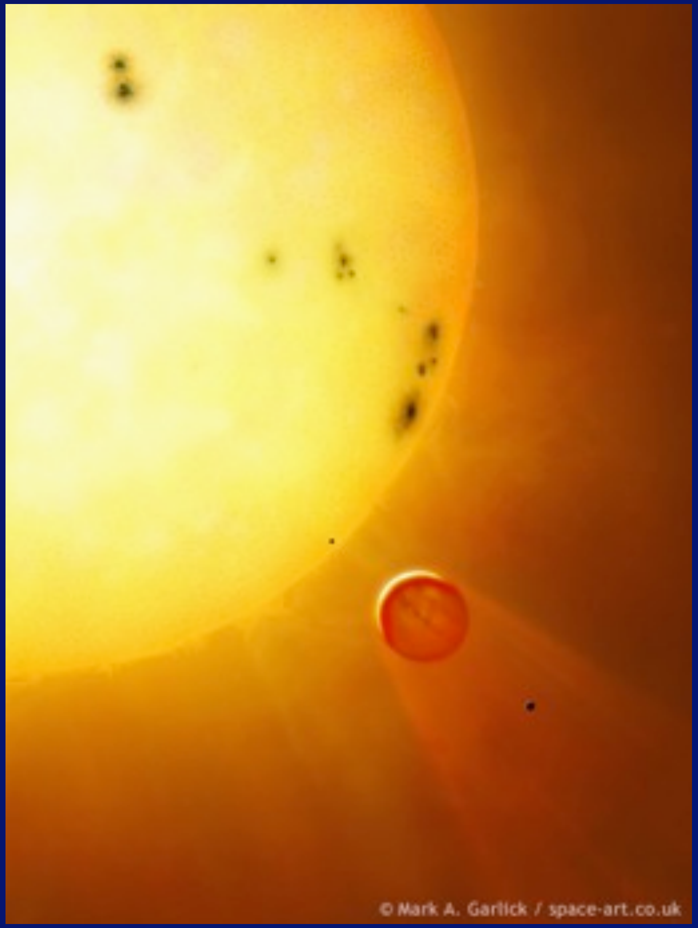
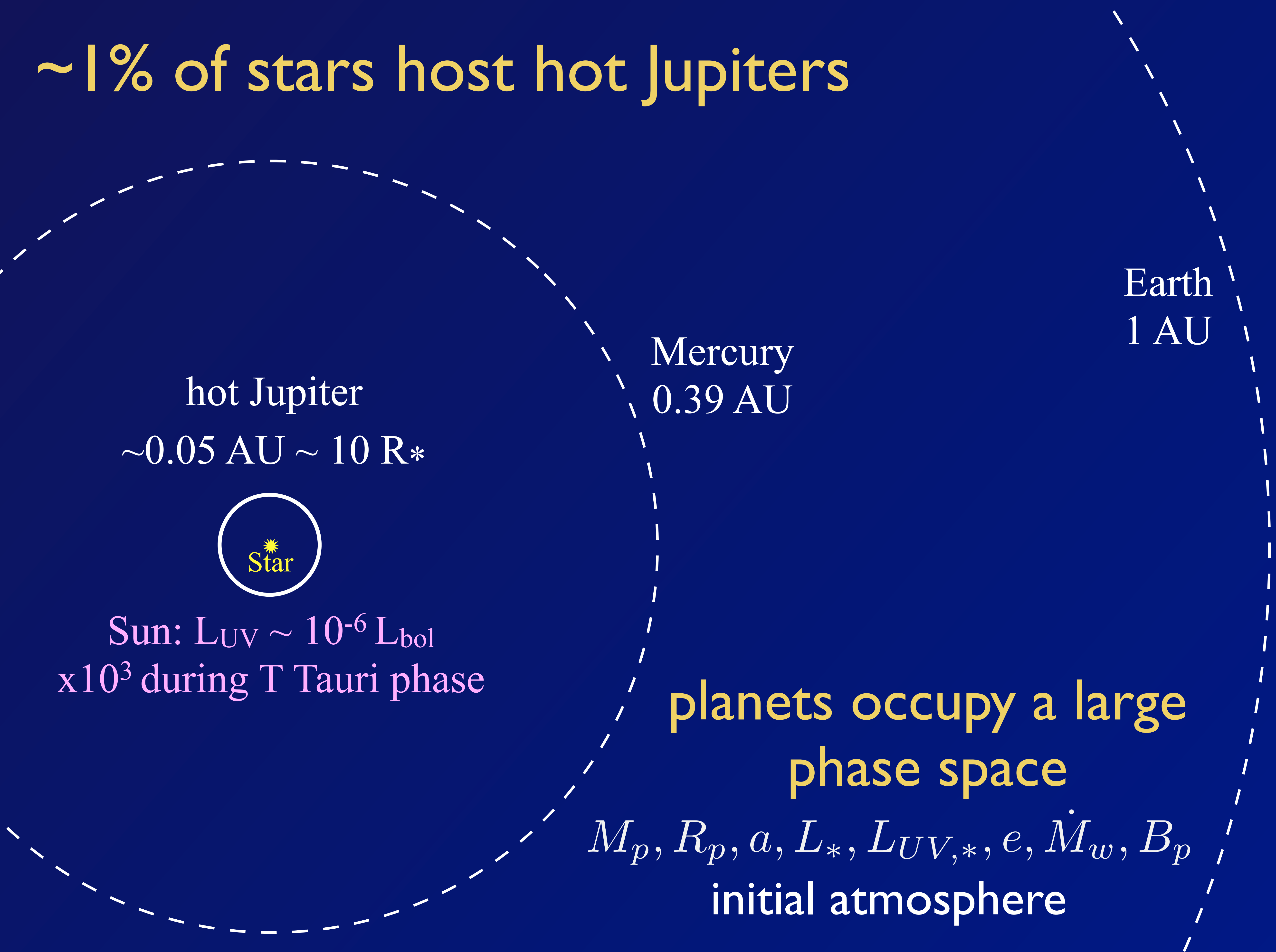
Hydrodynamic Escape from Highly Irradiated Atmospheres



Ruth Murray-Clay
Harvard-Smithsonian Center for Astrophysics

~1% of stars host hot Jupiters



planets occupy a large phase space

$$M_p, R_p, a, L_*, L_{UV,*}, e, \dot{M}_w, B_p$$

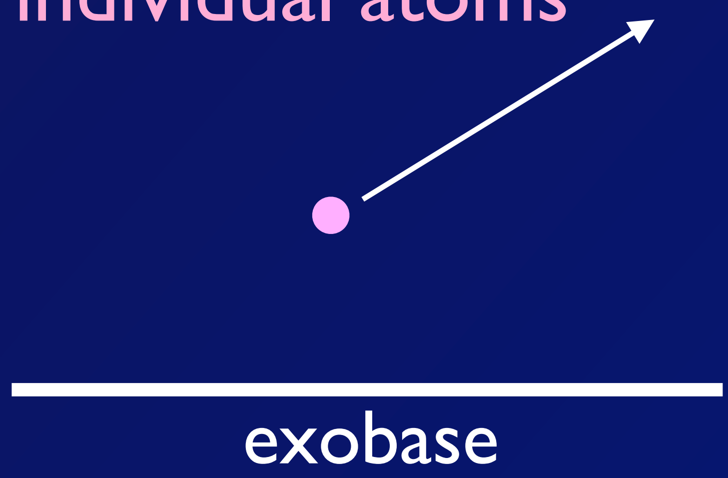
initial atmosphere

Two classes of escape mechanisms:

Each can be thermal or non-thermal

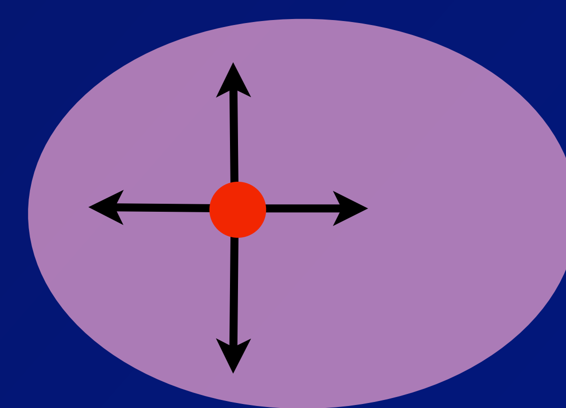
“kinetic”

loss to space of
individual atoms



“hydrodynamic”

bulk outflow of a
collisional fluid



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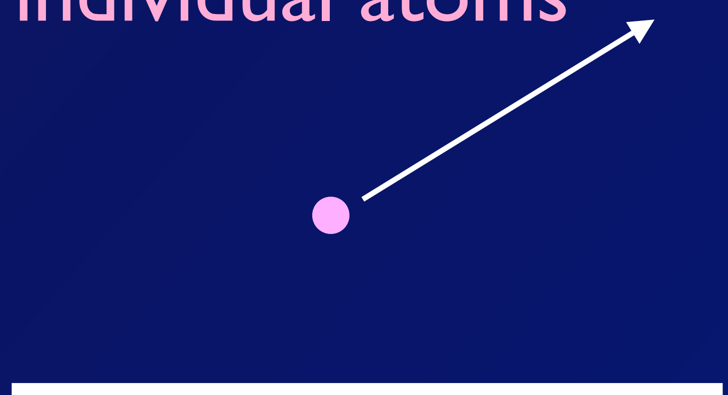
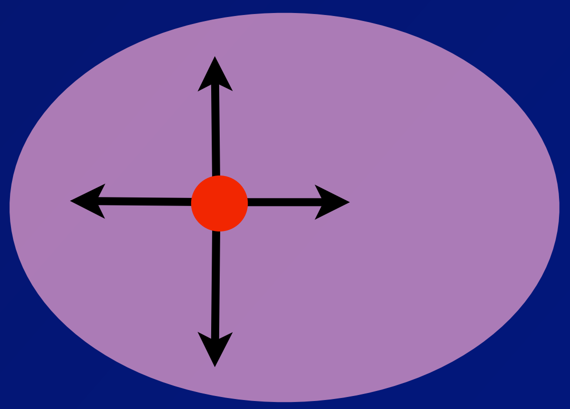


exobase

"hydrodynamic"

bulk outflow of a collisional fluid



limits of thermal escape

Jeans escape

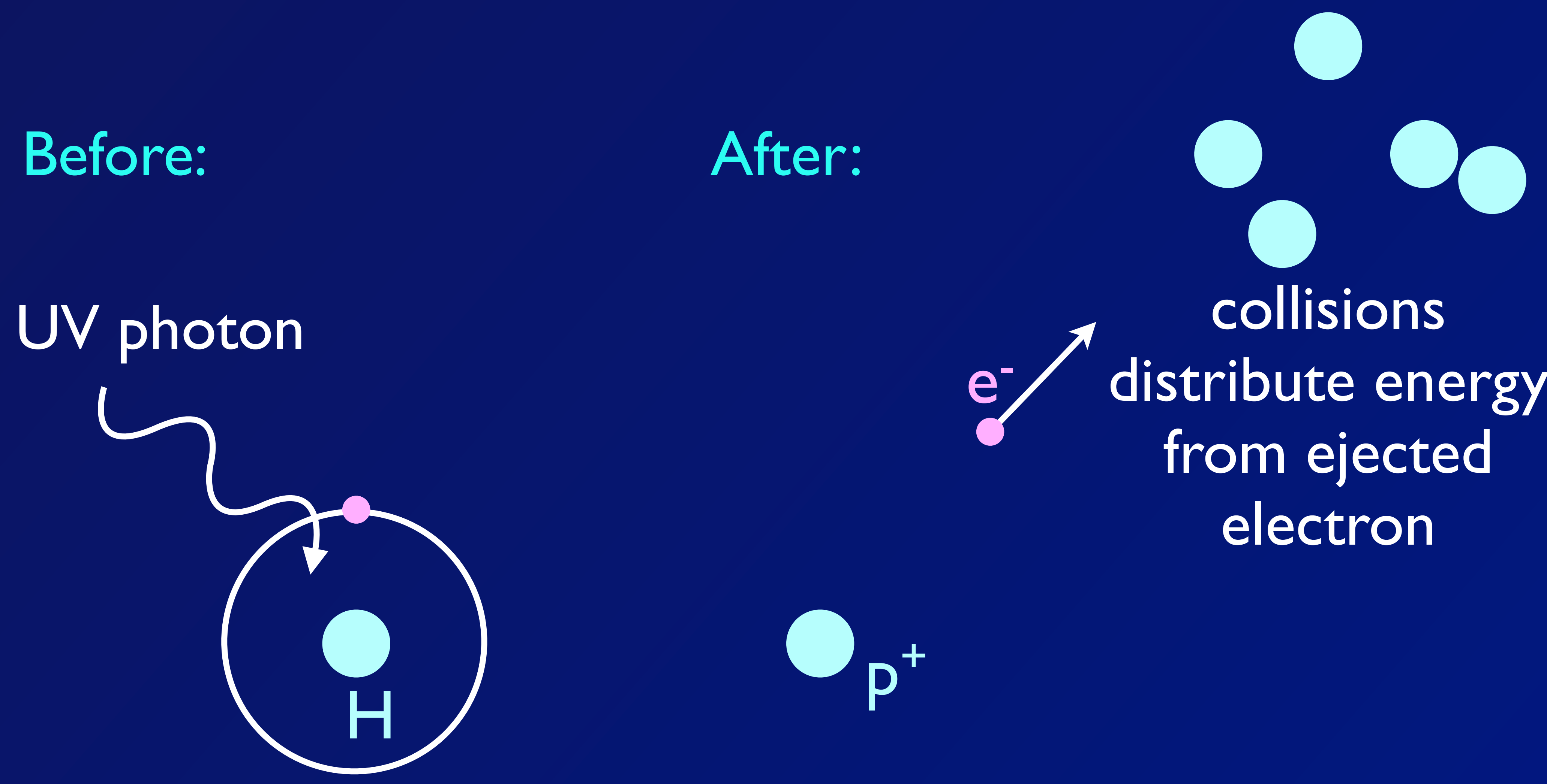
non-thermal processes, often mediated by B-fields

hydrodynamic escape

Roche lobe overflow

ram pressure stripping

UV photons heat the upper atmosphere by photoionization



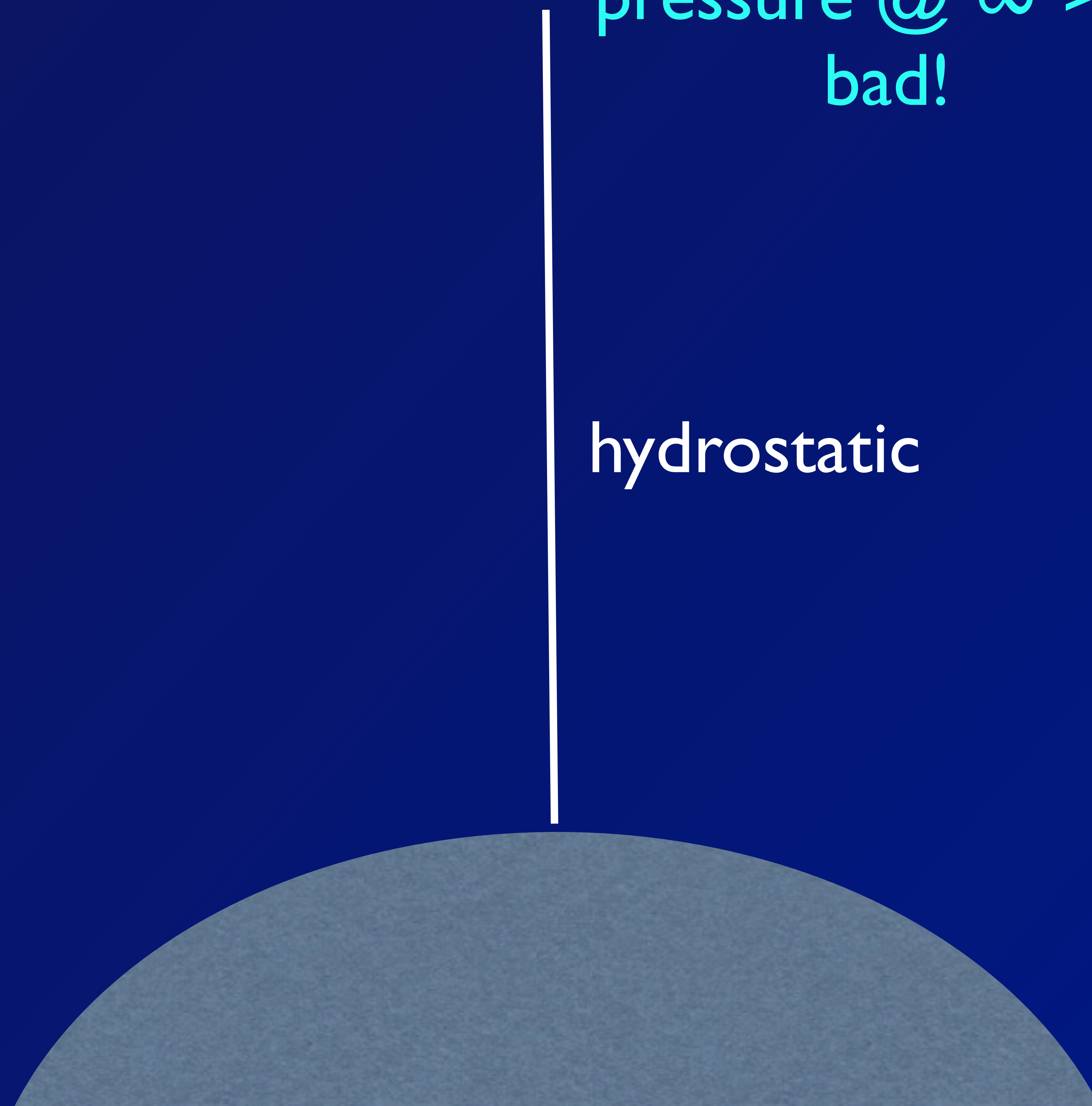
hot Jupiters cannot be evaporated, in spite of early results using "energy-limited escape" models meant for young Earth and Venus

What generates a Parker wind?

pressure @ ∞ > 0:
bad!

fluid,
isothermal

hydrostatic



What generates a Parker wind?

pressure @ ∞ > 0:
bad!

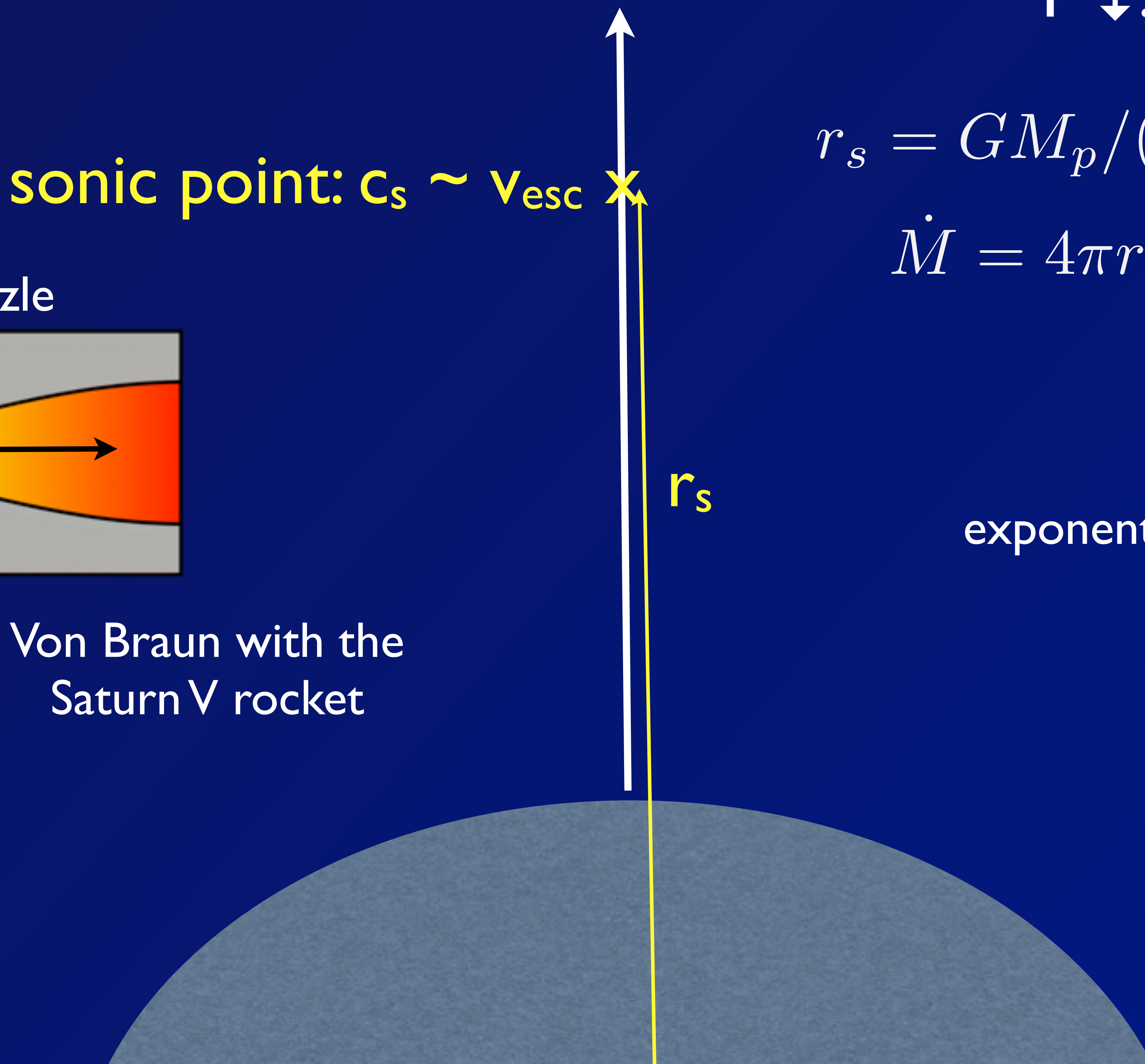
fluid,
isothermal

accelerates the gas outward

v

energy for PdV work in outward flow comes from this assumption

Parker winds flow through a critical point



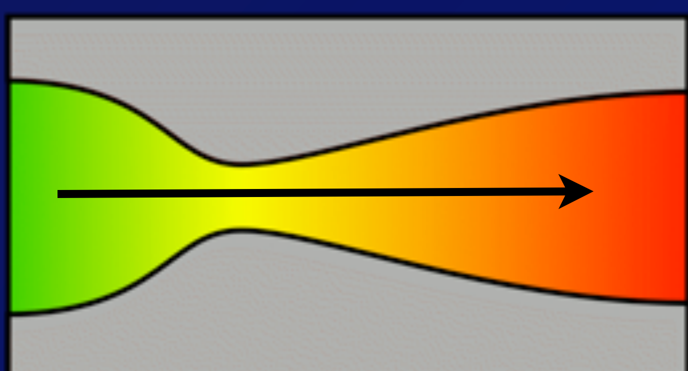
T ↓:

$$r_s = GM_p/(2c_s^2) \quad \uparrow$$

$$\dot{M} = 4\pi r^2 \rho v \quad \downarrow$$

exponential dropoff

De Laval Nozzle



Von Braun with the Saturn V rocket

Drop isothermal assumption

still assume fluid (collisional)

only photoionization heating
and pdV work

heating from photoionization
sets lower boundary condition

deposited primarily
at τ ~ 1 : $n_0 \sim \dfrac{1}{\sigma H}$

P ~ nanobars,
altitude set by lower atmosphere

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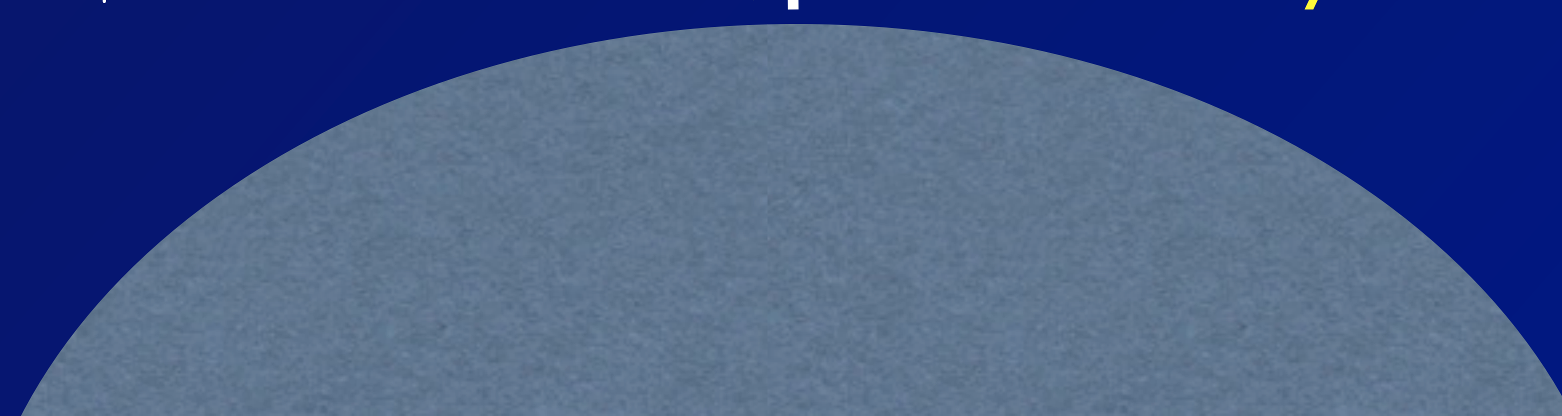
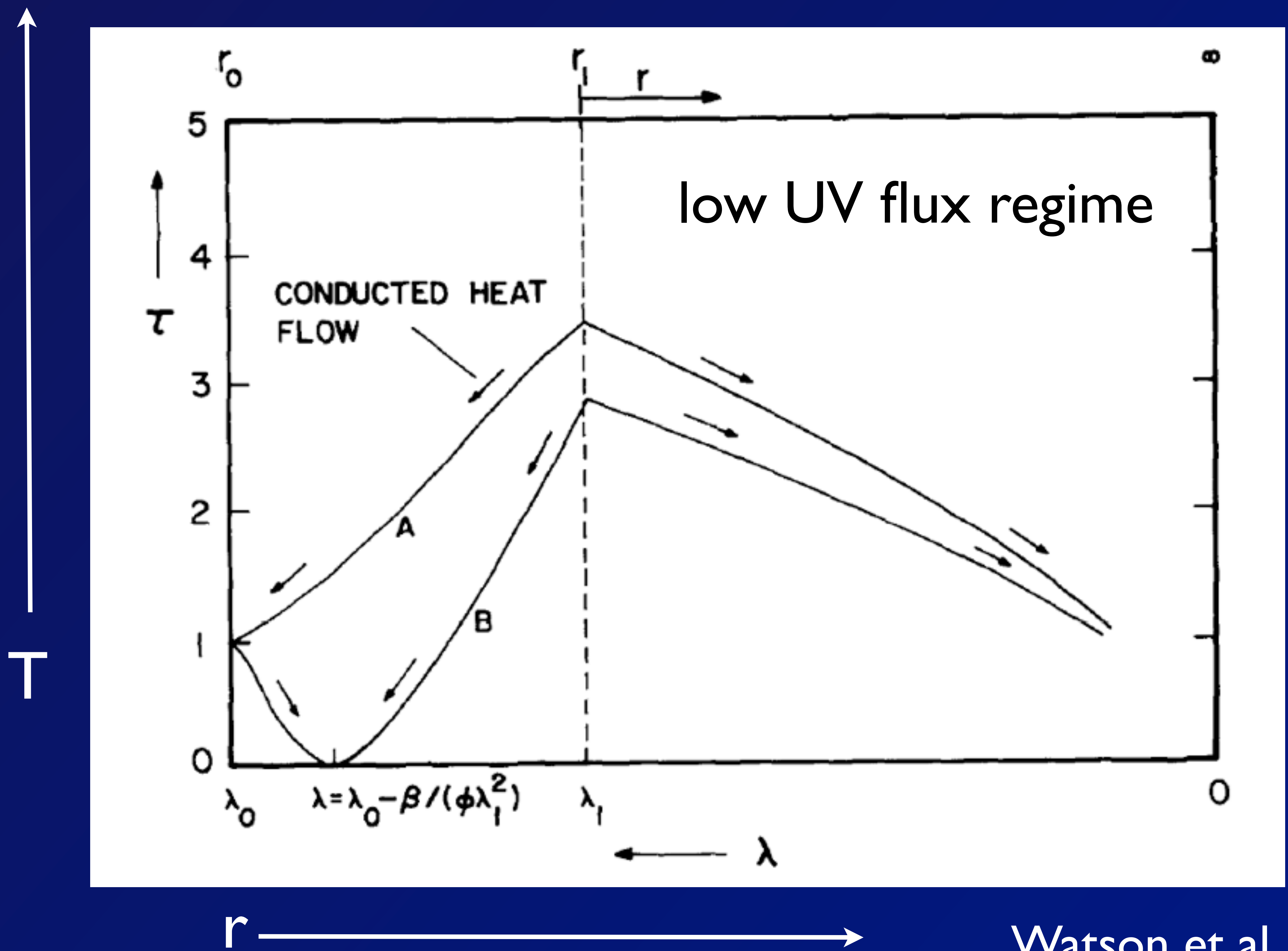
For high UV flux:

$$\frac{F_{\rm UV}}{h\nu_0}\sigma_{\nu_0} n_0 \sim n_+^2 \alpha_{\rm rec}$$

P ~ nanobars,
altitude set by lower atmosphere



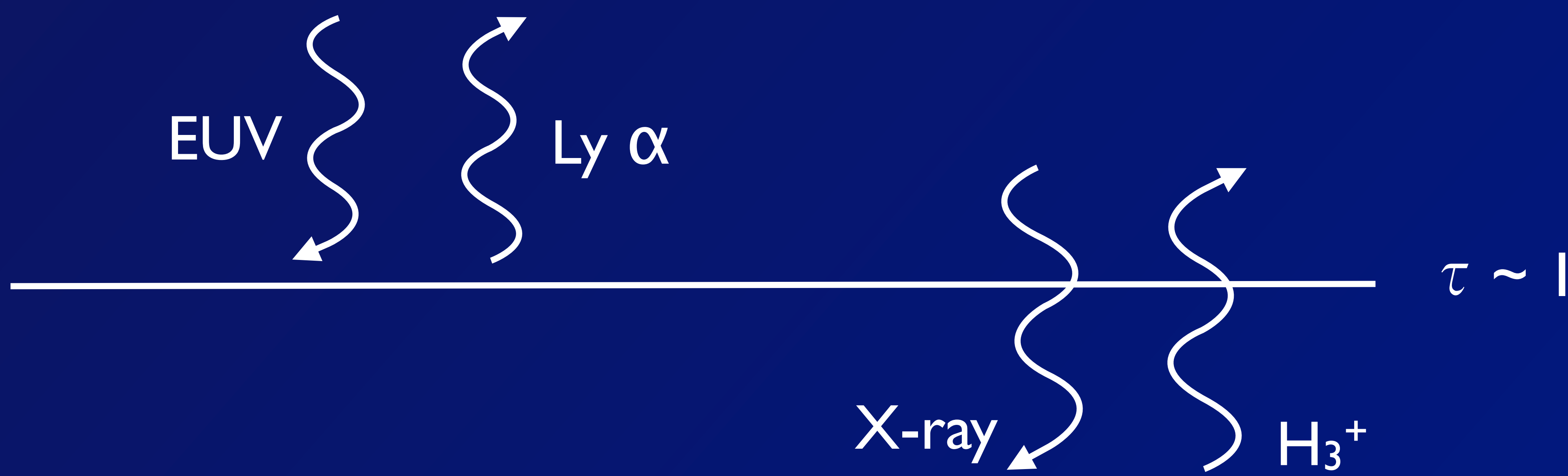
Conduction



Watson et al. 1981

Radiative cooling

T ~ 10^4 K



T ~ 10^3 K

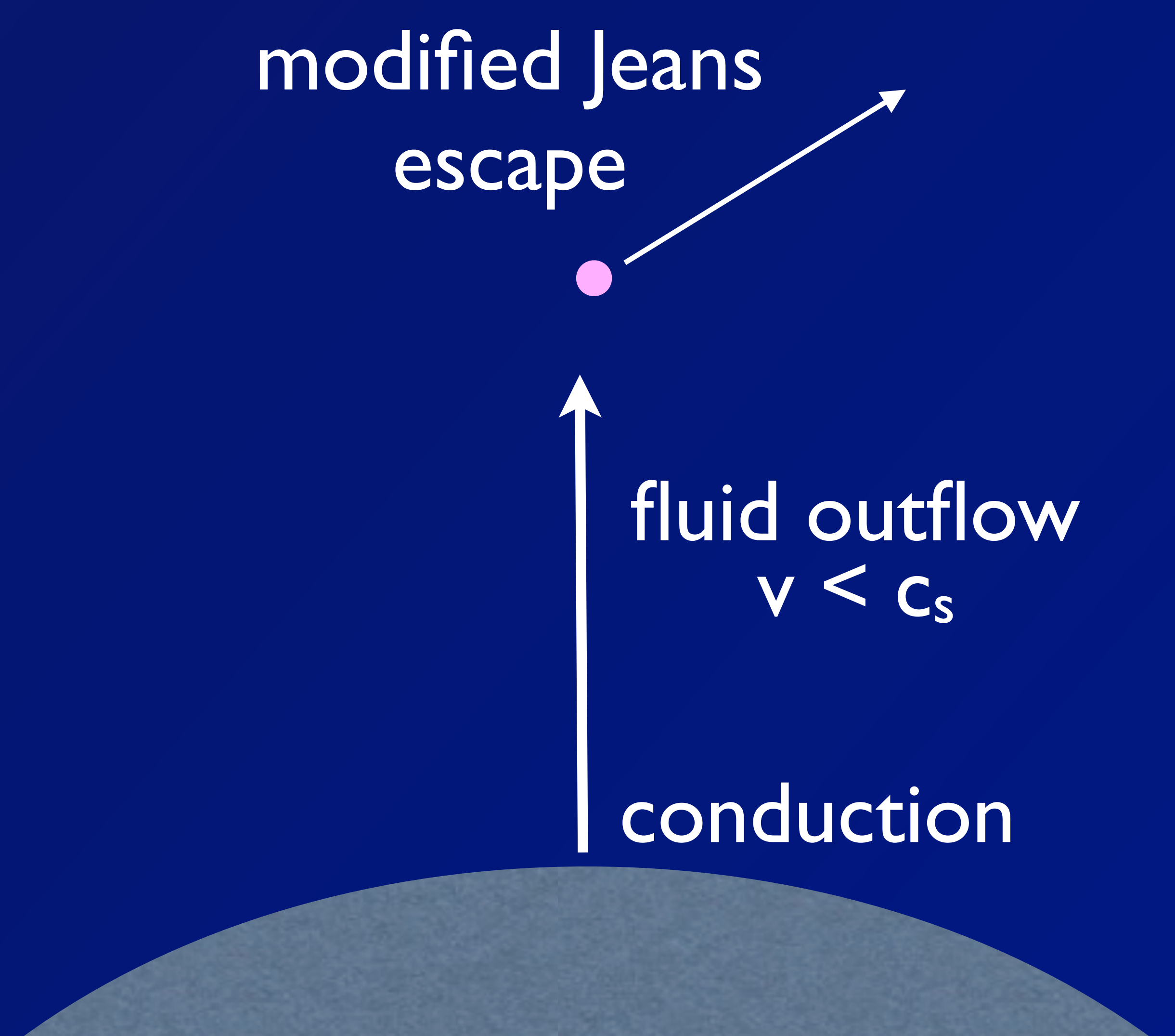
can kill flow altogether if too high

I haven't cared about the exobase!

If FUV low ⇒ many scale heights to sonic point;

no longer collisional & model isn't self-consistent

intermediate between hydrodynamic escape & Jeans escape:



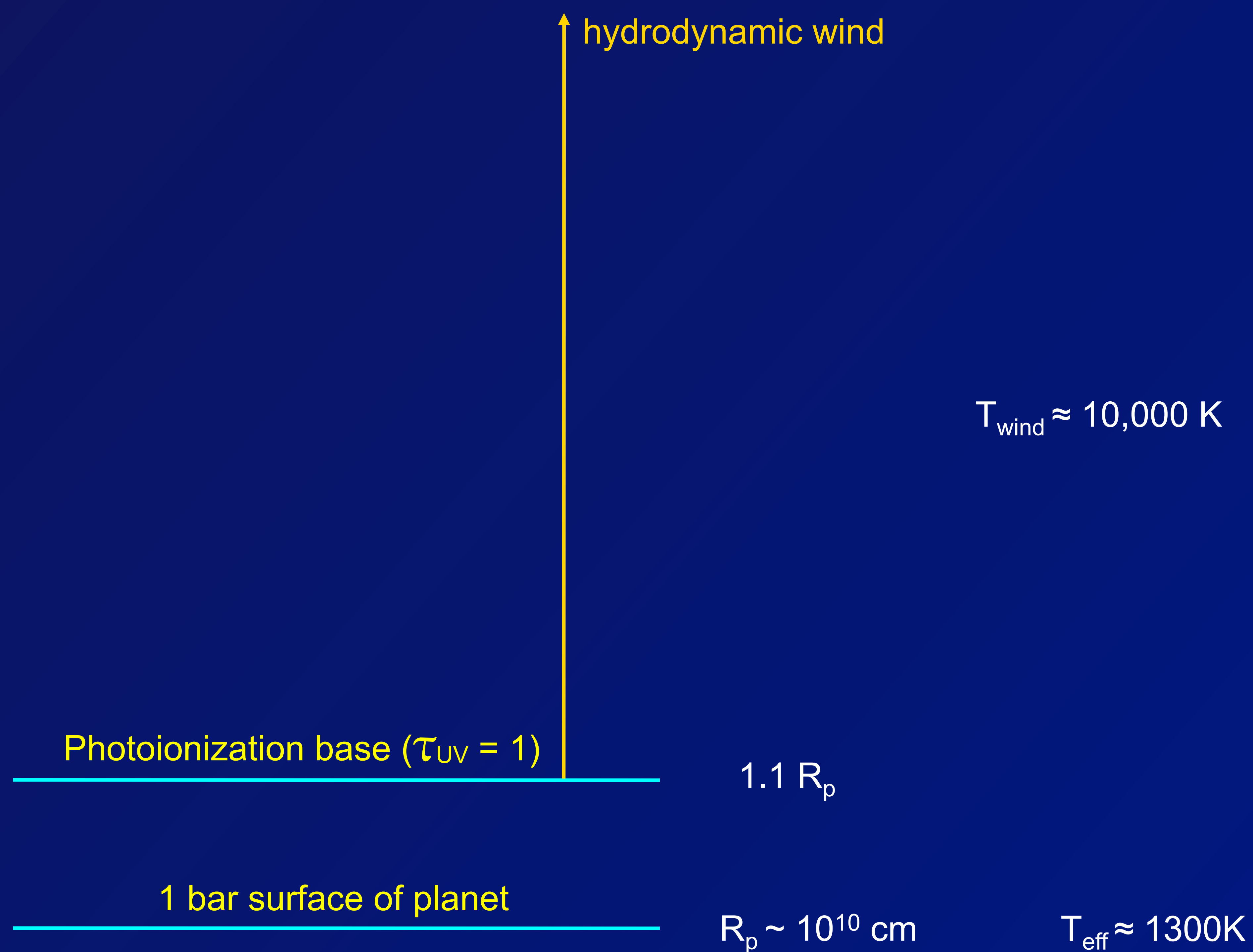
Hot Jupiter

1 bar surface of planet

$R_p \sim 10^{10}$ cm

$T_{eff} \approx 1300K$

Hot Jupiter


hydrodynamic wind
$T_{wind} \approx 10{,}000$ K
Photoionization base ($\tau_{UV} = 1$)
1.1 R_p
1 bar surface of planet
$R_p \sim 10^{10}$ cm
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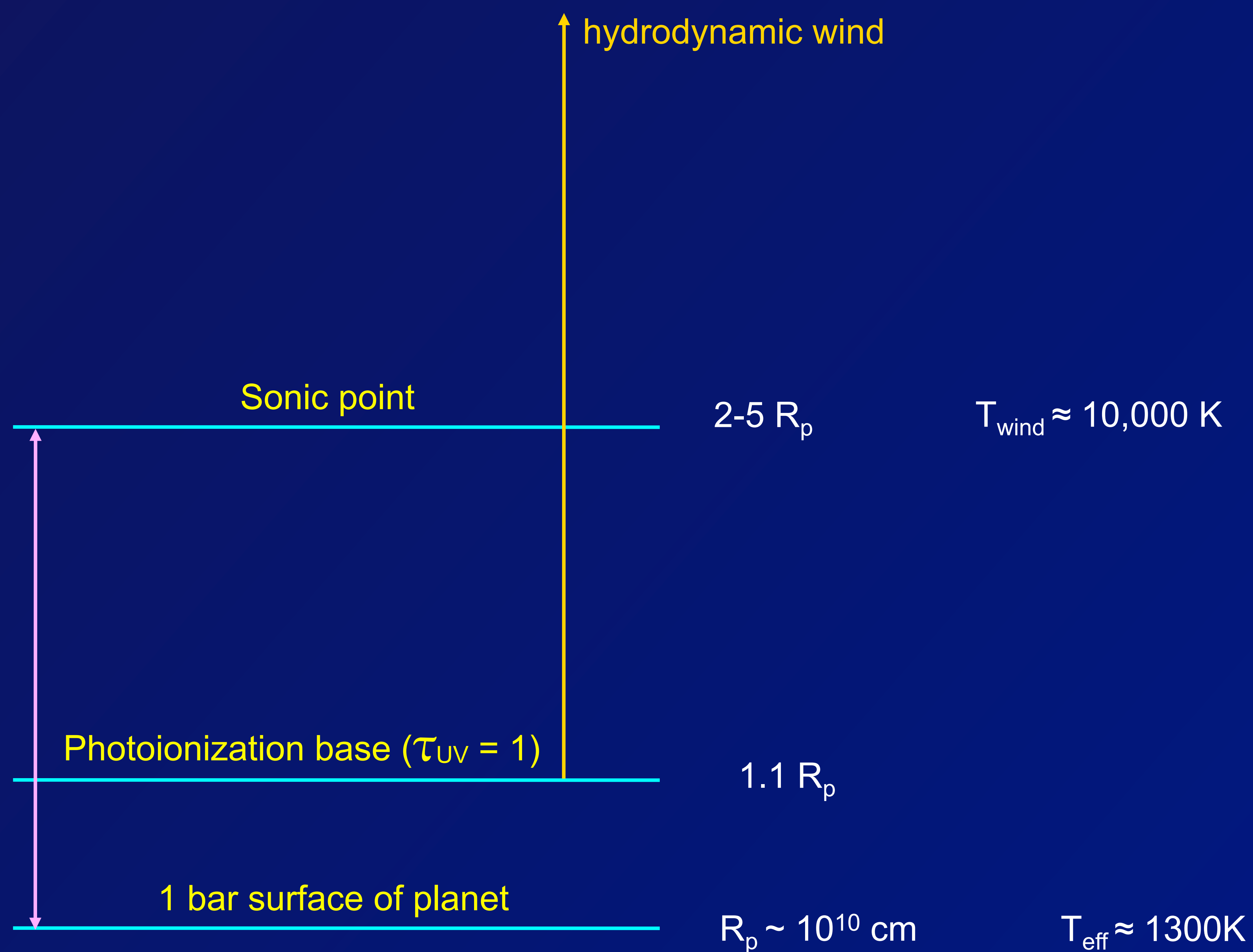
hydrodynamic wind
Sonic point
2-5 R_p
$T_{wind} \approx 10{,}000$ K
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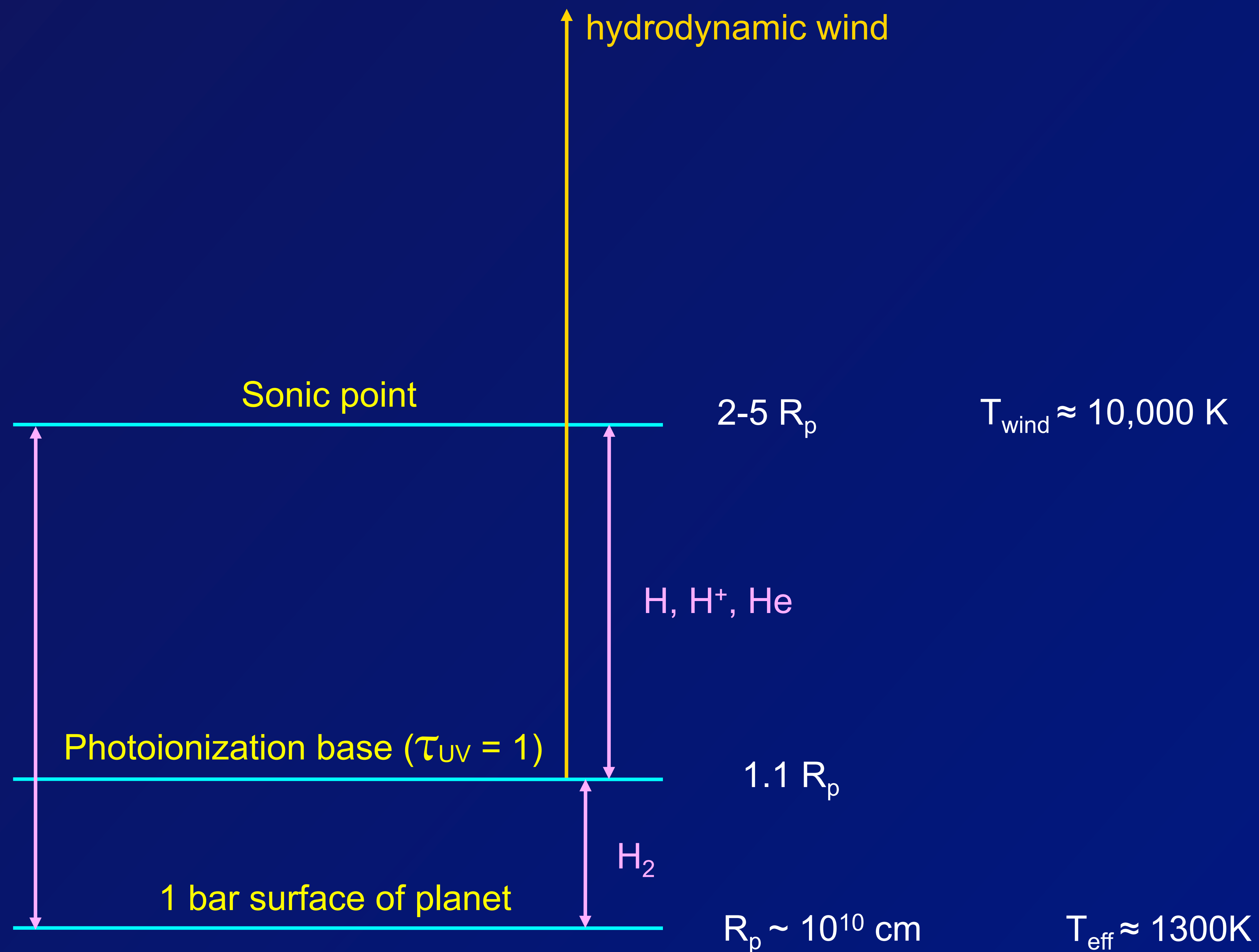
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H, H^+, He
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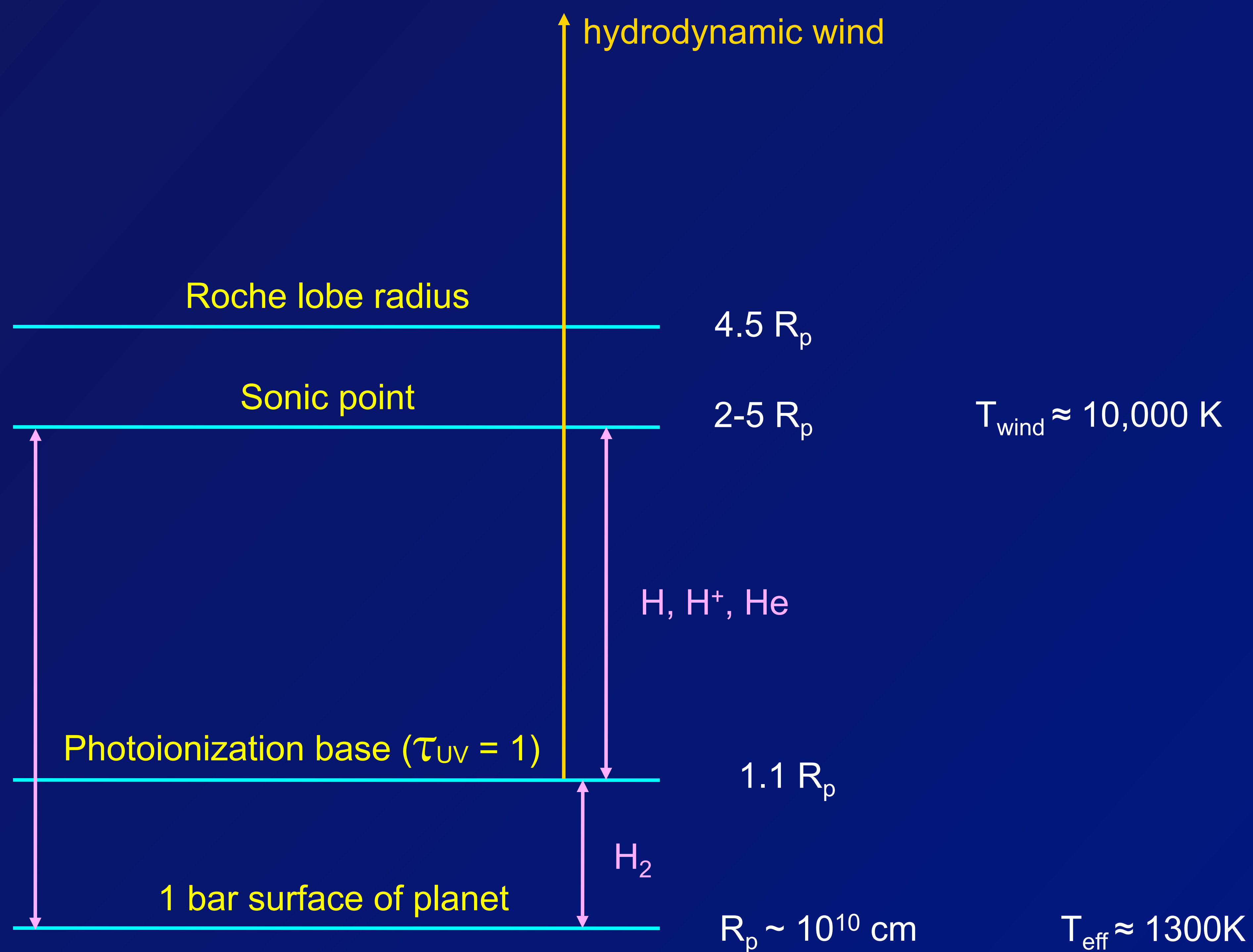
hydrodynamic wind
Roche lobe radius
4.5 R_p
Sonic point
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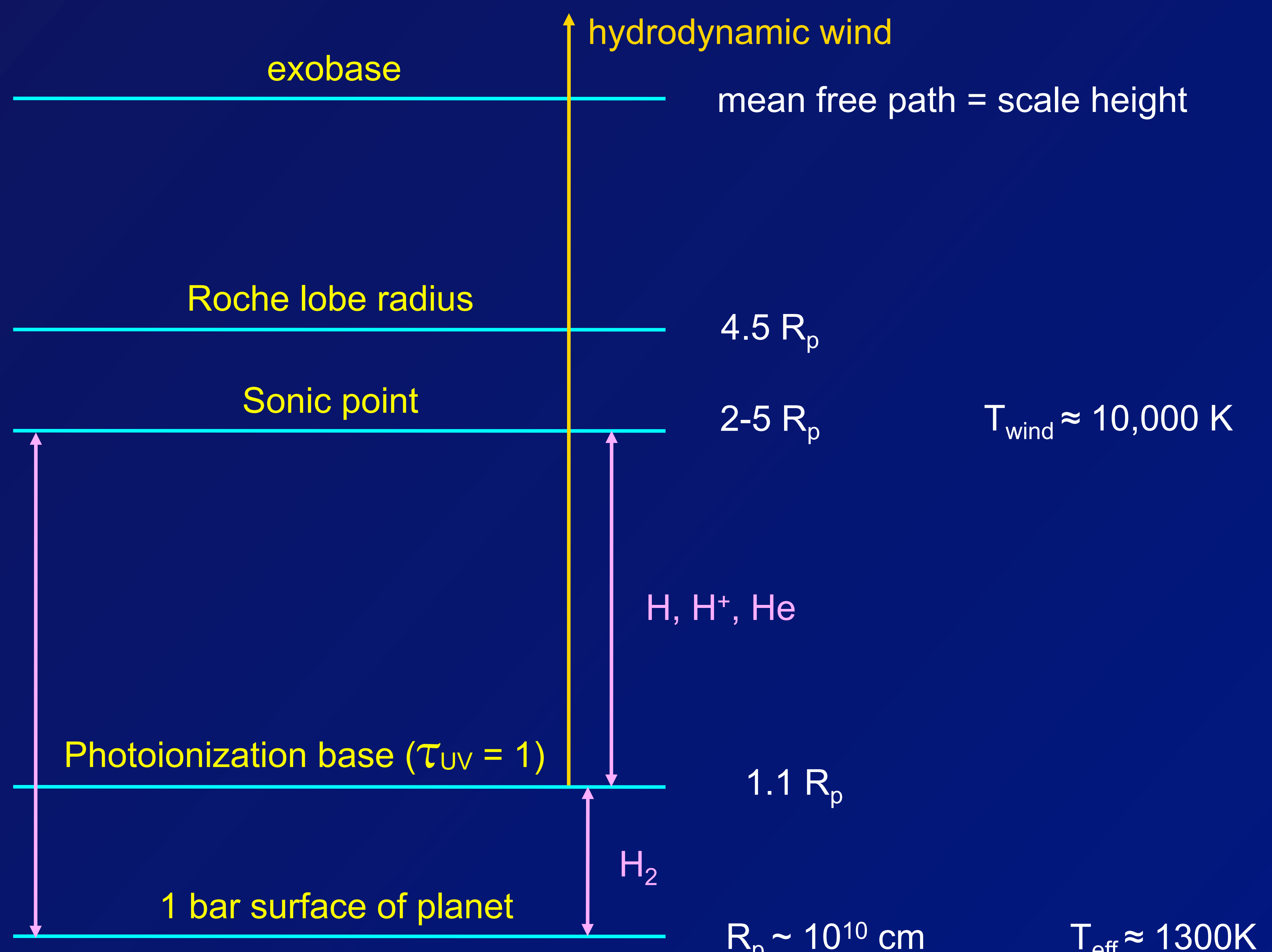

hydrodynamic wind
exobase
mean free path = scale height
Roche lobe radius
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Hydrodynamic Escape Equations

Mass continuity: $$\frac{\partial}{\partial r}(r^2 \rho v) = 0$$

Momentum: $$\rho v \frac{\partial v}{\partial r} = -\frac{\partial P}{\partial r} - \frac{G M_{\rm p} \rho}{r^2} + \frac{3 G M_* \rho r}{a^3}$$

Energy: $$\rho v \frac{\partial}{\partial r}\left[\frac{kT}{(\gamma-1)\mu}\right] = \frac{kTv}{\mu}\frac{\partial \rho}{\partial r} + \epsilon F_{\nu_0} e^{-\tau} a_{\nu_0} n_0 + \Lambda$$

Ionization equilibrium:

$$n_0 \frac{F_{\nu_0} e^{-\tau}}{h\nu_0} a_{\nu_0} = n_+^2 \alpha_{\rm rec} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 n_+ v)$$

Solved using a relaxation code

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Photoionization heating
+ Lyα cooling

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Solved using a relaxation code

Consistently solves ionization and energy equations.
Can be used for different regimes.

General boundary conditions

- Critical (sonic) point of transsonic wind (2 conditions)
- ionization fraction at depth is small
- density at depth is large enough that $\tau >> 1$
- temperature at depth is $< 10^4$ K
- self consistent optical depth to ionization

Solution for the current HD 209458b

Murray-Clay et al. 2009

$M_p = 0.7\ M_J$

$R_p = 1.4\ R_J$

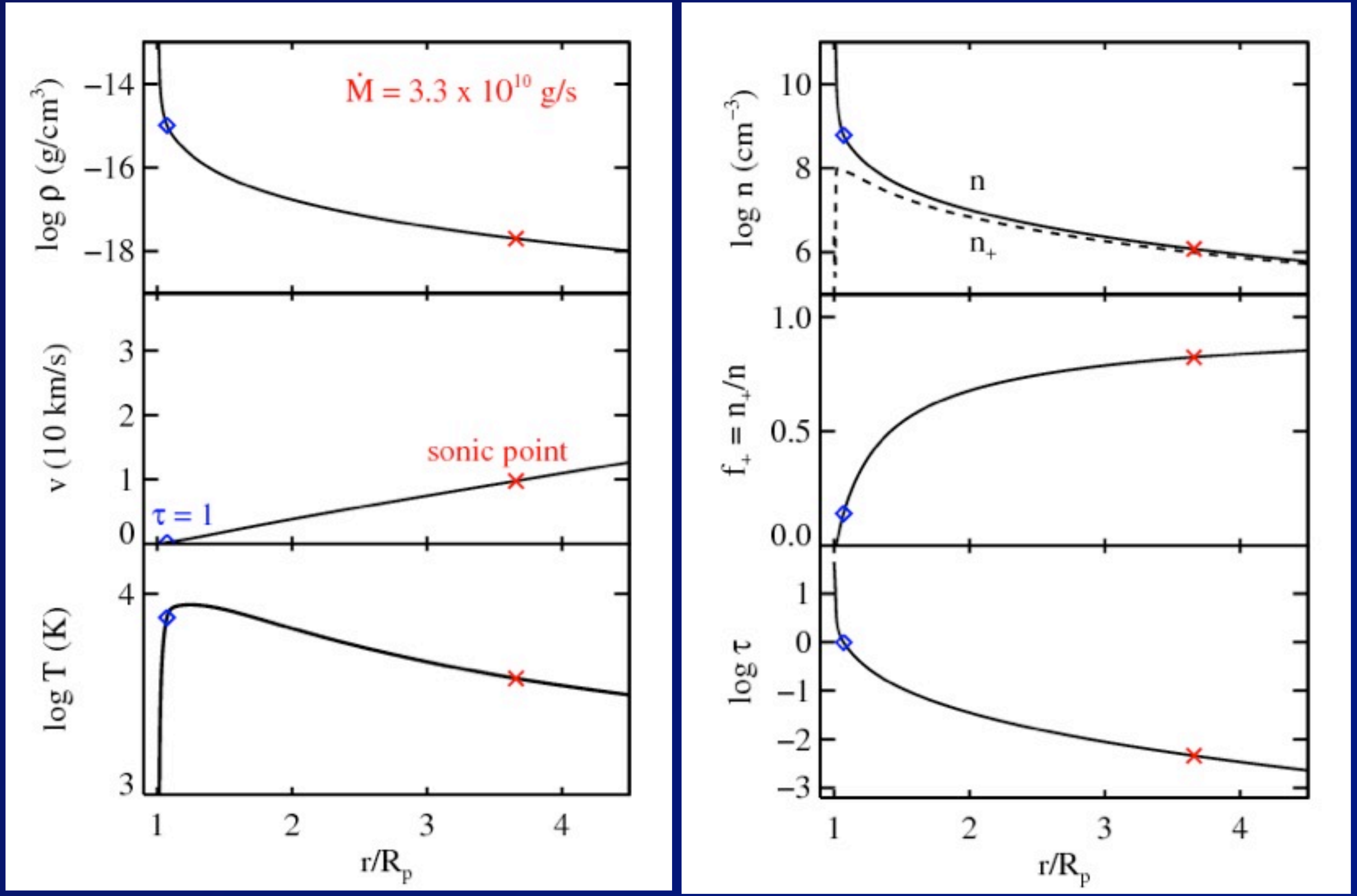
$h\nu_0 = 20\text{eV}$

$\rho_{base} = 4\times10^{-13}$ g

$T_{base} = 1000$ K

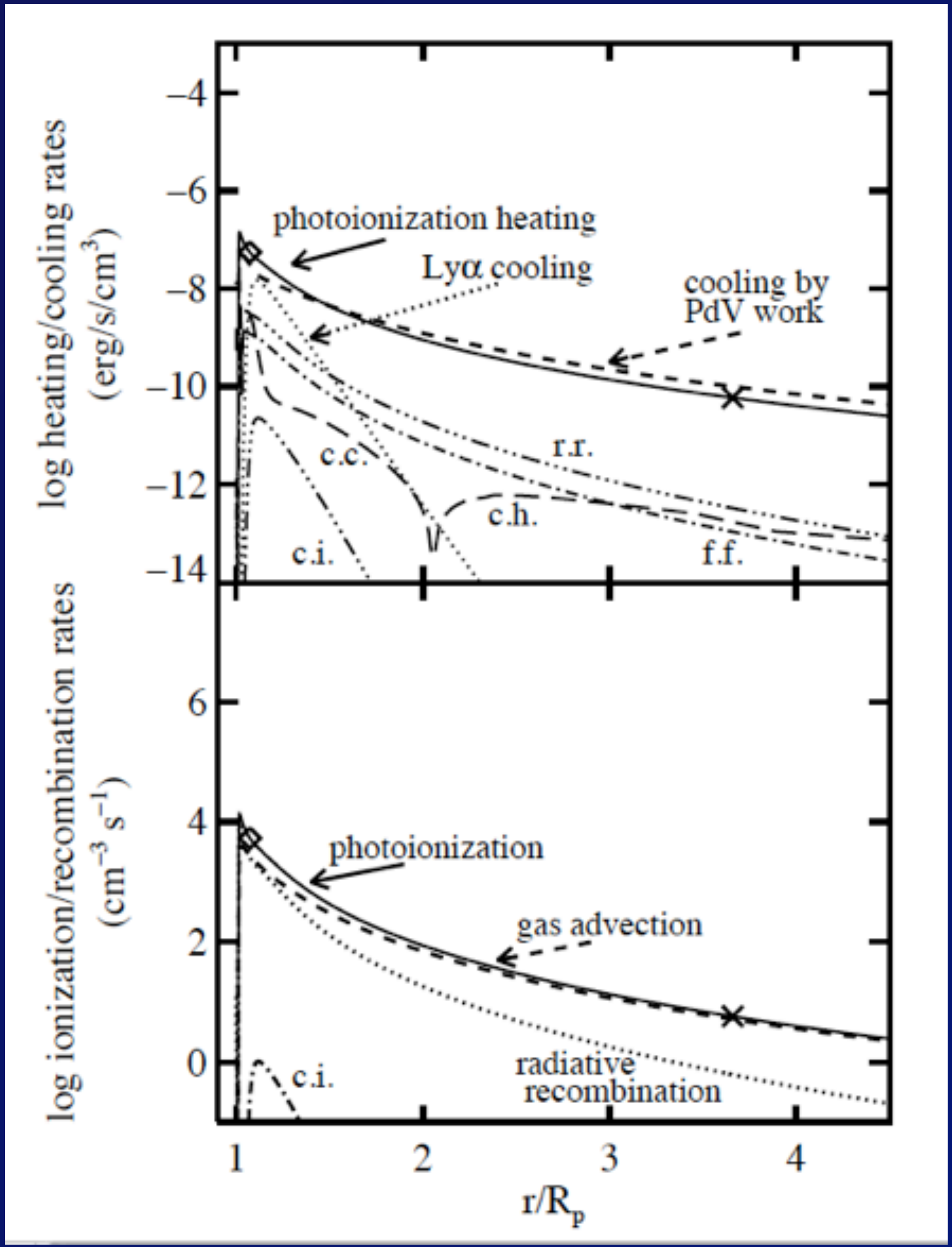
$f_{base} = 10^{-5}$

$\tau_{sp} = 0.0046$

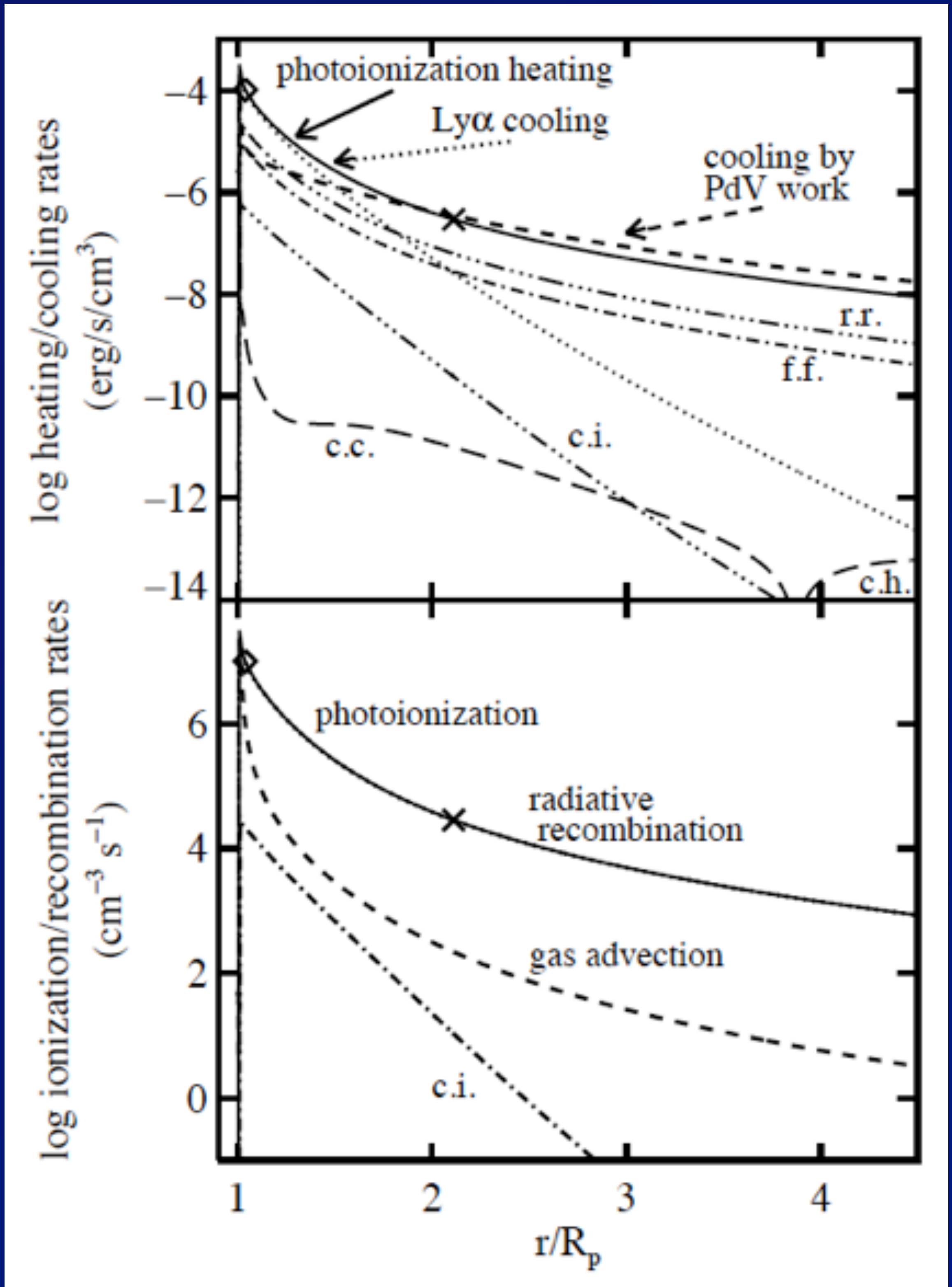


$F_{UV} = 450$ erg/cm²/s

Energy and ionization balance



Solar FUV



T Tauri FUV

Mass-Loss Rates: Dependence on UV Flux

Murray-Clay et al. 2009

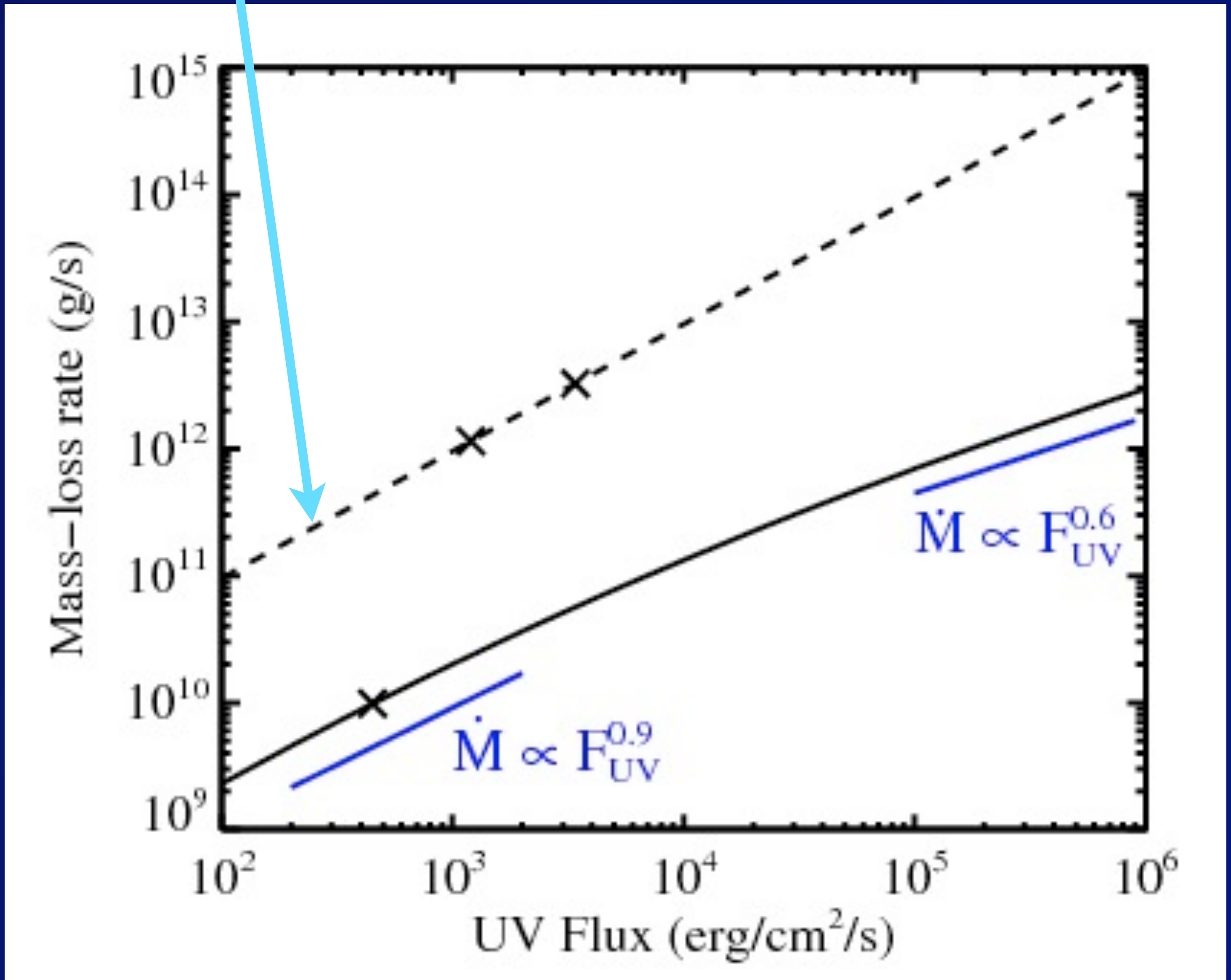
$$\dot{M} = \frac{\pi F_{\rm UV}(3R_{\rm P})^3}{GM_{\rm p}}$$

$\dot{M} \sim 3 \times 10^{12} \mathrm{g/s}$

HD 209458b:
T Tauri
~ 0.1% loss

HD 209458b:
main sequence
~ 1% loss

$\dot{M} \sim 10^{10}$ g/s



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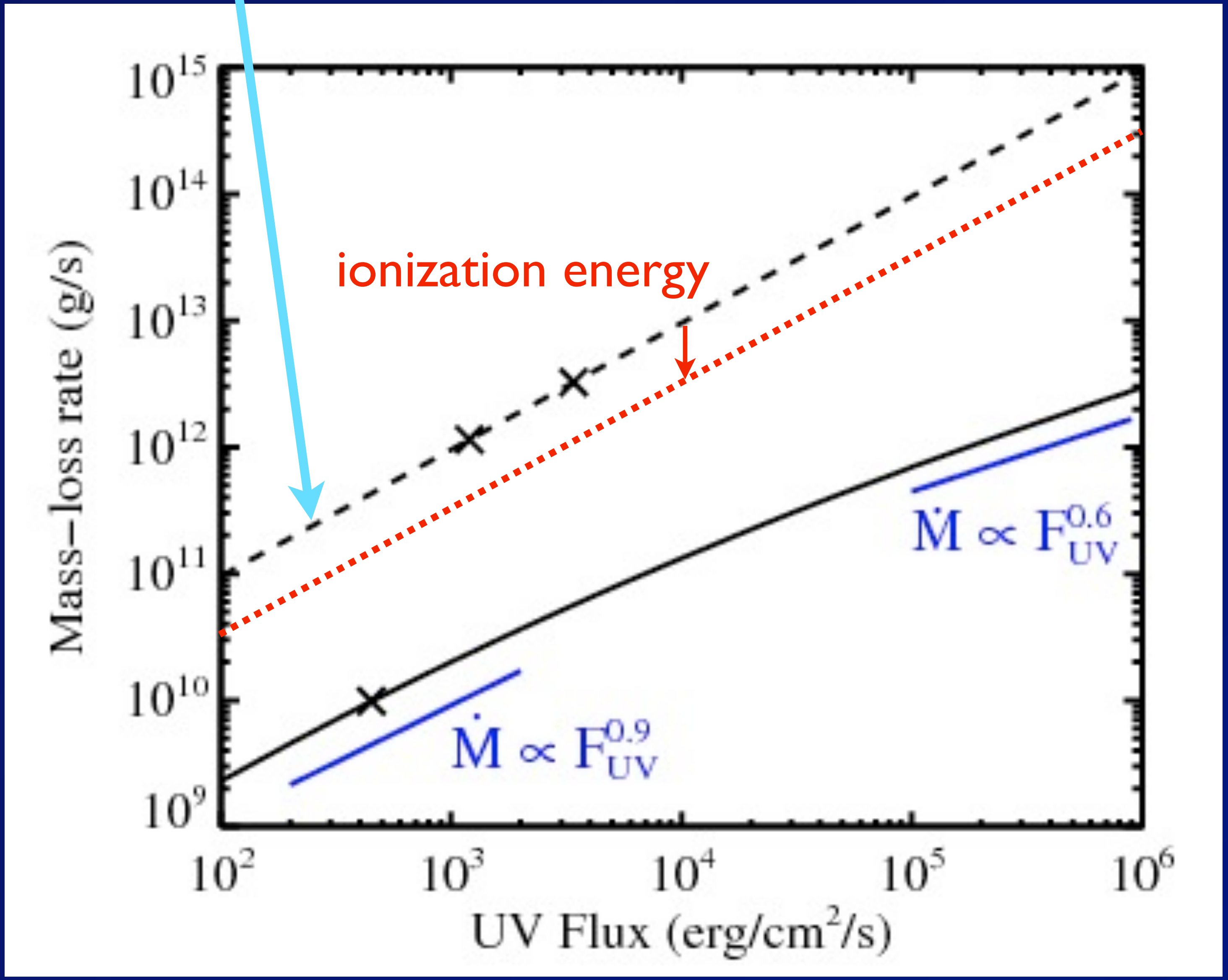

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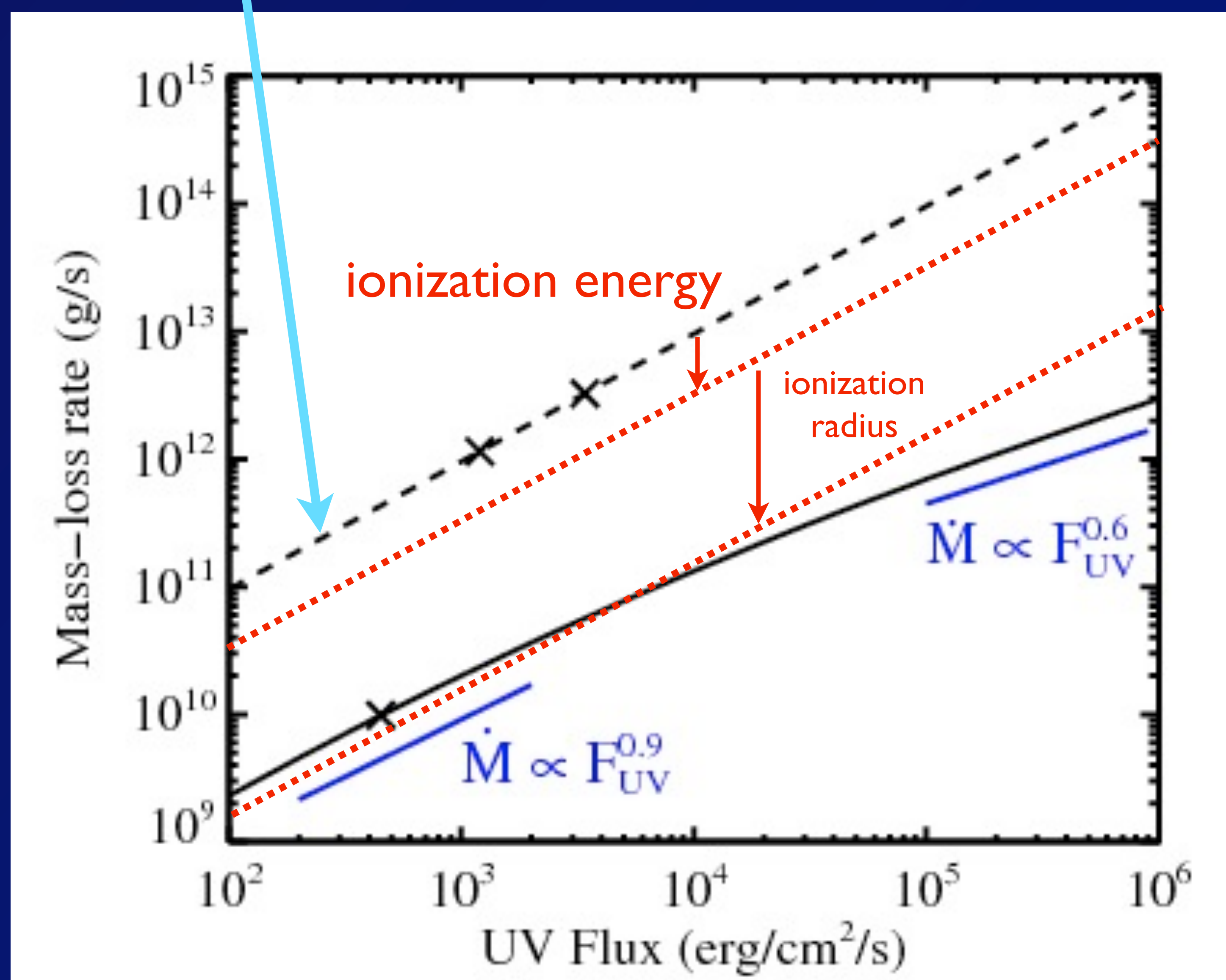

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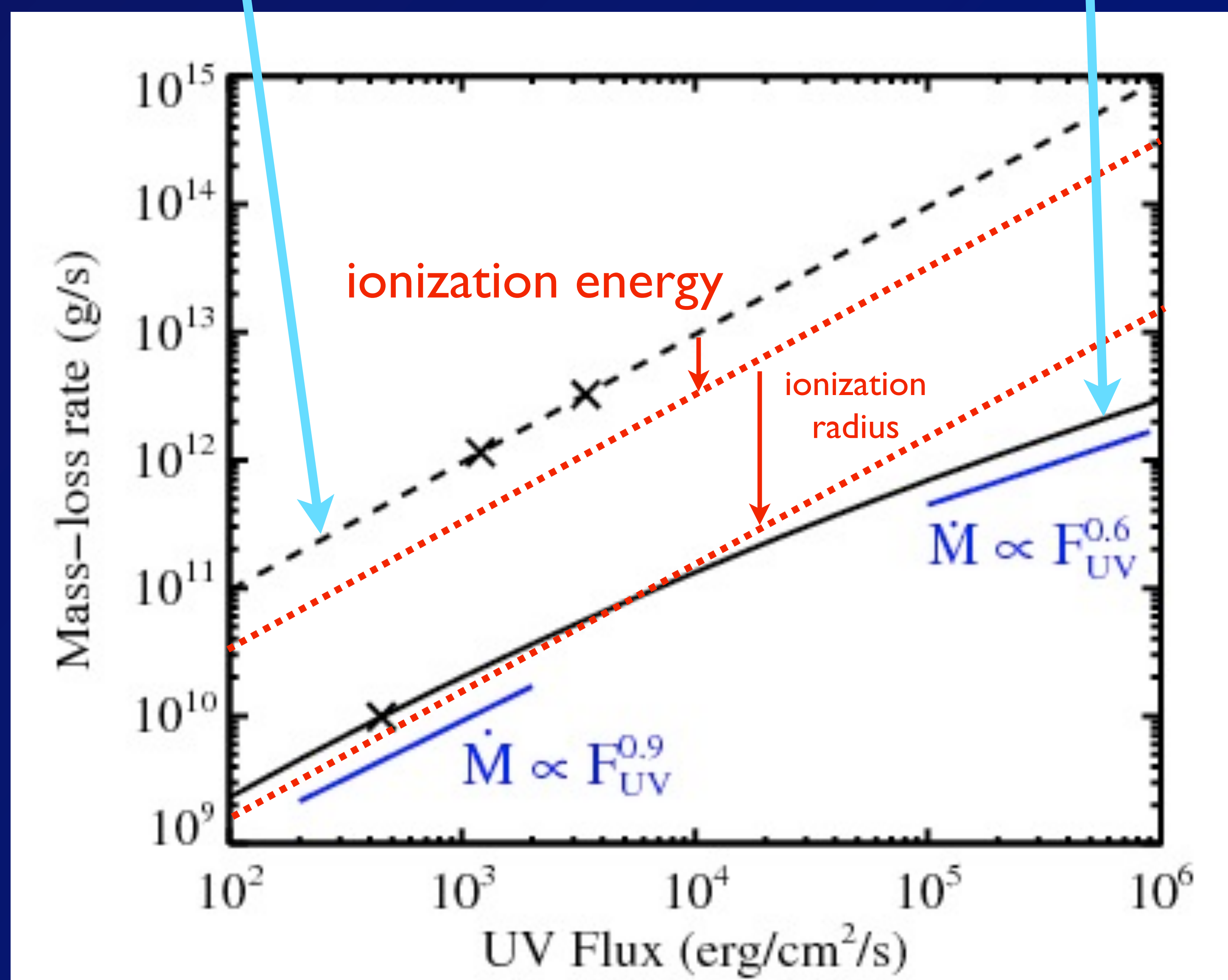
Lyα cooling



HD 209458b:
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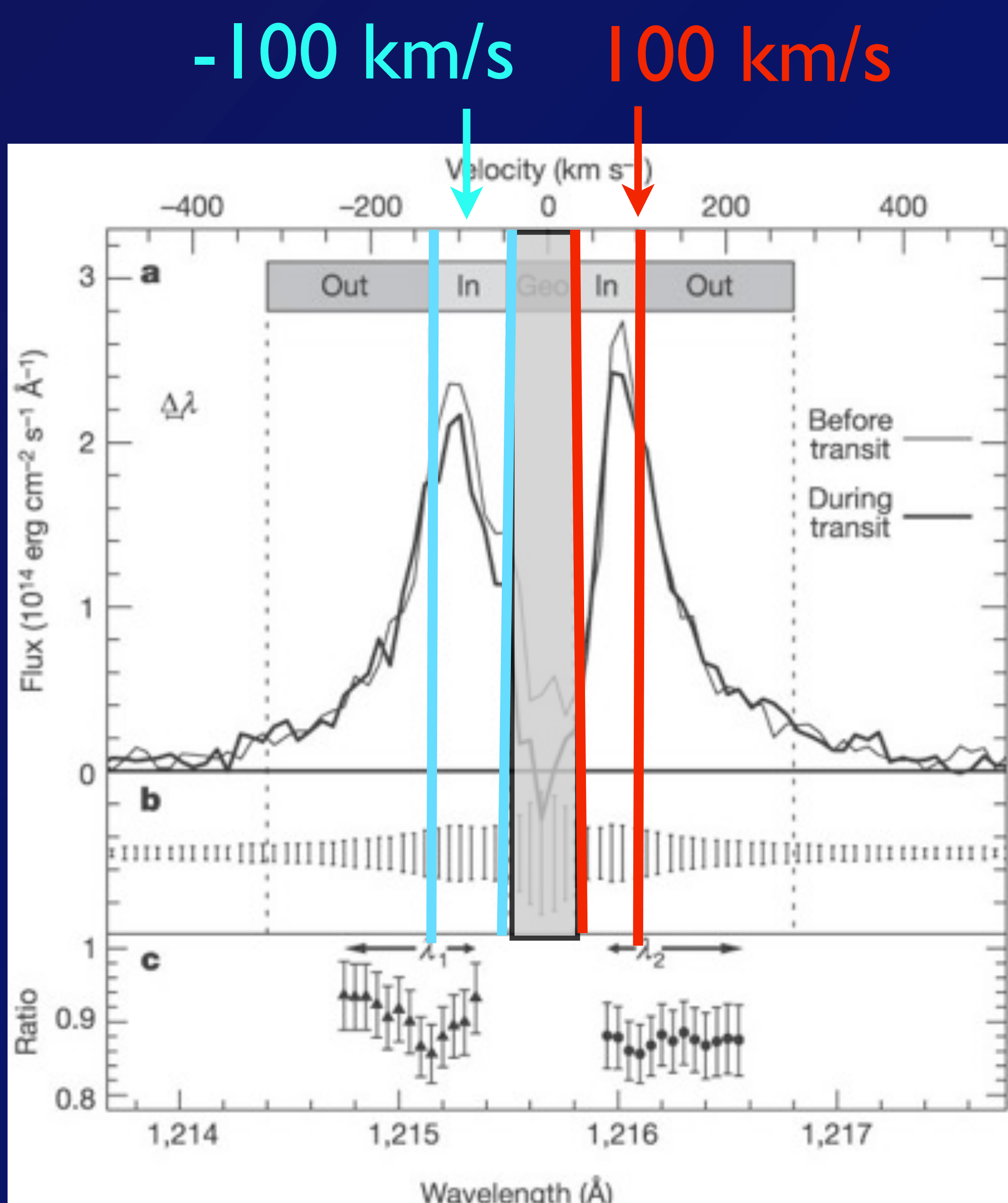
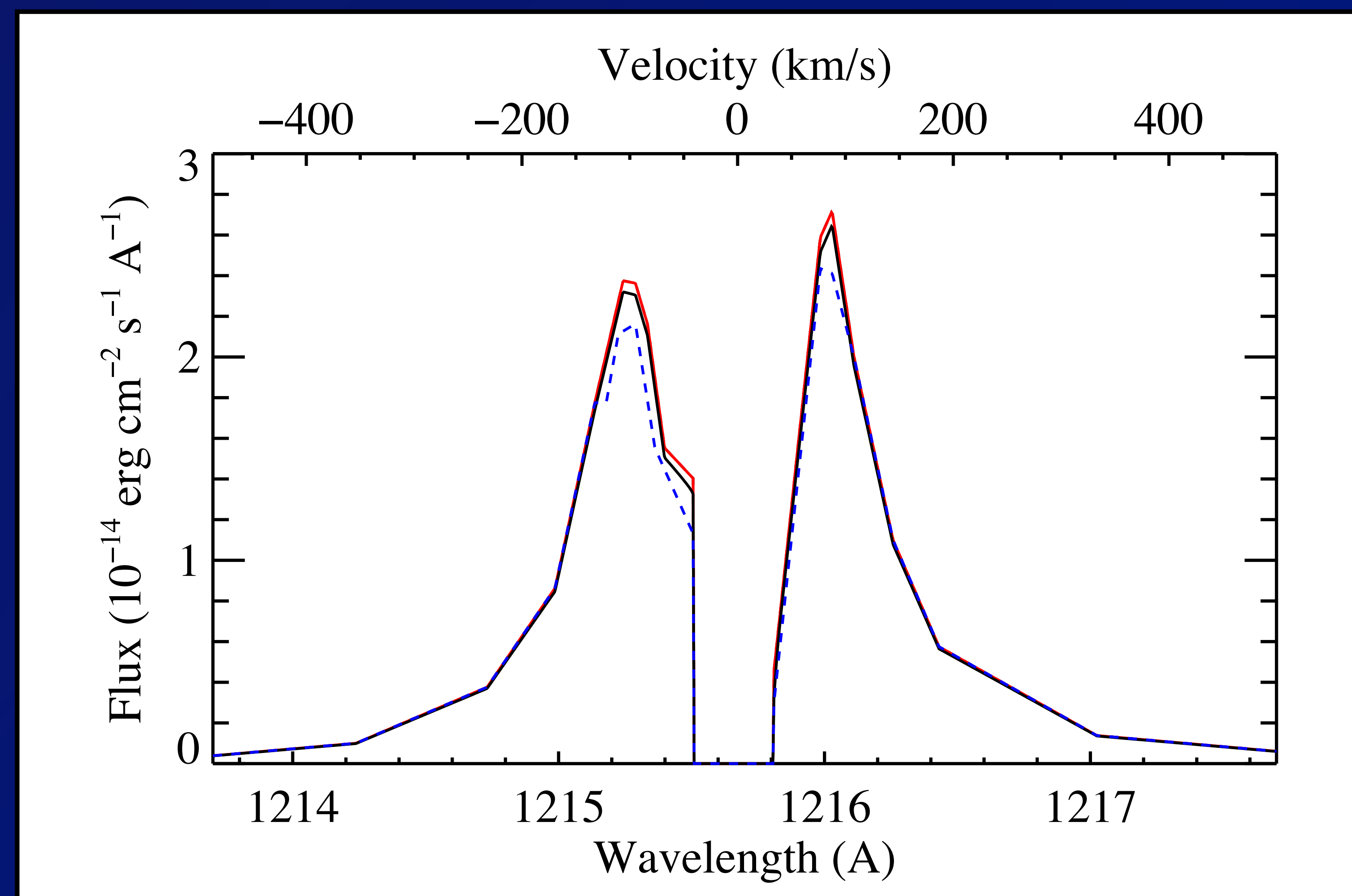
$$\dot{M} \sim 10^{10}\ \mathrm{g/s}$$

The wind cannot directly generate enough absorption at ±100 km/s to reproduce measurements of HD 209458b.

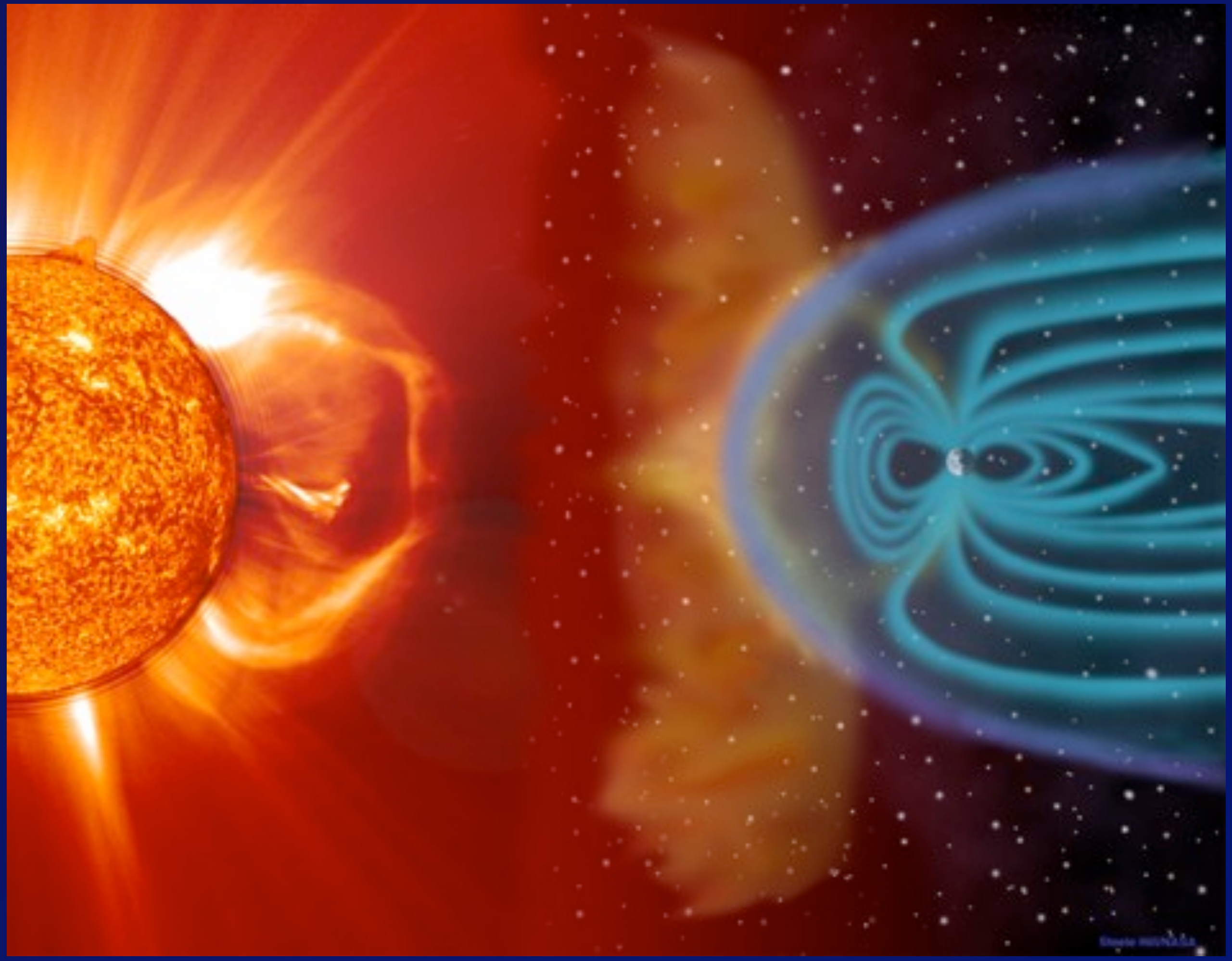


Vidal-Madjar et al. 2003



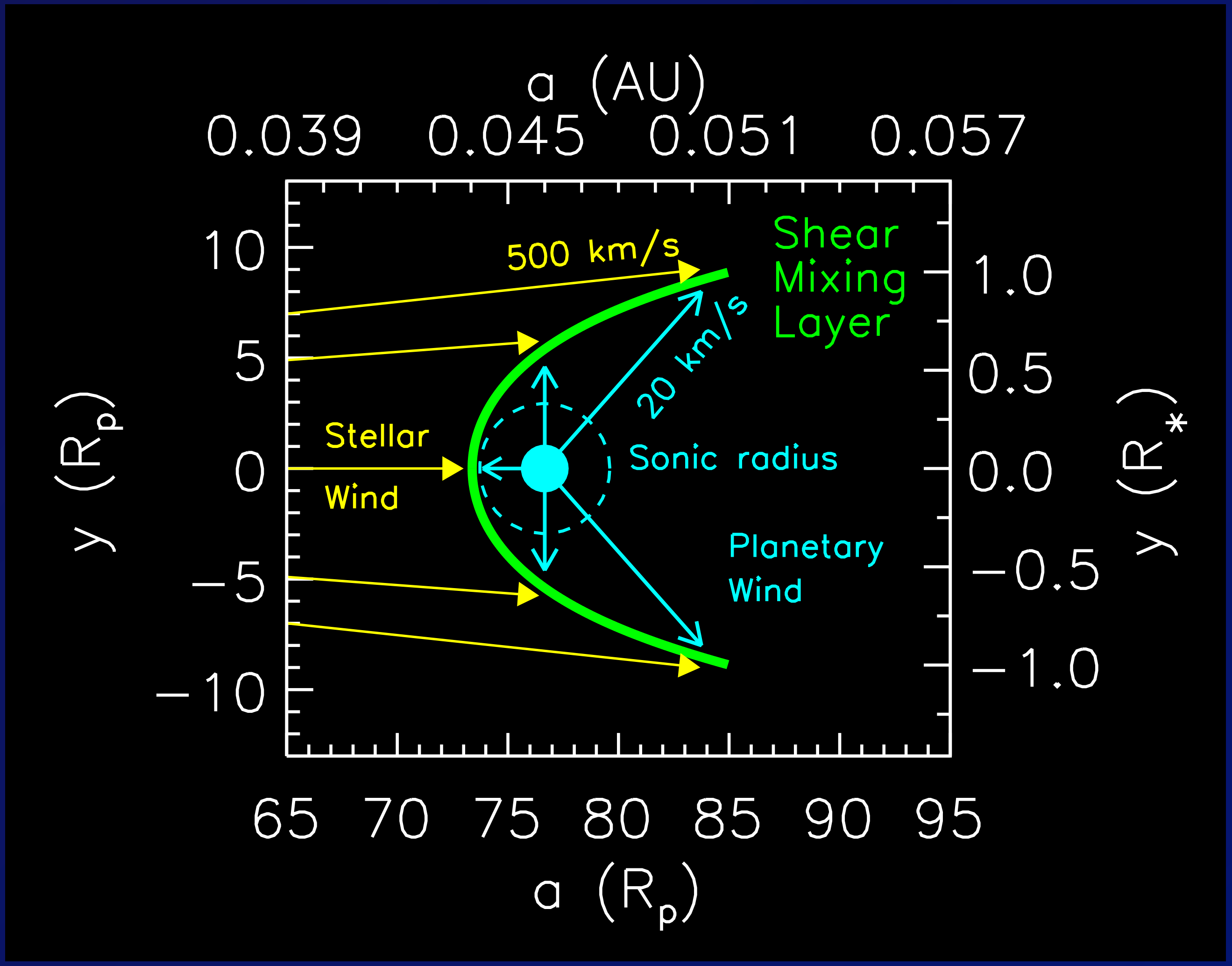
Murray-Clay, Chiang, & Murray 2009

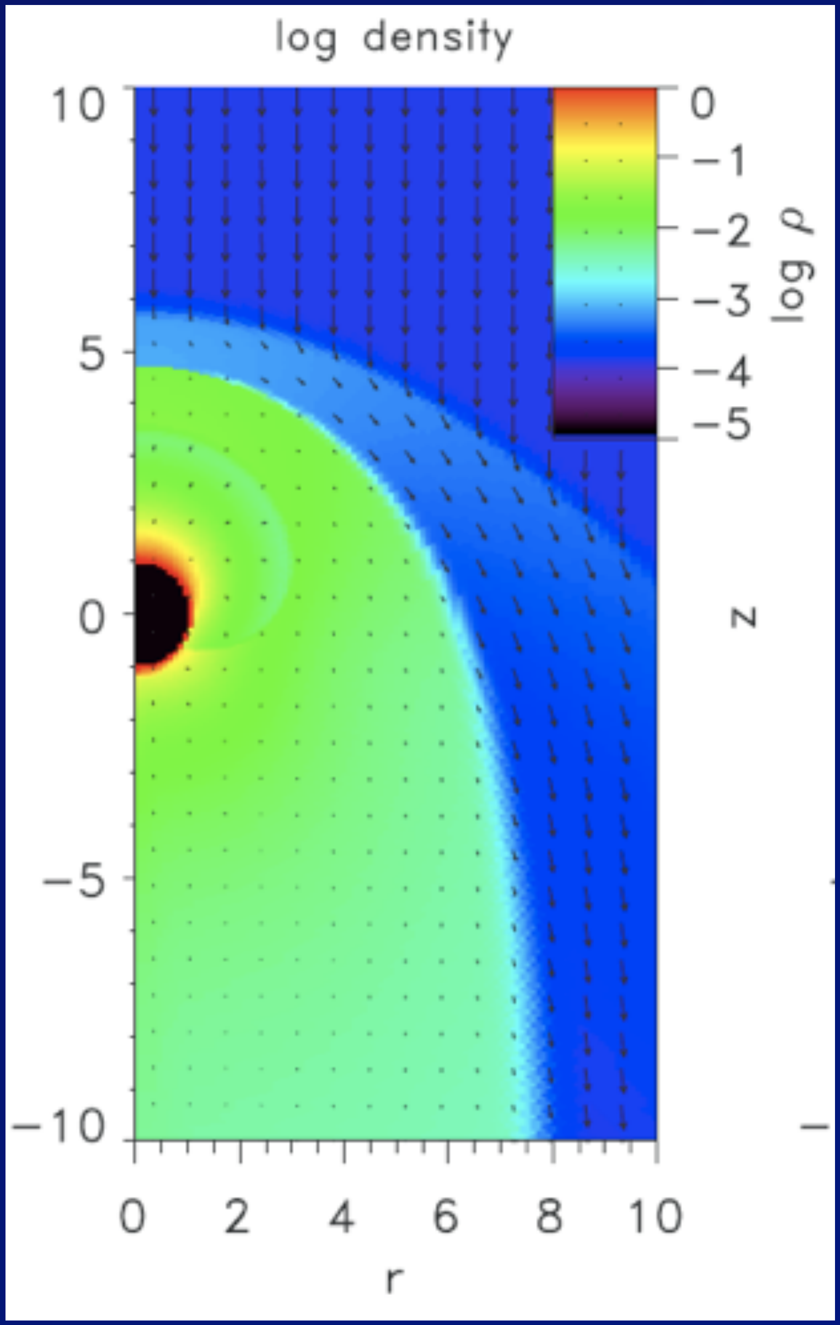
What about the stellar wind and the planetary magnetic field?



NASA

NASA



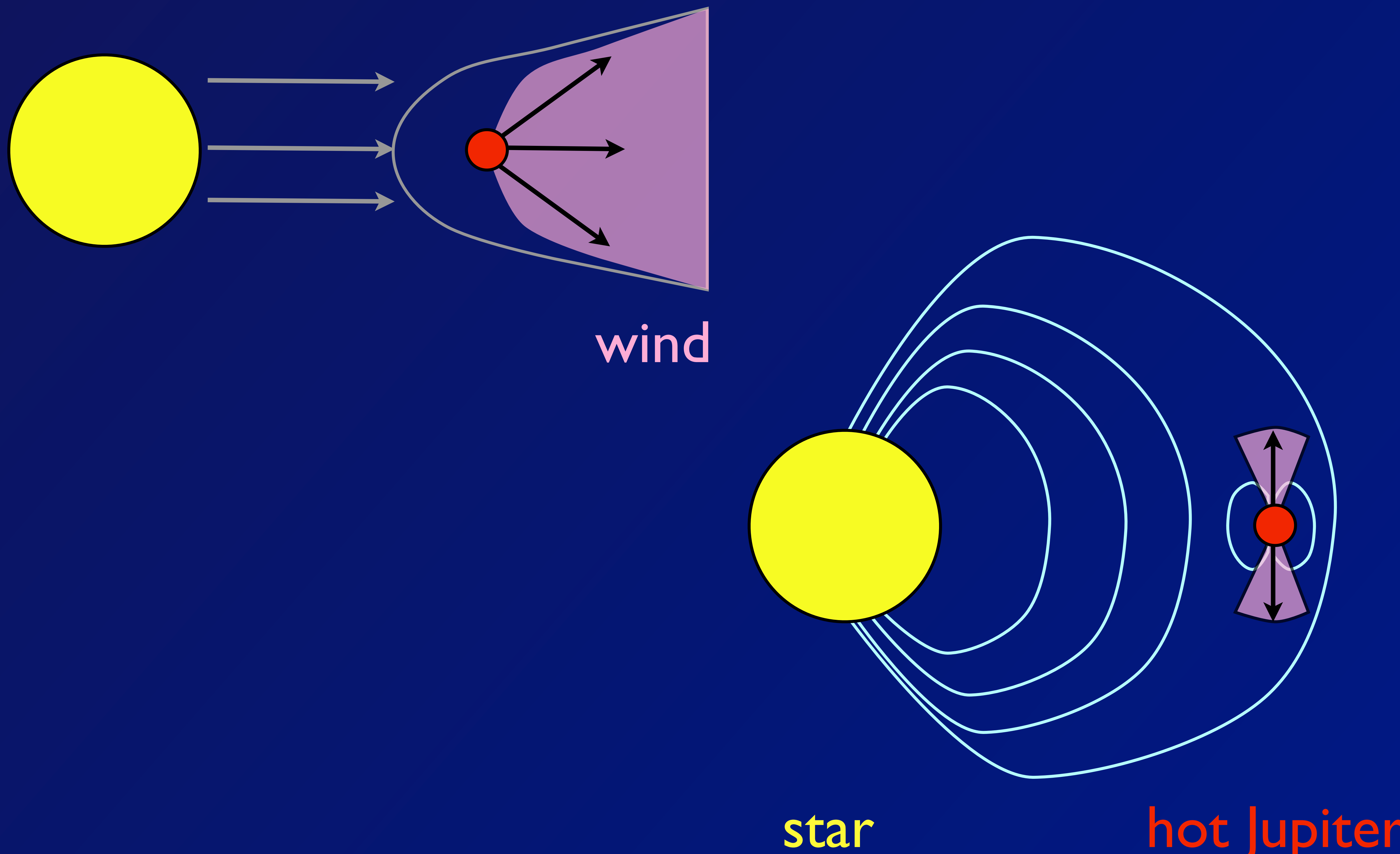


Stone & Proga 2009

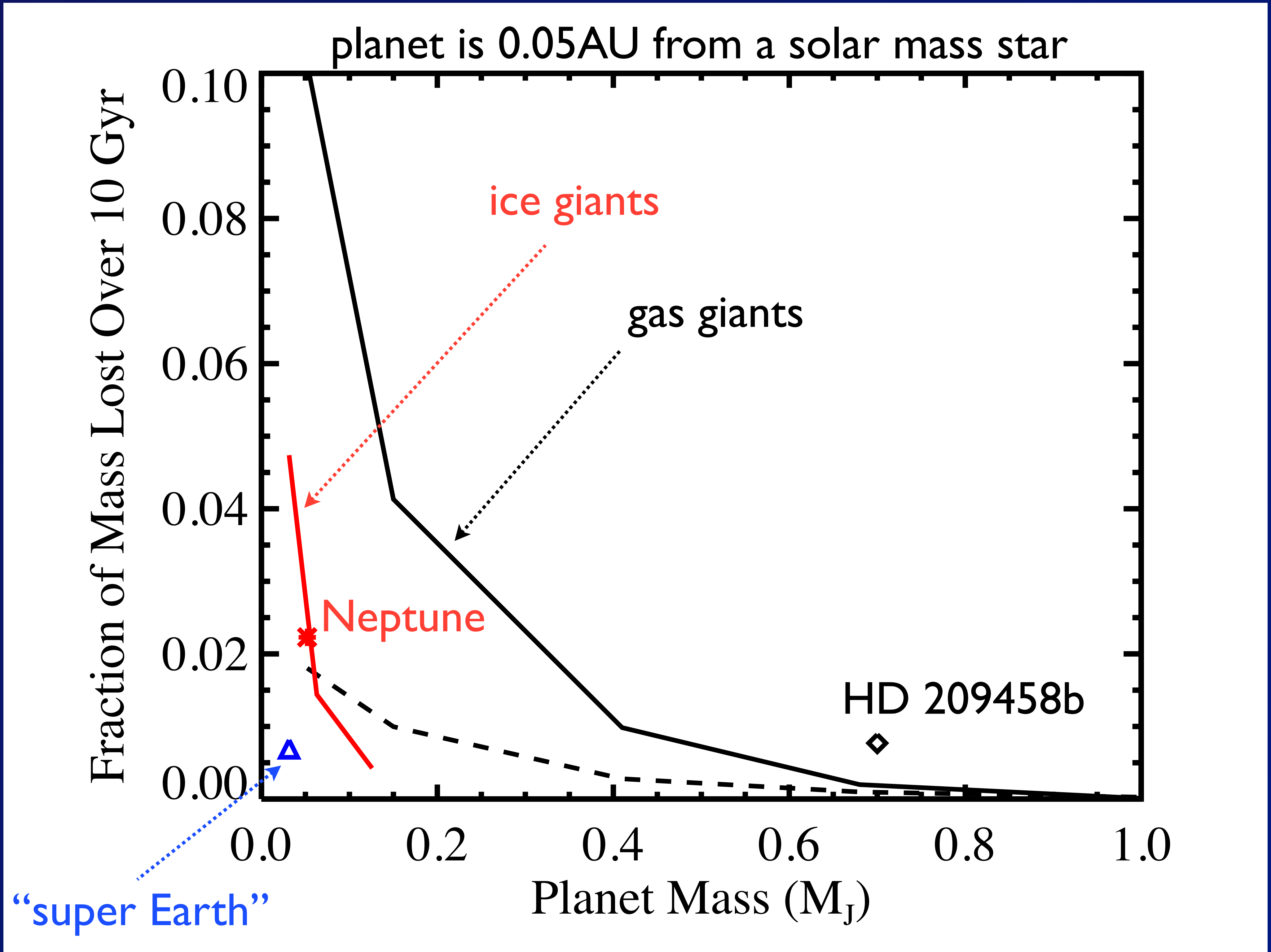
Possibilities to explain the observations:

- charge-exchange in the shock or planetary magnetosphere generates high-velocity neutrals
- 3D effects increase the neutral column

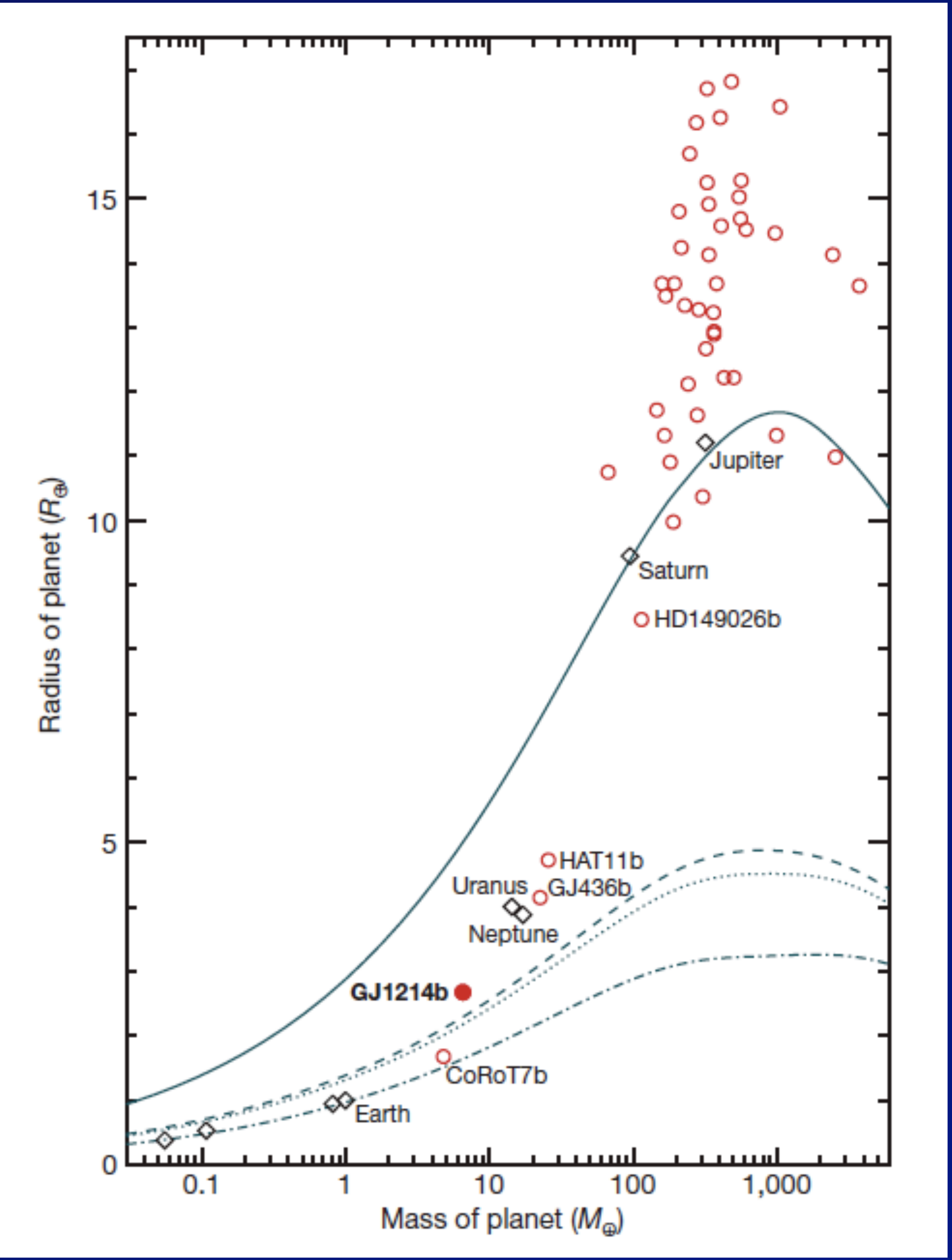
Both the stellar wind ram pressure and magnetic fields can reduce and/or shape mass loss



Low mass gas giants and the atmospheres of solid planets can be significantly depleted



Atmospheric escape is crucial to characterization of planetary atmospheres



Charbonneau et al. 2009

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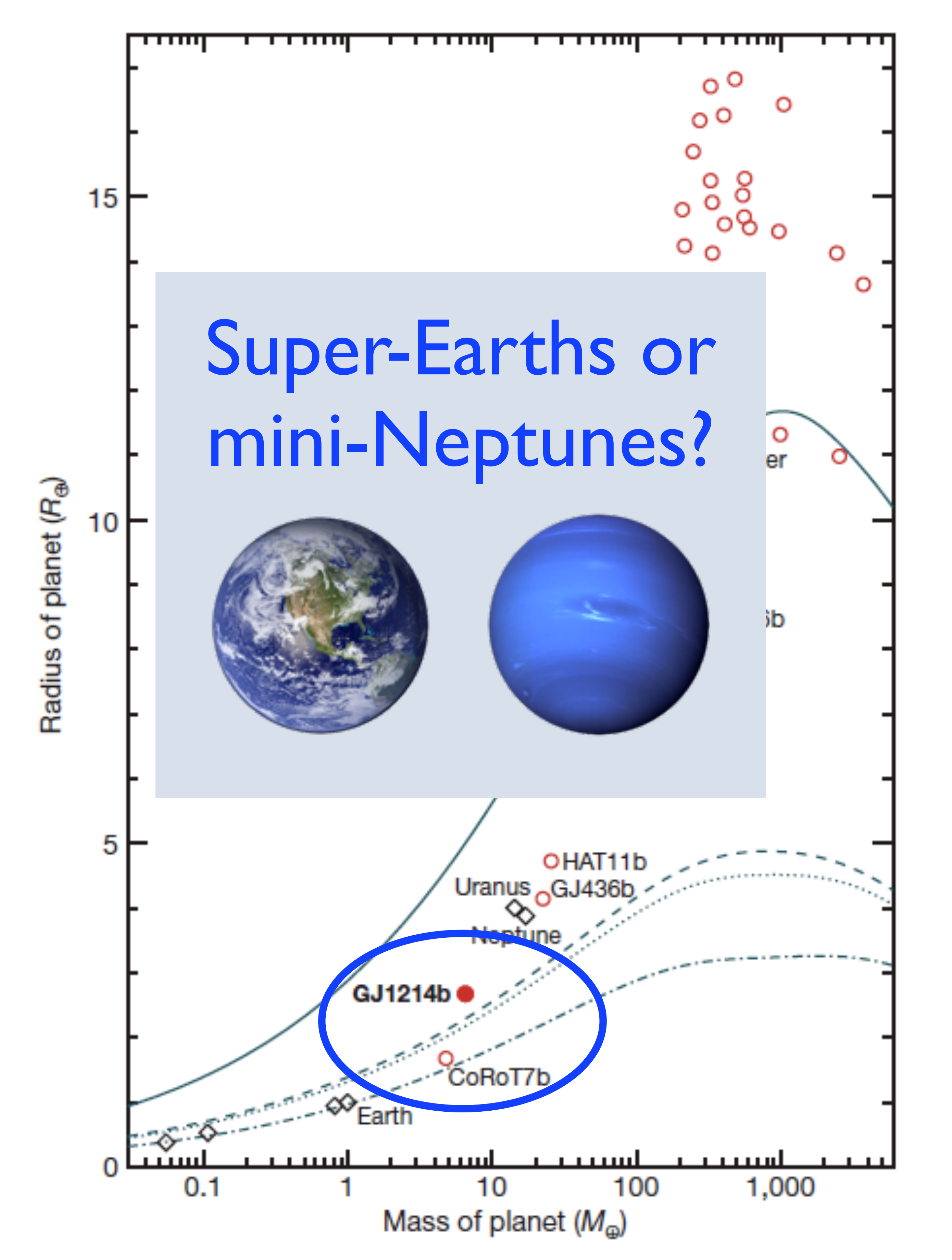

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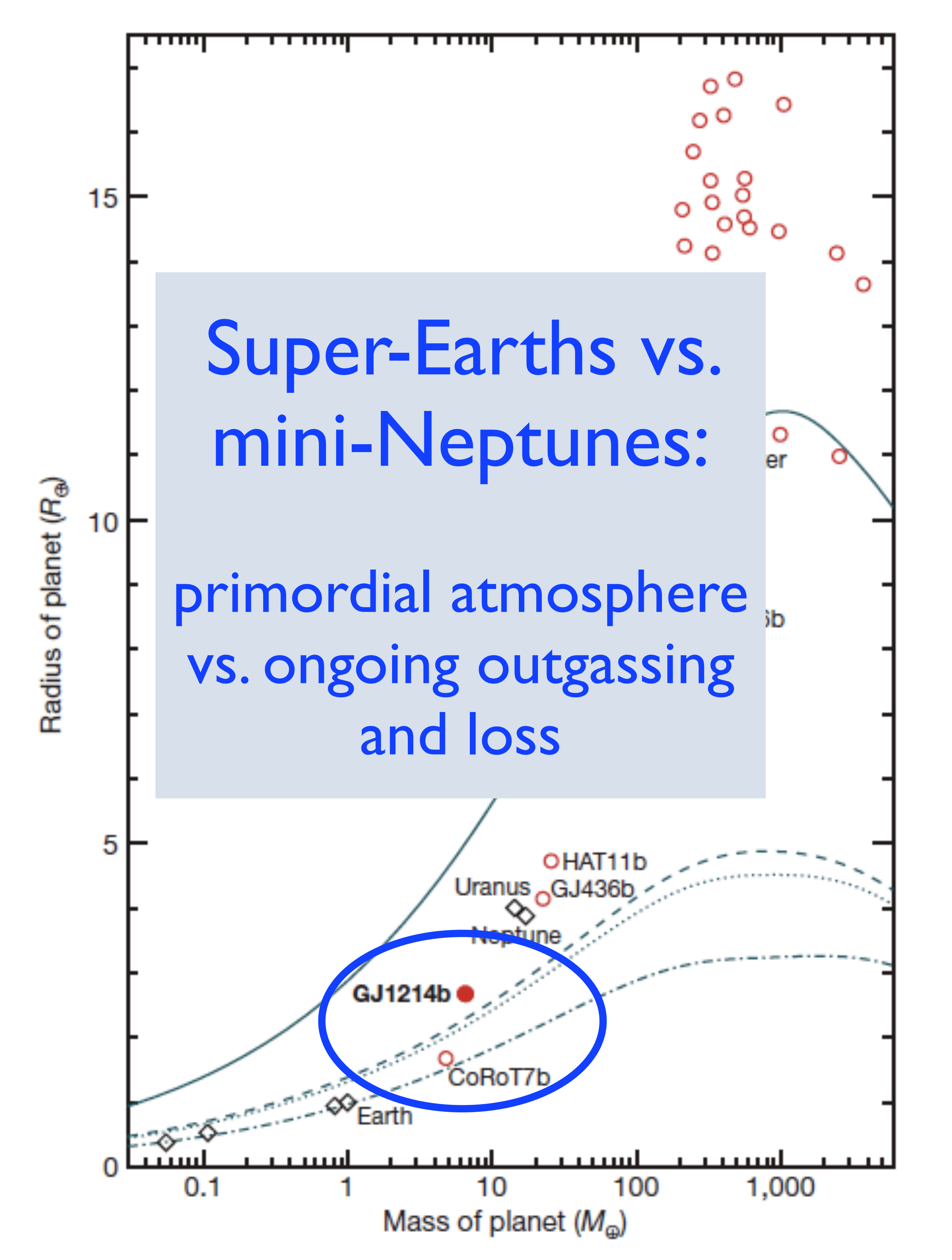

Charbonneau et al. 2009

Summary

- Given UV fluxes typical of hot Jupiters orbiting Sun-like stars, atmospheric escape is ~ hydrodynamic and "energy limited" with $r = R_p$ for observed exoplanets if they have hydrogen-dominated atmospheres, but for smaller radii, beware.
- At lower UV fluxes, beware!
- At higher UV fluxes, beware!
- A practical guide to estimating Mdot for hydrogen-dominated atmospheres given FUV, R_p, and M_p will be available soon.