Habitable Evaporated Cores

Vigorous Atmospheric Escape from Mini-Neptunes in the Habitable Zones of M Dwarfs

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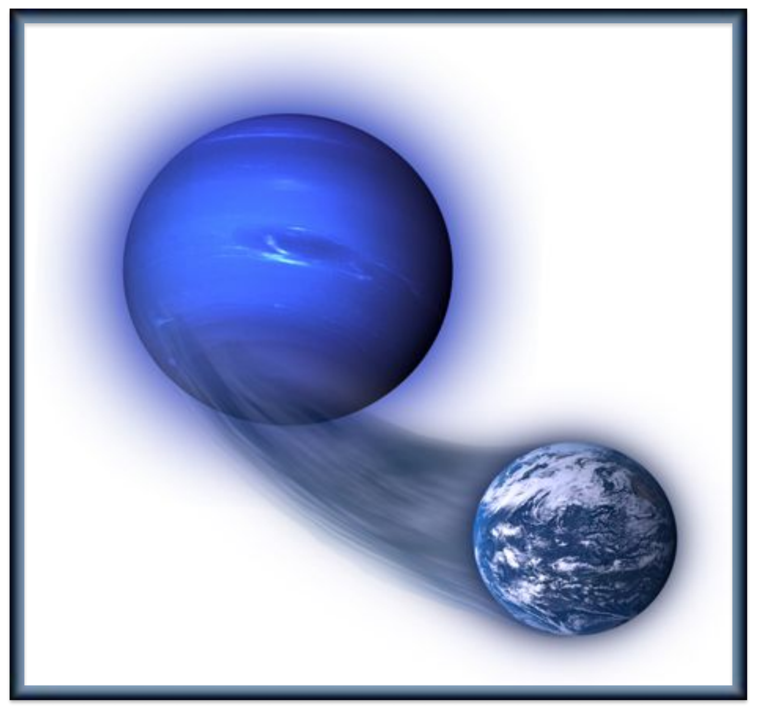

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The low masses and luminosities of M dwarfs make them ideal targets for the detection of terrestrial planets in the habitable zone (HZ[1]). However, studies suggest that planets formed only from material in the HZs of these stars are likely to be small and dry[2,3]. Moreover, the long contraction phase of M dwarfs results in these stars being superluminous for as long as 1 Gyr **(Figure 3)**, exposing planets that will eventually be in the HZ to extreme levels of radiation. Earth-like planets in this regime will enter a runaway greenhouse and may be completely desiccated by H loss to space, particularly around late M dwarfs **(Figure 4)**.

As a result, habitable planets around M dwarfs may preferentially form from bodies that migrate into the HZ from beyond the snow line. These planets are enhanced in volatiles and may have accreted large H/He envelopes, which could help shield the surface from the extreme radiation environment early on. In this study, we show that photoevaporation and Roche lobe overflow of migrating "mini-Neptunes" can lead to the complete loss of their gaseous envelopes, transforming them into potentially habitable worlds, which we call ***habitable evaporated cores*** **(HECs)**. We couple planet structure evolution models[4] with a simple Roche lobe overflow scheme and an extreme ultraviolet (XUV)-induced mass loss model[5,6]. We also couple the orbital effects of tidal evolution[7] and show that this coupling can lead to orbital changes that significantly enhance the mass loss rate.

HECs are most likely to form from small mini-Neptunes ($\lesssim 2$ M$_\oplus$) with up to ~50% initial hydrogen fractions orbiting M4 stars and later, and are likely to be similar in size to the Earth. Given the steep decrease in stellar XUV flux with time[8], mass loss is negligible after ~1 Gyr, at which point a habitable evaporated core is capable of degassing and maintaining a secondary atmosphere. This process could be a major formation mechanism for habitable planets around M dwarfs, and may be discovered in the next few years by upcoming missions such as TESS and PLATO.

Parameter	Range	Default
$M_\star$ ($M_\odot$)	0.08 – 0.4	-
M_p ($M_\oplus$)	1 – 10	-
R_{XUV} (R_p)	1.0 – 1.2	1.2
a	IHZ - OHZ	-
e	0.0 - 0.9	-
$P_{0,\star}$ (days)	1.0 – 100	30.0
f_H	10^{-6} – 0.5	-
ϵ_{XUV}	0.1 – 0.4	0.3
ξ_{min}	$1 + 10^{-5}$ – 3	3
Atmos. esc.	R/R-Lim / E-Lim	-
Tidal model	CPL/CTL	CTL
$Q_\star$	10^5 – 10^6	10^5
Q_p	10^1 – 10^5	10^4
$\tau_\star$ (s)	10^{-2} – 10^{-1}	10^{-1}
τ_p (s)	10^{-3} – 10^3	10^{-1}
β	0.7 – 1.23	1.23
t_{sat} (Gyr)	0.1 – 1.0	0.1
t_0 (Myr)	10.0 – 100.0	10.0
t_{stop} (Gyr)	0.01 – 5.0	5.0

Table 1: A list of free parameters and their ranges, as well as default values used in the plots.

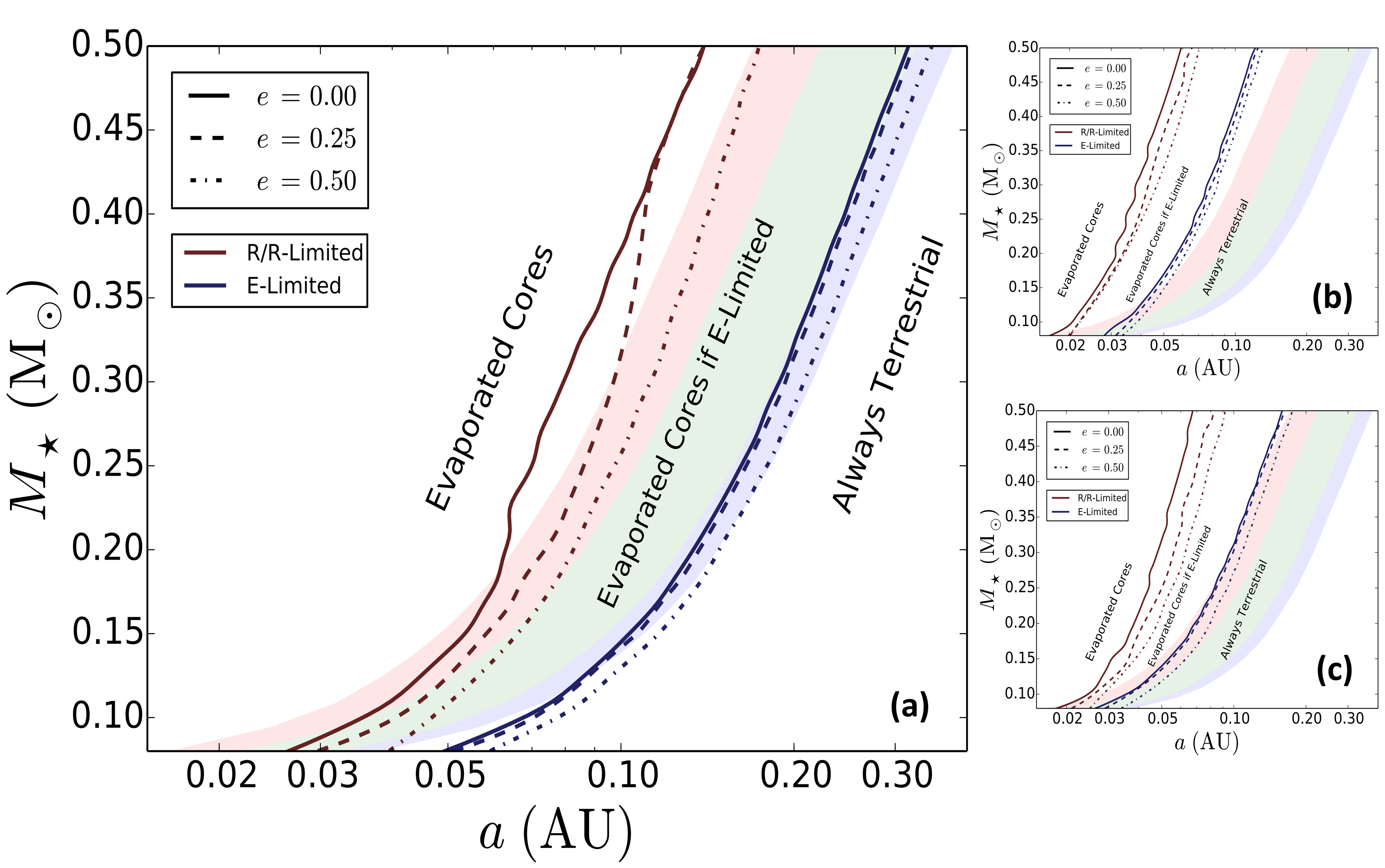

Figure 1: Regions of parameter space that may be populated by HECs. Terrestrial planets detected today occupying the space to the *left* of each contour line could be the evaporated cores of gaseous planets. Planets detected to the *right* of the contour lines have always been terrestrial/gaseous. Dark red lines correspond to mass loss dominated by radiation/recombination-limited escape, while dark blue lines correspond to the more vigorous energy-limited mechanism. Which mechanism operates will depend on the ratio of stellar EUV to X-ray luminosity[9]. Different line styles correspond to different eccentricities today. Terrestrial planets detected at higher eccentricity (dashed and dash-dotted lines) could be evaporated cores at slightly larger orbital separations than planets detected on circular orbits (solid lines). In the energy-limited regime, all 1M$_\oplus$ terrestrial planets in the HZ of low-mass M dwarfs could be habitable evaporated cores. **(a): The default run**, for M_{core} = 1M$_\oplus$ and $M_H \leq$ 1M$_\oplus$. **(b): Weak XUV run**, for t_{sat} = 0.1 Gyr and ε_{XUV} = 0.15. **(c): Super-Earth**, with M_{core} = 2M$_\oplus$ and $M_H \leq$ 2M$_\oplus$.

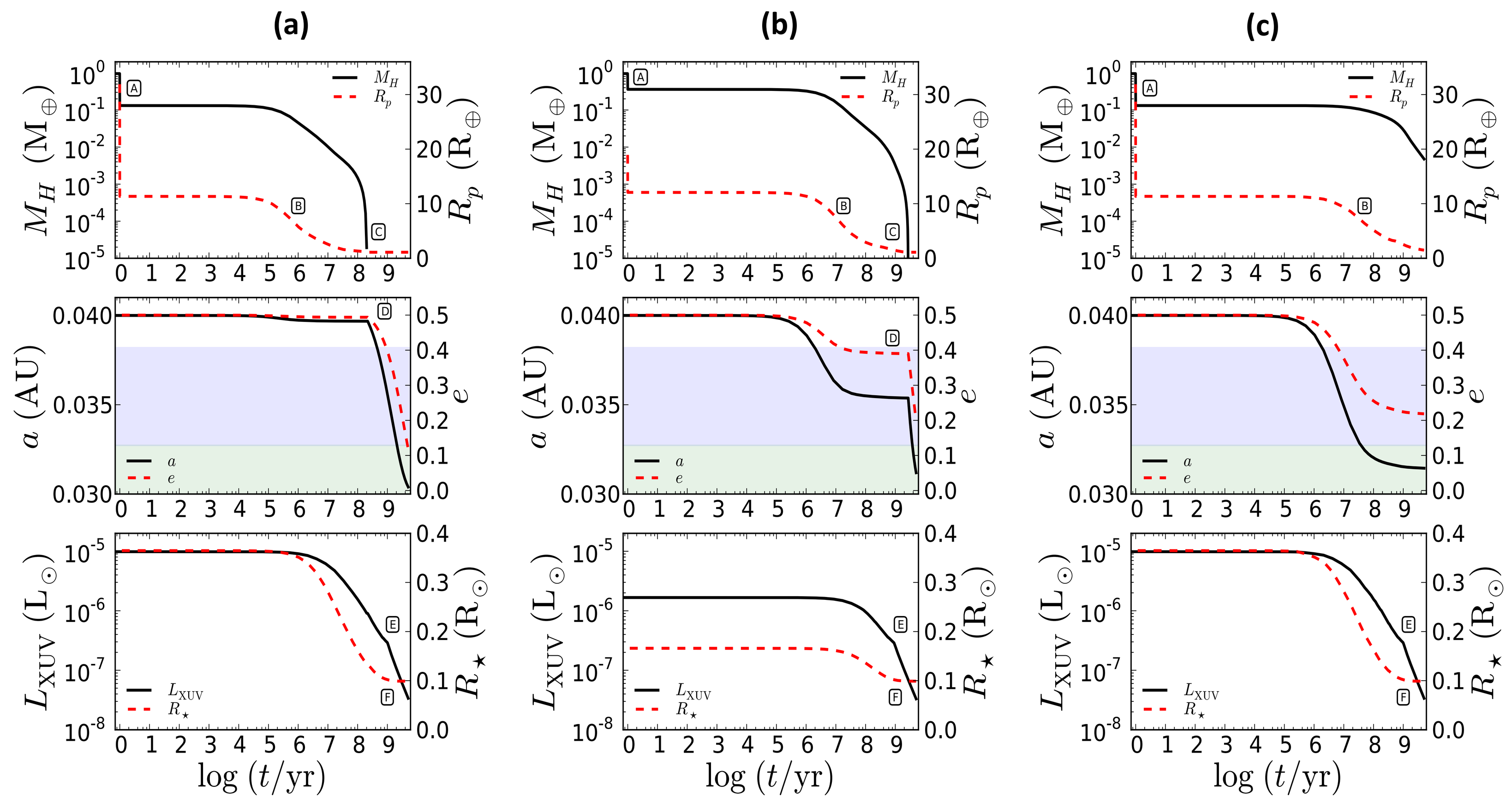

Figure 2: Three sample integrations of our code, showing envelope mass (M_H), planet radius (R_p), semi-major axis (a), eccentricity (e), stellar XUV luminosity (L_{XUV}) and radius (R_*) as a function of the time t since formation. The planet is initially a 1 M$_\oplus$ core with a 1 M$_\oplus$ envelope orbiting a 0.08 M$_\odot$ M-dwarf with e = 0.5 at a semi-major axis of 0.04 AU, just outside the OHZ (outer HZ; light blue shading). As it loses mass and tidally evolves, it migrates into the CHZ (center HZ; light green shading). **(a): Energy-limited escape.** The planet loses its entire envelope at $t \approx$ 100 Myr. **(b): Late migration**, with t_0 = 100 Myr. While the envelope still completely evaporates, this occurs at a much later time, $t \approx$ 2 Gyr. **(c): Radiation/recombination-limited escape.** Here, the envelope does not fully evaporate and tidal migration is noticeably weaker.

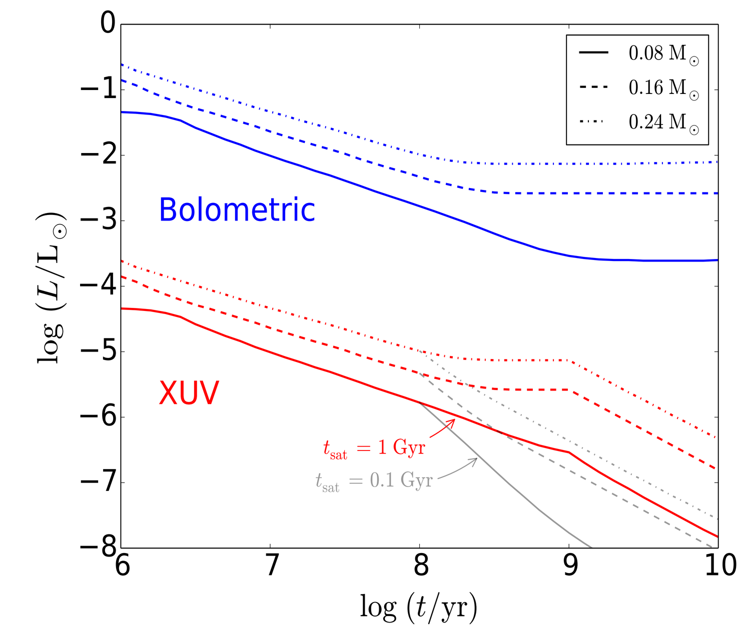

Figure 3: Evolution of the bolometric (blue) and XUV (red) luminosity for three different stellar masses (solid: 0.08M$_\odot$; dashed: 0.16M$_\odot$; dash-dotted: 0.24M$_\odot$) as a function of time. Two XUV saturation times are shown: 1 Gyr (red) and 0.1 Gyr (grey). Note the several order-of-magnitude drop in the first ~1 Gyr for the latest M dwarfs.

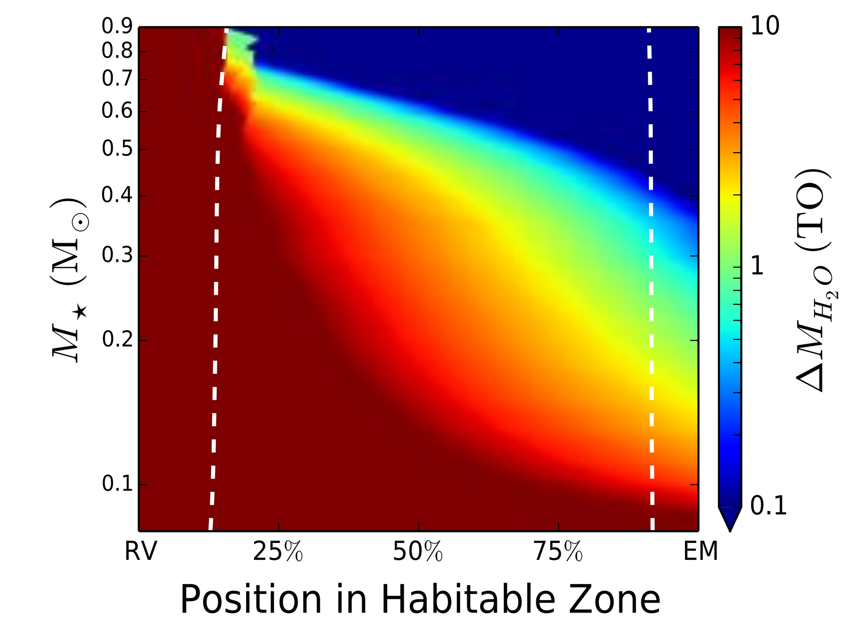

Figure 4: Mirage Earths? Because of the long contraction phase of M dwarfs, Earths formed in situ in the HZ may lose upwards of 10 Terrestrial Oceans (TO) of water in the first ~100 Myr, rendering them dry and uninhabitable. These planets may also build up hundreds of bars of O_2 in their atmospheres. ***Luger & Barnes, abstract #7382***

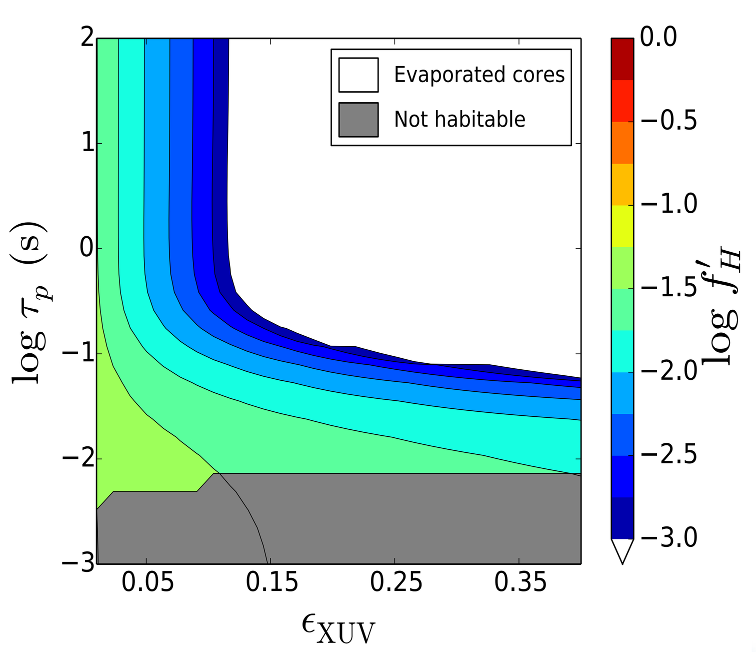

Figure 5: Final H fraction as a function of XUV absorption efficiency and tidal time lag for a sample run of our code. Mass loss and tidal evolution are strongly coupled in these systems.

References
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