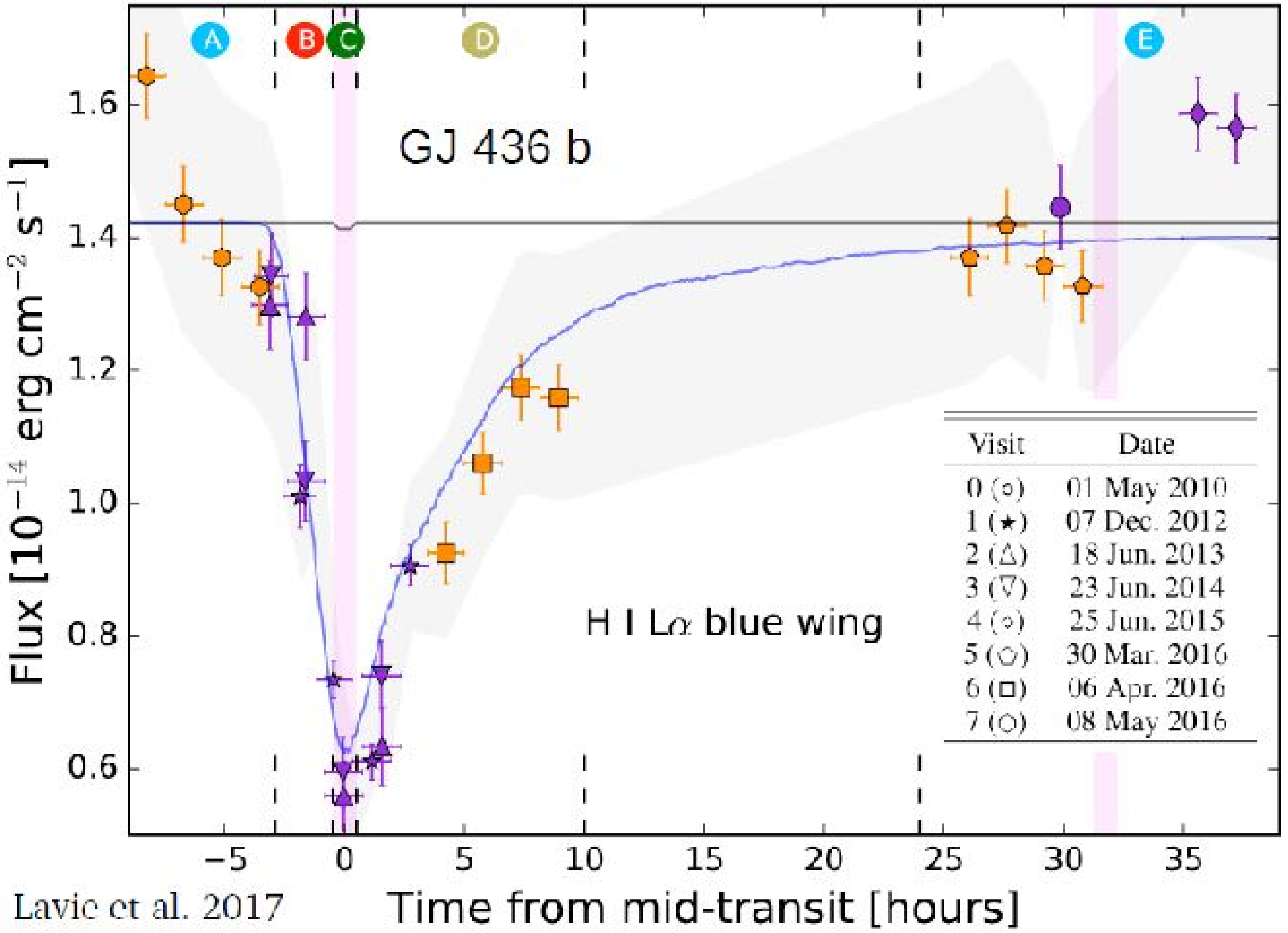
During transit, stellar radiation is transmitted through the exoplanet's atmosphere



1. Take a spectrum of the star at out-of-transit time
2. Take a spectrum of the star during transit
3. Divide the two to find % of absorption by the planetary atmosphere

Observations of escaping atmospheres

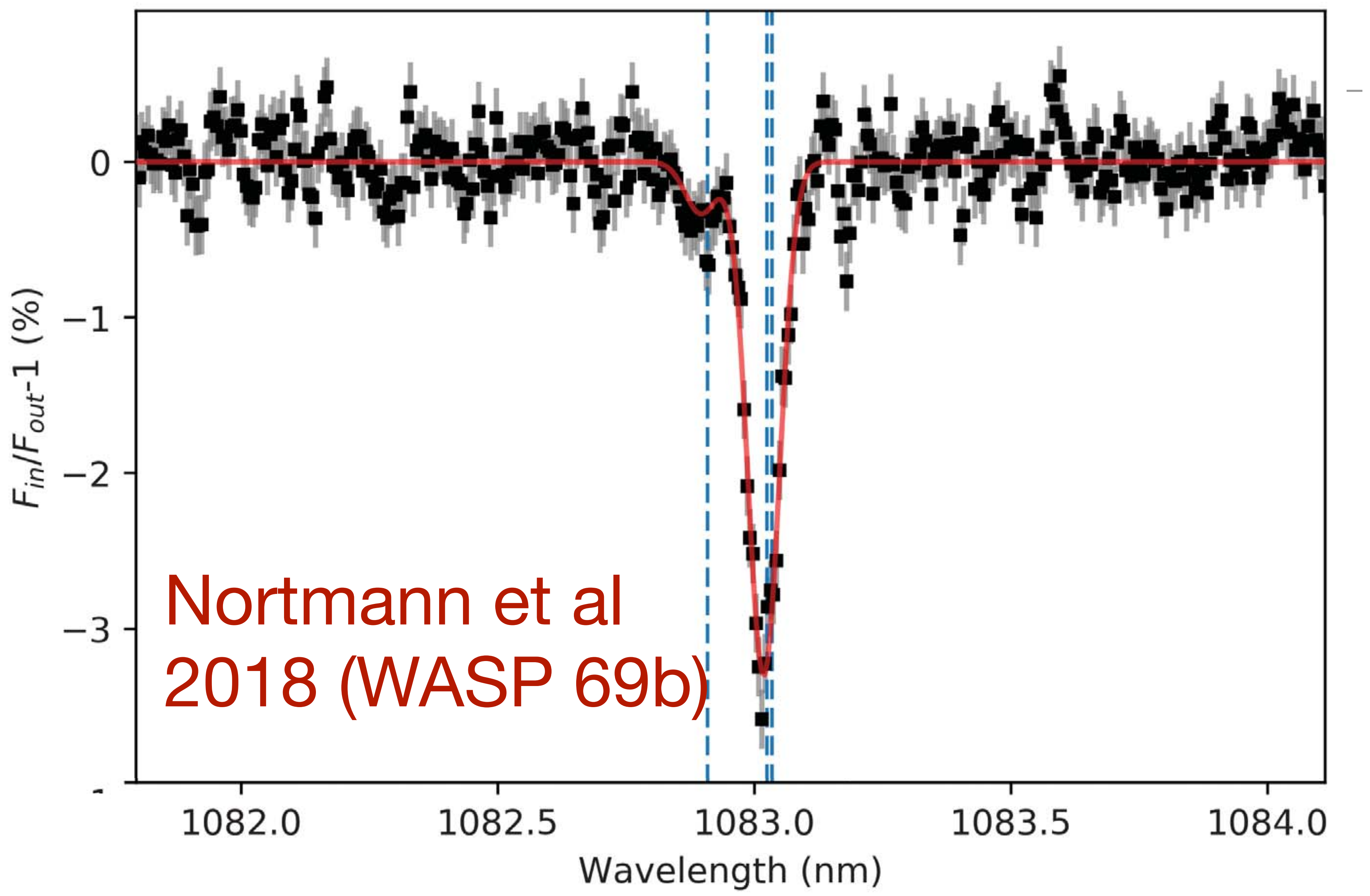
Ly-alpha observations



Lavie et al 2017 (GJ436b)

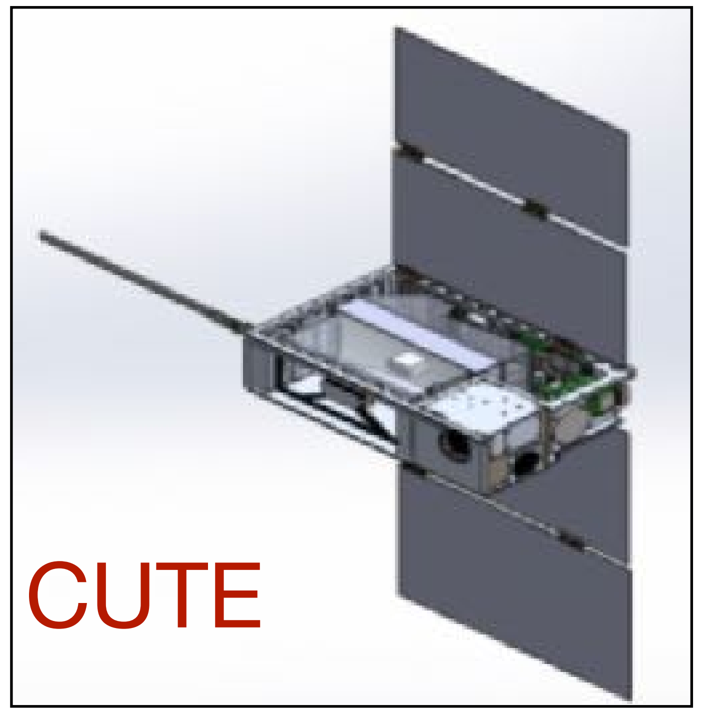
also: Kulow et al 2014; Ehrenreich et al 2015

HeI observations

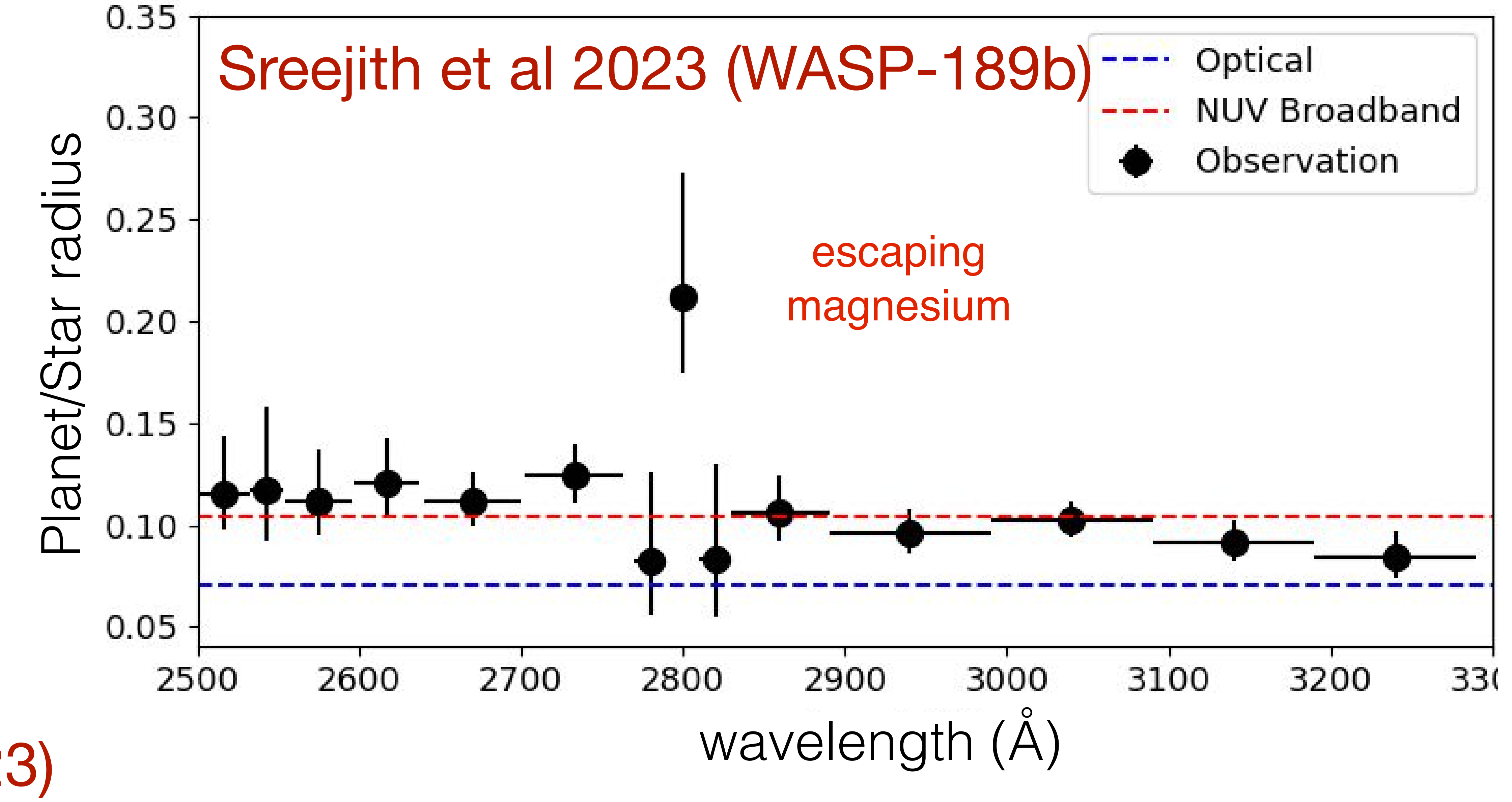


also: Spake et al 2018; Allart et al 2019

Observations of escaping metals



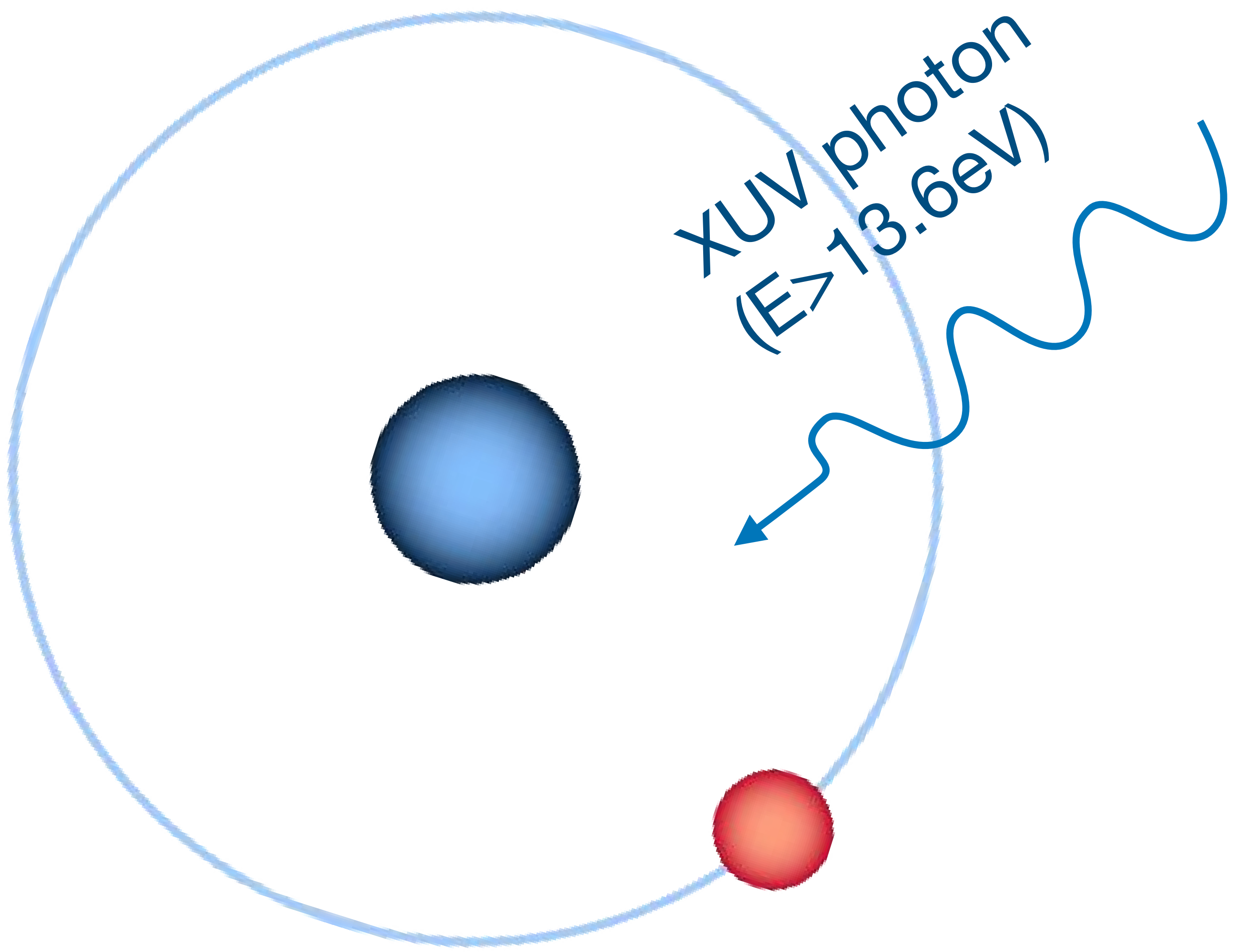
France et al (2023)



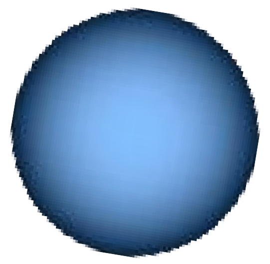
also: Fossati et al 2010,
Cubillos et al 2020

The impact of stellar activity and winds on the evolution of planets

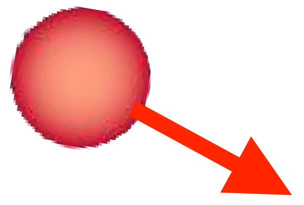
Hydrodynamic escape via photo-evaporation: how does it happen?



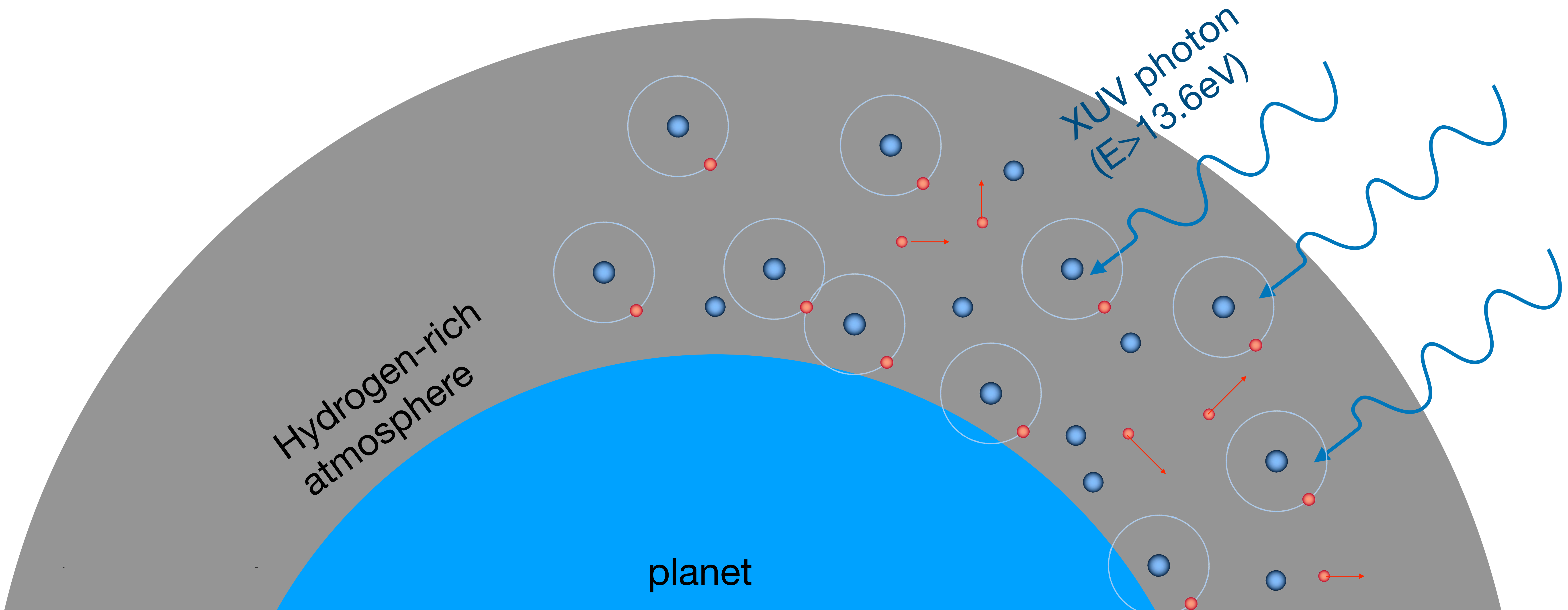
Ionises Hydrogen



uses 13.6eV…



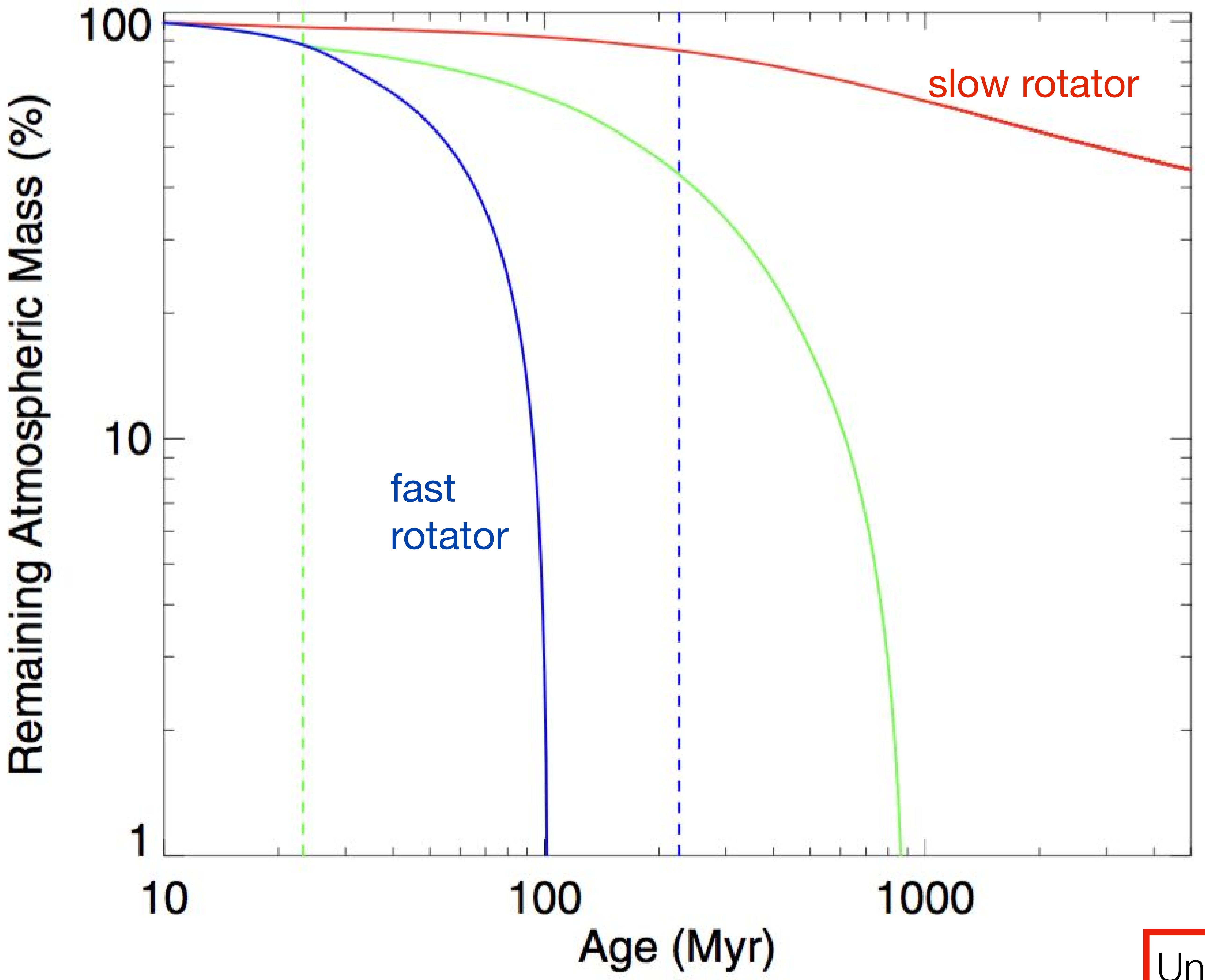
… and excess energy converted into thermal motions



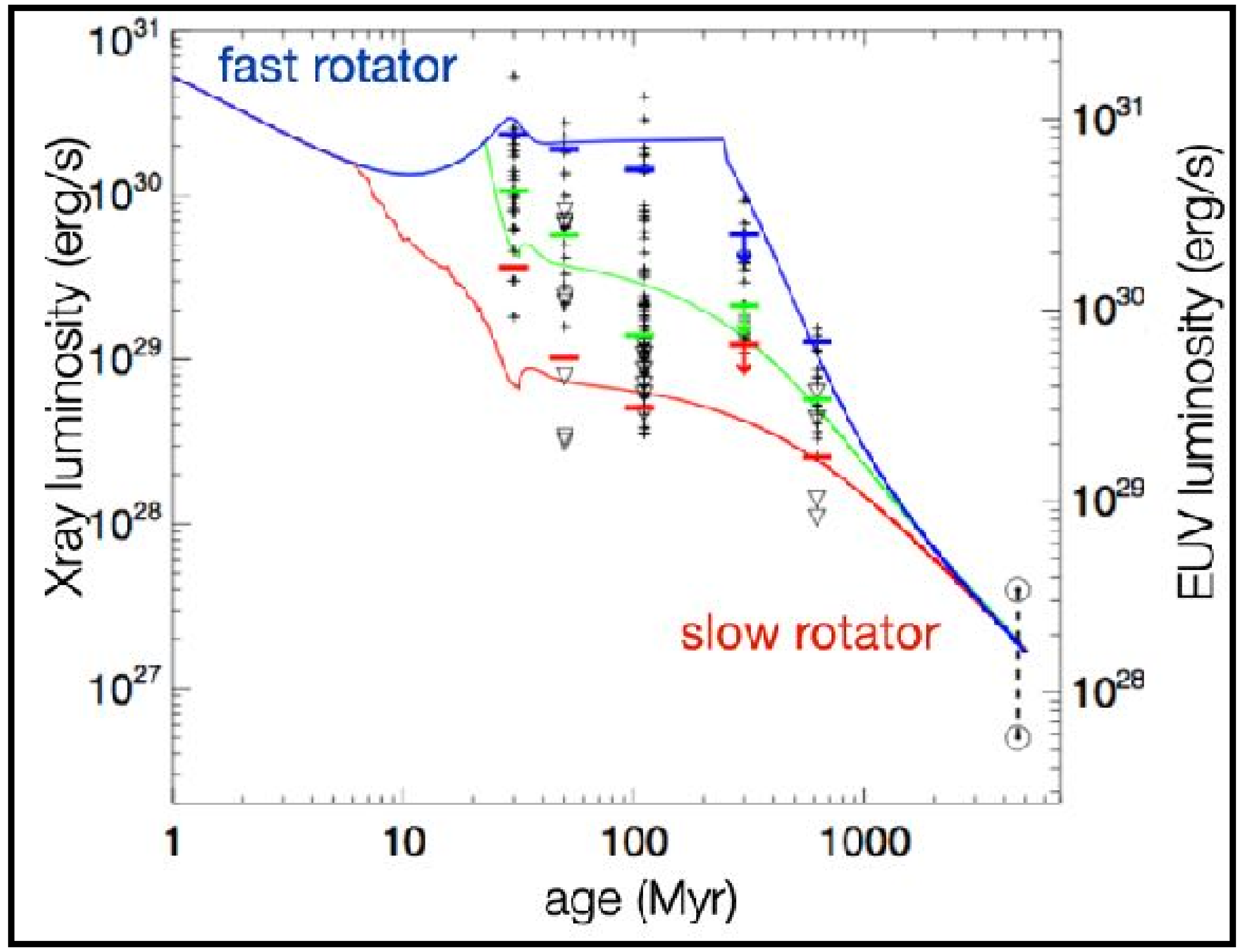
Outcome: increase atmospheric temperature → atmosphere "expands" & more easily evaporates

Survival of atmospheres depend on the XUV history of the host star

Atmospheric evaporation of a $0.5M_\oplus$ planet @ 1au
$M_{atm,initial}=0.5\%\ M_\oplus$



Tu et al 2015

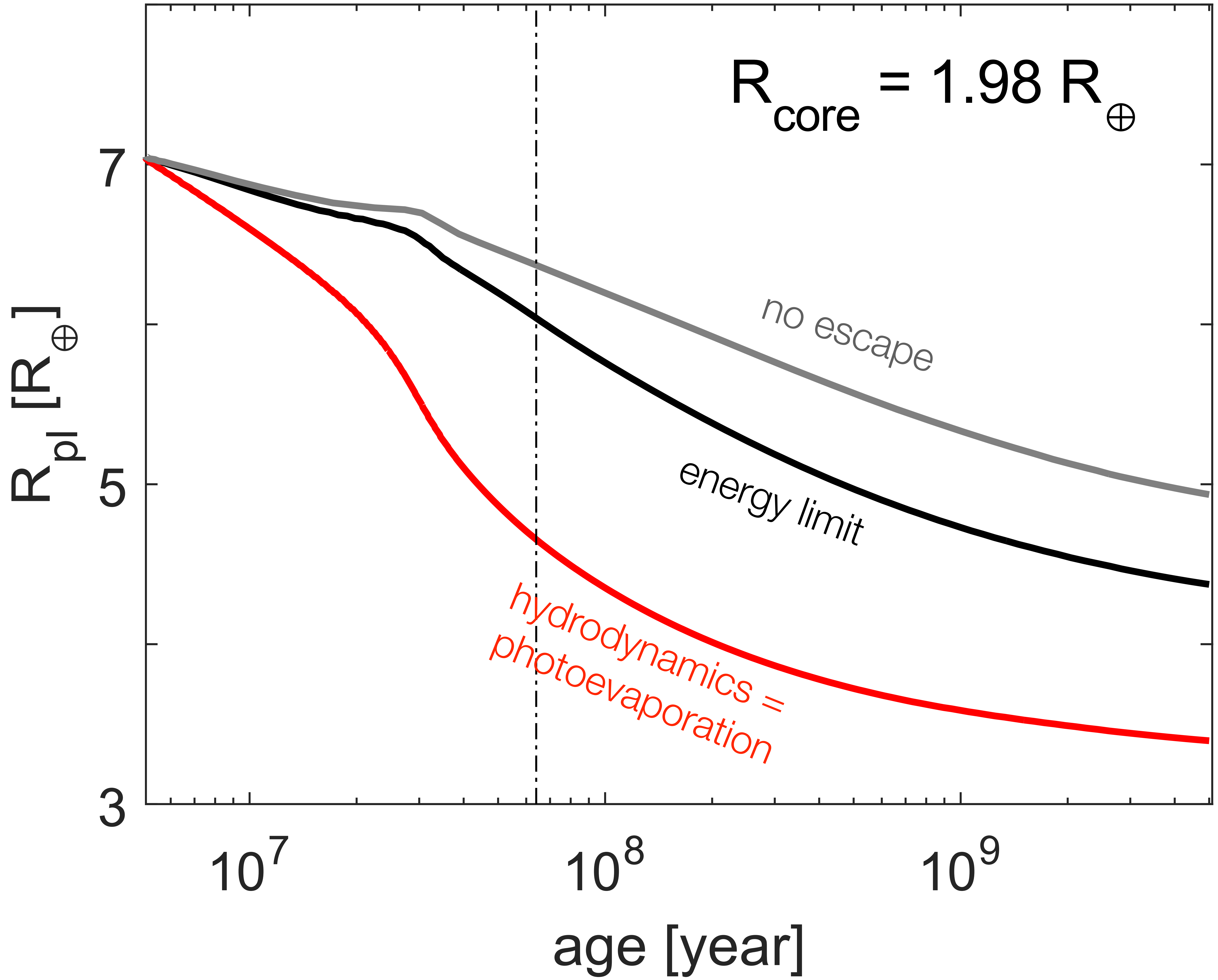


H content of the planetary atmosphere is very different if orbiting:

- slowly rotating star: 45% retention of initial atmosphere
- rapidly rotating star: entire atmosphere is lost < 100 Myr

Un-magnetised planet!

XUV history of star affects evolution of escape, which changes the internal structure of planet



Kubyshkina et al 2020
Kubyshkina & Vidotto 2021
Kubyshkina & Fossati 2022

Un-magnetised planet!

Free tools from Daria Kubyshkina!

python interpolator hydrodynamical model

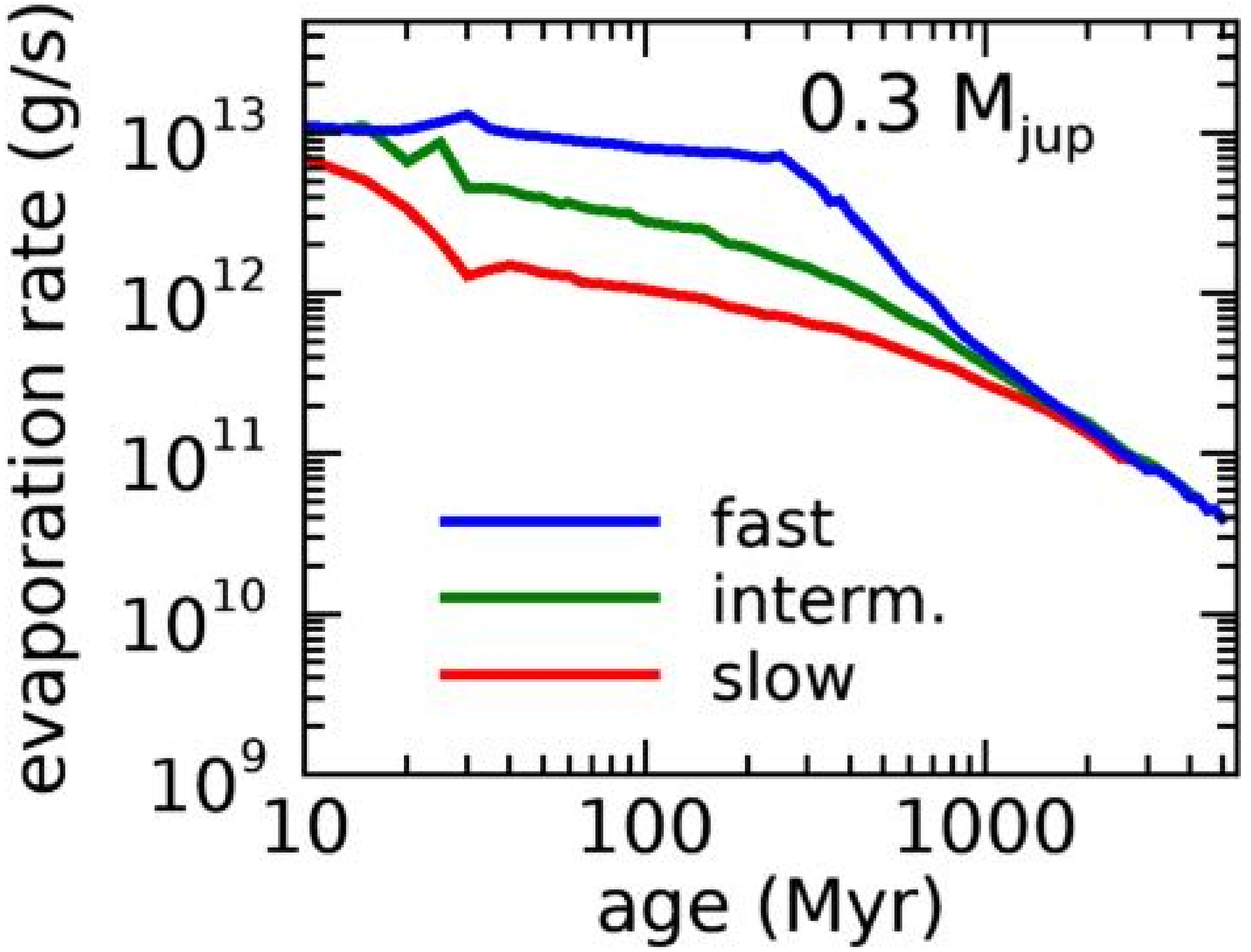
doi.org/10.5281/zenodo.4643823

MESA inlists

https://doi.org/10.5281/zenodo.4022393

Predicted observational signatures of atmospheres of close-in planets

Evaporation rates higher at young ages

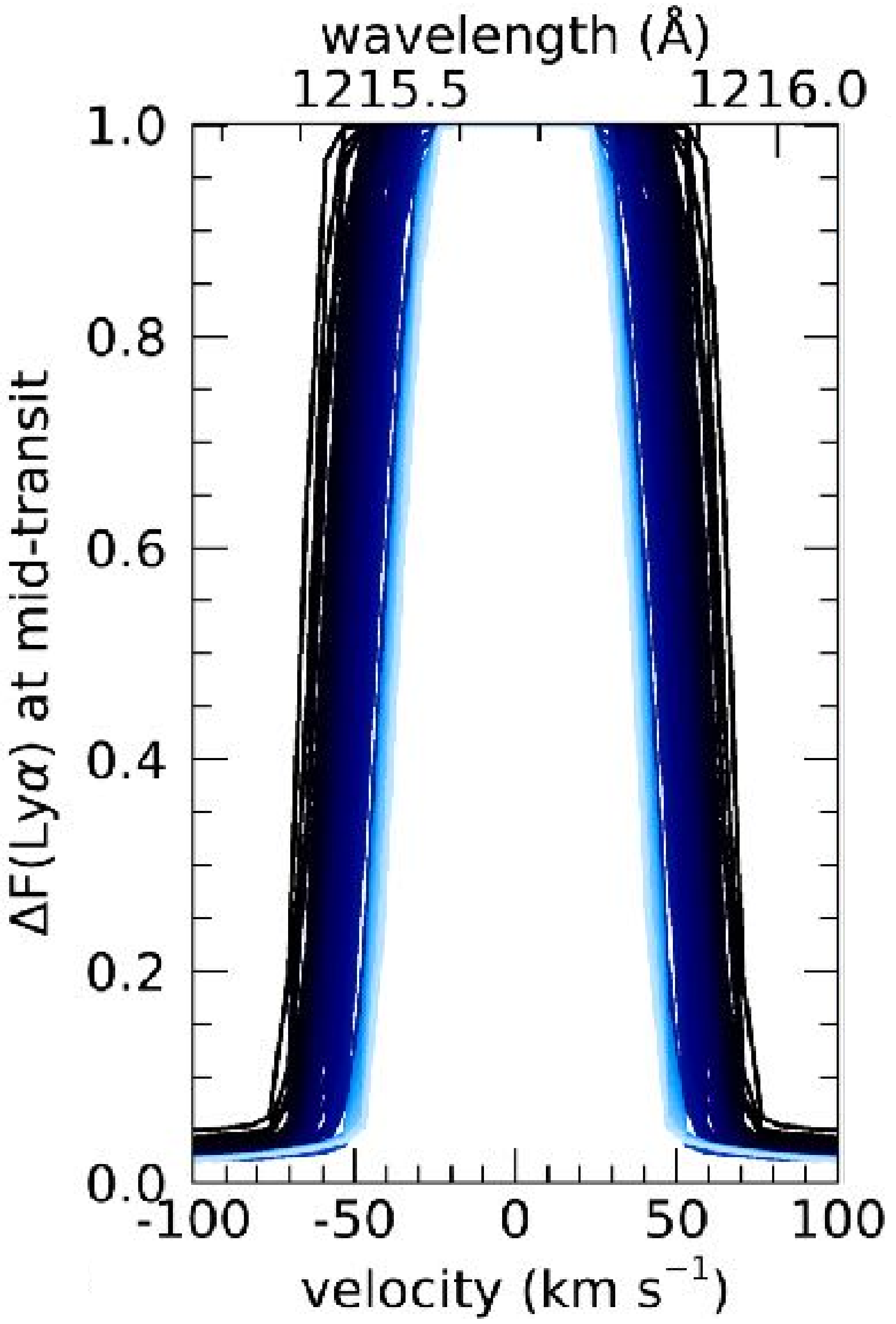


~20% mass lost through evolution

planet @ 0.045au

Allan & Vidotto 2019

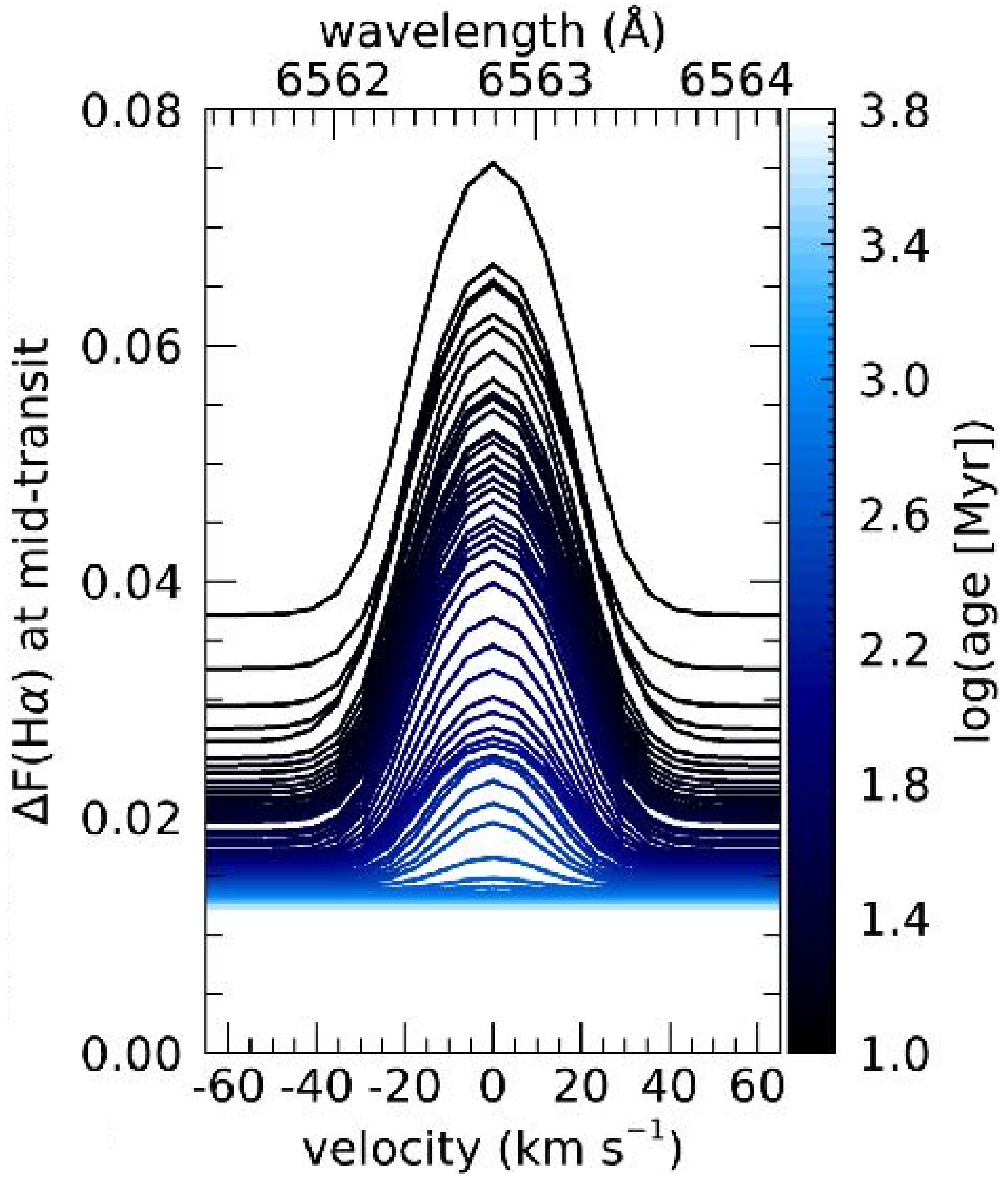
Ly-α



At younger ages:

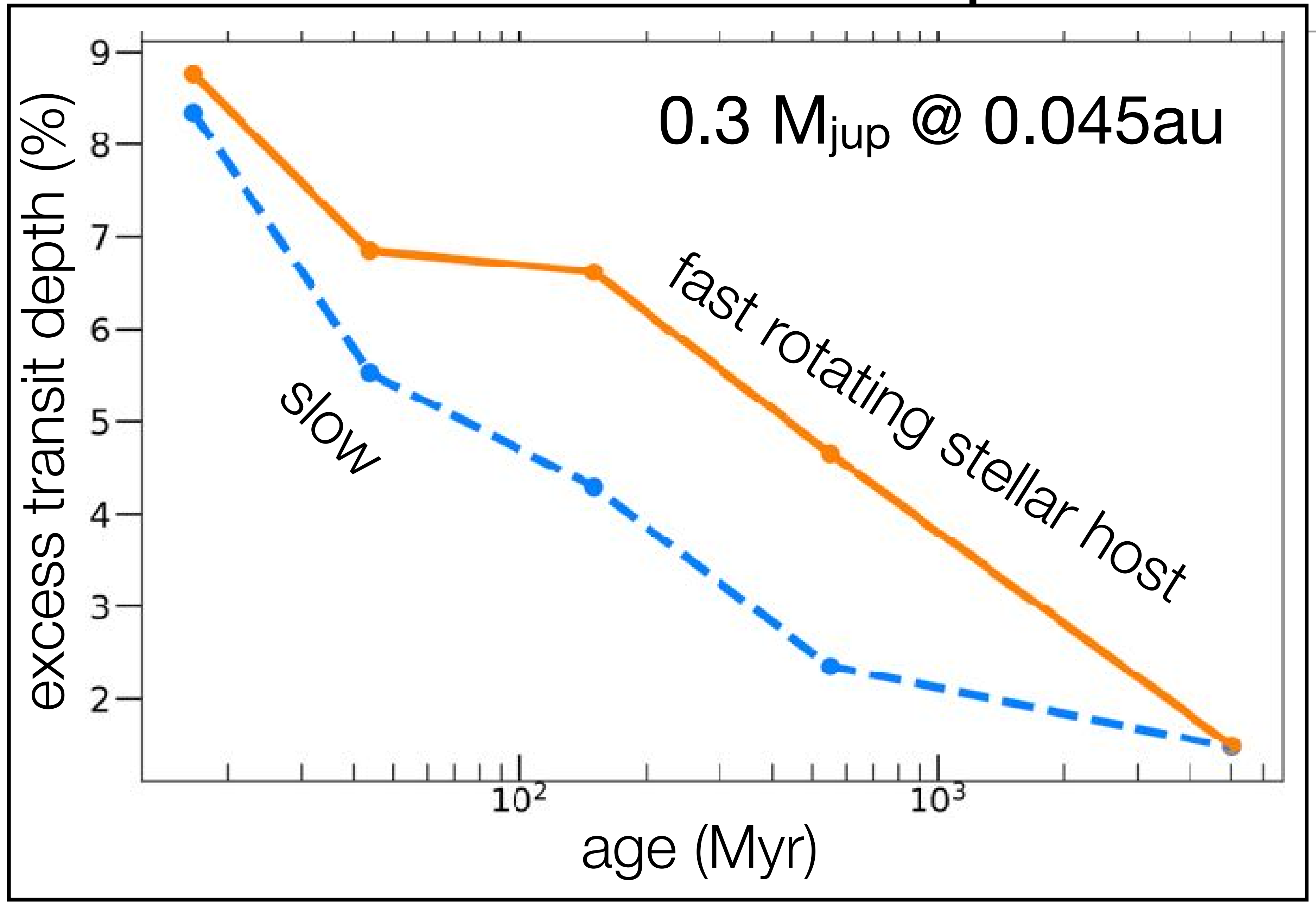
- broader (& saturated) mid-transit Lyα line at line-centre

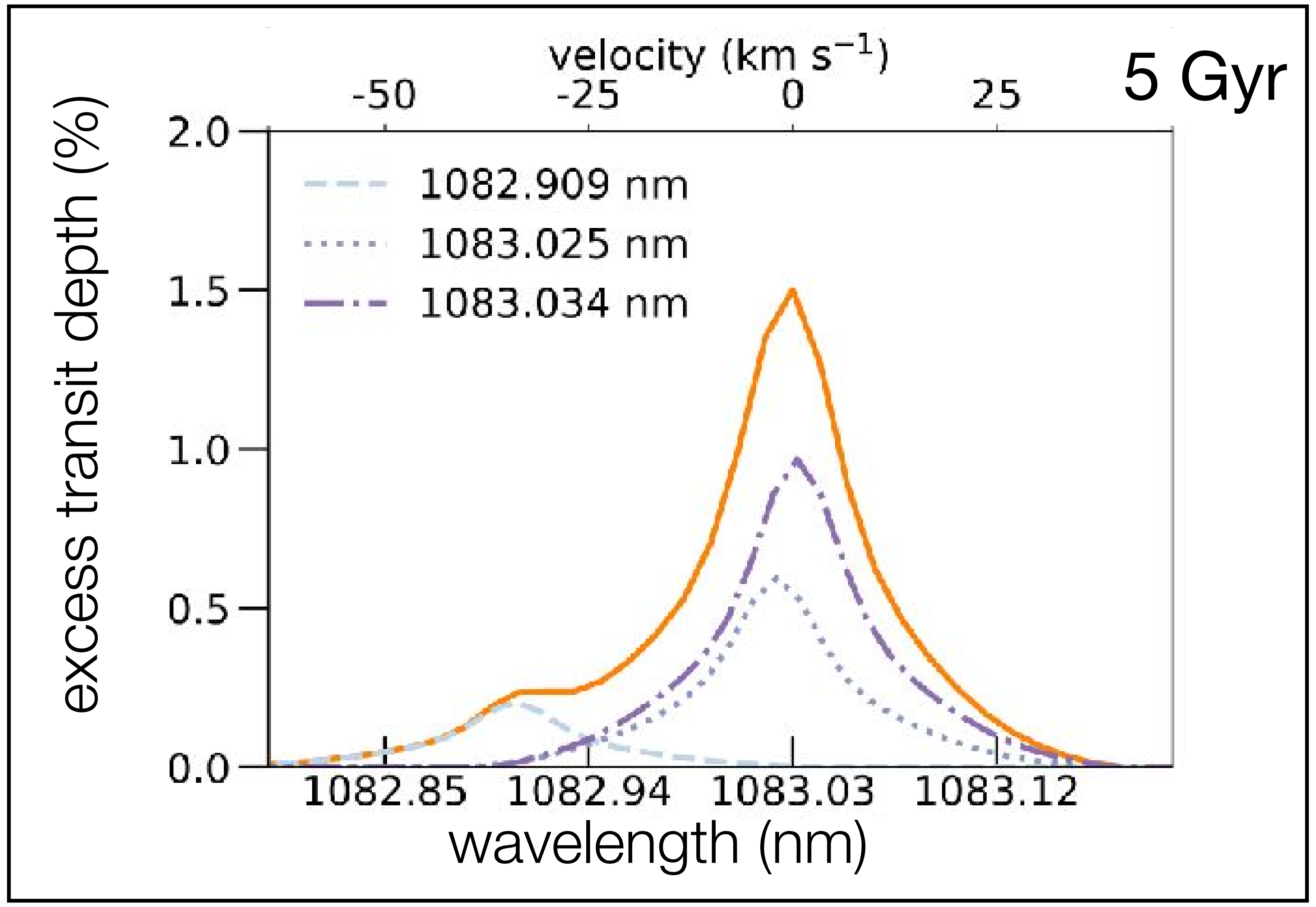
H-α



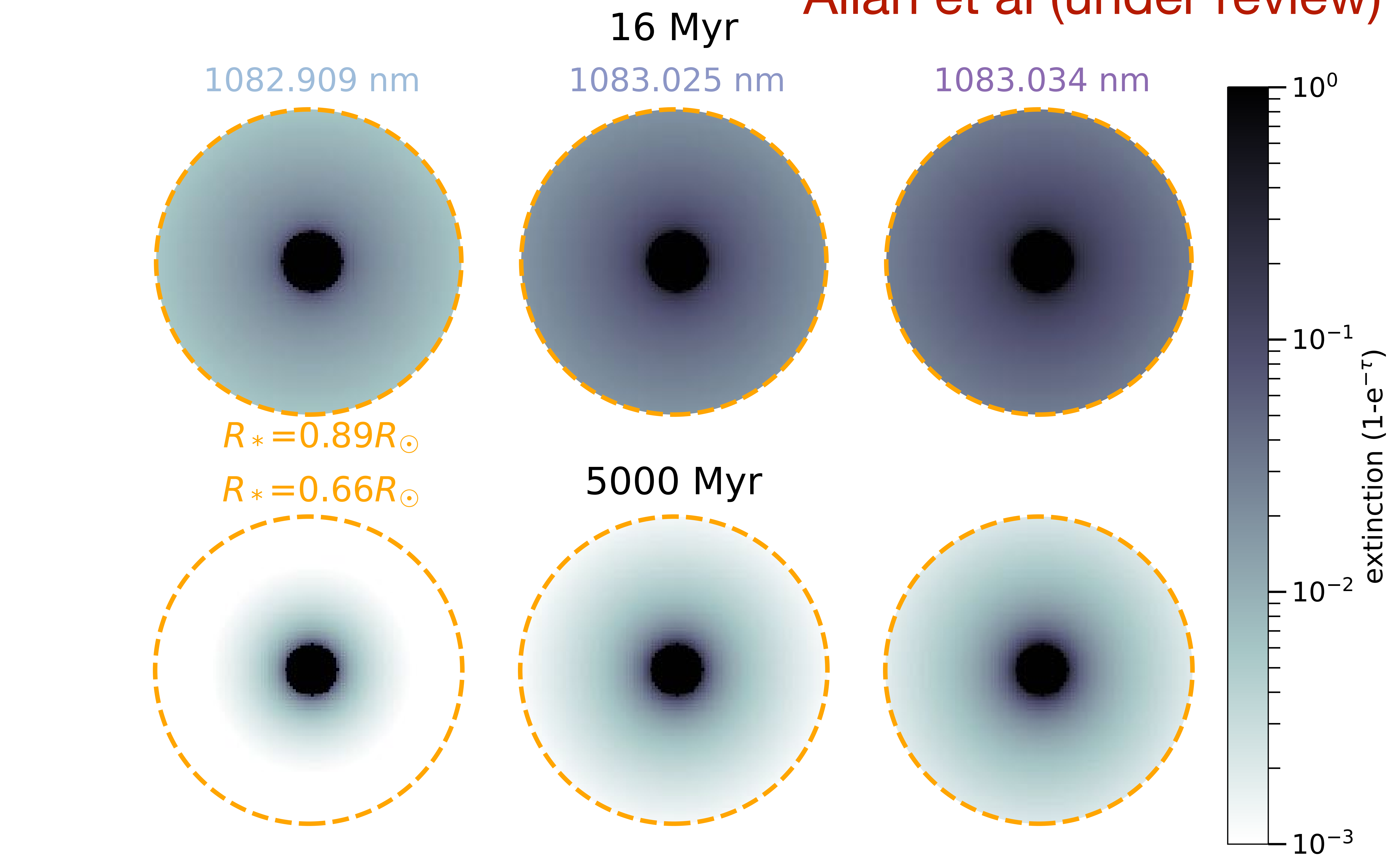
- Hα transits with depths ~3 - 4% in excess of geometric transit

Evolution of atmospheric escape as seen through the HeI line





Allan et al (under review)



Spherical symmetry → Symmetric line profiles: lack of stellar wind interactions

How stellar winds can affect atmospheres of close-in exoplanets

Create atmospheres
(HD219134, Vidotto+2018)

Prevent escape
(Vidotto & Cleary 2020)

Affect observational signatures
(Carolan et al 2020, 2021a,b)

Do nothing?

Erode atmospheres
(young Mars, Kulikov+2007)

2 Stellar wind and high-E (counter)effects on planetary atmospheres

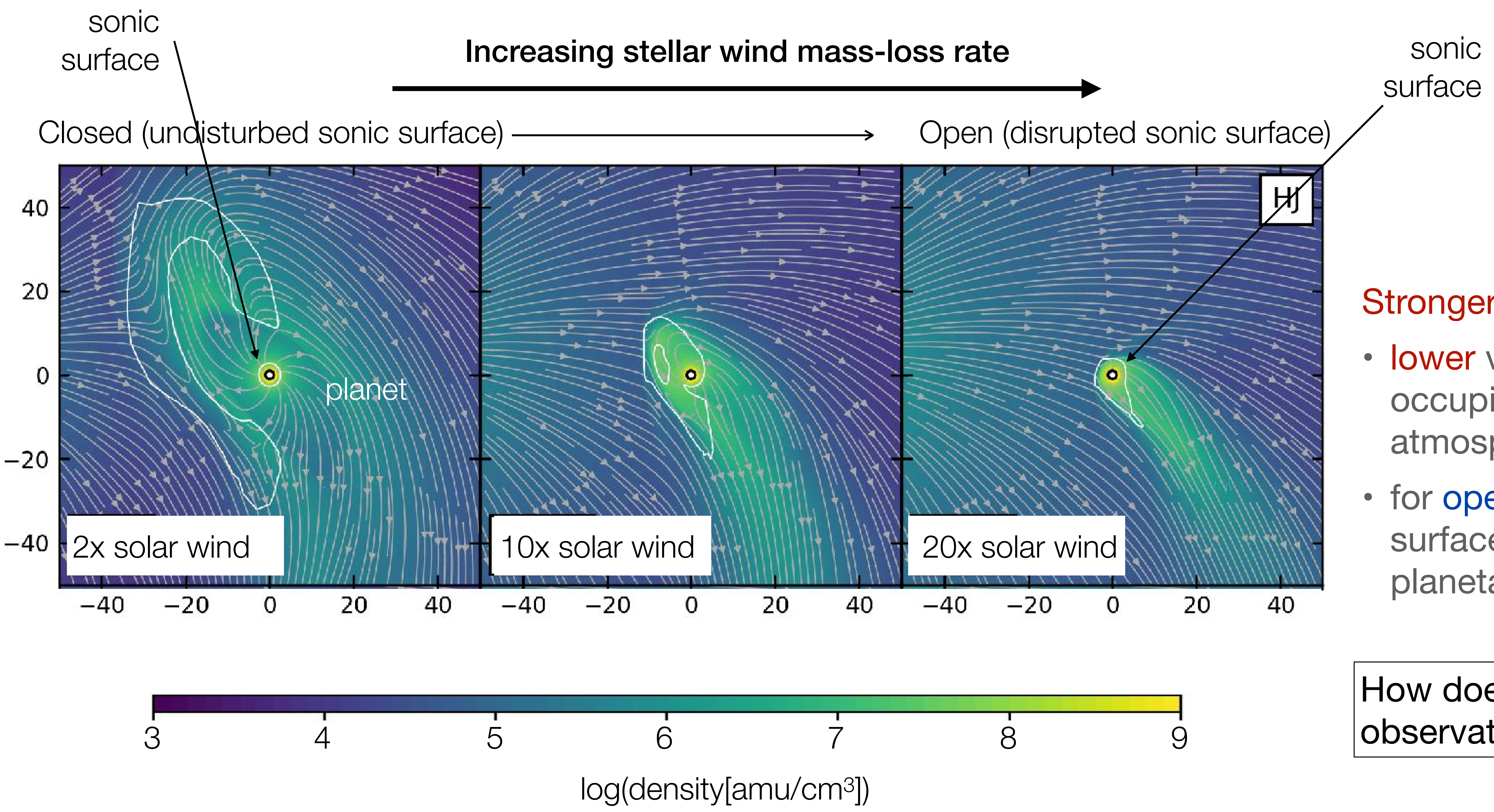

Stellar irradiation and stellar wind erosion
shape atmospheric evaporation
density (g/cc)
1E-15
1E-16
1E-17
1E-18
1E-19
1E-20
stellar wind
star
orbital motion
bow shock
planet's
shadow
(nightside)
tail shaped by the
stellar wind interaction
+ orbital motion
Carolan et al (20,21a,b)
Hazra et al (2022)
Kubyshkina et al (2022)

Stellar irradiation **plus** stellar wind shape atmospheric evaporation

Carolan, Vidotto et al 2021a

Lower escape rates after disruption of sonic surface

Carolan, Vidotto et al 2021a



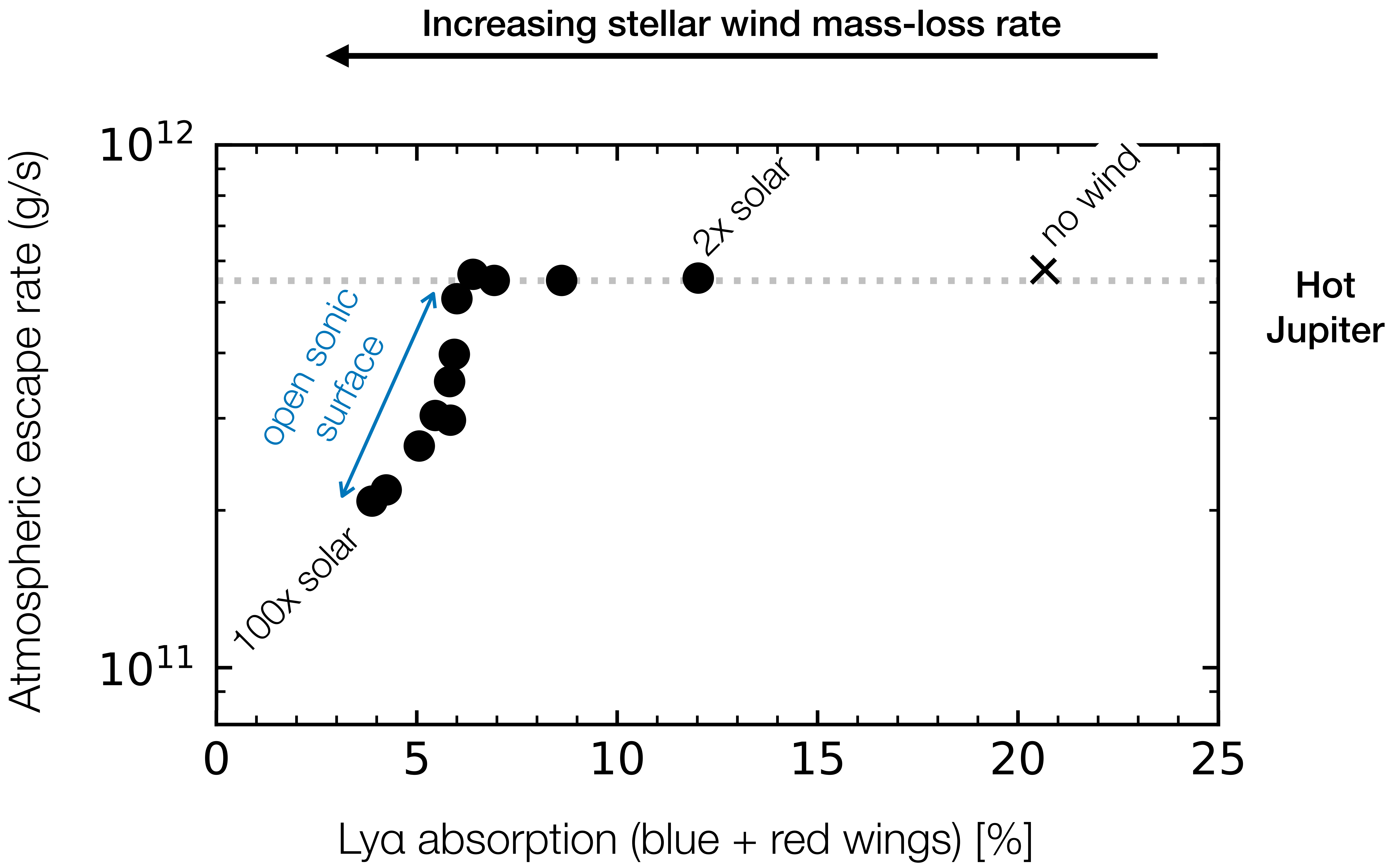
Stronger stellar winds:

- lower volume occupied by planetary atmosphere
- for open sonic surfaces: lower planetary escape rates

How does this affect observational signatures?

The effects of stellar winds on Lyα synthetic observations

Carolan, Vidotto et al 2021a



Observational signatures strongly affected by the presence of stellar winds even when planetary escape rates are not!

The dichotomy of AU Mic b

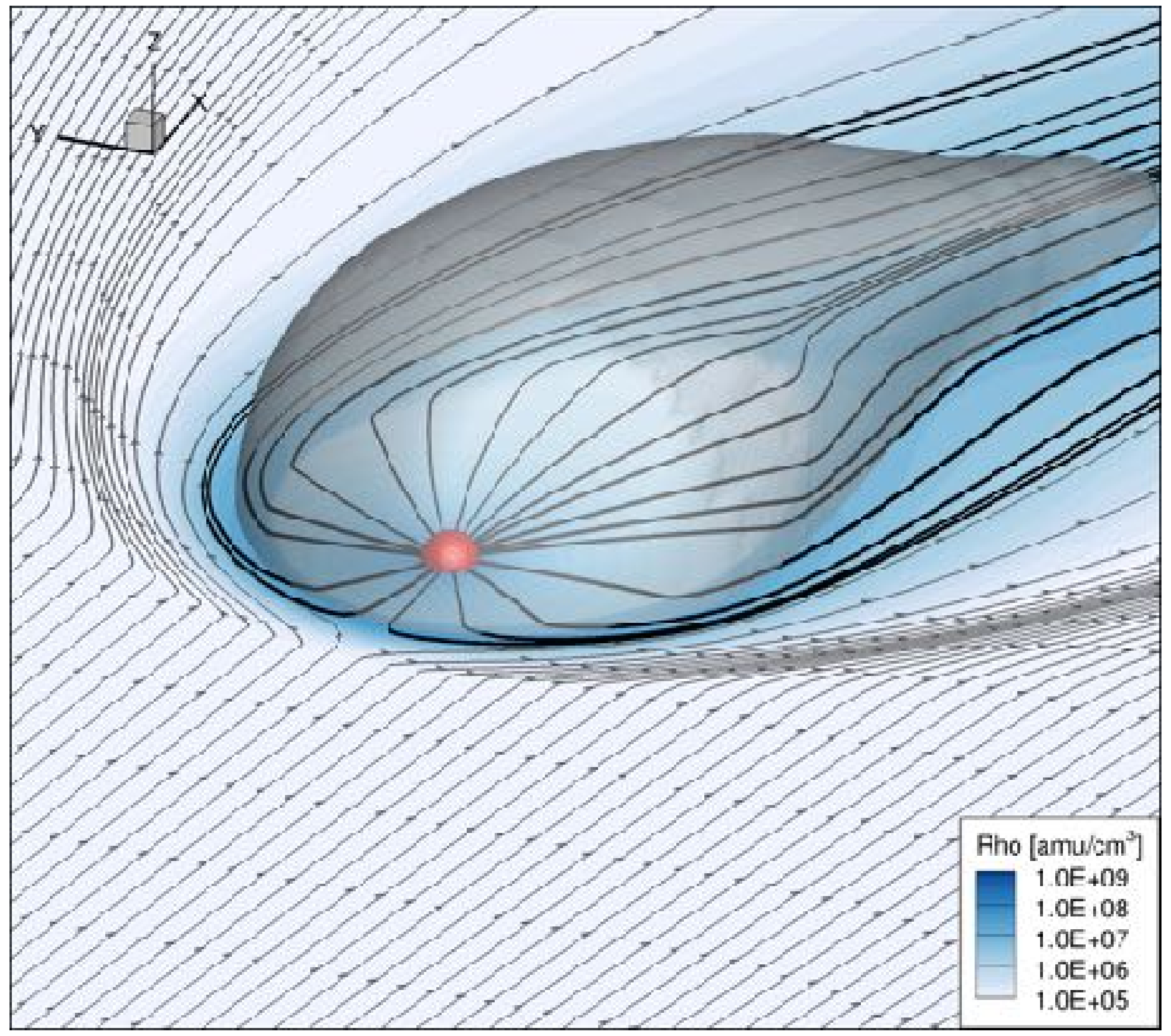
Carolan, Vidotto et al 2020

- AU Mic b: Neptune-size planet orbiting a 22 Myr-old, pre-main sequence M dwarf (Plavchan et al 2020)

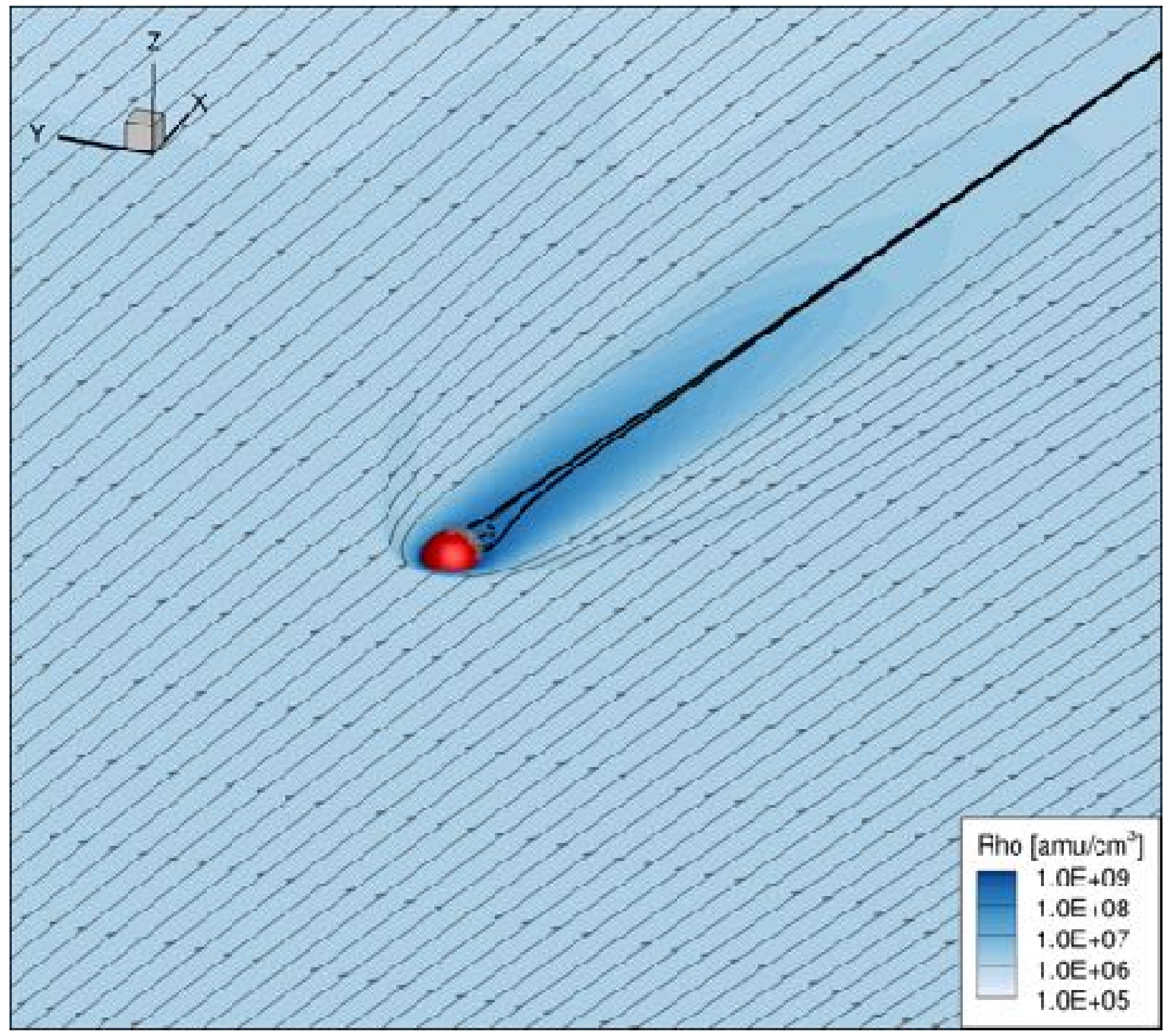
High EUV flux from the star causes strong evaporation in AU Mic b

Strong wind of AU Mic (10 to 1000x the solar wind mass-loss rate) prevents/reduces evaporation

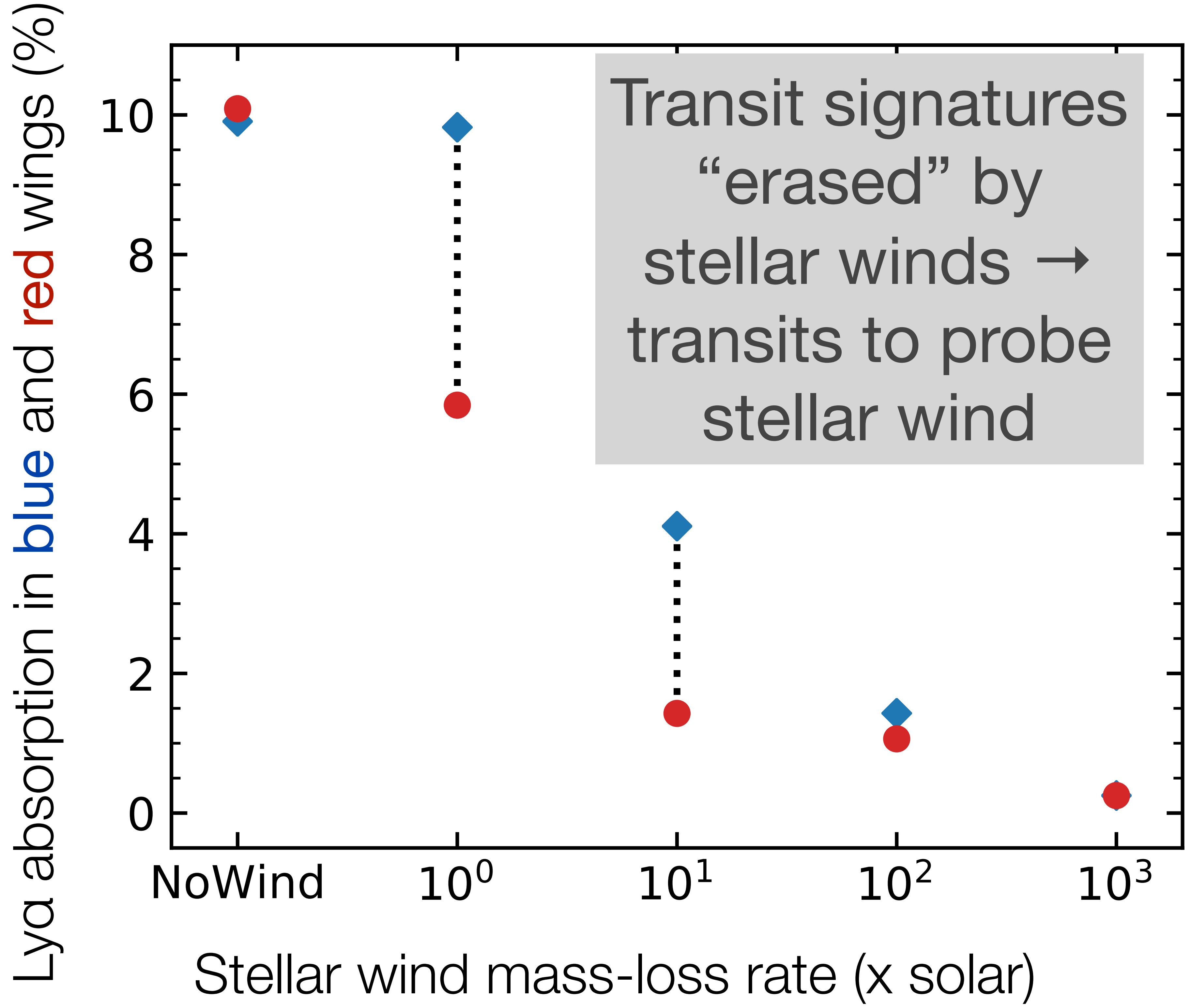
stellar wind: 10x solar



stellar wind: 1000x solar



evaporation rate: reduced by 50%



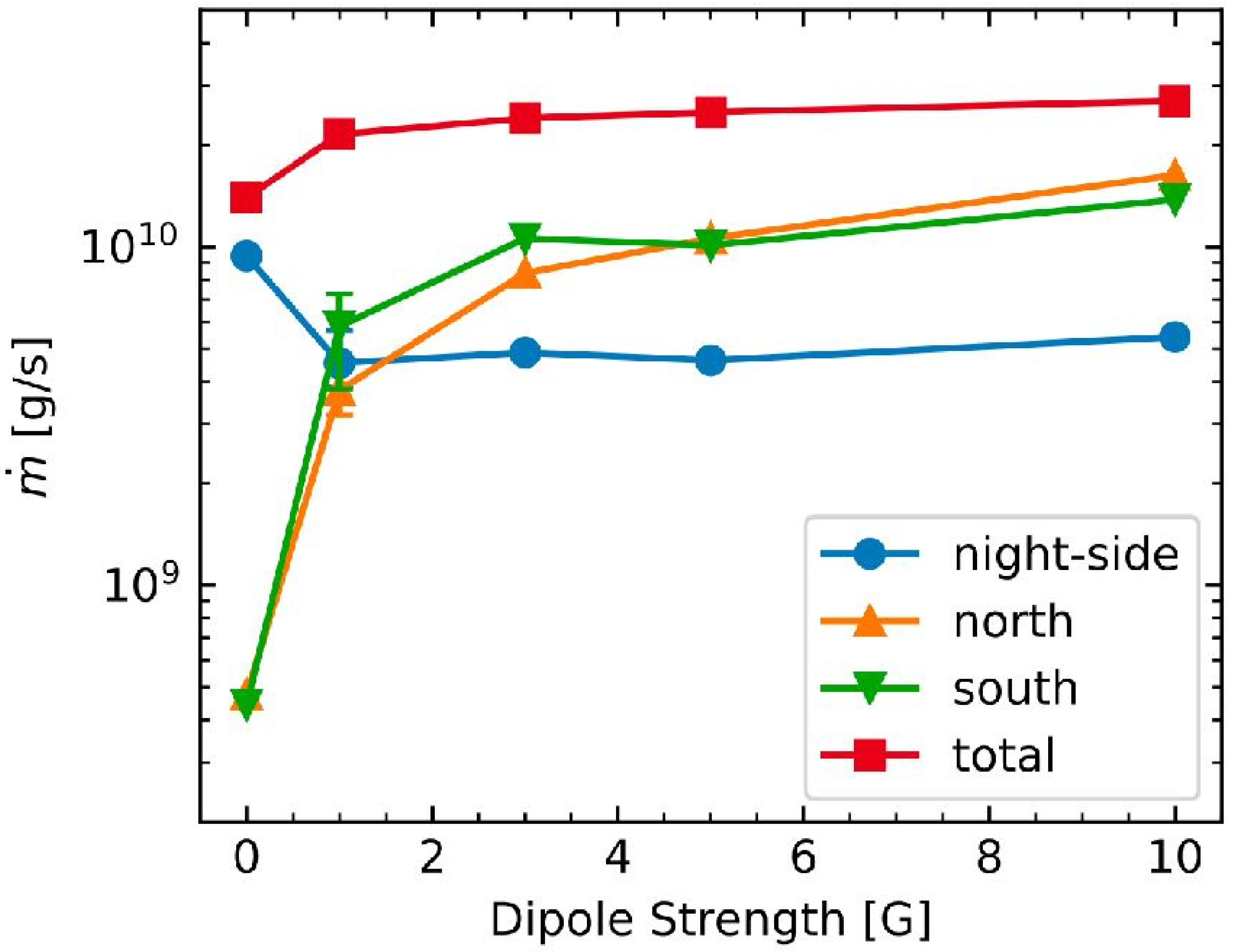
Magnetic field effects on atmospheric escape in hot Jupiters

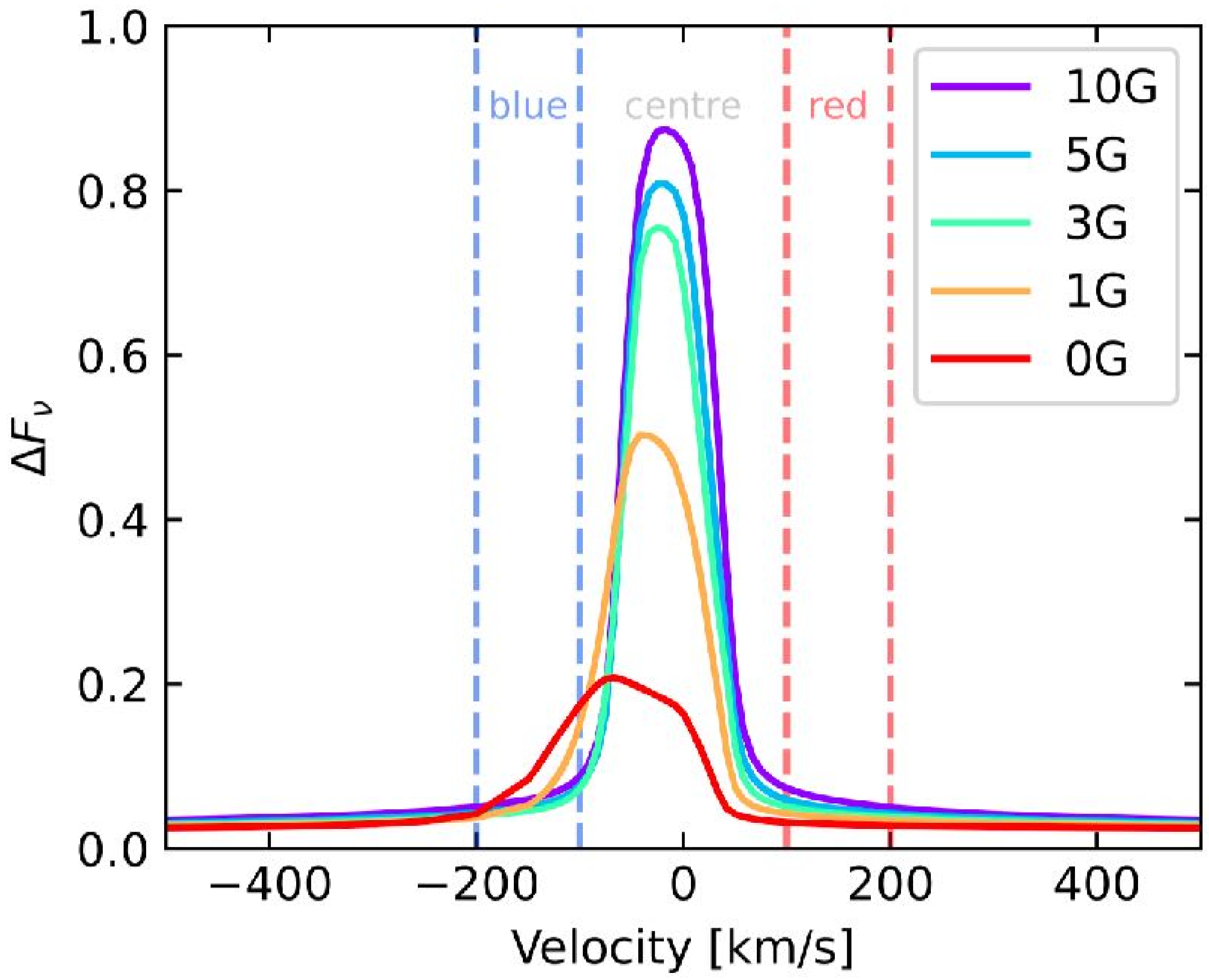
Carolan, Vidotto et al 2021b

- Radiation magneto-hydrodynamic escape simulations (in Hot Jupiters)
  - B changes the dynamics of the escaping atmosphere
  - formation of two “tails”

Magnetic field effects on atmospheric escape of close-in exoplanets

Carolan, Vidotto et al 2021b

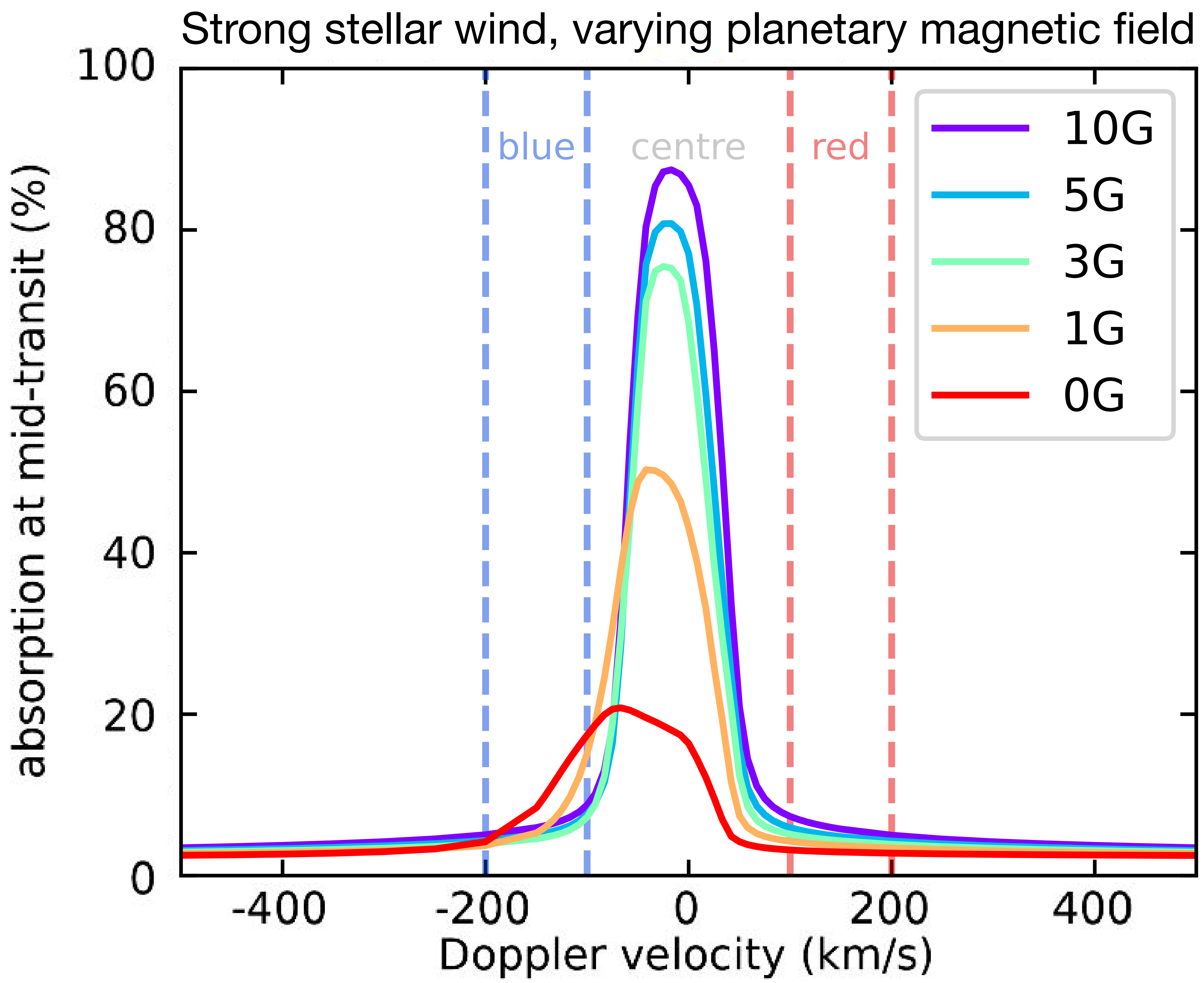




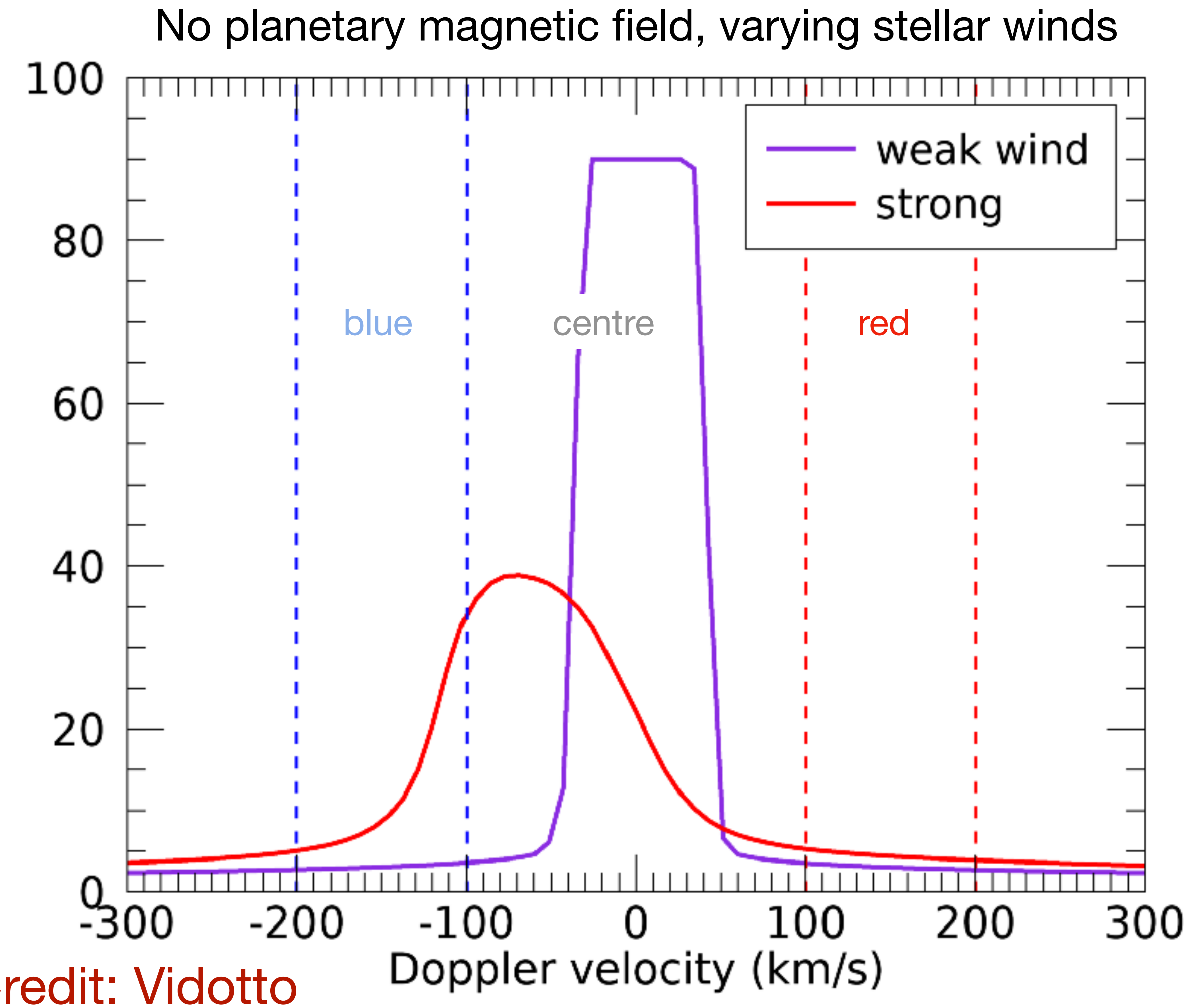
weak increase in escape rate with increase in B_{pl}…

… but **strong** effect on observational signature!

The Ly-alpha degeneracy problem: Is evaporation confined by the stellar wind or by the planetary B?



Carolan, Vidotto et al 2021b



Credit: Vidotto

Degeneracy between stellar wind confinement and planetary magnetic field effects can be removed with multi-line observations

Conclusions

Atmospheric escape and the evolution of planets depends on the XUV history of the host star.

Planetary magnetism can change the dynamics of the escaping atmosphere → affects observables.

Stellar wind can reduce atmospheric escape & "*erase*" Ly-α transit signatures in young systems

Stellar wind & planetary magnetic field can confine atmospheres: distinguish between effects with multi-λ obs.

PhD position to start Autumn 2024:
More info: avidotto.github.io
Application Deadline: 15 Nov 2023

Aline Vidotto