

# XUV-Driven Atmospheric Mass Loss of M Dwarf Planets due to Flaring

Laura Amáral<sup>1,2,3,4</sup>, Rory Barnes<sup>2,5</sup>, Antigona Segura<sup>2,3</sup>, and Rodrigo Lúge<sup>6</sup>

<sup>1</sup>School of Earth and Space Exploration, ASU (current)

<sup>2</sup>Instituto de Ciencias Nucleares, UNAM

<sup>3</sup>NASA Virtual Planetary Laboratory

<sup>4</sup>Consortium on Habitability and Atmospheres of M-Planets (CHAMPs)

<sup>5</sup>Department of Astronomy, UW

<sup>6</sup>Center for Computational Astrophysics, Flatiron Institute



Surfing the Climate Symposium | October 2023

ð' L'UaETECEgP+ ð'gVUgyM' tgthvHtMb+  
Uj



° ð'g' v\dyELðtM  
g' gM' gM' tPDEtM'g'U  
tPv/d aETECEgP  
° l' tM' Eyg'tM'sTs

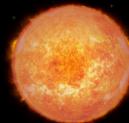
1. iron core And  
silicate mantle



t'g'gU'1D vPvExg' xPv'1Cv'  
tM'gVUDvPvCv'g' EwD  
IyCgEgPvU  
g' v'1CPEM'

48.6%

KtMtM'gVPPv'gPyM  
HtM'gUg'vK  
FPPvgg'vgtM'sTu



3. Habitable  
zone

AUg'gU'1L'U'1g'U'1g' d'P'Tu's tsT

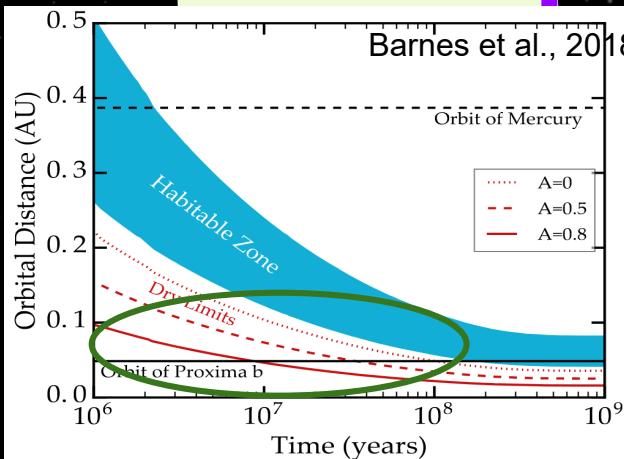
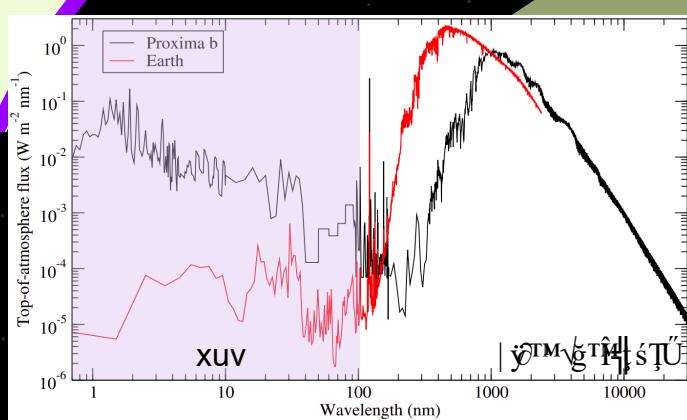


18 of the 20 planets  
with higher earth  
similarity index are  
around mdwarfs  
(PH, 2023)

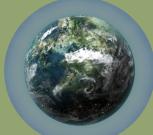
# PREMAIN SEQUENC

g'v'U'

INNER EDGE HZ



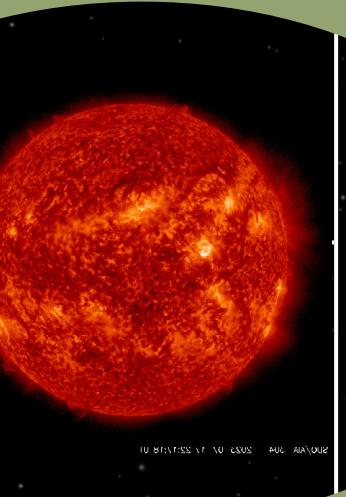
# MAIN SEQUENC



x̄t̄m̄ḡī t̄m̄v̄t̄m̄l̄c̄p̄ūv̄  
ōḡn̄ḡ v̄ȳūb̄v̄āv̄ ° C̄  
ḡ v̄k̄āc̄p̄ūt̄m̄ ḡ v̄x̄d̄Ā

# M DWAR ENVIRONME

FU BRIGHTNESS VARIATIONS AND ALBEDO



Å^!| :föN fd:fâ

:ÜP-L | T̄M̄T̄P̄V̄l̄t̄ v̄b̄  
ÅU | t̄ | Ts IP  
d aE^TCE | T̄ | a^M

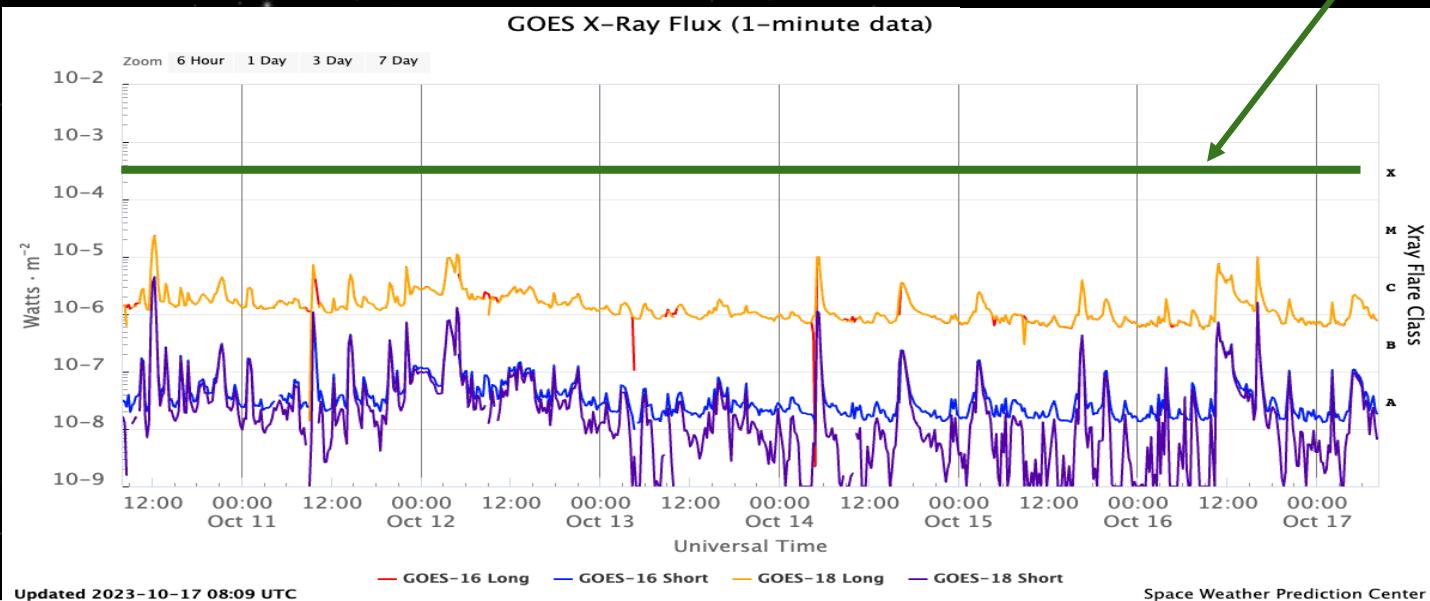
Åy^TM^TM^g^T̄M̄s̄T̄  
°ČUđ°°avg^T̄M̄s̄T̄U  
KTĒL̄v̄g^T̄M̄s̄T̄

Solar flare



†!° Dë†z̄N̄v̄UH̄  
Åxūs̄T̄

GOES X-Ray Flux (1-minute data)



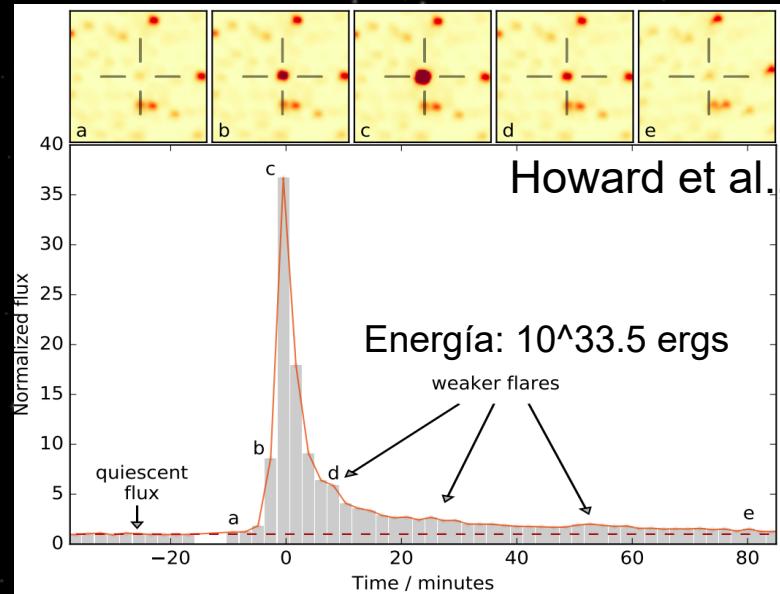
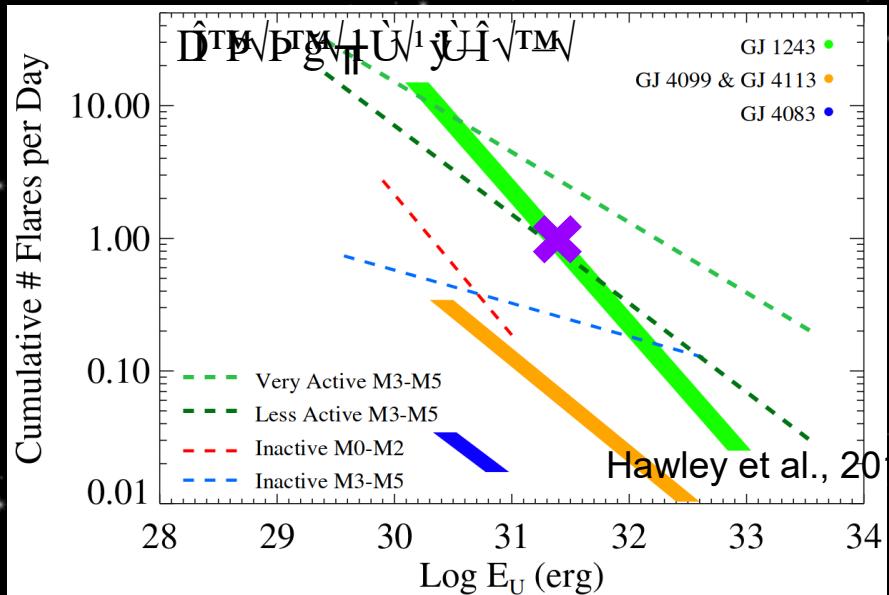
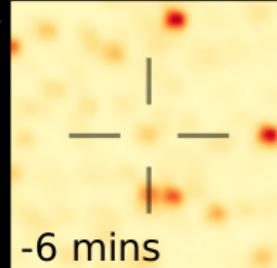
# d 58! | D föN fd:fâ

: ÜP-L  
ÅU  
d aE<sup>T</sup>ECE

T M T V N t V P-1  
t T S L P  
T a E M

Å y T M T M G T M s T T  
° C U ð ° ° a v g T M s T U  
K E l V g T M s T T

M DWARF flare (PROXIMA CEN)



ÅU ð T M V L E V Y R ° E ð P T u s t s t T

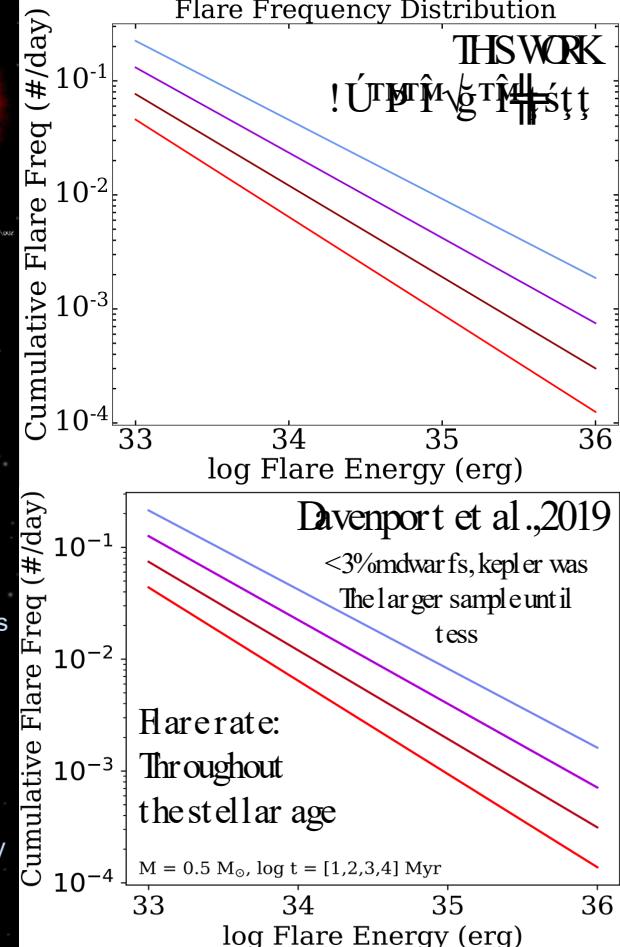
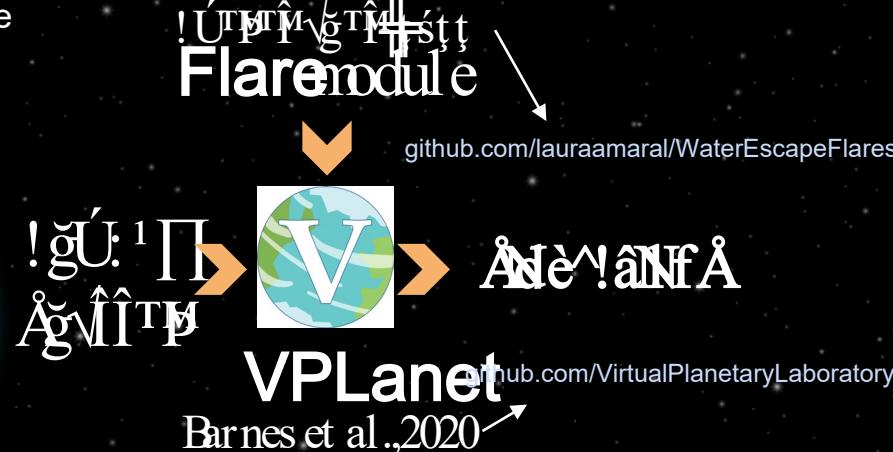
# δKâ!f5Kδ ð: 5Nδ+

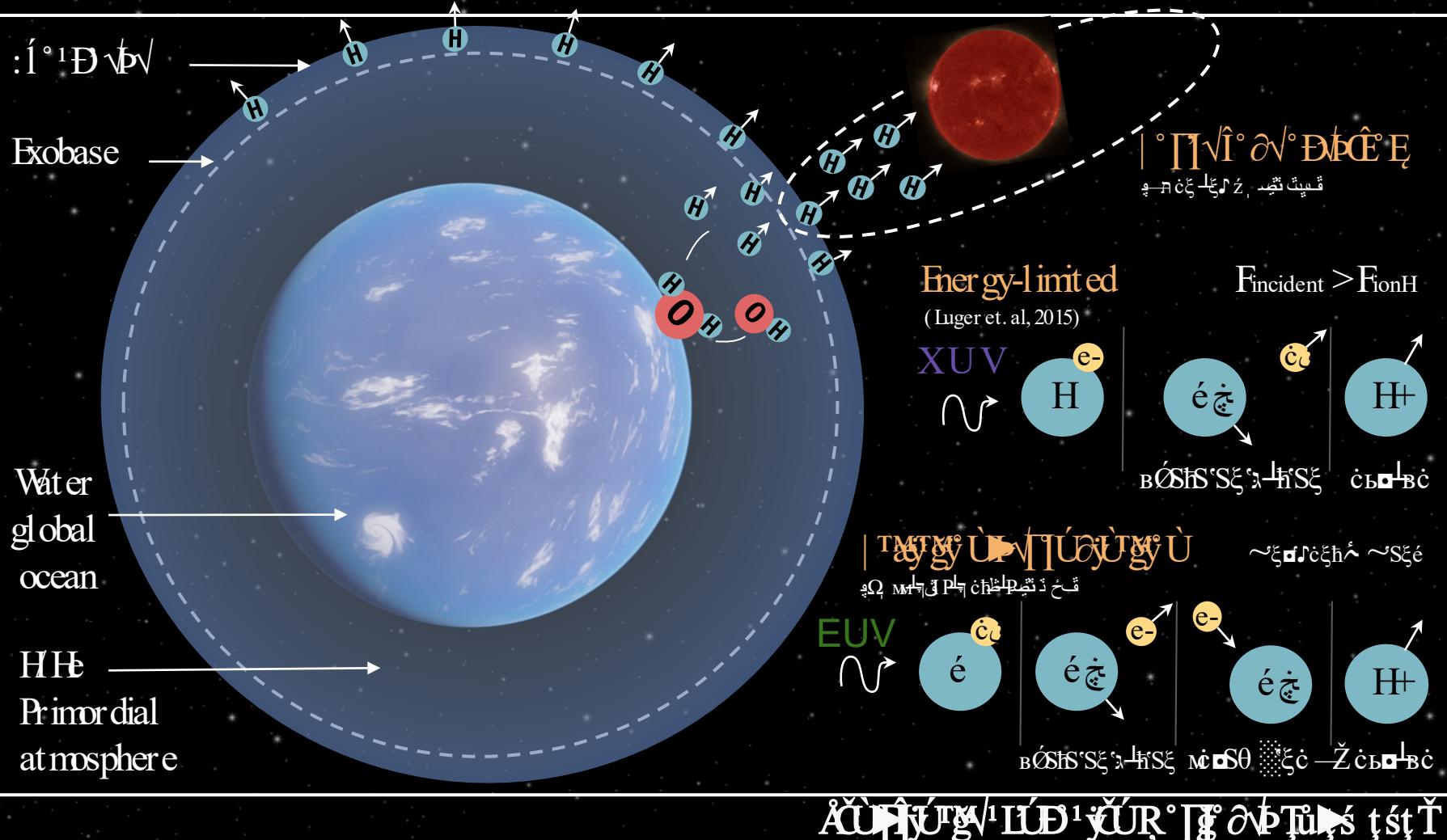
Ω ˜ C—±

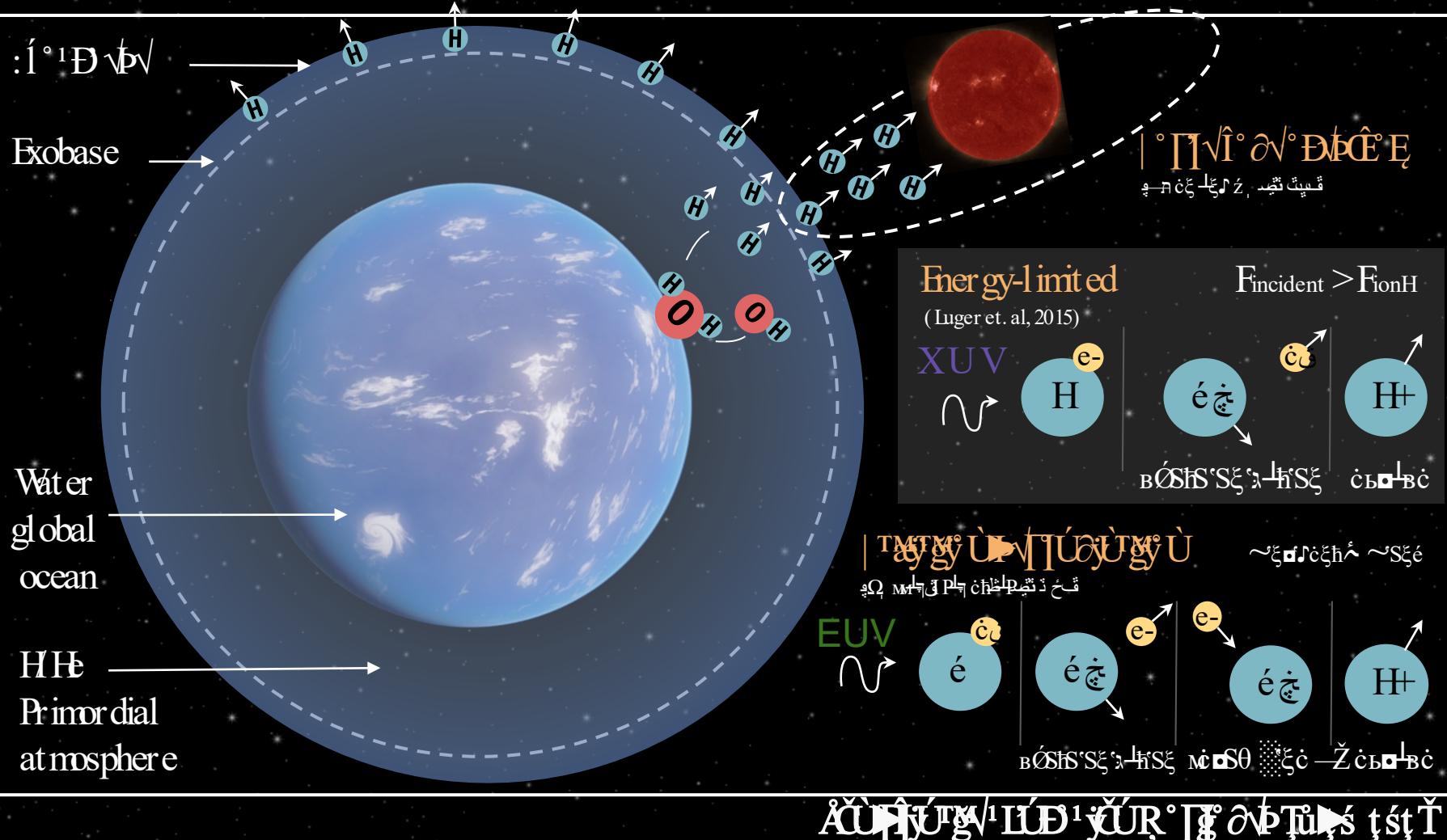
/!γè^!â: !gÚ¹D vPJTMæ ČPEW/ETM/̄P̄° 11  
aČPJU-g' vxdÅl Dl 5ð!| DÅ!| Å

!â yNd1F f t st T  
FFD constant along  
The stellar age

Kð+ → Add XM by flares







# Runaway Greenhouse Phase

## PARAMETERS

Planetary mass  
**0.55 M<sub>Earth</sub>**

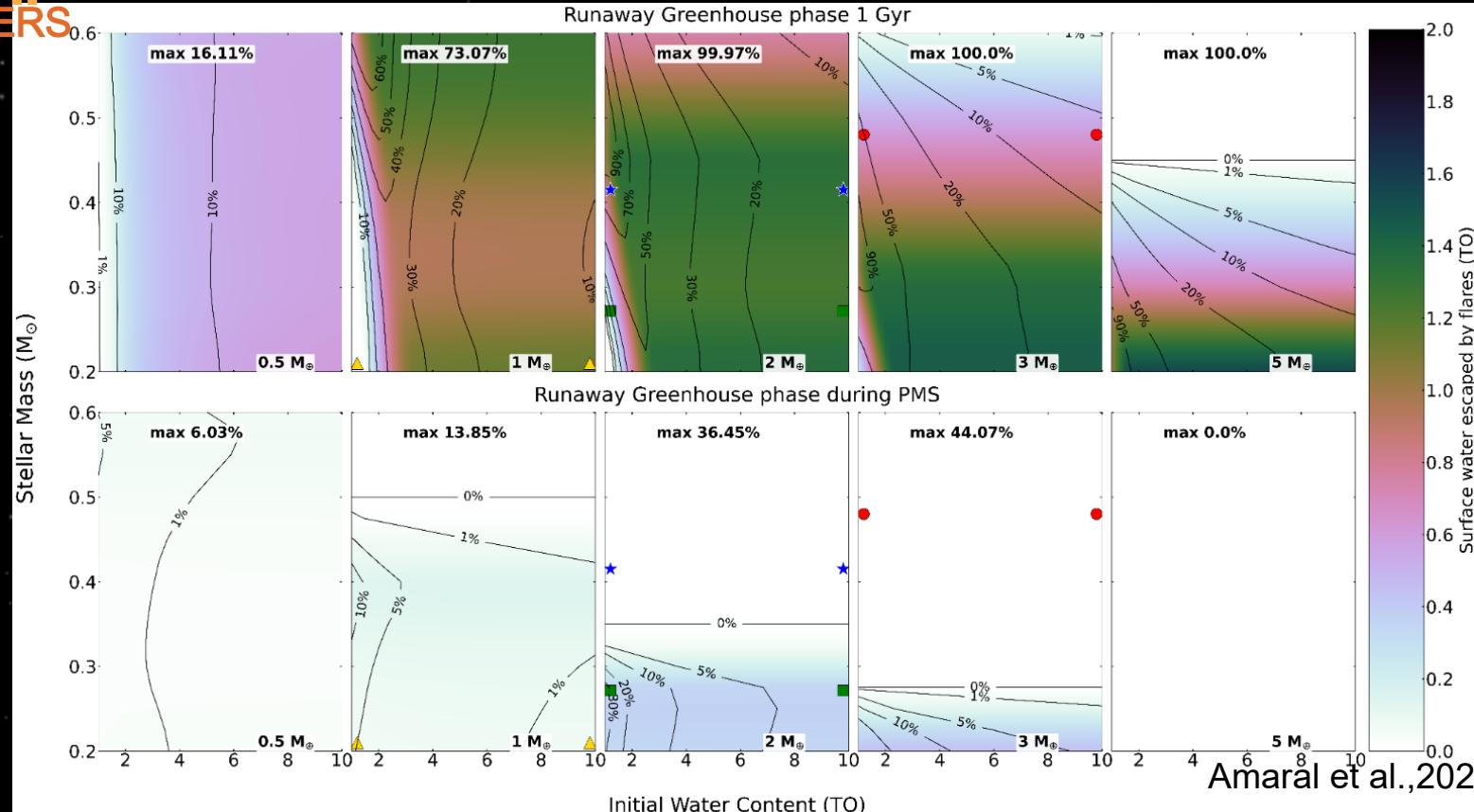
Stellar mass  
**0.20.6 M<sub>Sun</sub>**

Hare energy  
 **$10^3 - 10^6$  ergs**

Initial surface water  
**1-10 TO**

Distance  
**1 AU eq.  
(0.07- 0.3 AU)**

Simulated time  
**1 Gyr**



Amaral et al., 2022

# ! :Å^âÅx | /:fâ! F: 1DÅ| D/: ð!â: | 1Å-° D! | :Å

x| !d:â| Å

Planetary mass  
**0.55 Mearth**

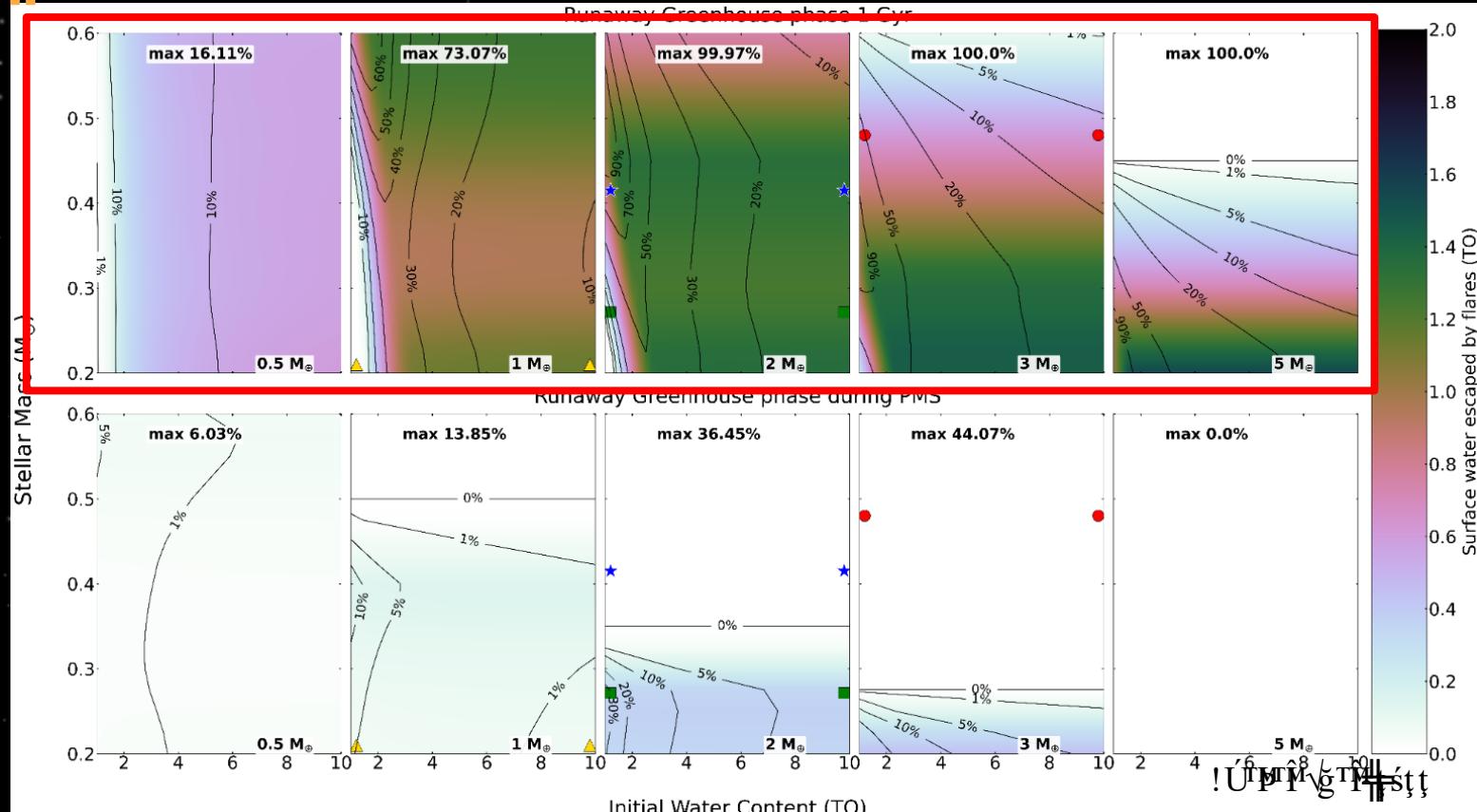
Stellar mass  
**0.20.6 Msun**

flare energy  
 **$10^3$ -  $10^6$  ergs**

Initial surface  
water  
**1-10 TO**

Distance  
**1 AU eq.**  
(0.07- 0.3 AU)

Simulated time  
**1 Gyr**



# ||:Å^âÅx| /:fâ!F: 1DÅ| D/: ð!â:| 1Å-°D!| :Å

x| !d:â| Å  
Planetary mass  
**0.55 Mearth**

Stellar mass  
**0.20.6 Msun**

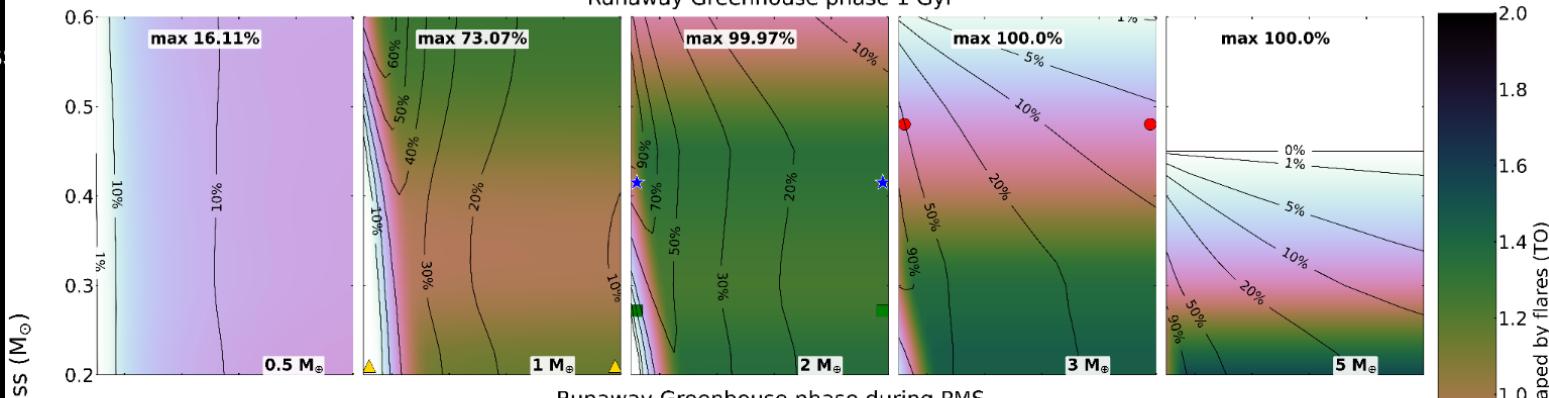
flare energy  
 **$10^3$ -  $10^6$  ergs**

Initial surface water  
**1-10 TO**

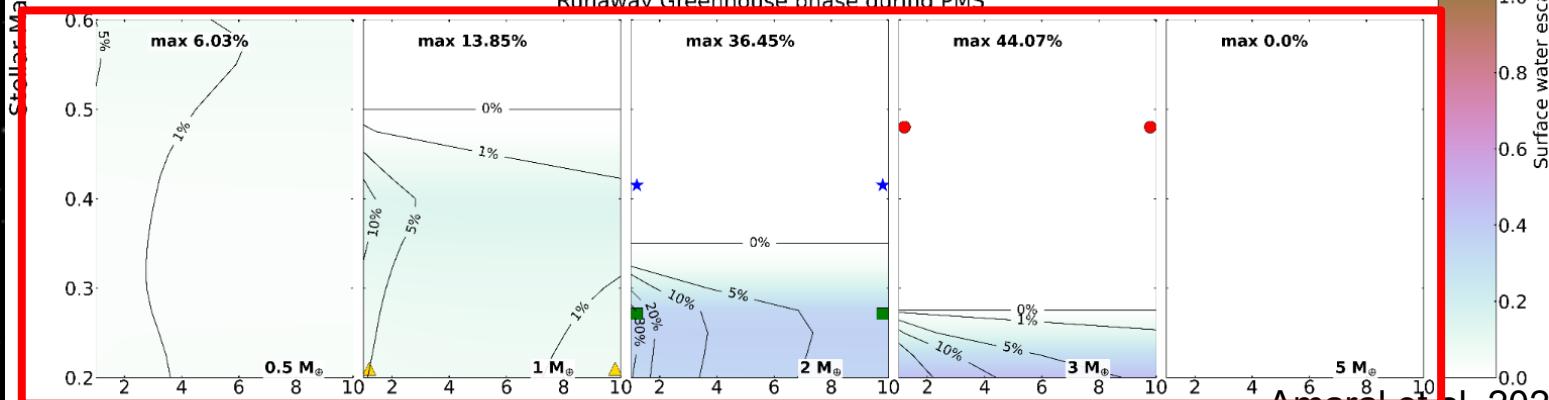
Distance  
**1 AU eq.**  
(0.07- 0.3 AU)

Simulated time  
**1 Gyr**

Runaway Greenhouse phase 1 Gyr



Runaway Greenhouse phase during PMS



Amaral et al., 2022

# RESUPERCENTAGE OF SURFACE WATER

x! | !d:â: | Å  
xîTMgHUM  
خیتمگهوم  
زیسته مهوم

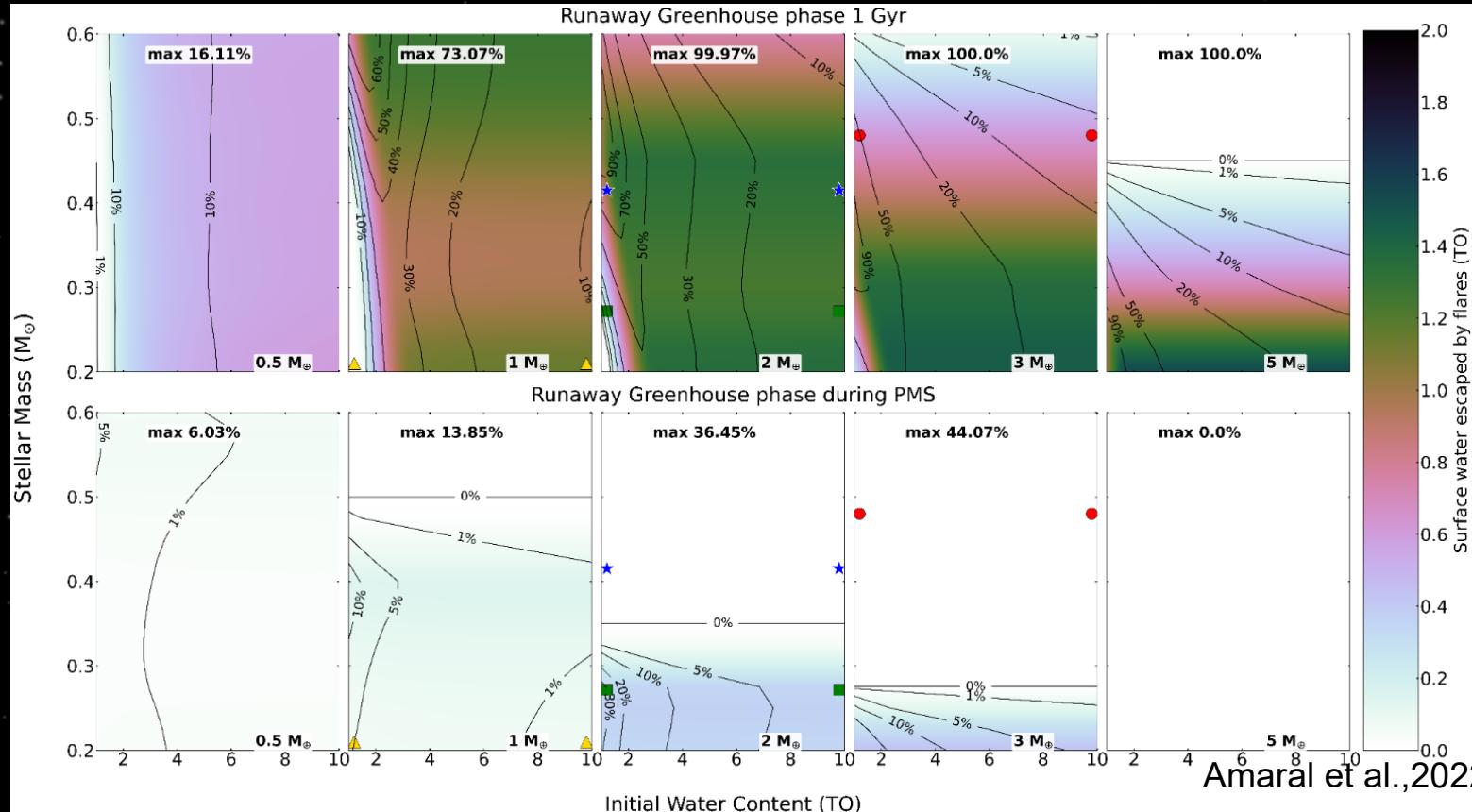
AgMÎTPÚRM  
آگمیتپورم  
زیسته مهوم

DTPV\NPL  
دیپونپل  
زیسته مهوم

NgyîČDEW  
نگیچدیو  
زیسته مهوم

5ygtMFI  
پی گت مفی  
زیسته مهوم

ÅUÜTMægjUV  
اُوُتِمæگجِوُ  
زیسته مهوم



# |-Å^åÅx| /:fâ! F: 1DÅ| D/: ð!â:| 1Å-° D!| :Å

## PARAMETERS

XîTMgHUTM  
نۇڭ ئەپتەن مۇ

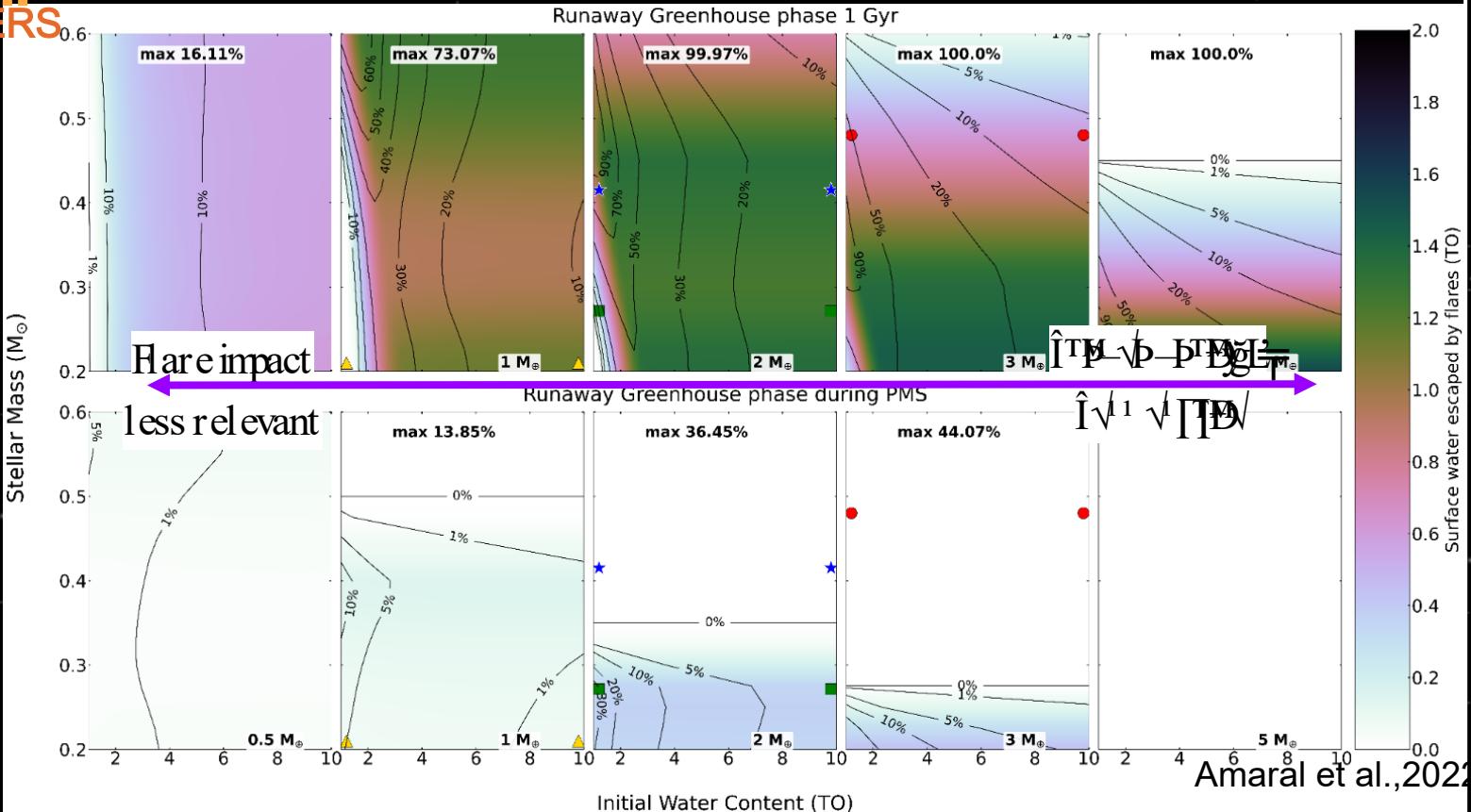
ÅgÂTUPÚTM  
نۇڭ ئەپتەن مۇ

DTPVÜPL  
بىشىق ئەپتەن

NgyÂTÇDEW/  
ETXâP  
ئەپتەن س

5ygtMFI  
تە ئەپتەن ئەپتەن

ÅUÅTgægjU/  
CJM



# Ääääx | /:fâ! F: 1DÄ| D/: ð!â: | 1Å-° D! | :Å

## PARAMETERS

$x^{\text{TO}}$   
MgHUM  
نیز  
قیمت  
M<sub>0</sub>

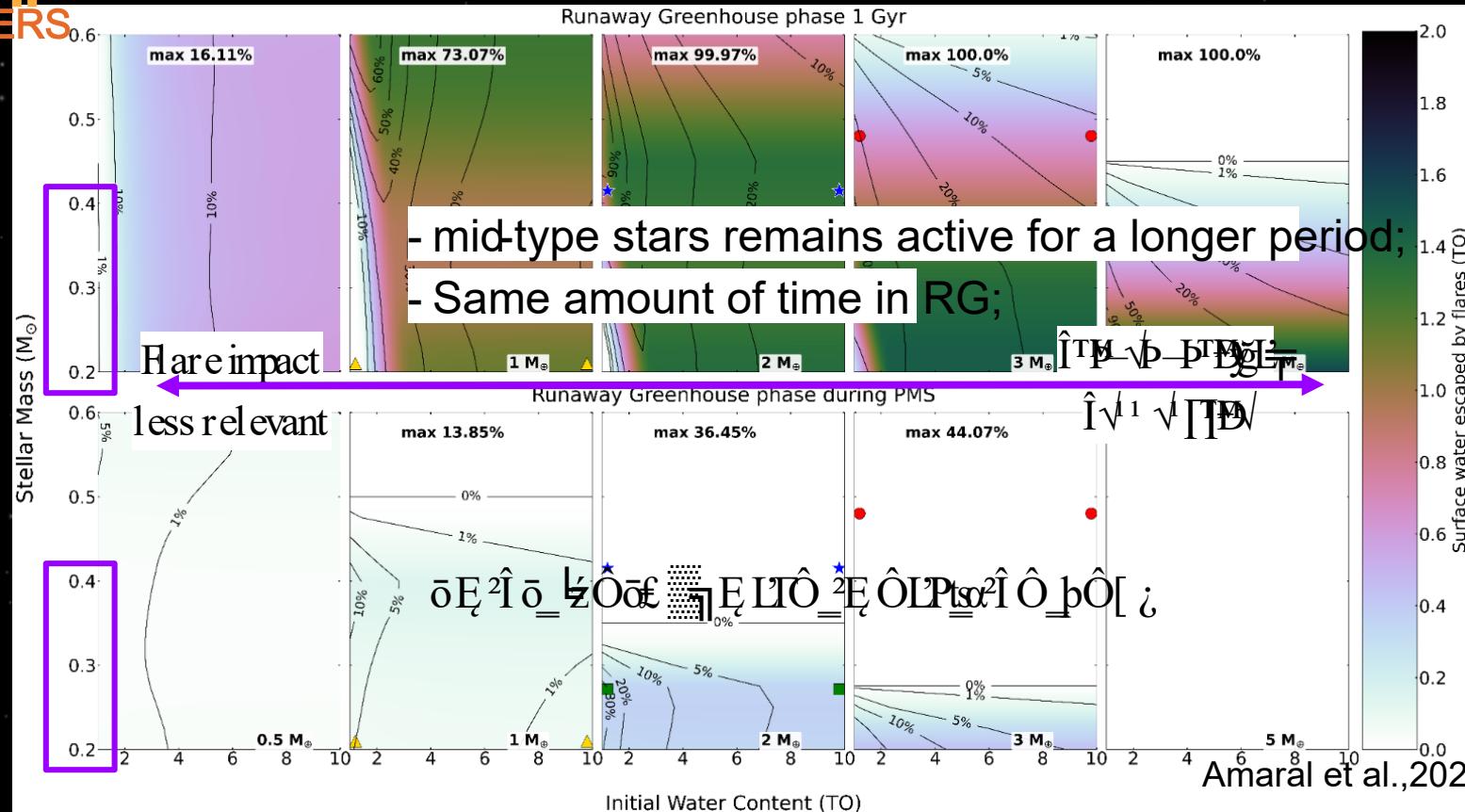
گیمپو  
نیز  
قیمت  
M<sub>0</sub>

DTPVUPL  
نیز  
قیمت  
CM<sub>0</sub>

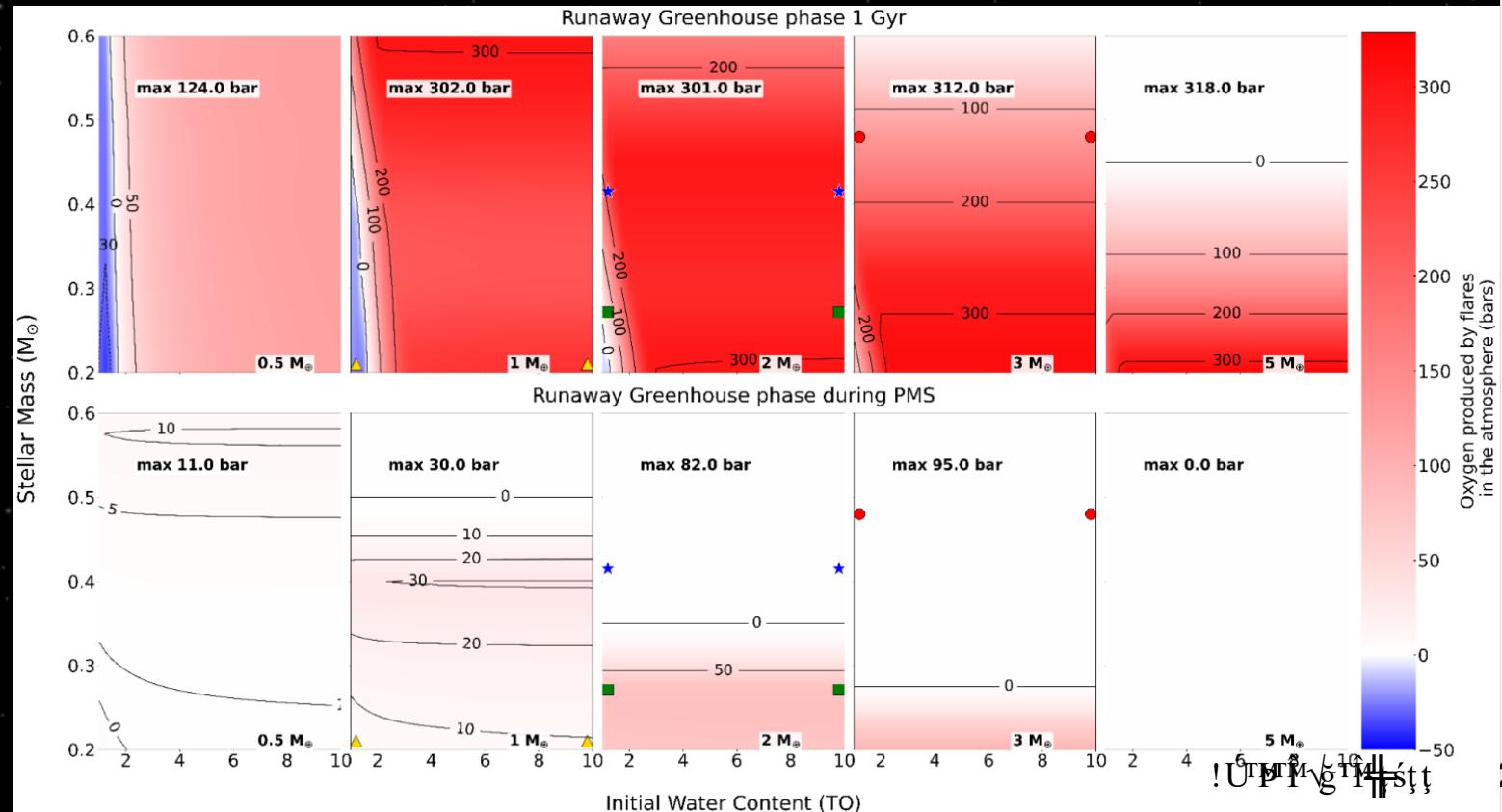
NgyvČDEW  
ETAP  
نیز  
S

5ygrqf  
نیز  
دکن  
نیز  
قیمت  
D

ÄÜTgægjU  
نیز  
C<sub>0</sub>M

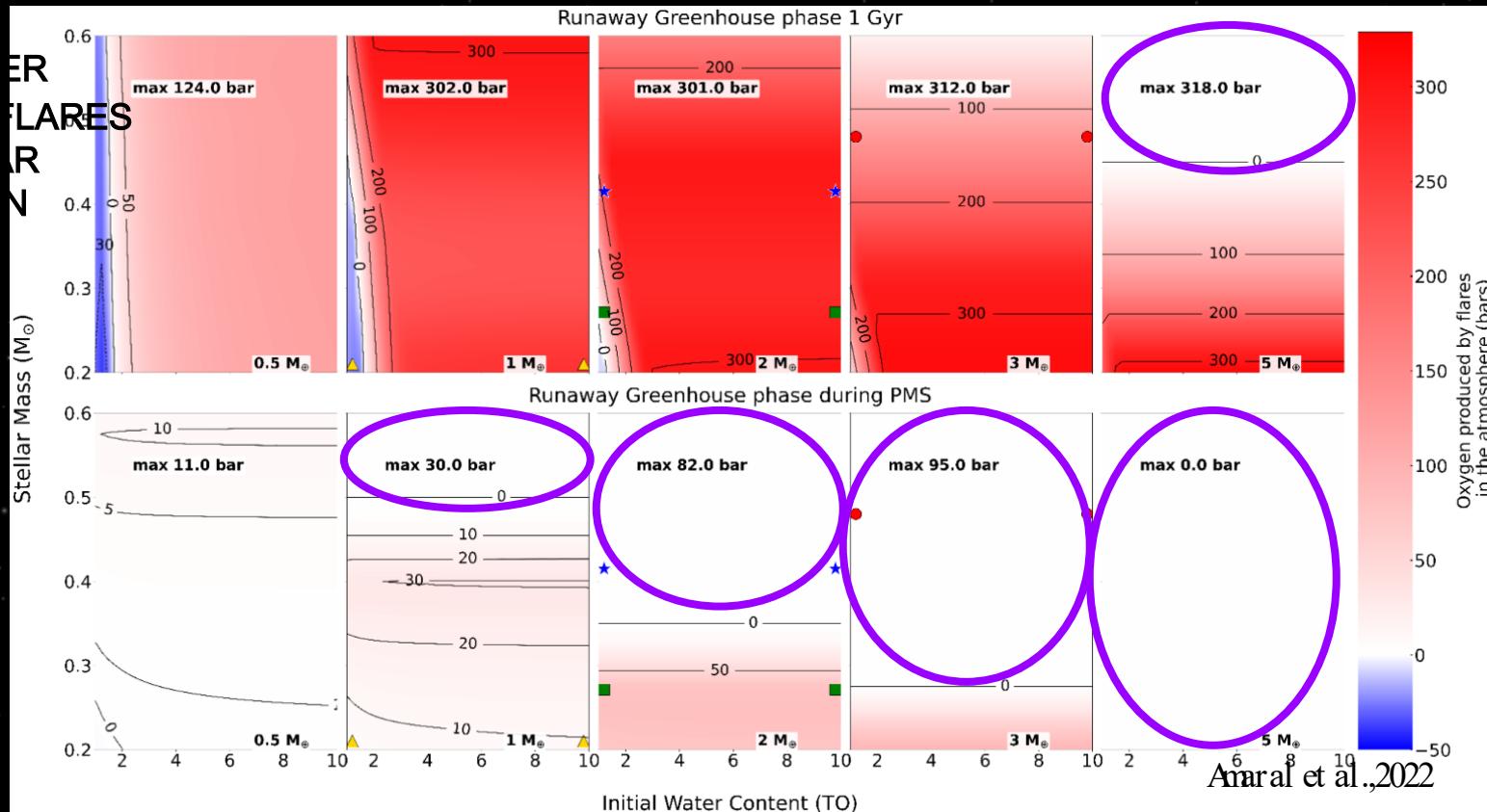


# RESULTS: EFFECT OF FLARES ON ATMOSPHERE



# Å Å Å D/ÅLDD! :Ålf!âd1ÅK|N1+°F:f

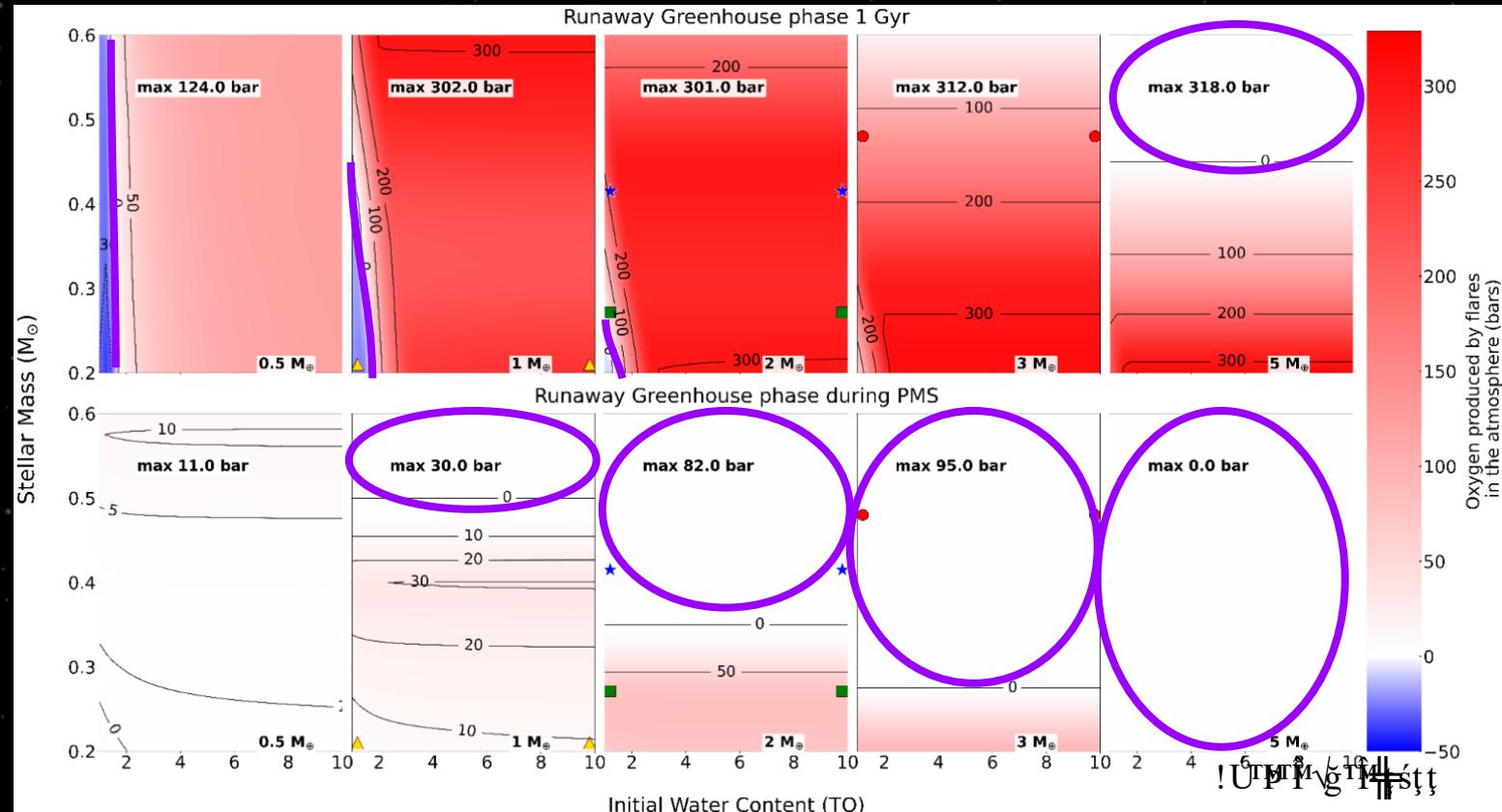
1 NO WATER  
ESCAPE BY FLARES  
OR STELLAR  
EVOLUTION



Amaral et al., 2022

# RESULTS: EFFECT OF FLARES ON ATMOSPHERE

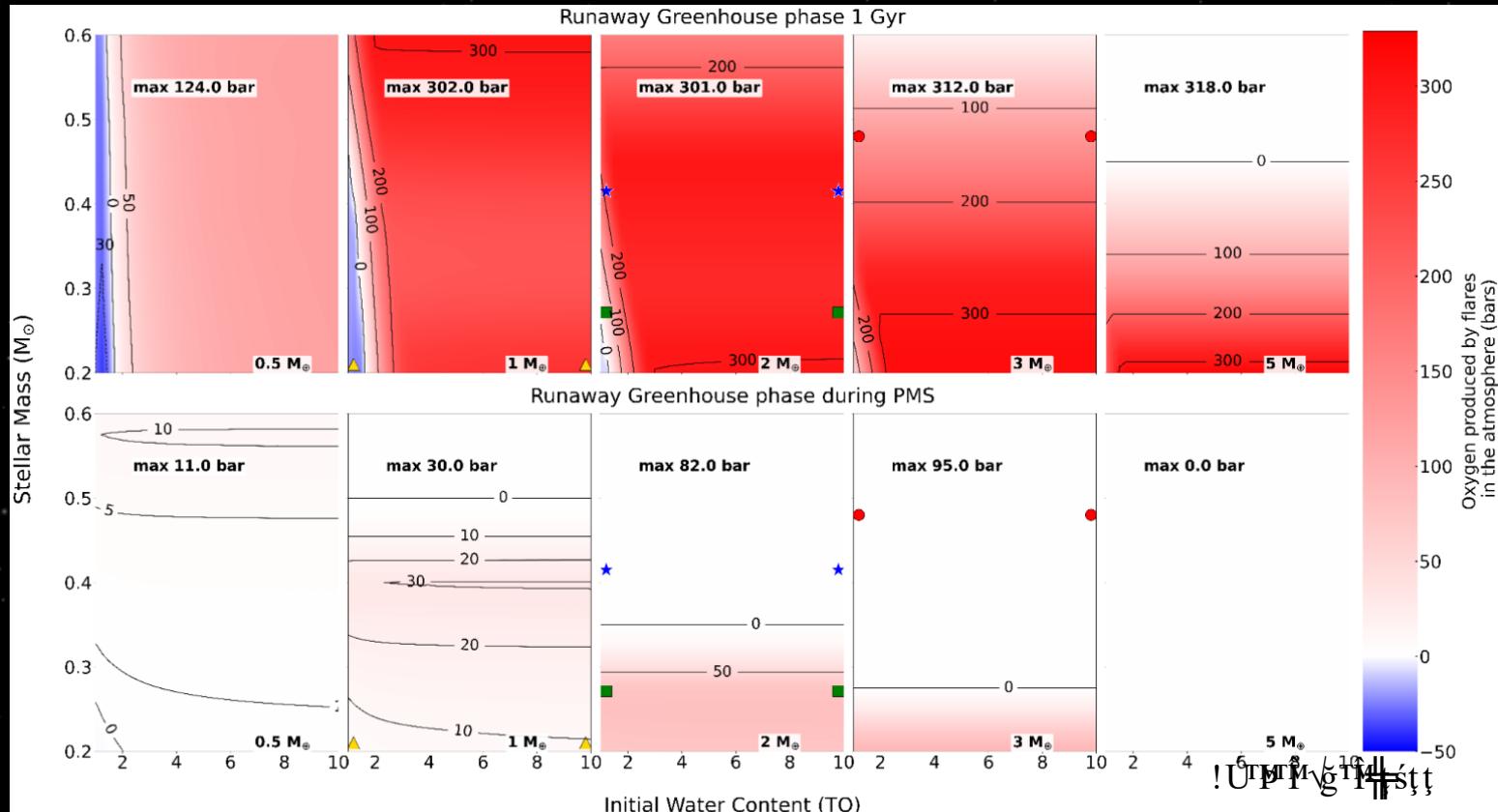
T=10!â:  
Å!x -°D!|:Å  
1| Å:~!|  
:ö!éanf



# RESULTS: EFFECT OF FLARES ON ATMOSPHERE

1 NO WAY  
ESCAPE BY  
FOR STELLAR  
EVOLVING

!â| :Å!x  
D1d Å| D/:=  
1†°Ff NÅK  
!âd1ÅK| :  
x°1ÿgD/DIC!

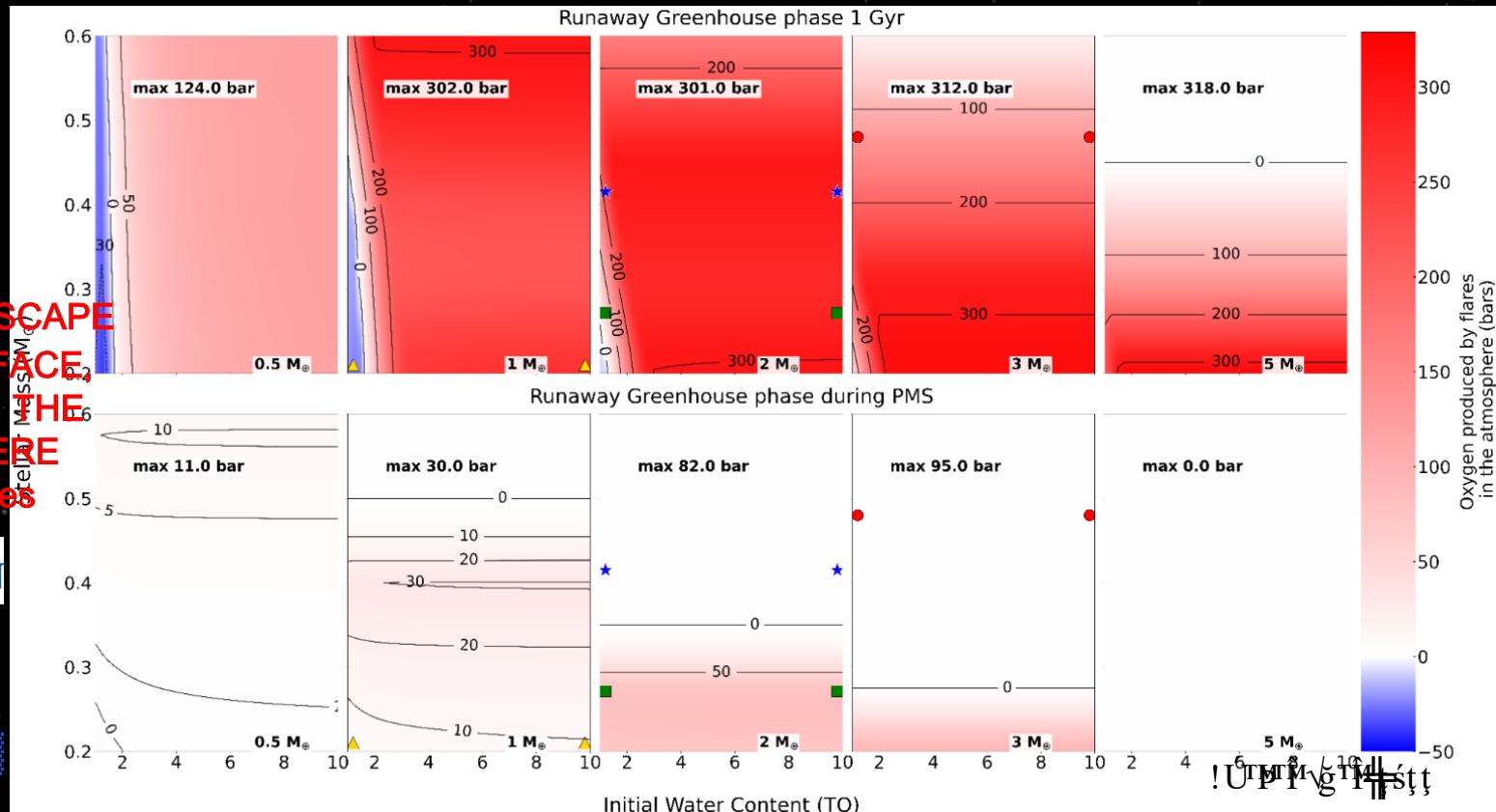


# RESULTS: EFFECT OF FLARES ON ATMOSPHERE

T=10!å:  
Å!x-D!:Å  
1| Å:~!|  
:ö!éanf

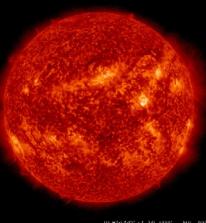
2 WATER ESCAPE  
FROM SURFACE,  
OXYGEN IN THE  
ATMOSPHERE  
(Positive values)

T=15°f!dN  
|:Fn: d!\:\:Å  
x15e:/51°F:f  
:Å!x Å:DNFa°  
Fn gD!C!



# SUMMARY

q Í F~~A~~Í~~Z~~~~A~~ A~~O~~eL~~\_b~~~~O~~~~I~~ Ô~~A~~b a~~\_A~~~~T~~~~\_b~~~~A~~ F~~O~~~~G~~~~I~~ Ô~~A~~~~\_G~~~~I~~ I~~\_z~~~~a~~~~Ä~~~~Ö~~~~a~~ A~~A~~e E~~E~~~~\_A~~~~e~~ F~~A~~~~\_G~~~~T~~~~e~~  
~~\_b~~~~O~~~~T~~~~a~~P~~E~~~~Ä~~~~A~~~~O~~~~a~~<sup>2</sup>~~z~~~~\_b~~~~O~~~~L~~~~a~~~~\_A~~~~T~~~~\_b~~~~O~~~~T~~~~O~~~~|~~L~~p~~~~t~~~~s~~L~~e~~ F<sup>2</sup>~~b~~~~\_B~~~~\_Ö~~~~a~~L~~z~~~~\_G~~~~T~~~~O~~~~a~~~~I~~~~G~~~~A~~~~A~~~~O~~~~Ä~~~~a~~~~h~~



The flaring relevance in the water escape increases with the planet's mass; less massive ones, the XUV from the quiescent evolution of the star is enough to drive the loss.

Considering the results in this work, we focus in looking for water on planets around early-type M dwarfs since these stars provide a better environment for water retention.

ð~~b~~~~O~~~~A~~E L~~P~~~~s~~~~\_a~~L~~z~~L~~T~~~~E~~~~\_E~~ Ô~~e~~ z~~I~~~~L~~~~|~~ P~~A~~~~\_G~~~~|~~ %~~L~~ F~~A~~~~\_G~~~~z~~~~b~~~~L~~~~\_L~~~~a~~~~\_a~~~~|~~ P~~S~~~~T~~~~A~~~~T~~~~e~~ | ~~A~~~~P~~~~A~~  
z~~I~~~~L~~~~|~~ Ô~~A~~~~z~~~~A~~~~a~~~~O~~~~z~~~~L~~~~a~~~~<sup>2</sup>~~~~<sup>2</sup>~~~~|~~ Ô~~%~~~~L~~~~a~~~~<sup>2</sup>~~~~|~~ e~~A~~~~\_P~~~~S~~~~O~~~~<sup>2</sup>~~~~e~~ ~~\_G~~~~T~~~~O~~~~a~~~~|~~ G~~A~~~~A~~~~z~~~~a~~~~Ä~~~~Ö~~~~a~~<sup>2</sup>~~z~~~~\_b~~~~O~~~~O~~~~a~~~~A~~~~e~~  
<sup>2</sup>~~e~~~~Ö~~~~L~~~~Ö~~~~A~~~~E~~~~L~~~~T~~~~E~~~~\_T~~~~A~~~~<sup>2</sup>~~~~L~~~~e~~ z~~I~~~~L~~~~A~~~~O~~~~a~~~~O~~~~a~~<sup>2</sup>~~e~~~~\_b~~~~O~~~~O~~~~z~~~~a~~~~Ä~~~~Ö~~~~a~~



# To consider in the future

- Update the results with TESS data, Kepler has only a few M dwarfs (If do you have the TESS flare data, please let me know!);
- Expand the study for late-type M dwarfs (Amaral et al. in prep) and K dwarfs (35x less-X-ray in the HZ, see Richer & Howell et al. 2023);
- This are upper results because we considered superflares;
- Considering planetary interior process in the model;
- Add a secondary atmosphere.

è ΓÈΤÚž ĆTЦ

õ ŠΔĆ<sup>1</sup>/<sub>4</sub> · ΓΦ  
u fi Rž' ΔA· FG

6 · F Řf EĆAřo È· õ EÈG  
ZPřf ÈřuŠΔĆ<sup>1</sup>/<sub>4</sub> ΓPř žj · Γk  
flΔĆk žj Èš Èk · ΓRk  
ÈÈAfi Čfl<sup>1</sup>/<sub>4</sub>Afi · ΓuřuŠžTk  
õ RÈTEĆuĐuž ĆF

Especial thanks to the organization invited and choose me to represent

Thomas Metcalf Travel

ØL e k ſ y L e w A y L e w πo i e o

