Wind-AE: An Open-source, Fast, 1D Photoevaporation Atmospheric Escape Model

NOW *with* METALS & X-rays!

Madelyn Broome (UC Santa Cruz)

NASA ExoExplorers

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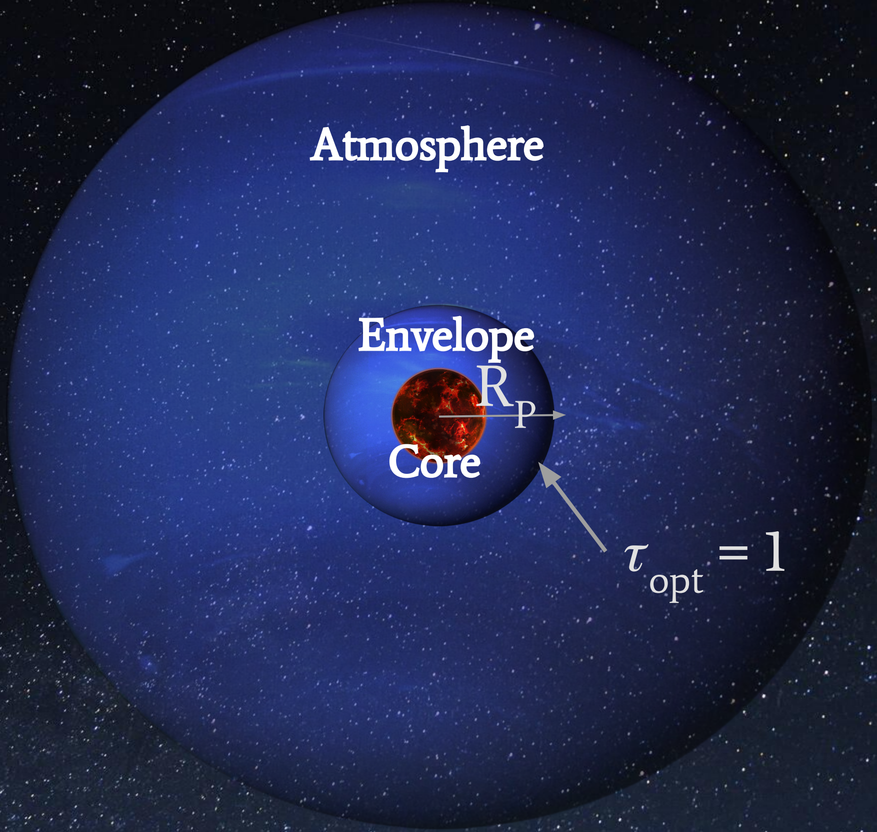
Overview

1. Introduction to photoionization-driven atmospheric escape
2. Wind-AE 1D relaxation model
3. The limits of energy-limited mass loss rates
4. Wind-AE and observables

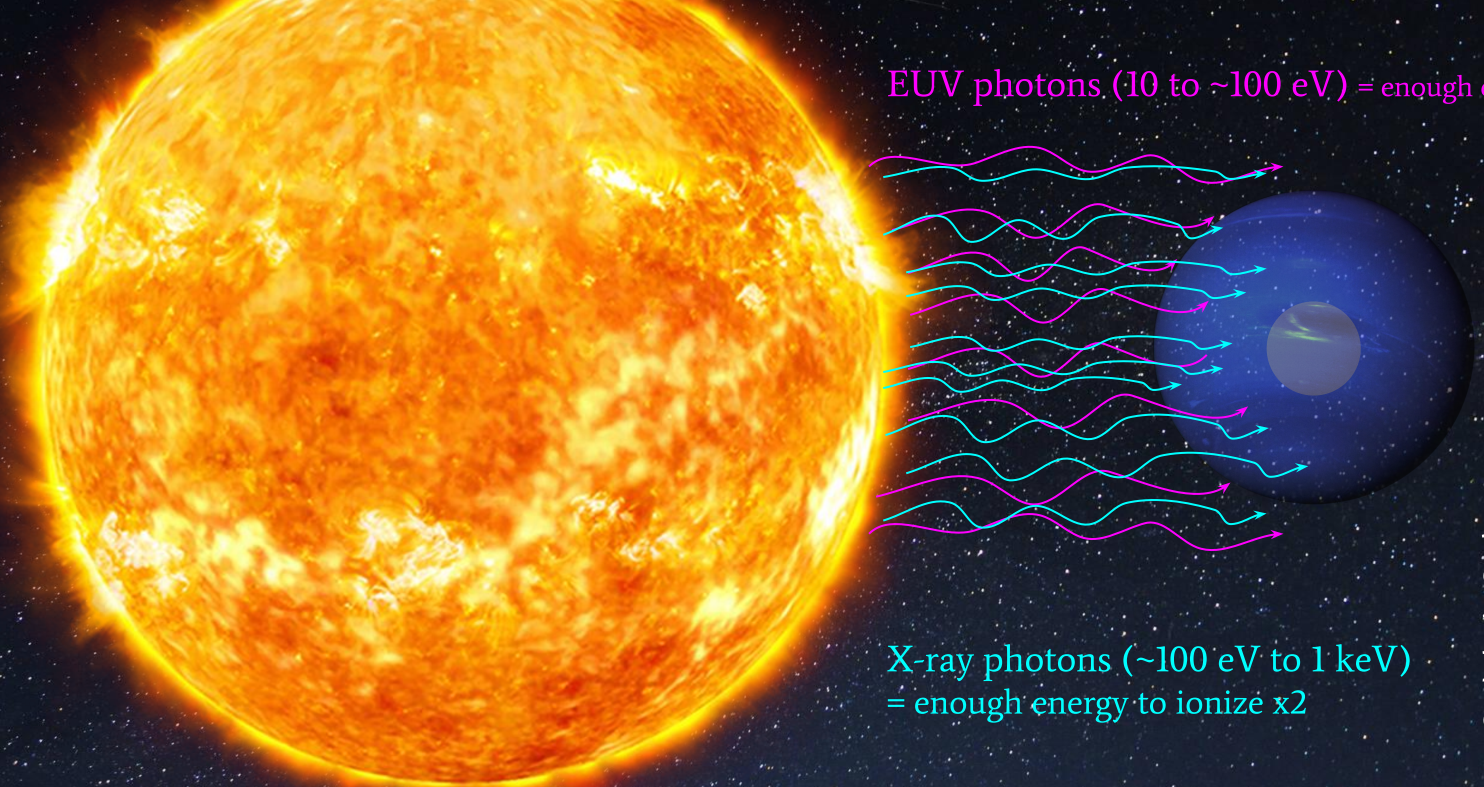

Atmosphere
Envelope
R_P
Core
$\tau_{opt} = 1$

Three Regimes of Atmospheric Escape Mass Loss for Close-in Planets

= P<100 days

1. Boil-off
2. Core-powered mass loss
3. Photoionization-driven (a.k.a., photoevaporation)
    a. Especially strong around young stars, which are X-ray + Extreme UV (XUV) active
    b. Ongoing throughout planet's life
    c. Can drive observable outflows

Photoionization-driven Parker Wind

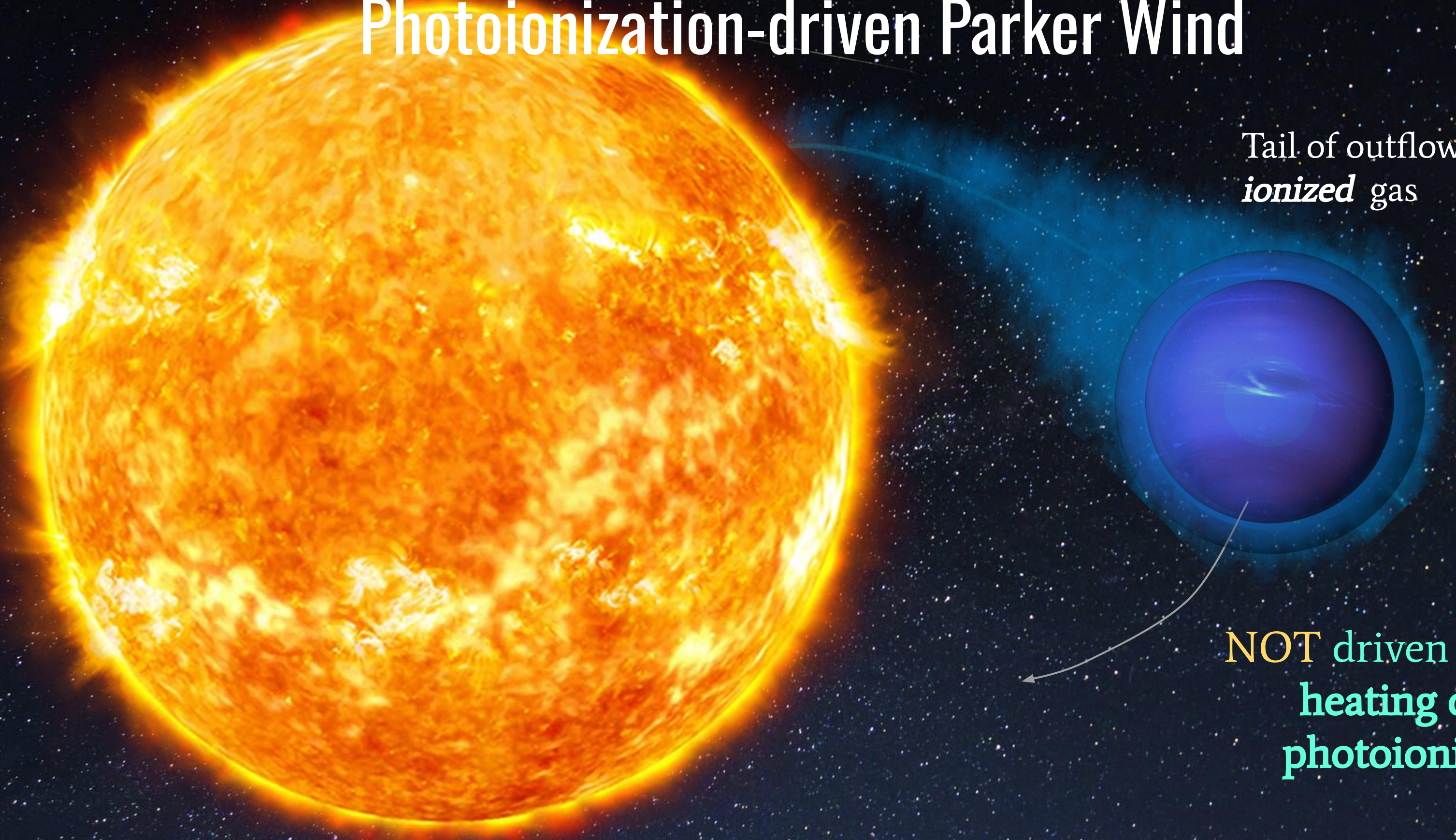


XUV photons can penetrate *deeper**.

Atmo can't cool efficiently at those depths, so heating drives outflow.

*STILL UPPER LAYERS OF ATMOSPHERE

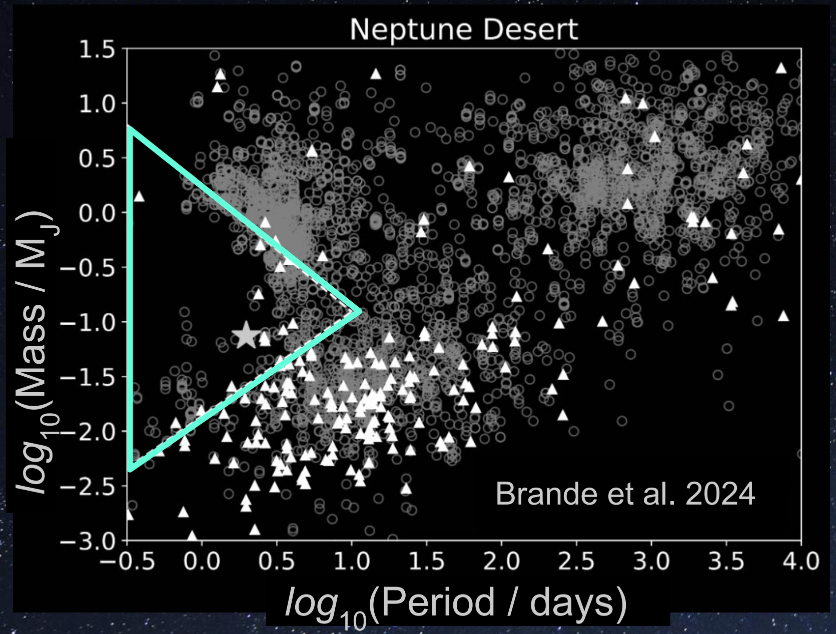
Photoionization-driven Parker Wind



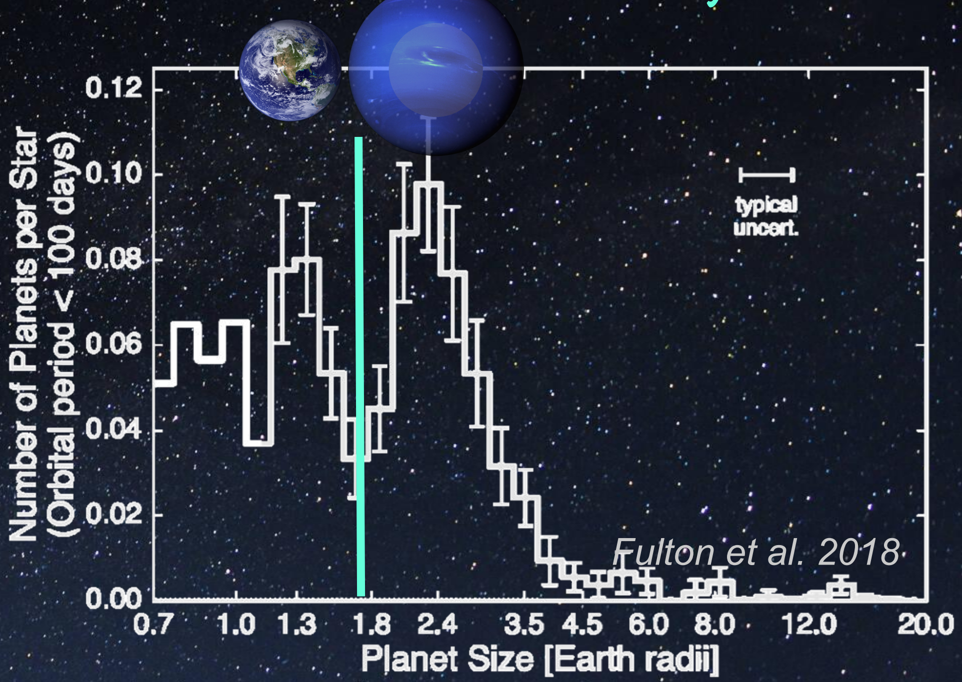
Pressure gradient drives a transonic "Parker Wind"

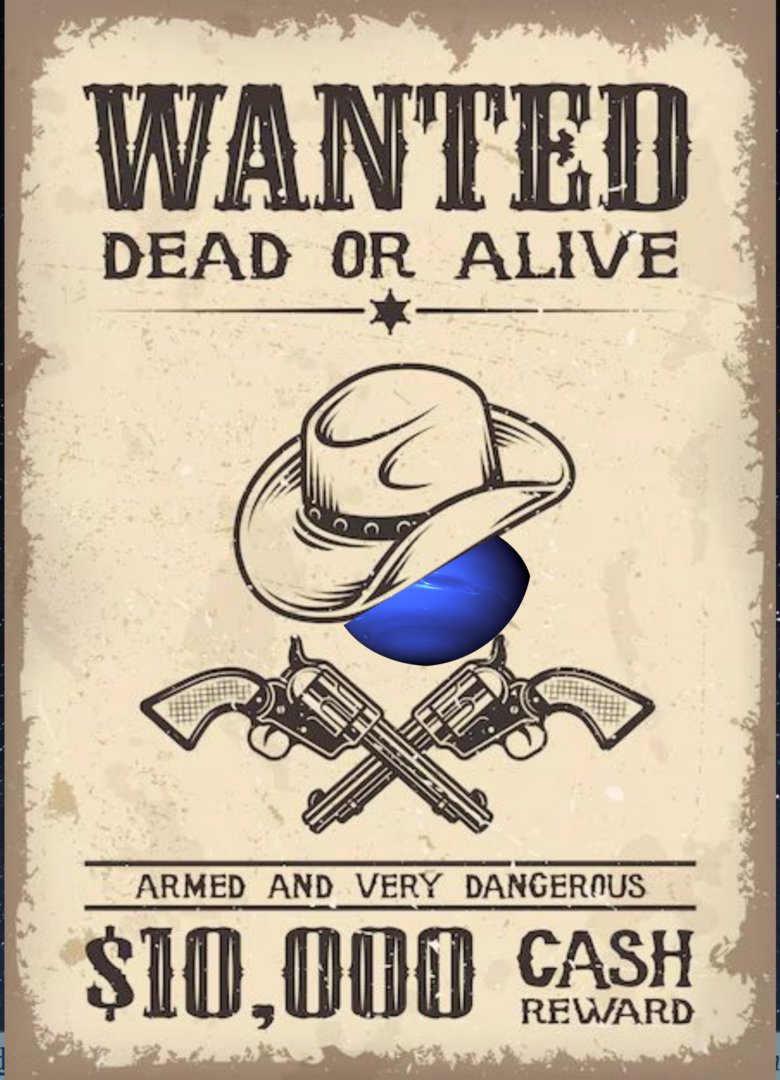
NOT driven by T_{eff}, but **heating due to photoionization**

Photoevaporative (Neptune) Desert



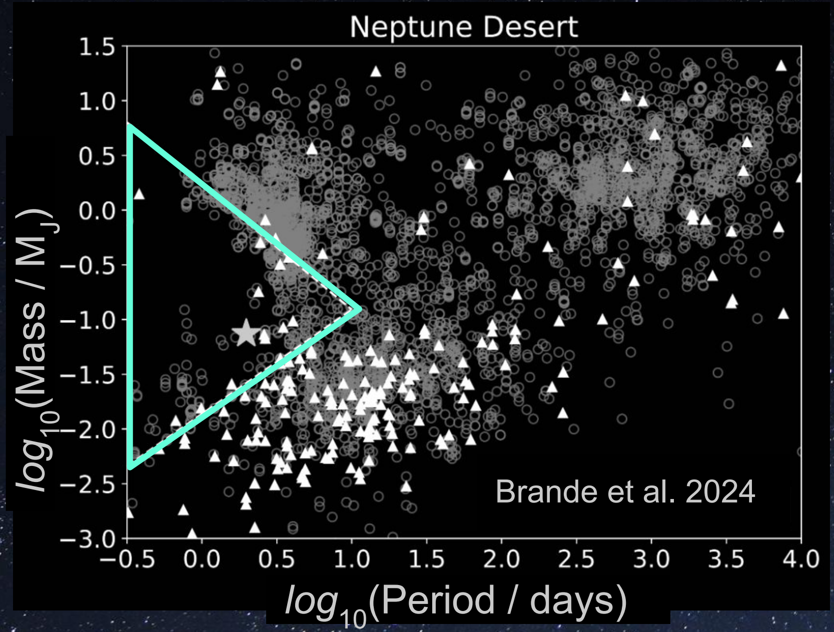
Period Radius Valley



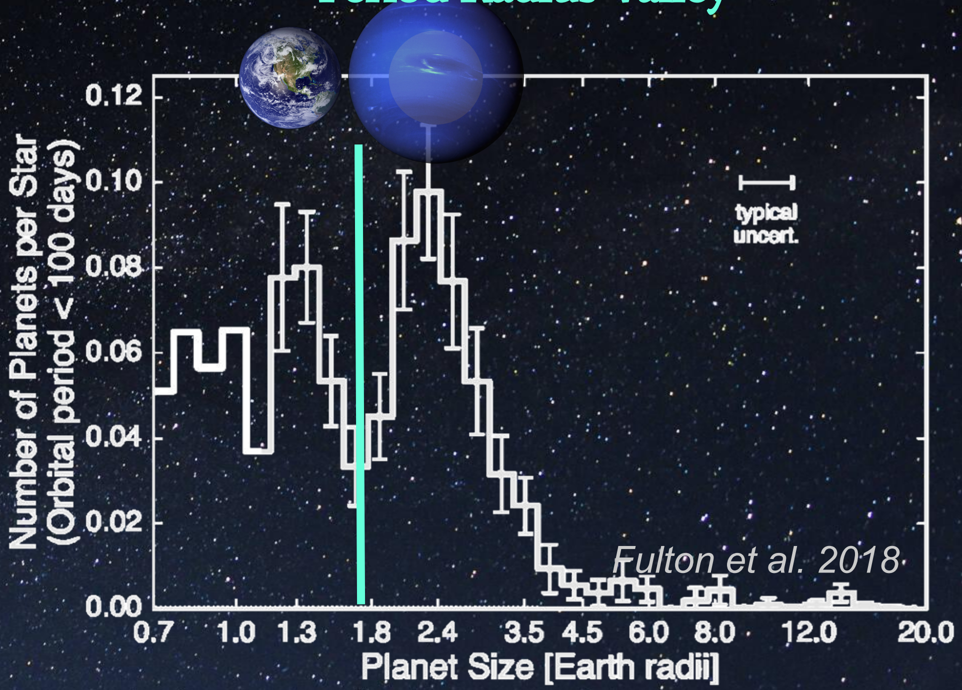

WANTED
DEAD OR ALIVE
ARMED AND VERY DANGEROUS
$10,000 CASH
REWARD

Mass loss is a part of the evolutionary history of close-in (P<100 days) planets

Photoevaporative (Neptune) Desert

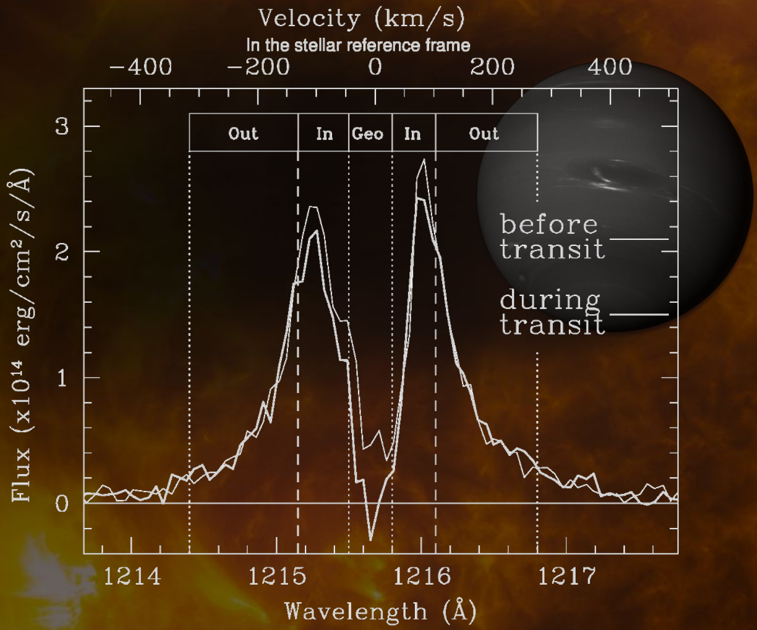


Period Radius Valley



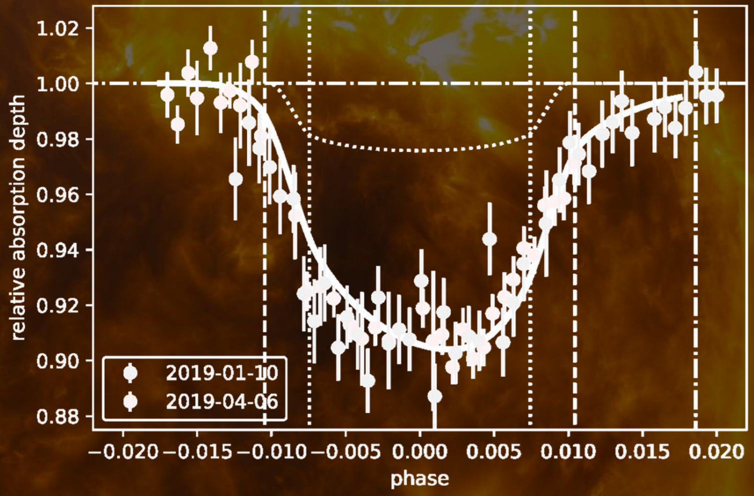
Cannot directly observe mass loss rates, only infer from models

Lyman-α emission line broadening



Vidal-Madjar & Lecavelier (2004)

Metstable He 10830Å Transit



Spake et al. 2021

Existing Tools

Late Times (a few Gyrs): Photoionization is **EUV dominated** , energy limited b/c **low flux** (García-Muñoz, 2007; Murray-Clay et al. 2009)

Single frequency/Pure-H/no diffusion, no X-rays

Early Times (Myrs): **X-ray dominated** , radiative limited and recombination limited b/c **high flux** (Cecchi-Pestellini, 2006; Owen & Jackson, 2012)

Assumps. (like ionization equi.) are only valid in high flux limit or for high densities

Other **fast codes** have limiting assumptions (Owen & Jackson 2012), don't solve for $\dot{M}$ (p-winds, Dos Santos et al. 2021), or have limited metallicity (ATES, Caldiroli et al. 2021)

Time-evolving, 3D hydrodynamic codes are considerably **slower codes**

1. Mass loss is a part of the evolutionary history of close-in (P<100 days) planets

2. Can't directly observe mass loss rates, only infer from models

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Mass loss rate

$$\dot{M} \approx 4\pi R_{sp} \rho v$$

Sonic point

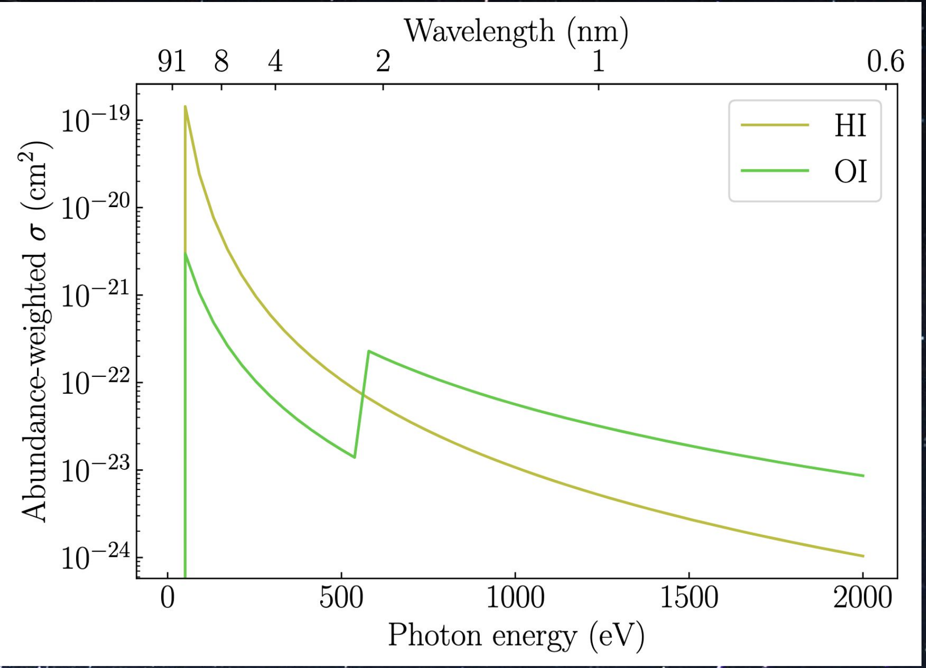
Wind-AE

A 1D, multifrequency, multispecies, hydrodynamic, transonic Parker Wind, steady-state photoionization relaxation code based on Murray-Clay et al. (2009)

NOW with METALS & X-rays!

Important physics:
X-rays and Metals

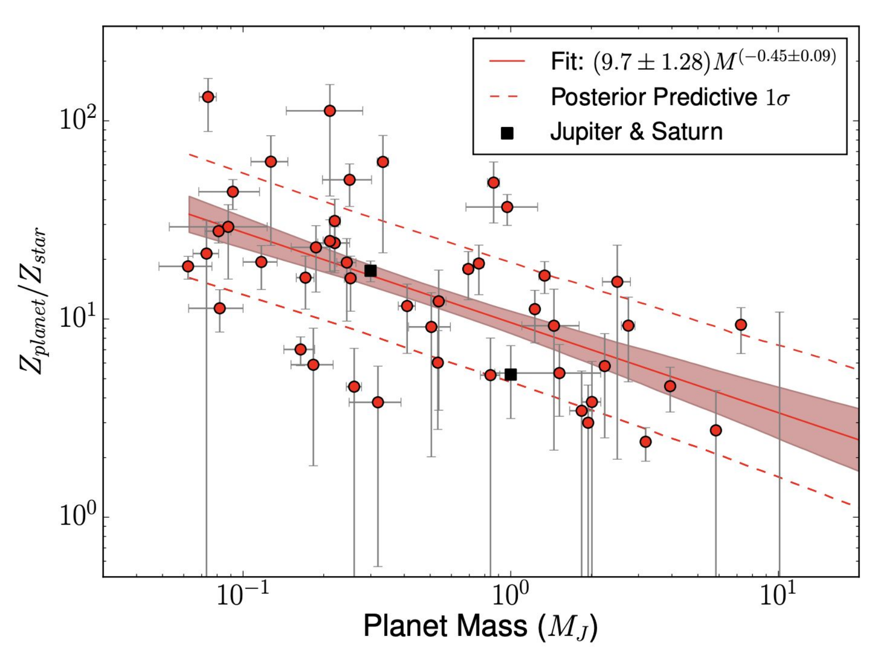
- Young hot stars strong in the XUV
- Metals have large X-ray ionization cross sections



Throngren et al. 2016

Important physics:
X-rays and Metals

- Young hot stars strong in the XUV
- Metals have large X-ray ionization cross sections
- Planets likely high metallicity
- Metals in outflows may be observable



Throngren et al. 2016

User inputs:

- Planet parameters
- Metals/Metallicity*
- Stellar spectrum*
- Boundary conditions*

*Can be set to defaults.

Outputs:

- Temperature
- Density
- Velocity
- Ionization fraction*
- Column density (τ)*

*Per species.

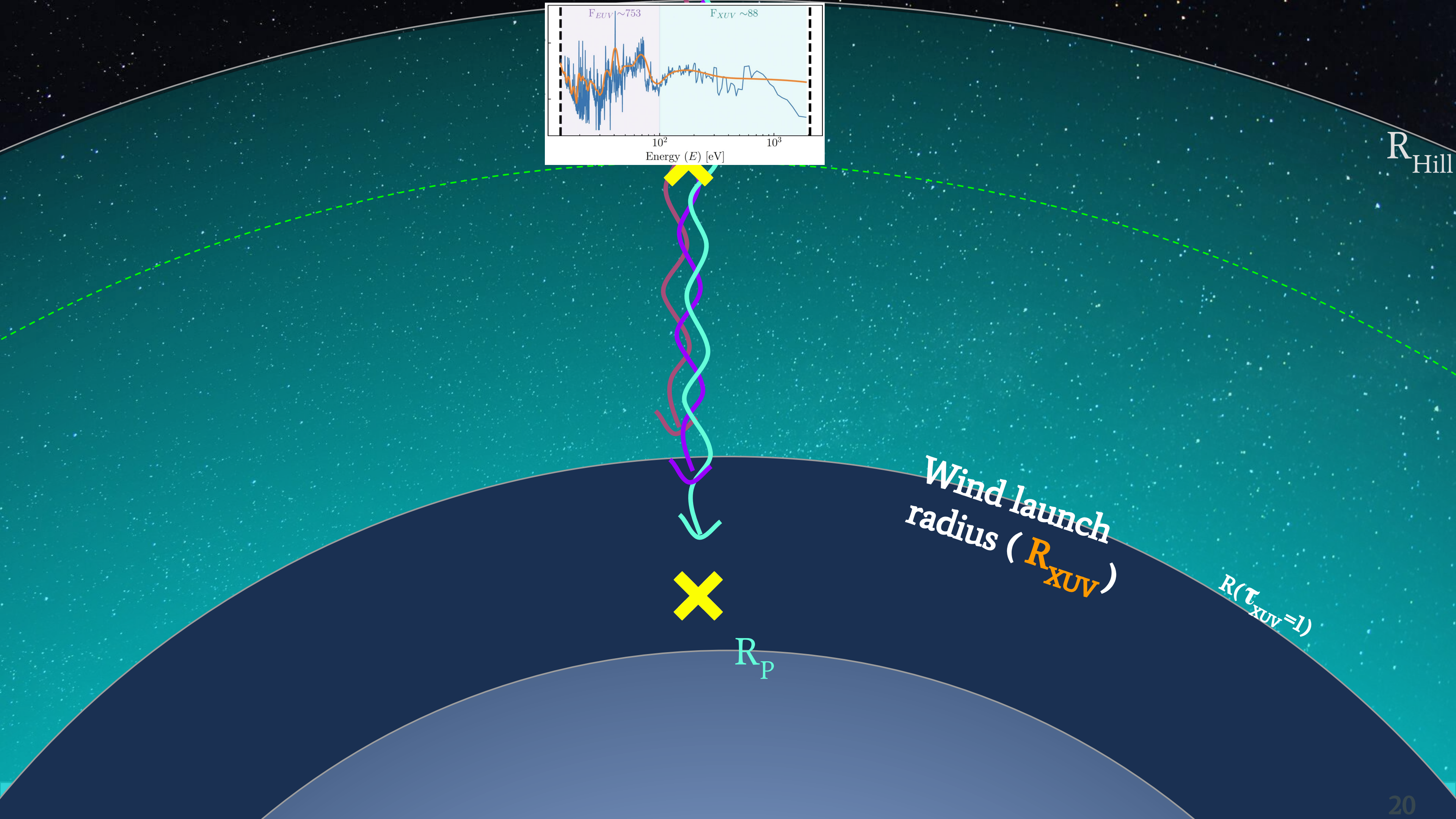
Limitations

Non-time evolving

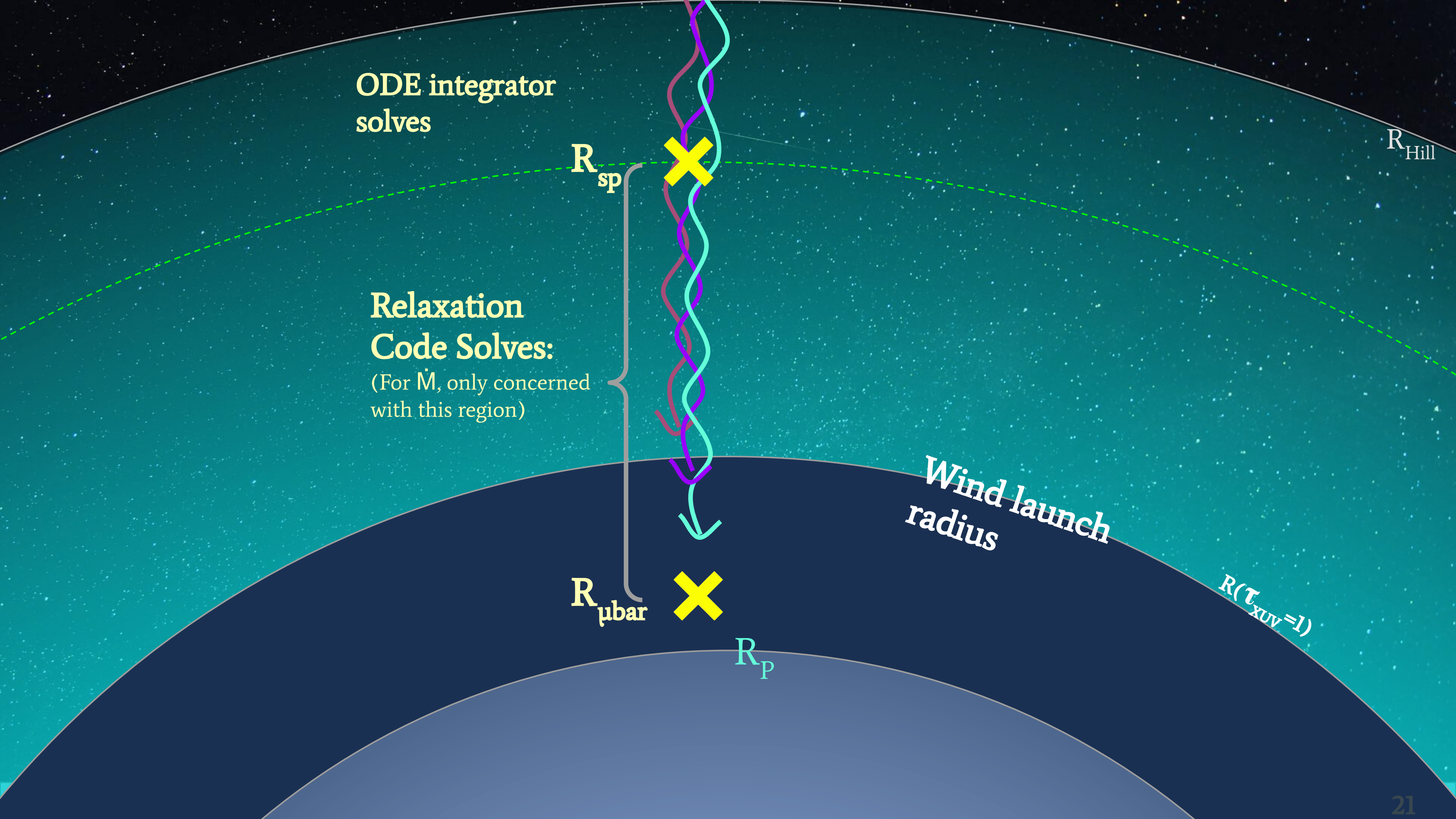
No diffusion or drag

No magnetic fields

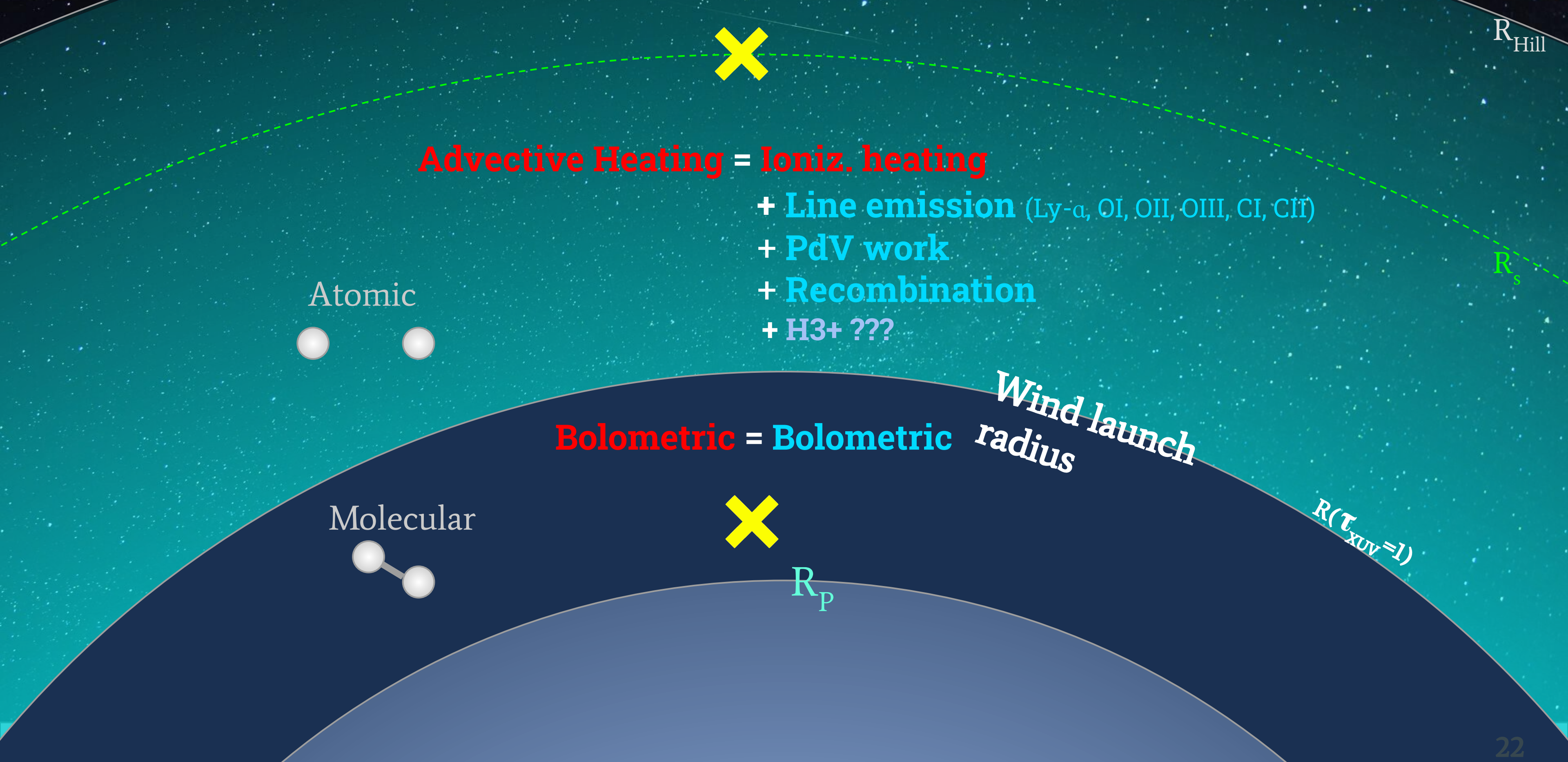
Assumptions only valid up to Coriolis (turning) radius



F_{EUV} ~753
F_{XUV} ~88
10^2
10^3
Energy (E) [eV]
R_{Hill}
Wind launch radius (R_{XUV})
$R(\tau_{XUV}=1)$
R_P


ODE integrator solves
R_{sp}
Relaxation Code Solves:
(For $\dot{M}$, only concerned with this region)
$R_{\mu bar}$
R_P
Wind launch radius
$R(\tau_{XUV}=1)$
R_{Hill}

Energy Conservation



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Energy Limited Mass Loss Rates

Assumes some fraction, ε, of incident photon energy is converted into outflowing:

$$\dot{M}_{Elimit} = \frac{\epsilon F_{\mathrm{XUV}} \pi R^3}{G M_P}$$

* (times a tidal correction term)

Energy Limited Mass Loss Rates

Typically, R, is taken to be R_p and ε is 0.15-0.4 in the literature

$$\dot{M}_{Elimit} = \frac{\epsilon F_{\mathrm{XUV}} \pi R_p^3}{G M_P}$$

* (times a tidal correction term)

But where is the energy really absorbed?

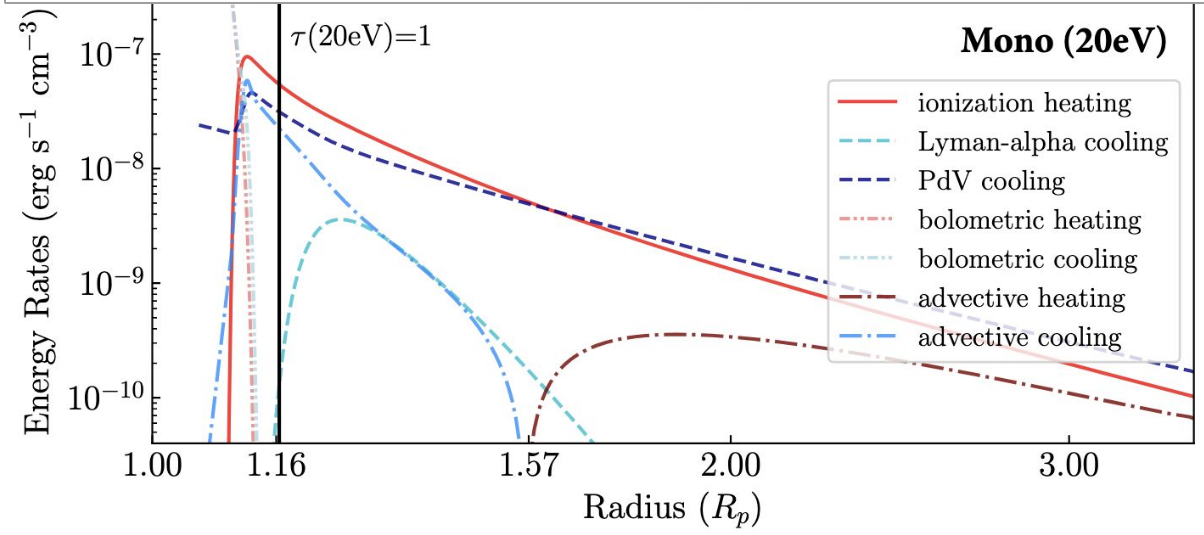
Where is the XUV energy absorbed?

Quintessential system:

Planet: HD 209458b (Hot Jupiter)

Star: Old (low flux)

Atmo: H, He



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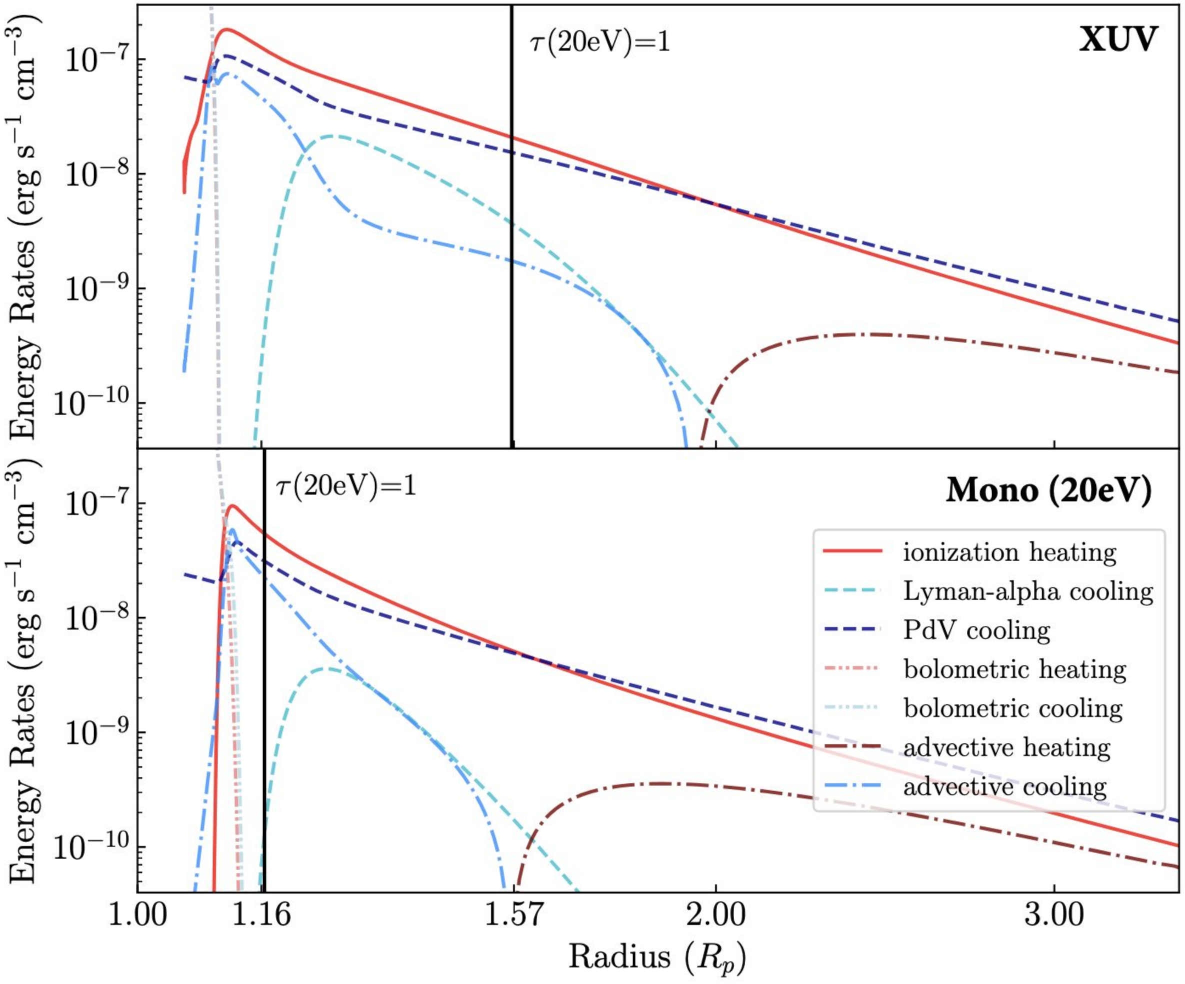
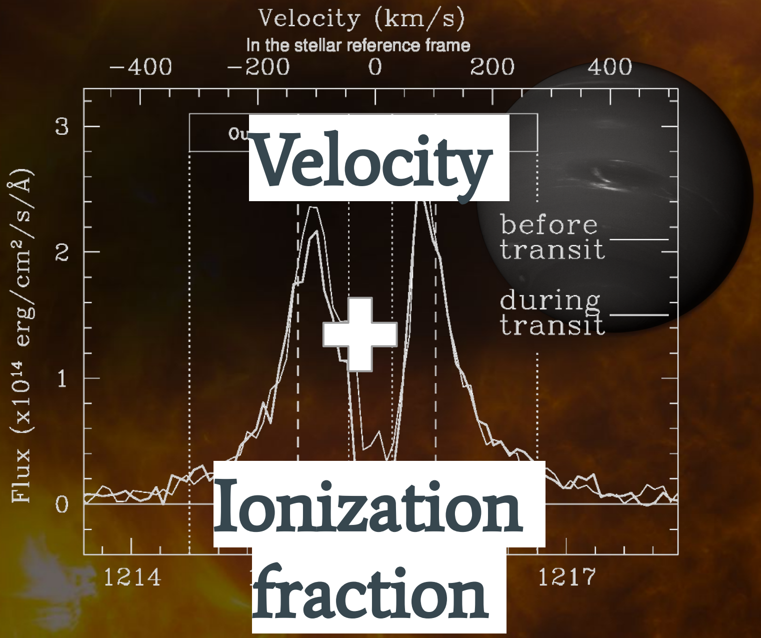


Features of a wind that affect observables

Lyman-α emission line broadening



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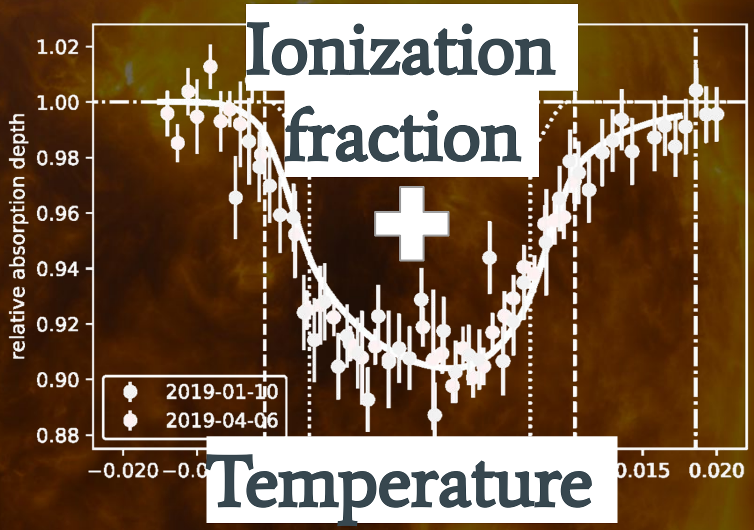
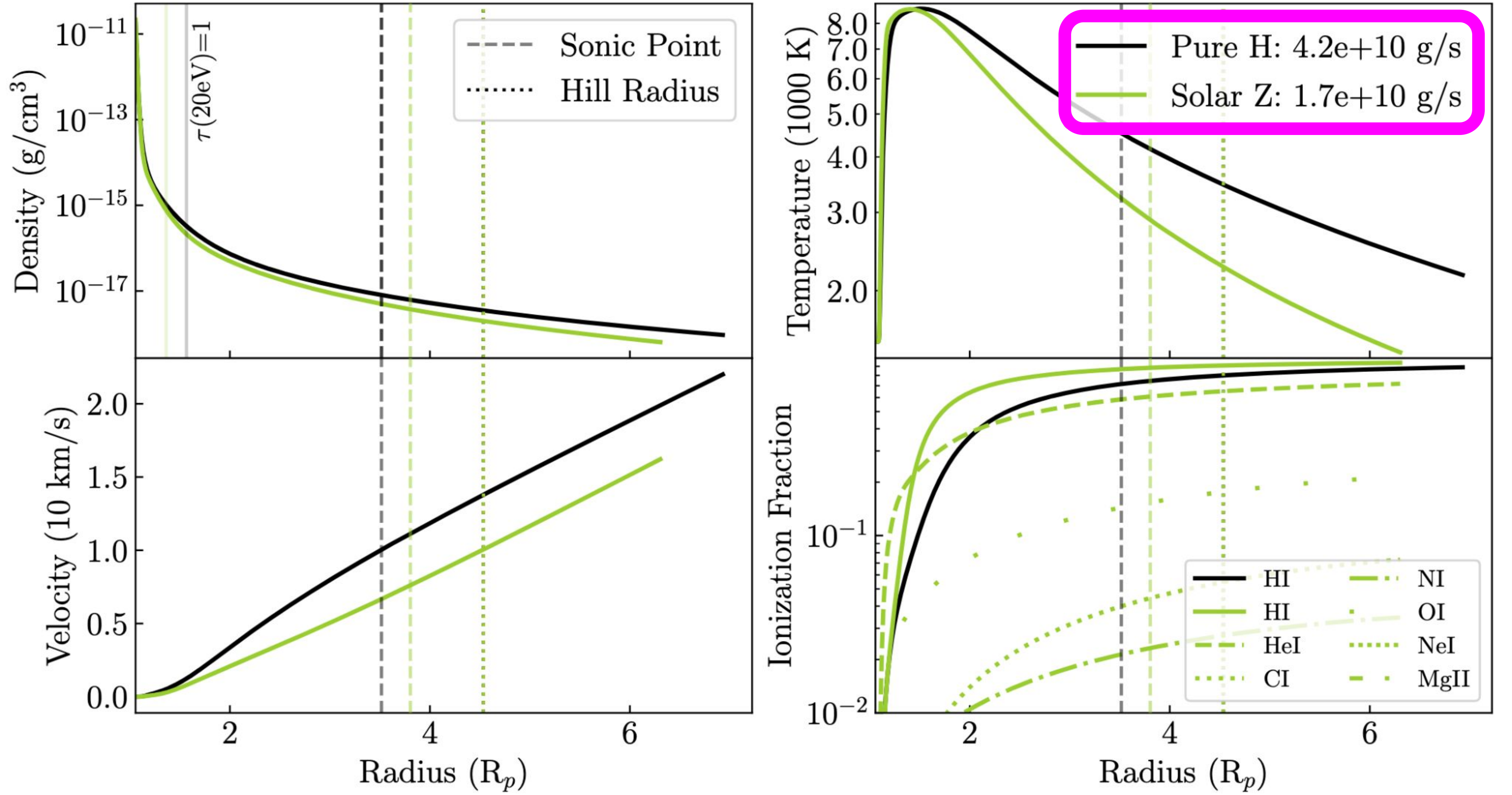


Spake et al. 2021


Density (g/cm³)
τ(20eV)=1
Sonic Point
Hill Radius
Temperature (1000 K)
Pure H: 4.2e+10 g/s
Solar Z: 1.7e+10 g/s
Velocity (10 km/s)
Ionization Fraction
HI
HI
HeI
CI
NI
OI
NeI
MgII
Radius (R_p)
Radius (R_p)

So, when is it appropriate to use the energy limited mass loss rate?

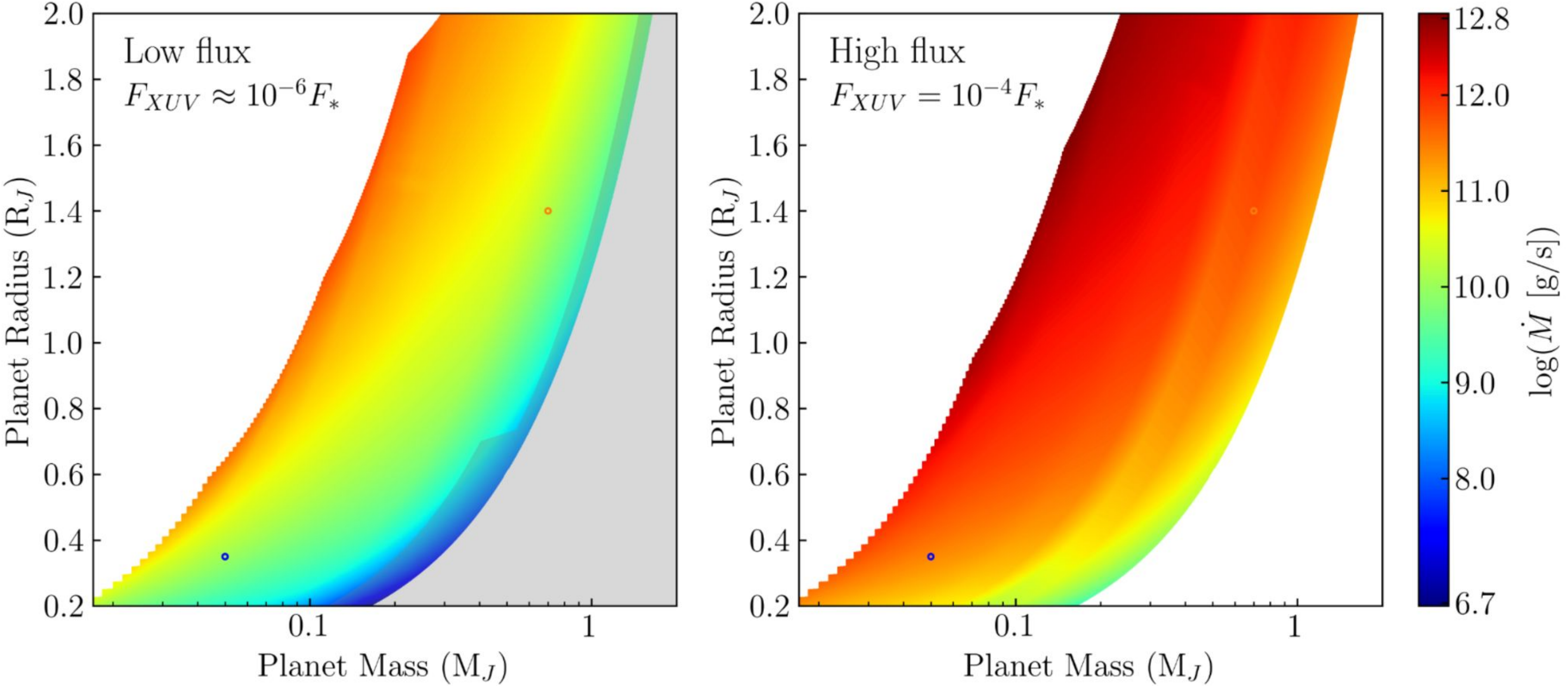
Energy Limited Mass Loss Rates

Typically, R, is taken to be R_p and ε is 0.15-0.4 in the literature

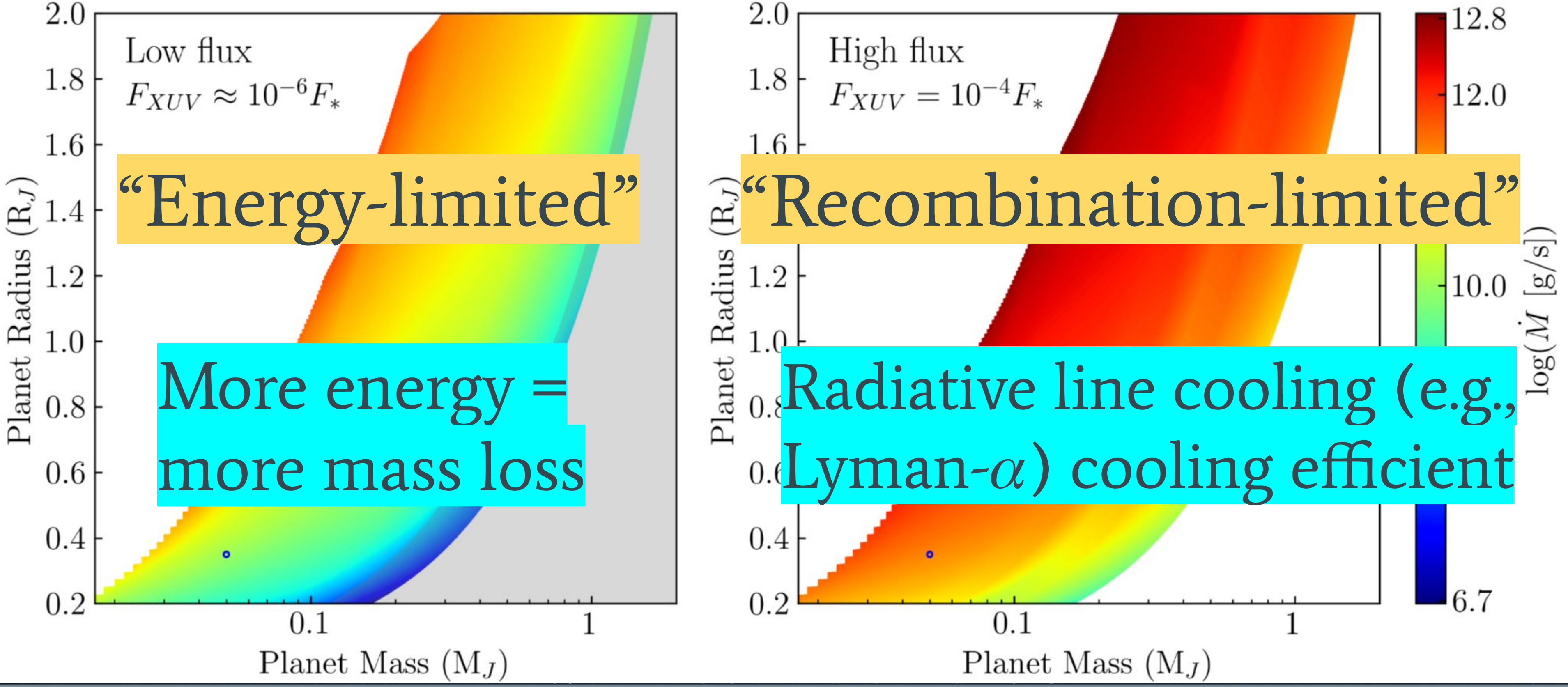
$$\dot{M}_{Elimit} = \frac{\epsilon F_{\rm XUV} \pi R_p^3}{G M_P}$$

* (times a tidal correction term)

Mass loss rate grids - H/He atmospheres



Mass loss rate grids - H/He atmospheres



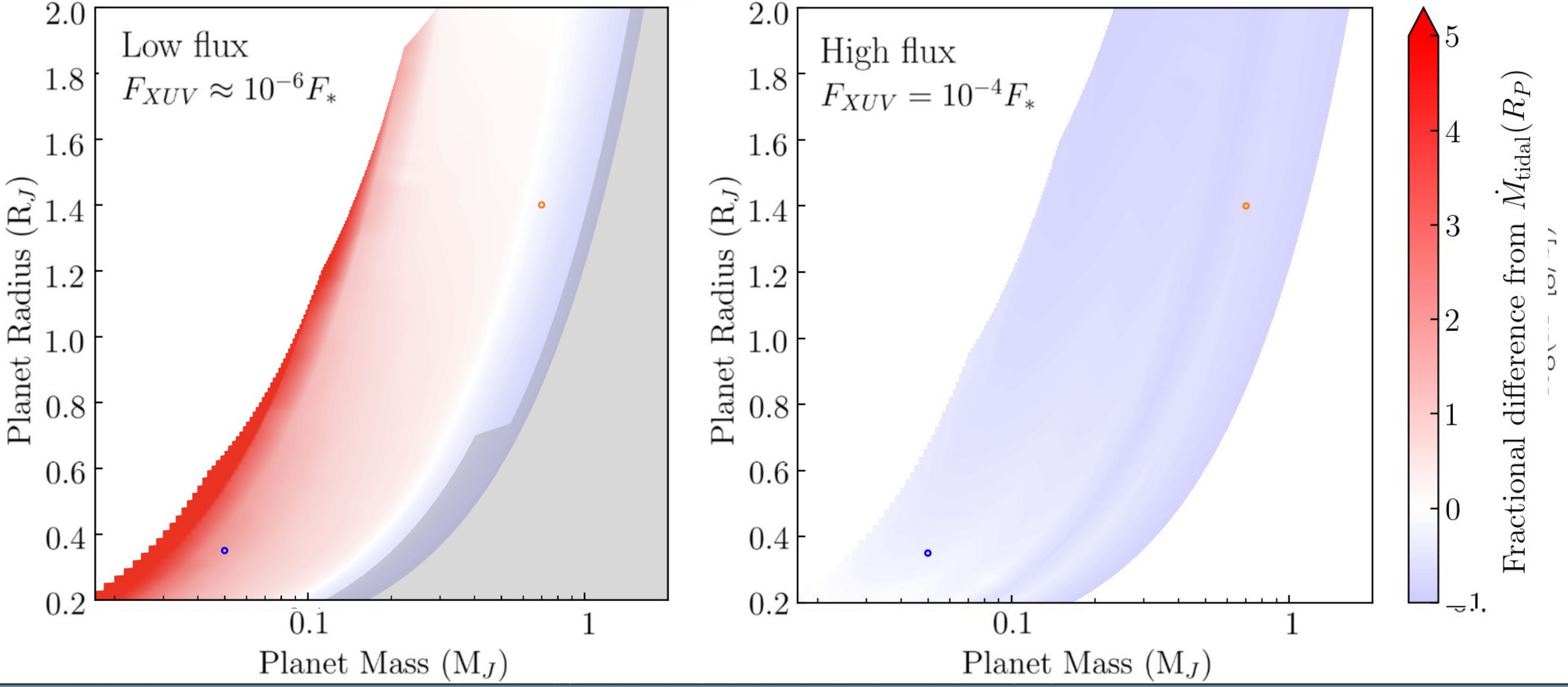
"Energy-limited"

More energy = more mass loss

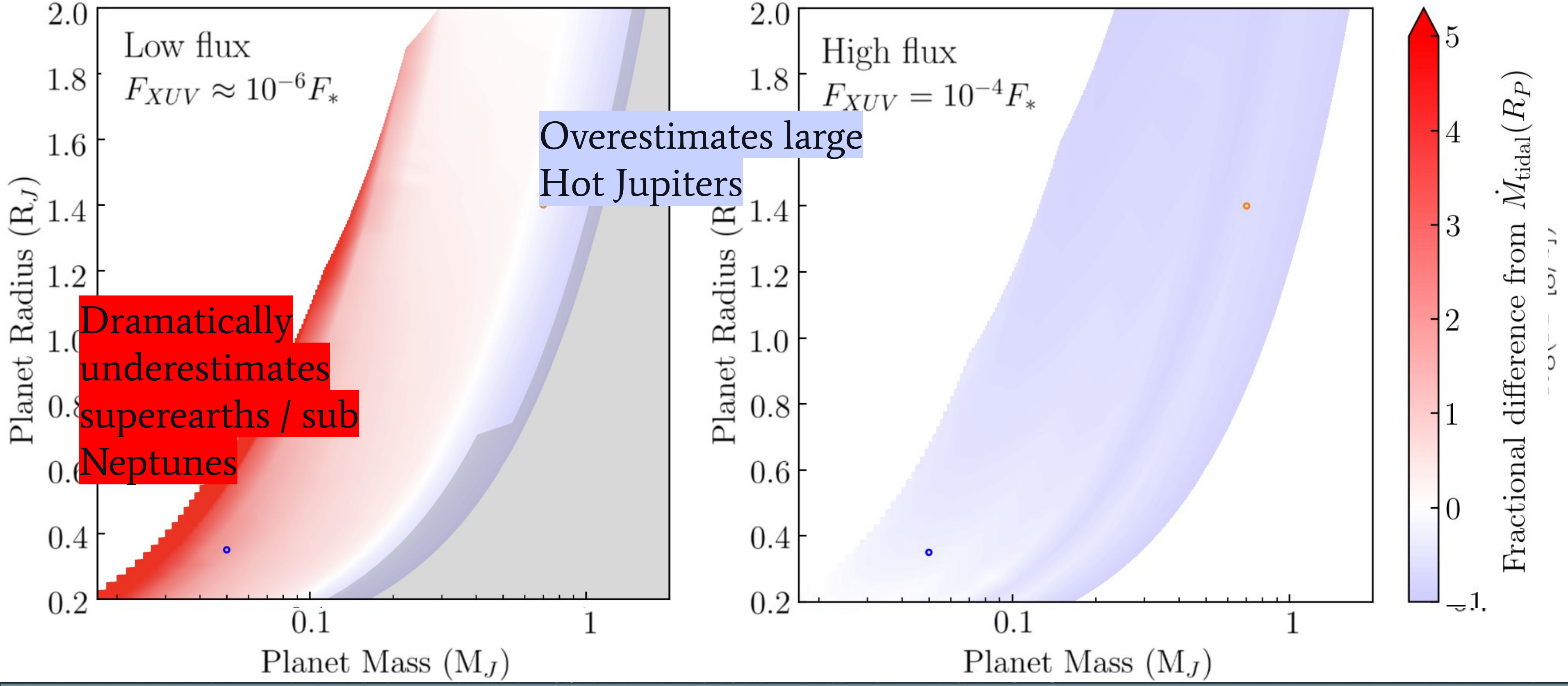
"Recombination-limited"

Radiative line cooling (e.g., Lyman-α) cooling efficient

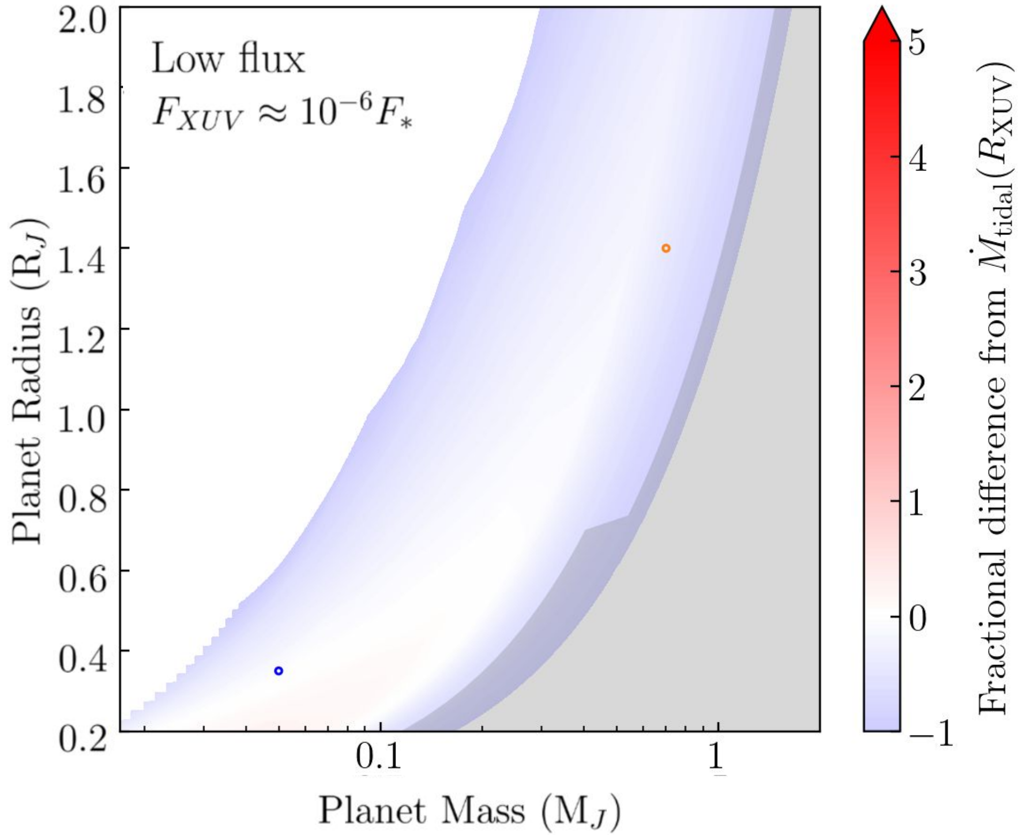
$\dot{M}_{Elimit}(R_P,\varepsilon)$ overestimates & $\dot{M}_{Elimit}(R_P,\varepsilon)$ underestimates



$\dot{M}_{Elimit}(R_P,\varepsilon)$ underestimates & $\dot{M}_{Elimit}(R_P,\varepsilon)$ overestimates



$\dot{M}_{Elimit}(R_{XUV},\varepsilon)$ overestimates & $\dot{M}_{Elimit}(R_{XUV},\varepsilon)$ underestimates



ε = 0.24 (superearths) - 0.37 (HJs)

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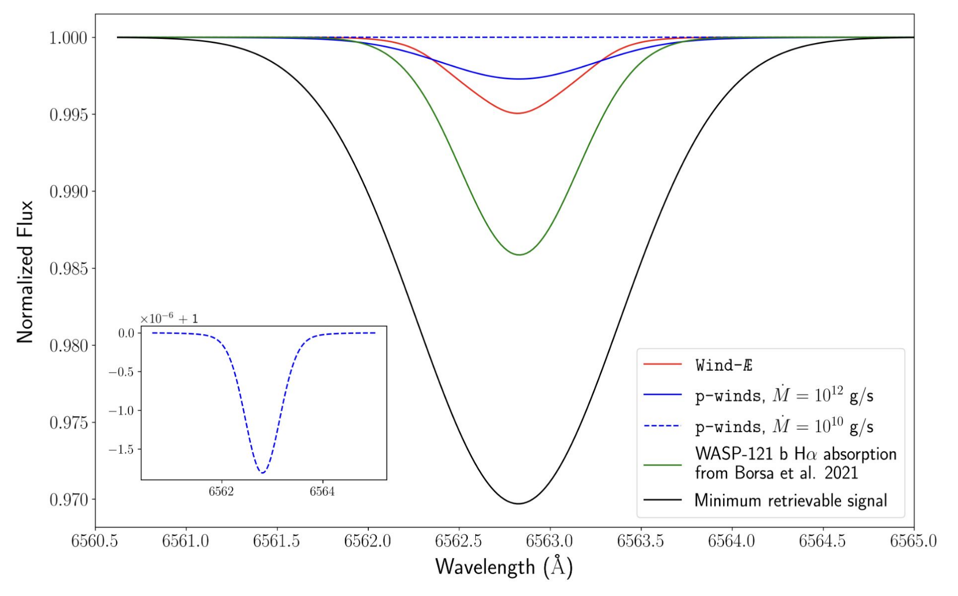
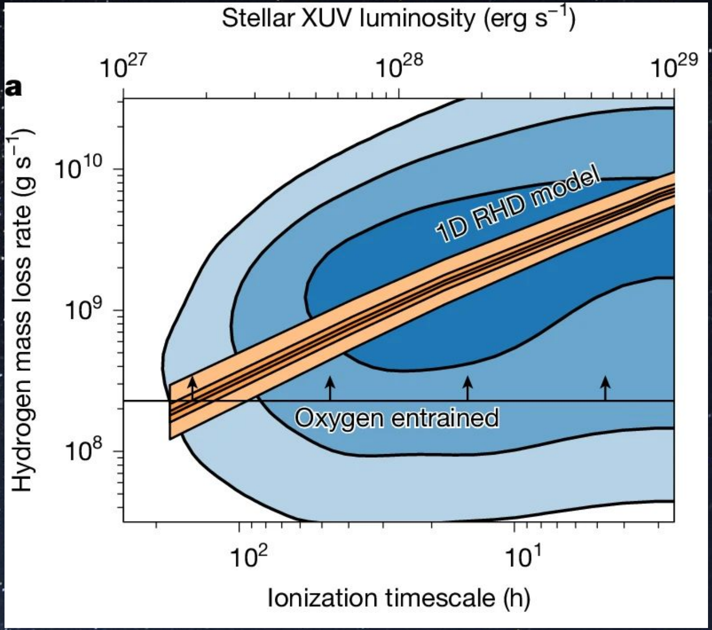
Confirming WASP-12b Hα surprising non-detection
(Pai-Asnodkar et al. 2024)



Superearths TOI-776b,c are losing H, not H2O atmos
(Parke et al. 2025)



github.com/mibroome/wind-ae

Conclusions

1. XUV radiation photoionizes atmospheres of close-in planets driving observable outflows.
2. Wind structure and $\dot{M}$ sensitive to inclusion of X-rays & metals.
3. At low fluxes $\dot{M}_{Elimit}(R_{XUV})$ is more accurate than $\dot{M}_{Elimit}(R_p)$.
4. $\dot{M}_{Elimit}(R_p)$ dramatically underestimates mass loss for superearths and overestimates for large Hot Jupiters. (OK for typical HJs)
5. Outflowing metals may explain HD 189733b's unusually deep X-ray transit.
6. <u>Future</u>: High metallicity grids

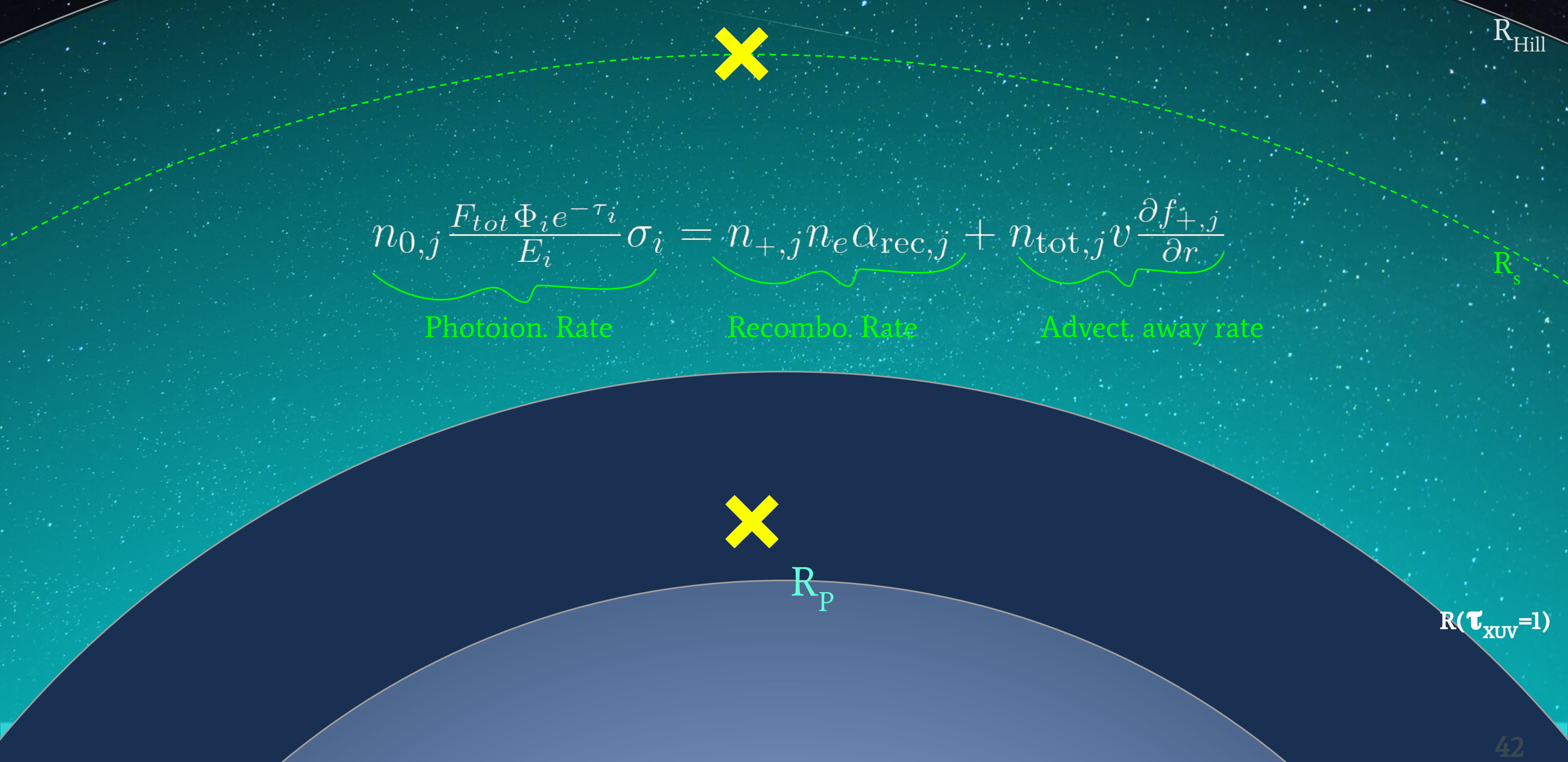
<u>Special Thanks:</u> Yao Tang, Jonathan Fortney, Renata Frelikh, Imperial Atmospheric Escape Group (James Owen, Ethan Schreyer, Matthäus Schulik, Richard Booth, James Rogers, Laura Harbach)

...and the 2025 ExoExplorers and ExoGuides

Extra Slides

Ionization Balance

$$\underbrace{n_{0,j}\frac{F_{tot}\Phi_i e^{-\tau_i}}{E_i}\sigma_i}_{\text{Photoion. Rate}} = \underbrace{n_{+,j}n_e\alpha_{\text{rec},j}}_{\text{Recombo. Rate}} + \underbrace{n_{\text{tot},j}v\frac{\partial f_{+,j}}{\partial r}}_{\text{Advect. away rate}}$$

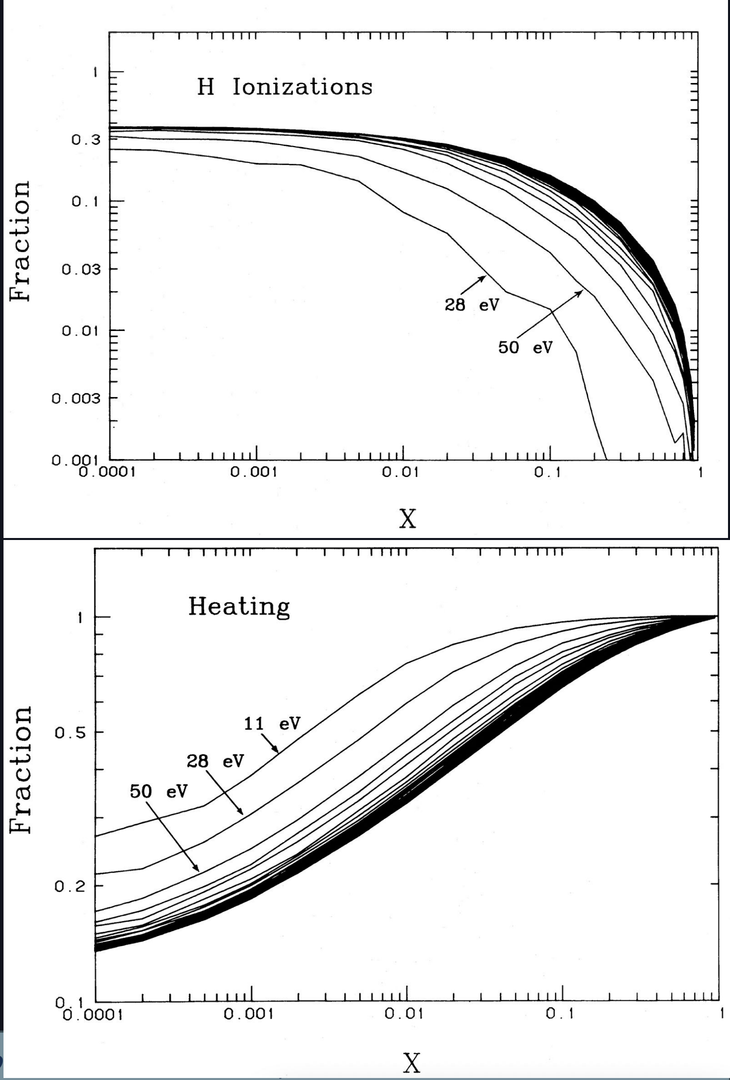


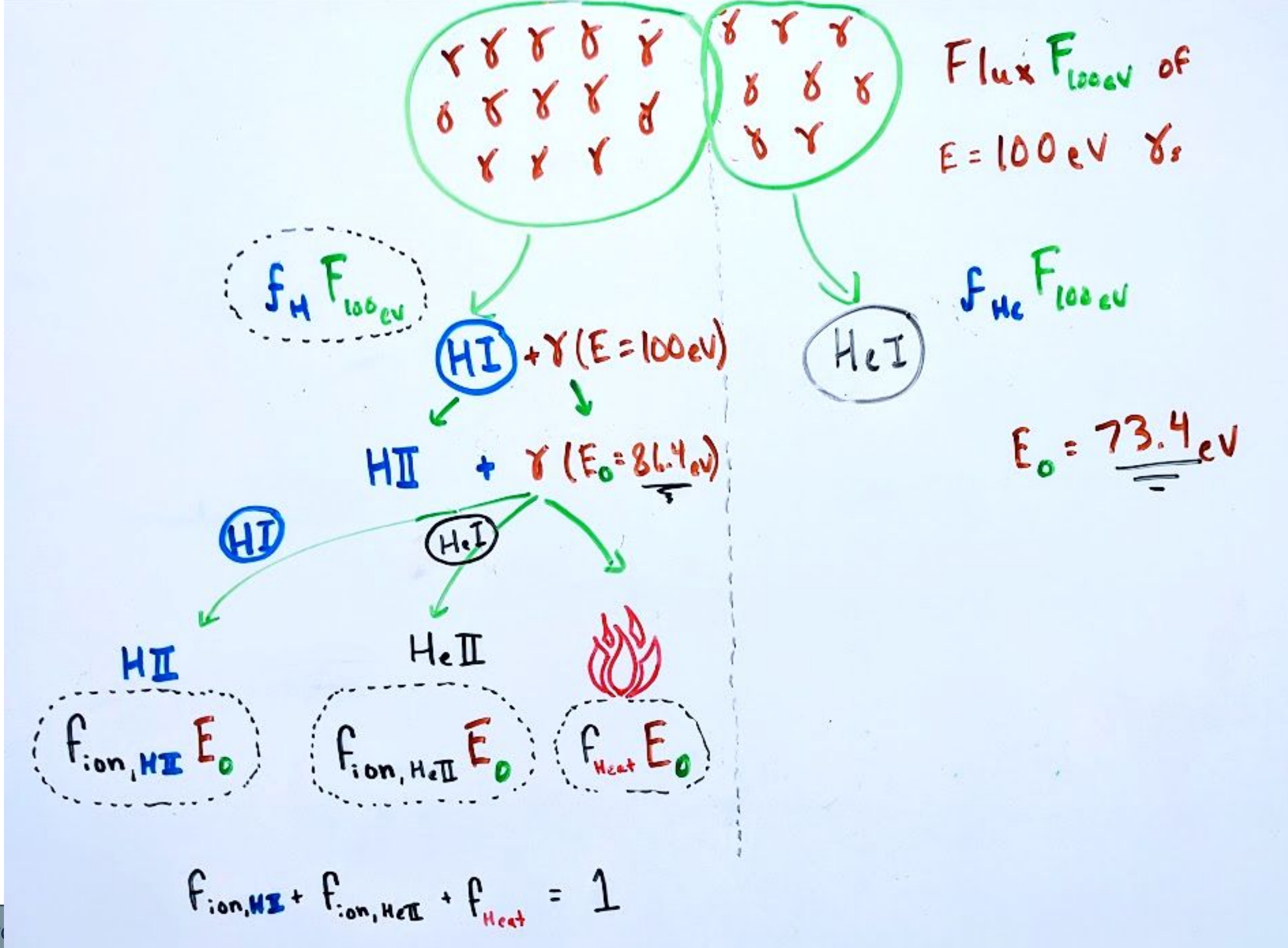
X-ray Considerations

X-rays ionize certain species' K-shells (innermost shell) instead of outermost shell, meaning a **much** larger ionization cross section, σ

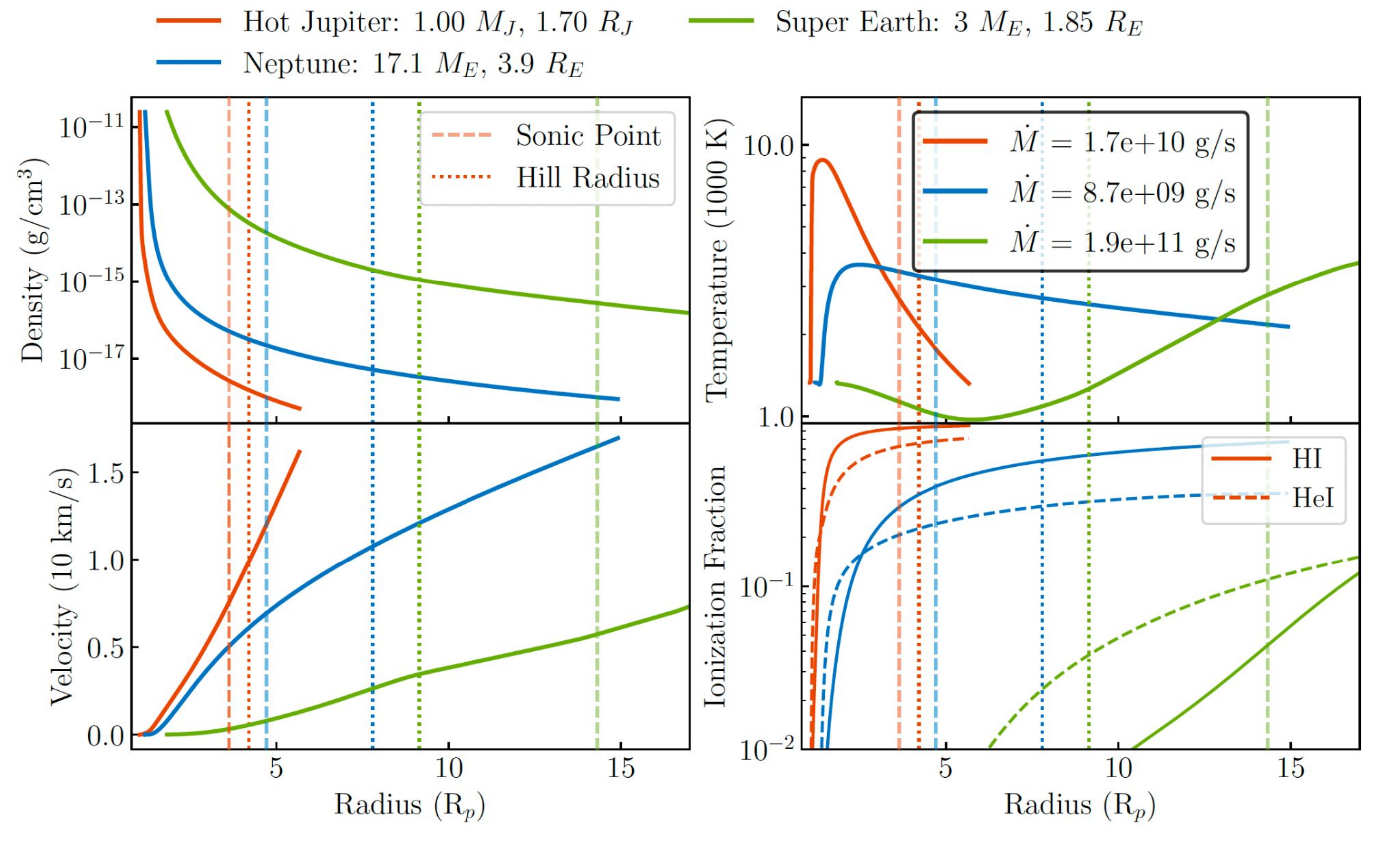
X-ray photons carry much higher energy than ionization energy (>100 eV relative to 13.6 eV to ionize H)

> Leftover energy in photon can be used to ionize another species OR to heat




Flux F100eV of
E = 100 eV γs
fH F100eV
HI + γ (E = 100eV)
HII + γ (E0 = 86.4 eV)
HI
HeI
HII
HeII
fion,HII E0
fion,HeII E0
fHeat E0
fHe F100eV
HeI
E0 = 73.4 eV
fion,HII + fion,HeII + fHeat = 1

1 solar mass, 1 solar luminosity, H, He



$$
\begin{aligned}
E_{1j} &\equiv \Delta_j \rho - \frac{d\rho}{dr}\Delta_j r \\
&= \Delta_j \rho + \rho\left(\frac{2}{r} + \frac{1}{v}\frac{dv}{dr}\right)\Delta_j r = 0 \qquad (9)
\end{aligned}
$$

$$
\begin{aligned}
E_{2j} &\equiv \Delta_j v - \frac{dv}{dr}\Delta_j r \\
&= \Delta_j v - \frac{v}{v^2 - \gamma kT/\mu}\Big[2\gamma kT/(\mu r) - (\gamma - 1)Q/(\rho v) \\
&\qquad - GM_{\rm p}/r^2 + 3GM_* r/a^3\Big]\Delta_j r = 0 \qquad (10)
\end{aligned}
$$

$$
\begin{aligned}
E_{3j} &\equiv \Delta_j T - \frac{dT}{dr}\Delta_j r \\
&= \Delta_j T - \Big[(\gamma - 1)\left(\frac{Q}{\rho v}\frac{\mu}{k} + \frac{T}{\rho}\frac{d\rho}{dr}\right) \\
&\qquad - \frac{T}{(1 + f_+)}\frac{df_+}{dr}\Big]\Delta_j r = 0 \qquad (11)
\end{aligned}
$$

$$
\begin{aligned}
E_{4j} &\equiv \Delta_j \tau - \frac{d\tau}{dr}\Delta_j r \\
&= \Delta_j \tau + \frac{(1 - f_+)\rho}{m_{\rm H}}\sigma_{\nu 0}\Delta_j r = 0 \qquad (12)
\end{aligned}
$$

$$
\begin{aligned}
E_{5j} &\equiv \Delta_j f_+ - \frac{df_+}{dr}\Delta_j r \\
&= \Delta_j f_+ - \frac{m_{\rm H}}{\rho v}\Big[\frac{F_{\rm UV} e^{-\tau}}{h\nu_0}\sigma_{\nu 0}\frac{(1 - f_+)\rho}{m_{\rm H}} \\
&\qquad - \alpha_{\rm rec}\left(\frac{f_+\rho}{m_{\rm H}}\right)^2\Big]\Delta_j r = 0 \qquad (13)
\end{aligned}
$$

Boundary Conditions

Sonic Point

Column Density

$$\left[v^2 = \frac{\gamma kT}{\mu}\right]_{r_{\rm s}} \qquad \text{(BC1)}$$

and

$$\left[\frac{2\gamma kT}{\mu} - \frac{GM_{\rm p}}{r} - \frac{(\gamma - 1)Qr}{\rho v} + \frac{3GM_* r^2}{a^3}\right]_{r_{\rm s}} = 0$$

R_P

Mass density, Temperature, Ionization fraction

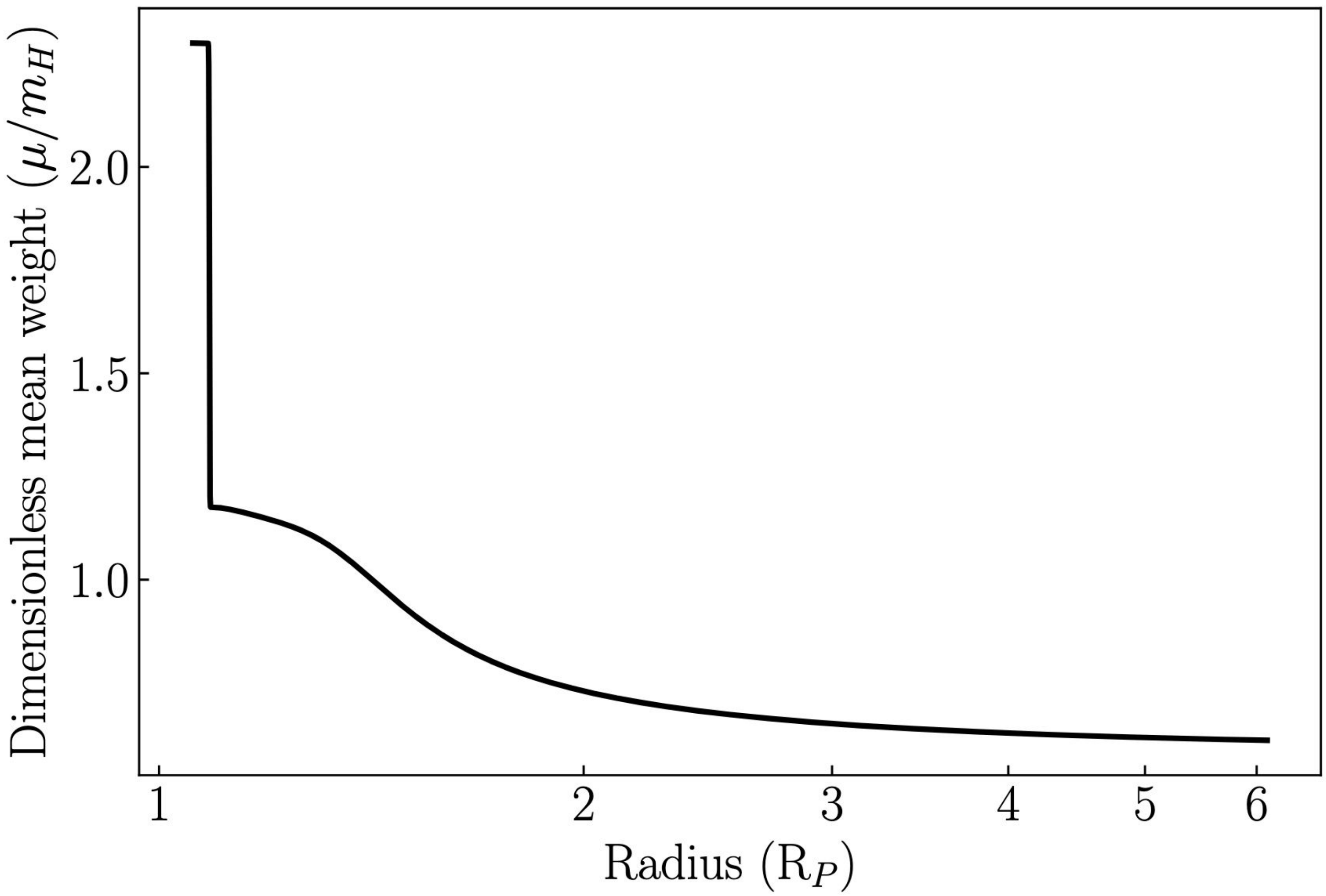
Agnostic boundary conditions (only depend on L_{bolo} and pressure)

Lower BCs

$$R_{\rm min}(P_{R_{\rm min}}) = \left[\frac{c_s^2}{GM_P}\ln\left(\frac{P_{R_{\rm min}}}{P(R_P)}\right) + \frac{1}{R_P}\right]^{-1}$$

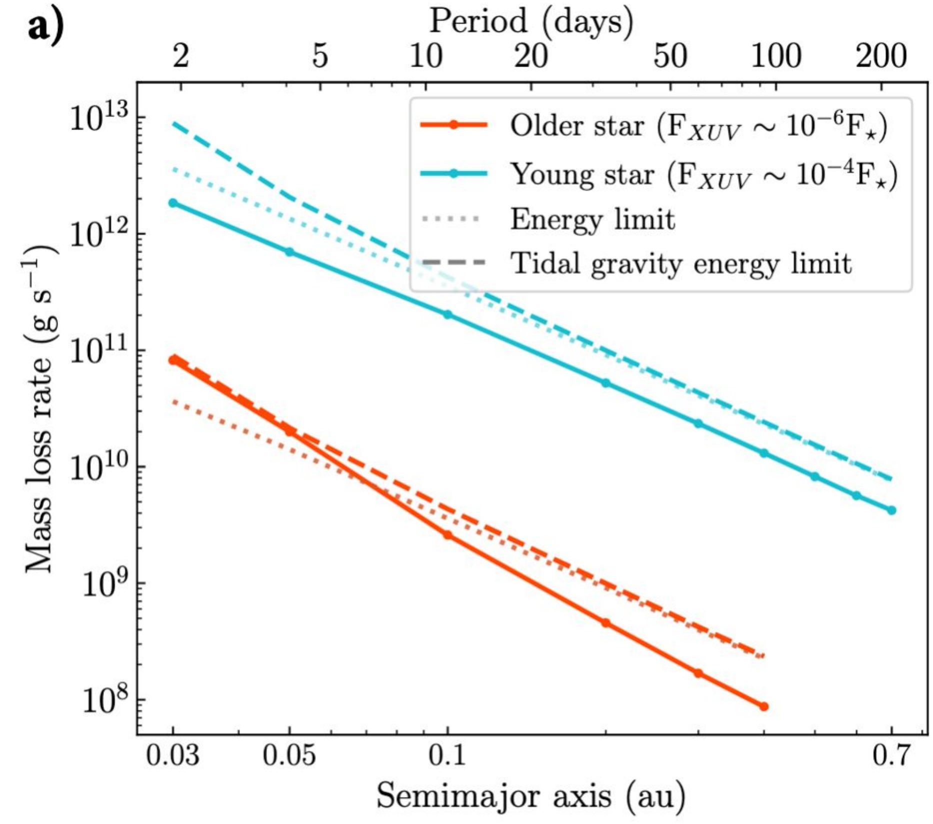
$$\rho(R_{\rm min}) = P_{R_{\rm min}}\frac{\mu_{mol}}{k_B T_{\rm skin}},$$

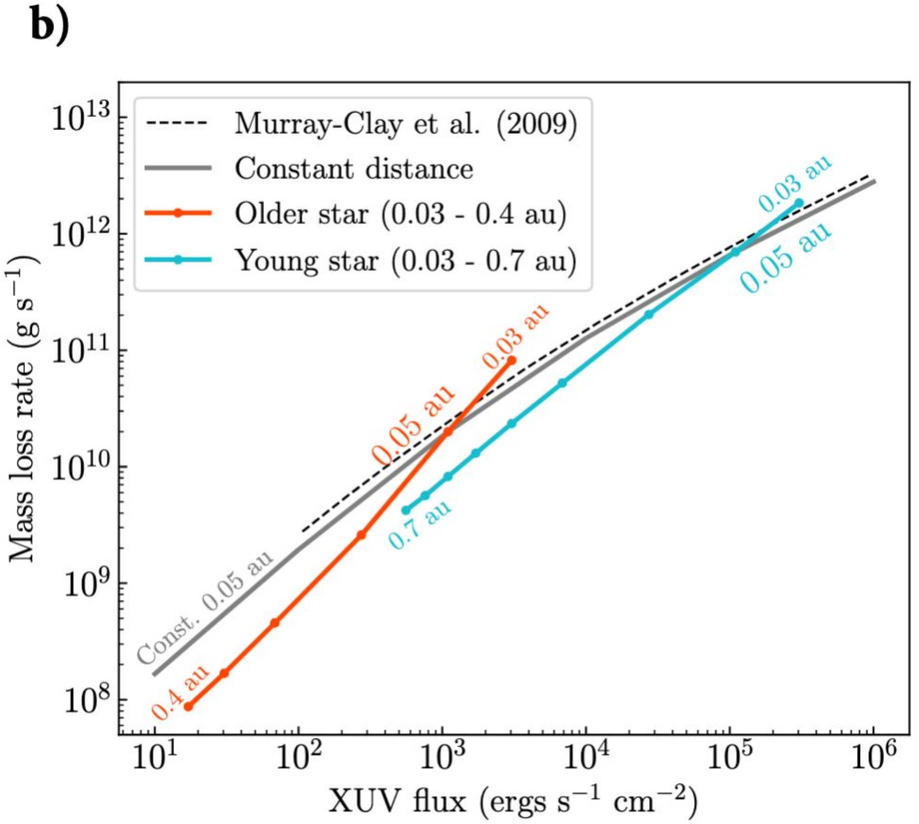
$$T_{\rm skin} = \left[\frac{F_*(\kappa_{\rm opt} + \kappa_{\rm IR}/4)}{2\sigma_{SB}\kappa_{\rm IR}}\right]^{1/4}$$



Dimensionless mean weight (μ/m_H)
2.0
1.5
1.0
1
2
3
4
5
6
Radius (R_P)

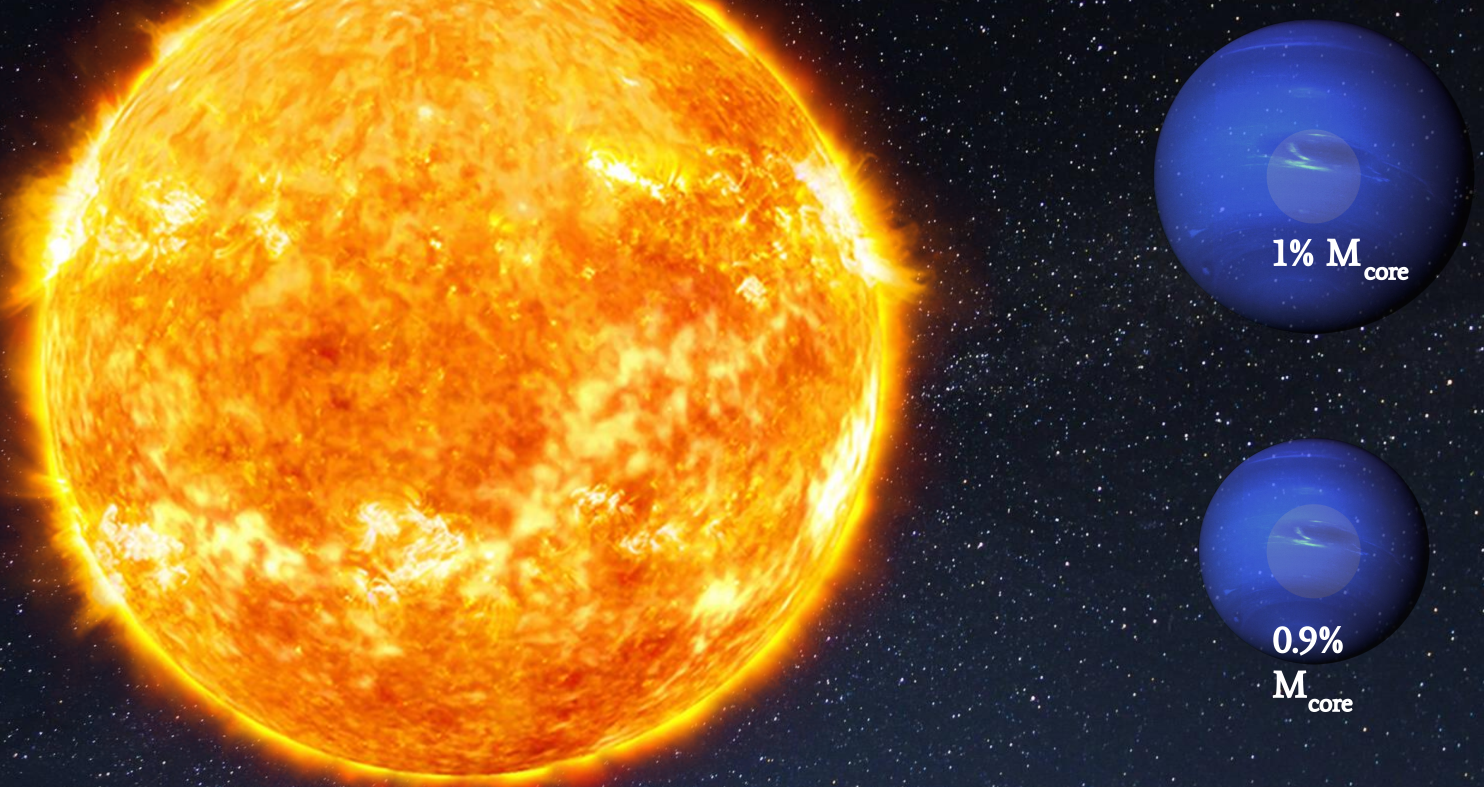
What do tides do?





Before Photoevaporation

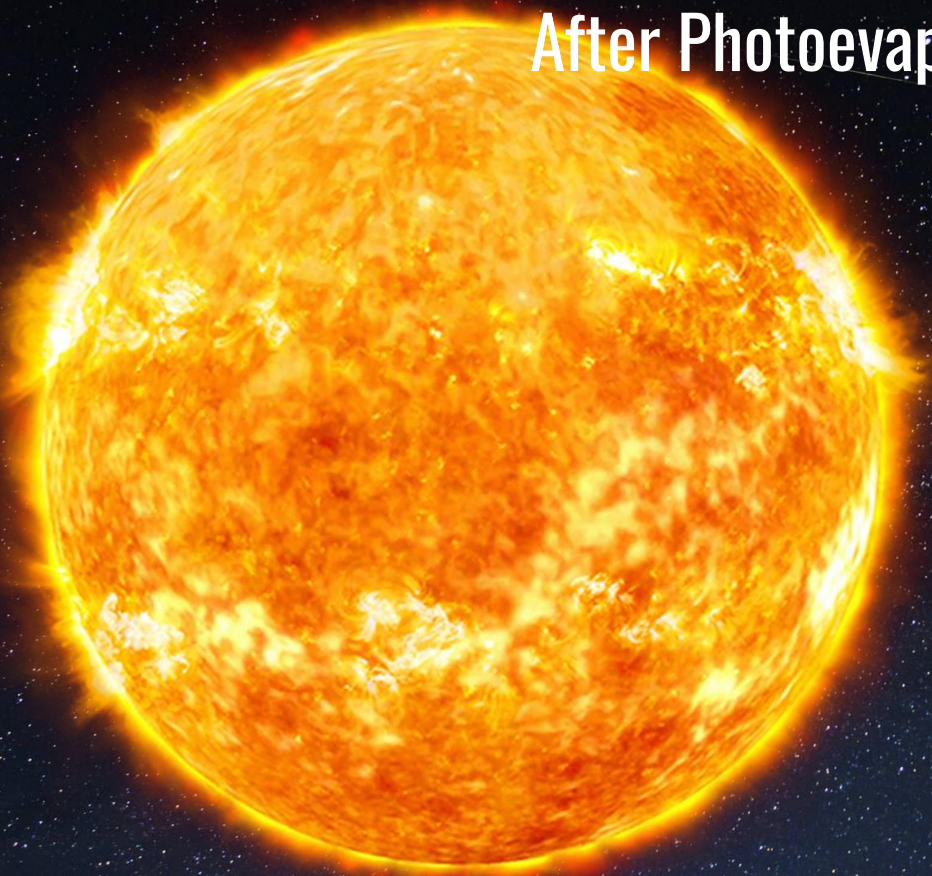
$t = 1$ Myr



FOR A FIXED CORE MASS

After Photoevaporation

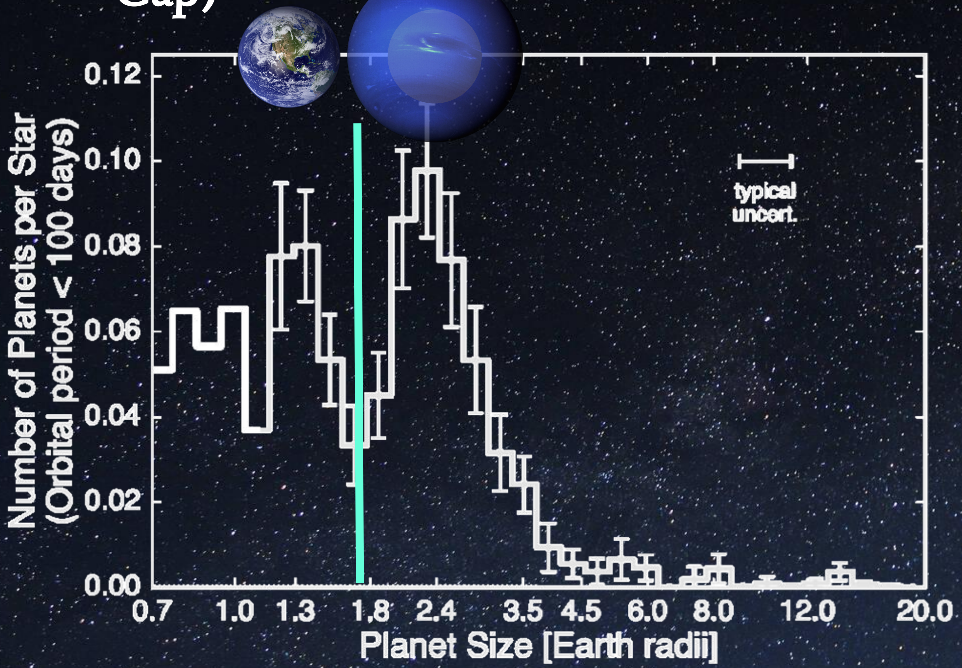
t = 100 Myr



FOR A FIXED CORE MASS

Other possibilities

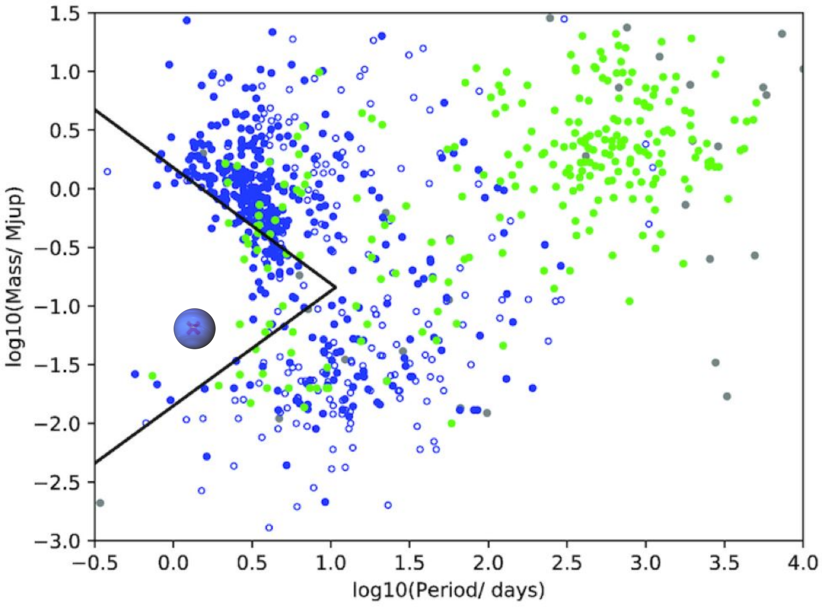
Period-Radius Valley (a.k.a., Fulton Gap)



- Core masses may have underlying mass distribution that contributes to atmospheric fraction and size differences (Lee et al. 2022)
- Core powered mass loss (Gupta & Schlichting, 2022)
- Water worlds (Luque, 2022)

Other possibilities

Photoevaporative (Neptune) Desert



- Photoevaporation can't clear the top of the desert (Vissapragada et al. 2022)
- Top maybe: Tidal disruption barrier for gas giants undergoing high-eccentricity migration (Owen & Lai, 2018)

Spherical Obscuration Fraction

$$\mathrm{Obscuration}(\nu) = \frac{\left[\mathrm{R}_{\mathrm{max}}^2 - \int_{\mathrm{R}_{\mathrm{min}}}^{\mathrm{R}_{\mathrm{max}}} 2\mathrm{b} \cdot \mathrm{e}^{-\tau(\mathrm{b},\nu)} \mathrm{db}\right]}{\mathrm{R}_*^2}$$

Tau is slant path optical depth, where we assume the cross section is photoionization cross section.