VI Astrobion – September 2026

Atmospheric Escape and Tidal Heating

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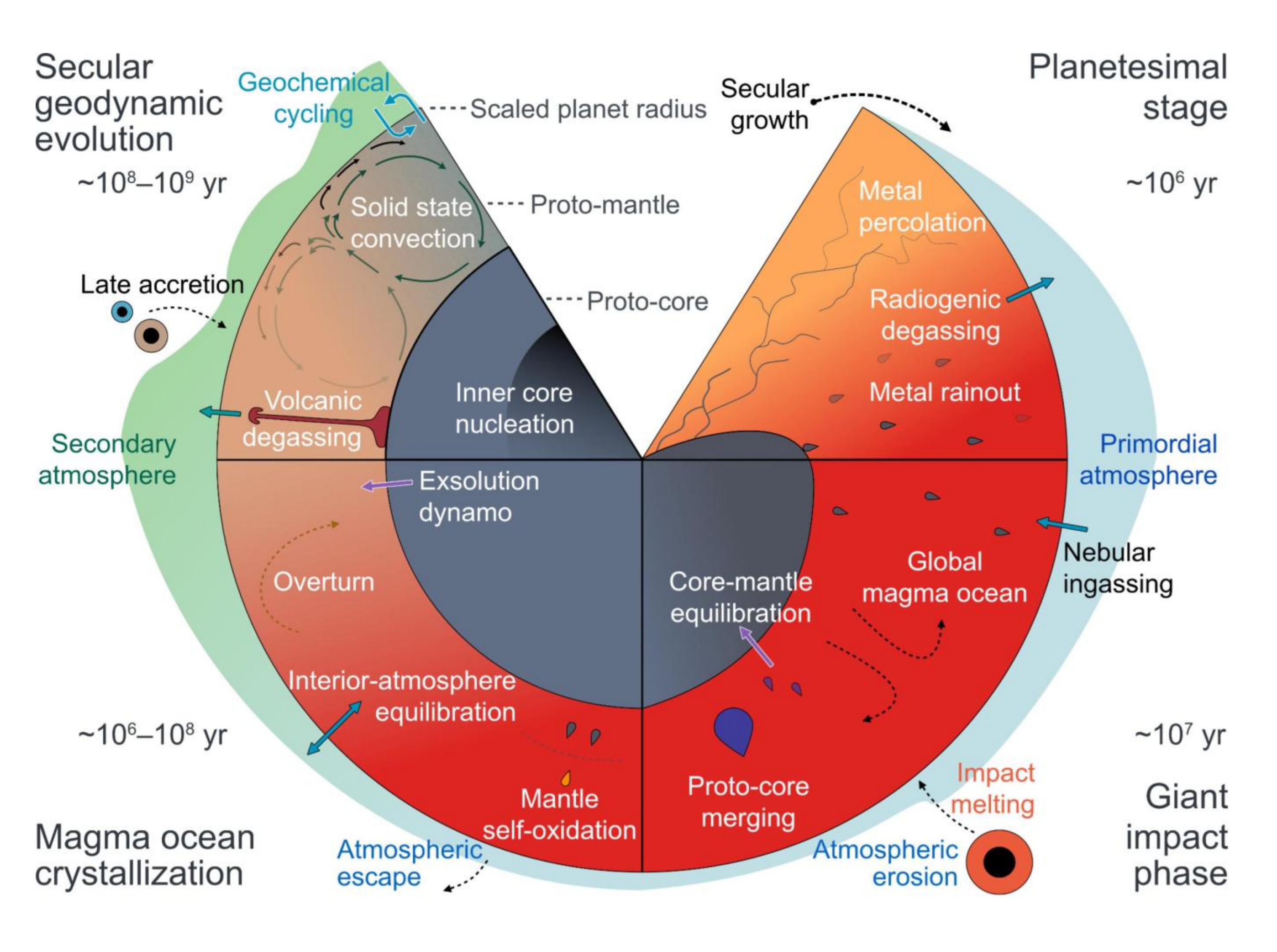
Atmosphere-Interior Evolution

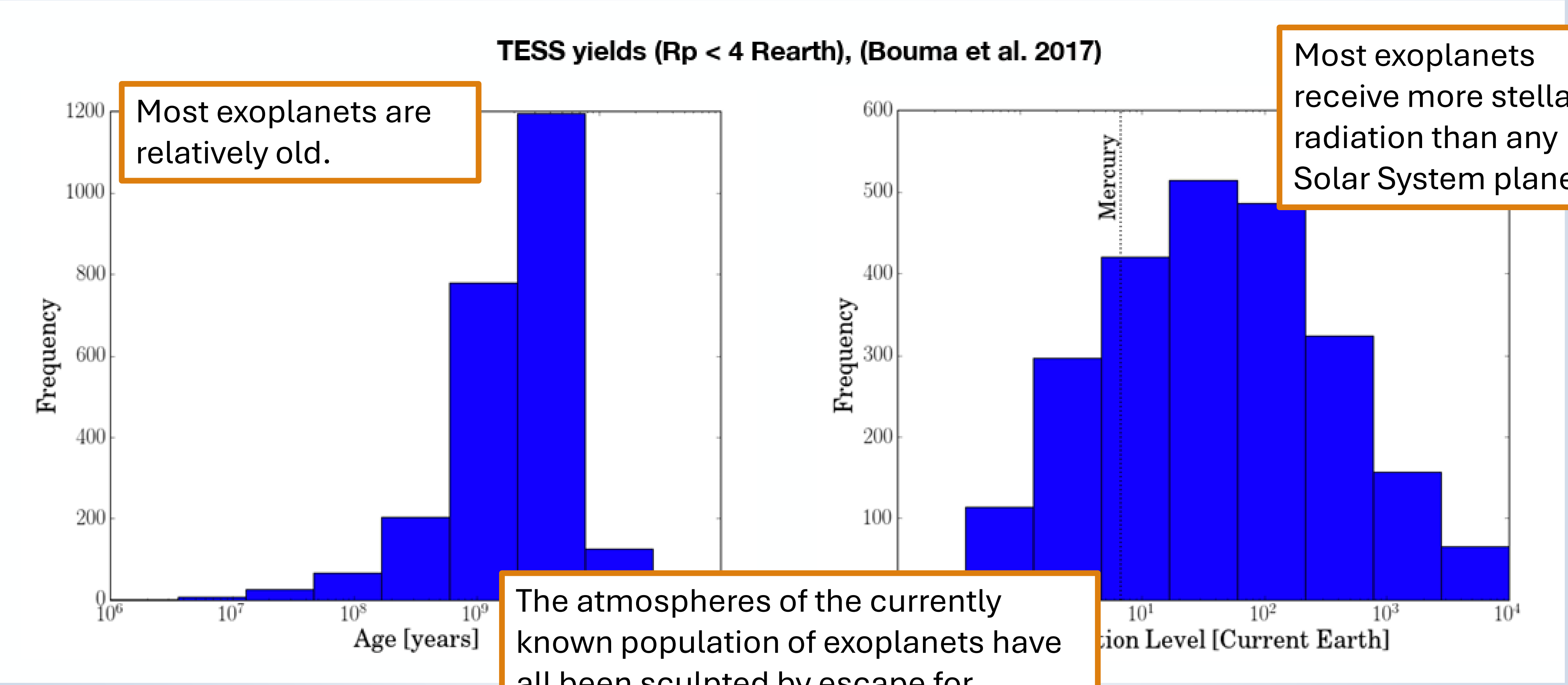
Life-essential elements (CHNOPS) interact with all layers of a rocky planet during the process of planet formation and evolution.

The availability of these elements at the surface depends on the integrated history of the planet.



Lichtenberg et al. (2022) Protostars and Planets VII

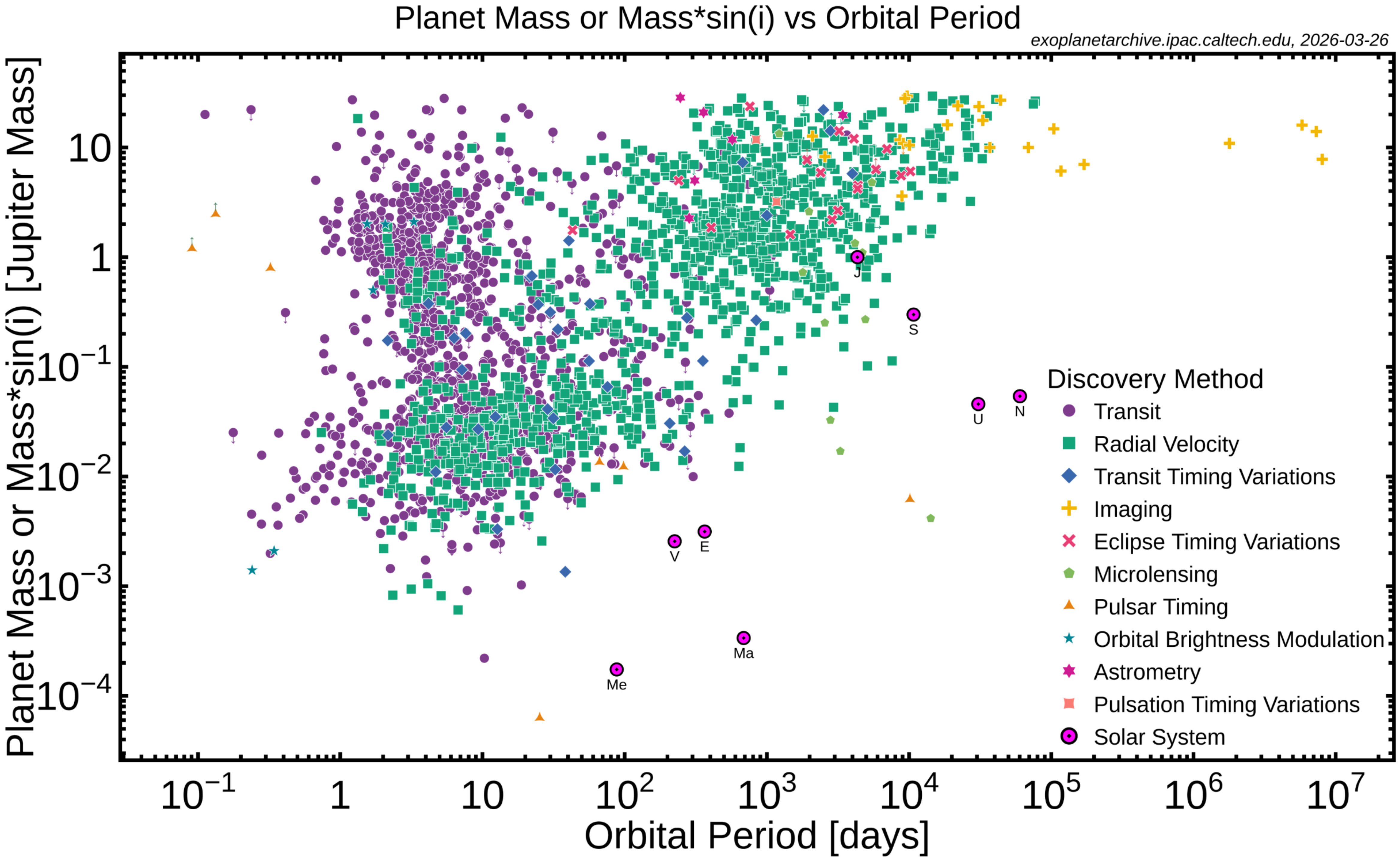
Why is escape important?



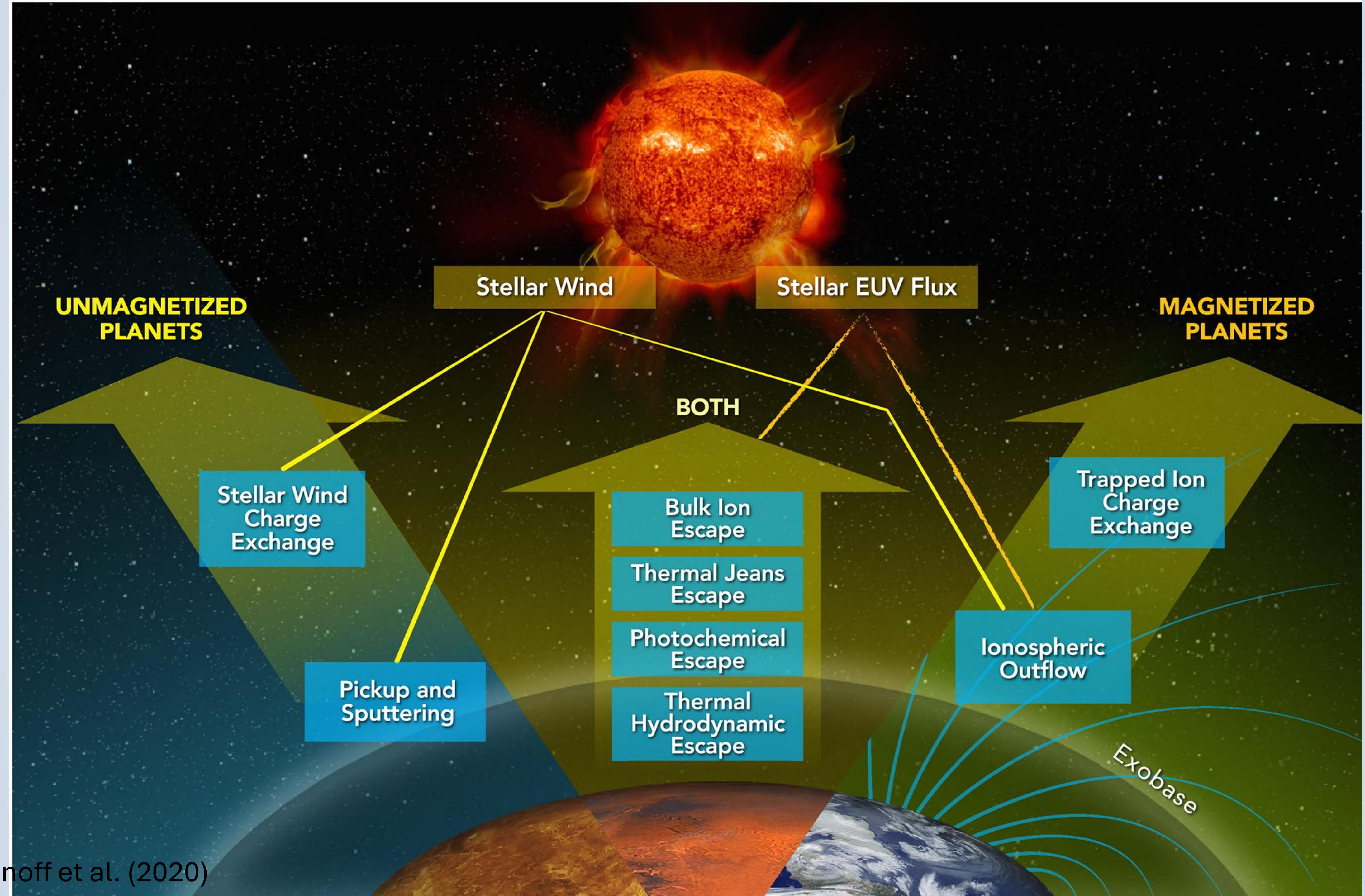
Most exoplanets are relatively old.

Most exoplanets receive more stellar radiation than any Solar System planet.

The atmospheres of the currently known population of exoplanets have all been sculpted by escape for billions of years.

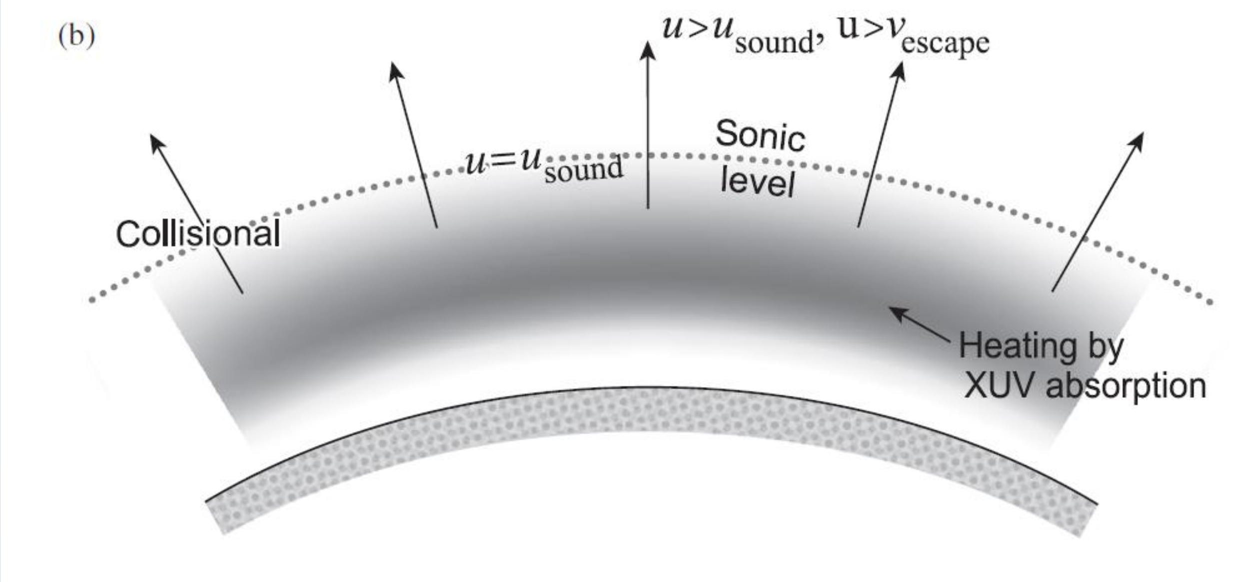


https://exoplanetarchive.ipac.caltech.edu



Gronoff et al. (2020)

Planetary Wind = Hydrodynamic escape



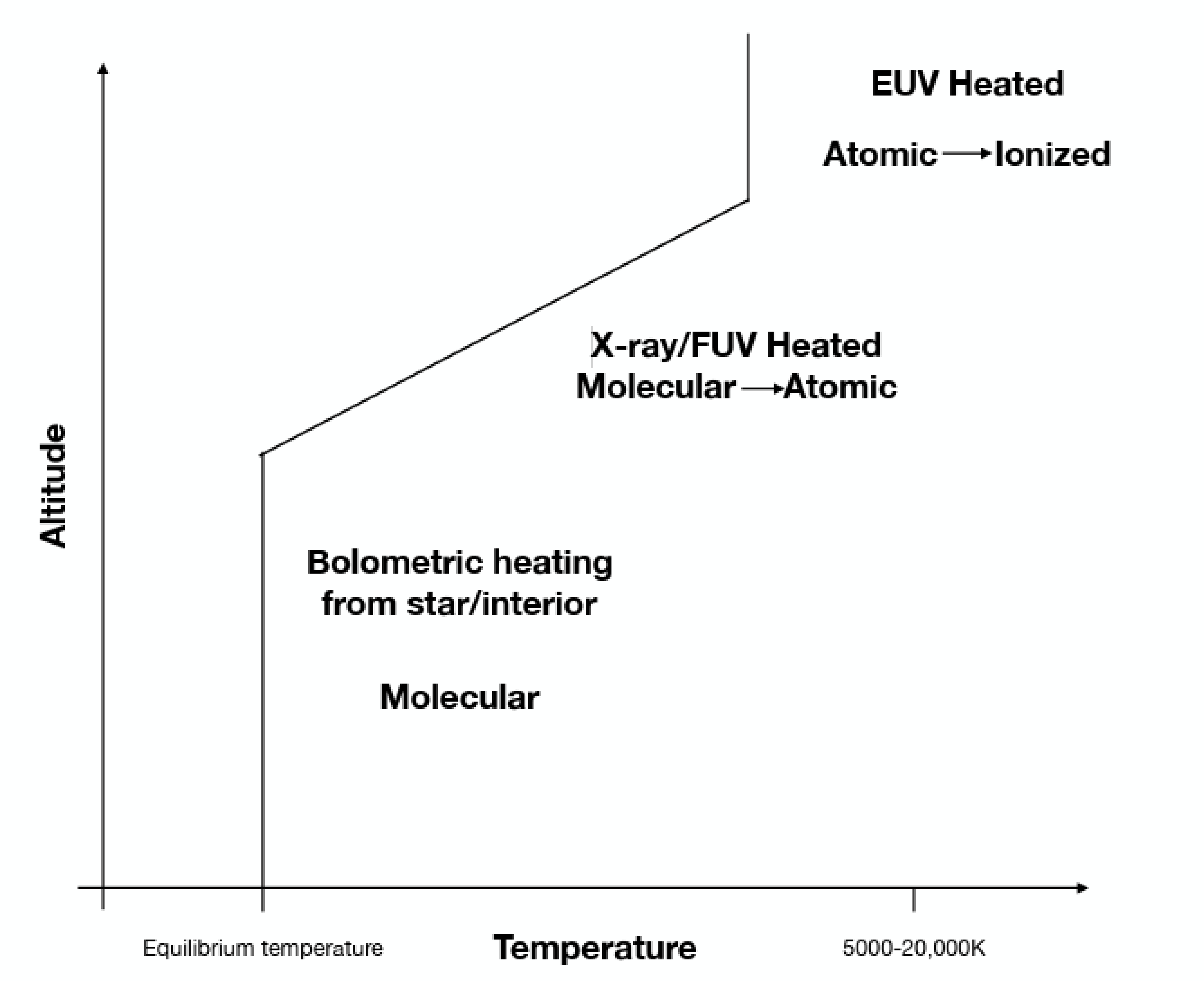
Catling & Kasting (2018)
Fig. 5.2b

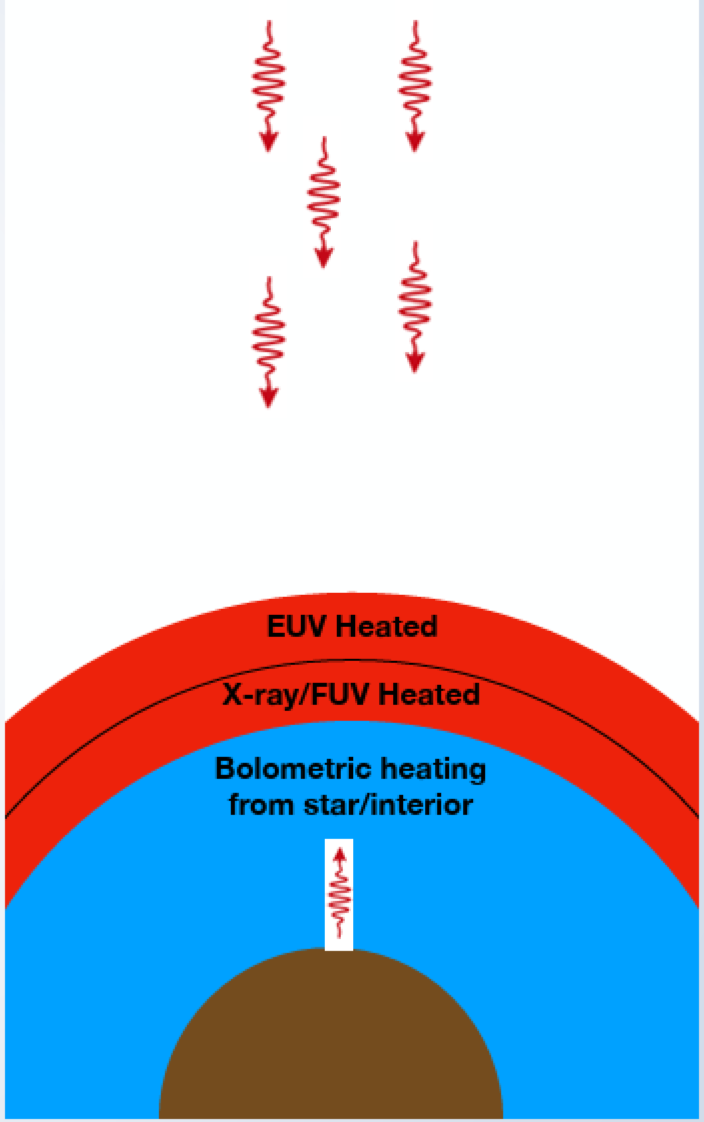
Hydrogen-rich atmospheres on low-gravity planets or very hot hydrogen-rich atmospheres on bigger planets can escape via hydrodynamic winds.

The solar wind is fully ionized and is driven by electromagnetic forces. For a planet's atmosphere (which is mostly neutral), the energy must come from somewhere else.

Almost always, it comes from absorption of Xray and Extreme UltraViolet (EUV) radiation from the star by the upper layers of the atmosphere.

In hydrodynamic escape, the whole atmosphere above the heated layer is accelerated, leading to a bulk outflow of gas.


EUV Heated
Atomic → Ionized
X-ray/FUV Heated
Molecular → Atomic
Bolometric heating
from star/interior
Molecular
Altitude
Equilibrium temperature
Temperature
5000-20,000K


EUV Heated
X-ray/FUV Heated
Bolometric heating
from star/interior

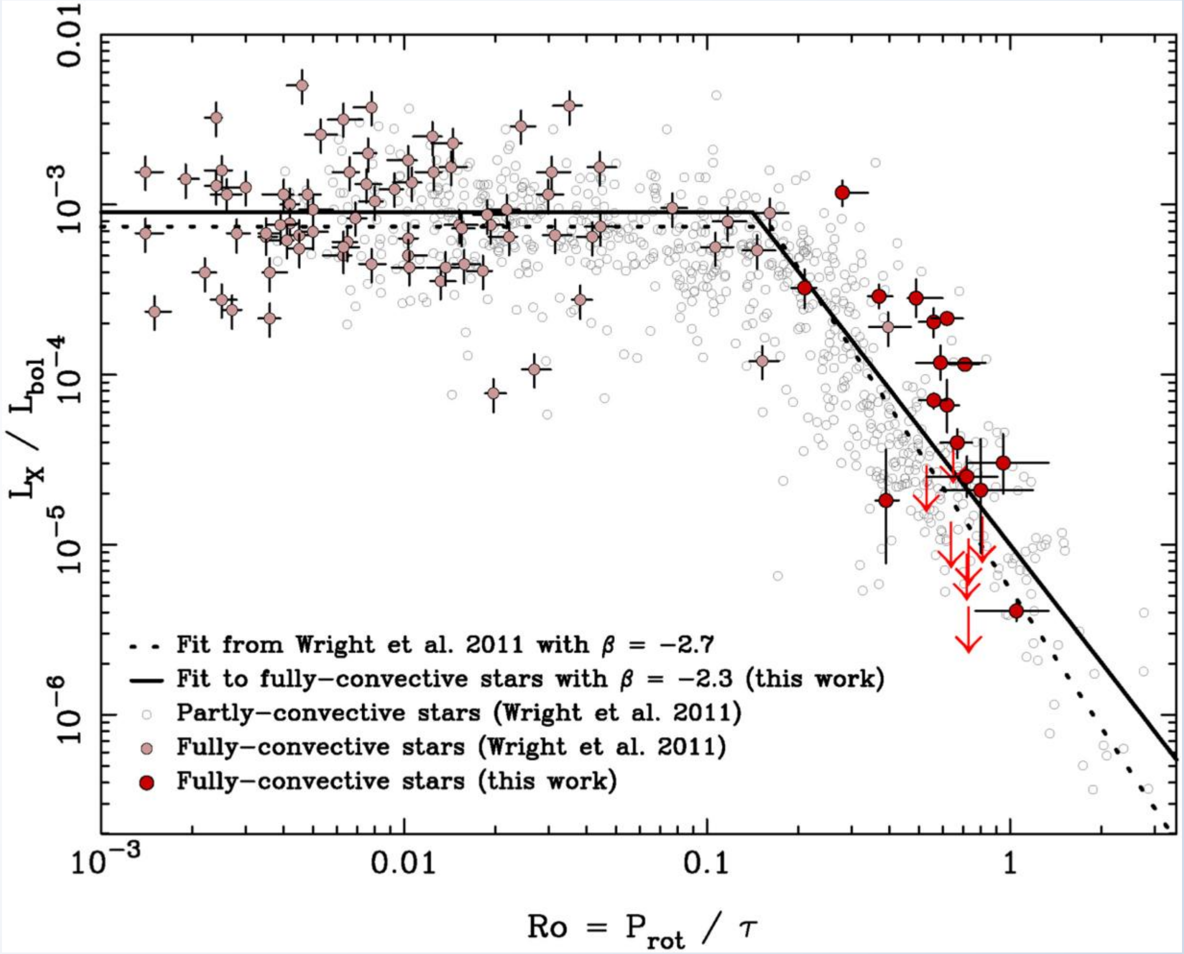
Stellar XUV evolution

X-ray and Ultraviolet radiation are emitted by a star most strongly during the early evolution.

Measurements have shown that they are a constant (“saturated”) fraction of the total luminosity of the star until some cutoff time, after which they decline significantly.

The saturation fraction is similar for all stars, but the saturation time is much longer for smaller stars.

t_{sat} (G-star) ~ 100 Myr
t_{sat} (M-star) ~ 500 – 1000 Myr



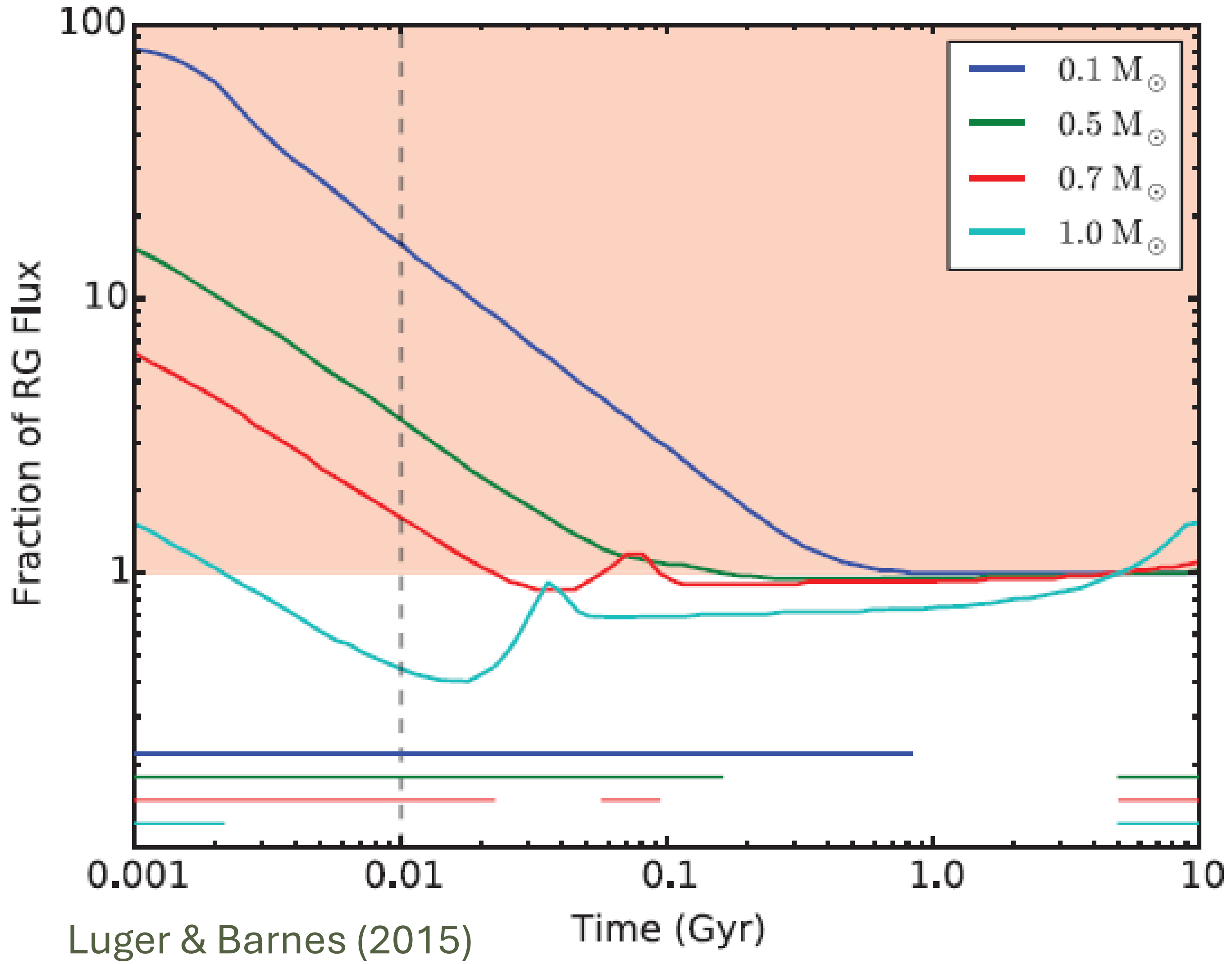
Gronoff et al. (2020)

$$\frac{L_{HE}}{L_{bol}} = \begin{cases} L_{sat} & \text{for } t \leq t_{sat} \\ L_{sat}\left(\frac{t}{t_{sat}}\right)^{-1-\alpha} & \text{for } t > t_{sat}, \end{cases}$$

Stellar Radiation Changes with Time & Mass

Total stellar radiation also changes with time and stellar mass.

The brightness of a very small star changes by a lot more than the lifetime of a Sun-like star over the course of their evolution.



Luger & Barnes (2015)

Energy-limited escape

Energy-limited mass loss

$$\dot{M}_{\rm EL} = \frac{\epsilon_{\rm XUV} \pi \mathcal{F}_{\rm XUV} R_{\rm p} R_{\rm XUV}^2}{G M_{\rm p} K_{\rm tide}}$$

Energy-limited escape is a simplified mathematical treatment of hydrodynamic escape.

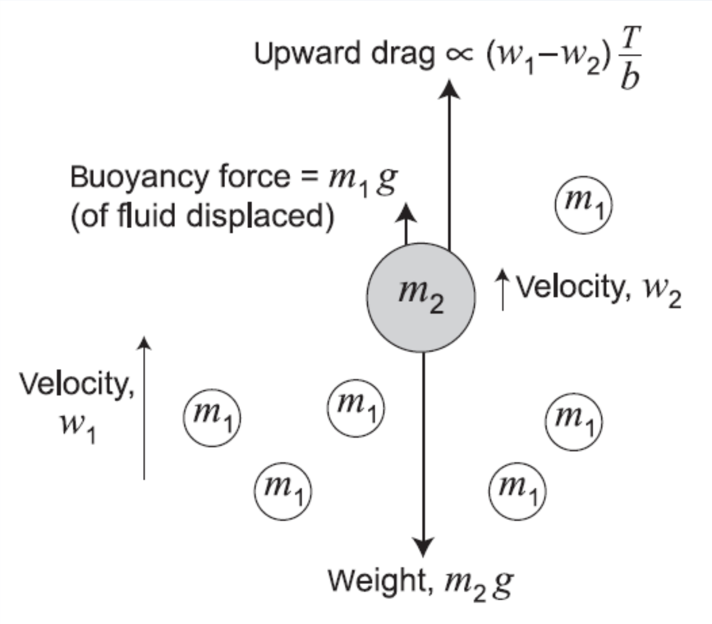
It was first developed to study the loss of early atmospheres from Earth and Venus in the 1970s and 1980s.

The model just says that the energy needed for escape depends on the energy deposited into the atmosphere (F_{XUV}) at some extended atmospheric radius (R_{XUV}). An efficiency factor ($\epsilon_{\rm XUV}$) hides all the complicated physics. The efficiency factor is between 0.01 – 0.2 for H_2-rich atmospheres.

Mass Fractionation

Hydrodynamic escape is mostly thought to be driven by atomic H (sometimes molecular H_2) in the upper atmosphere.

However, friction (or drag) due to collisions between atoms in the escaping region can lead to the escape of other, heavier atoms and molecules that wouldn't otherwise have sufficient energy to escape.



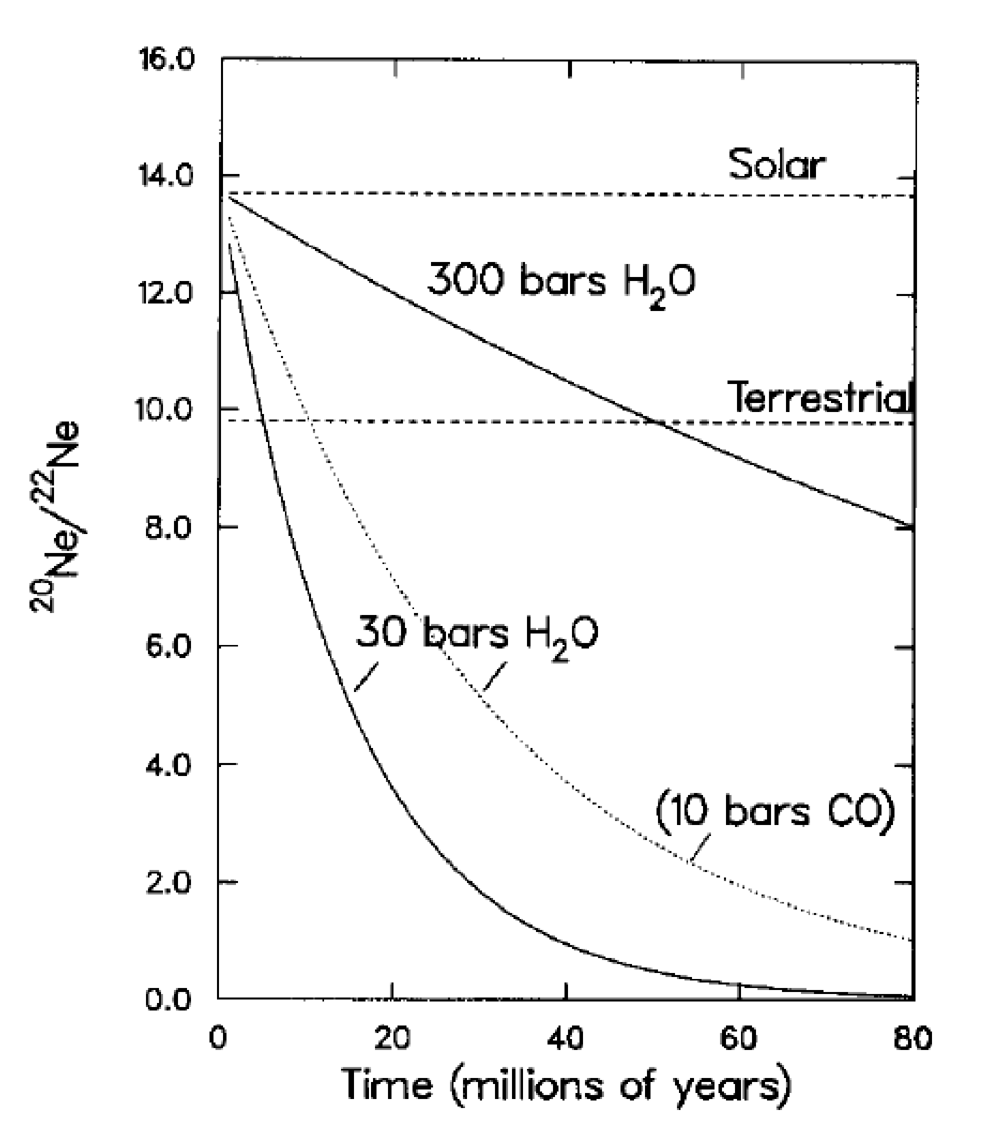
Mass Fractionation

This figure shows calculations for how much the abundance of Neon (mass = 20 & 22 amu) would be depleted for different atmospheric escape models for Mars.

$$M_{crossover} - M_1 = \frac{kTF_1}{bgm_H X_1}$$

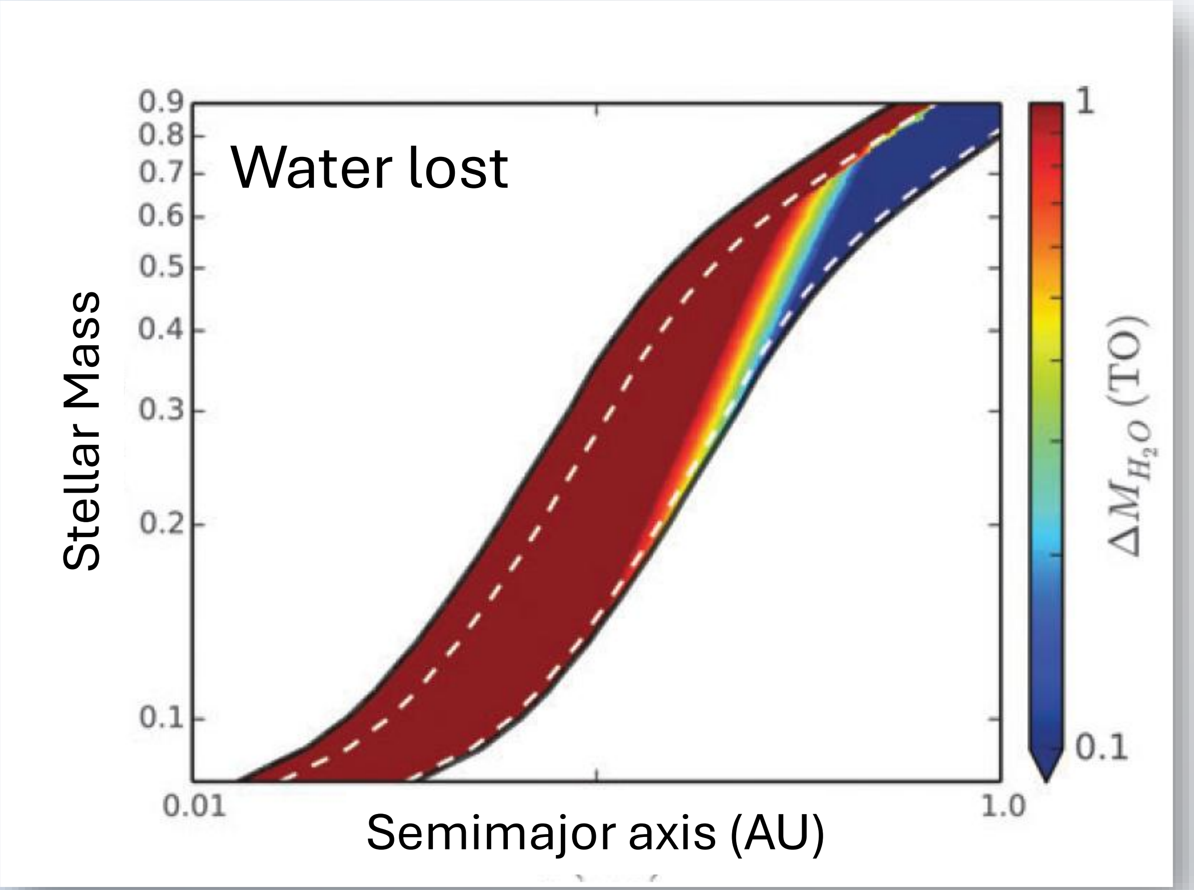
The heaviest gas that can escape is given by the **crossover mass**, which depends on the relative concentration of H_2 (X_1) and its escape flux (F_1).

Noble gas escape from Mars



Zahnle et al. (1990)

Escape from young rocky planets



Luger & Barnes (2015)

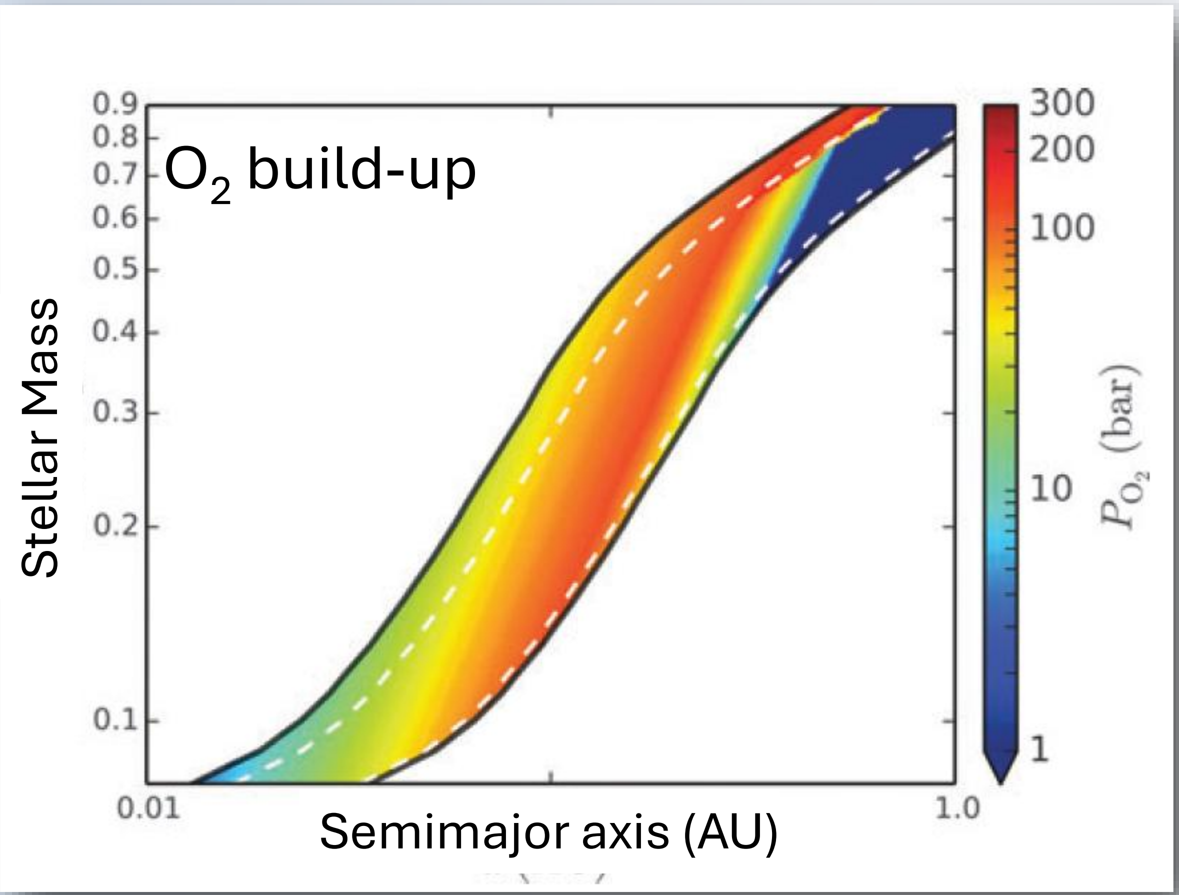
Energy-limited mass loss

$$\dot{M}_{\rm EL} = \frac{\epsilon_{\rm XUV}\pi\mathcal{F}_{\rm XUV}R_{\rm p}R_{\rm XUV}^2}{GM_{\rm p}K_{\rm tide}}$$

A water-vapor dominated early atmosphere, as expected for young rocky planets during a magma ocean phase, can also go through early hydrodynamic escape.

XUV would photo-dissociate water molecules into H and O atoms in the upper atmosphere.

Abiotic O_2 build-up



Luger & Barnes (2015)

Energy-limited mass loss

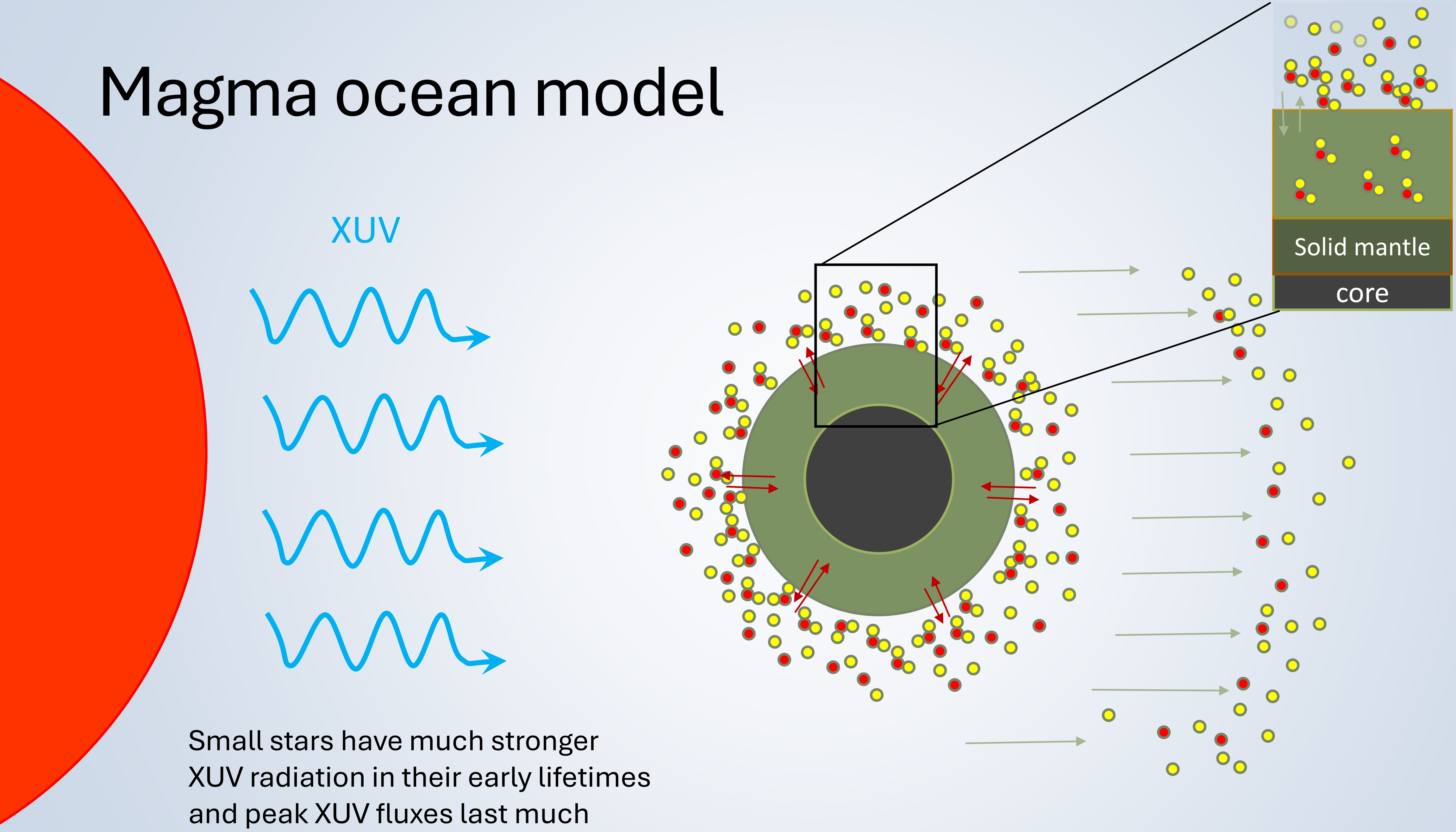
$$\dot{M}_{\mathrm{EL}} = \frac{\epsilon_{\mathrm{XUV}} \pi \mathcal{F}_{\mathrm{XUV}} R_{\mathrm{p}} R_{\mathrm{XUV}}^2}{G M_{\mathrm{p}} K_{\mathrm{tide}}}$$

Oxygen build-up

$$\dot{M}_{\mathrm{EL}} = \dot{m}_{\mathrm{H}}^{\uparrow} + \dot{m}_{\mathrm{O}}^{\uparrow}$$

$$\dot{m}_{\mathrm{O}}^{\uparrow} + \dot{m}_{\mathrm{O}}^{\mathrm{atm}} = 8 \dot{m}_{\mathrm{H}}^{\uparrow}$$

Magma ocean model



Small stars have much stronger XUV radiation in their early lifetimes and peak XUV fluxes last much longer than for larger stars.

Atmospheric O_2 uptake by magma ocean

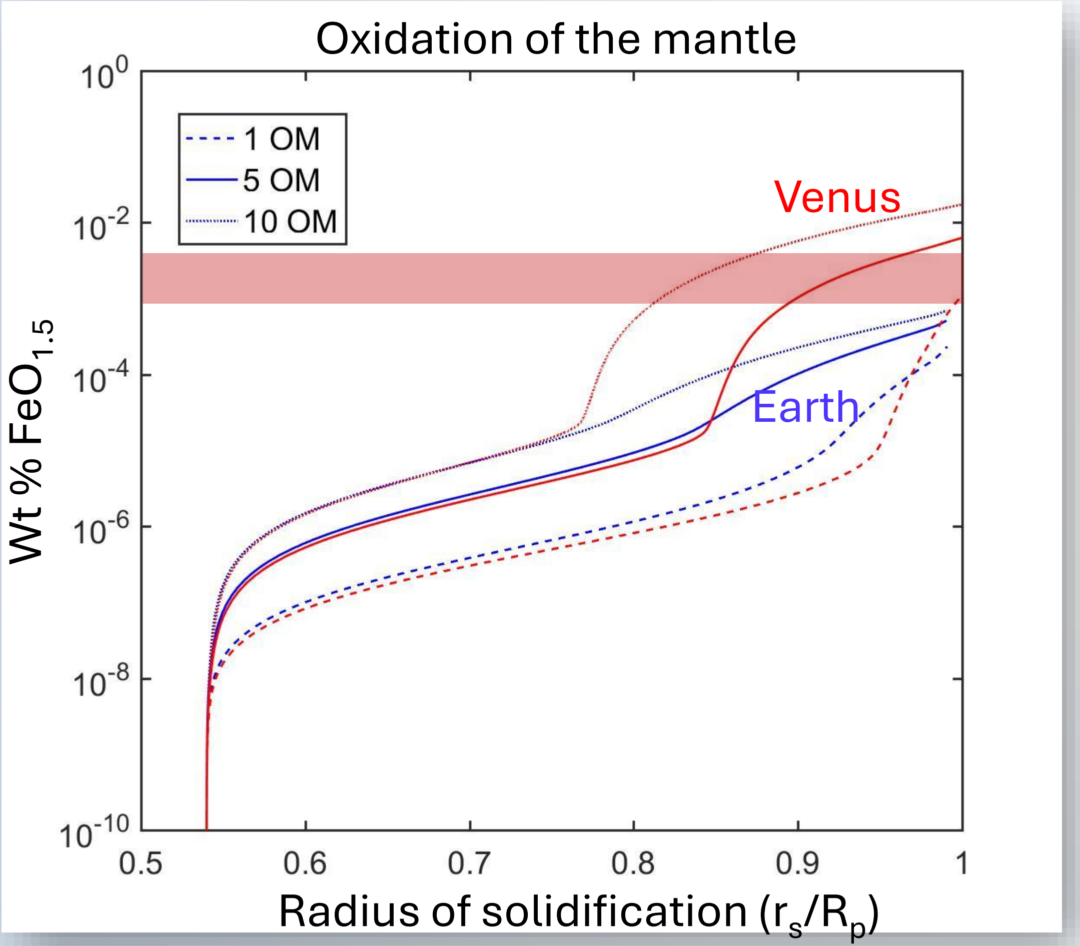
- Photodissociation of H_2O in atmosphere

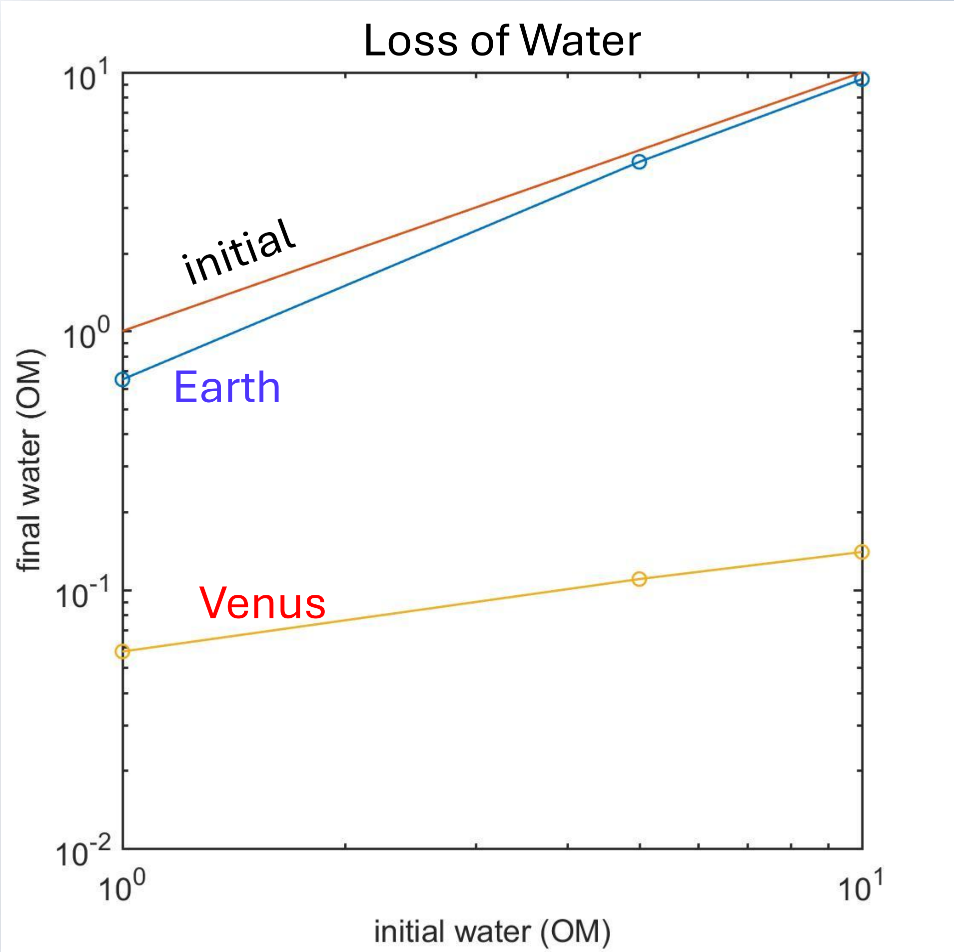
$$H_2O\ (g) + h\nu = H(g) + 2O(g)$$

- escape of H driven by stellar radiation produces net free O
- Reaction with FeO in magma ocean produces more Fe^{3+}

$$FeO(melt) + 0.5\ O(g) = FeO_{1.5}\ (melt)$$

Oxidation of Earth & Venus by atmosphere



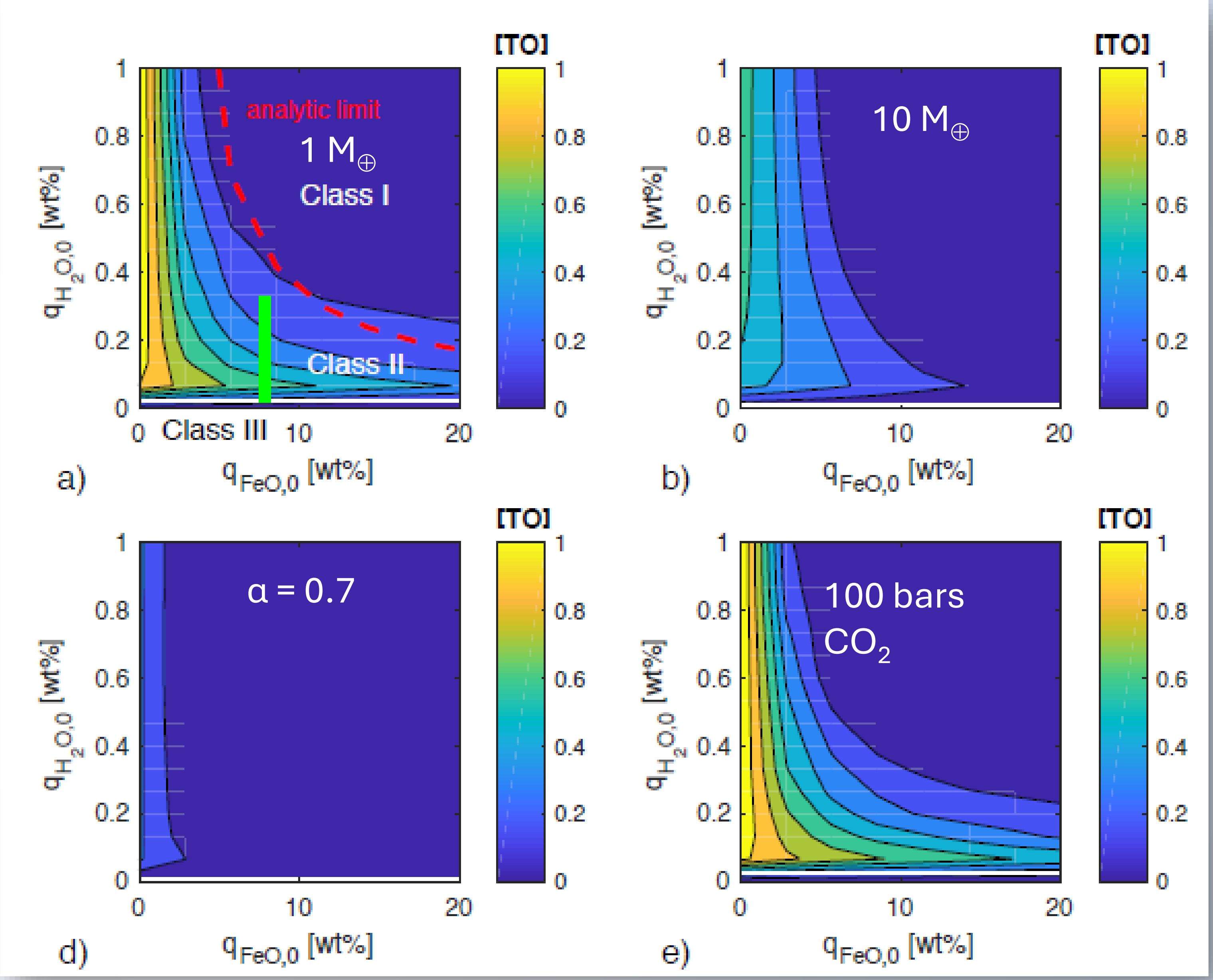


Based on Schaefer et al. (2016), Wordsworth et al. (2018)

Abiotic O_2

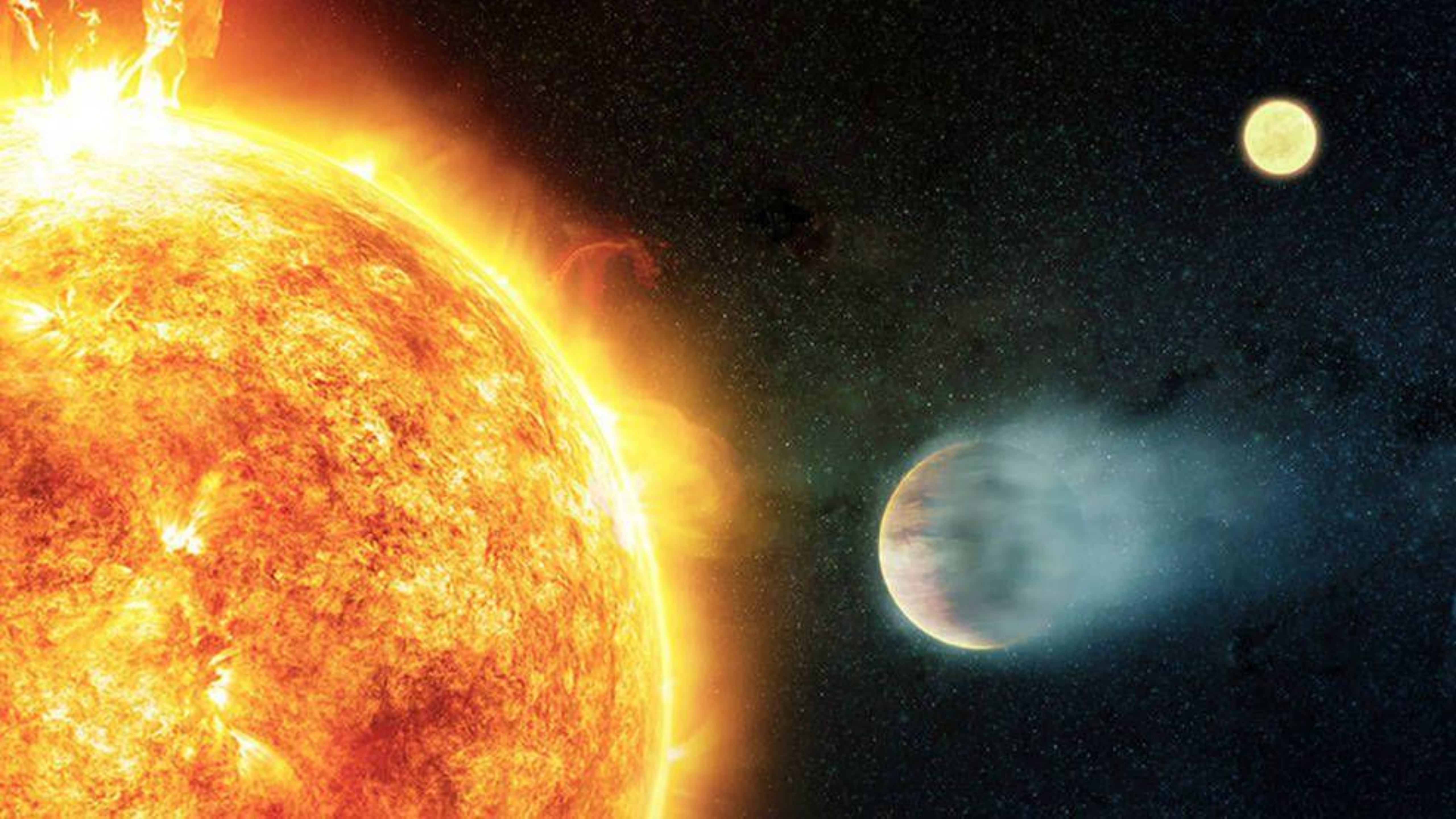
- most sensitive to
  - Orbit
  - Albedo
  - Planet mass

Assumes no initial mantle Fe^{3+} and perfect uptake of O_2 by mantle during magma ocean stage.



Wordsworth et al. (2018) ApJ

Observations of Escape



Escape observations

Atmospheric escape has been observed since nearly the beginning of transit observations in a number of hot Jupiters.

Escape can be shown to happen if the radius measured by the transit is larger than the planet's Roche limit.

$$\delta \geq \left(\frac{R_{\rm Roche}}{R_*}\right)^2 \approx 0.13 \left(\frac{a}{0.025\,{\rm AU}}\right)^2 \left(\frac{M_p}{M_J}\right)^{2/3} \left(\frac{R_*}{{\rm R}_\odot}\right)^{-2} \left(\frac{M_*}{{\rm M}_\odot}\right)^{-2/3}$$

If the Roche radius is full of optically thick gas, the transit depth will be much larger than the planet radius alone. However, in practice, the escaping flow is not fully optically thick, so the transit depth is often smaller than predicted from that assumption.

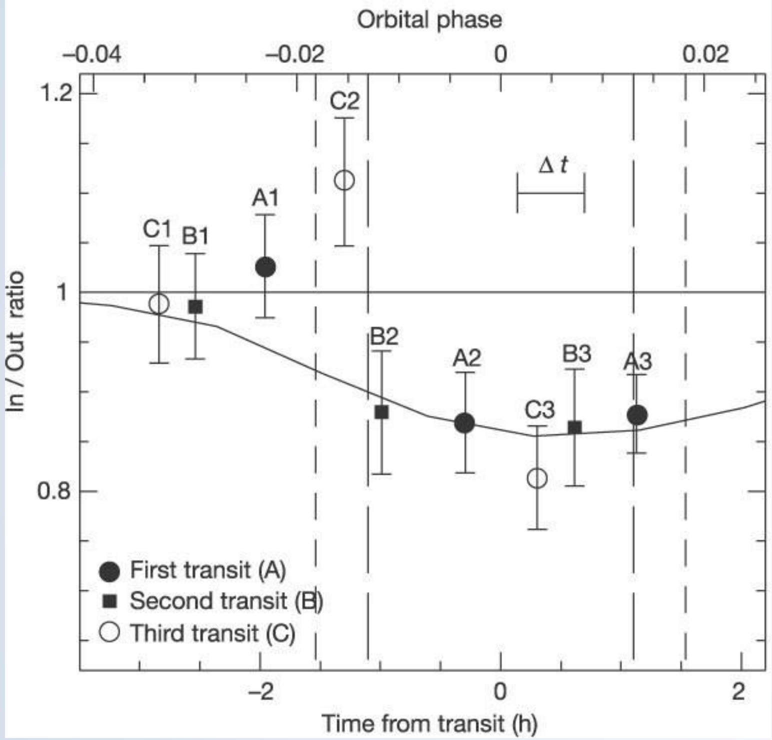
Roche radius (= Hill sphere):

$$\mathrm{R}_{\mathrm{Roche}} \approx a\left(\frac{M_p}{3M_*}\right)^{1/3}$$

Technically, the Roche limit is calculated from the full 3D gravitational potential of the star-planet system and extends all the way to the L1 Lagrange point (therefore with a pointed, not spherical shape).

But in practice, calculations typically adopt the Hill Sphere, which approximates the distance to the L1 point when $M_* >> M_p$

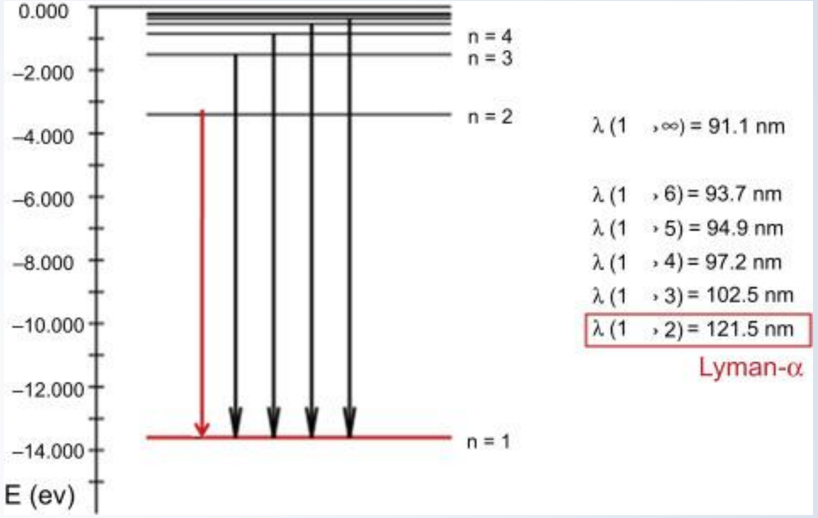
Hydrogen escape



Vidal-Madjar et al. (2003)

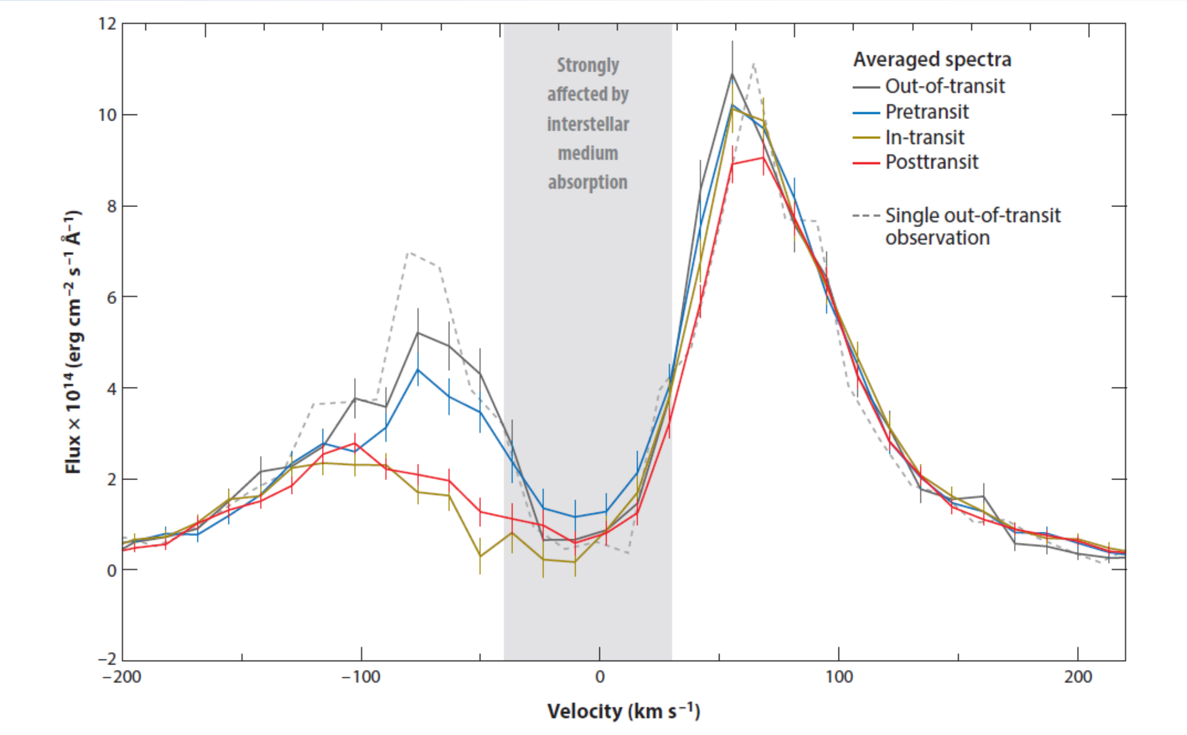
The first observation of hot Jupiter HD 209458b in Lyman-α found a **15% transit depth** (only 1.5% in optical), indicating gas well beyond the planet's Roche limit.

Lyman-α H absorption line



Lyman-alpha is the wavelength absorbed (transmitted) for the electron transition between *n*=1 and *n*=2 levels of hydrogen gas. It is very sensitive to low densities of hydrogen and transits observed at this wavelength can be much deeper than in typical optical wavelengths.

Hydrogen escape



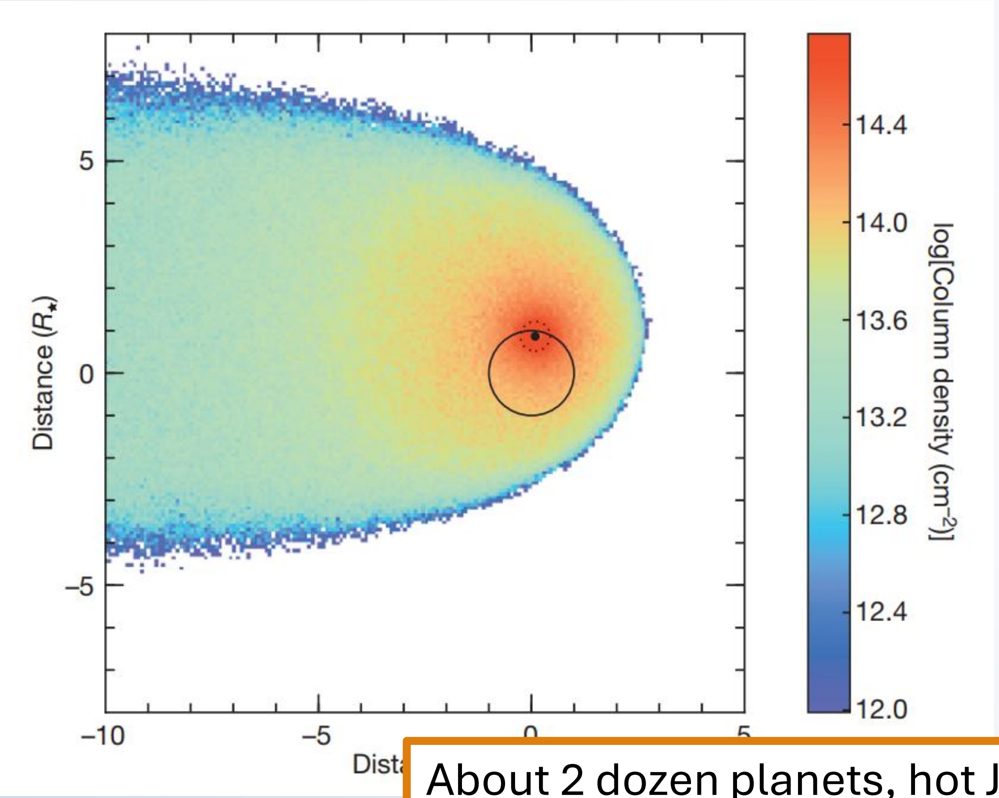
Owen (2019)

The hot Neptune GJ 436b showed **a transit depth of 56%!!!** in Lyman-α, compared to an optical transit depth of ~0.56%.

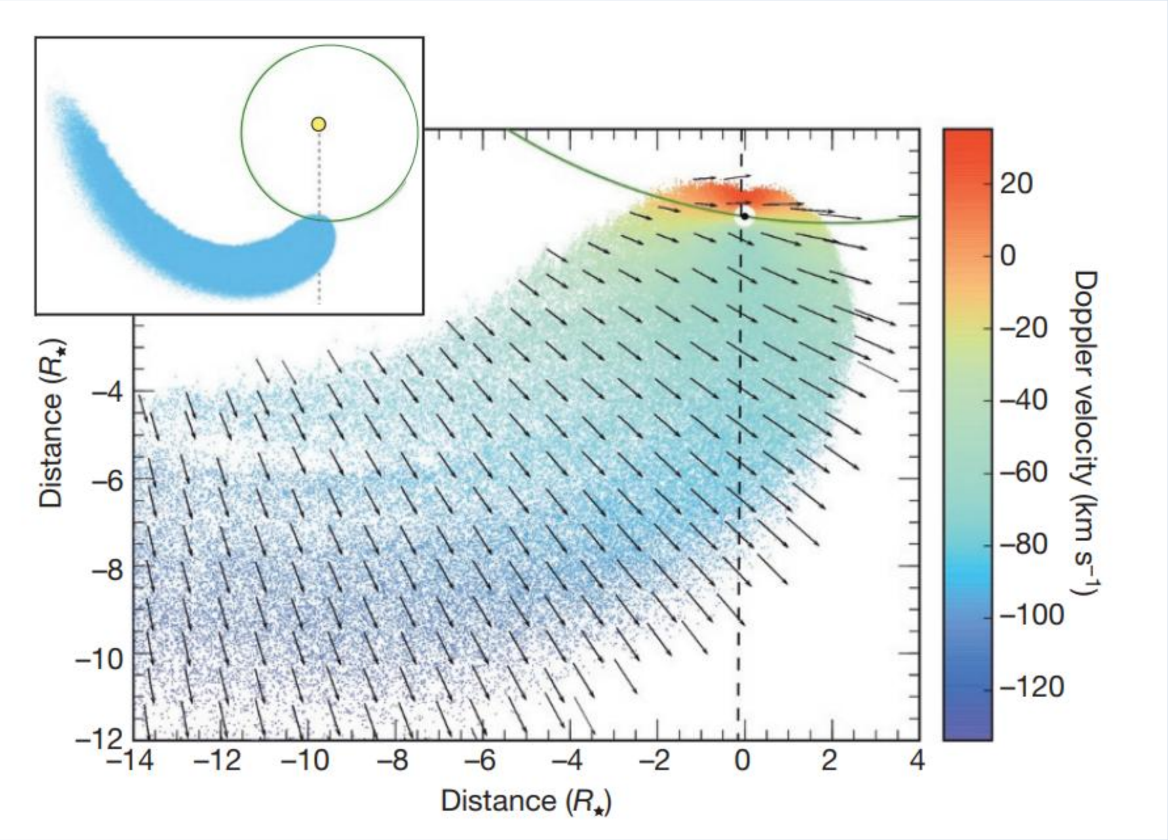
The red and blue shifts of the line show that the escaping material has velocities of ~100 km/s, which is much faster than expected from hydrodynamic escape models (~5-10 km/s, ~2-5x the sound speed).

Possible explanations include radiation pressure or charge exchange with stellar wind protons, which could further accelerate the escaping gas.

GJ 436b



Ehrenreich et al. (2



A simulation of the escape from the hot
e GJ 436b. The mass loss rate is
ed to be ~$10^8 – 10^9$ grams per second,
% of its atmosphere in a billion years.

About 2 dozen planets, hot Jupiters and hot Neptunes, have been detected with escaping atmospheres using Lyman-α, almost all observations using HST.

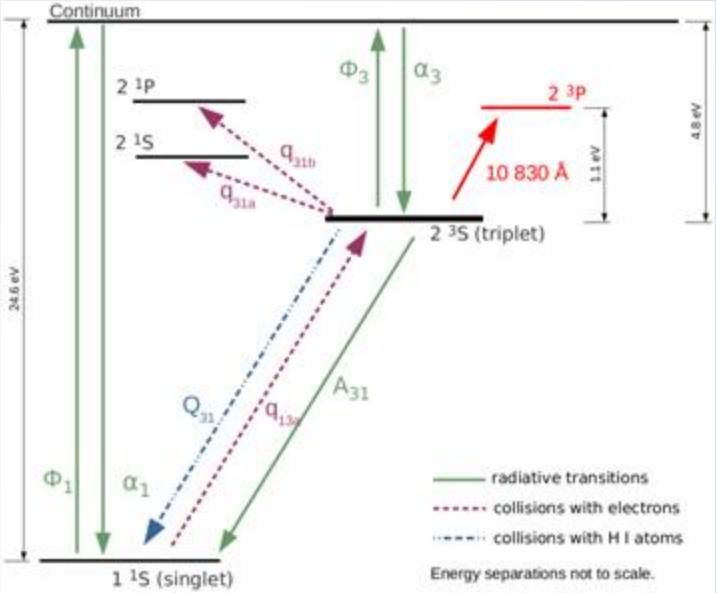
He escape - models

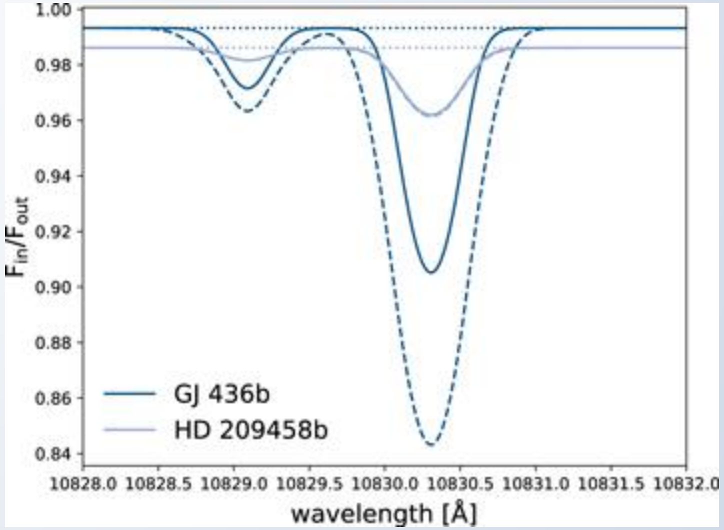
Hydrogen escape detected through Lyman-alpha is somewhat limited.

It can only be observed from space (UV wavelength), it is strongly affected by absorption by the cold hydrogen gas of the interstellar medium (ISM), and is very sensitive to stellar activity.

A metastable He line was theoretically proposed to also be strongly measurable in hydrodynamic outflows. It has the benefit of being measurable from the ground using high resolution near-IR spectroscopy.

While transit depths are somewhat smaller than hydrogen, it is much less affected by ISM and by Earth's atmosphere.

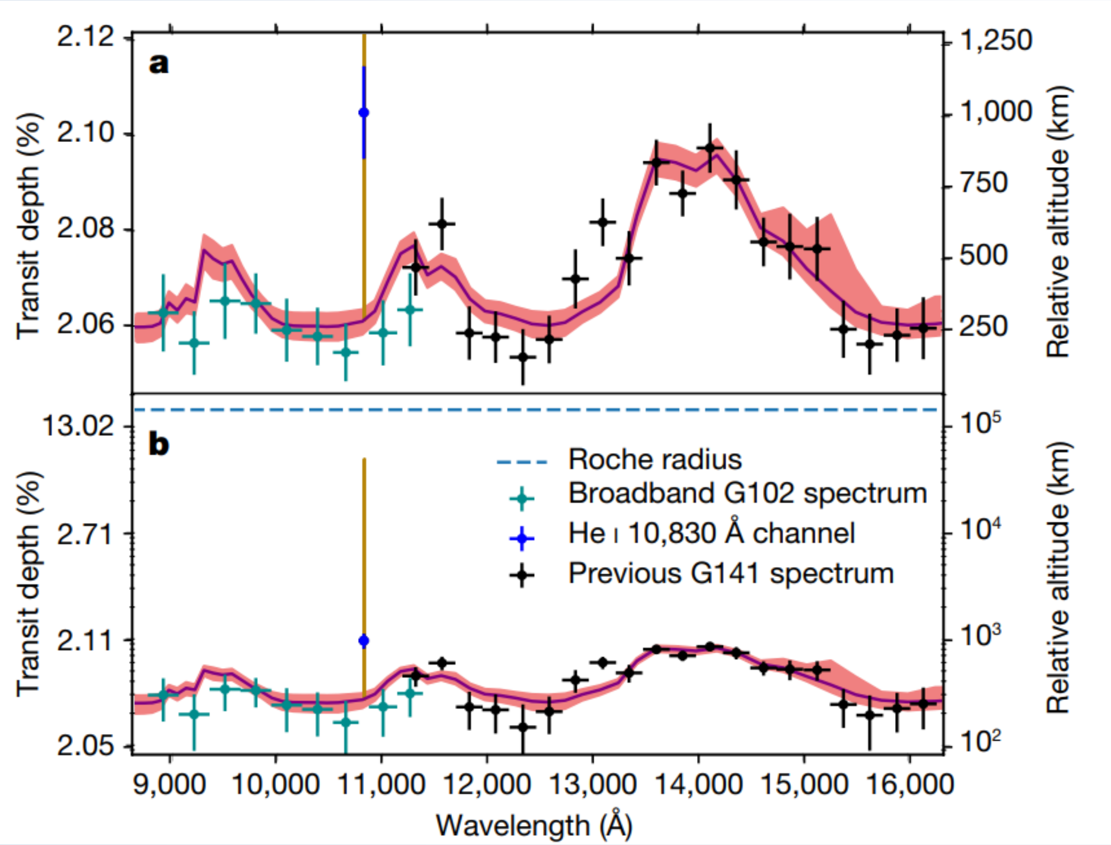




Oklopčić & Hirata (2018)

He escape - observations

WASP-107b



Spake et al. (2018)

The hot Jupiter WASP-107b was the first with detected He signature of escape.

The observations suggest an escape rate of $10^{10} - 10^{11}$ g/sec, or 0.1-4% of its total mass per billion years.

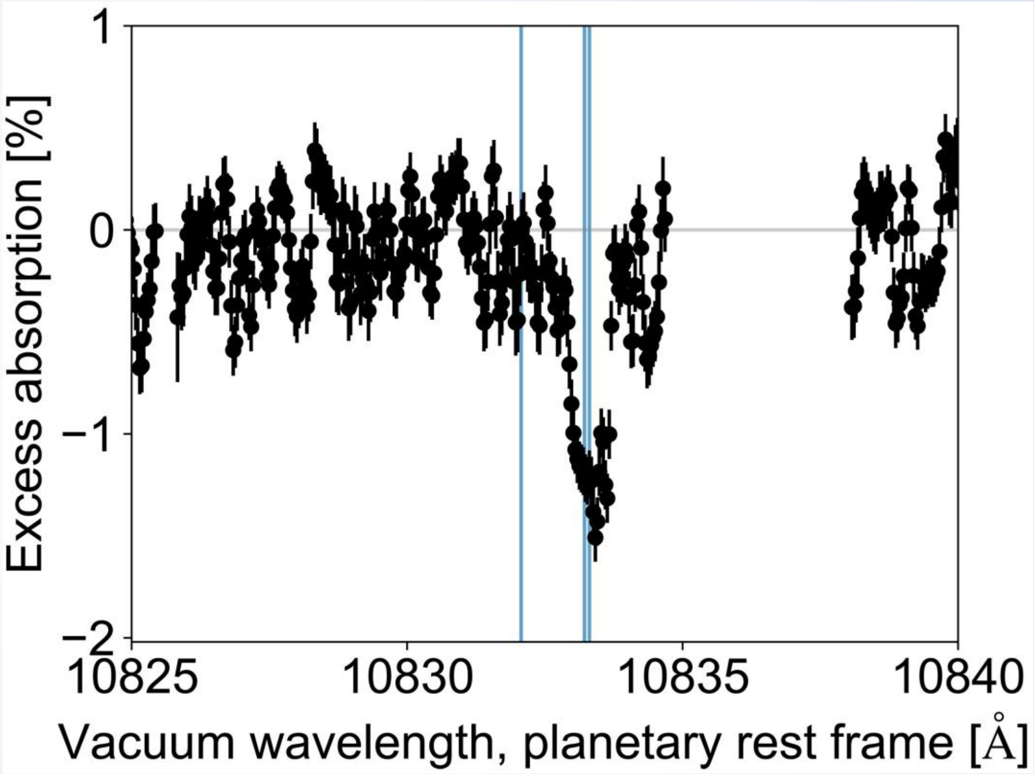
More than 30 planets have been detected in He I now, down to sub-Neptune sizes.

LHS 1140 b – rocky world with He escape

There has been a recent claim of He escape detected in the atmosphere of a rocky planet in the Habitable Zone of its star.

These observations were done with the ground-based WINERED instrument on the Magellan Clay telescope at Las Campanas Observatory.

He was detected in 2024 data but not in data taken in 2025.



Cherubim et al. (2026)

LHS 1140 b – rocky world with He escape

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No Helium Detected in LHS 1140 b from Four JWST NIRISS/SOSS Transits

Katherine A. Bennett,[1] Carlos Gascón,[2] Jacob Lustig-Yaeger,[3] Guangwei Fu,[4] David K. Sing,[1,4] Kevin B. Stevenson,[3] Jonathan Brande,[5] Munazza K. Alam,[2] Jeff A. Valenti,[2] Mercedes López-Morales,[2] Sten J. Vermeiren,[6] Megan Weiner Mansfield,[5] Sarah E. Moran,[5] Kristin S. Sotzen,[3] Jegug Ih,[2] and Sarah Peacock[7,8]

Strict Limits on Helium Absorption from LHS 1140 b from Four JWST NIRISS Transits

Michael Radica[1,*]

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No Persistent Helium Absorption in LHS 1140 b: Four JWST/NIRISS SOSS Transits and Multi-epoch Stellar He I Variability

Amélie Gressier,[1] Charles Cadieux,[2] René Doyon,[1,3] Louis-Philippe Coulombe,[4,1] Romain Allart,[1,5] Etienne Artigau,[1,3] and François Bouchy[2]

[1]Institut Trottier de recherche sur les exoplanètes, Département de Physique, Université de Montréal, Montréal, Québec, Canada
[2]Observatoire de Genève, Département d'Astronomie, Université de Genève, Chemin Pegasi 51, 1290 Versoix, Switzerland
[3]Observatoire du Mont-Mégantic, Québec, Canada
[4]Planétarium de Montréal, Espace pour la Vie, 4801 av. Pierre-de Coubertin, Montréal, Canada
[5]Université de Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

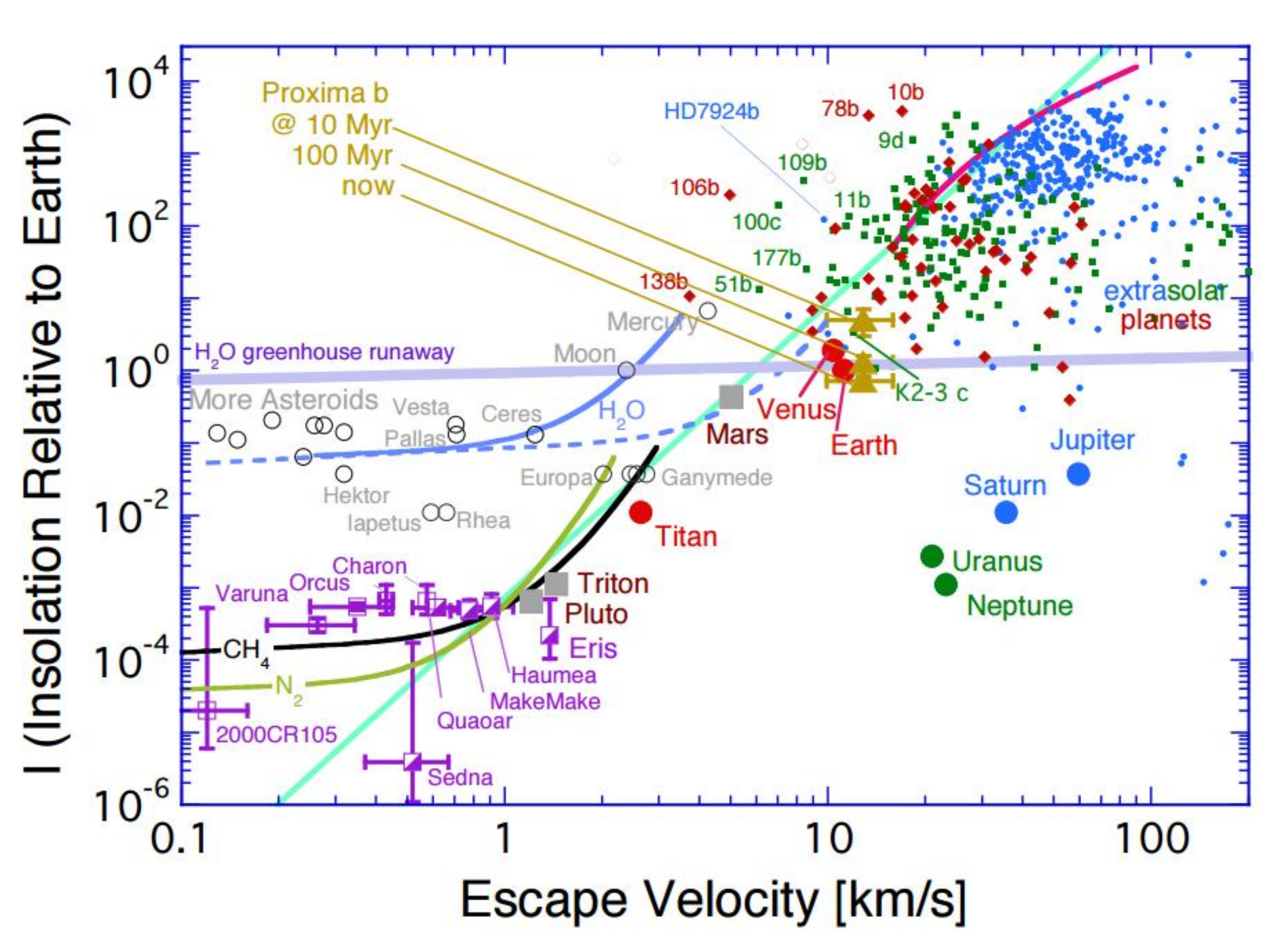
Rocky Exoplanet atmospheres???

Cosmic Shoreline

The Cosmic Shoreline was proposed in 2017, based on empirical relationships from the presence/absence of atmospheres on Solar System objects.

The idea is that there is some critical threshold of XUV insolation a planet can receive over its lifetime and still retain an atmosphere, scaled by the size (escape velocity) of the planet.

Above the "shoreline", we should expect atmospheres to escape. Below the shoreline, the atmospheres are stable.



Zahnle & Catling (2017)

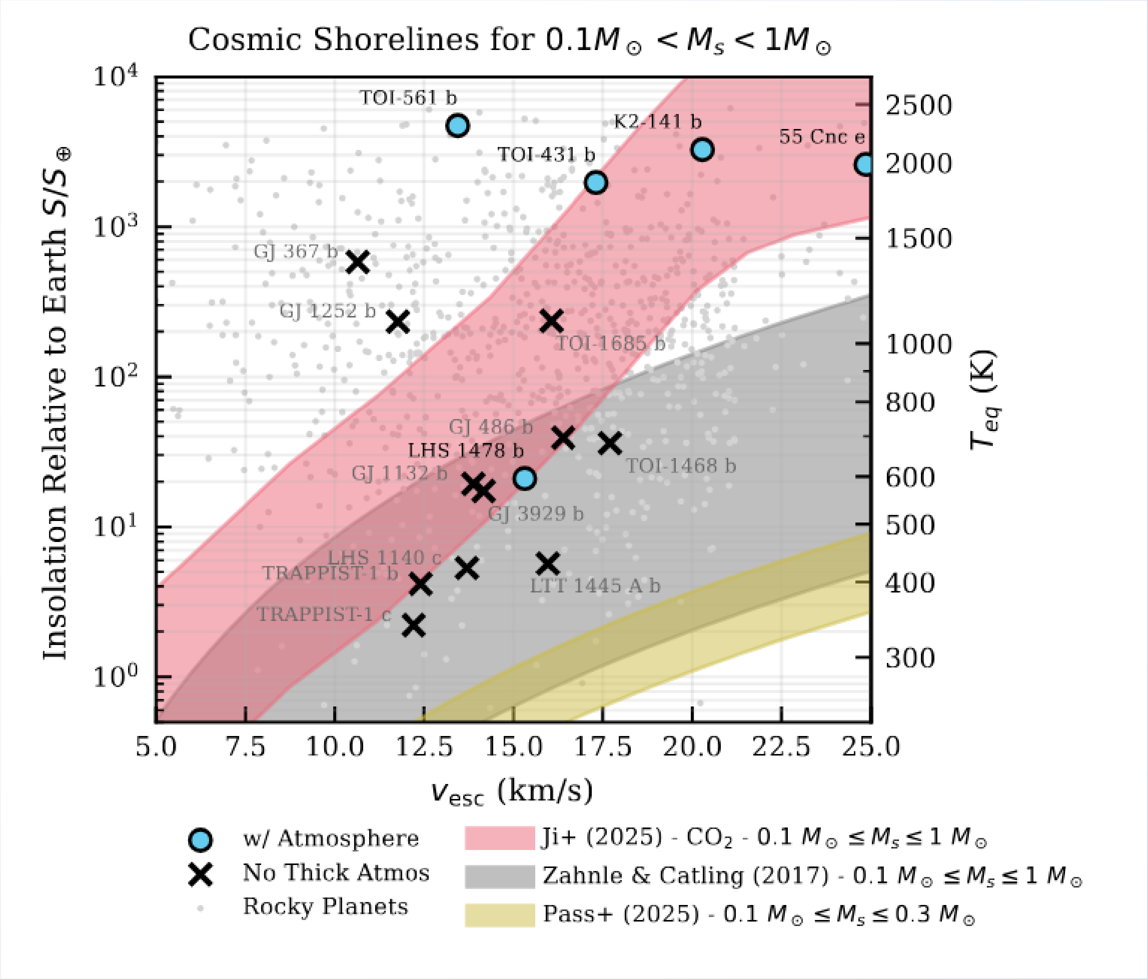
Observed Cosmic Shoreline

Observations of small planets are now testing the predictions of the Cosmic Shoreline model.

Updates to the model have also been made with additional considerations of different types of escape and different stellar types.

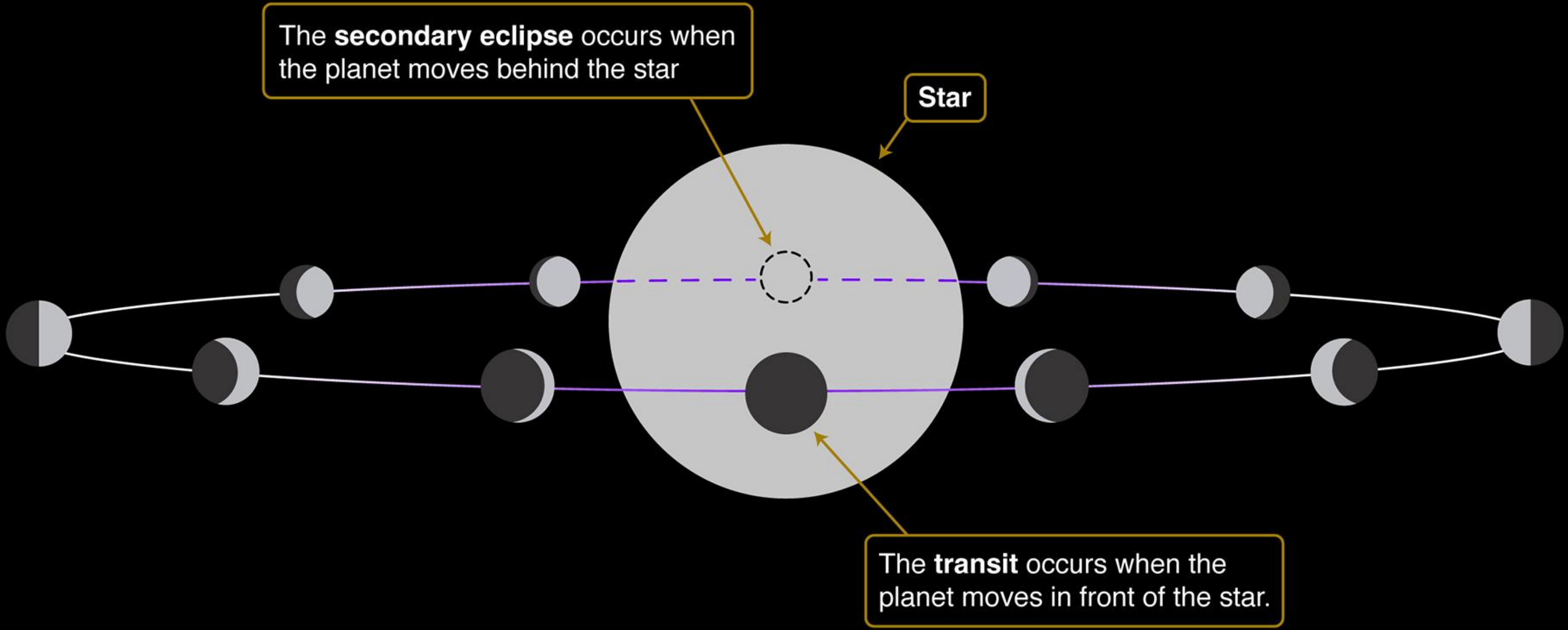
So far, most small planets seem to be bare rocky planets, without atmospheres, consistent with predictions.

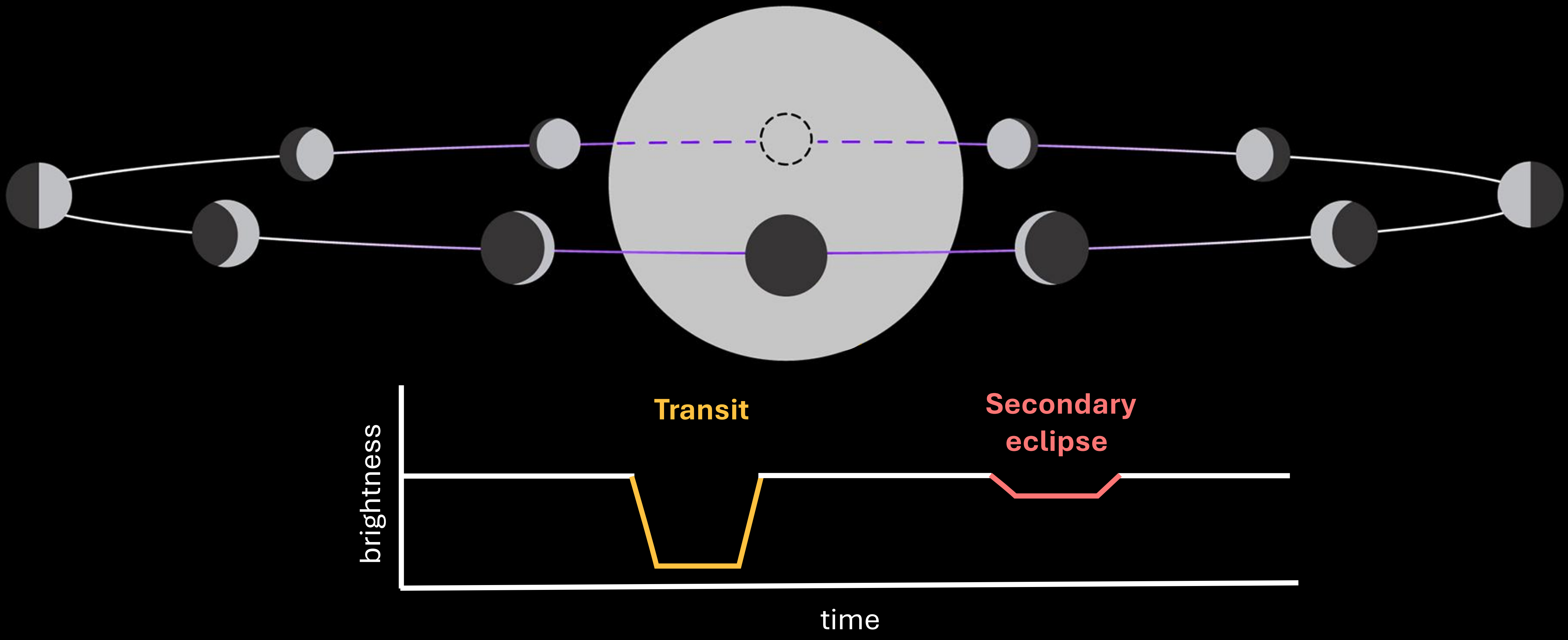
However there are some surprises! Observations are also probing more planets close to the shoreline to test its boundaries.



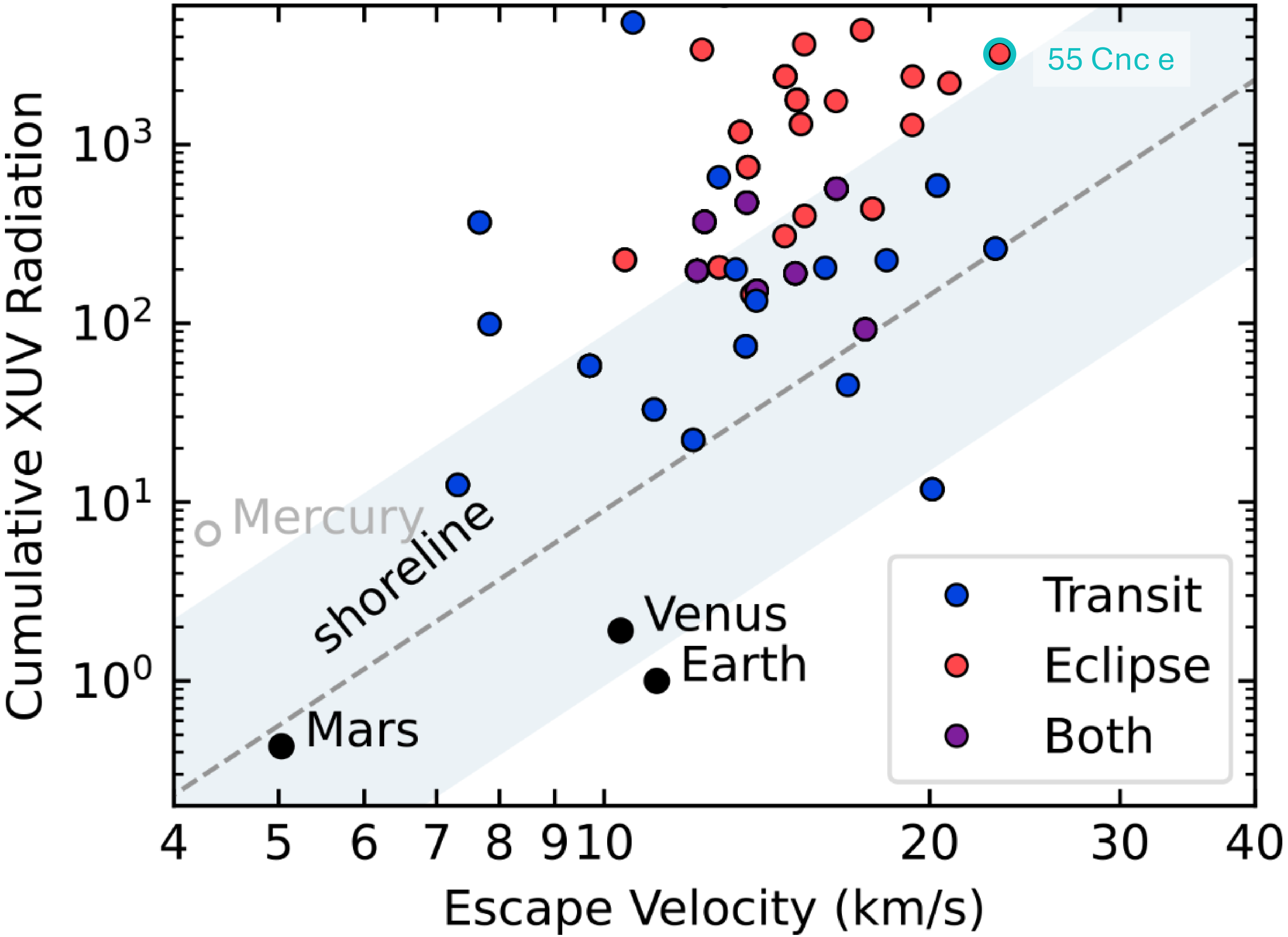

REDUCED AIRFLOW
LOW RH

The star blocks the light of the planet. **A hotter planet is brighter**, so it produces a deeper secondary eclipse.

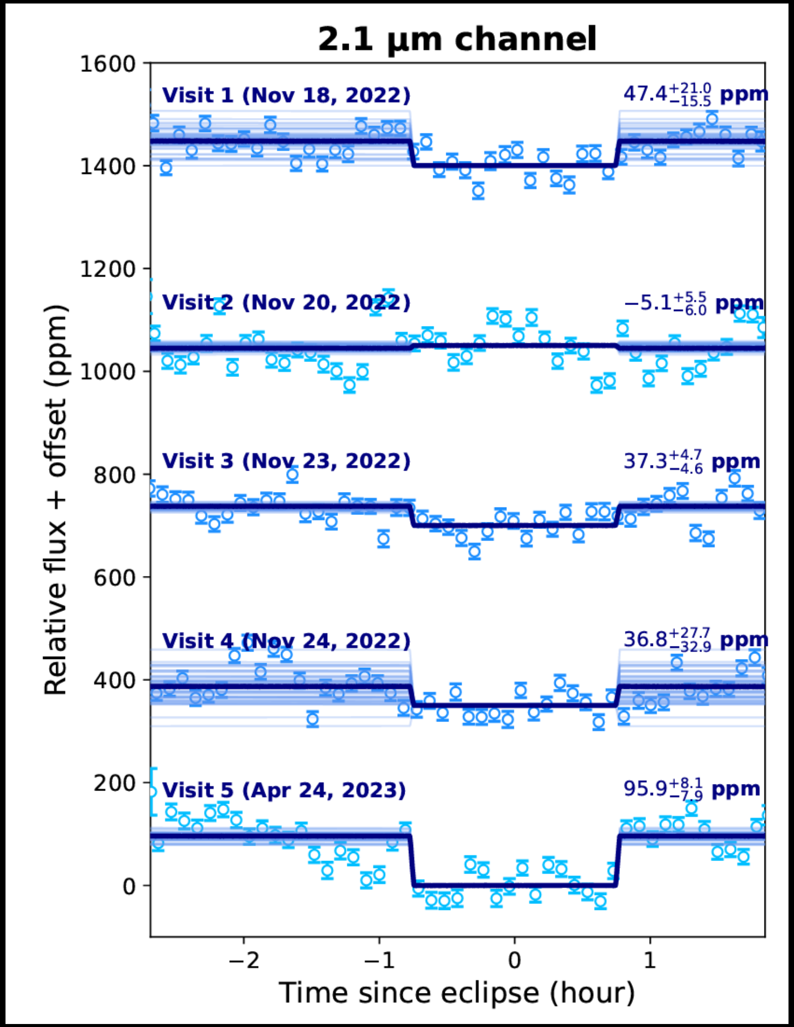




Transit
Secondary
eclipse
brightness
time

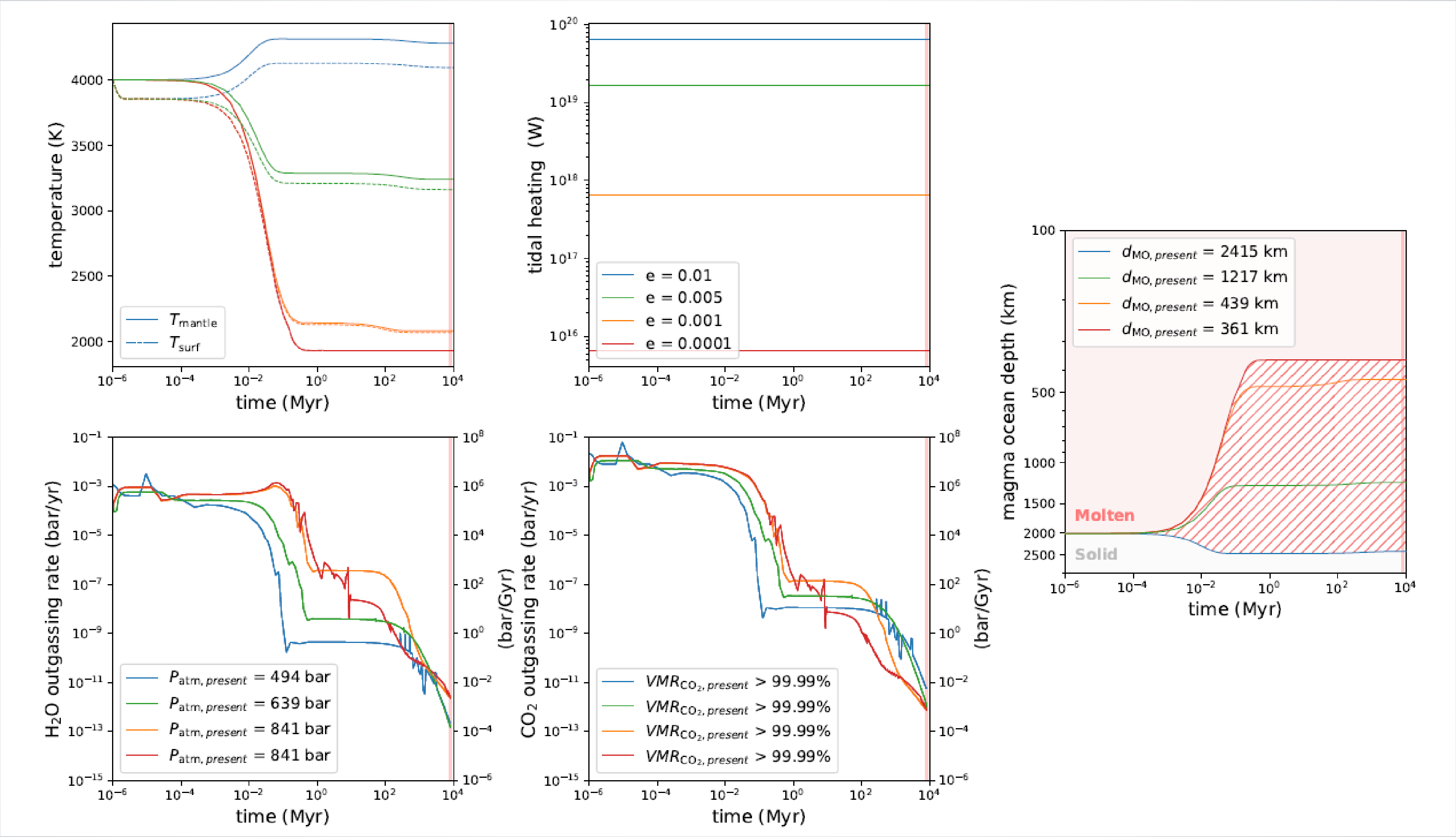

55 Cnc e
Mercury
shoreline
Venus
Earth
Mars
Transit
Eclipse
Both
Cumulative XUV Radiation
10^0
10^1
10^2
10^3
4
5
6
7
8
9
10
20
30
40
Escape Velocity (km/s)

Lava World 55 Cancri e has shown variability!



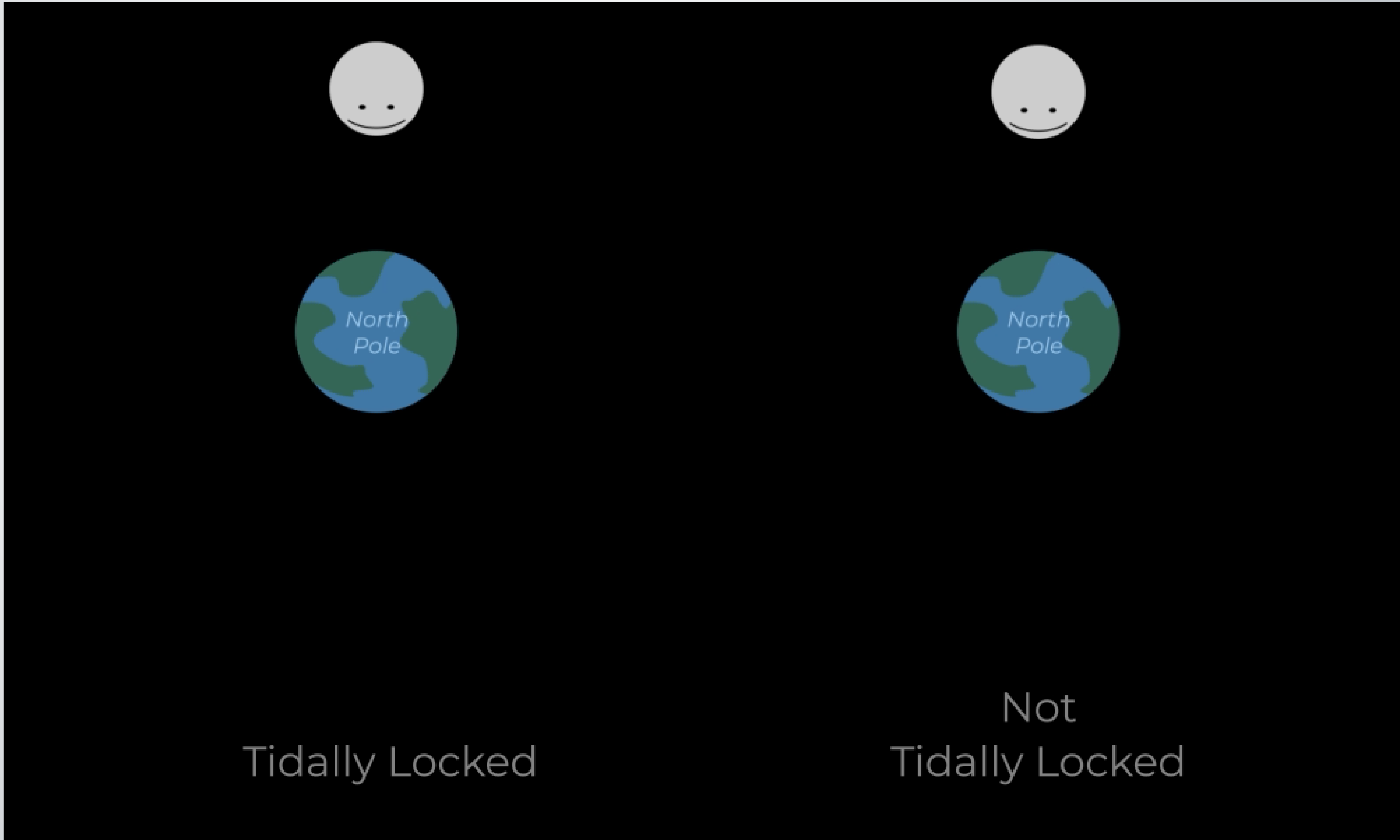
Patel et al. (2024)

Tidal heating prolongs outgassing – 55 Cnc e



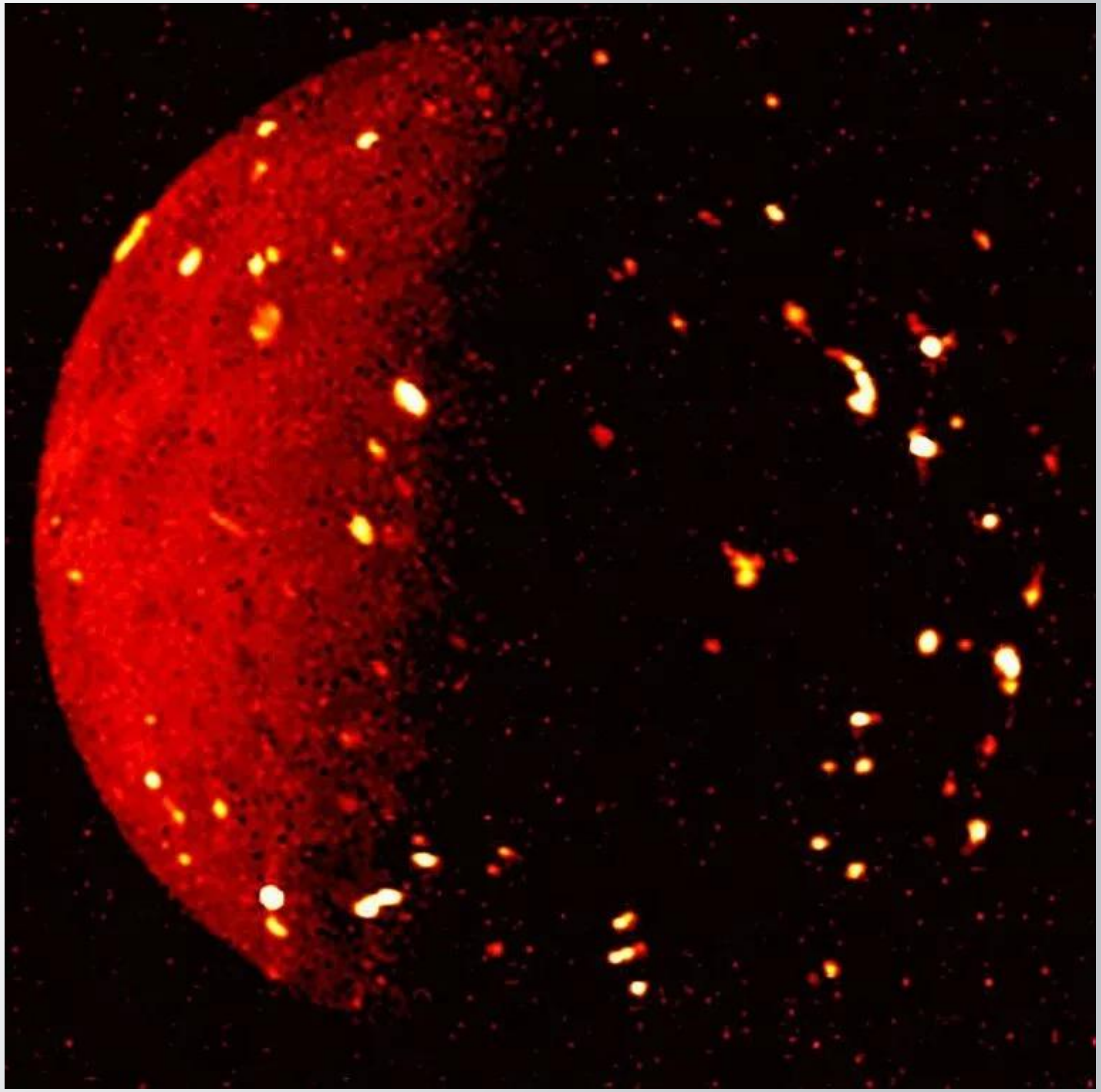
Nguyen et al. (2026) ApJ

Tidal locking



Tidal heating

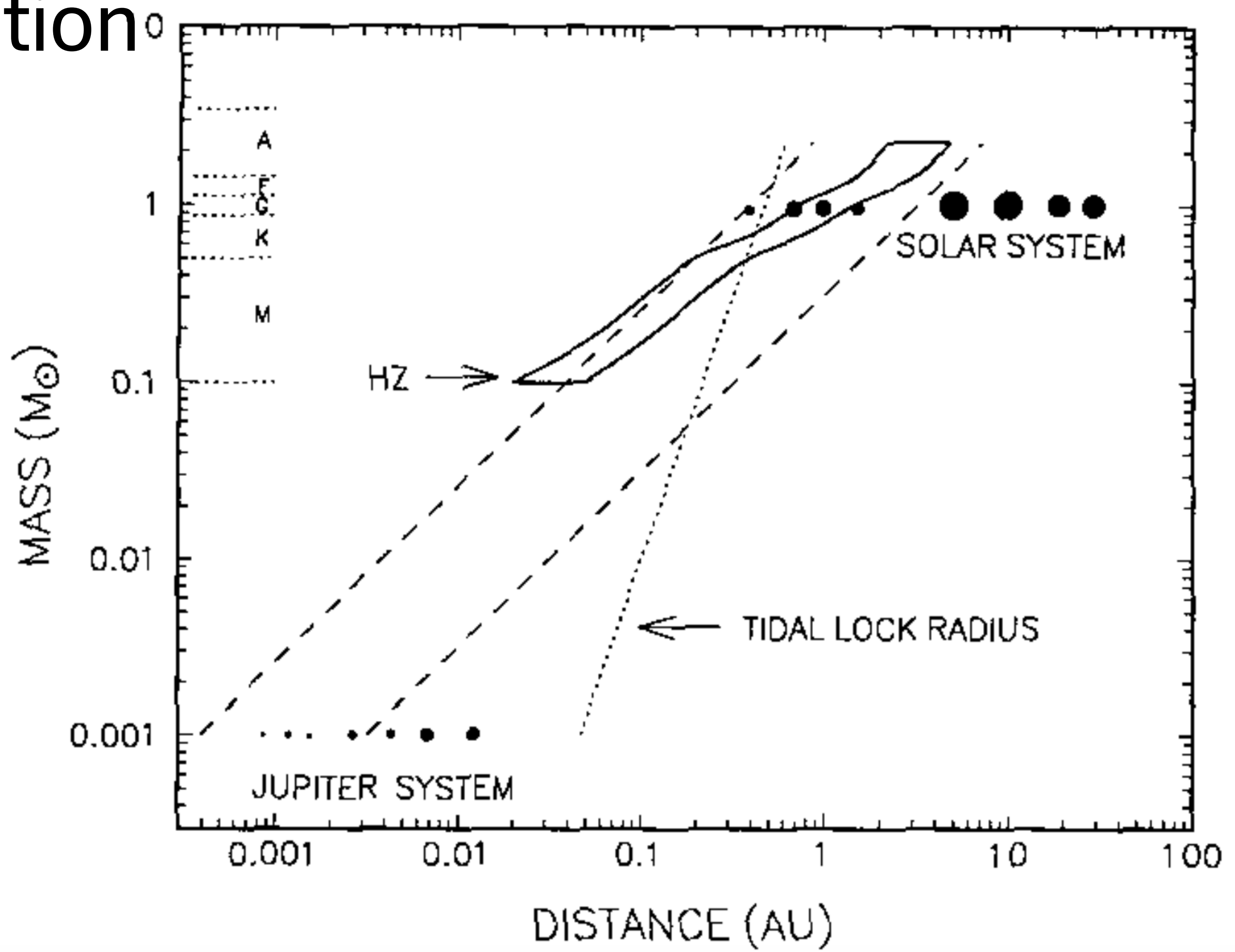
- Tides deform planet, creating internal friction
- Dissipates energy via heat



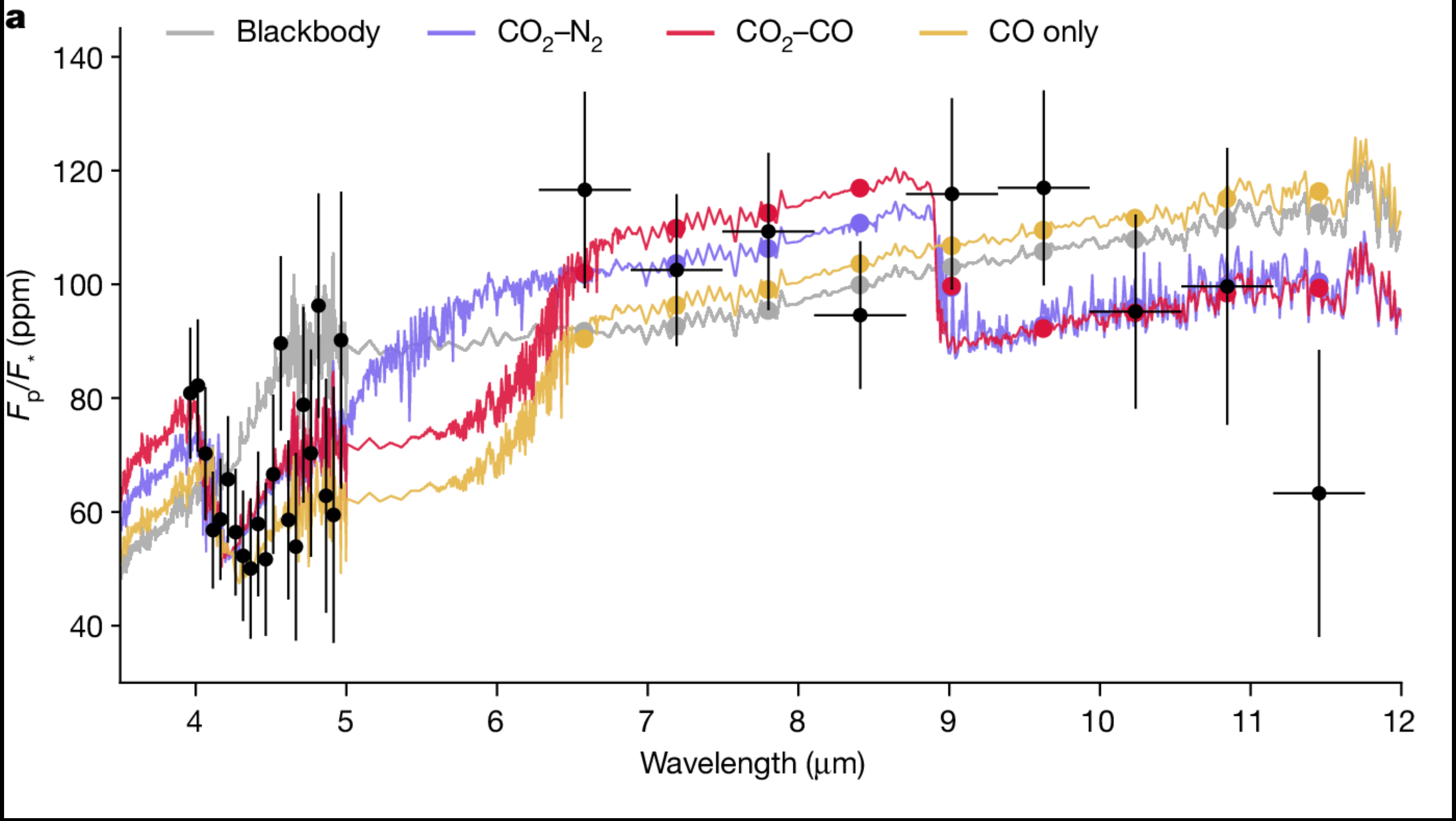
Tidal circularization

- Tidal lock radius: distance where planets get locked

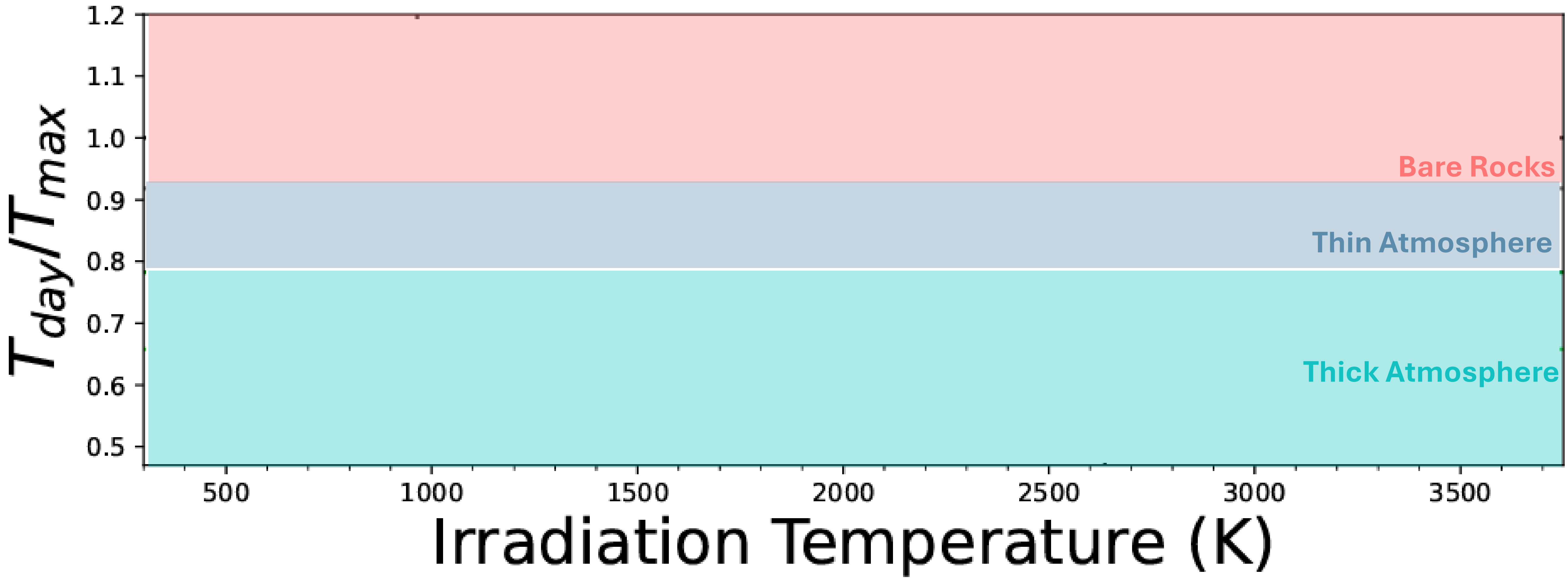
- Closer when star is less massive



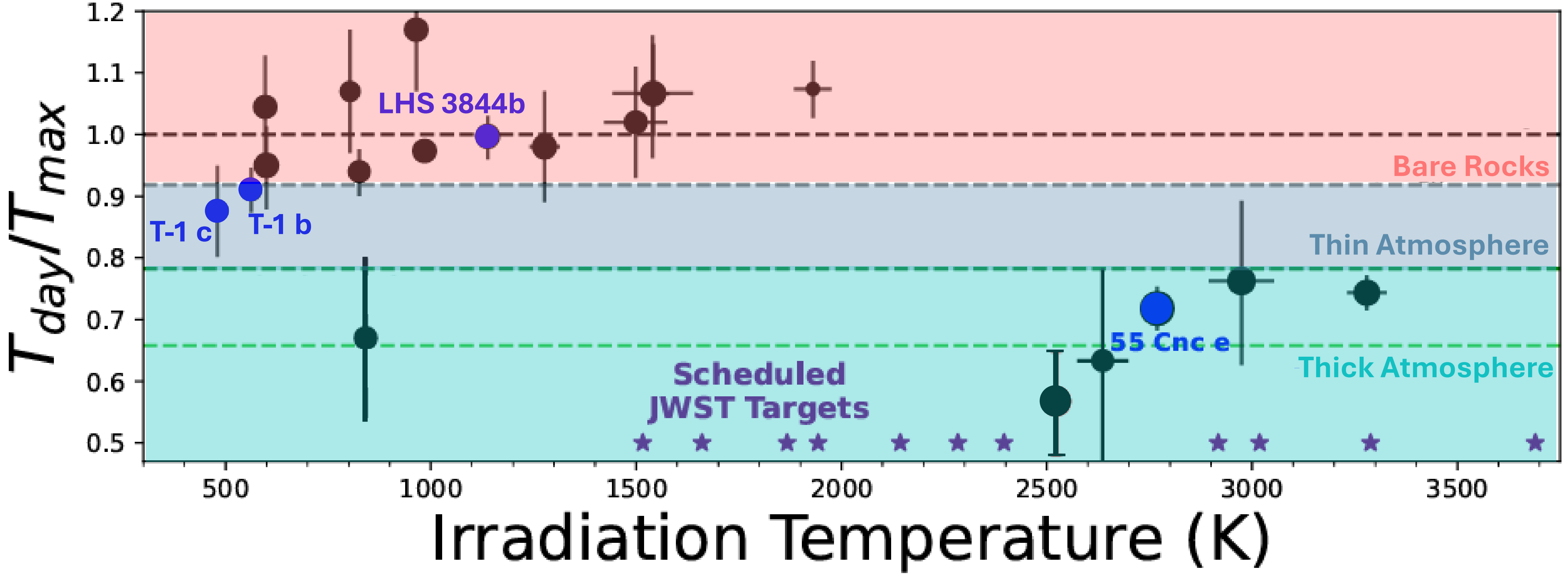
JWST reveals that 55 Cnc e, one of the hottest rocky planets, seems to have an atmosphere!



Hu et al. (2024)



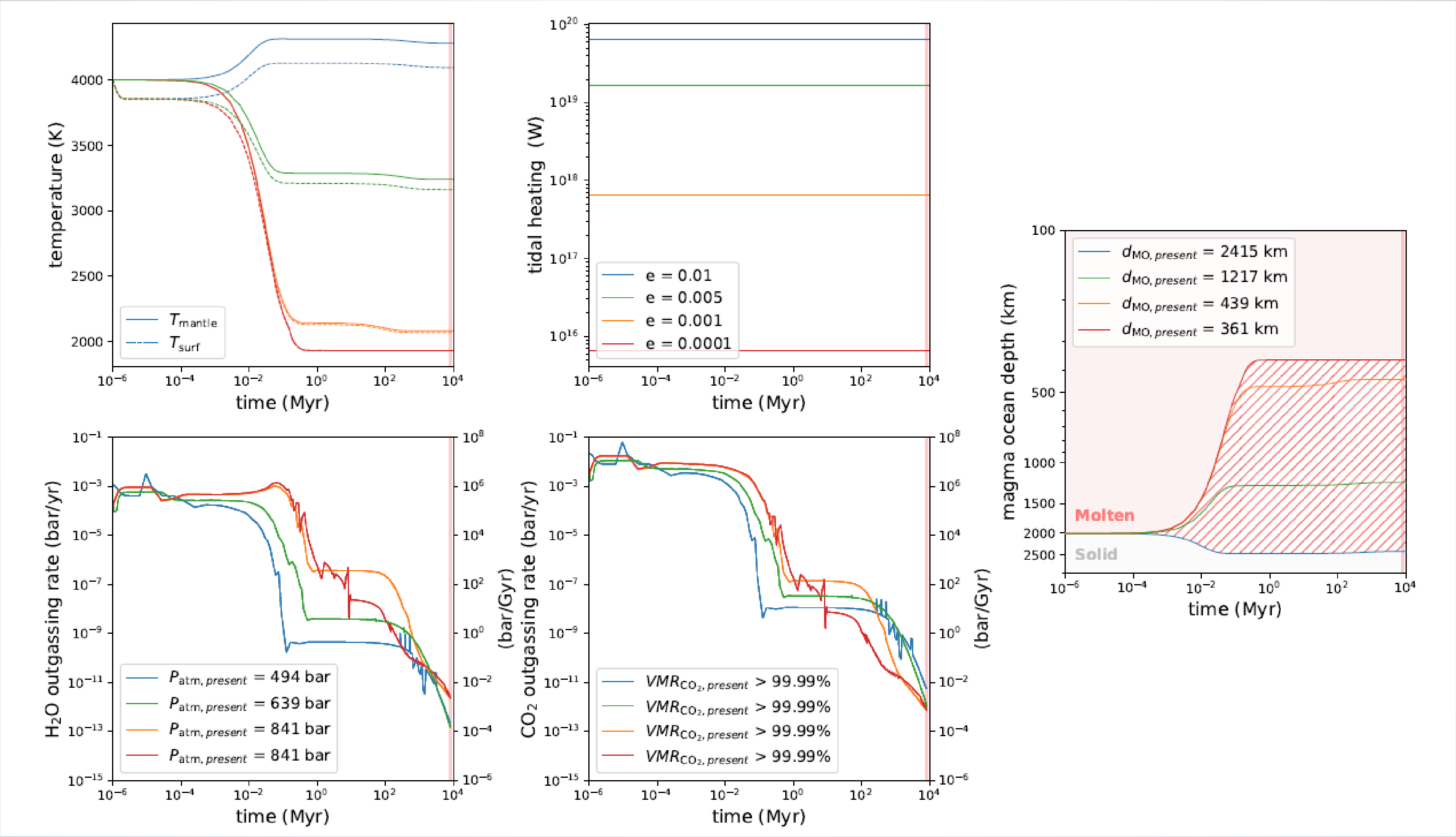
Coy et al. (2026)



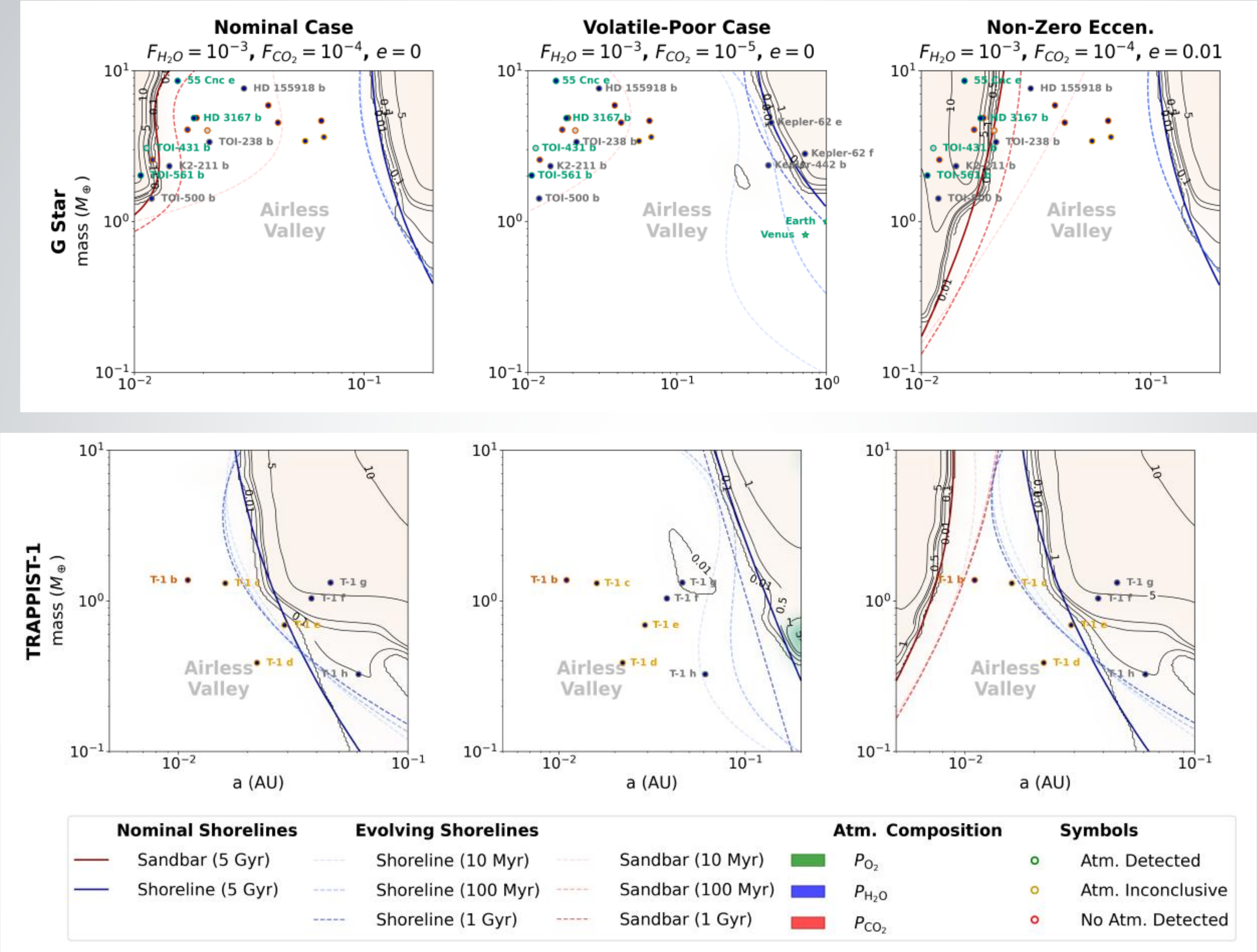
Coy et al. (2026)

The hottest planets show the strongest signatures of atmospheres!

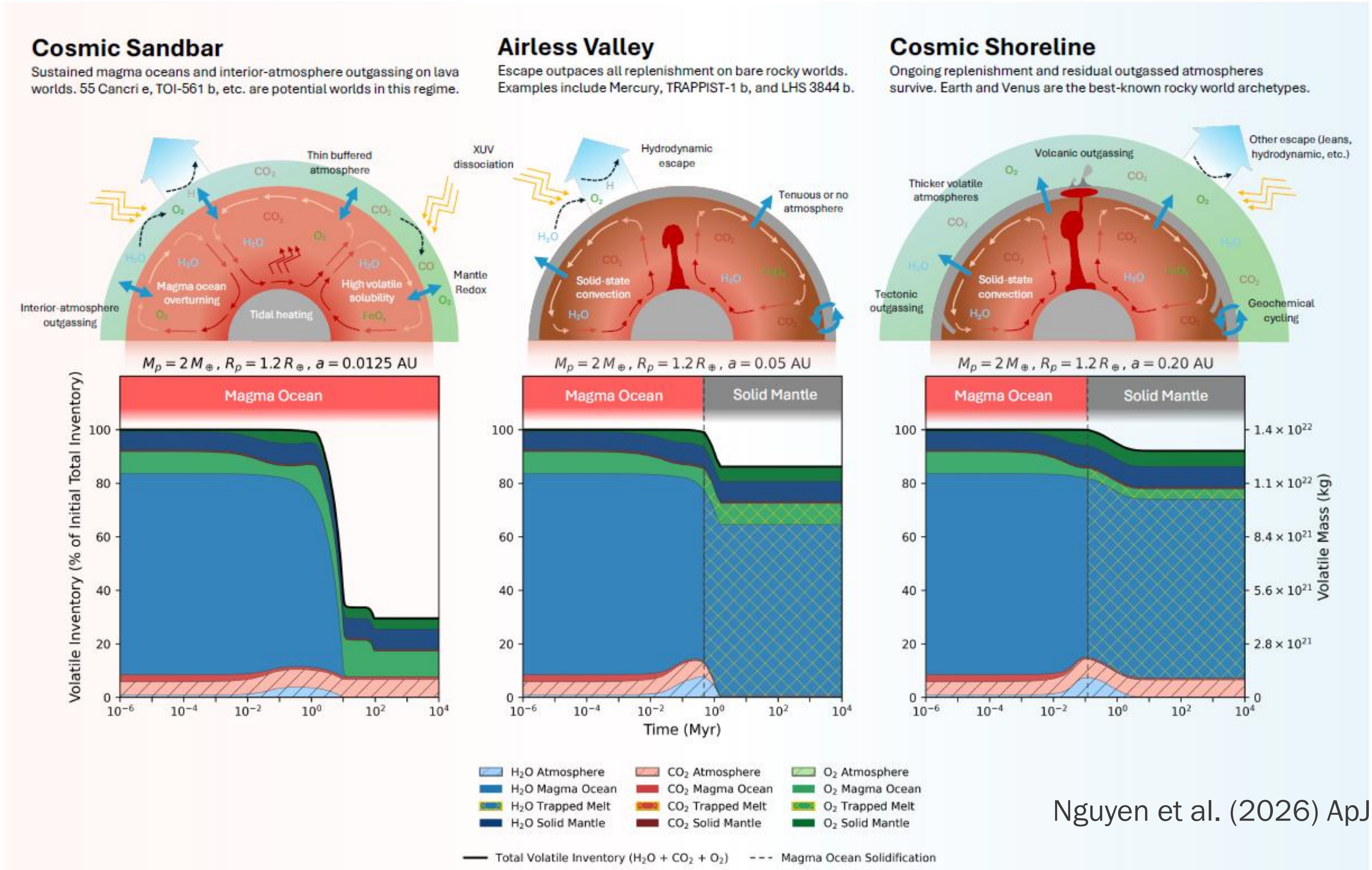
Tidal heating prolongs outgassing – 55 Cnc e



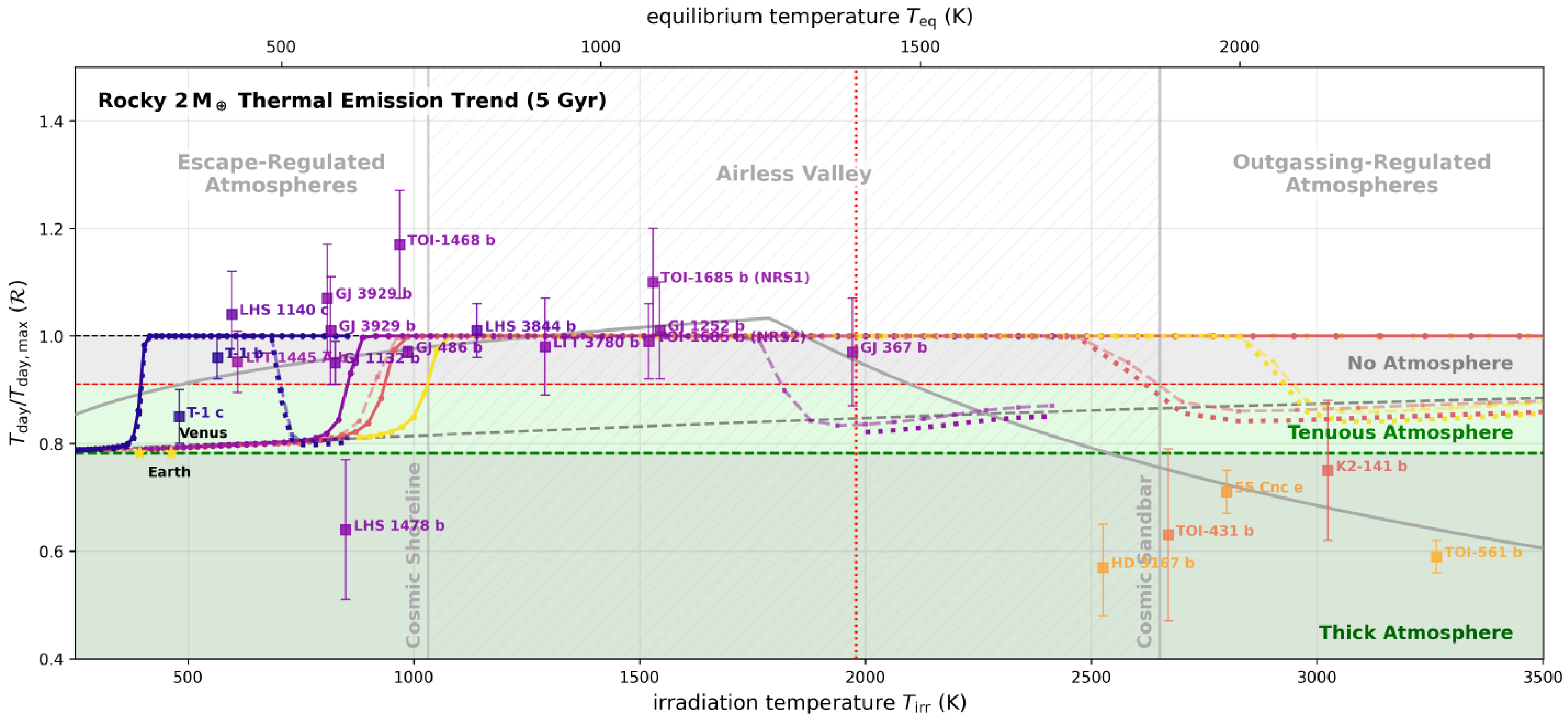
Nguyen et al. (2026) ApJ



Nguyen et al. (2026) ApJL



Nguyen et al. (2026) ApJL

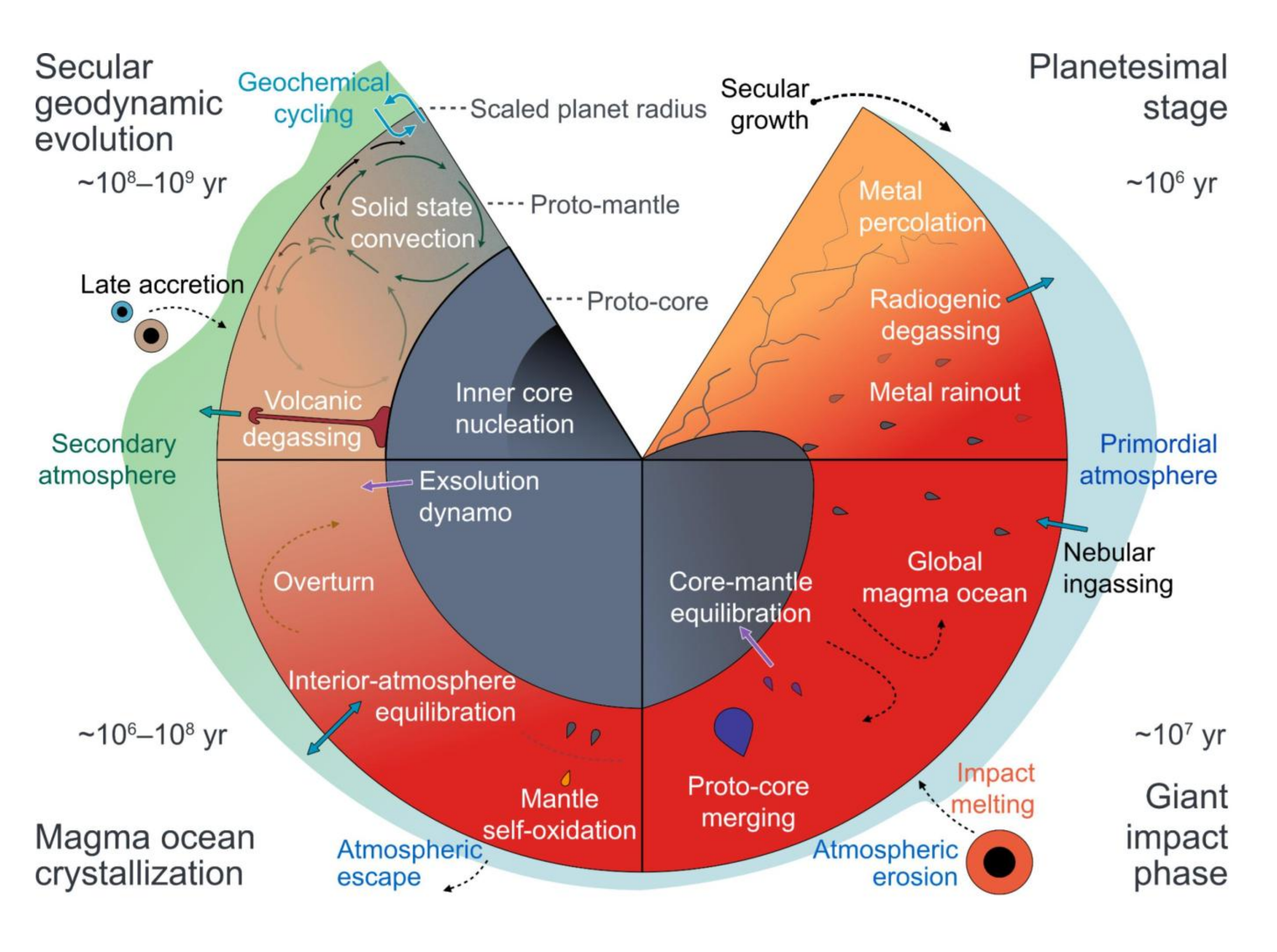


Nguyen et al. (2026) ApJL

Atmosphere-Interior Evolution

Life-essential elements (CHNOPS) interact with all layers of a rocky planet during the process of planet formation and evolution.

The availability of these elements at the surface depends on the integrated history of the planet.



Lichtenberg et al. (2022) Protostars and Planets VII

Recap

- Thermal escape processes have likely sculpted the close-in planet populations that we see today
- Active escape has been observed from H-dominated atmospheres of hot Jupiters, Neptunes and mini-Neptunes
- Super-Earths and Sub-Neptunes may have started as a single population of planets that have been changed by escape.
- Many small rocky exoplanets may have lost all of their atmosphere (Cosmic Shoreline), especially those orbiting small stars

Ignan Earths

Table 4
Candidate Ignan Earth's

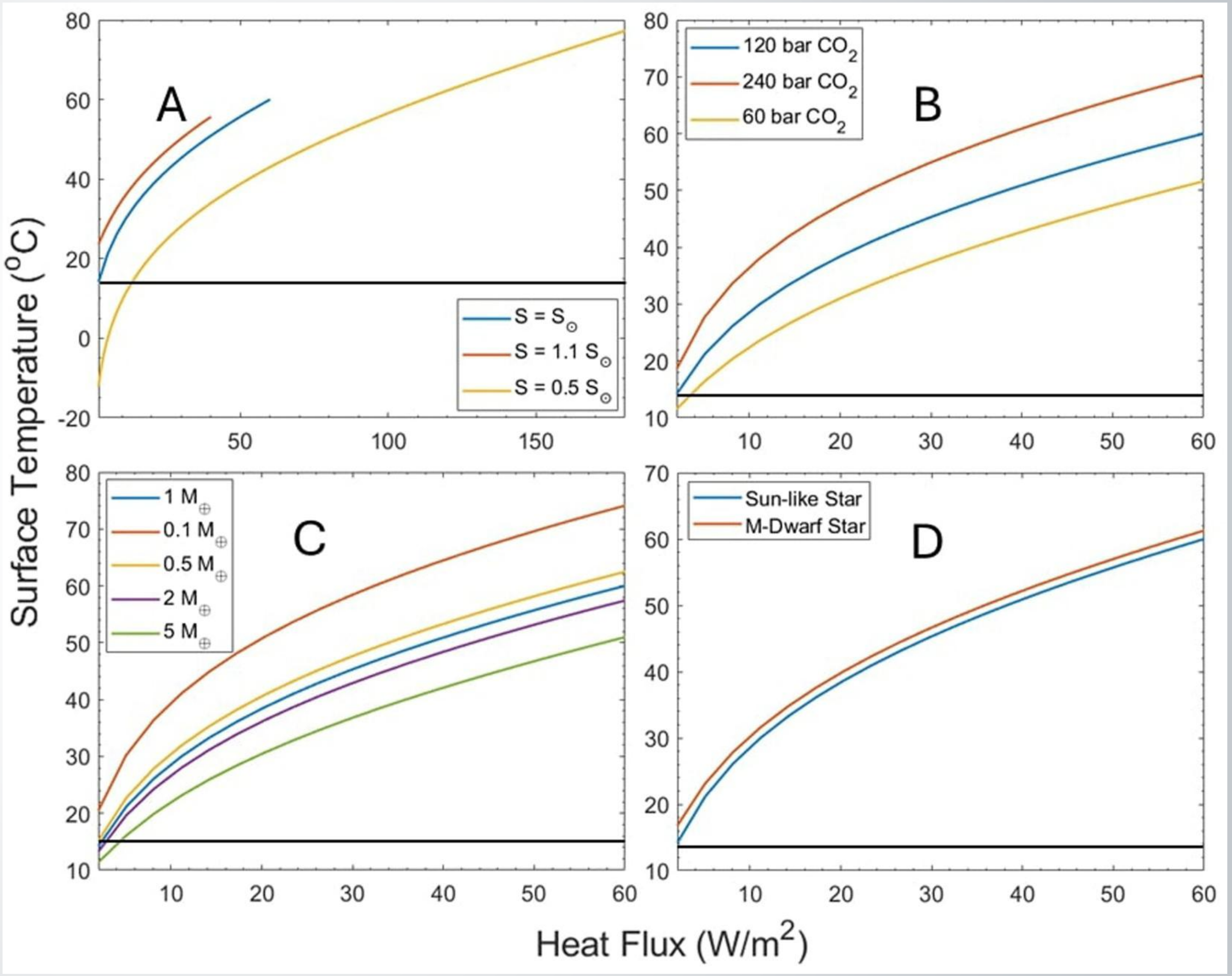
Planet	Tidal heat flux (W m^{-2})	Possible Ignan Earth?
TRAPPIST-1 d	0.14–1.27	Maybe
TRAPPIST-1 e	0.022–2.4	Maybe
TRAPPIST-1 f	0.025–0.4	Maybe
Teegarden's Star b	392	No
Teegarden's Star c	5.98	Yes
Proxima Centauri b	33.31	Yes
GJ 1061 c	344	No
GJ 1061 d	42.28	Yes
Ross 128 b	8.02	Yes

Note. Tidal heat flux estimates for select planets, all in units of W m^{-2}.

"Ignan Earths" = planets with extreme tidal heating

We investigated their habitability using a heat pipe model and a carbonate-silicate climate model.

We found that planets with < 60 W/m^2 of tidal heating are generally habitable!



Reinhold & Schaefer (2025)