Photolysis and photoevaporation

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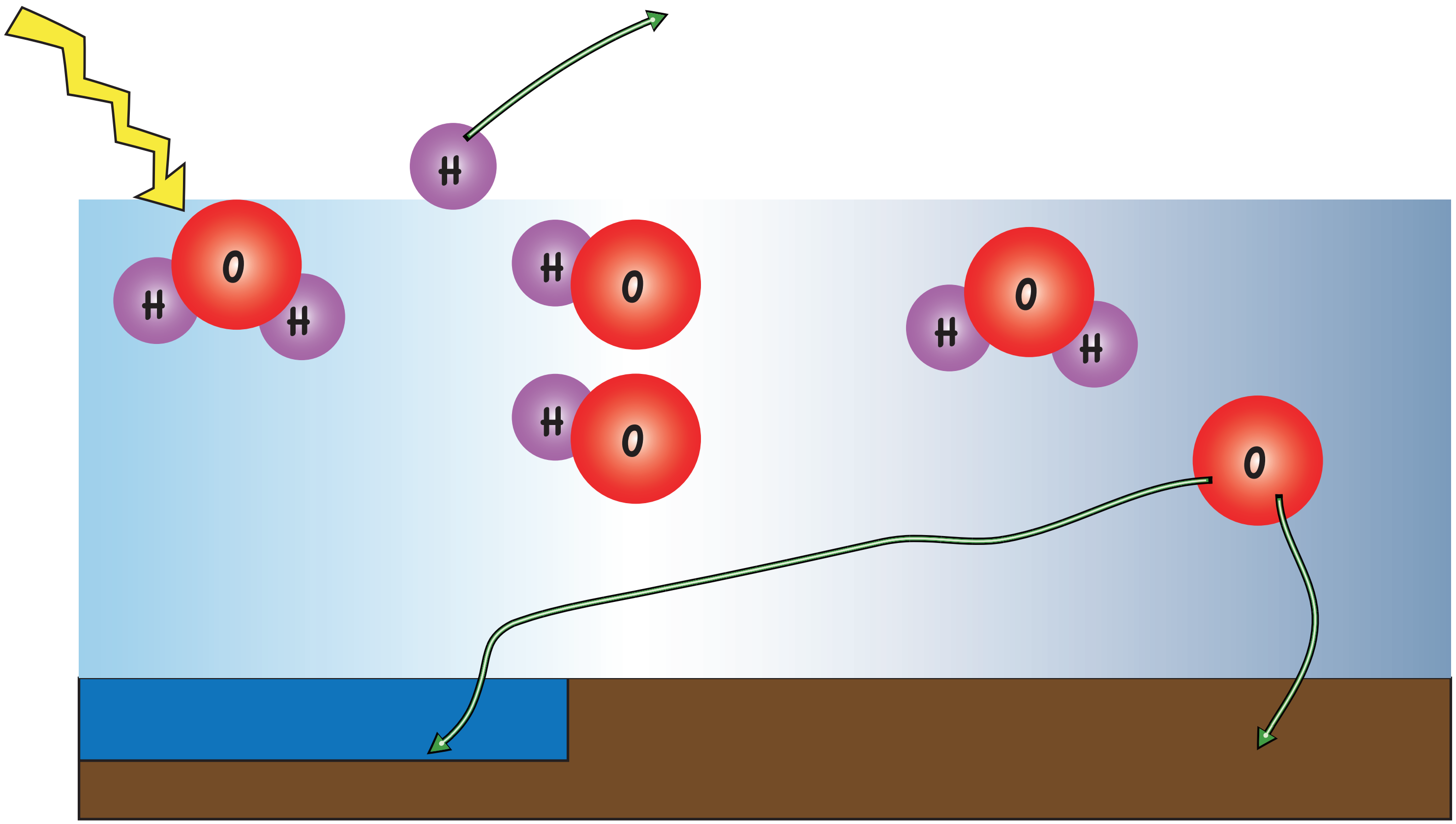
Photoevaporation is ...

Escape of atmospheric constituents from the planet's gravity well...

- ... due to absorption of radiant energy (light) from the planet's star
- (hence *photo*-)
- Escaping mass carries away energy, somewhat like evaporation from a liquid
- (but no phase change involved).

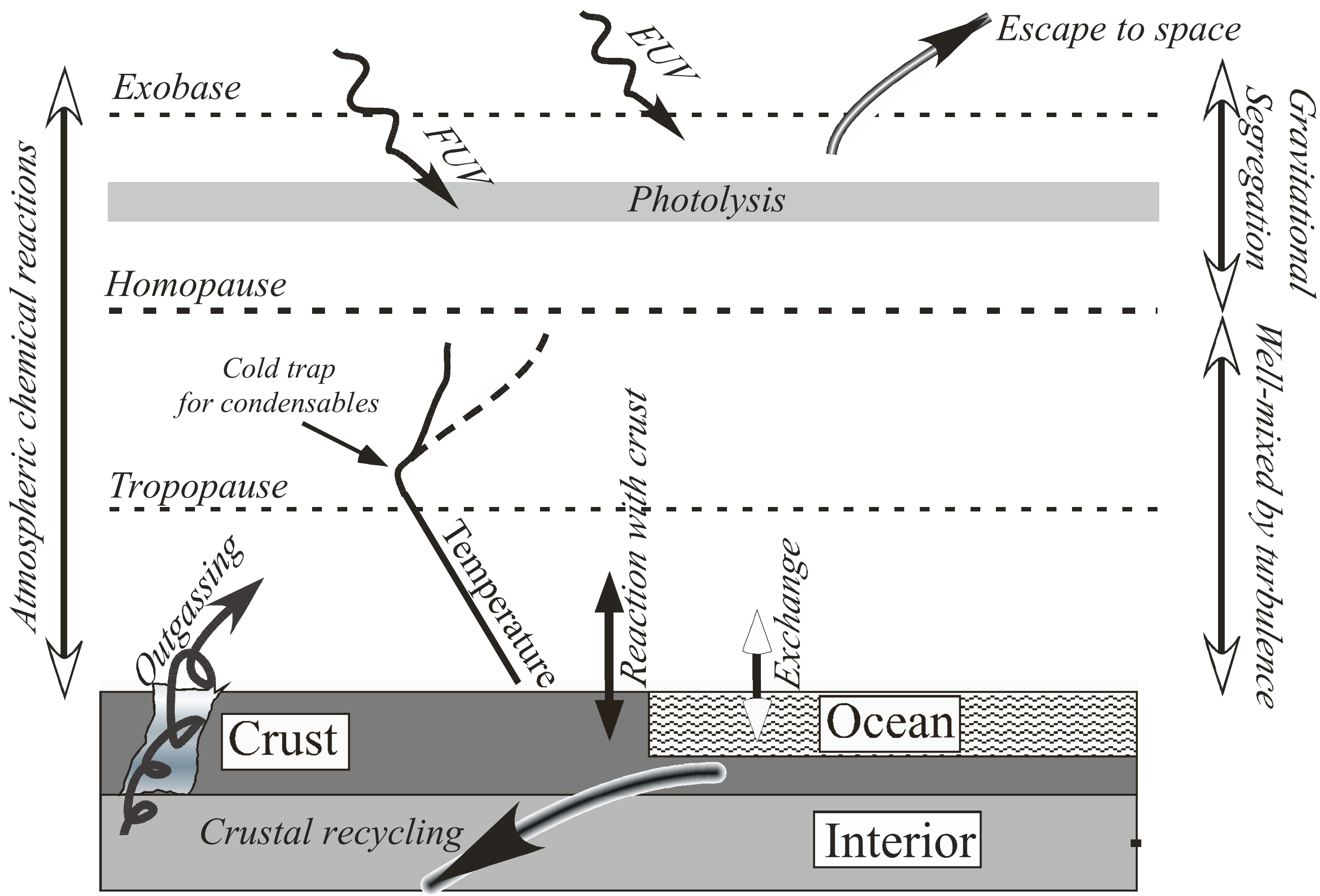
Photolysis is ...

Breakup of heavy molecules into lighter components, due to energy provided by absorption of photons.



Lighter particles escape more easily.

Atmospheric Escape provides upper boundary for evolution of atmospheric and even planetary chemical composition



Why we should care about photoevaporation

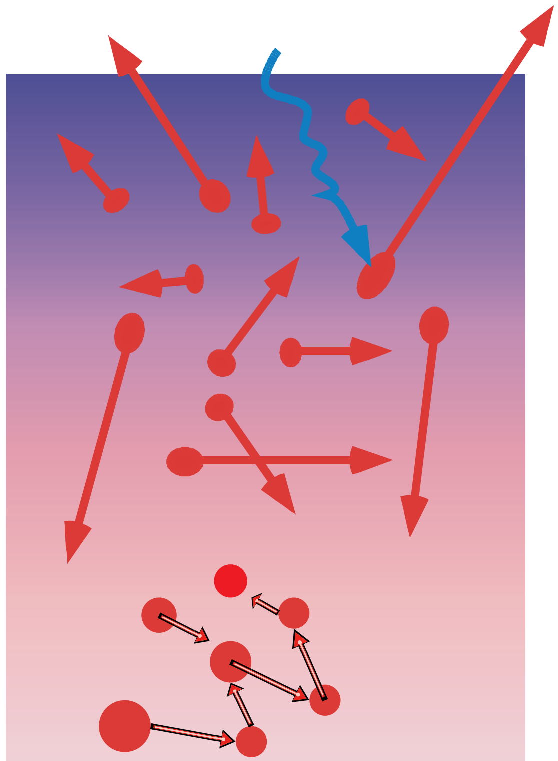
- What could be in atmospheres of hot-close orbit planets, e.g 55 Cancri-e?
- Can M-dwarf habitable zone planets retain an atmosphere?
- Nature of low-density Super-Earths like GJ1214b (cf. Lecture 3)
- Risk of early N_2 loss from M-dwarf habitable zone planets
  Hard to regenerate an N_2 atmosphere by outgassing
  ... but N_2 necessary for life as we know it.
  ... and also shields a planet from water loss.
  (Wordsworth and Pierrehumbert *ApJ* 2013)

Why we should care about hydrogen escape in particular

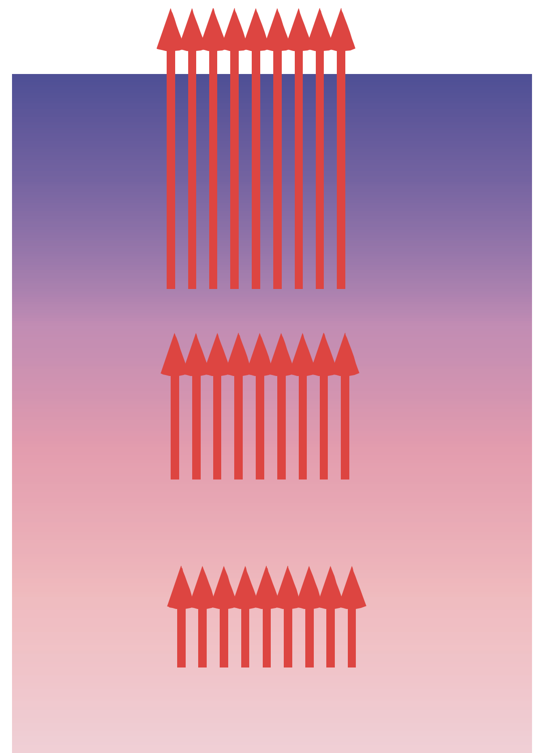
- H escape rate determines concentration of H_2 that can build up in an atmosphere, with implications for:
  - Extended H_2 habitable zone
    (Pierrehumbert and Gaidos, *ApJL*)
  - Early Earth $H_2 - N_2$ greenhouse
    (Wordsworth and Pierrehumbert, *Science*)
  - Pre-biotic synthesis
- Lifetime of Hot Jupiters, density distribution of planets.
- Drives evolution of oxidation state of the planet,
  and even its rocky interior.
- Key role in permanent water loss during a runaway greenhouse
- Planet detection: Atmospheres in blowoff state are very extended, and may be detectable in extrasolar systems via Lyman-α.

It's all about energy

Need to reach escape energy $m \cdot g \cdot r$; many ways to do it.



Random Motion
(thermal or nonthermal)



Organized Flow

A simple energy-limited escape calculation

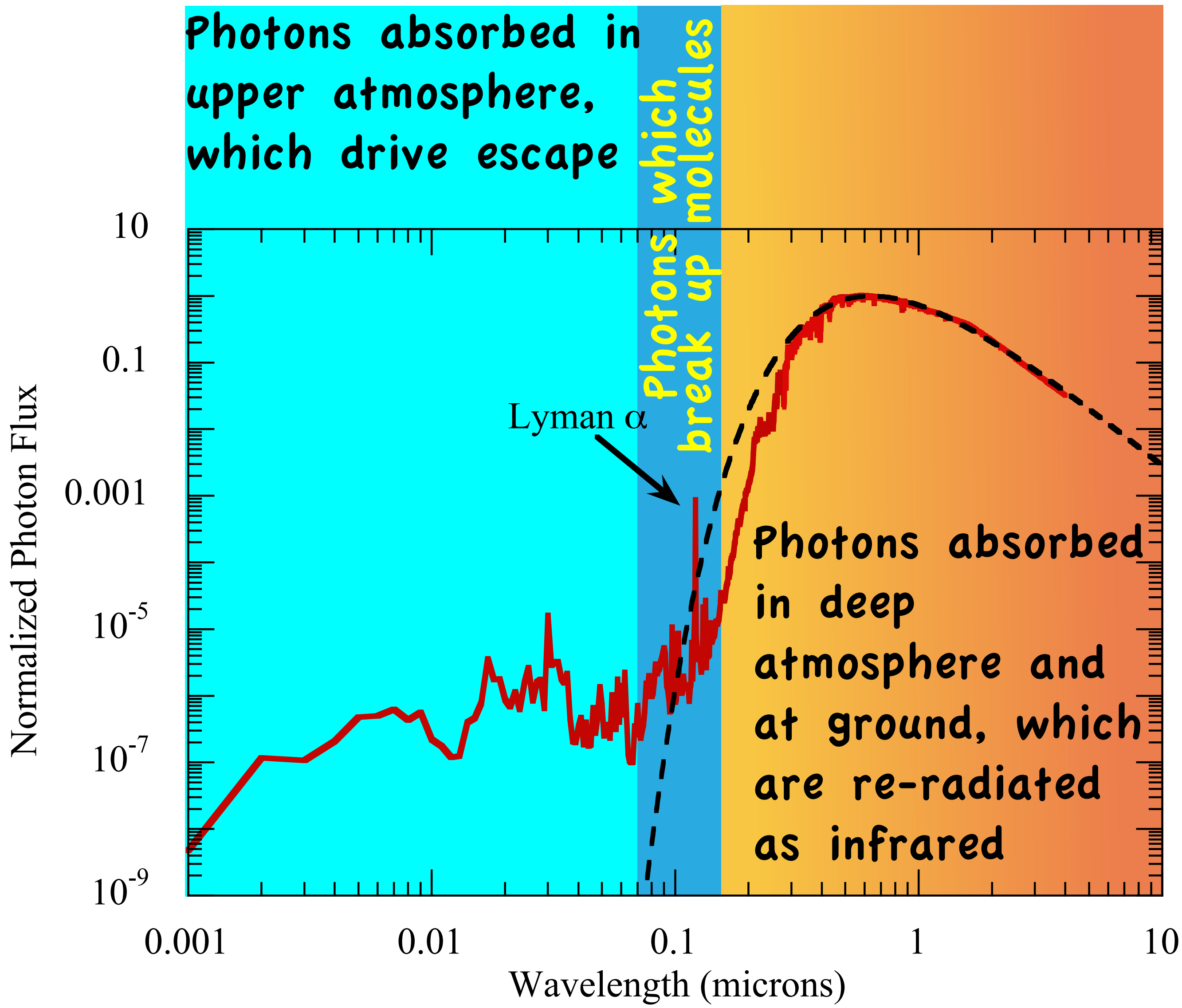
- Potential energy of Earth's atmosphere per square meter of surface

  $$= Mga = p_s a$$

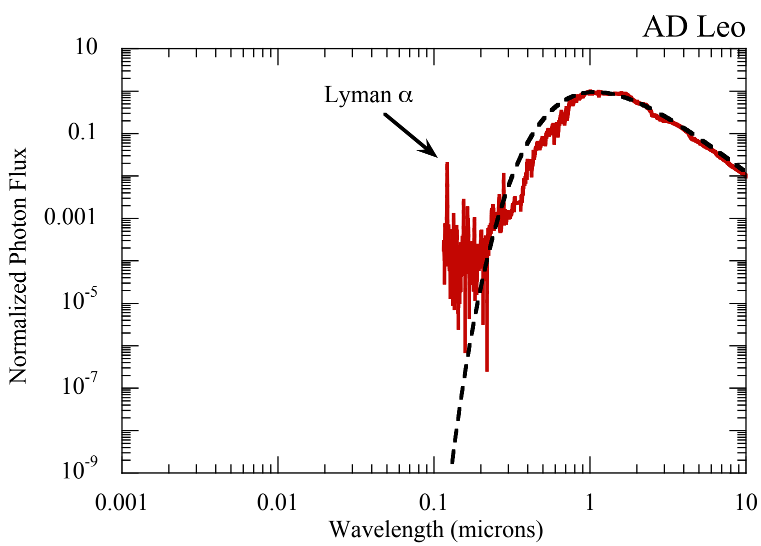
- Energy supplied by solar flux $S \approx 200\mathrm{W/m}^2$
- Enough energy to lose atmosphere in time $t = p_s a/S$
- Only 100 years!

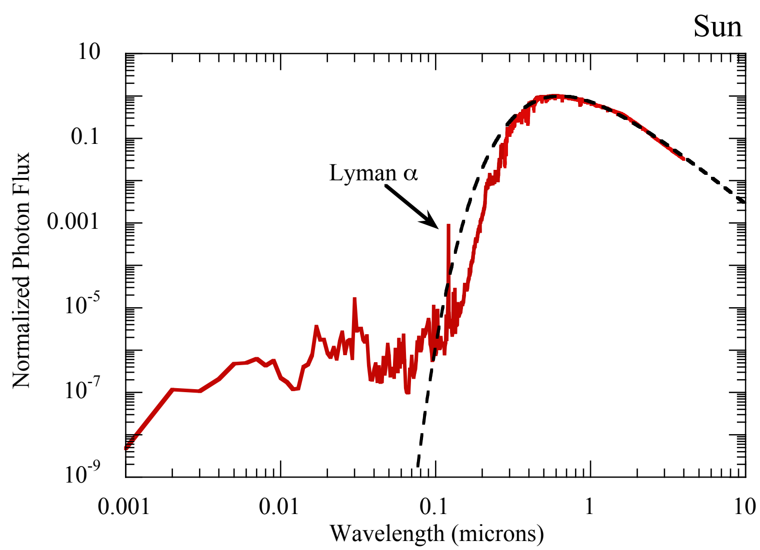
Why doesn't this happen?

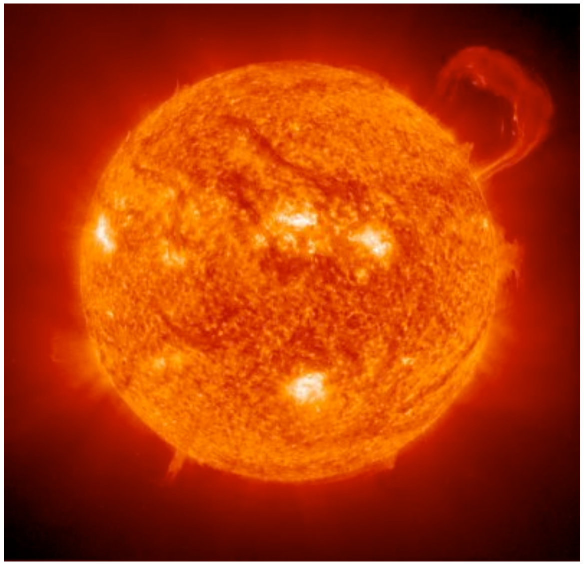
It's all about the photons: where they go, what they do

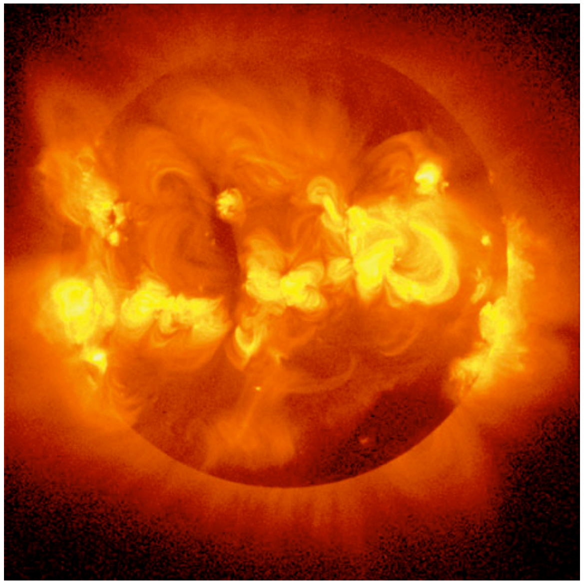


AD Leo (M-star) vs Sun (G-star)



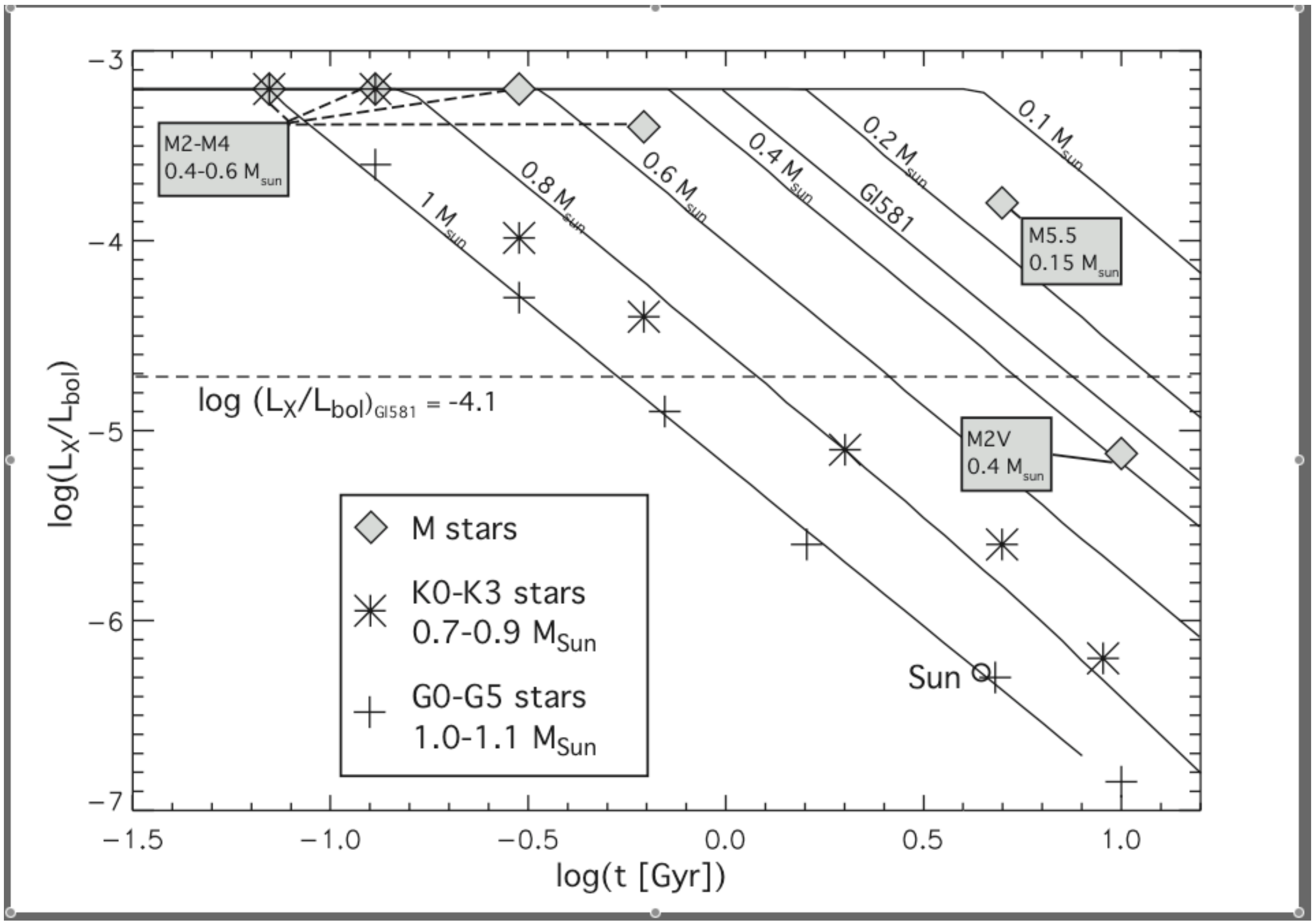






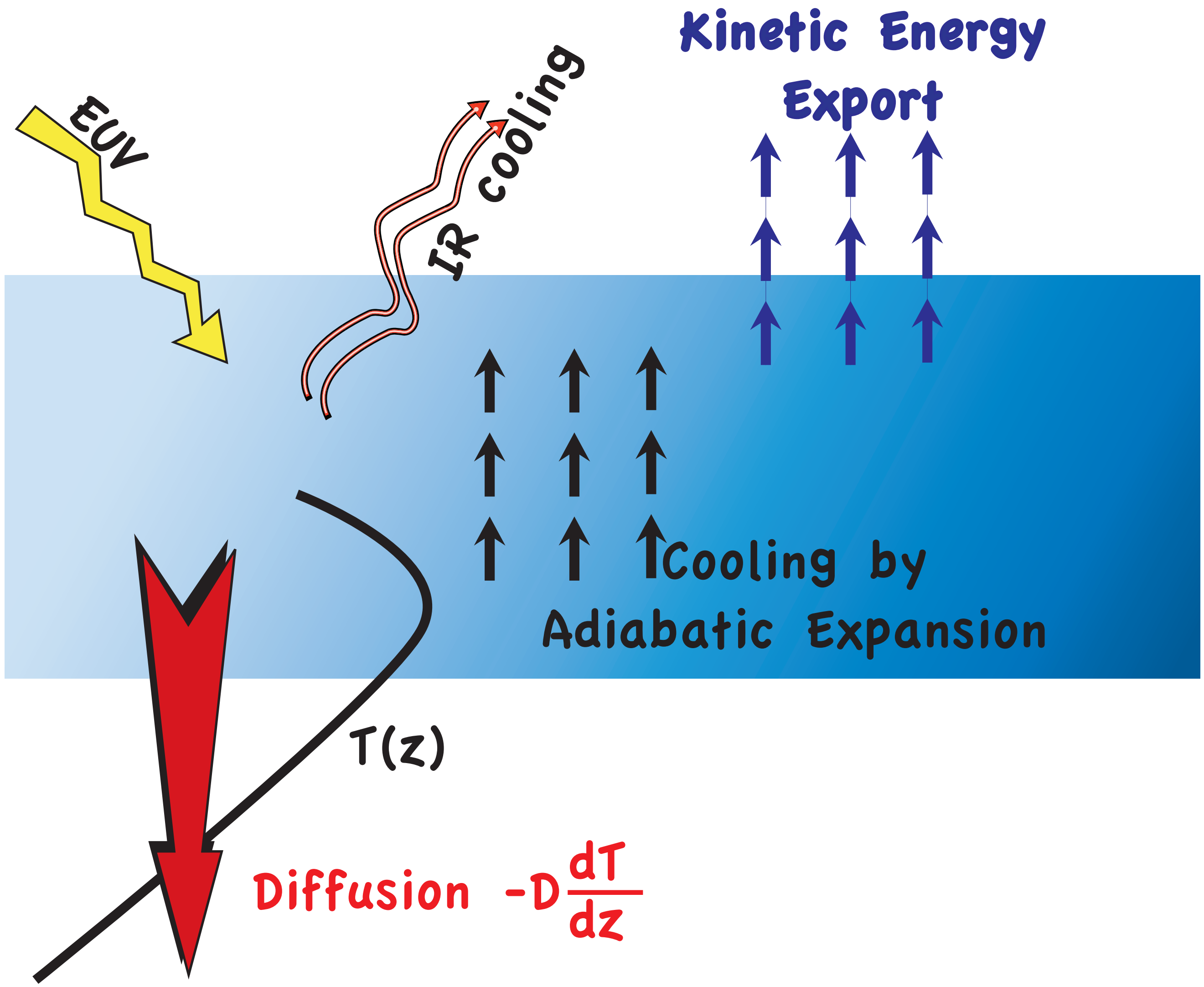
- EUV and X-Ray is coronal, and greatly exceeds emission expected from a blackbody at the photospheric temperature
- Young stars have more of it, as do rapidly rotating stars (e.g. M-dwarfs)

X-ray luminosity declines with age of star

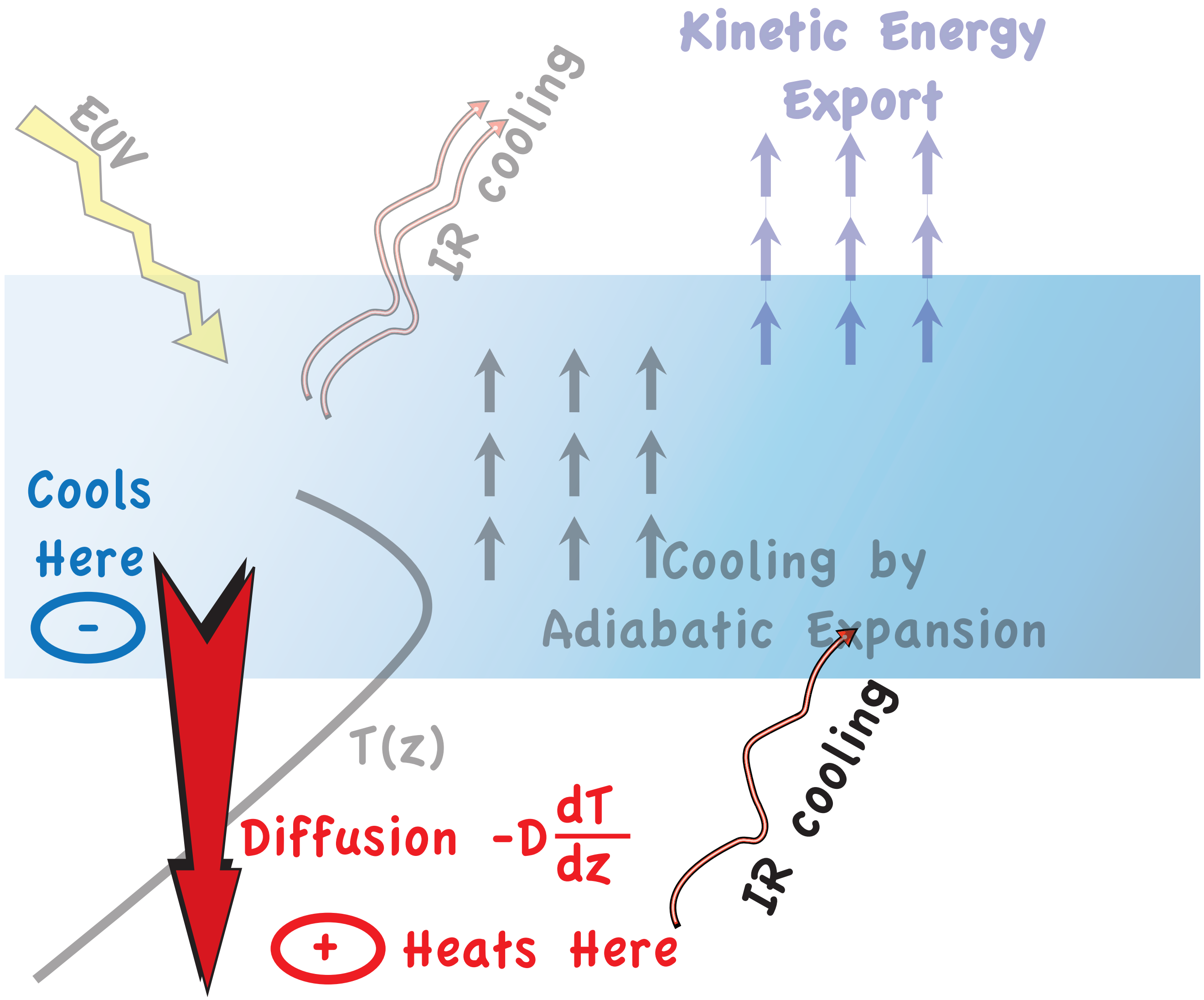


From Selsis *et al*

Energy balance of an escaping atmosphere



Diffusion only reduces escape if it increases radiative loss



Two limiting cases:

- EUV heating balanced mostly by IR radiative cooling, adiabatic expansion, and heat diffusion to colder lower atmosphere
  $\rightarrow$ weak wind w, hydrostatic balance.
- EUV heating balanced largely by vertical flux of kinetic energy
  $\rightarrow$ w large, nonhydrostatic

Hydrodynamic escape: Some history

- Parker – Theory of the solar wind
- Watson, Donahue and Walker, 1981 –
  Steady solutions with EUV heating
- Kasting and Pollack 1983 – Comprehensive atmospheric chemistry
  but were not able to satisfy a consistent boundary condition at infinity
- Tian *et al* 2005. Transient simulations with cool homopause. Major downward revision in previous estimates of hydrogen loss rates
- Kutamoto et al. *EPSL 2013* – Tian's numerics wrong?
- H escape for exoplanets, esp. Hot Jupiters, Super Earths
  Helmut Lammer, Ruth Murray-Clay, others.

An elementary point...

An adiabatic, hydrostatic atmosphere has finite depth

$$\theta \equiv T \cdot (\frac{p}{p_o})^{-R/c_p}$$

$$\frac{dp}{dz} = -g \frac{p_o}{R\theta} (\frac{p}{p_o})^{1-R/c_p}$$

$$(\frac{p}{p_o})^{R/c_p} = 1 - \frac{g}{R\theta}(z - z_o)$$

For hydrodynamic escape,

w *has to get large enough to defeat hydrostatic balance*

Start with the momentum equation and mass continuity

$$\rho w \frac{dw}{dr} = -\frac{dp}{dr} - \rho g_s \frac{r_s^2}{r^2}$$

$$\Phi \equiv (\rho w A(r))/A(r_s) = \rho w (r/r_s)^2 = const$$

The boundary condition at infinity

- Subsonic flow has finite pressure, density at infinity
- Therefore, to ”patch to empty space,”
  flow must be supersonic at infinity
- Problem is hyperbolic at infinity;
  details of flow downstream don’t affect upstream
- *but* must patch to sluggish subsonic flow at low altitudes
- Therefore, must cross the sonic point (Mach 1) at some position

The Transonic condition:Rewrite pressure gradient...

$$\frac{1}{\rho}\frac{dp}{dr} = c^2\frac{d\ln(\theta)}{dr} - c^2\frac{d\ln(\rho)}{dr}$$

$c^2 \equiv \gamma RT$, the *adiabatic* sound speed.

...Eliminate ρ using mass continuity, sub in momentum eqn, eh voila:

$$(1 - \frac{c^2}{w^2}) w \frac{dw}{dr} = c^2 \frac{d \ln(A/\theta)}{dr} - g_s \frac{r_s^2}{r^2}$$

The Transonic Rule

If $w(r)$ is to be smooth near a point r_c where $w = c$, then

$$c^2 \frac{d \ln(A/\theta)}{dr} = g_s \frac{r_s^2}{r^2}$$

In adiabatic case without gravity, reduces to the requirement that $A(r)$ have a minimum at r_c.

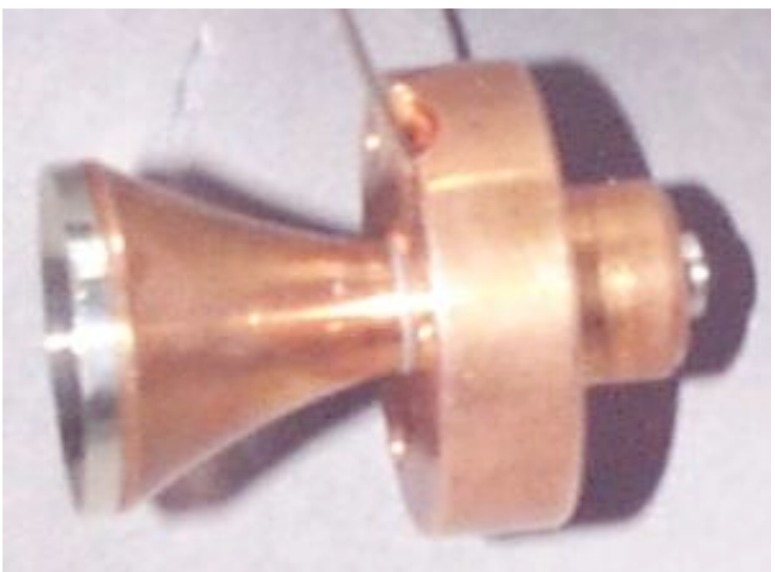
Define Mach number: $M \equiv \frac{w}{c}$

ThIs ain’t rocket science

Well, actually...

First, we're launching an atmosphere to escape velocity by burning EUV "fuel" , and ...

... then there's the De Laval Nozzle



Conservation is more than just a personal virtue...

First law: $c_p dT - \rho^{-1} dp = \delta Q$

Momentum equation integrates to:

$$E = \frac{1}{2}w^2 + c_p T - \frac{1}{2} 2 g_s r_s \frac{r_s}{r} = const. + \mathfrak{H}(r)$$

Calculation of the base temperature and density (adiabatic case)

- Transonic rule implies $c^2 = \gamma RT = \frac{1}{2} g_s \frac{r_s^2}{r_c^2} r_c$ at r_c
- Density at critical point is a free parameter. $w = c$ there so we know escape flux
- Assume w small at base of escaping flow, and apply energy conservation

$$c_p T_b = g_s r_s \frac{r_s}{r_b} + \frac{5-3\gamma}{4(\gamma-1)} g_s r_s \frac{r_s}{r_c}$$

Gives values on order of $g_s r_s / c_p$; very large unless g is small.

4400K for H_2 on Earth but only 244K for H_2 on Titan

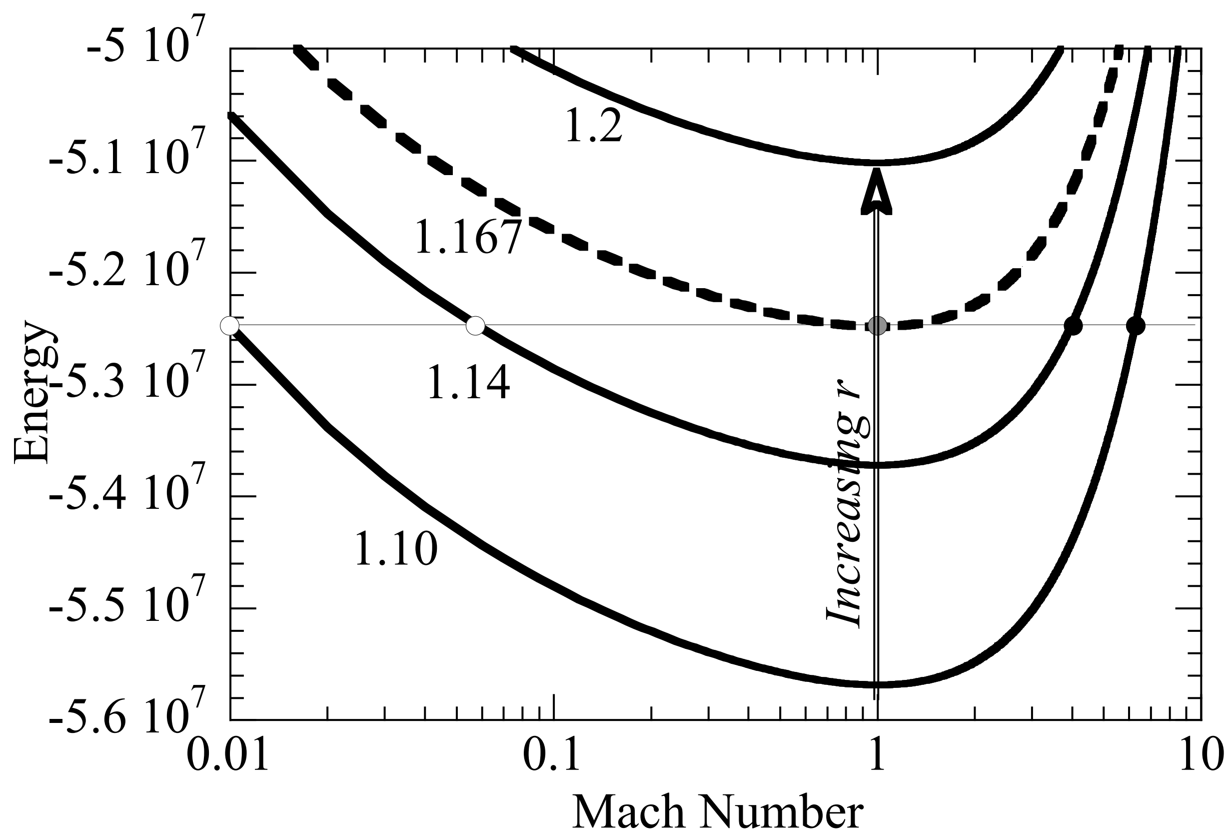
(Molecular weight comes in through c_p; 60,000K for N_2 on Earth)

Energy and the transonic rule

- Use adiabatic assumption to get $T(\rho)$, plus a lot of dull manipulations of thermodynamics
- Yields a function $E(M|r,\theta)$..
- $E(M|r,\theta)$ has a minimum at $M = 1$ for any fixed r,θ
- Transonic rule is equivalent to saying that the *value* of E at the minumum must have a turning point at the sonic point r_c.

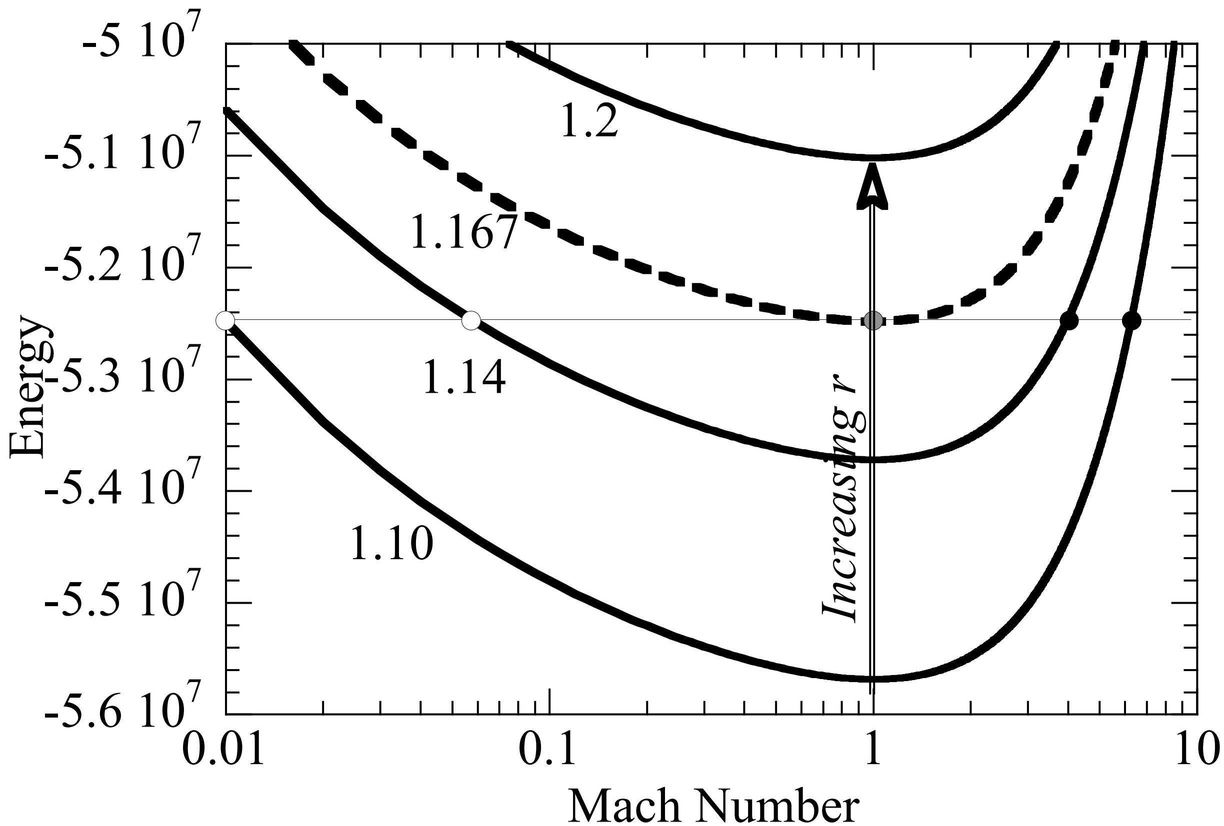
What happens if transonic rule not satisfied?

Subsonic everywhere:Stay on left branch



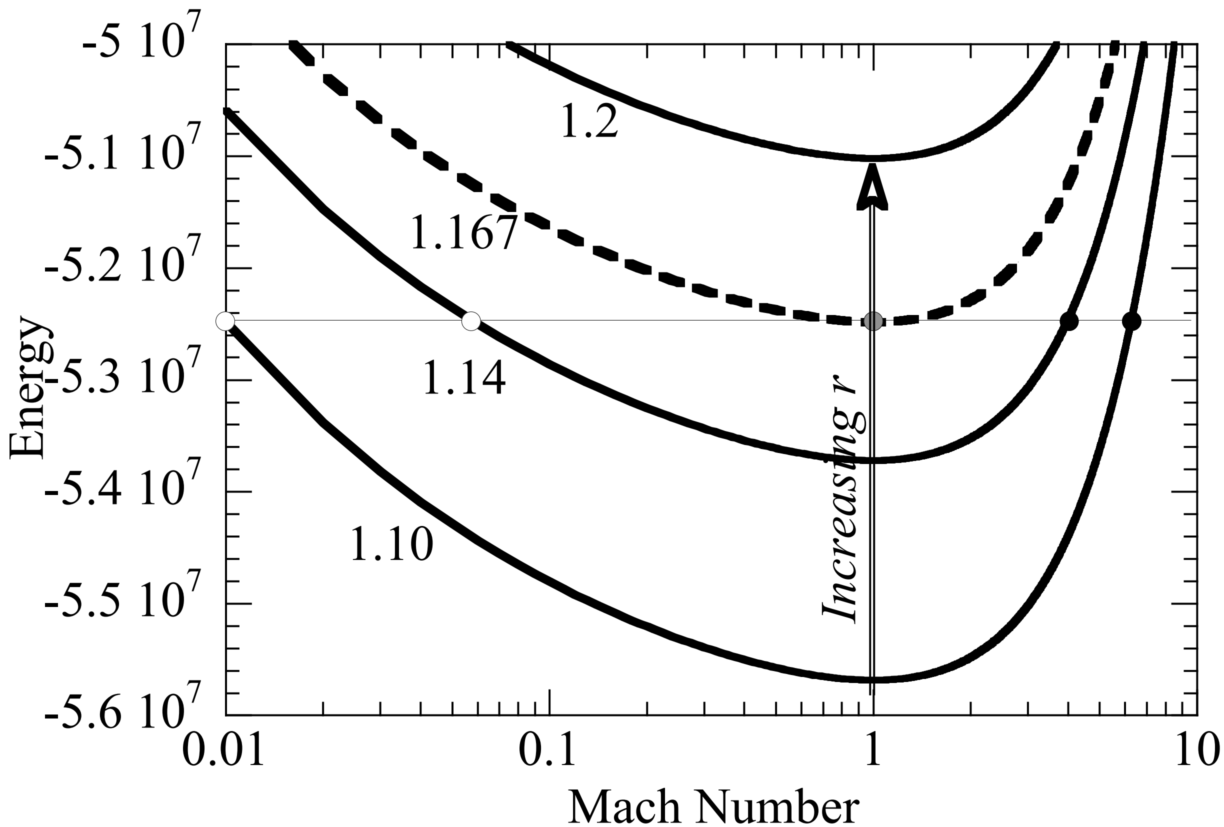
What happens if transonic rule not satisfied?

Supersonic everywhere:Stay on right branch



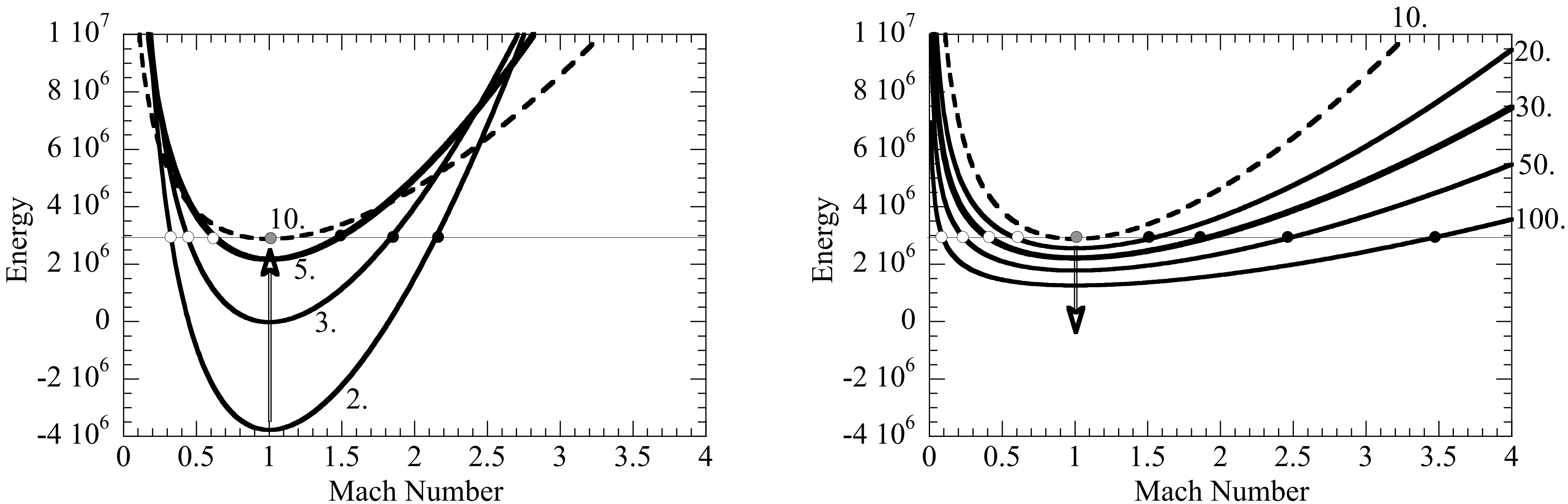
But if you try to go transonic ”against the law”?

dw/dr singular at sonic point, no continuation past

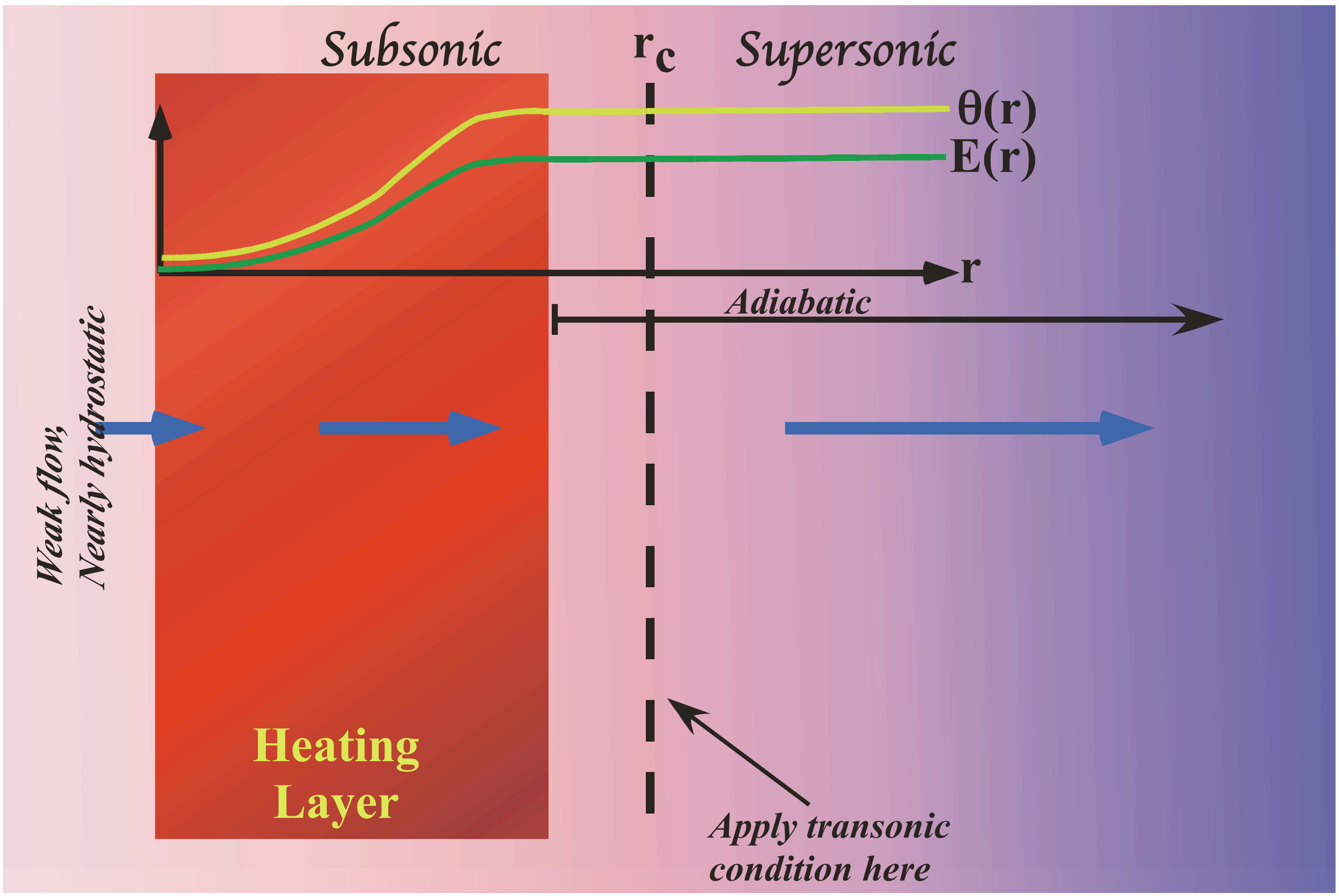


You run out of energy at the sonic point. This is a generalization of the finite depth of a hydrostatic, adiabatic atmosphere

But if instead you satisfy the transonic rule...



Now introduce EUV heating



Energy constraint and 'low temperature' limiting flux

- Use energy equation with heating term retained
- Assume c_pT and w^2 small compared to gravational potential at base
- Balance absorbed EUV flux against kinetic energy flux at infinity
- Defines a critical mass flux Φ_{crit}

$$\Phi_{crit} = \frac{1}{4} EUV_{\odot}/(g_s r_s)$$

What about molecular weight?

$$\Phi_{crit} = \frac{1}{4} EUV_{\odot}/(g_s r_s)$$

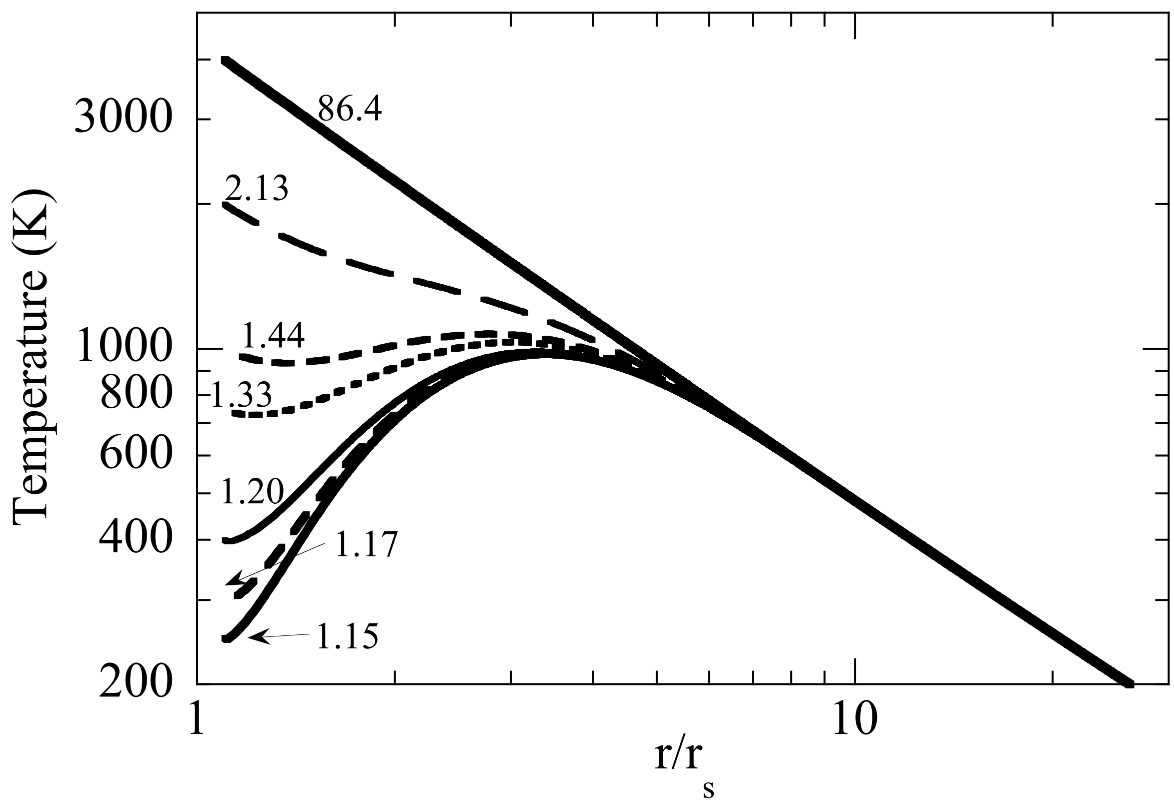
- Molecular weight does not appear in the critical flux
- Continuum hydrodynamics doesn't know about particles ...
- ... but c_p knows! (Think degrees of freedom per kg)

Scaling with heating, gravity and molecular weight

Characteristic temperature defined by: $c_p T^* = 2 g_s r_s$

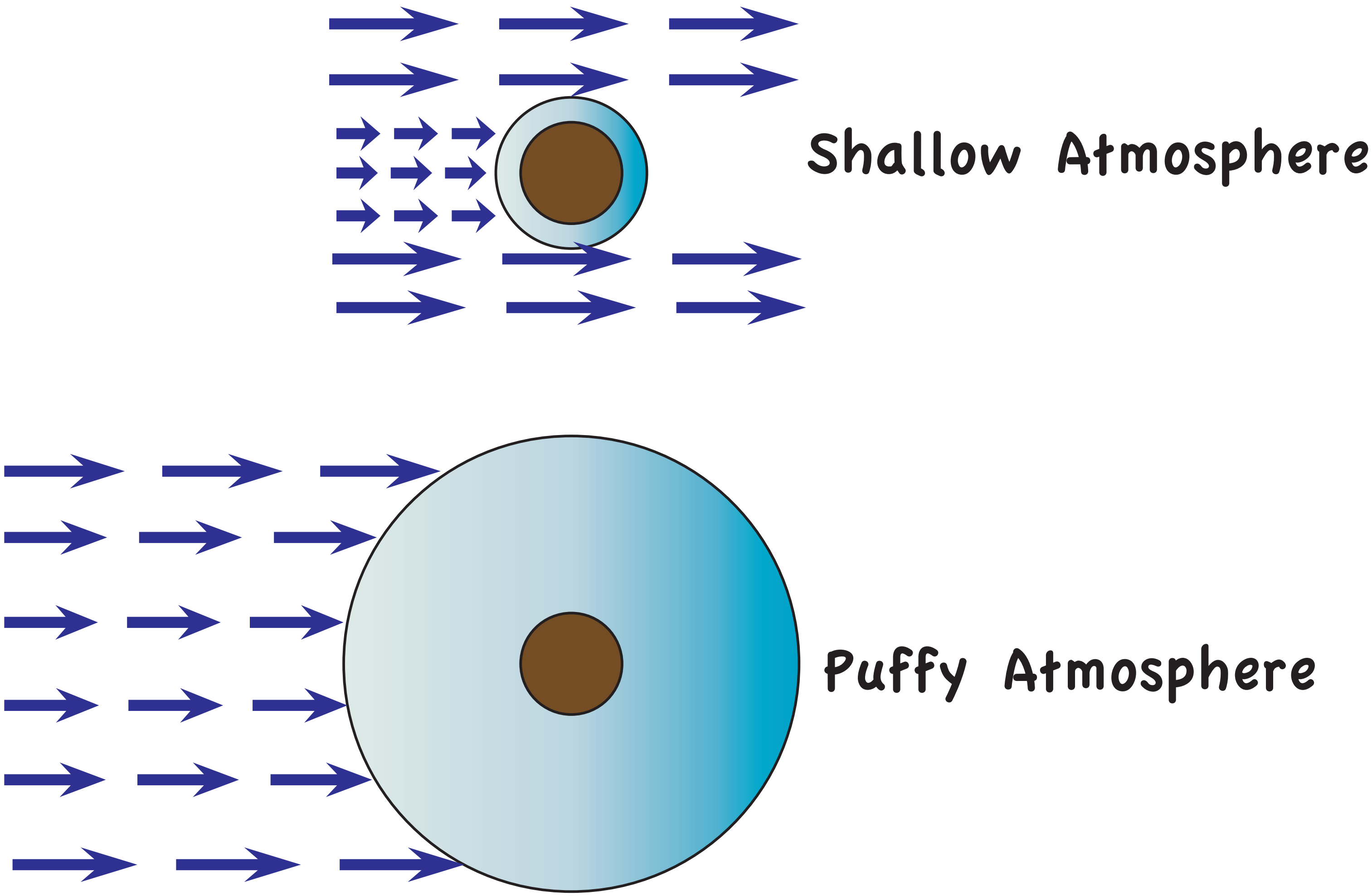
- Higher molecular weight or gravity $\rightarrow$ higher T^*
- Nondimensionalized temperature profile $T(z)/T^*$ independent of c_p

Temperature vs distance for EUV-heated atmosphere (Earthlike, H_2, fixed $r_c/r_s = 30$)



Numbers on curves give nondimensional escape flux

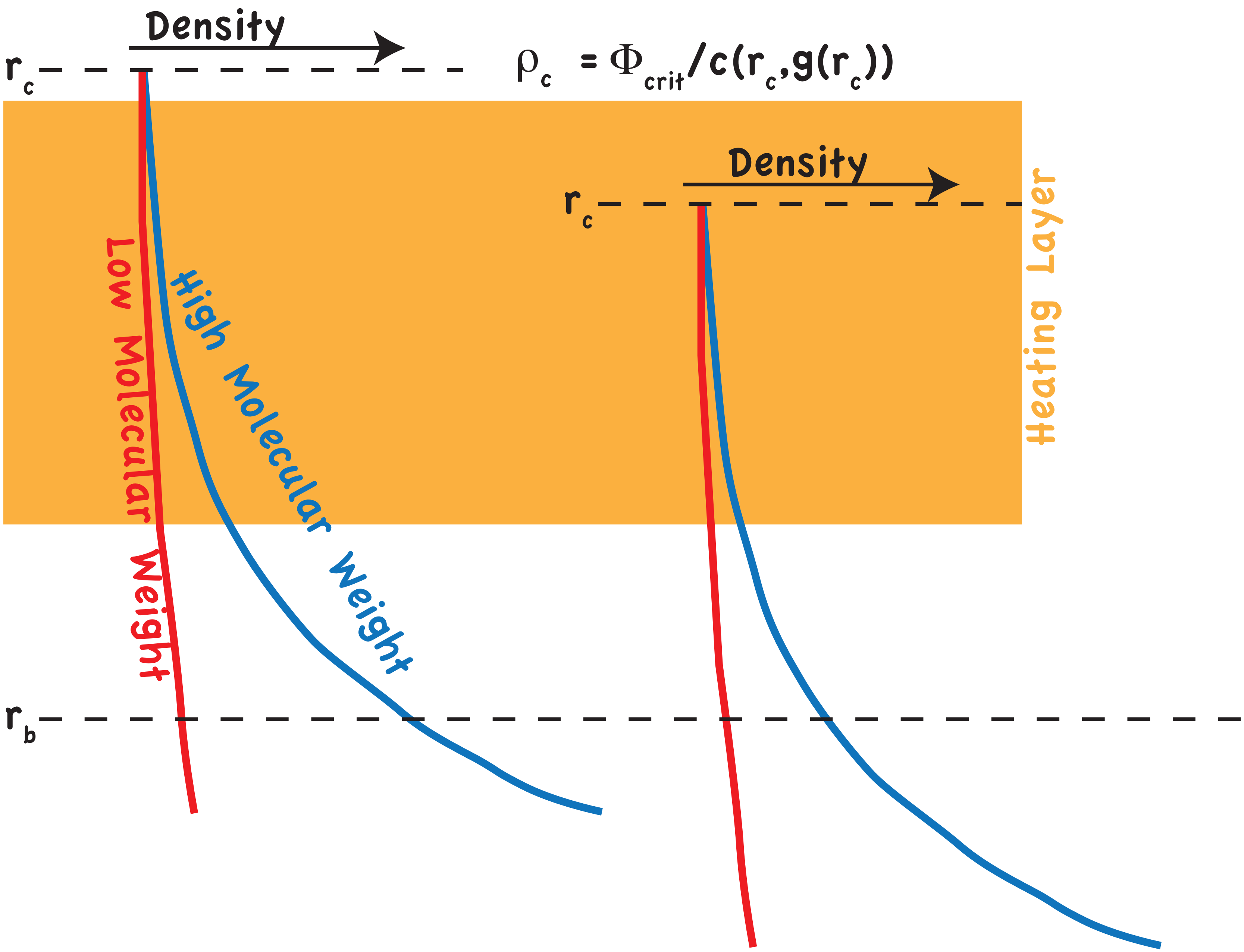
Hydrodynamic escape makes puffy atmospheres which extend many planetary radii, and act as large ”antennas” to catch more EUV



Very visible in Ly-α transits!

Summary of the general behavior

- If base temperature is cool
  (compared to Parker Wind threshold temperature),
  $\Phi = \Phi_{crit}$, which represents escape of mass at rate that balances absorption of EUV energy.
- *This has to be so, because there is no place for absorbed EUV energy to go except to escape as kinetic energy.*
- Once r_c known we know wind, and from Φ we know density ρ_c there
- Base density $\rho_o \approx \rho_c \exp(a \cdot (T^*/T_o)(r_c/r_s - 1))$, $a = O(1)$.
- Adjust r_c until you match boundary condition on density at base. (Note solutions with $r_c/r_s \approx 1$ unphysical, since then velocity becomes large at the base, i.e. escape flow is not being accelerated from rest.)



Density
r_c
$\rho_c = \Phi_{crit}/c(r_c, g(r_c))$
Low Molecular Weight
High Molecular Weight
Density
r_c
Heating Layer
r_b

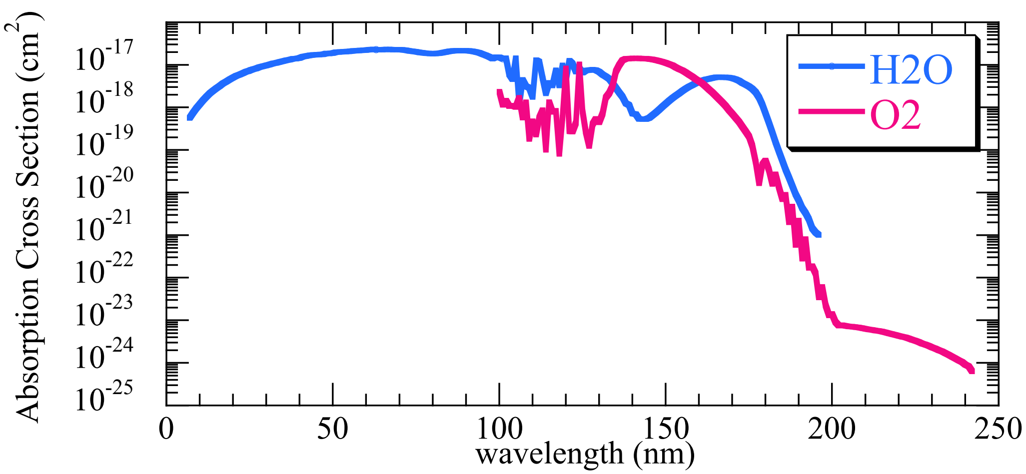
Essential to consider non-hydrodynamic energy loss mechanisms

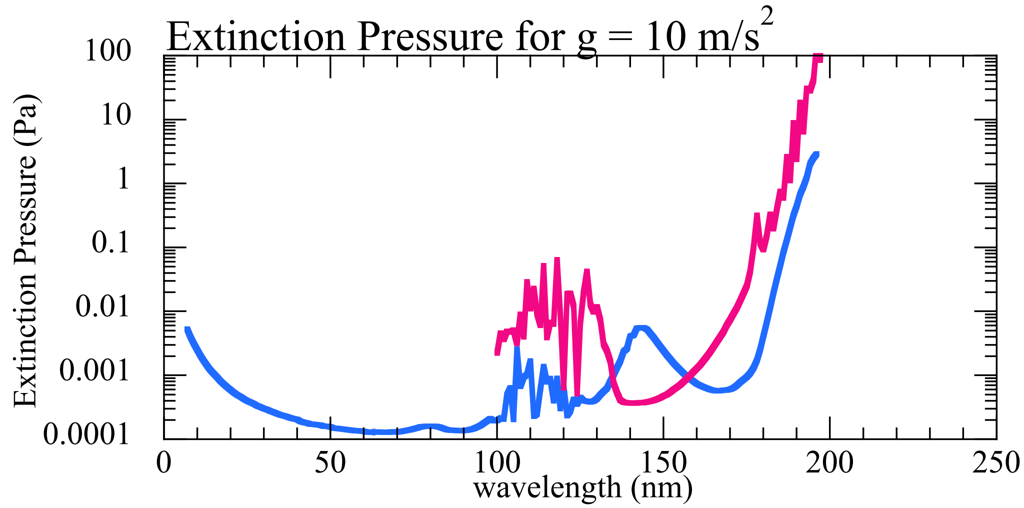
- It is not always possible to match the density and temperature boundary conditions at the base with a purely hydrodynamic energy balance.
- In particular, for high molecular weight gases it is hard to match a reasonable base density unless escape flux (and EUV heating) is very small.
- When the pure hydrodynamic balance is impossible, the atmosphere will heat up until radiative cooling and diffusive energy loss to lower atmosphere come into play ...
- ... and these mechanisms will steal energy from ”energy limited” escape, and reduce escape flux below Φ_{crit}

Photolysis: Where does it happen, and how fast?

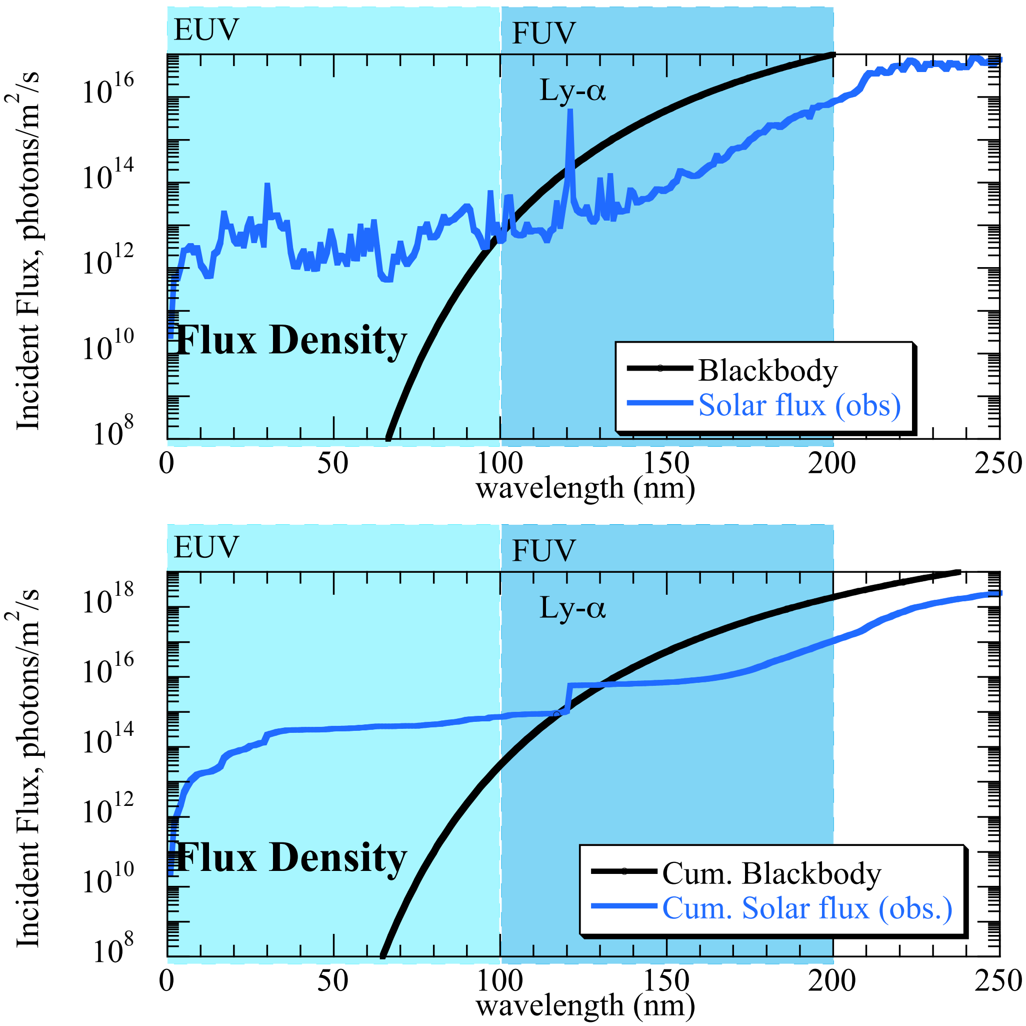
Will use H_2O photolysis as example

Photolysis occurs in a very thin layer

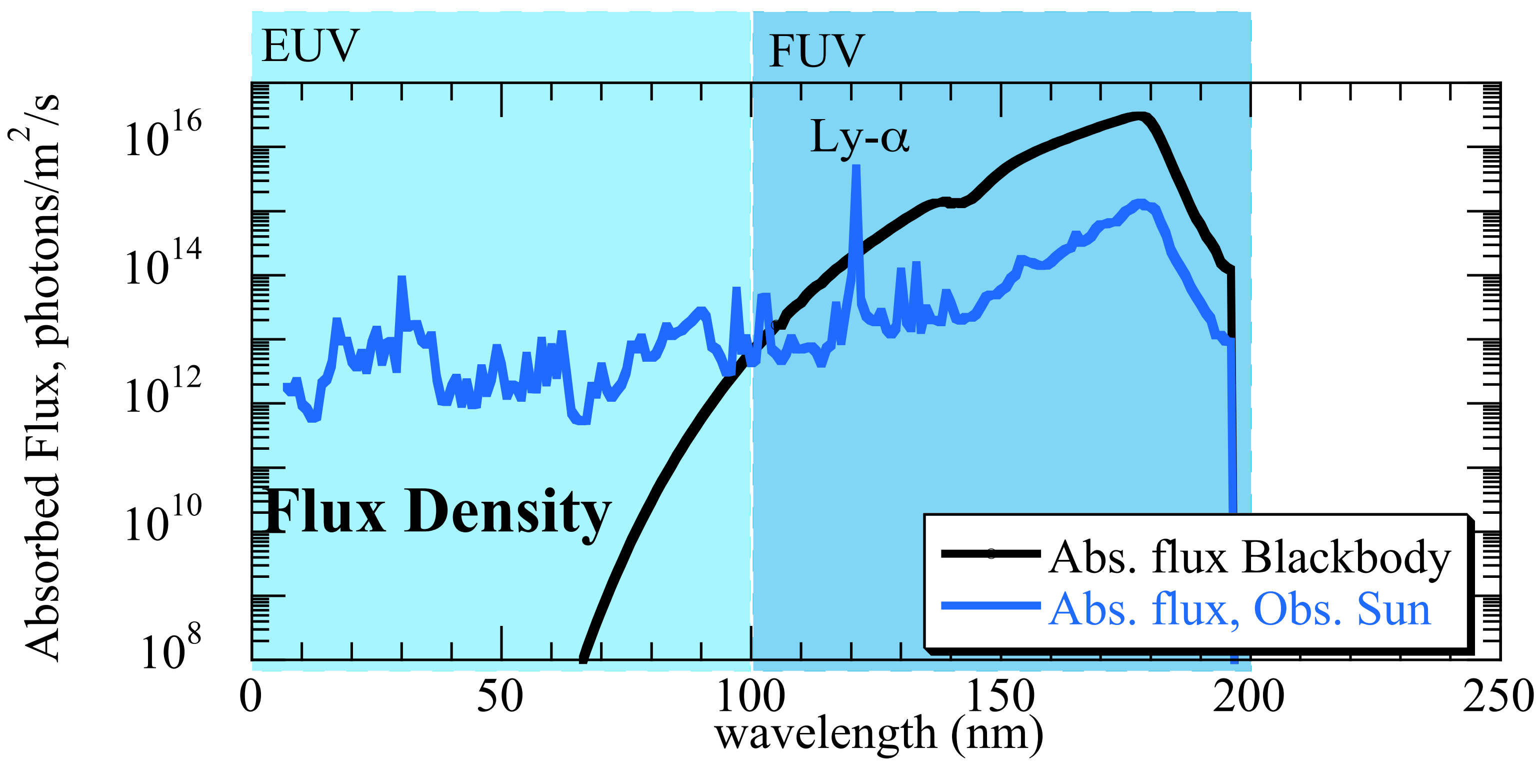




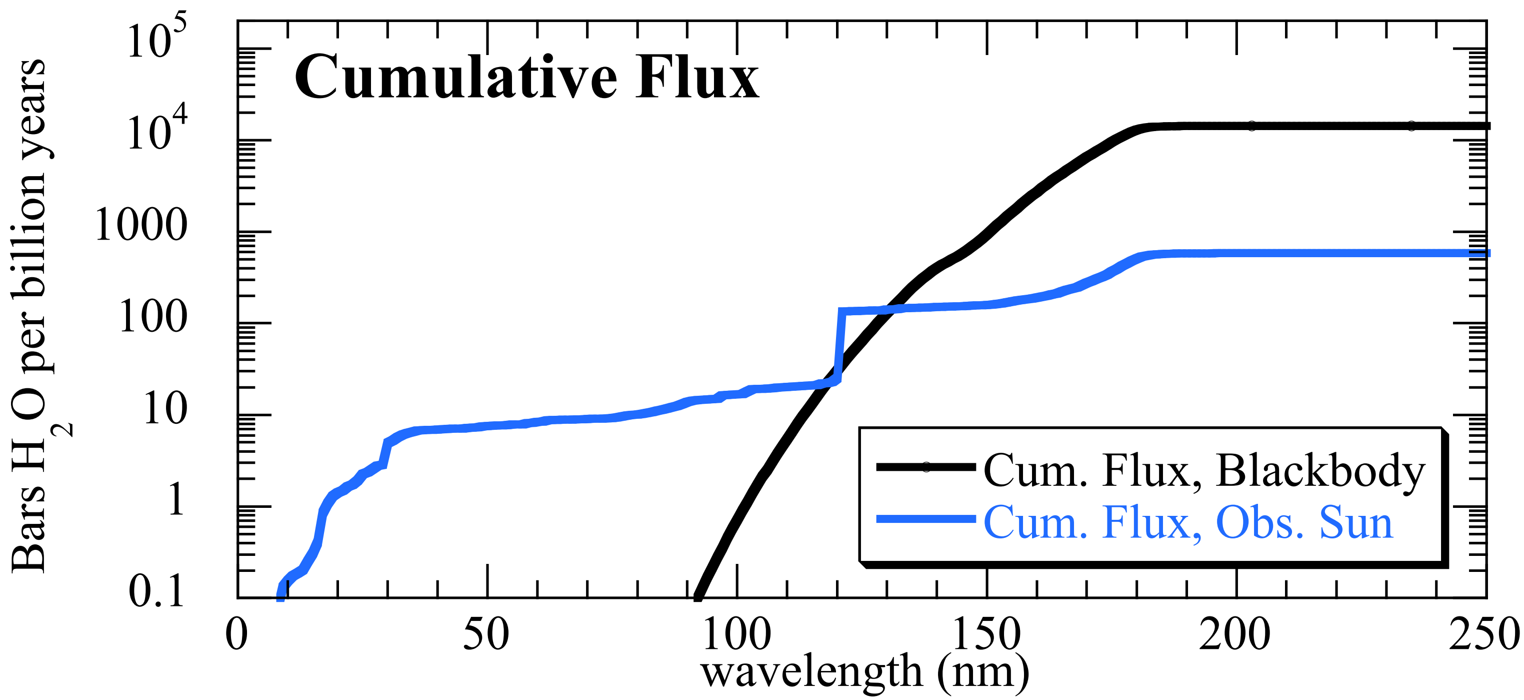
Solar photon flux at Earth orbit



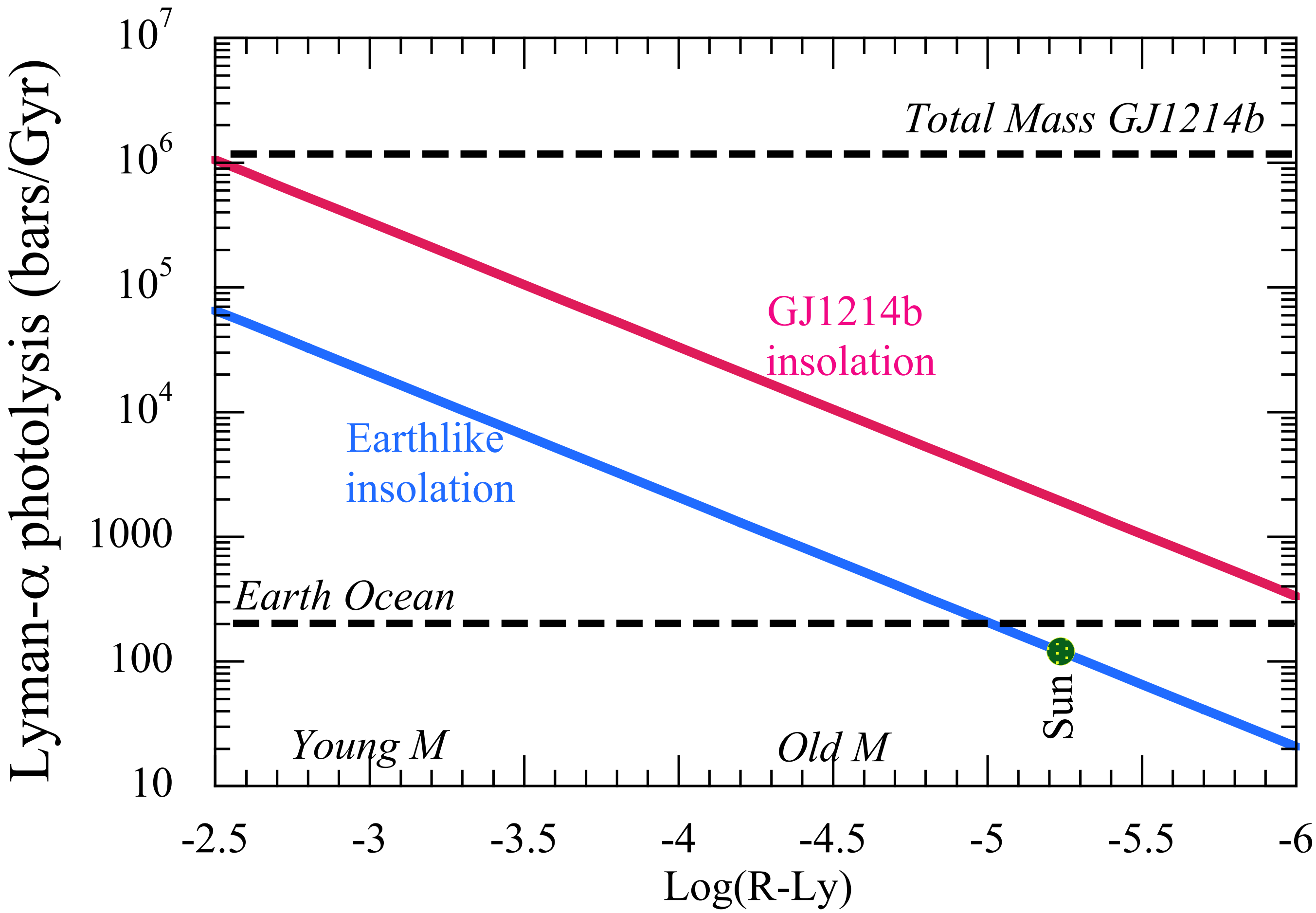
G star photon flux absorbed by H_2O



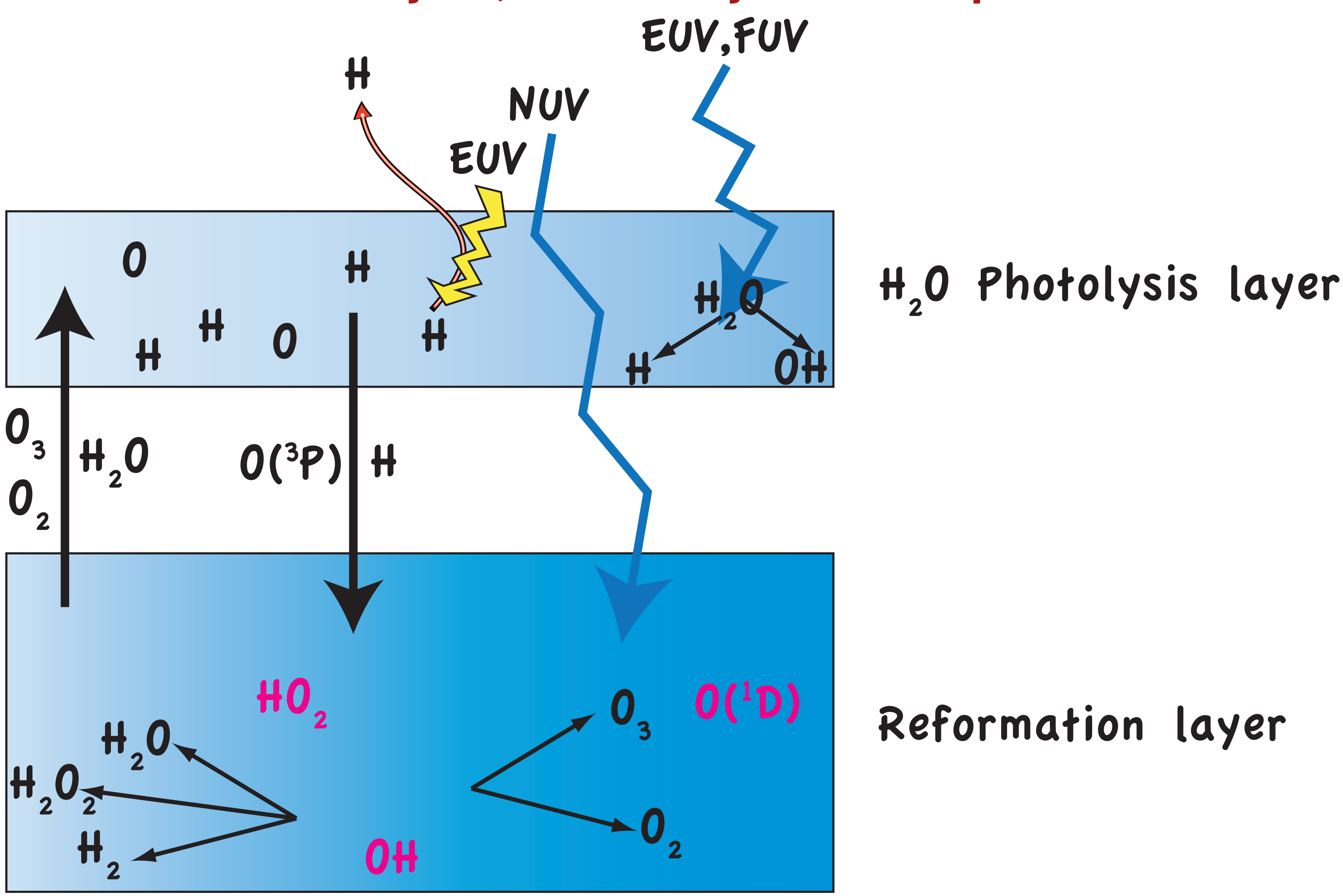
Lets count photons!



For M stars, H_2O photolysis dominated by Ly-α



Photolysis, Chemistry and Escape:



Some take-home points

- There are plenty of photons available to dissociate atmospheric constituents...
- ... even for M-stars, where most chemistry is driven by Ly-α.
- Escape rate is the limiting factor for volatile loss (e.g. water).
- Mass will always escape hydrodynamically at the rate Φ_{crit} needed to balance EUV heating *unless diffusive or radiative loss carries away part or all of the energy instead*.
- i.e. you'll *always* get the ”energy limited” escape rate unless you explicitly put in the other loss mechanisms.
- Recombination with accumulating oxygen could also restrict water (or CO_2) loss
- UV astronomy provides critical information for atmospheric evolution *but we will have essentially no UV capability after Hubble goes.*