How stellar irradiation and erosion can shape the early evolution of planetary atmospheres

@AlineVidotto

2021 Sagan Summer Workshop

erc

Universiteit
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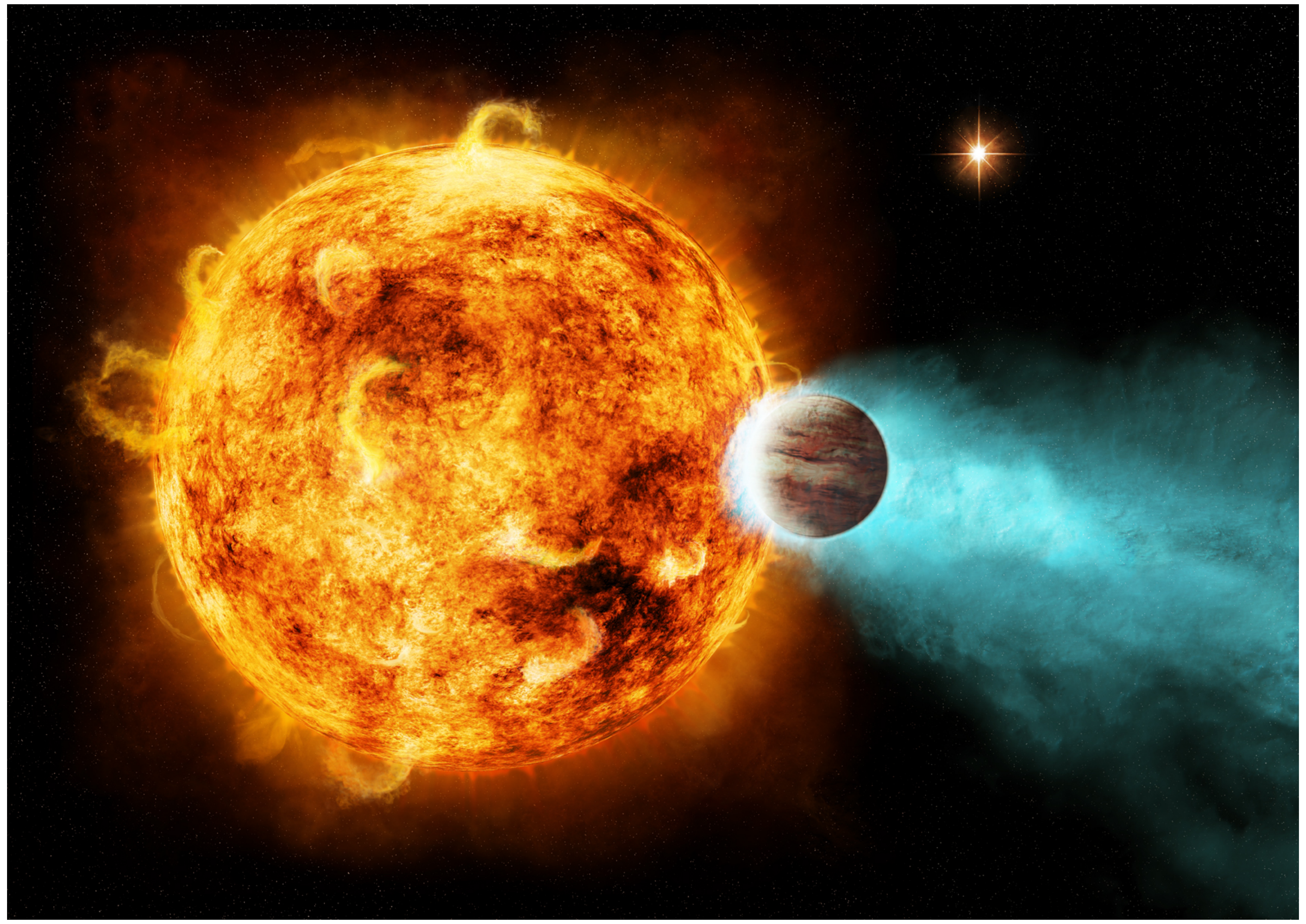
What is the relevance of a planetary atmosphere?

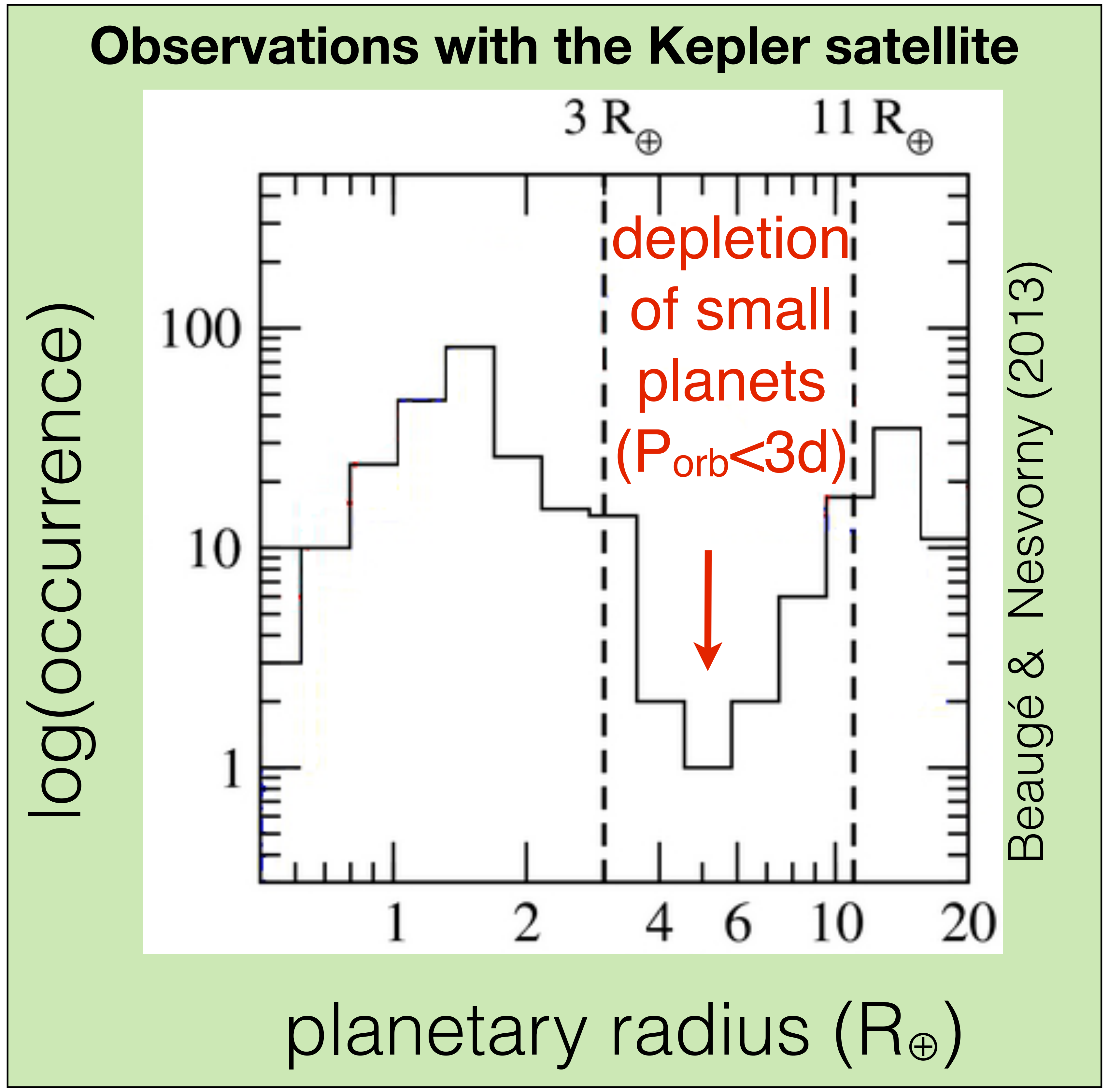
Do habitable worlds exist?

Presence of atmosphere: fundamental for planet to develop life



How do exoplanets evolve?

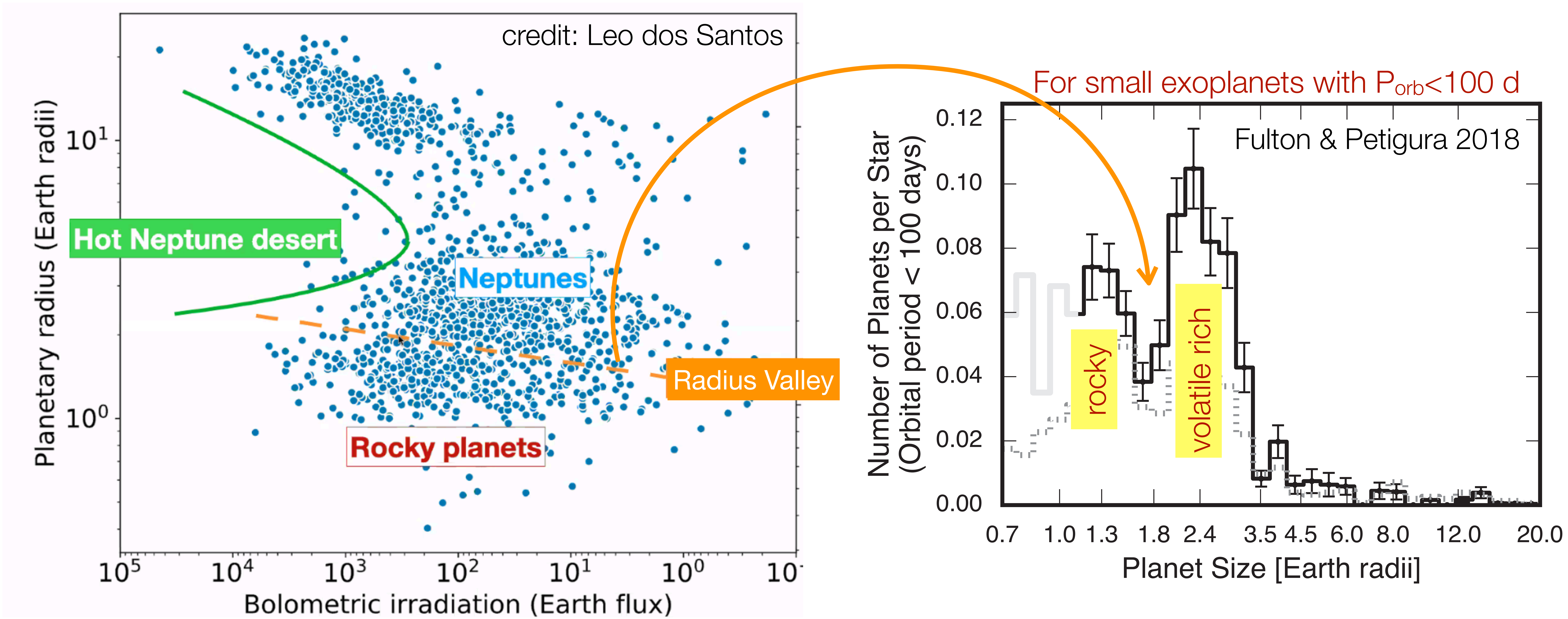
Atmospheric loss sculpts planet and changes mass-radius distribution



Outline

1. How do we know exoplanetas are evaporating? And why do they evaporate?
2. The evolution of stellar radiation & winds (mostly focused on early ages)
3. Stellar wind interaction with atmospheres of exoplanets

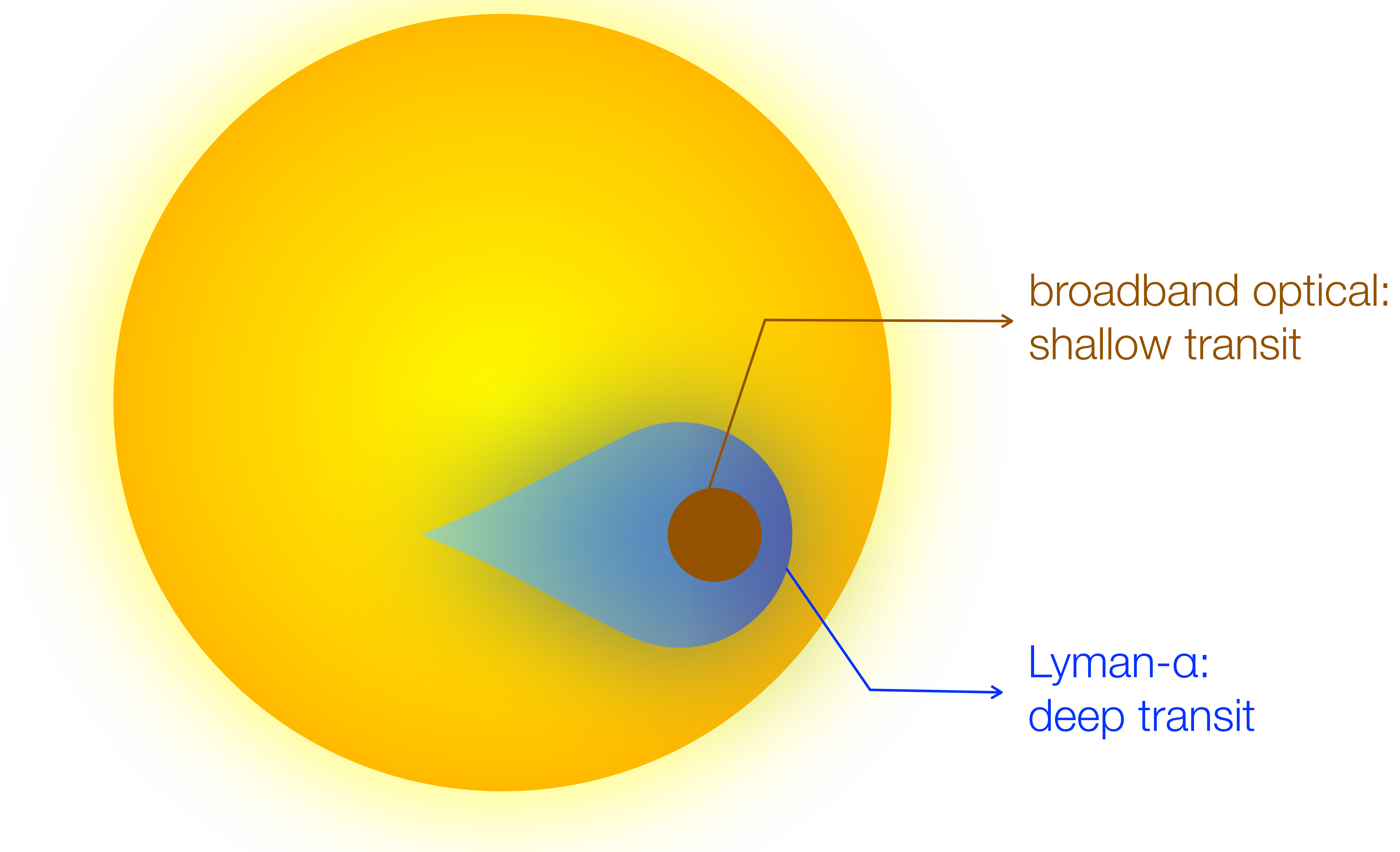
Indirectly: evaporation through population studies



Possible interpretation:

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

Directly: through transmission spectroscopy

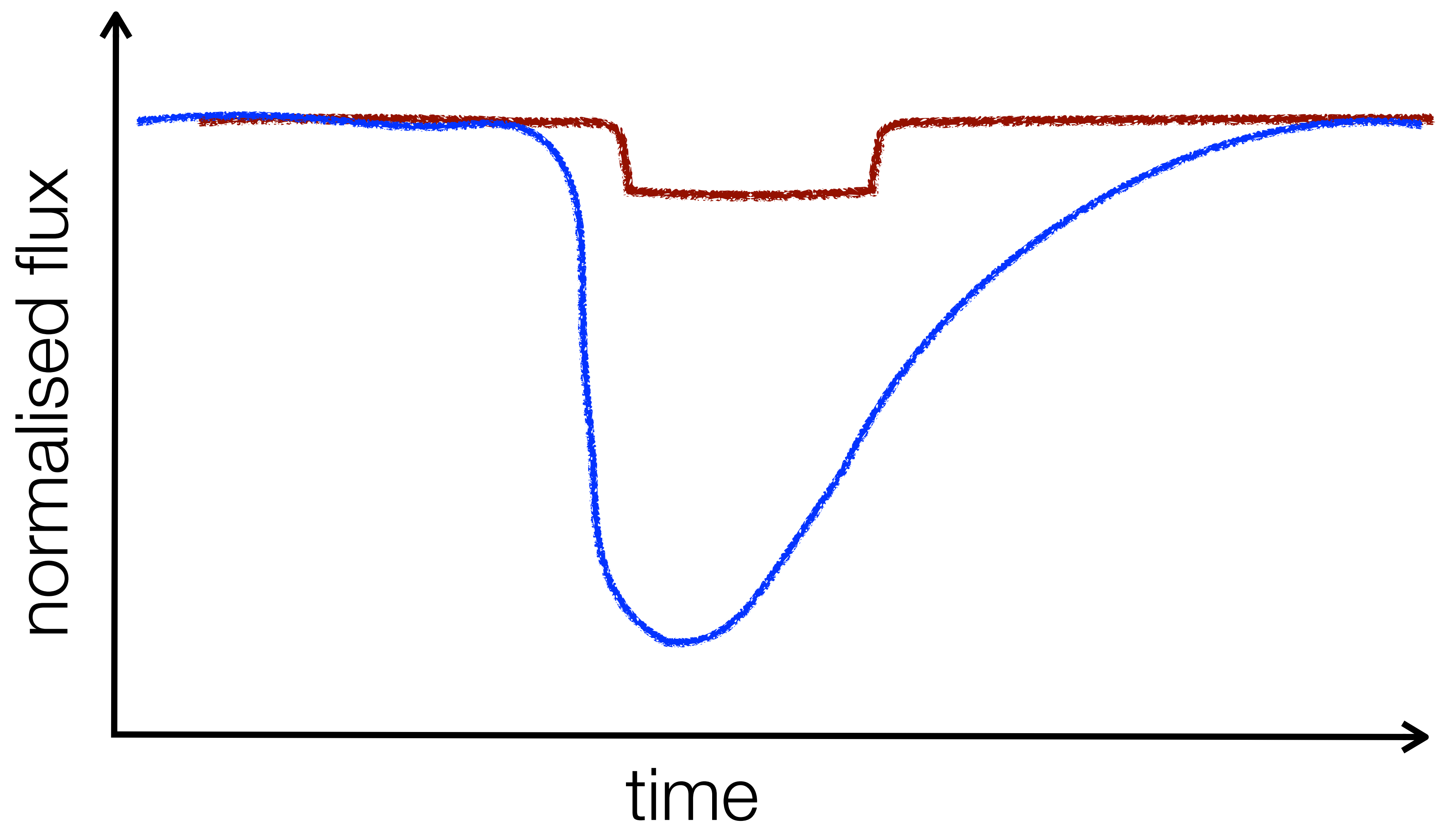


broadband optical:
shallow transit

Lyman-α:
deep transit

Transmission spectroscopy

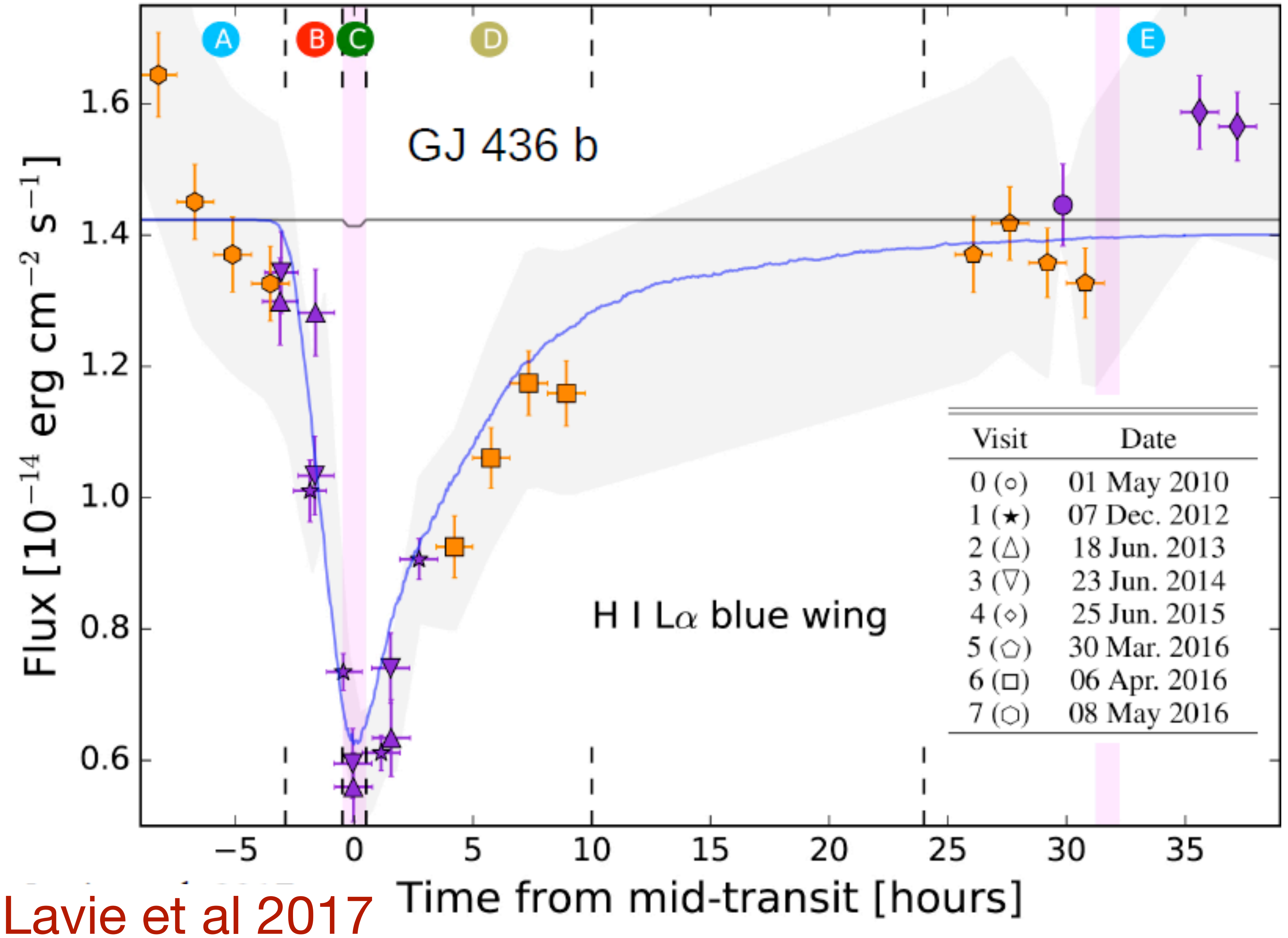
During transit, stellar radiation is transmitted through the exoplanet's atmosphere



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

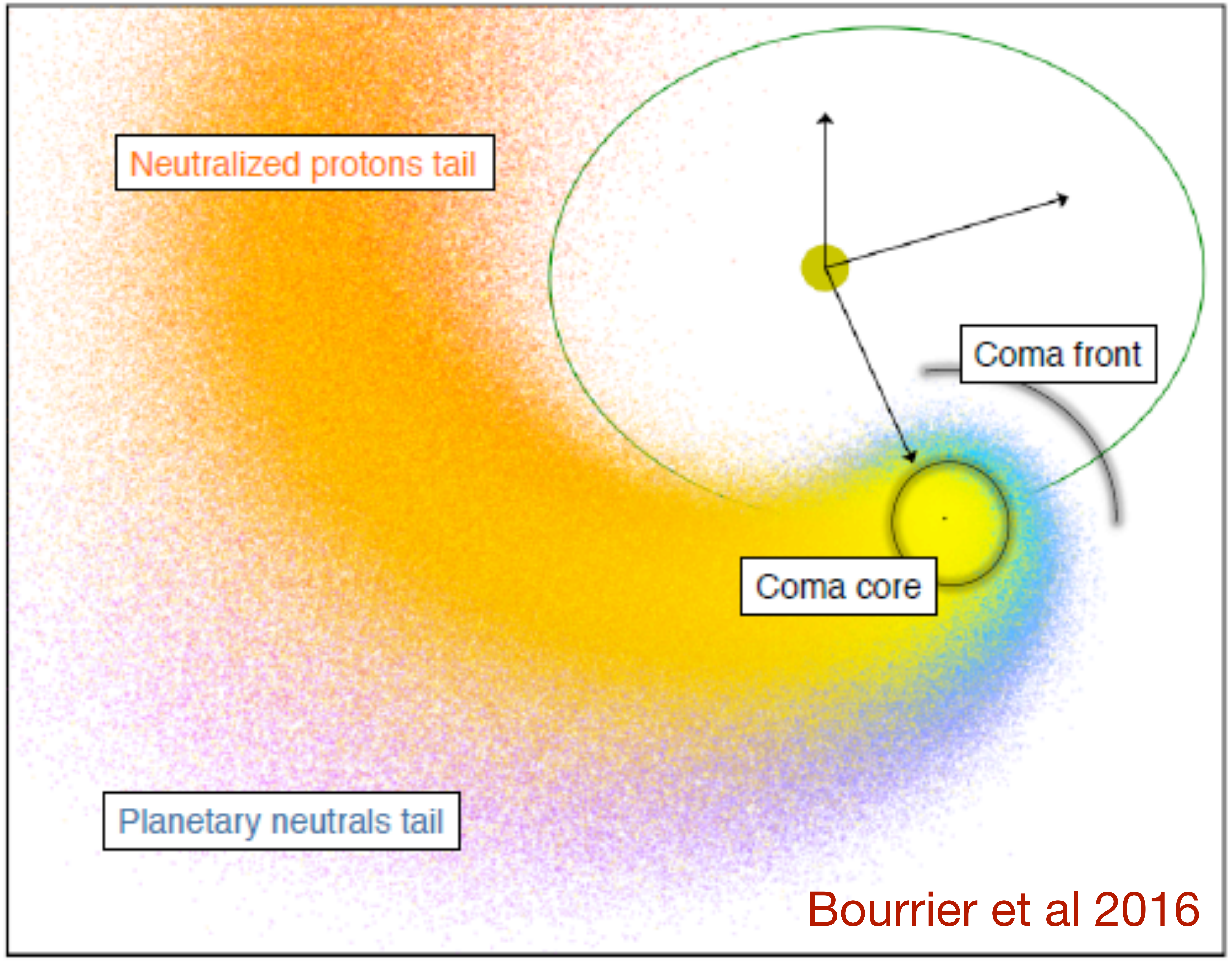
Escaping atmosphere of GJ436b (Ly-α)

Transit depth ~ 60% (!)



Lavie et al 2017

also: Kulow et al 2014; Ehrenreich et al 2015

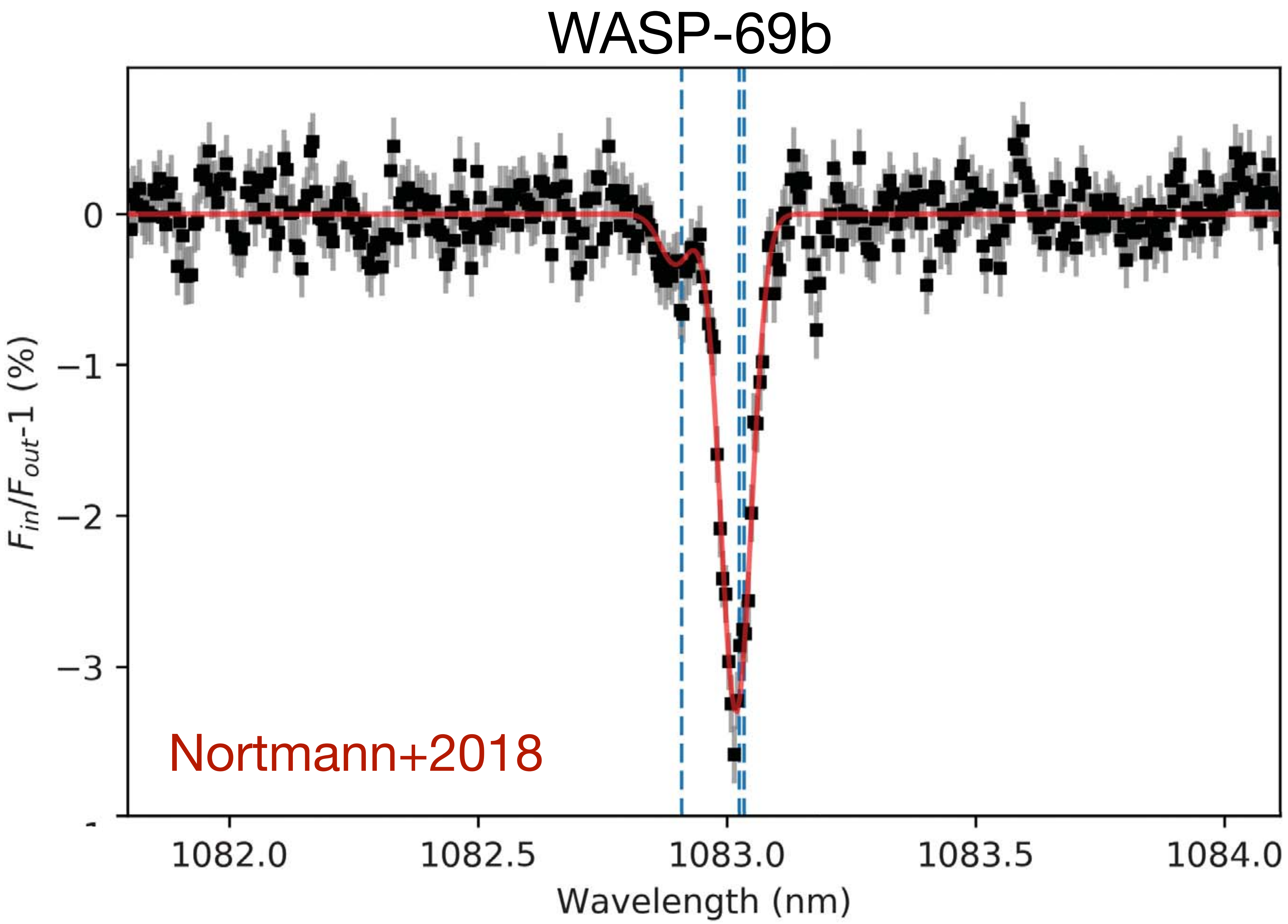


Bourrier et al 2016

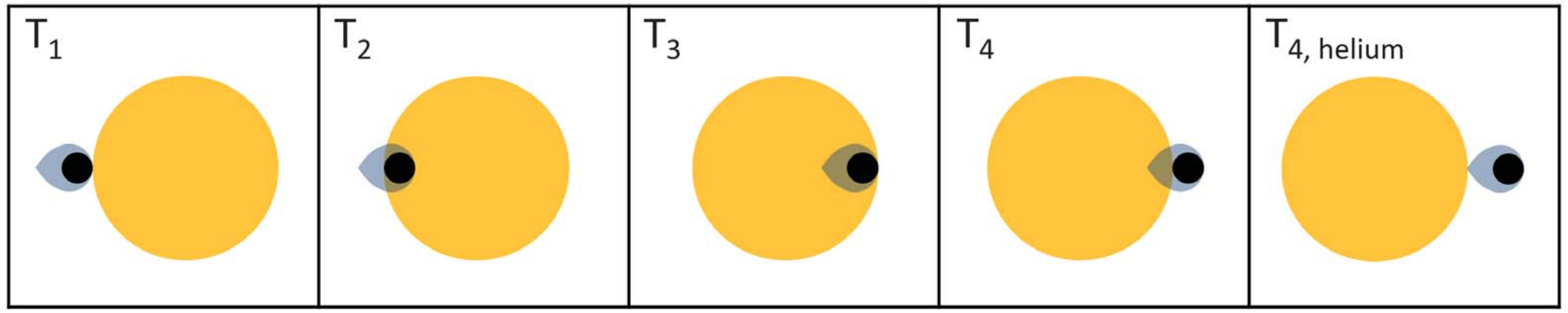
Escape rates $\approx 2 \times 10^8 - 10^9$ g/s

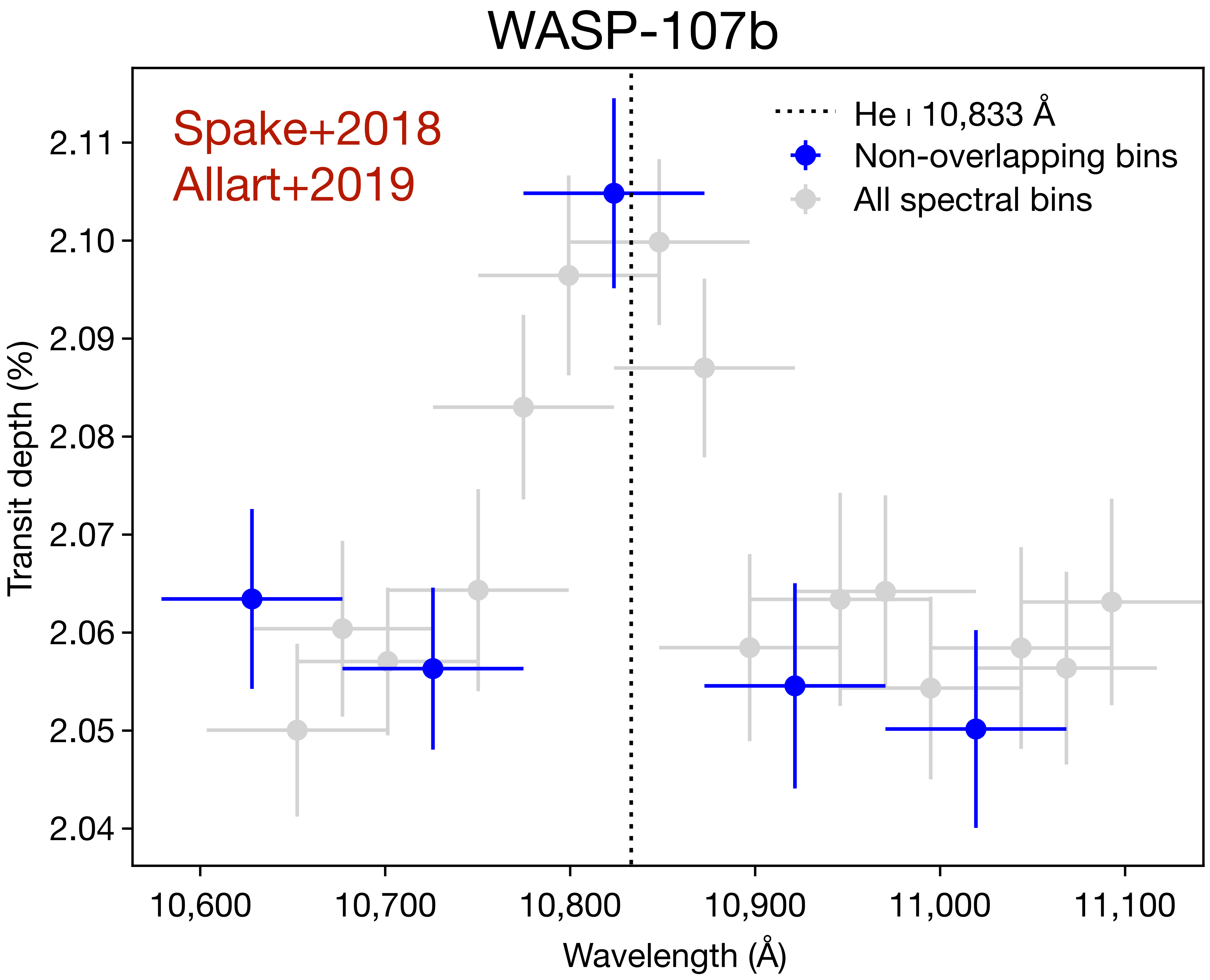
Infrared: Carmenes, HST

Atmospheric evaporation in Helium lines



Nortmann+2018



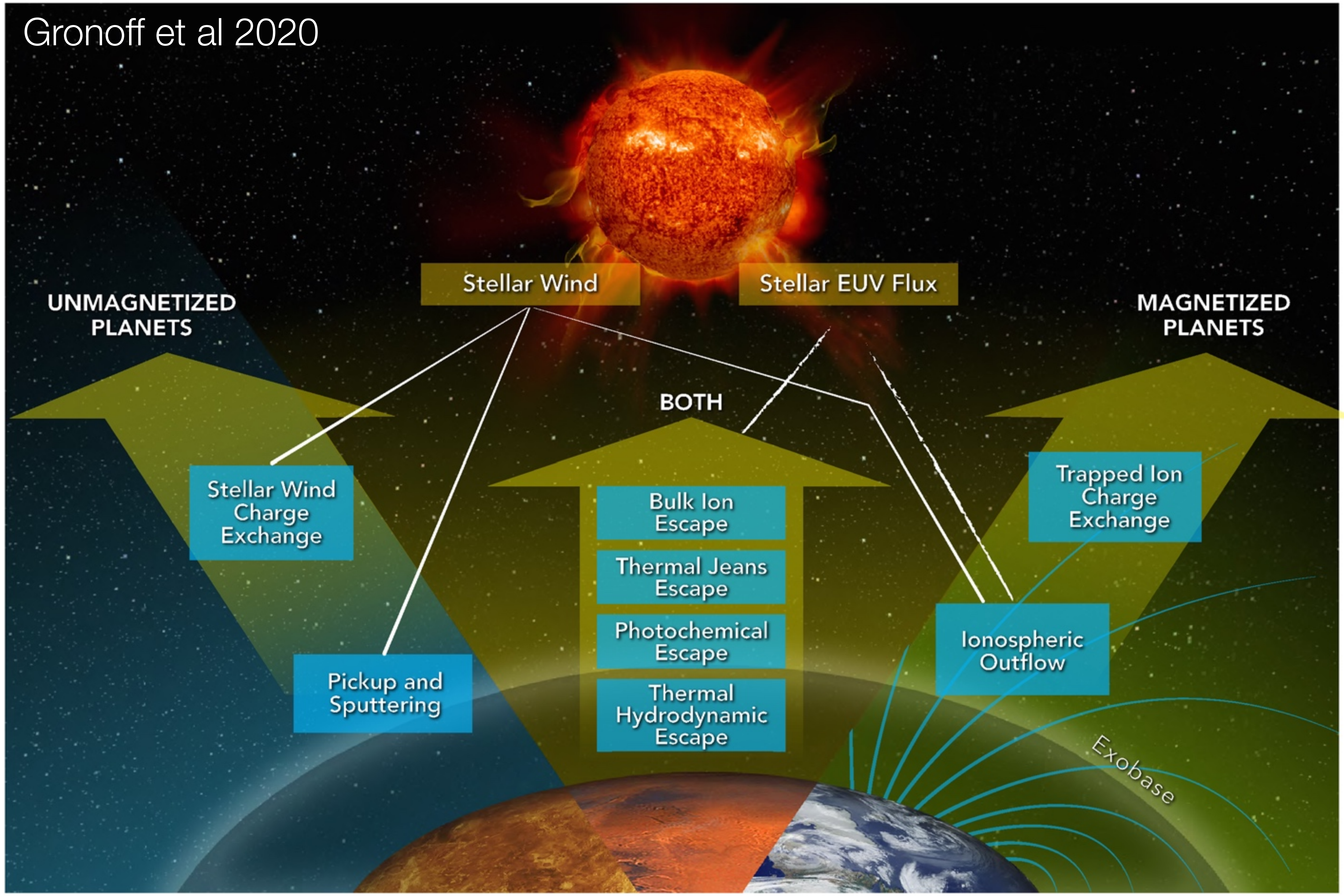


Spake+2018
Allart+2019

Common feature: relatively active stars: needs EUV to lift the atmospheres

What are the physical causes of evaporation in these close-in planets?

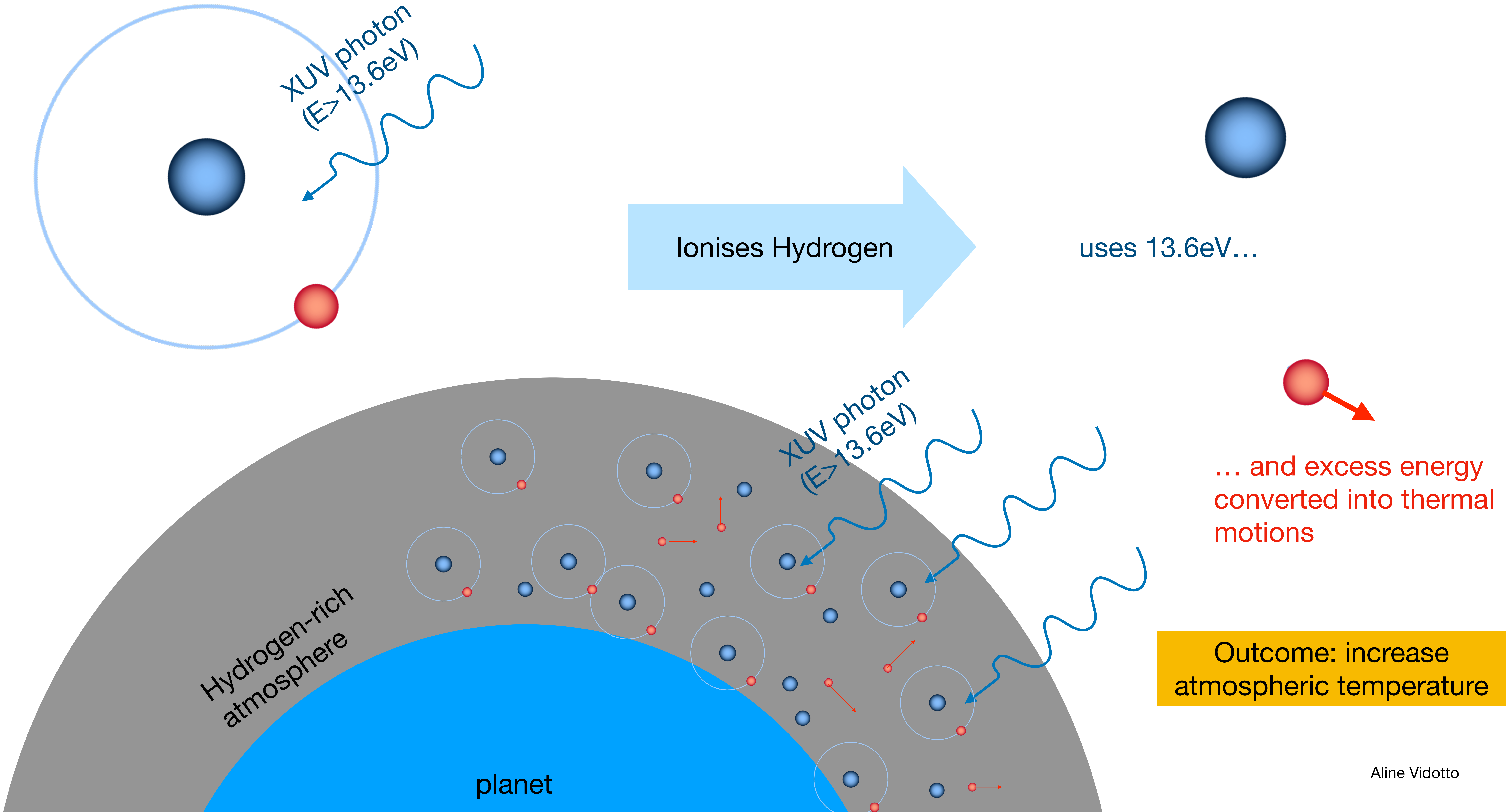
Atmospheric Loss processes


Gronoff et al 2020

*Plus: stellar wind stripping (due to ram pressure), impacts that can blast atmosphere into space, condensation of atmosphere, stellar tidal forces (Roche lobe overflow), etc

- Several loss processes, divided into “kinetic” and “fluid” types
  - kinetic: individual particles are lost
  - fluid (or hydrodynamic): bulk outflow
- Simple “assessment”
  - bloated planet (ie, low gravity) and highly irradiated (ie, close-in or active star): bulk outflow
  - bulk outflow is very important for youngish / close-in exoplanets!
  - 2 suggested “avenues” of evaporation for these planets:
    - ➡ photo-evaporation (external)
    - ➡ core heating (internal)

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



Ionises Hydrogen

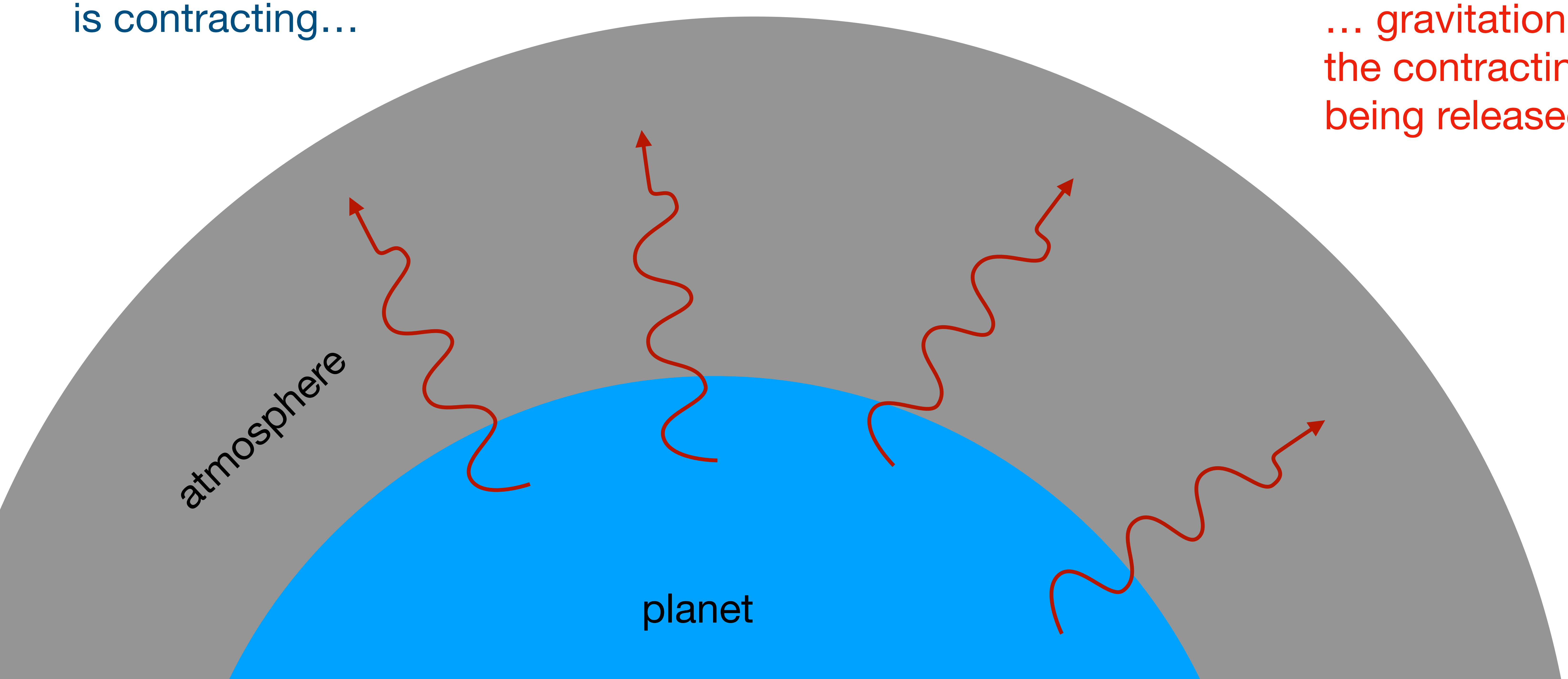
uses 13.6eV…

… and excess energy converted into thermal motions

Outcome: increase atmospheric temperature

Hydrodynamic escape via core luminosity: how does it happen?

after formation: planet is contracting…

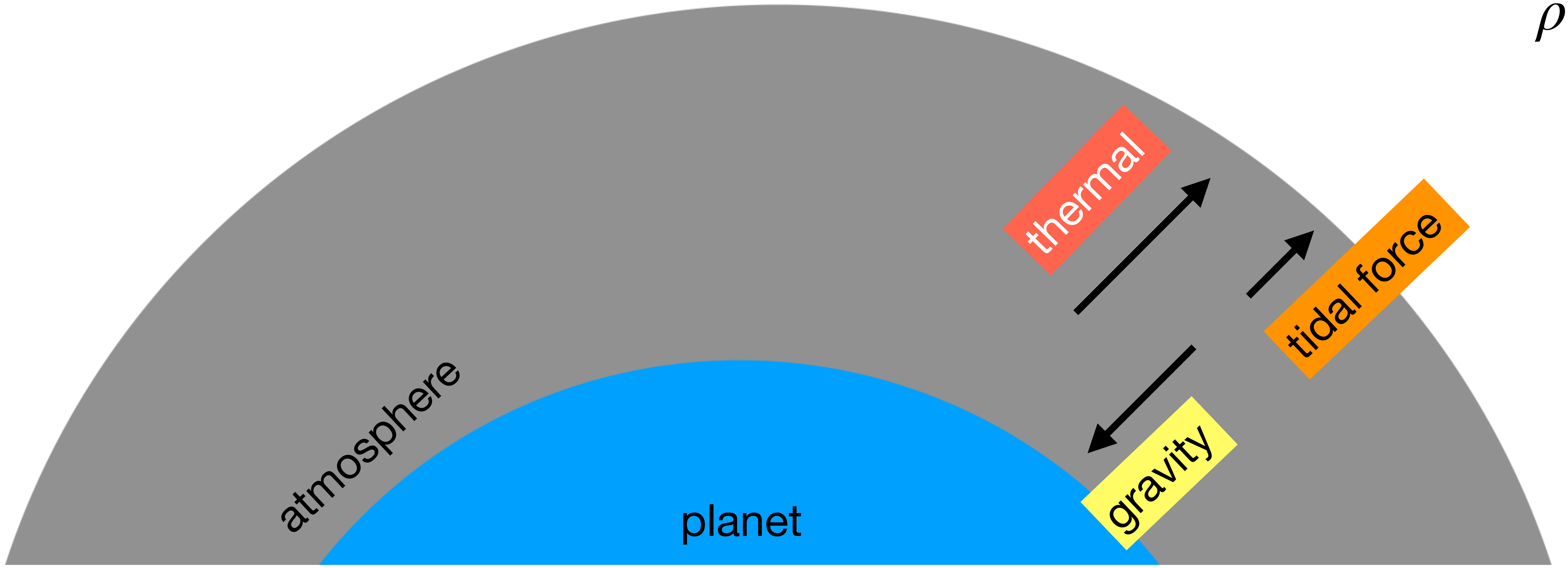


… gravitational energy of the contracting core is being released

Outcome: increase atmospheric temperature

Why is the high temperature so important?

High T generates a gradient of pressure → force that drives the planetary outflow



$$\rho a = \text{planet gravity} + \text{tidal} + \text{thermal forces}$$

$$\rho u \frac{du}{dr} = -\frac{\rho G M_p}{r^2} + \frac{3\rho G M_\star r}{a^3} - \frac{dP}{dr}$$

*in fluid dynamics, mass is replaced by density and forces are given per unit volume..

** eqs assume 1D geometry, spherical symmetry and steady state

Momentum equation does not care what is causing the gradient of pressure (core heating, stellar photoionisation, or something else!)

This distinction enters in the energy equation.

Interested in the derivation? https://rdcu.be/cjs9q
Check Section 5.2.1 of Vidotto 2021, Living Reviews in Solar Physics

Energy-limit escape: a particular limit of hydrodynamic escape

1 assumption

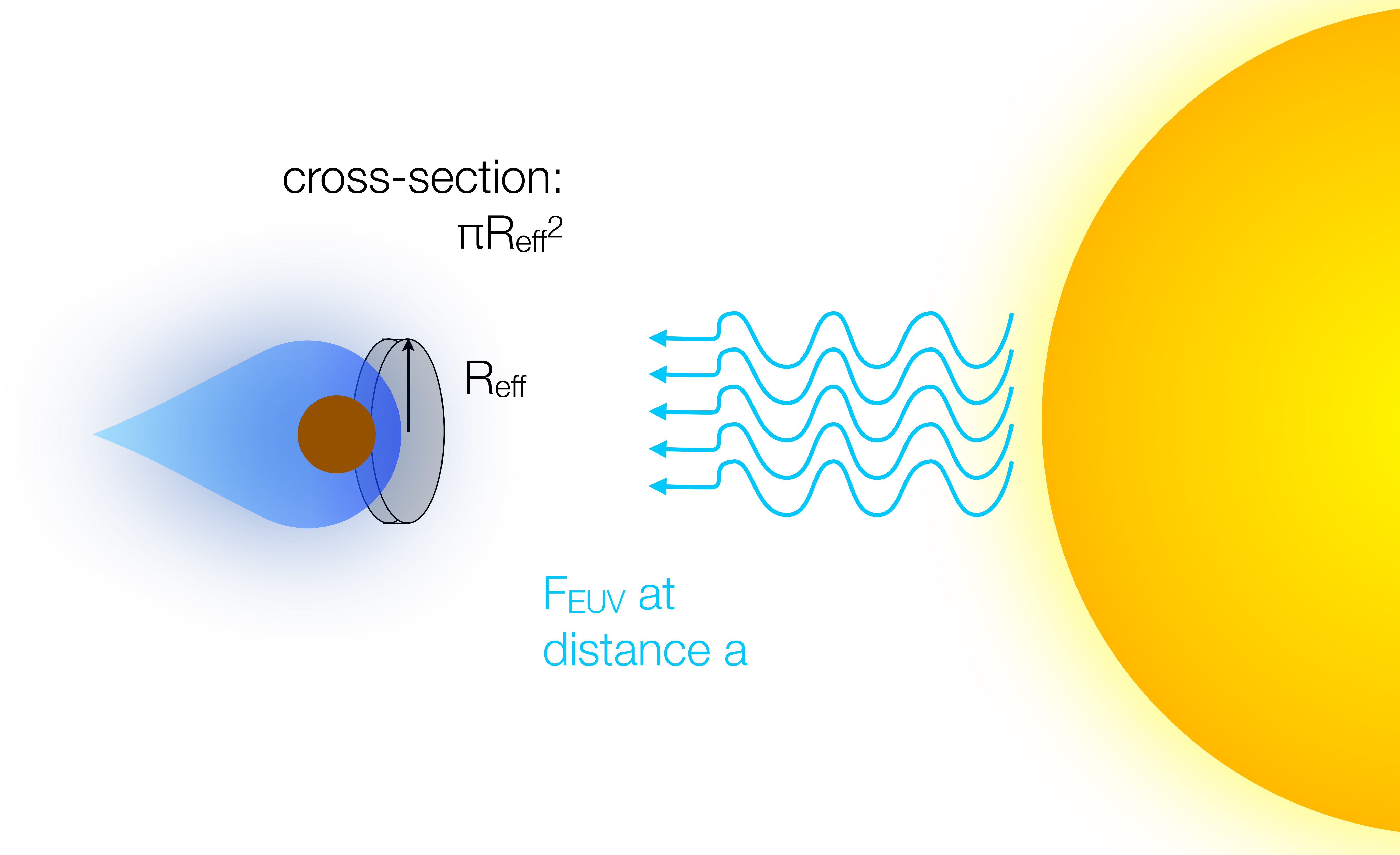
$$E_{\text{irradiation,input}} = E_{\text{kinetic,output}}$$

a fraction ε of the energy flux is intercepted by the planet cross-section…

… and is used to accelerate the outflow to its terminal velocity

$$\epsilon F_{\text{EUV}}(\pi R_{\text{eff}}^2) = \frac{\dot{M} u_{\text{term}}^2}{2}$$

evaporation rate (g/s)



2 assumption

The terminal velocity is on the order of the surface escape velocity

$$v_{\text{esc}} = \left(\frac{2GM_{\text{p}}}{R_{\text{p}}}\right)^{1/2}$$

$$\dot{M}_E = \epsilon \frac{F_{\text{EUV}}(\pi R_{\text{eff}}^2)}{GM_{\text{p}}/R_{\text{p}}}$$

Allan & Vidotto 2019

Energy-limit escape: a particular limit of hydrodynamic escape

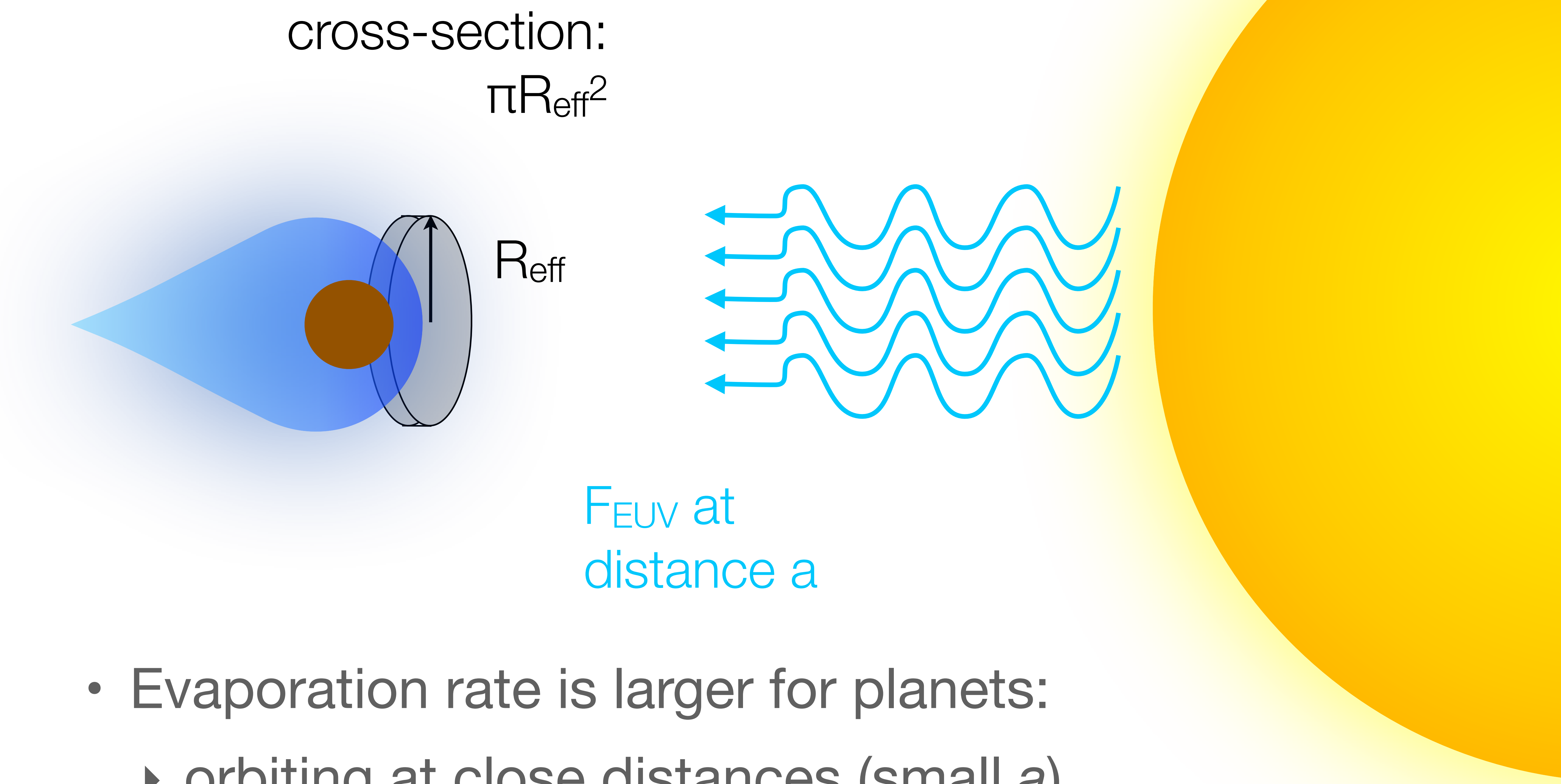
$$\dot{M}_E = \epsilon \frac{F_{\rm EUV}(\pi R_{\rm eff}^2)}{GM_{\rm p}/R_{\rm p}}$$

$$F_{\rm EUV} = \frac{L_{\rm EUV}}{4\pi a^2}$$

$$\dot{M}_E = \frac{\epsilon}{4} \frac{L_{\rm EUV}(R_{\rm eff}/a)^2}{GM_{\rm p}/R_{\rm p}}$$

$$\bar{\rho} = \frac{M_p}{\frac{4}{3}\pi R_p^3}$$

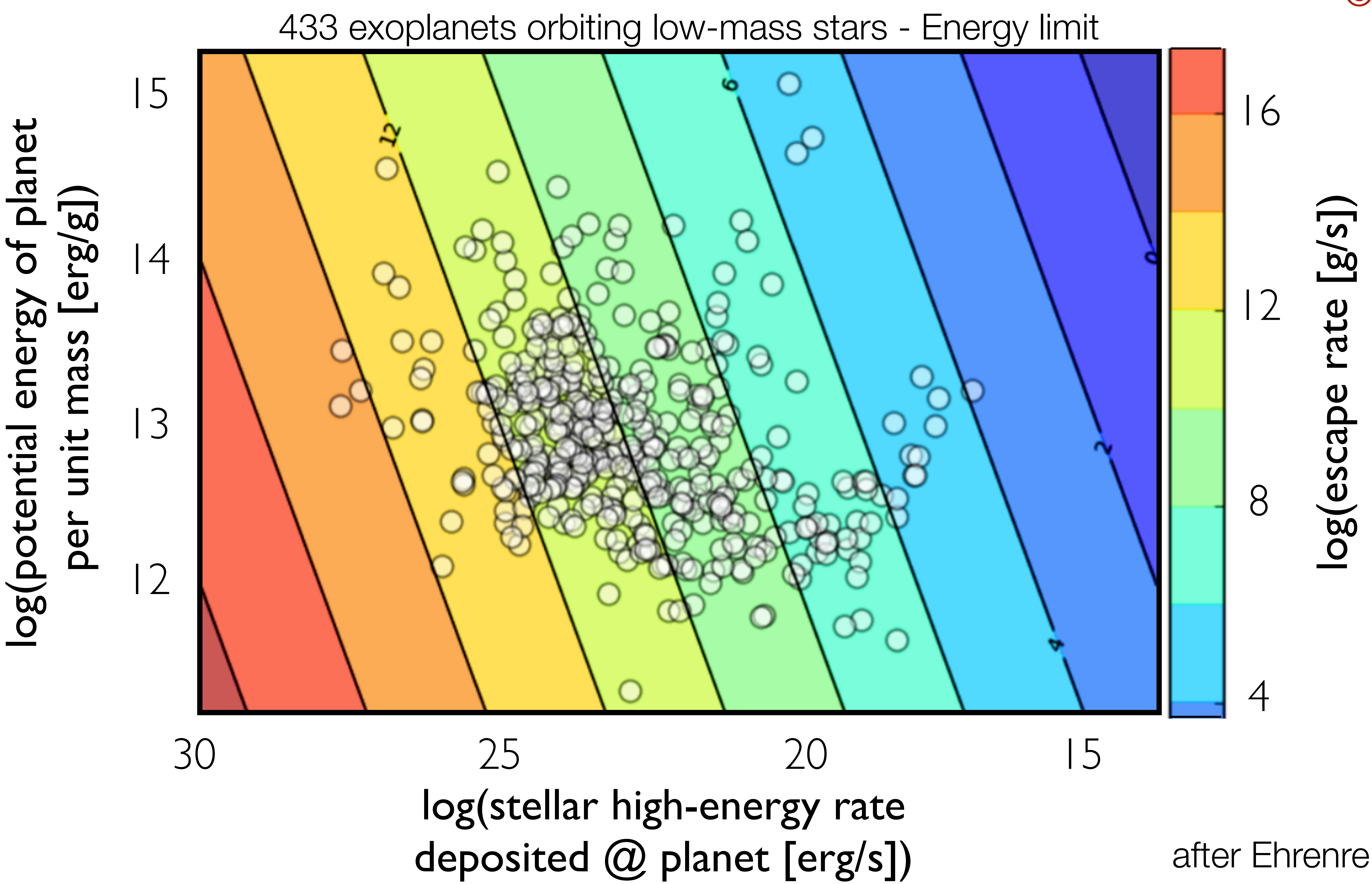
$$\dot{M}_E \simeq \frac{3\epsilon}{16} \frac{L_{\rm EUV}/a^2}{G\pi\bar{\rho}}$$



- Evaporation rate is larger for planets:
  - orbiting at close distances (small *a*)
  - smaller average densities (e.g., gas giants)
  - orbiting stars that are active (large high-energy luminosities): usually young(er) stars
- Important form of escape in hot Jupiters & planets orbiting young stars

Mass loss estimates for exoplanets

© Maeve Upton



433 exoplanets orbiting low-mass stars - Energy limit

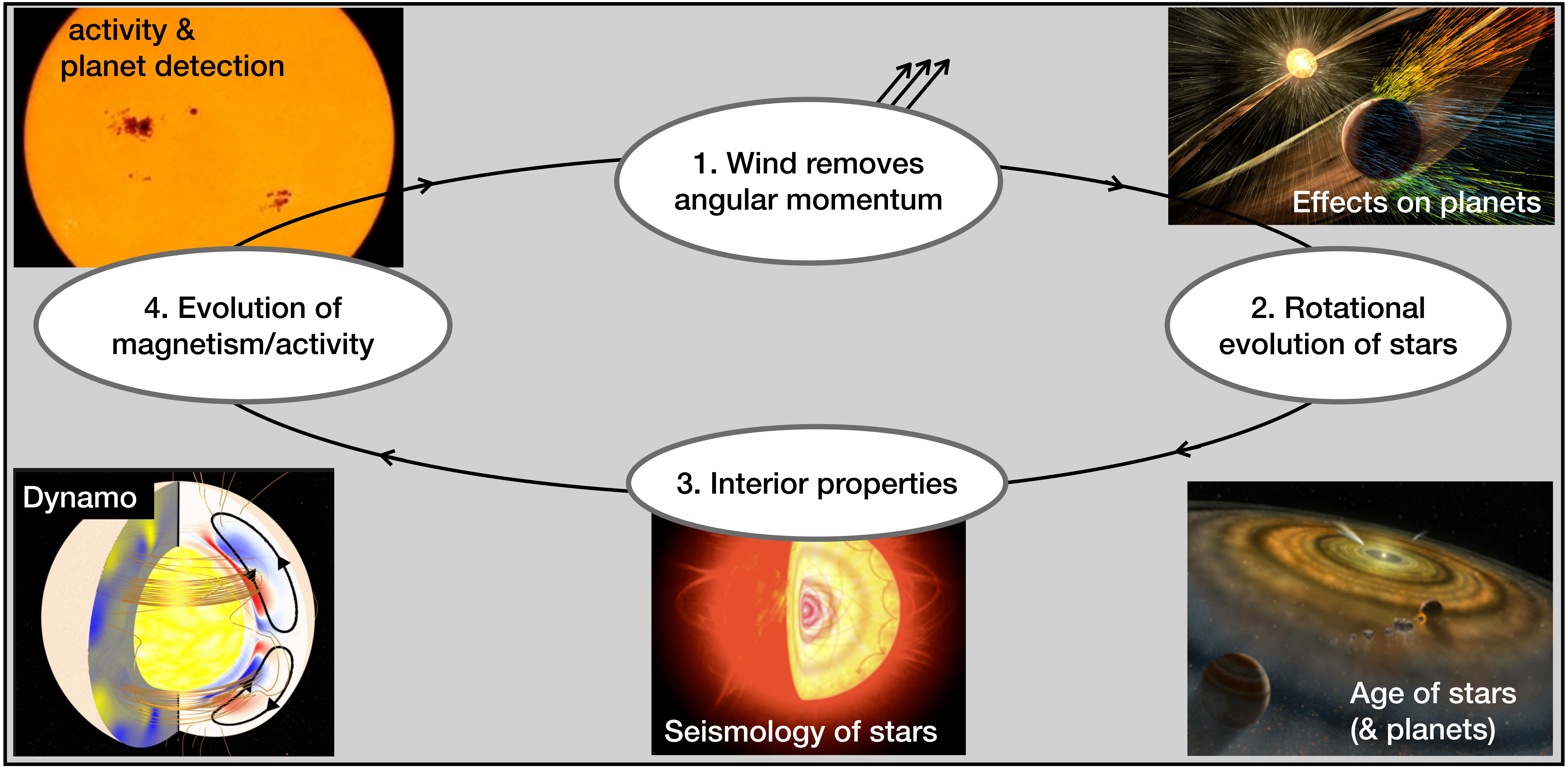
after Ehrenreich & Desert 2011

Stellar irradiation and stellar wind erosion shape atmospheric evaporation

©Garlick/U.of Warwick

2 The evolution of stellar radiation & winds (mostly focused on early ages)

The BIG picture: evolution of winds/activity of cool dwarf stars



activity &
planet detection

1. Wind removes angular momentum

Effects on planets

2. Rotational evolution of stars

3. Interior properties

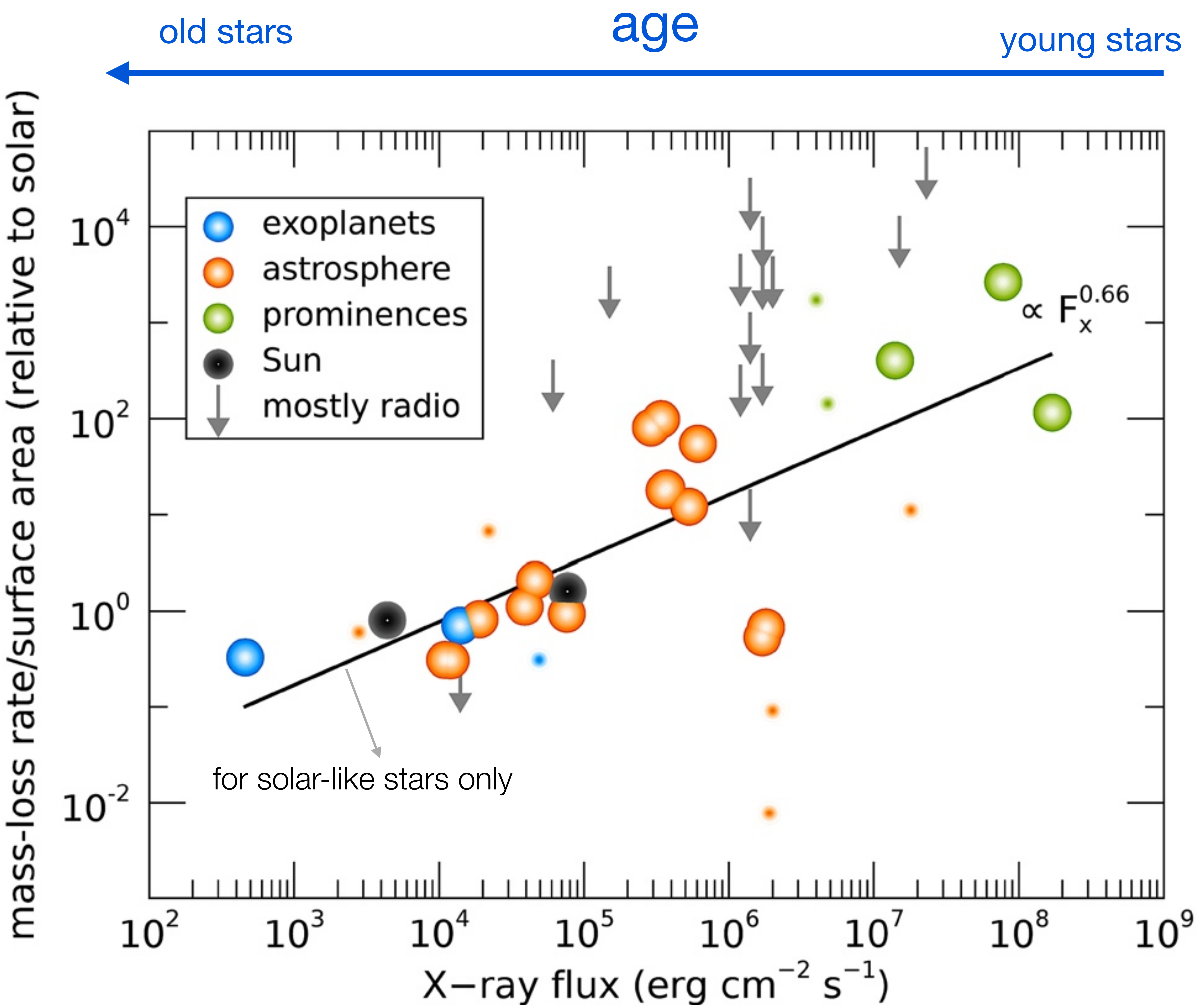
4. Evolution of magnetism/activity

Dynamo

Seismology of stars

Age of stars
(& planets)

How do winds, activity & planets evolve?



Open questions

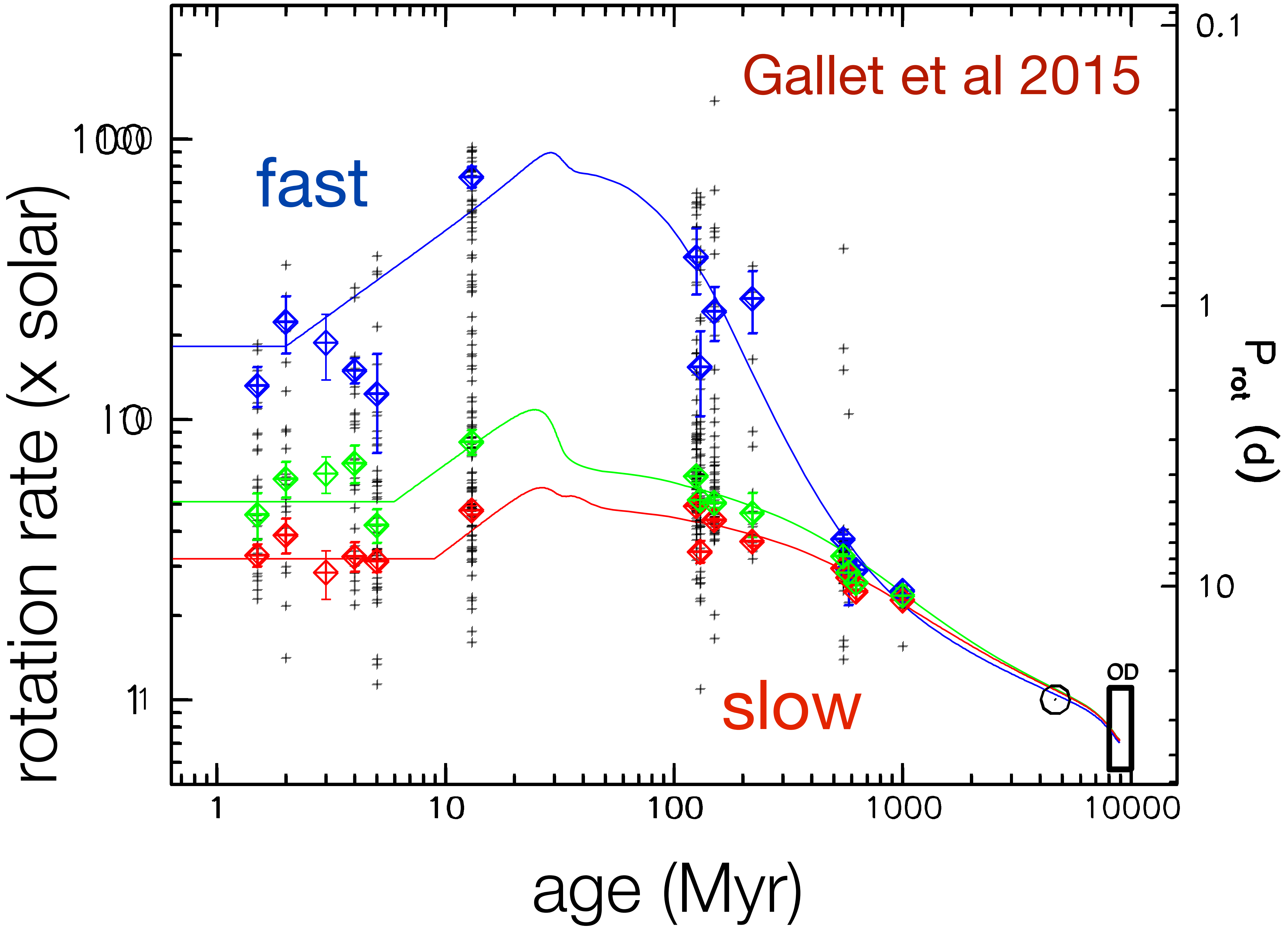
- How has the solar wind evolved in the past 4 billion years?
- What is the implication for young exoplanetary systems?
- How do stellar winds affect exoplanets (magnetosphere and atmosphere)?

● solar-like stars (MS)
○ M dwarfs/evolved stars
● Sun
↓ upper limits

Vidotto 2021, Living Reviews in Solar Physics

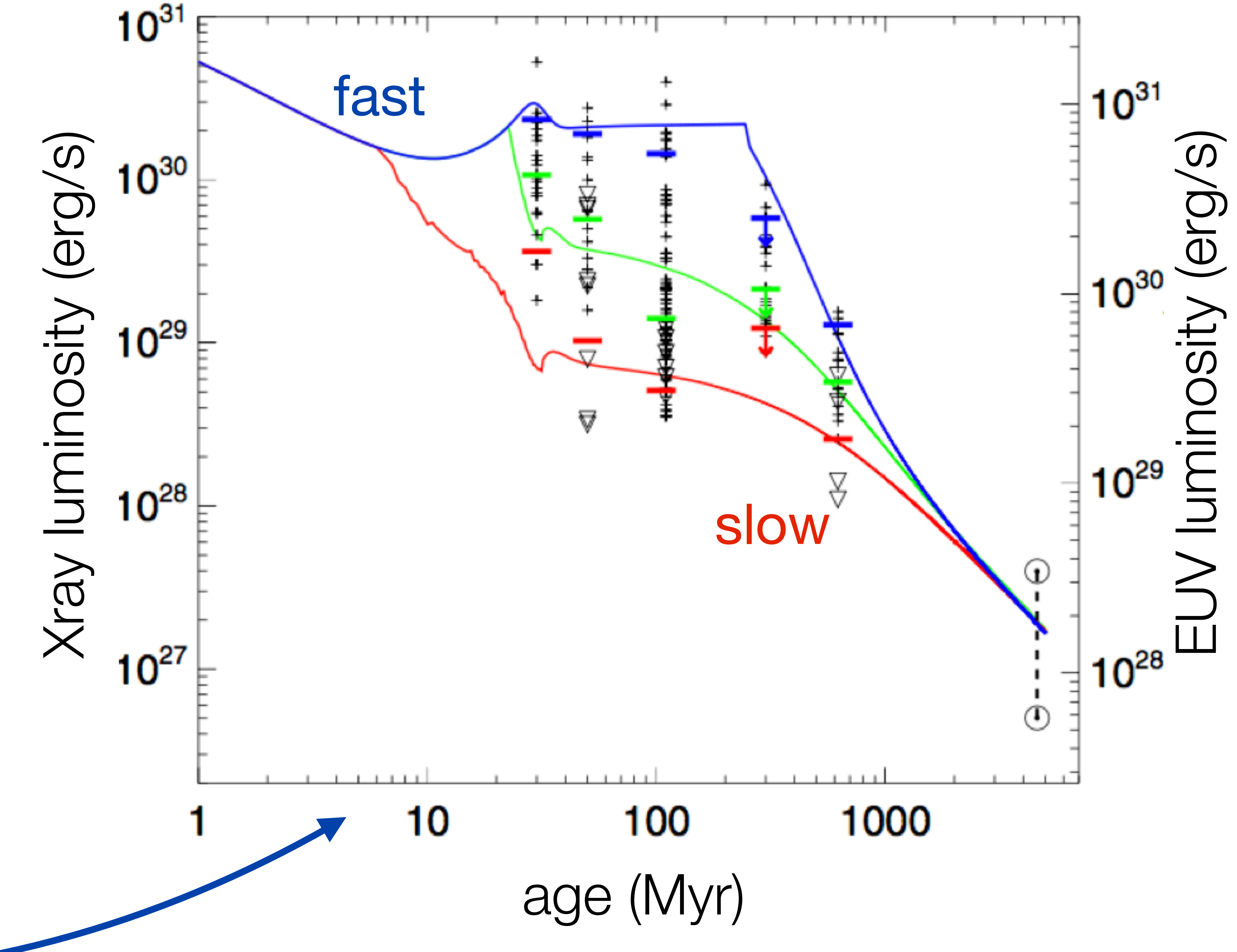
Planetary evaporation in evolutionary timescales: stellar X/EUV flux

Observations of stellar rotation at different ages



Tu et al 2015

Stellar rotation ⟷ age ⟷ Stellar activity

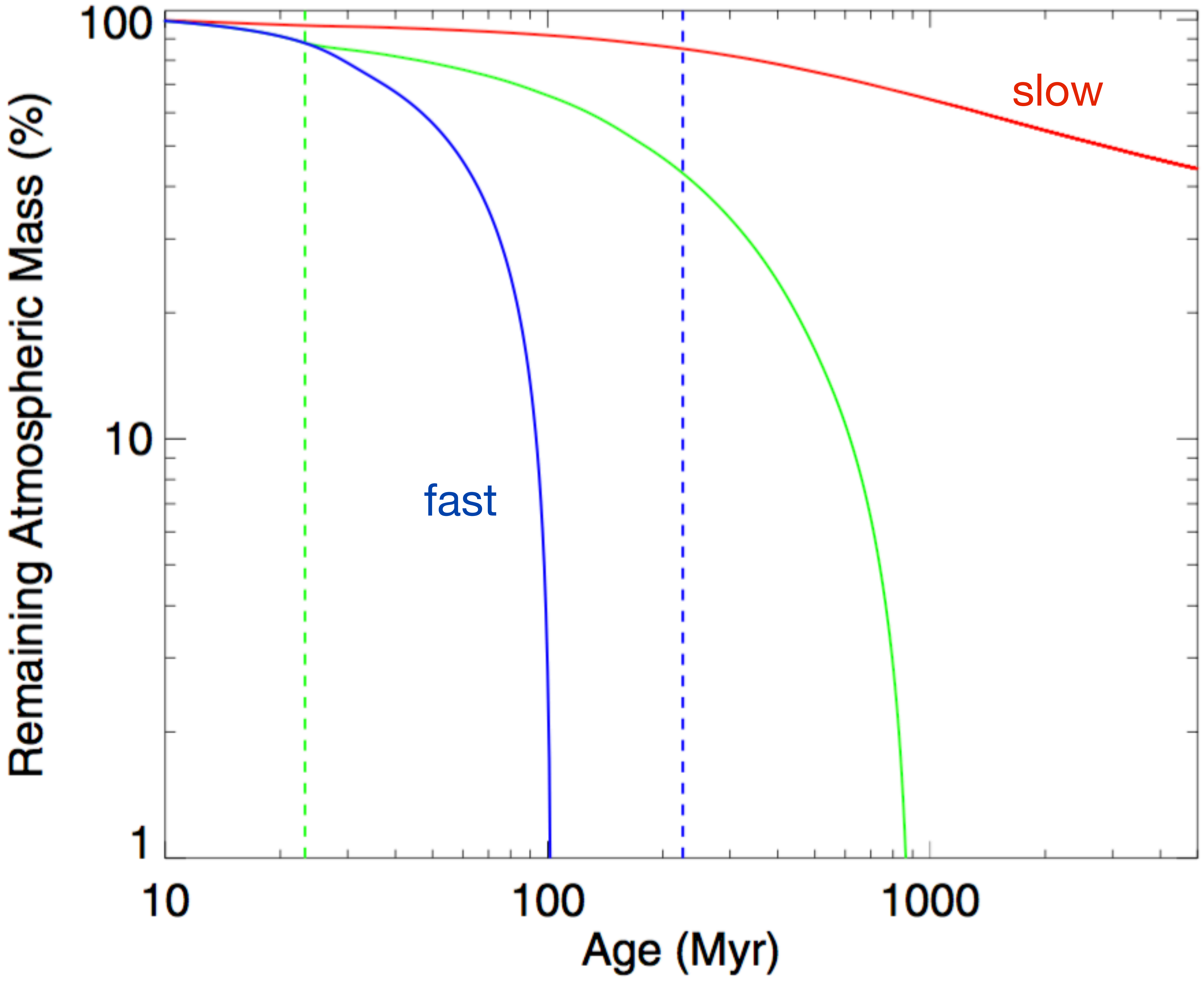


The extreme ultraviolet and X-ray Sun in Time: evaporation of planetary atmosphere

Tu et al 2015

Atmospheric evaporation of a 0.5$M_\oplus$ planet @ 1au

$M_{atm,initial}$=0.5% $M_\oplus$

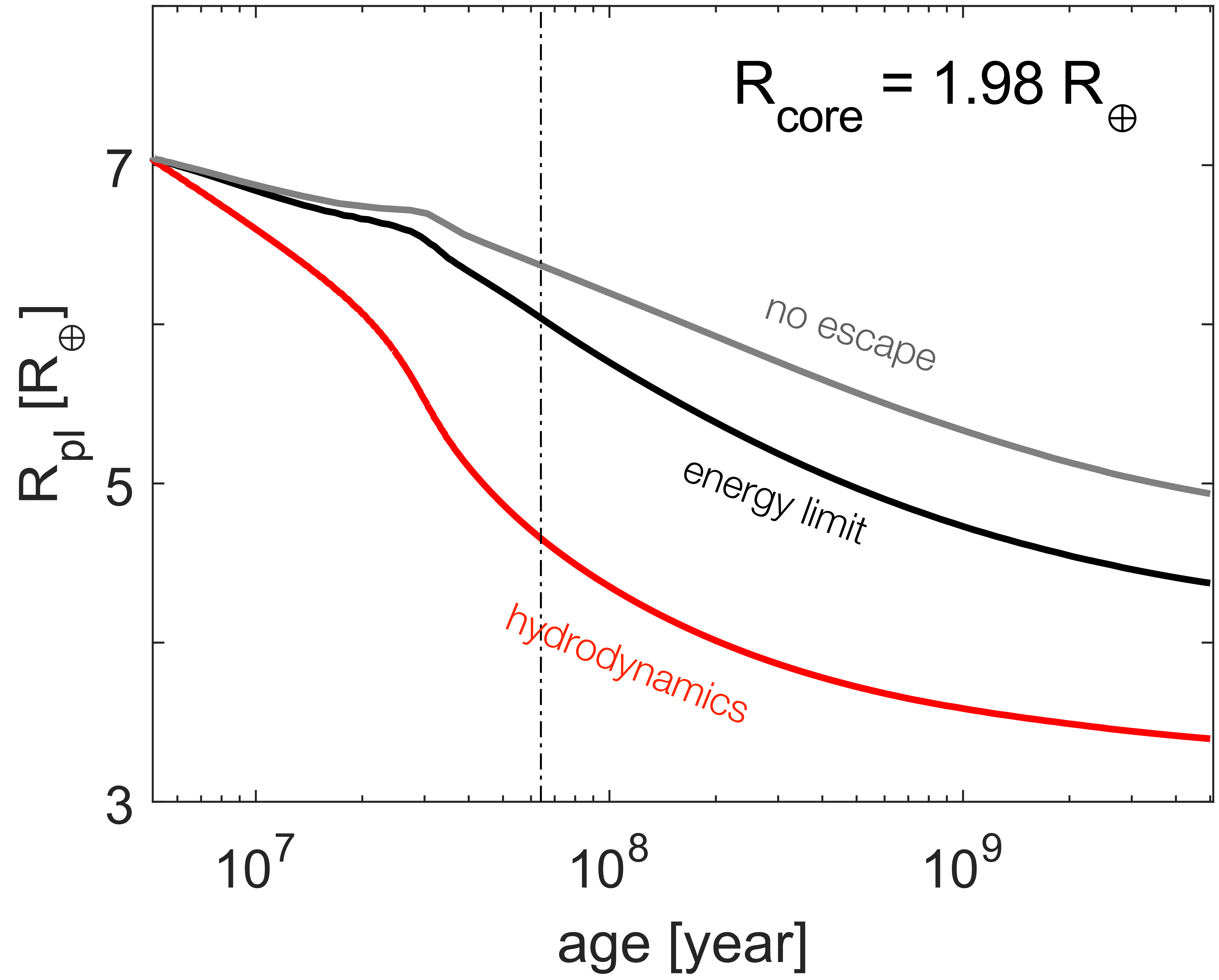


H content of the planetary atmosphere is very different if orbiting:

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

Escape affects the internal structure of the planet

Kubyshkina et al 2020, Kubyshkina & Vidotto 2021



Free tools!

If you don’t have access to a hydrodynamical model, python interpolator tools from Daria Kubyshkina available at

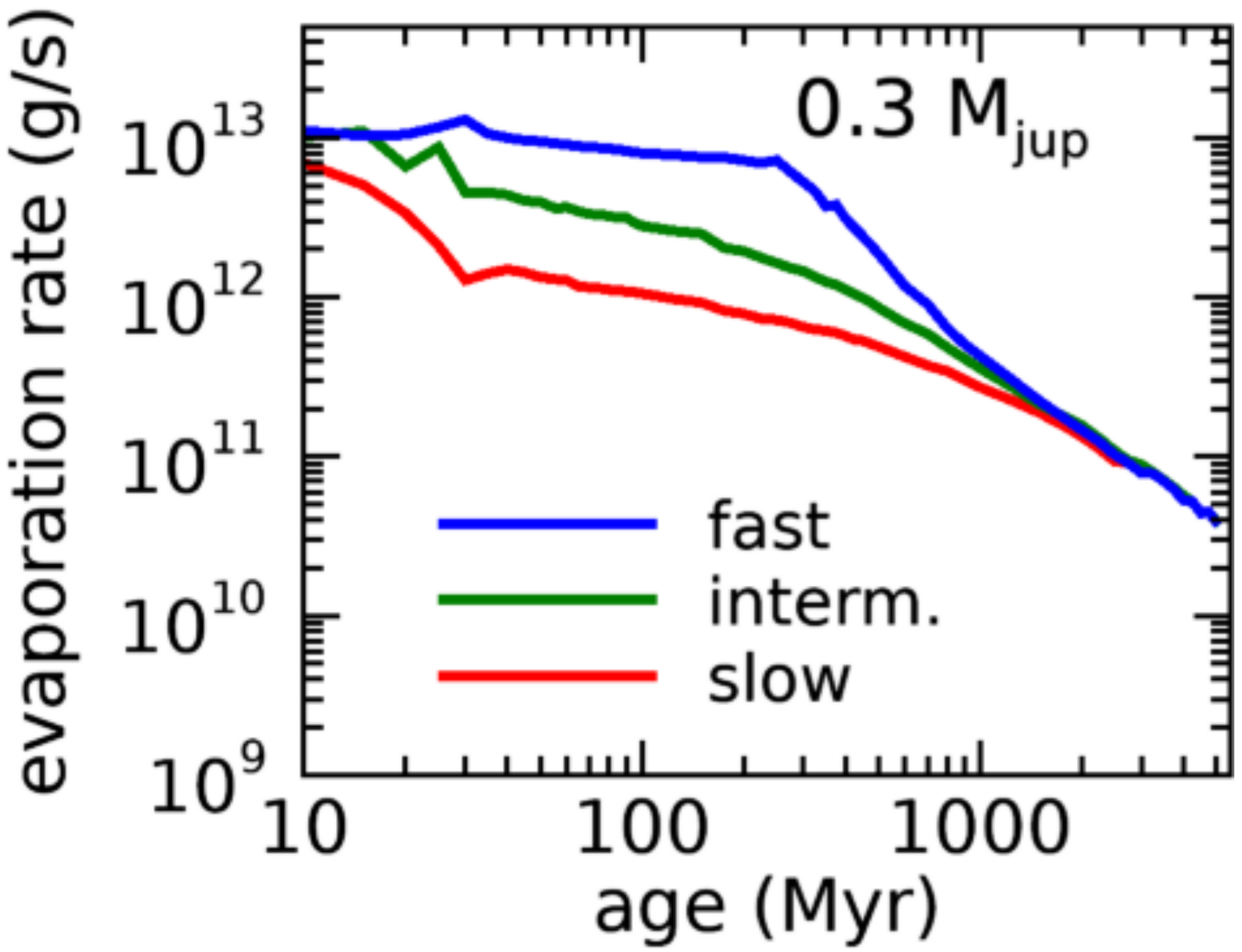
doi.org/10.5281/zenodo.4643823

Planetary evolution with MESA & atmospheric escape
* Run your own model! inlists publicly available

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

Predicted observational signatures of atmospheres of close-in planets

Evaporation rates higher
at young ages



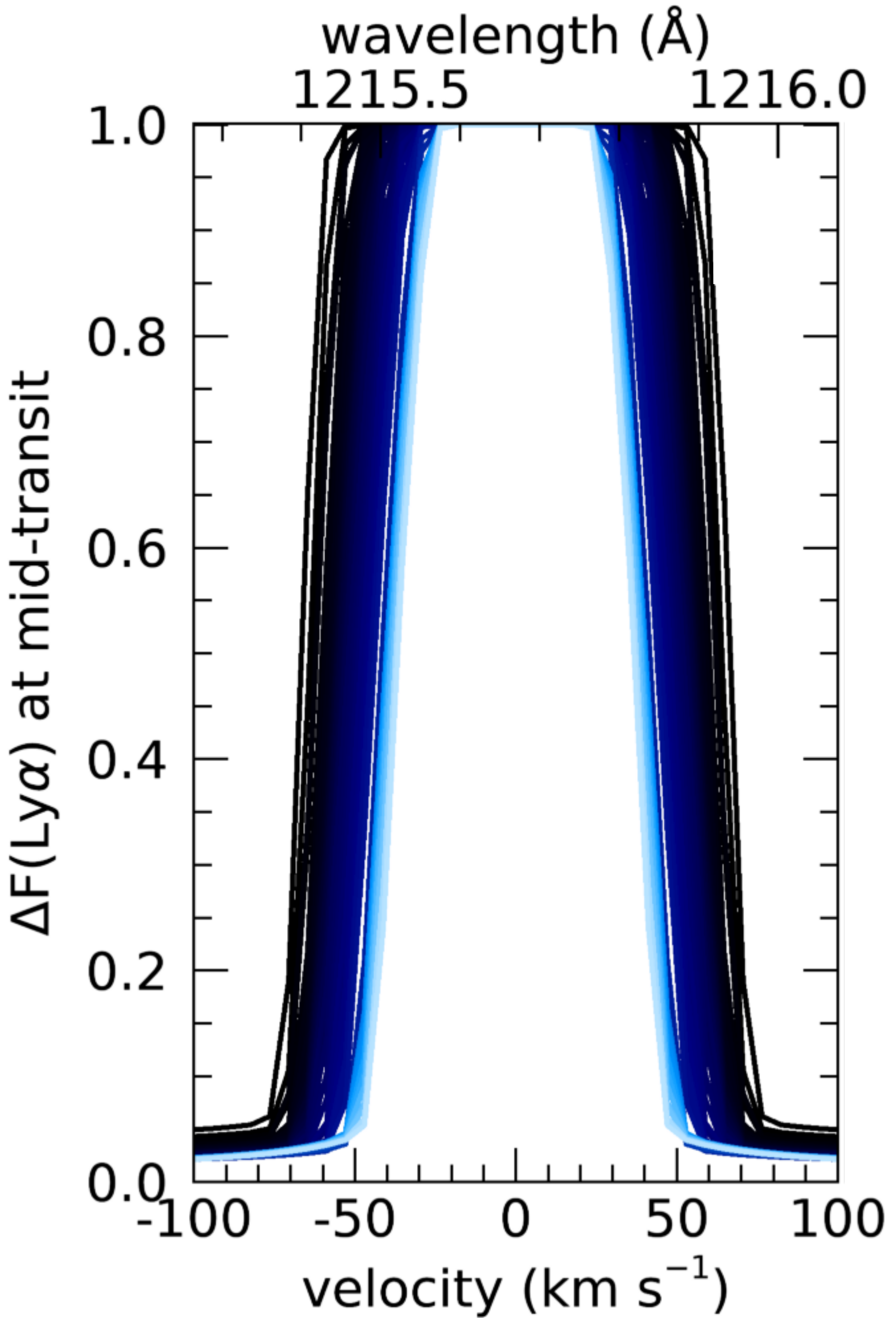
~20% mass lost through evolution

planet @
0.045au

Symmetric profiles: lack of stellar wind interactions

Allan & Vidotto 2019

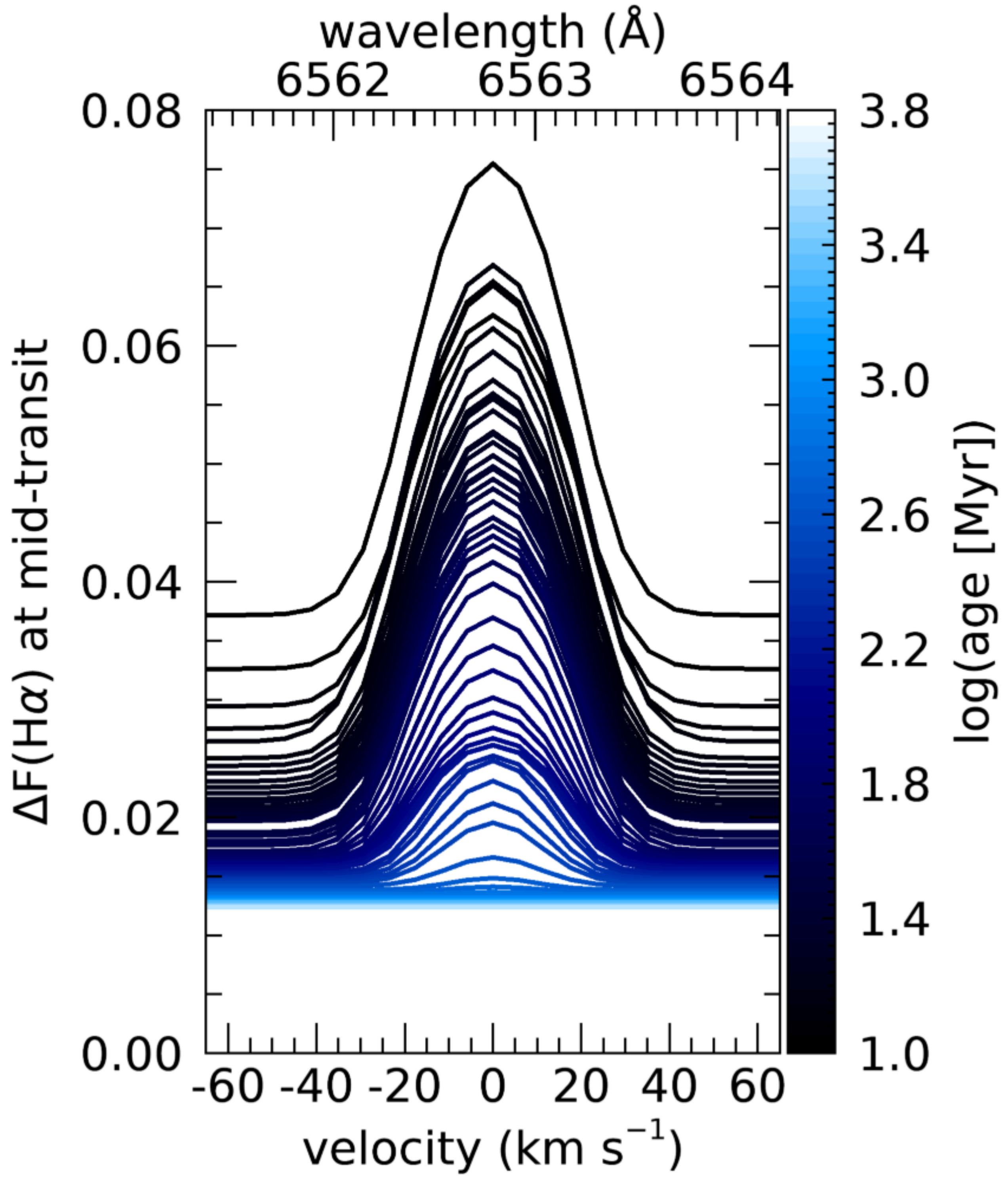
Ly-α



At younger ages:

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

H-α



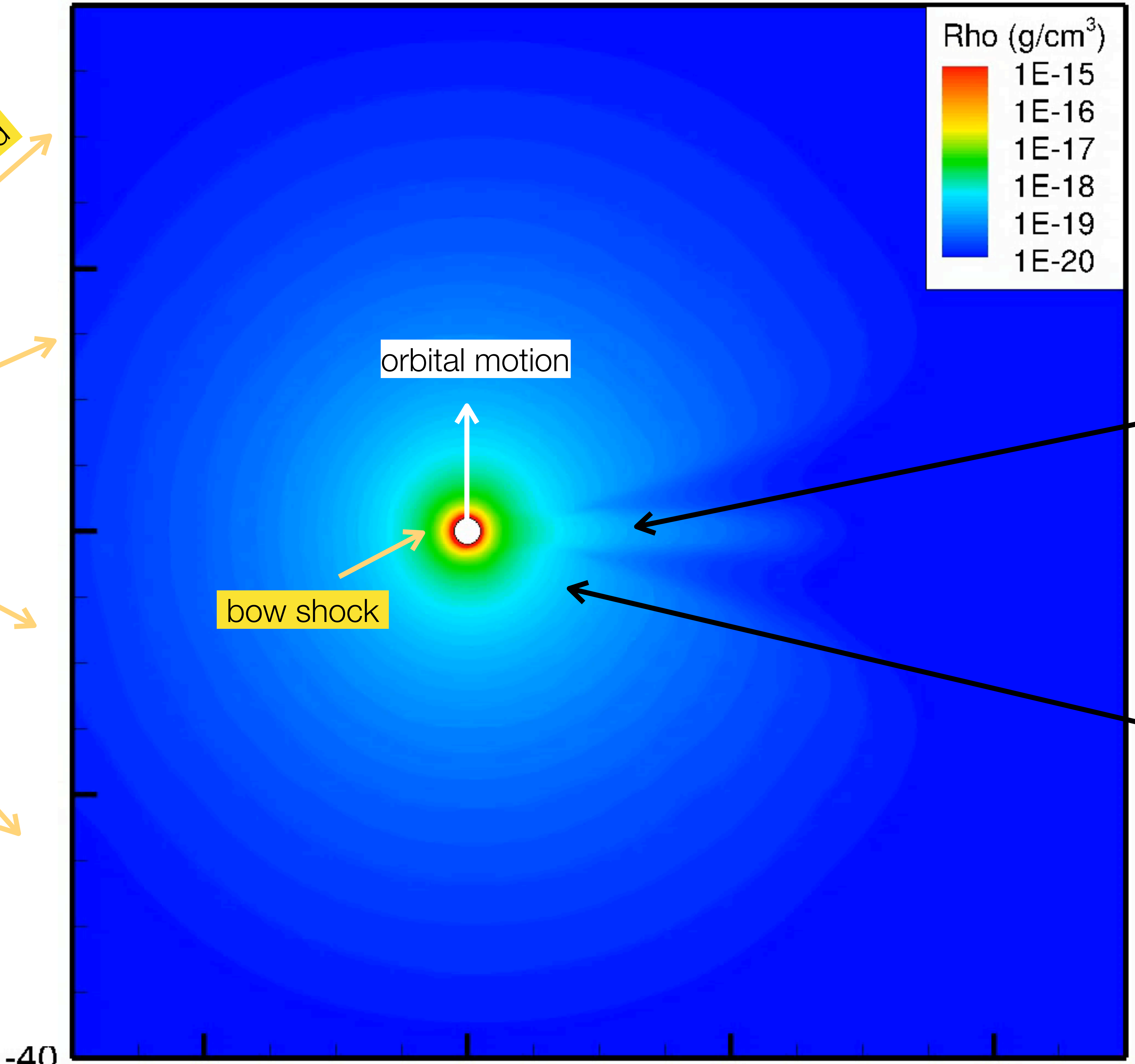
- Hα transits with depths ~3 - 4% in excess of geometric transit

3 Stellar wind interaction with atmospheres of exoplanets

©Garlick/U.of Warwick

Stellar wind stripping

Carolan, Vidotto et al
in prep.



stellar wind

star

orbital motion

bow shock

planet’s shadow (nightside)

tail shaped by the stellar wind interaction + orbital motion

How can stellar winds affect atmospheres of close-in exoplanets?

Create atmospheres
(HD219134, Vidotto+2018)

Erode atmospheres
(young Mars, Kulikov+2007)

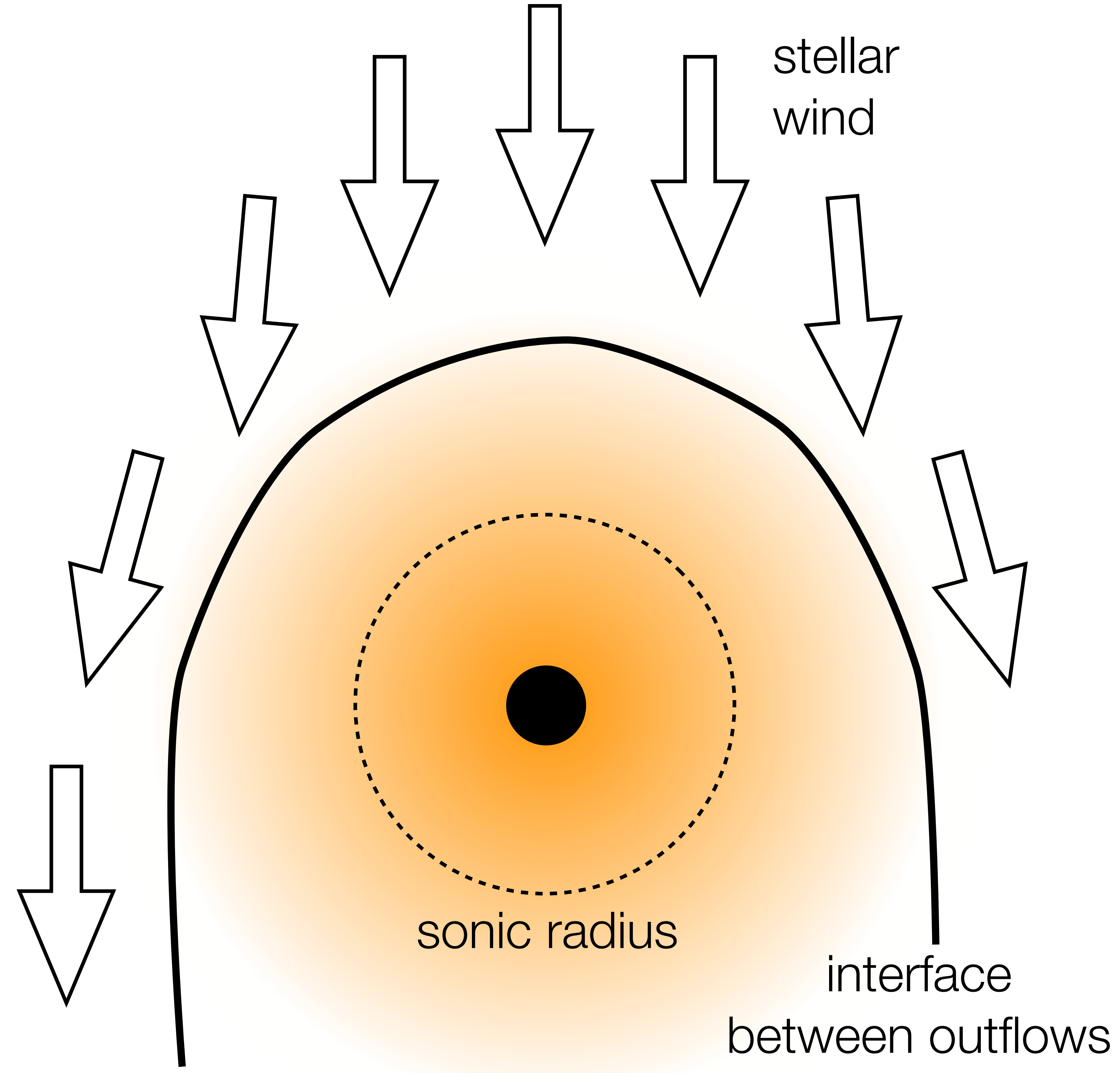
Prevent escape
(Vidotto & Cleary 2020, next slides)

Do nothing?

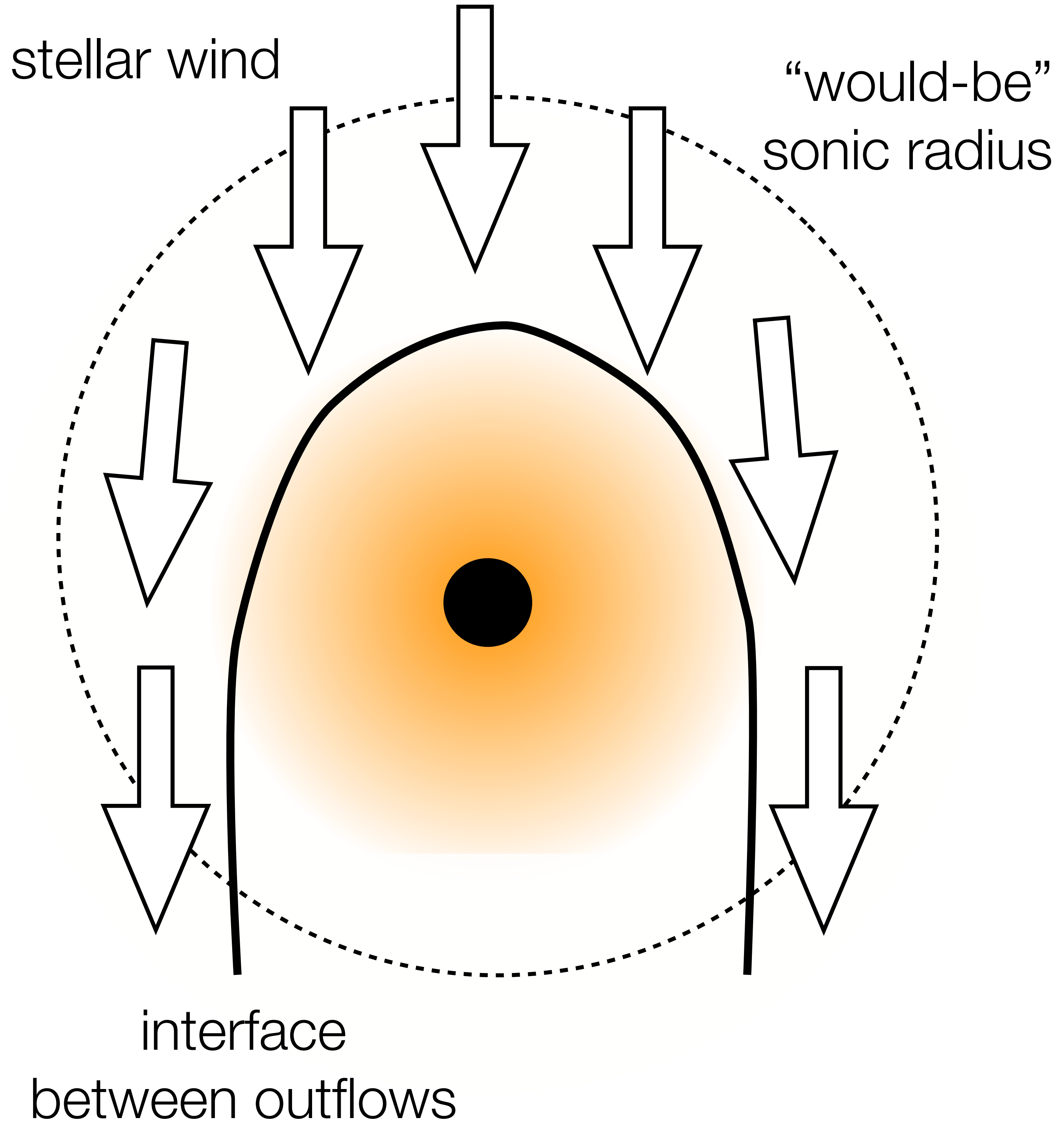
How stellar outflows influence planetary mass loss

Vidotto & Cleary 2020

Stellar wind shapes planetary outflow, affecting observational signatures, but not escape rates



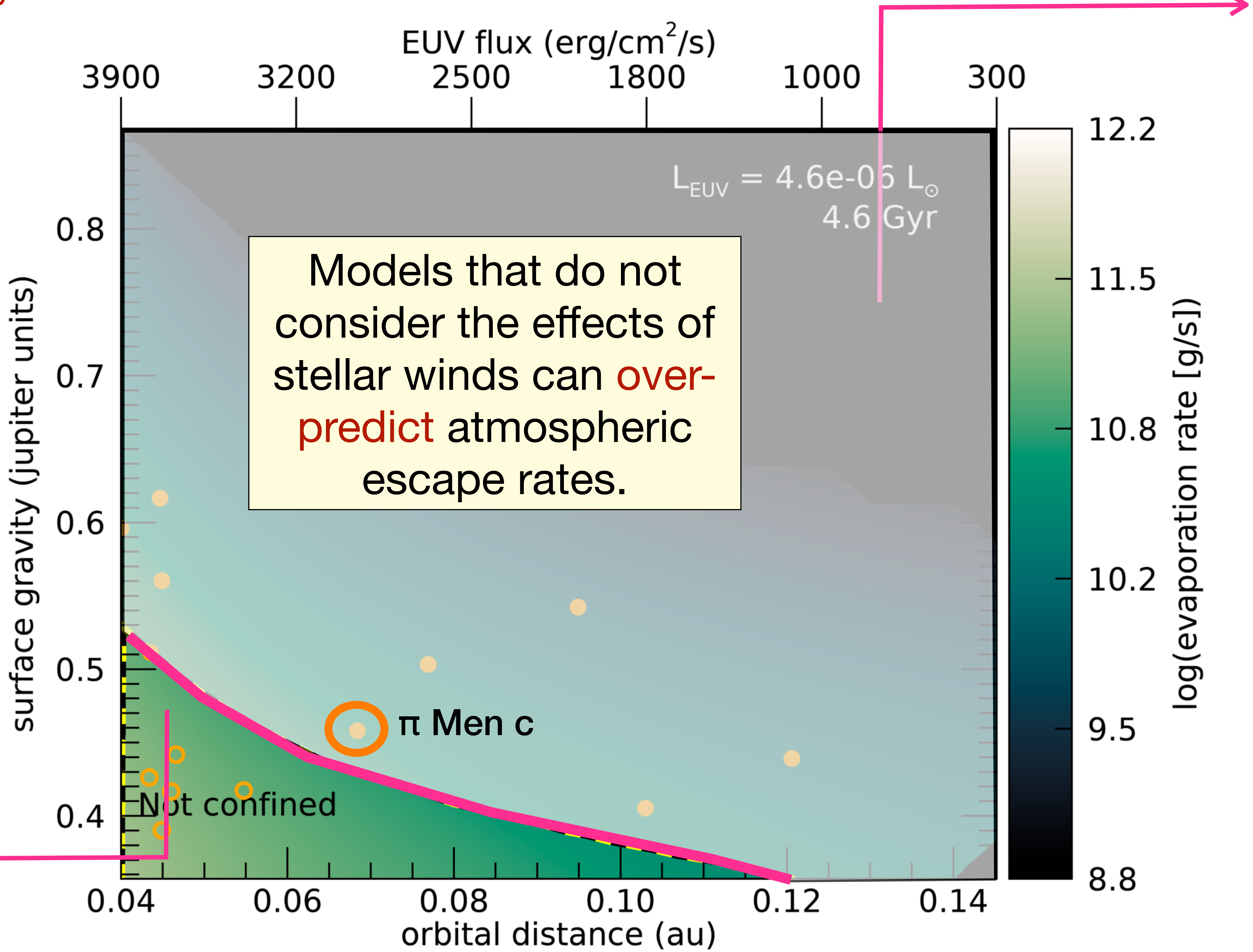
Stellar wind squashes planetary outflow, reducing/preventing atmospheric escape



Stellar winds can reduce or even suppress mass loss from their exoplanets

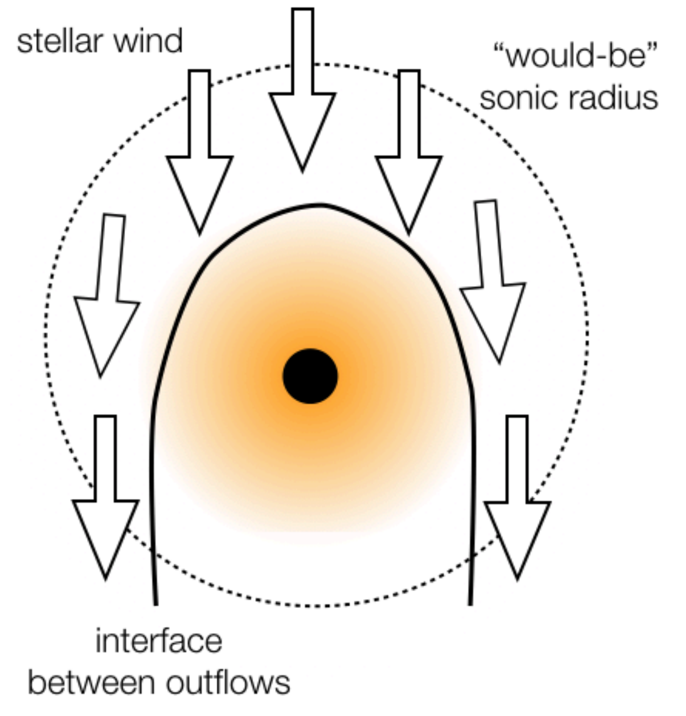
Stellar winds **confine** atmospheric escape of close-in planets

Vidotto & Cleary 2020



Models that do not consider the effects of stellar winds can over-predict atmospheric escape rates.

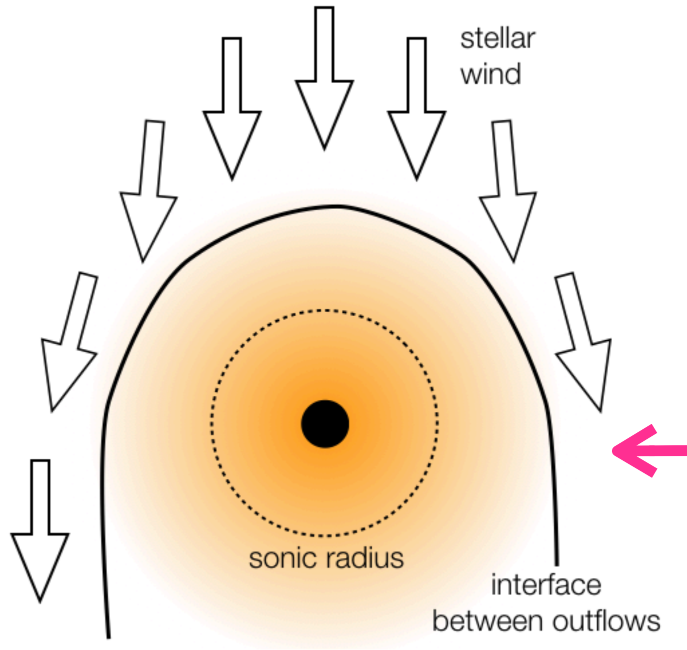
Confined



π Men c: expected strong atmospheric escape, but none was detected! (Garcia-Munoz et al 19)

Confined by stellar wind?

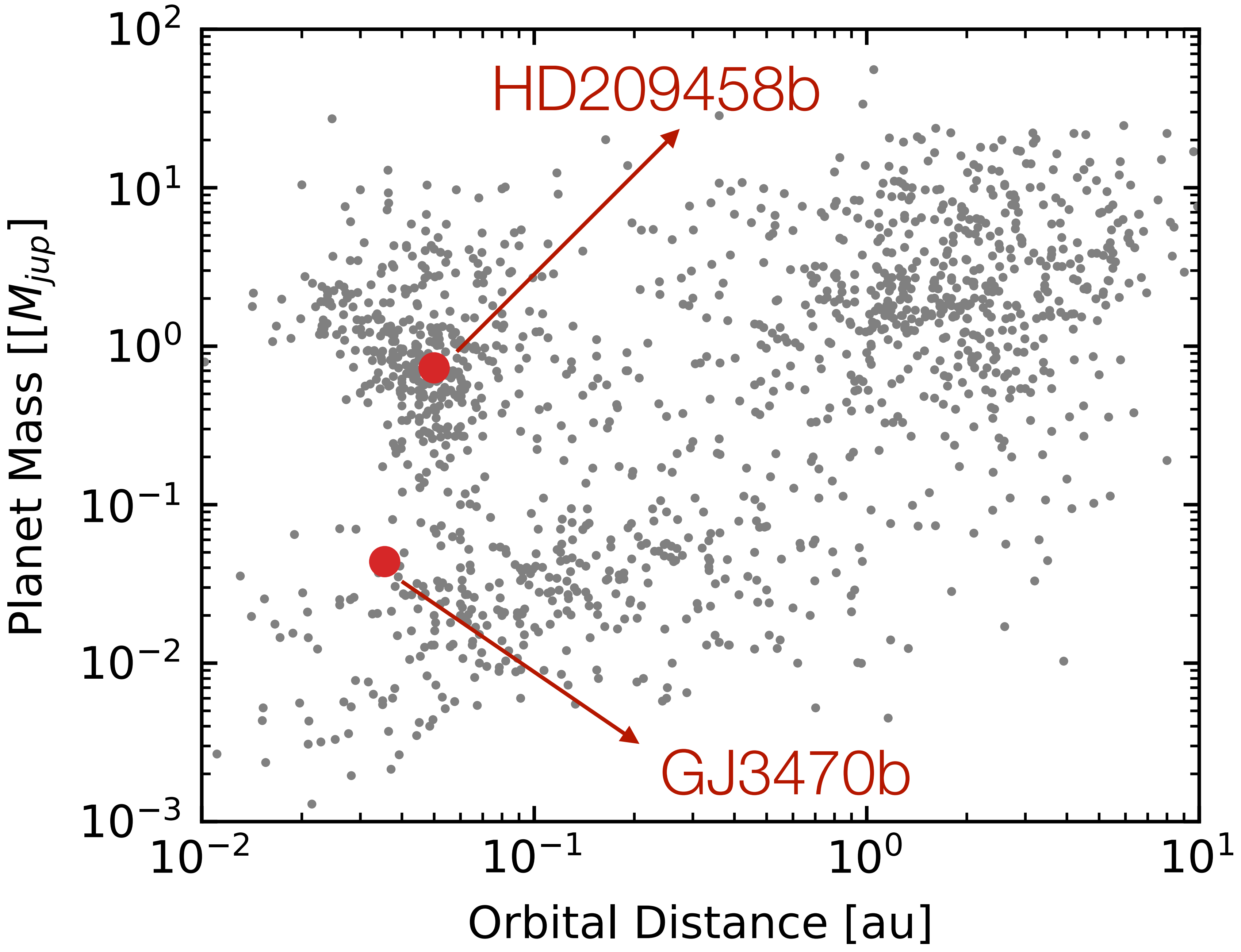
Not confined

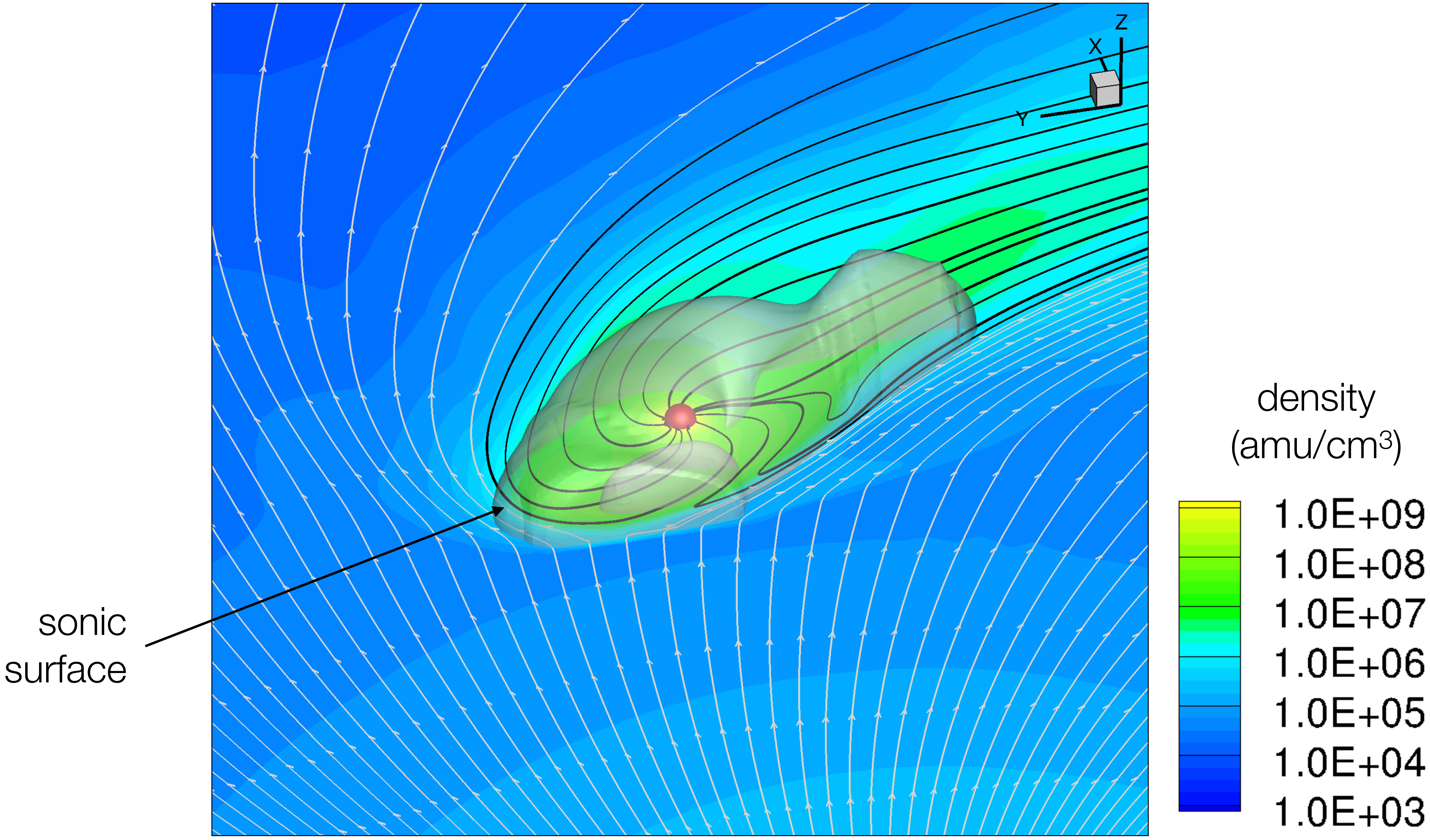


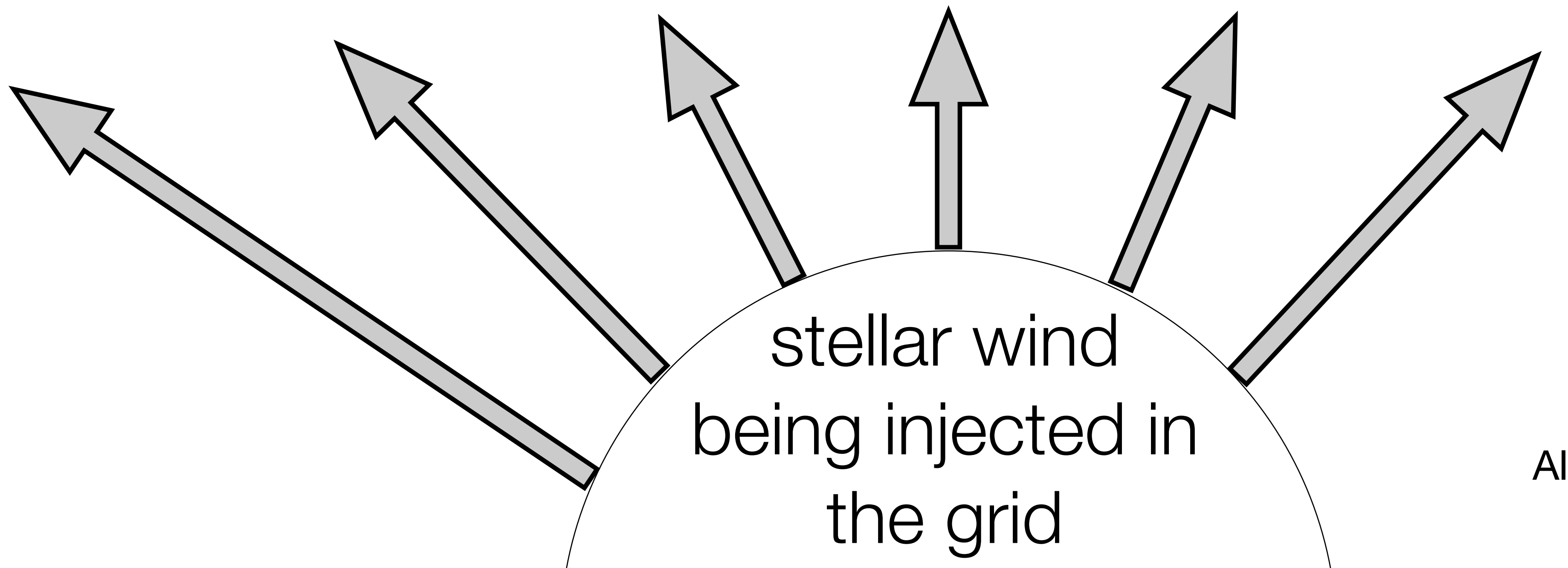
Studies of stellar wind confinement in 3D

Carolan, Vidotto et al 2020b

- Vidotto & Cleary 2020: 1D radiative hydrodynamics simulations → cannot include stellar wind effects
- 3D hydrodynamic simulations of typical hot Jupiter & warm Neptune







Lower escape rates after disruption of sonic surface

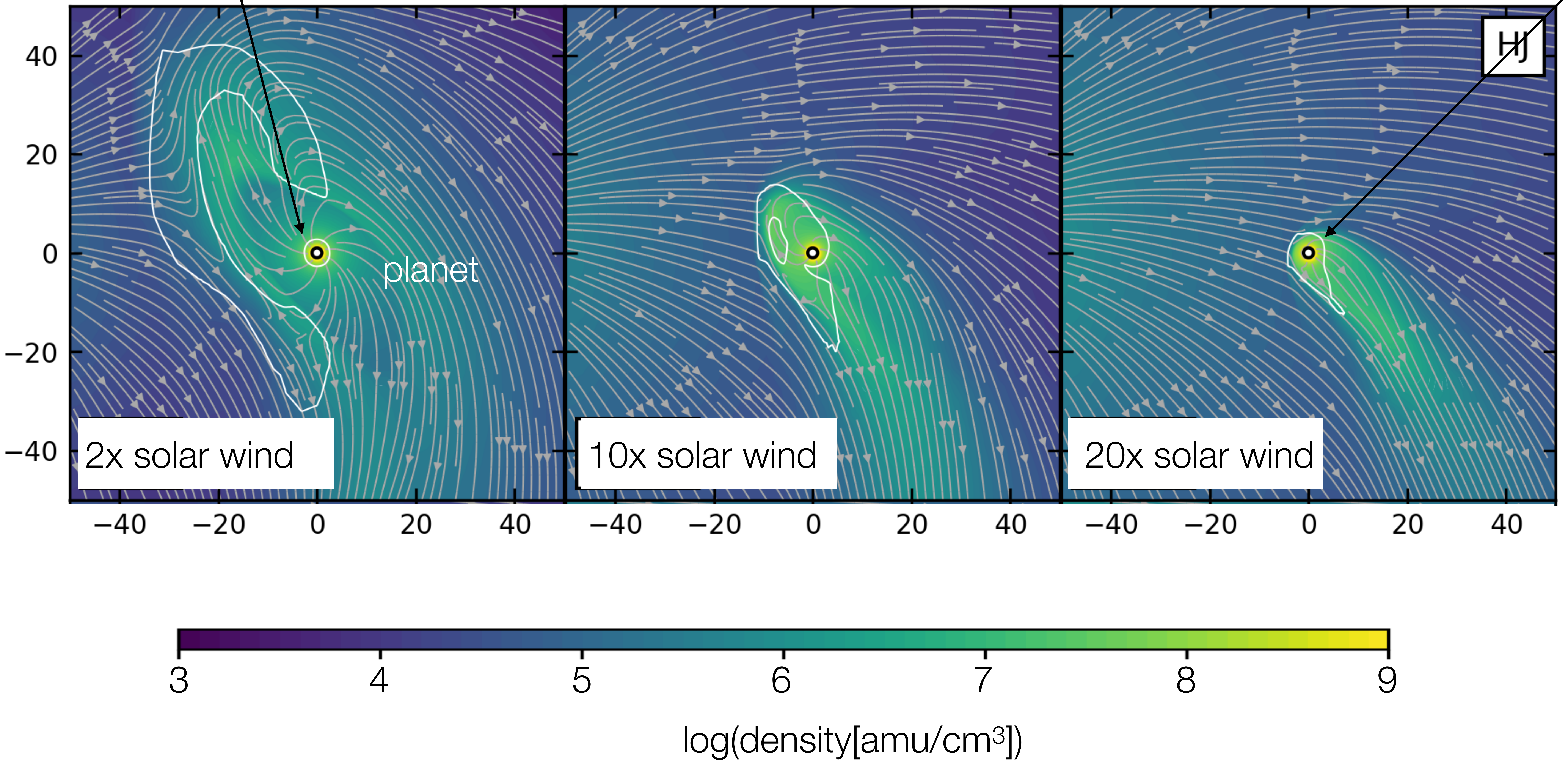
Carolan, Vidotto et al 2020b

sonic surface

Increasing stellar wind mass-loss rate

sonic surface

Closed (undisturbed sonic surface) → Open (disrupted sonic surface)



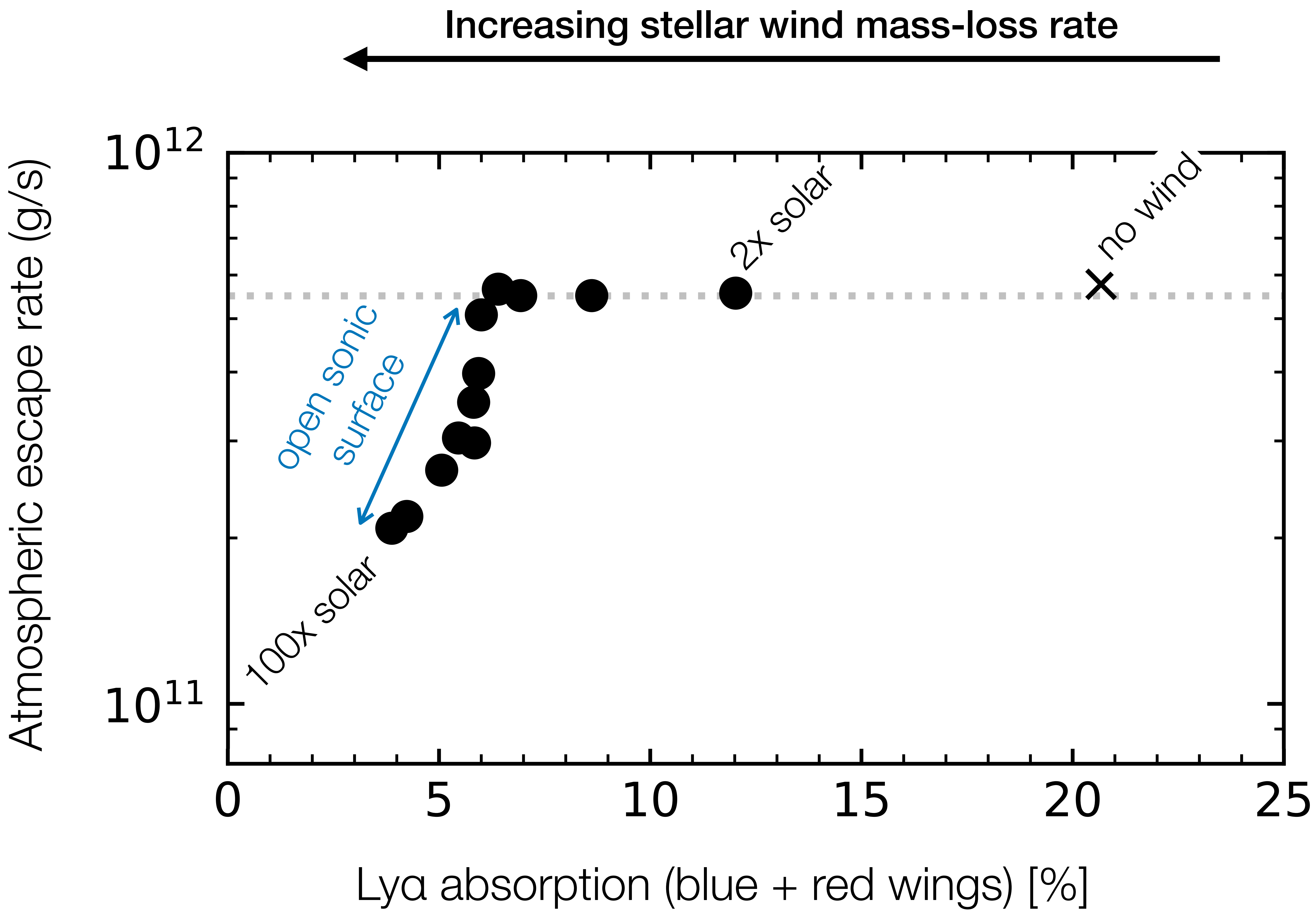
Stronger stellar winds:

- 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 2020b



Hot Jupiter

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

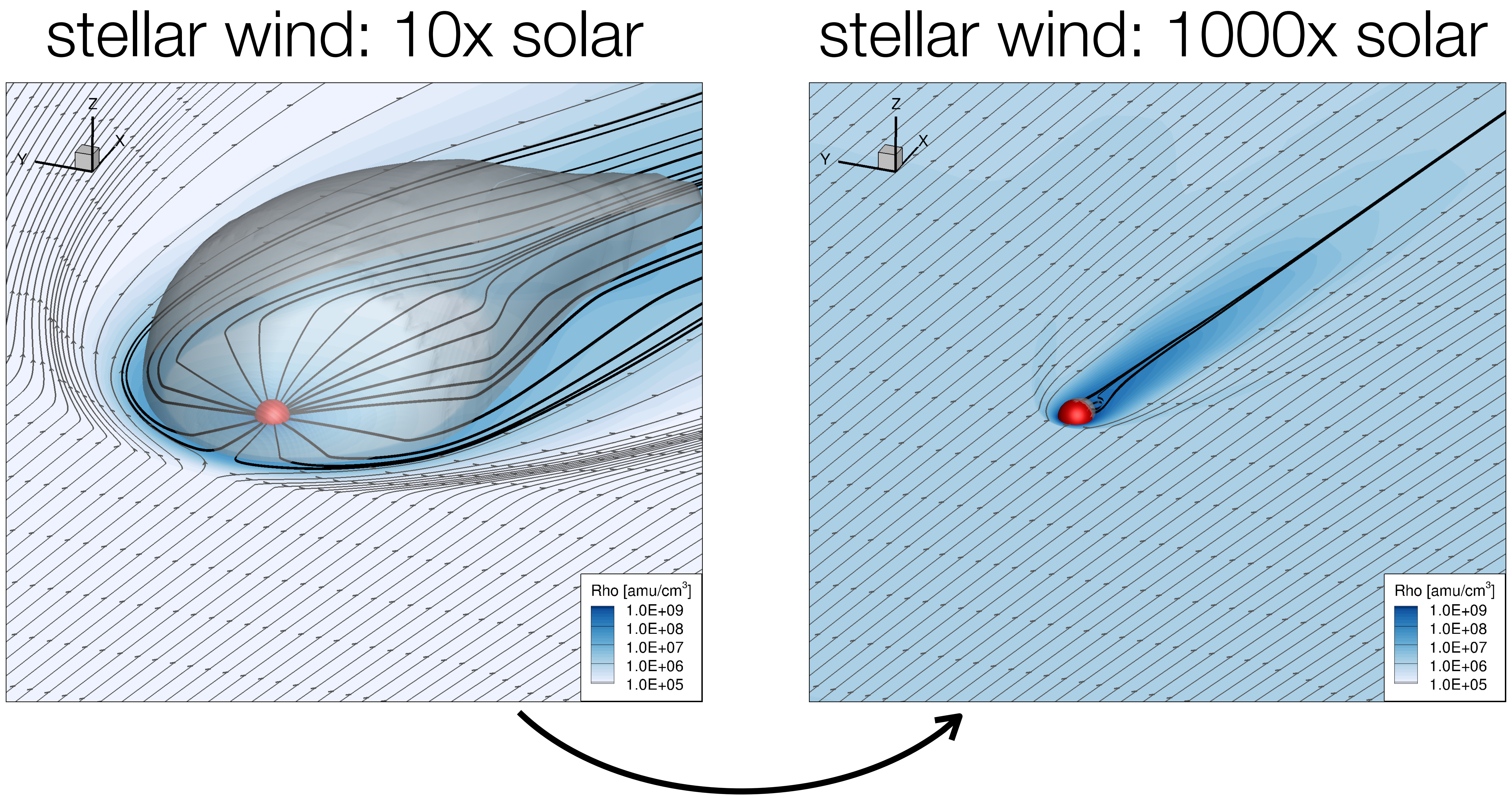
The dichotomy of AU Mic b

Carolan, Vidotto et al 2020a

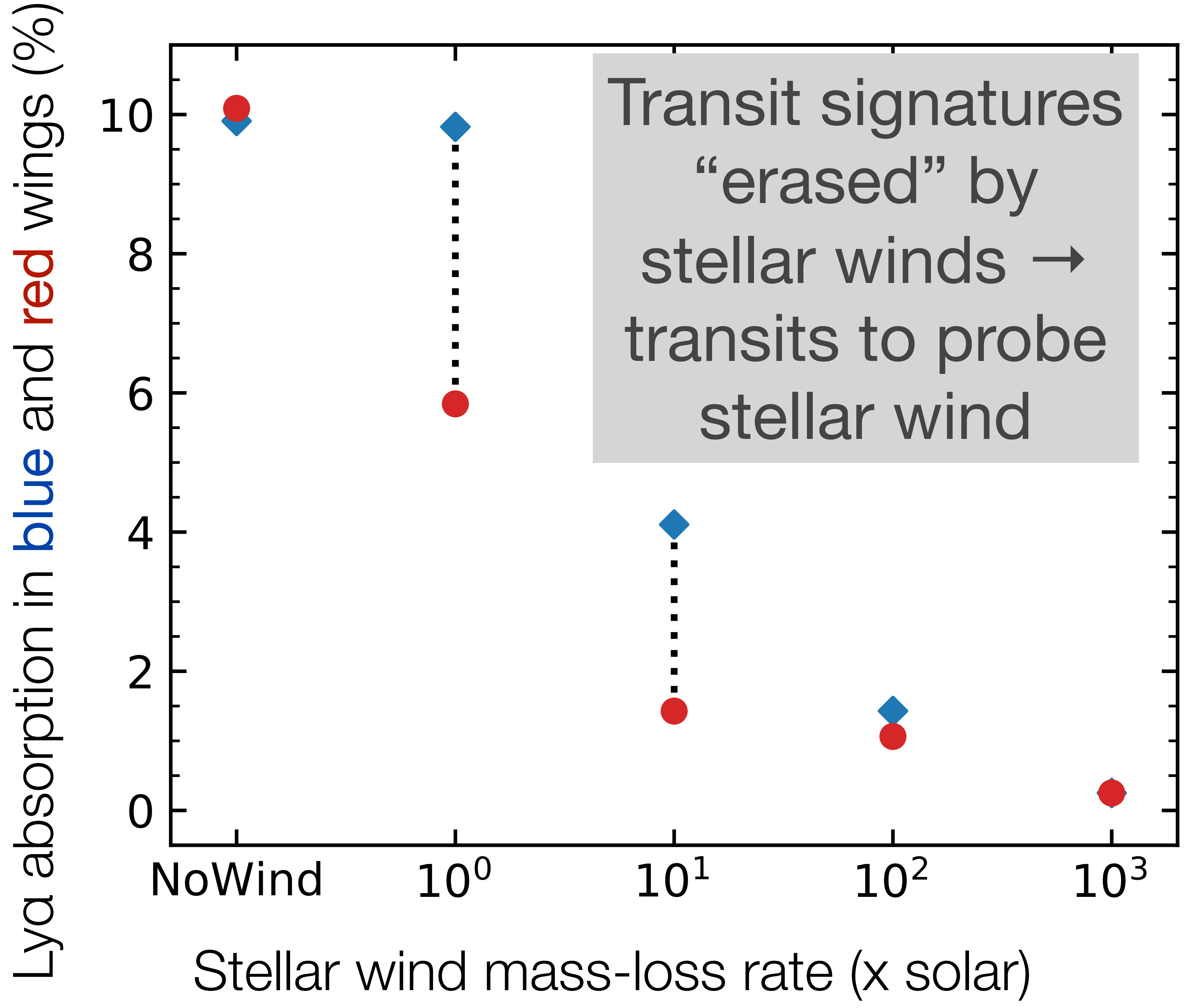
- AU Mic b: Neptune-size planet orbiting a 22 Myr-old, pre-main sequence M dwarf (Plavchan et al 2020)

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



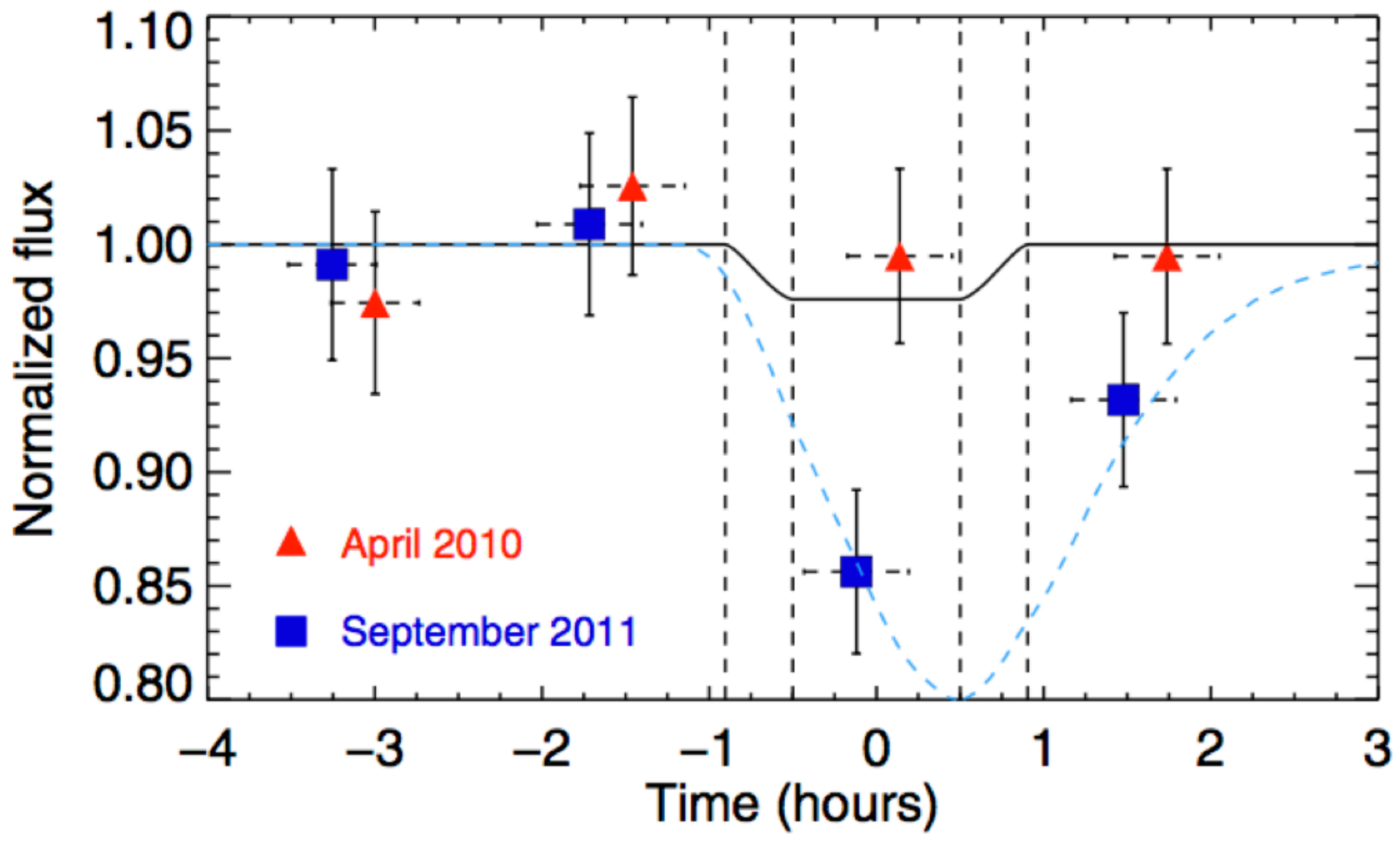
evaporation rate: reduced by 50%

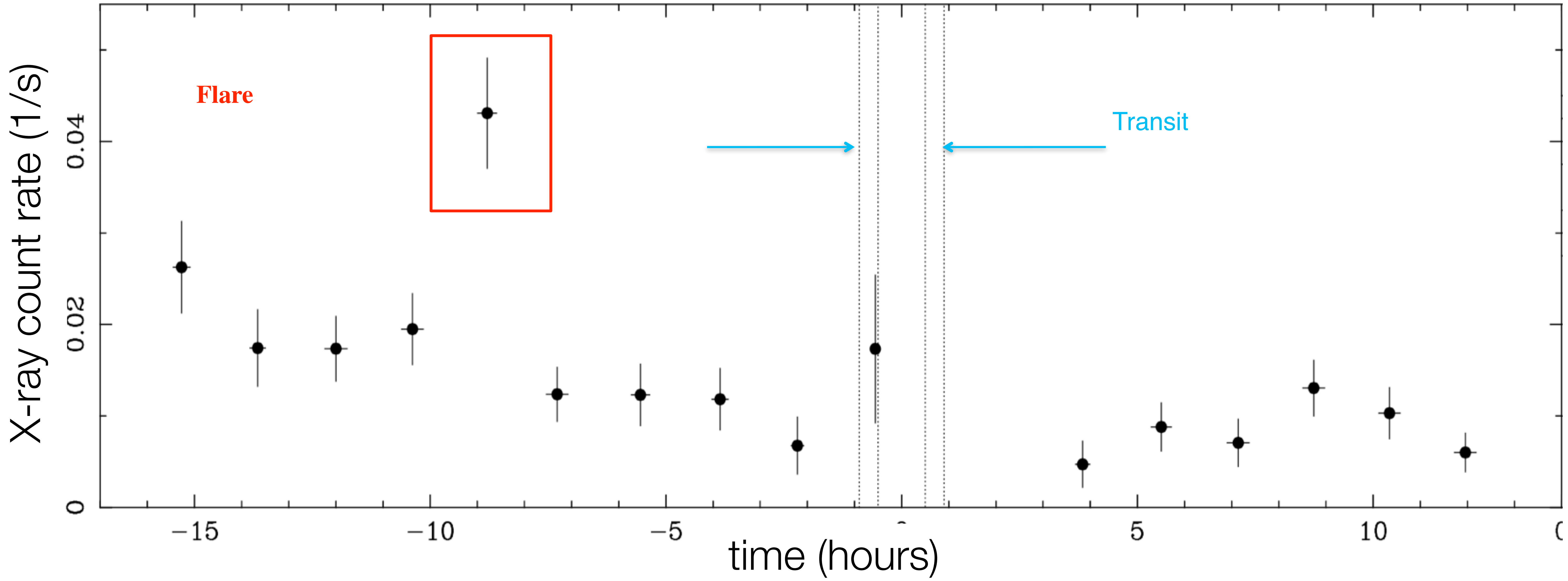


Transit signatures "erased" by stellar winds → transits to probe stellar wind

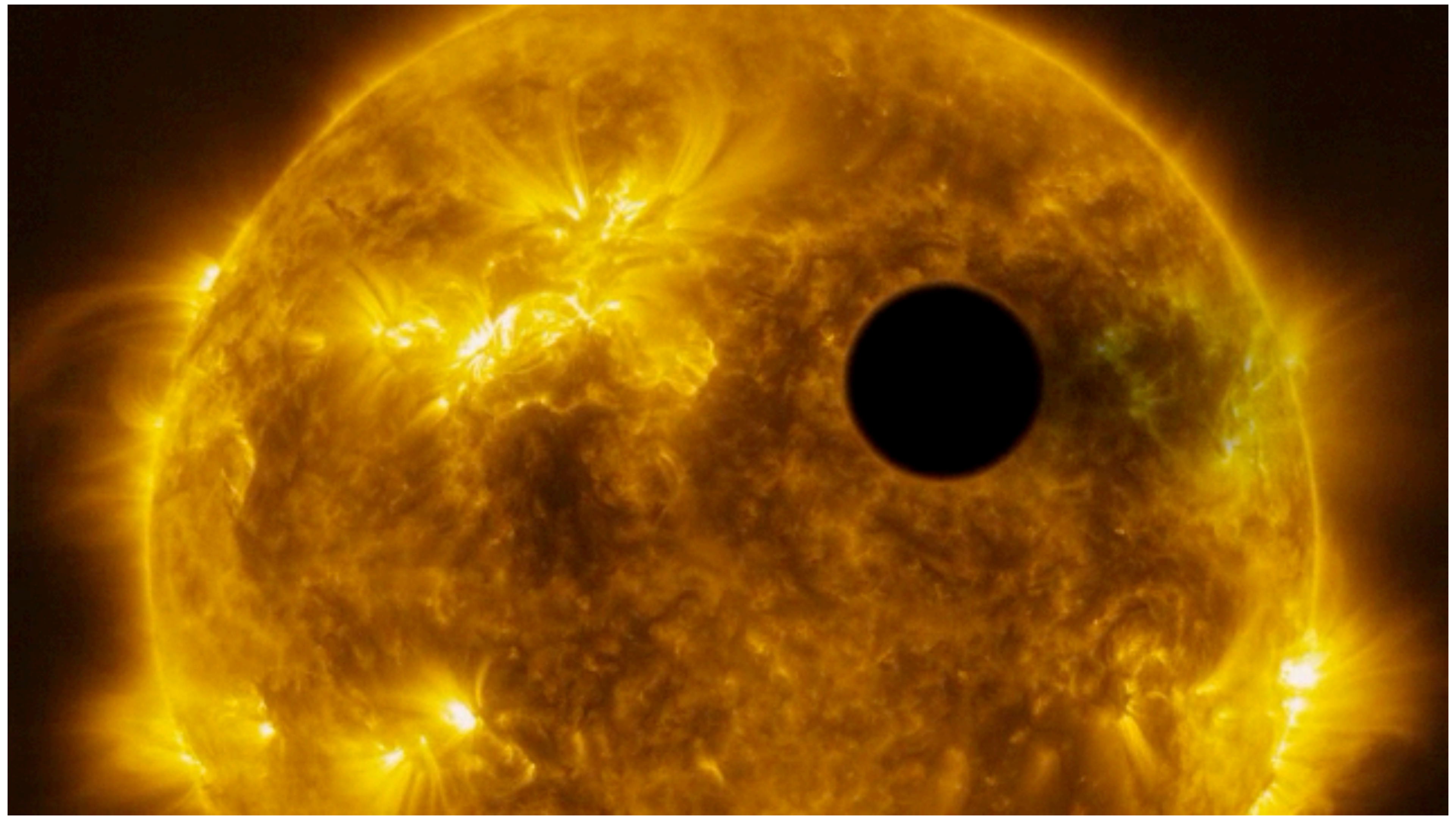
Effects of stellar activity on planetary escape

Temporal variations in the exosphere of HD189733b





Lecavelier +12,
Bourrier +13



Credit: NASA, ESA, L. Calçada, SDO

Possible scenarios:

1. Change of stellar wind properties (passing of a Coronal Mass Ejection)
2. Increase of stellar energy input into the planet’s upper atmosphere

(a) Case-I: Quiescent phase

(b) Case-II: Flare case

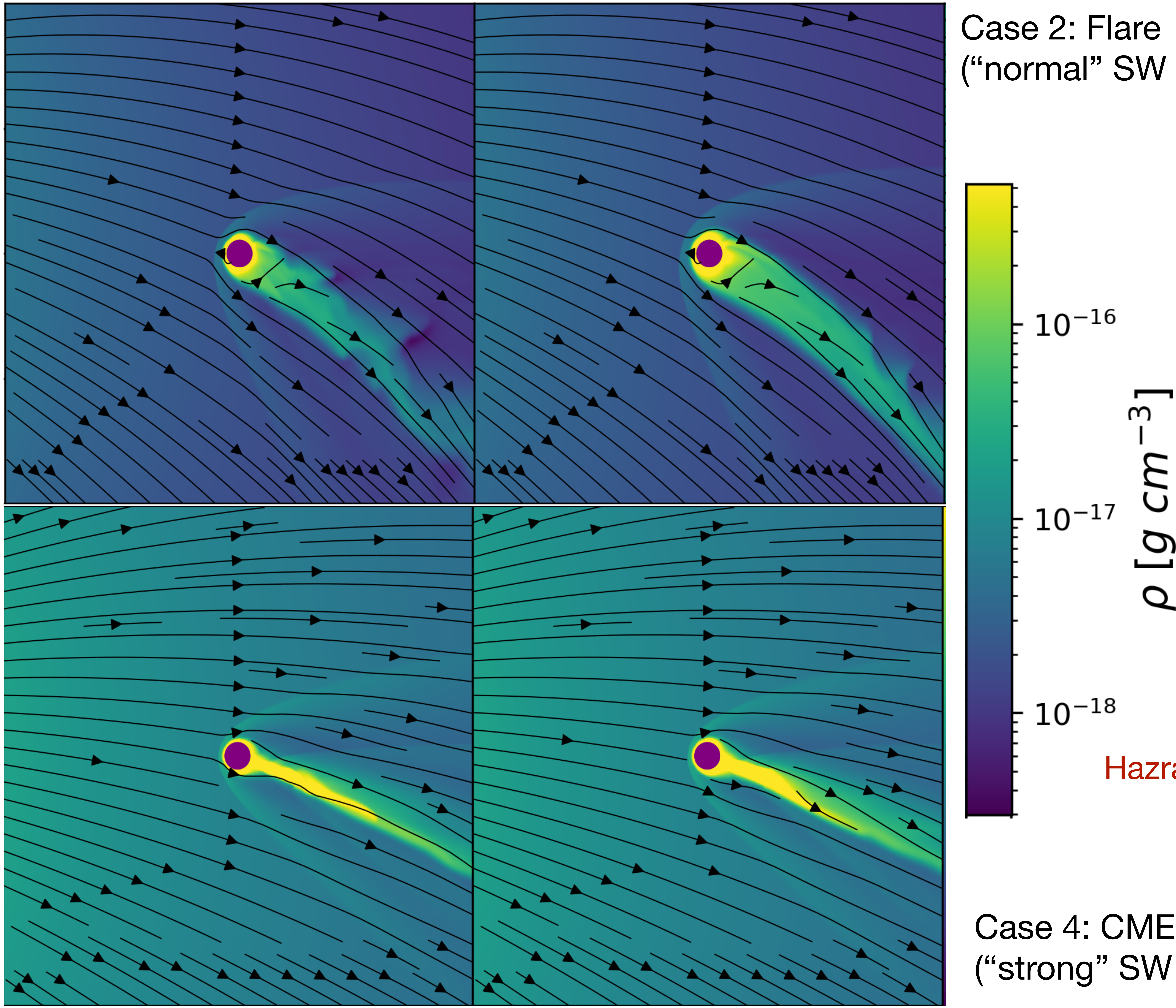
(c) Case-III: CME case

(d) Case-IV: CME and Flare

Hazra, Vidotto et al, submitted

Case 1: Quiescent
(“normal” Stellar wind
+ “normal” F_{xuv})

Case 2: Flare
(“normal” SW + high F_{xuv})



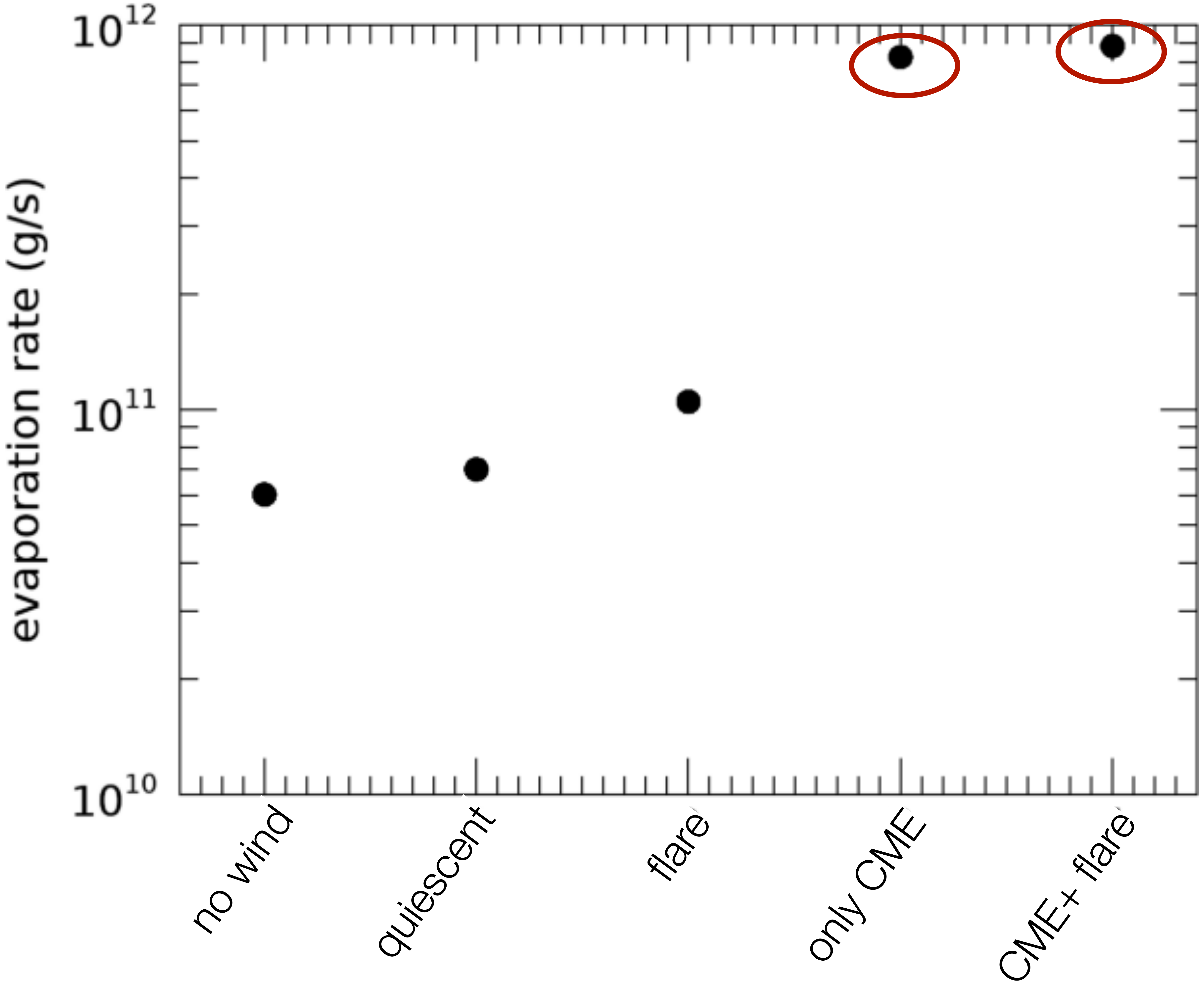
Case 3: CME
(“strong” SW + F_{xuv})

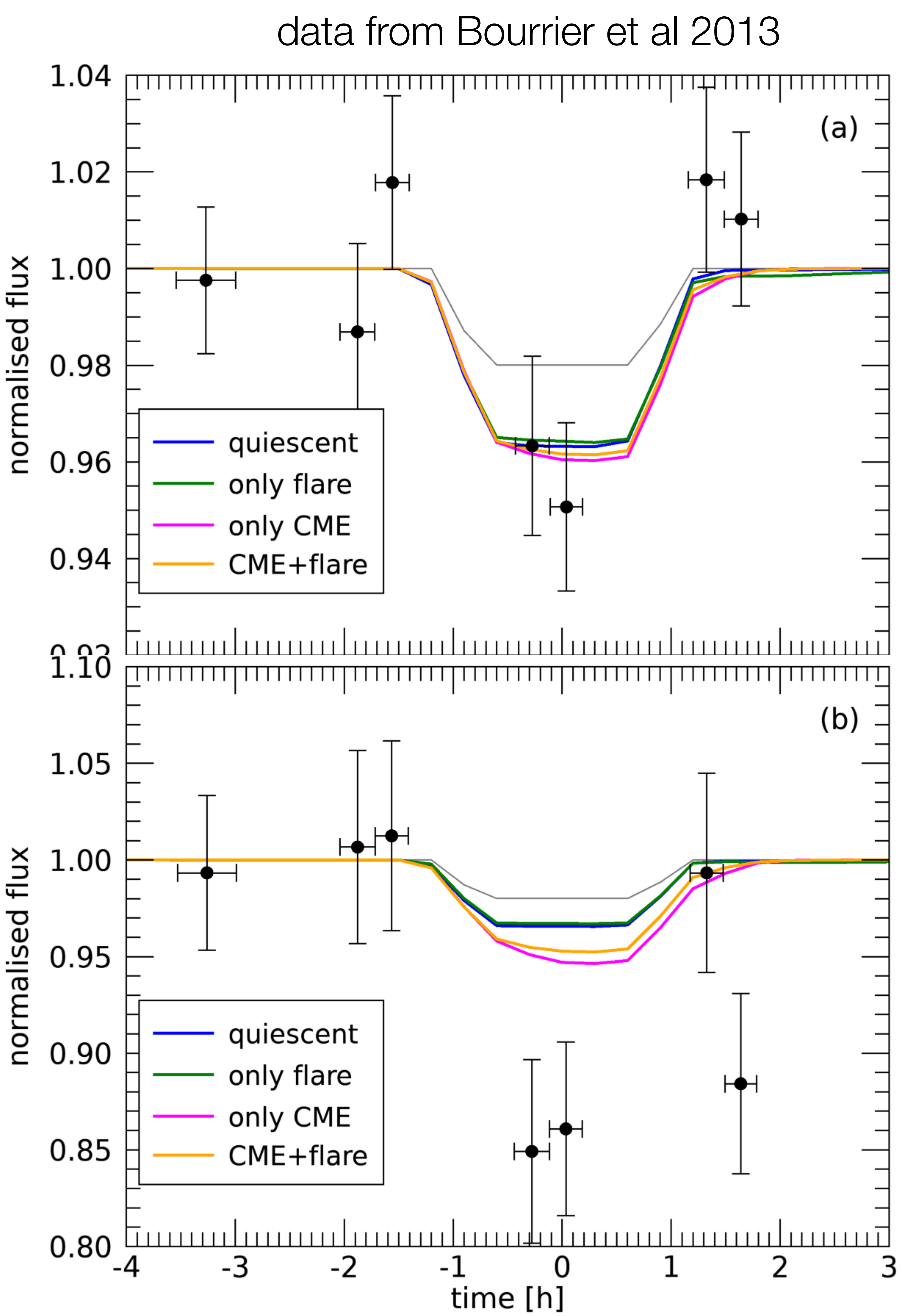
Case 4: CME and Flare
(“strong” SW + high F_{xuv})

Hazra, Vidotto et al,
submitted

Simulated Ly-alpha transits of HD189733b

Hazra, Vidotto et al, submitted




data from Bourrier et al 2013

signature within the full line

✓

signature only considering the blue wing

✗

- Flare alone does not change evaporation significantly
- CMEs are more effective at removing planetary material

What’s next? Effects of magnetic fields on evaporation

“Local” escape simulations of magnetised hot Jupiters (© Carolan)

Conclusions

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

Stellar wind can “*erase*” Ly-α transit signatures in young systems

Stellar winds play important role in atmospheric evaporation: from retention to stripping of atmospheres

Variation in stellar outflows (quiescent wind vs CMEs) can affect planetary evaporation momentarily

@AlineVidotto