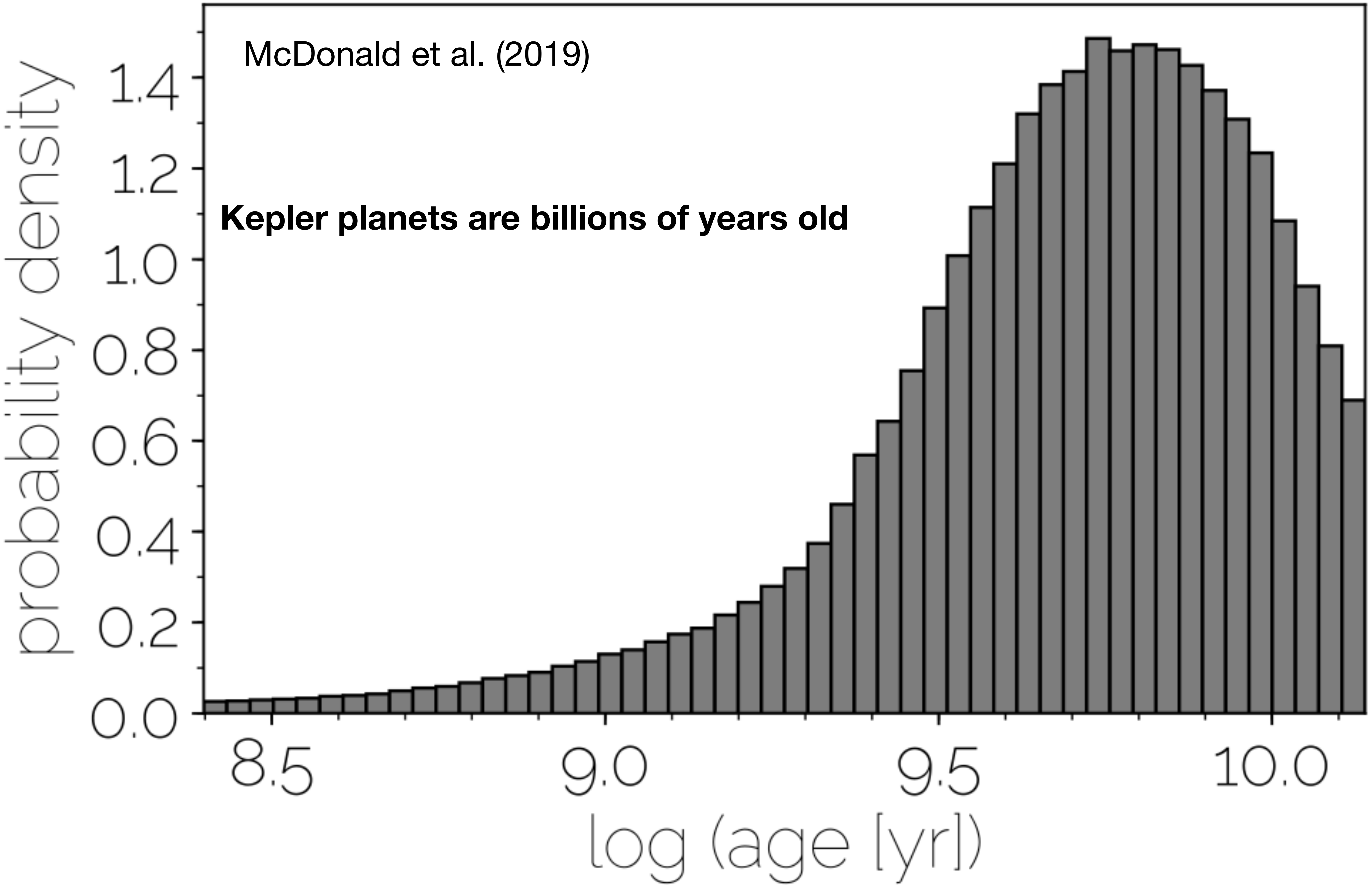
Atmospheric Escape

James Owen (Imperial College London)

Outline

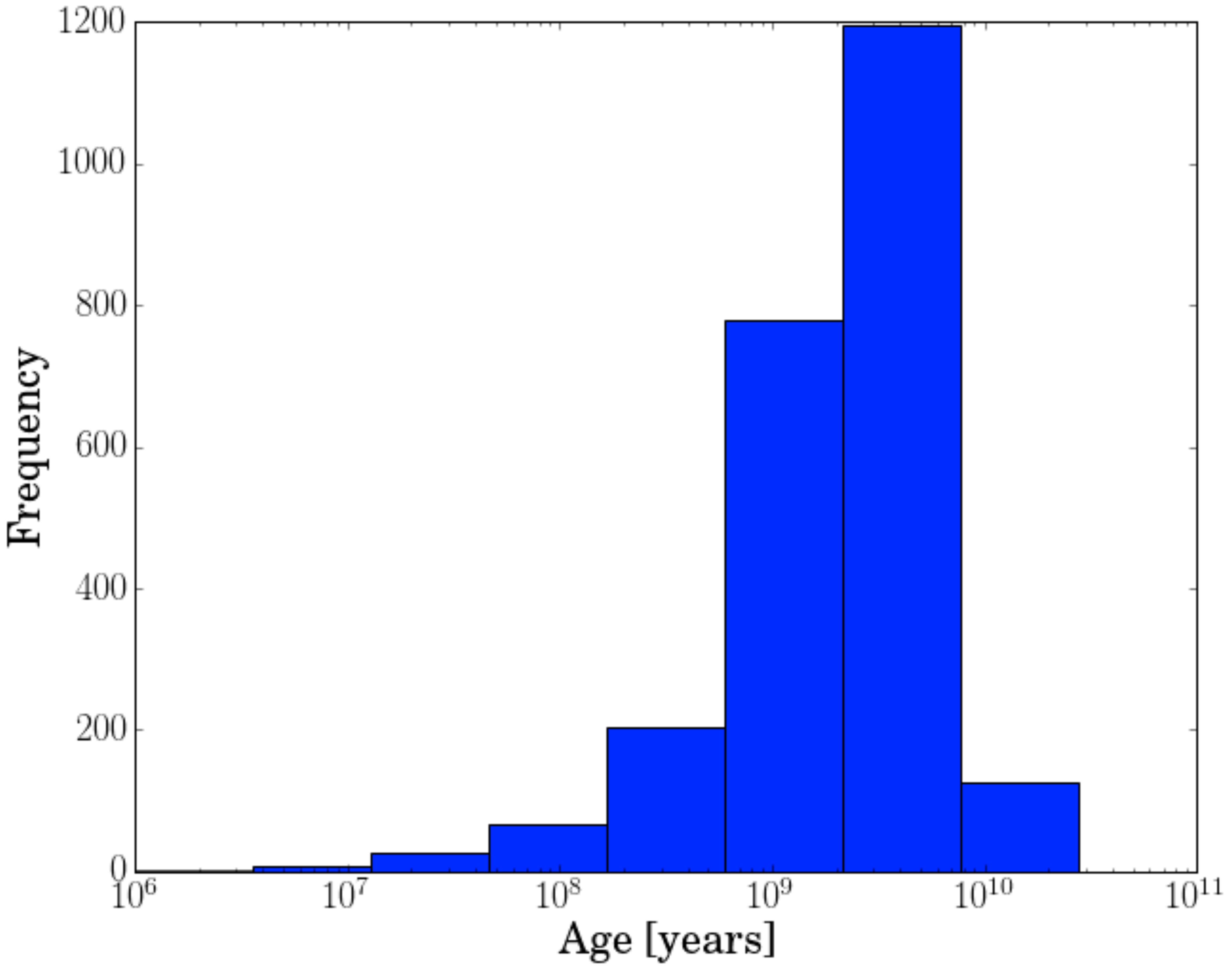
- Basics of escape and a discussion of different escape mechanisms
- Thermodynamics of the upper atmosphere, leading to thermal escape
- Hydrodynamic escape for close-in exoplanets
- Evolution of planets with escaping atmospheres
- Observations of atmospheric escape
- Future

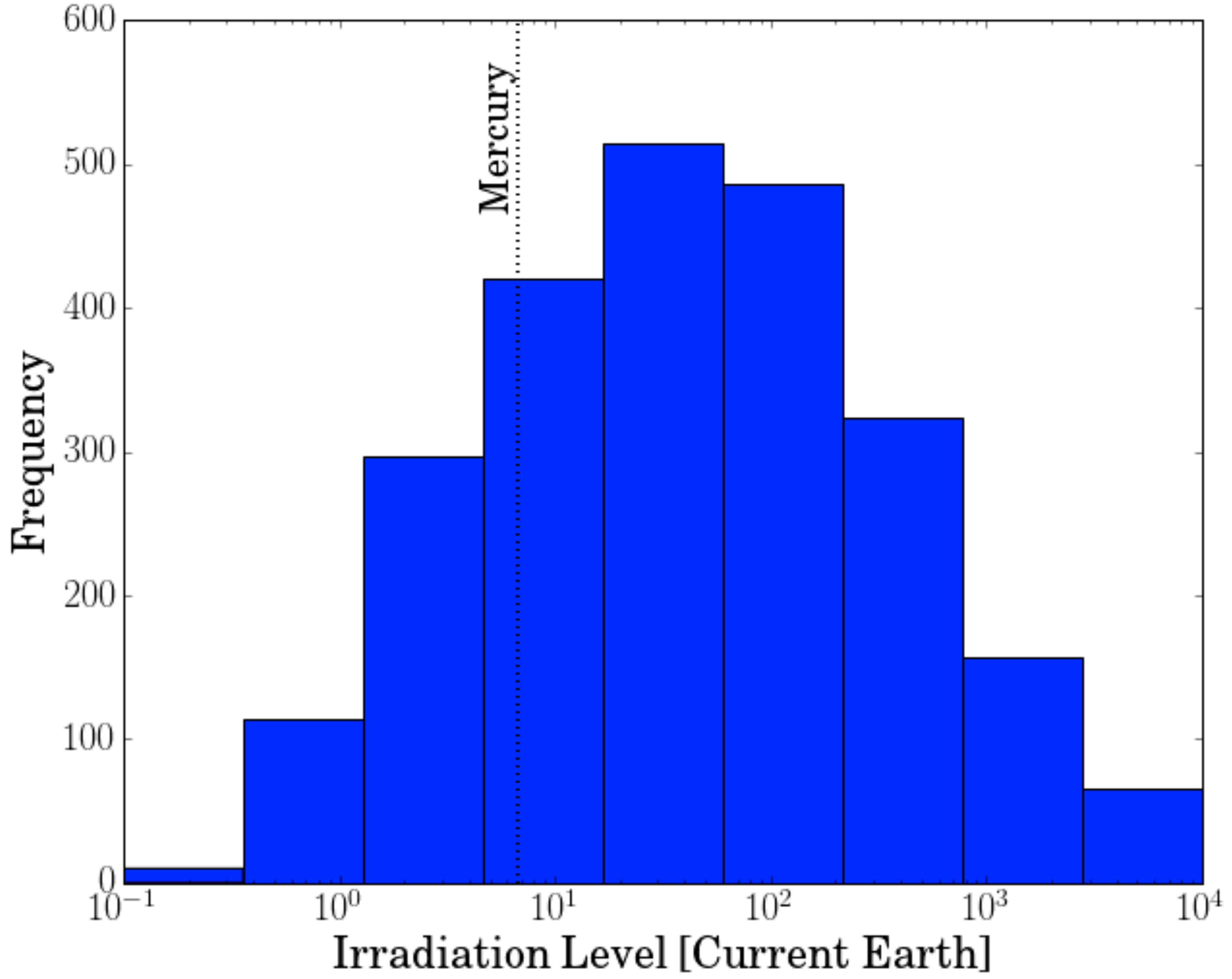
Why is atmospheric escape important?



Why does escape matter?

TESS yields (Rp < 4 Rearth), (Bouma et al. 2017)

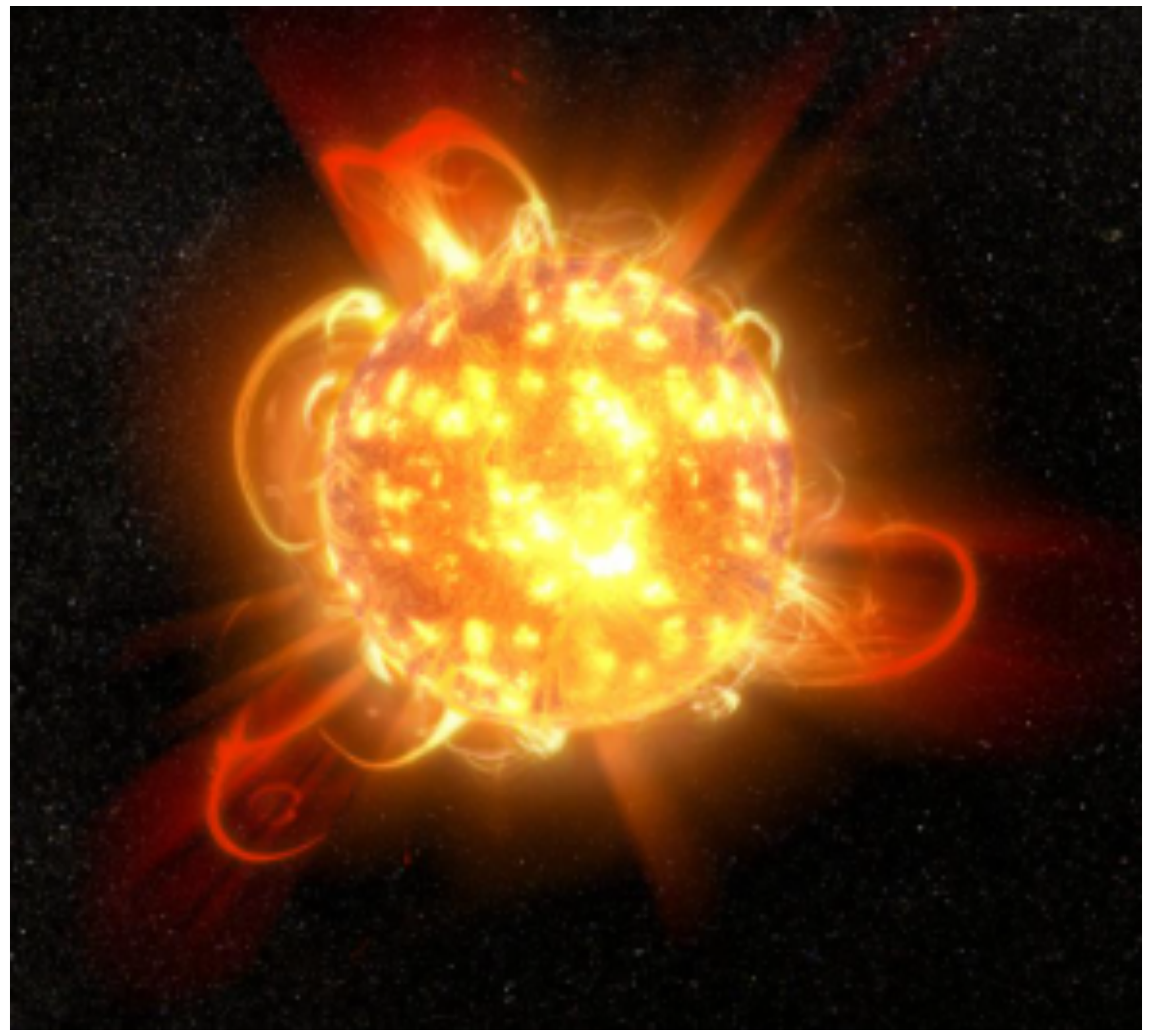




For most exoplanets which we want to study their properties, formation or atmospheres

atmospheric escape will have already sculpted their atmospheres.

Atmospheric escape is a collection of processes

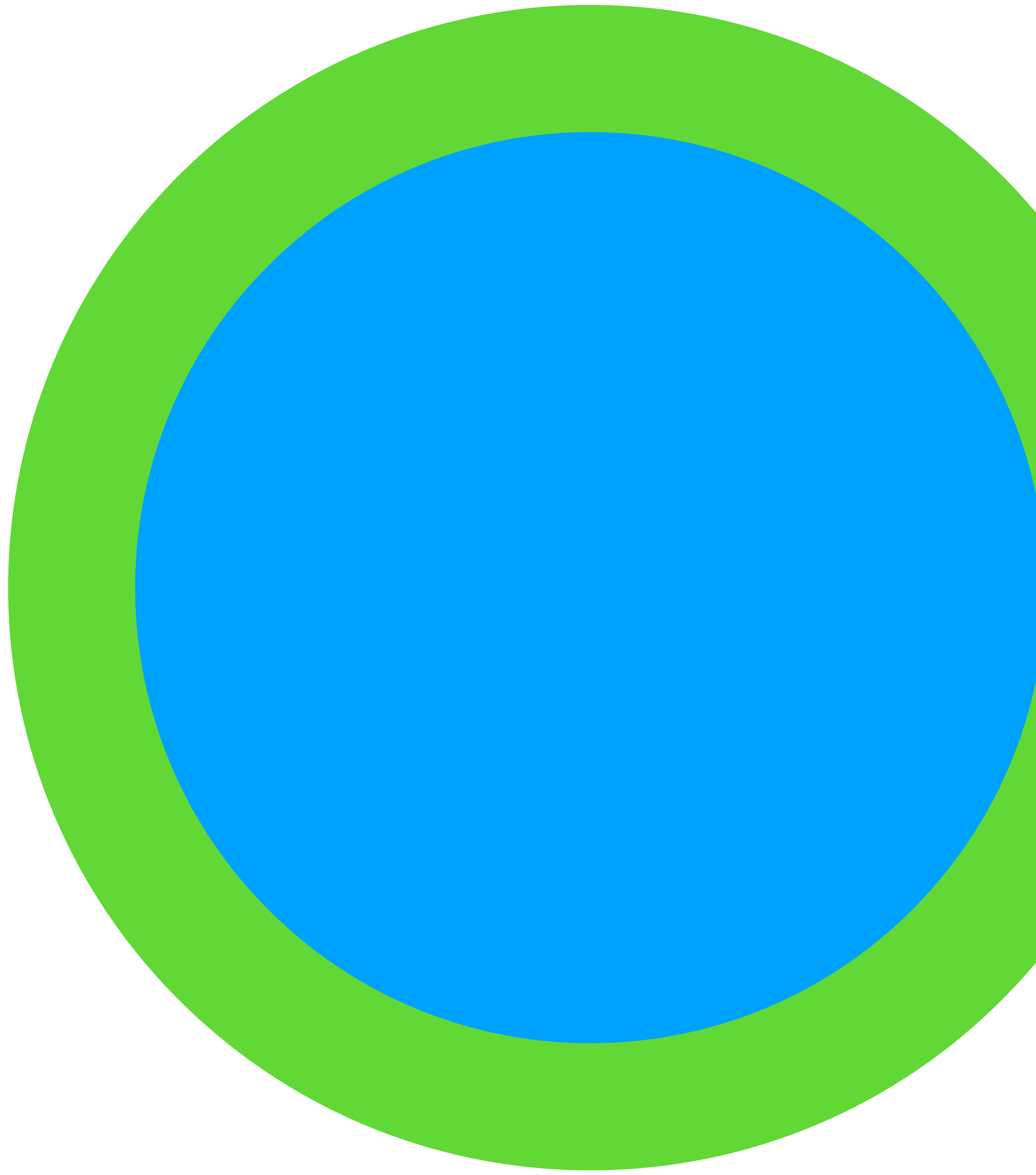


Stellar Irradiation

Bolometric, and
high energy (XUV) photons

Stellar wind

Rapidly moving (100s km/s)
charged particles



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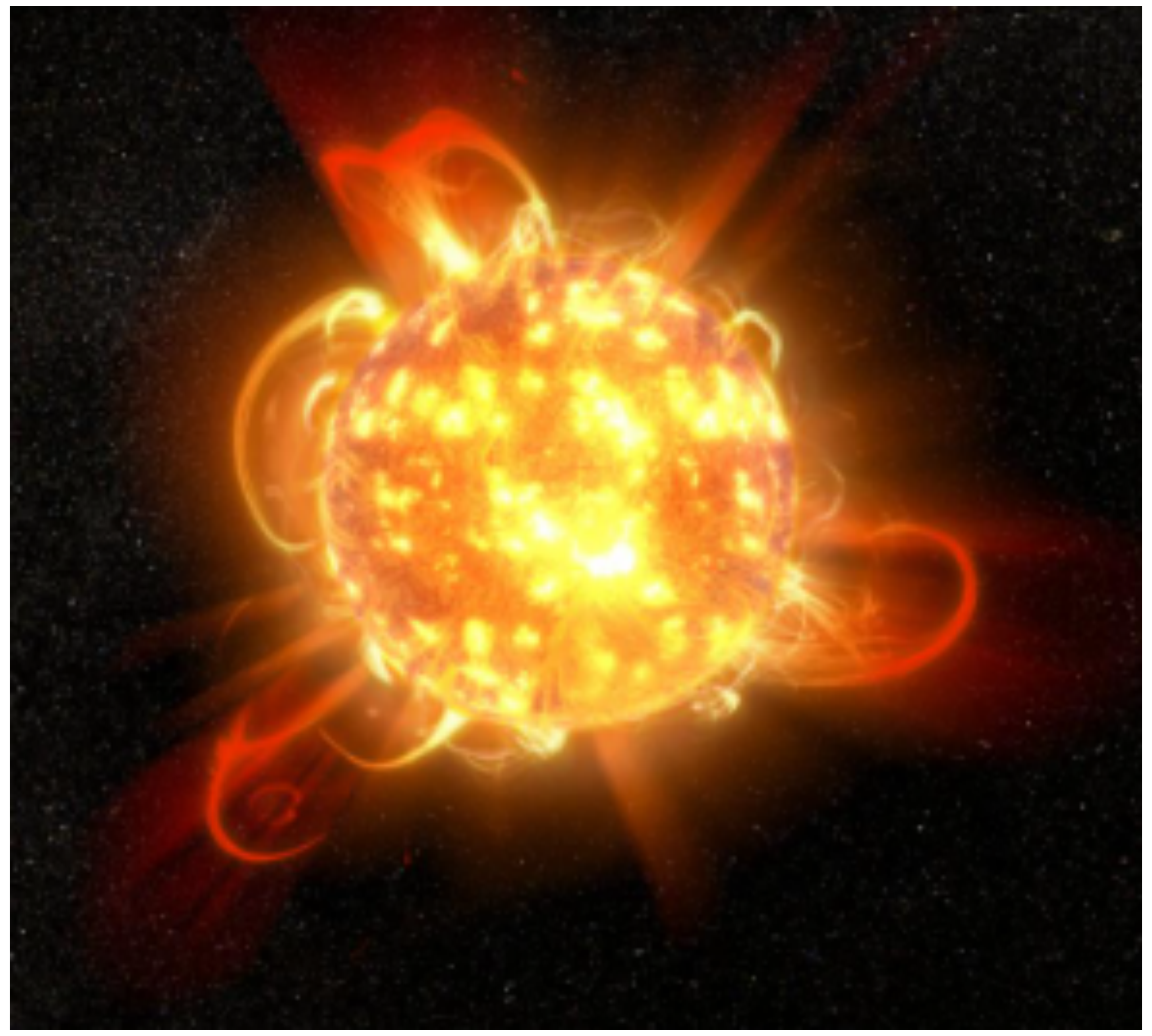

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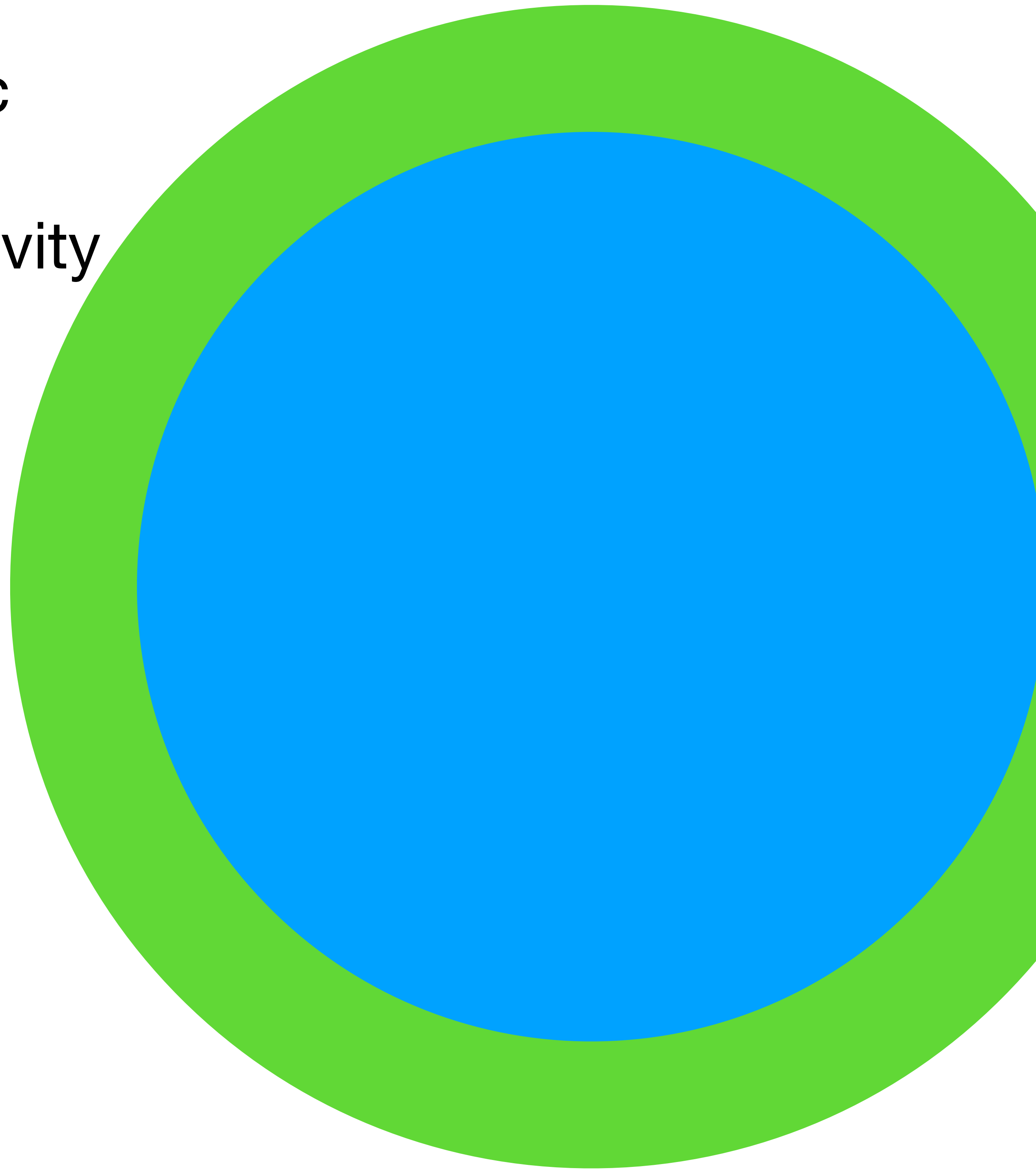

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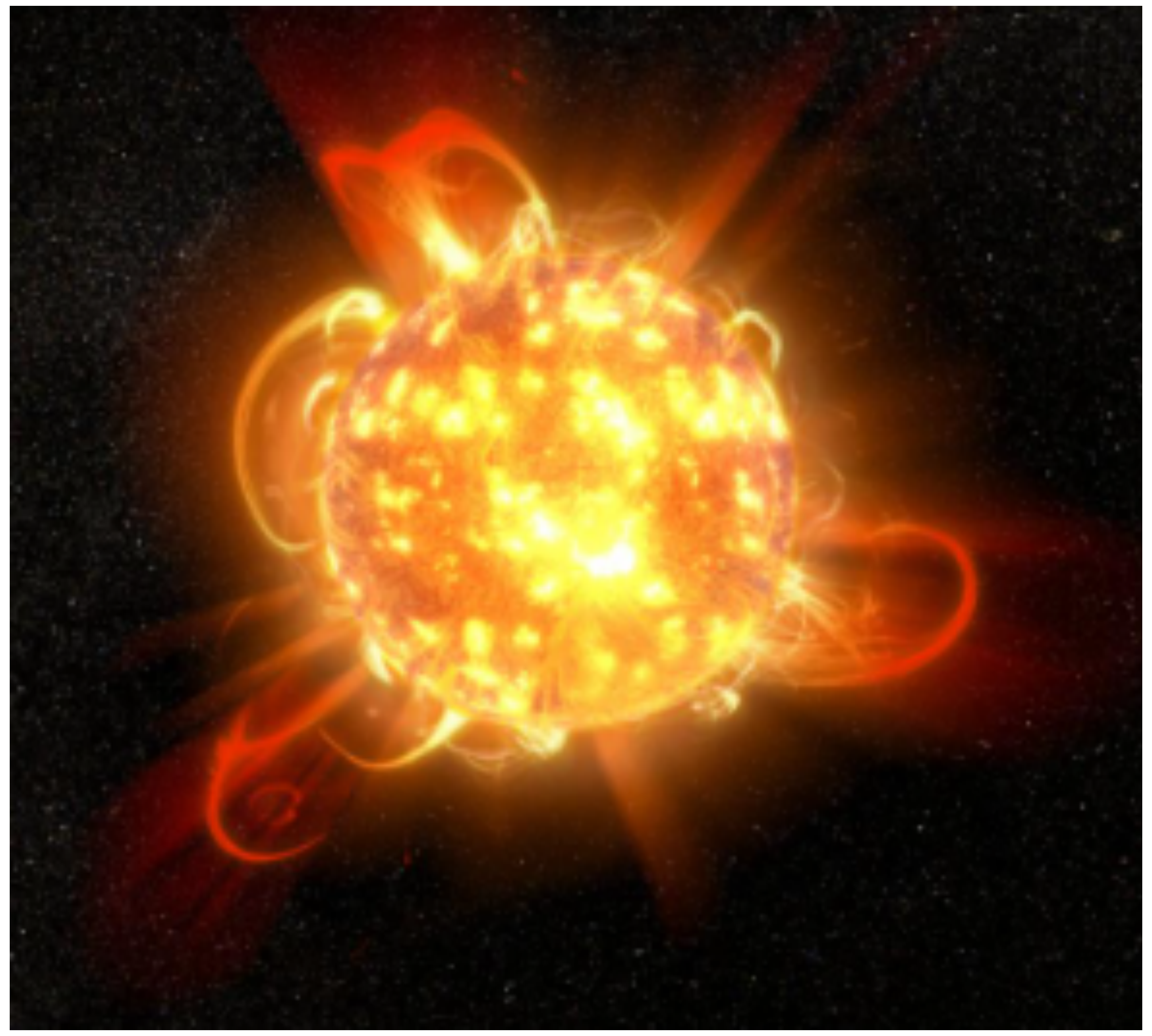

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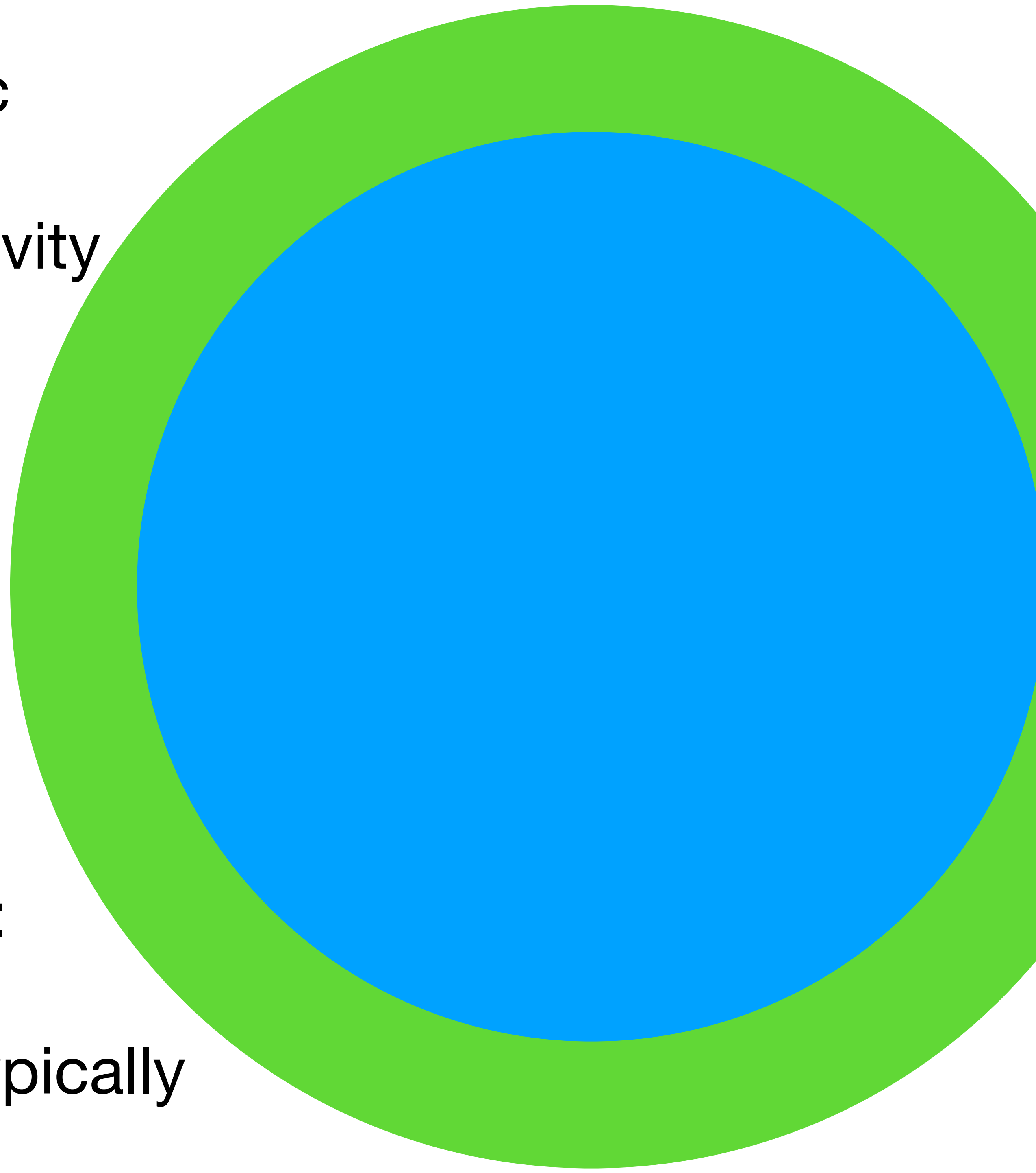

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(Suprathermal) complex processes, typically at the individual particle level.

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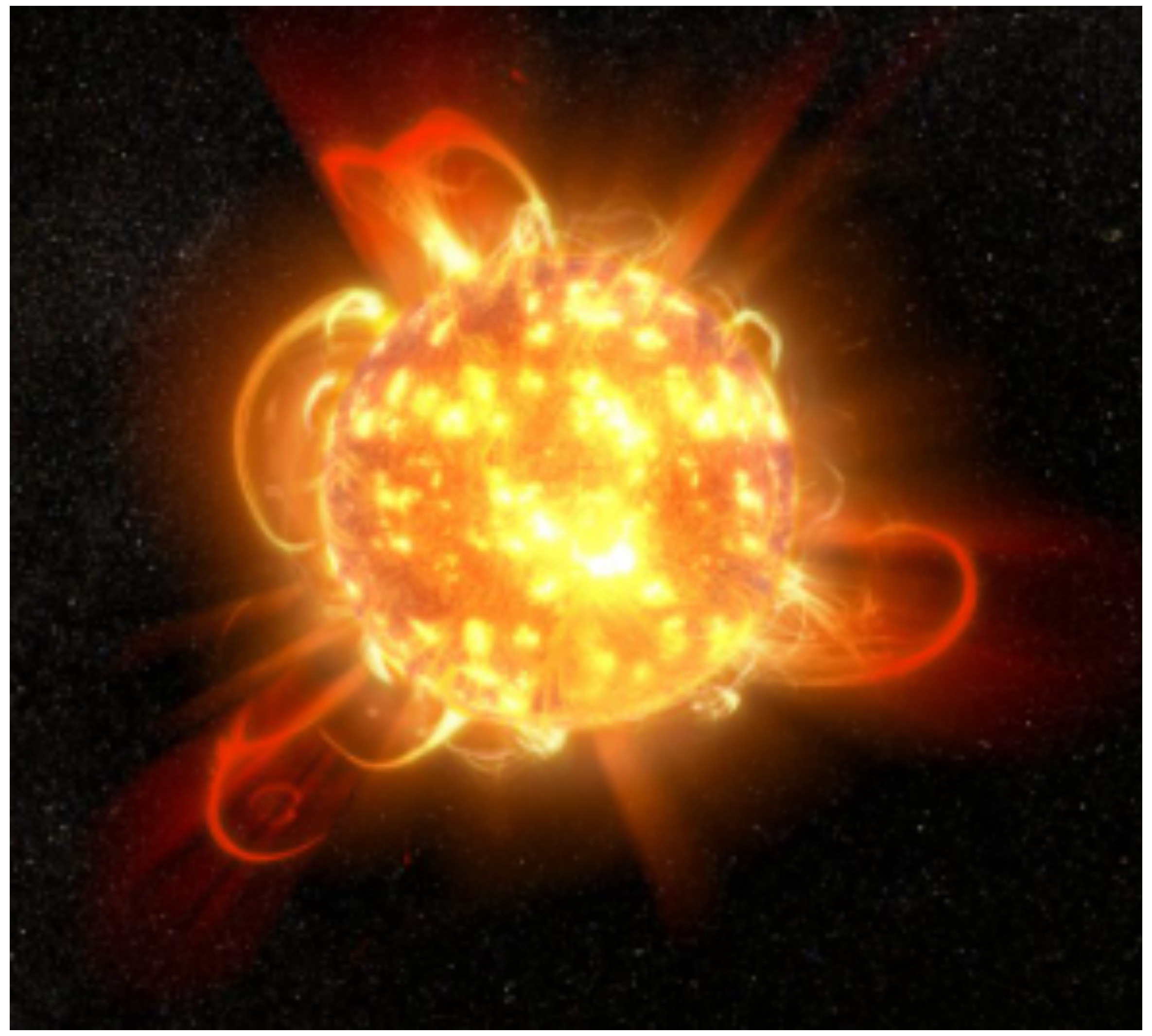

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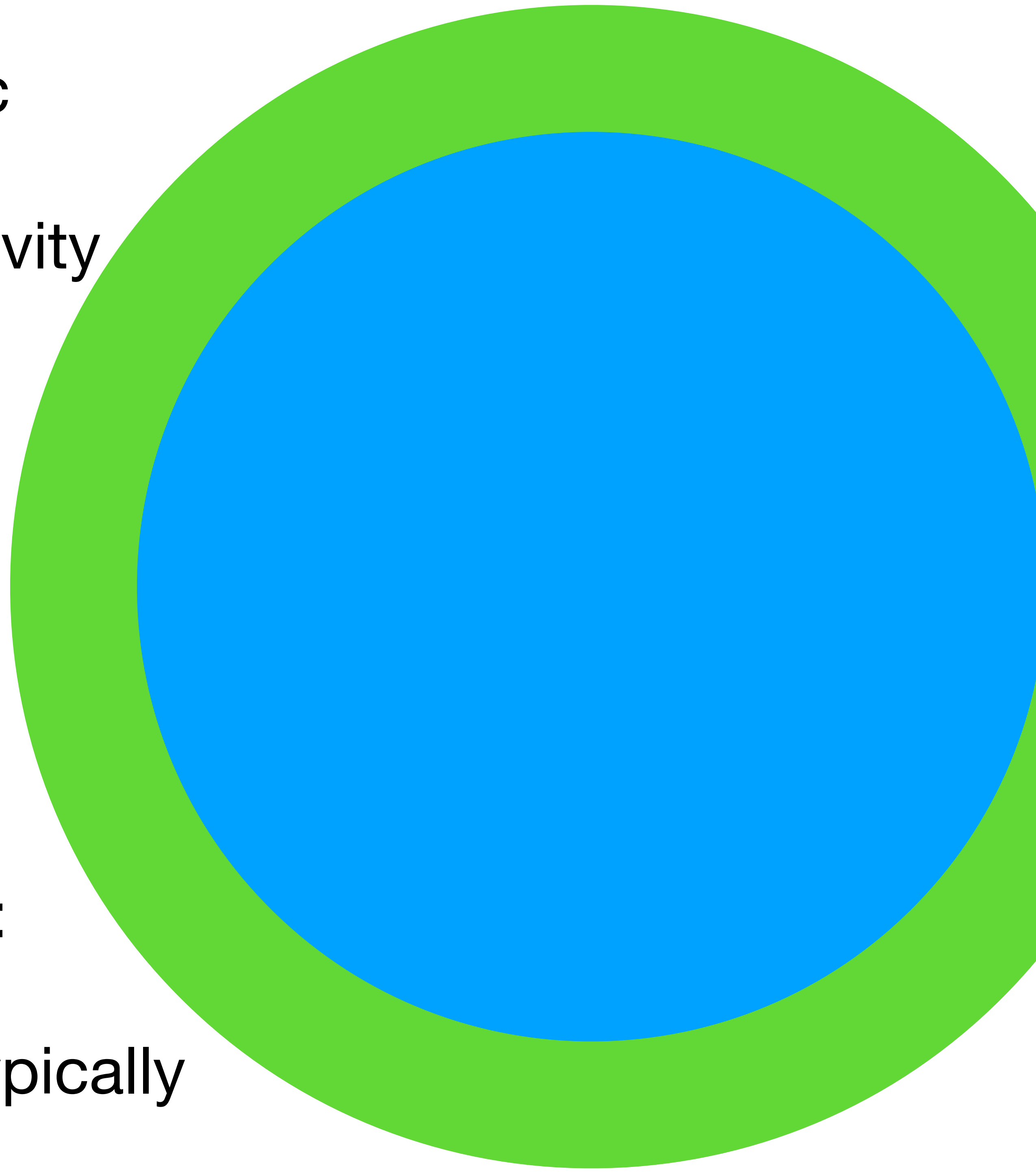

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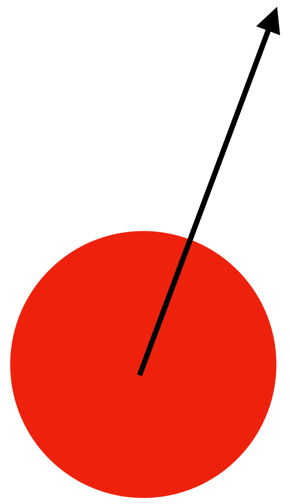

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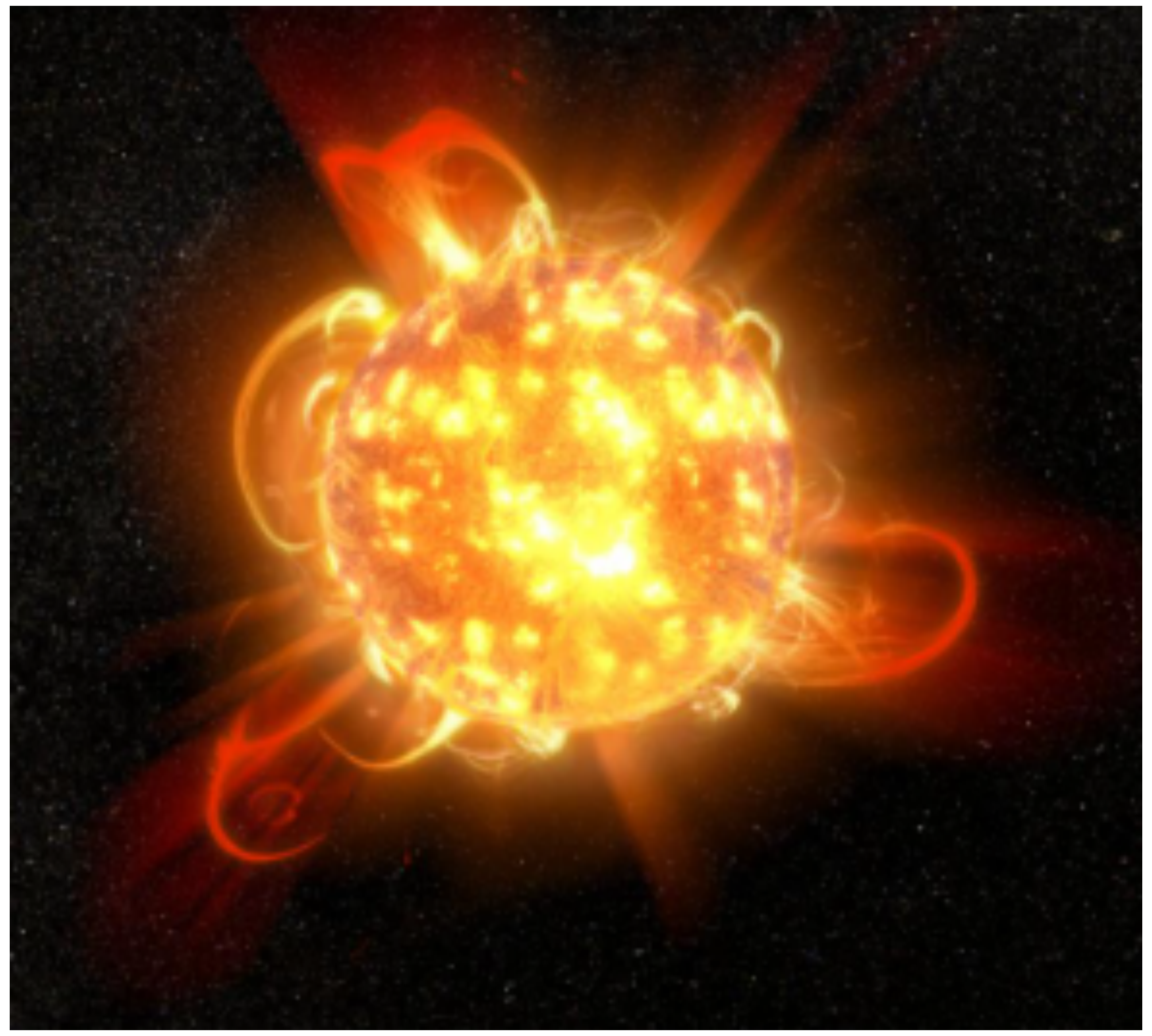

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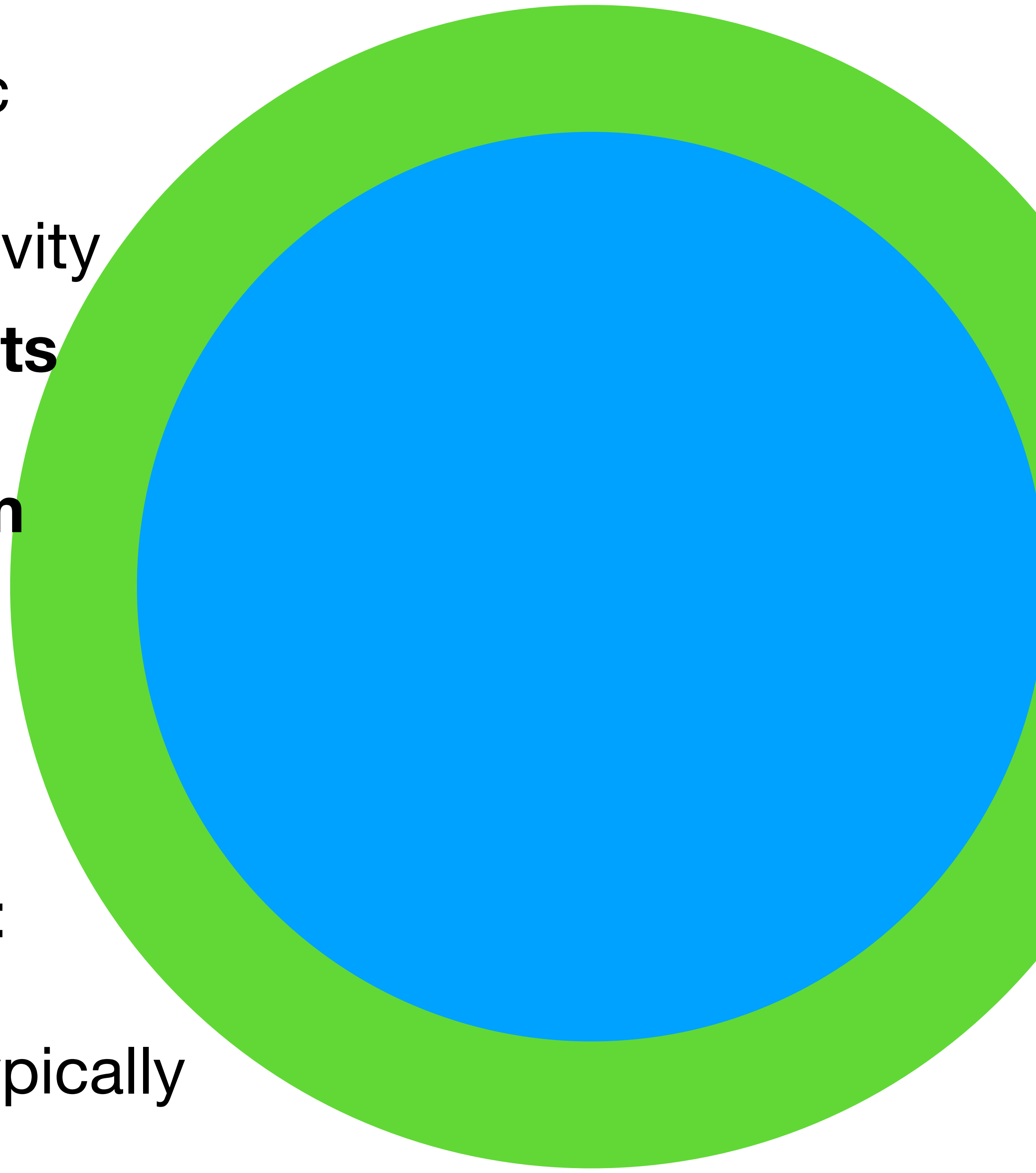

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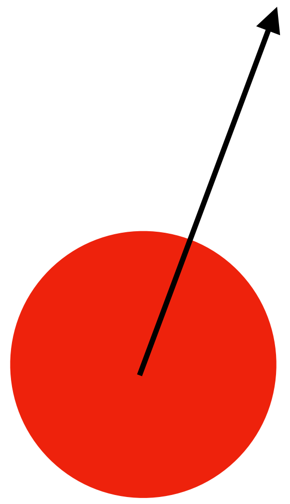

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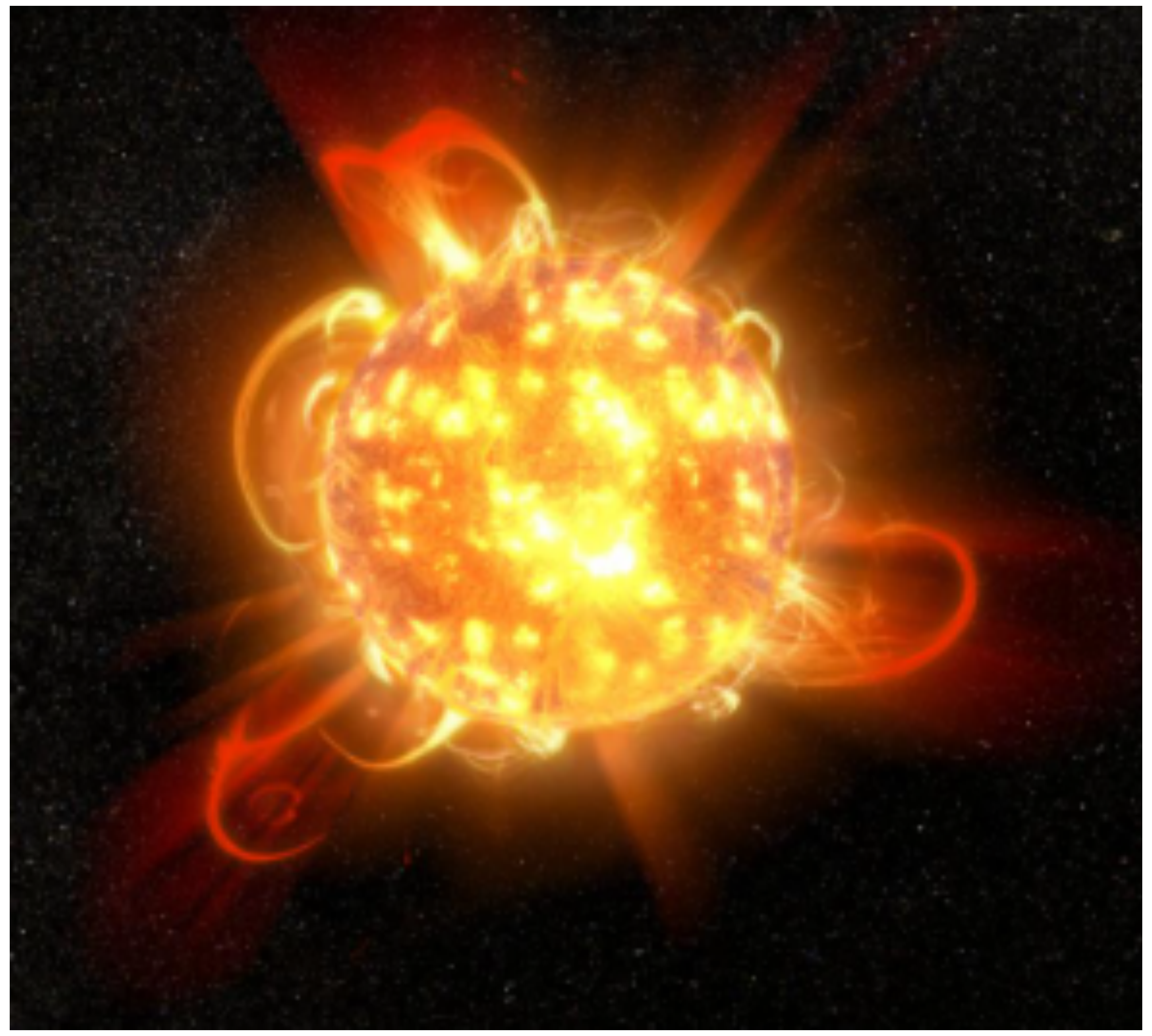

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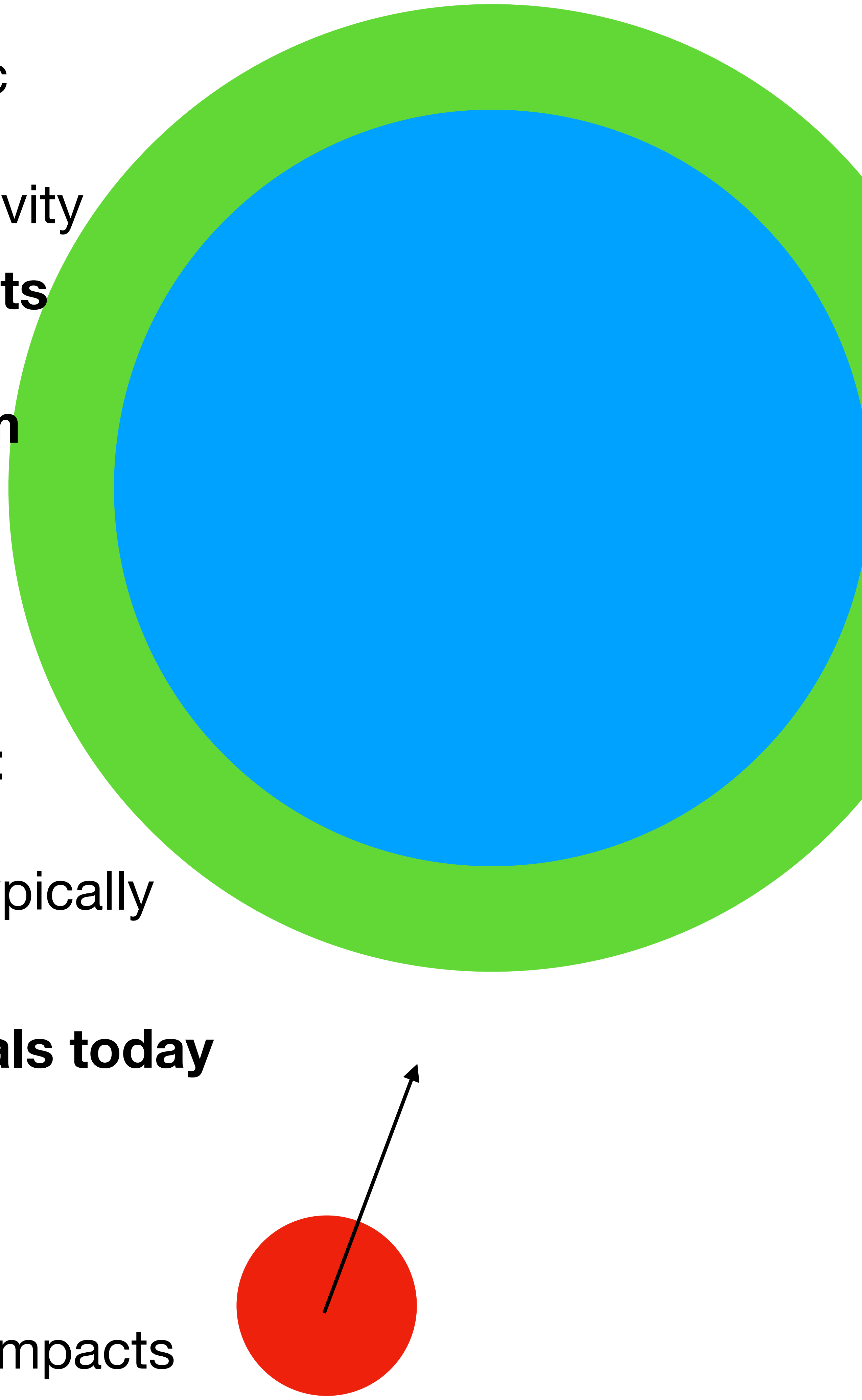

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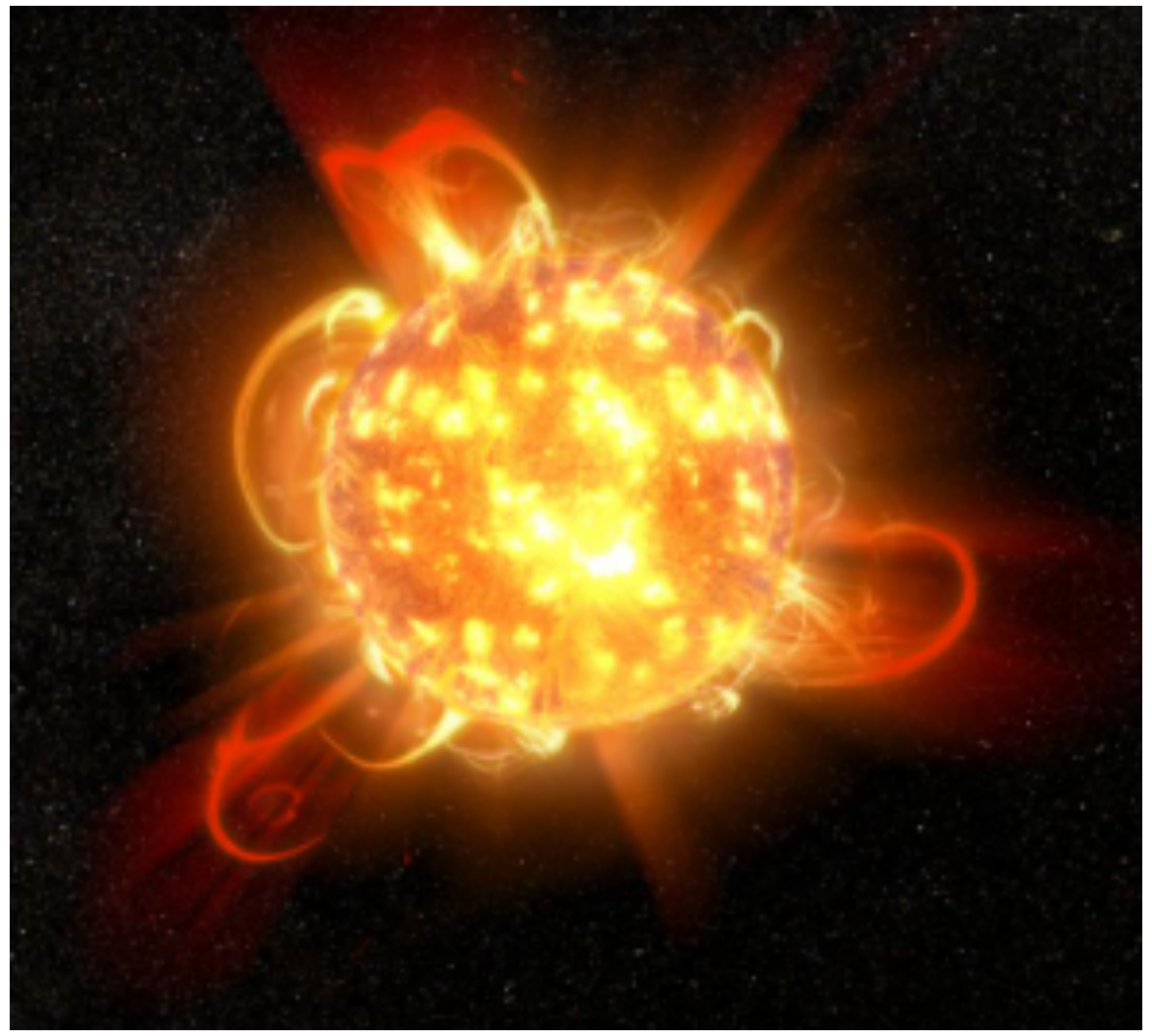

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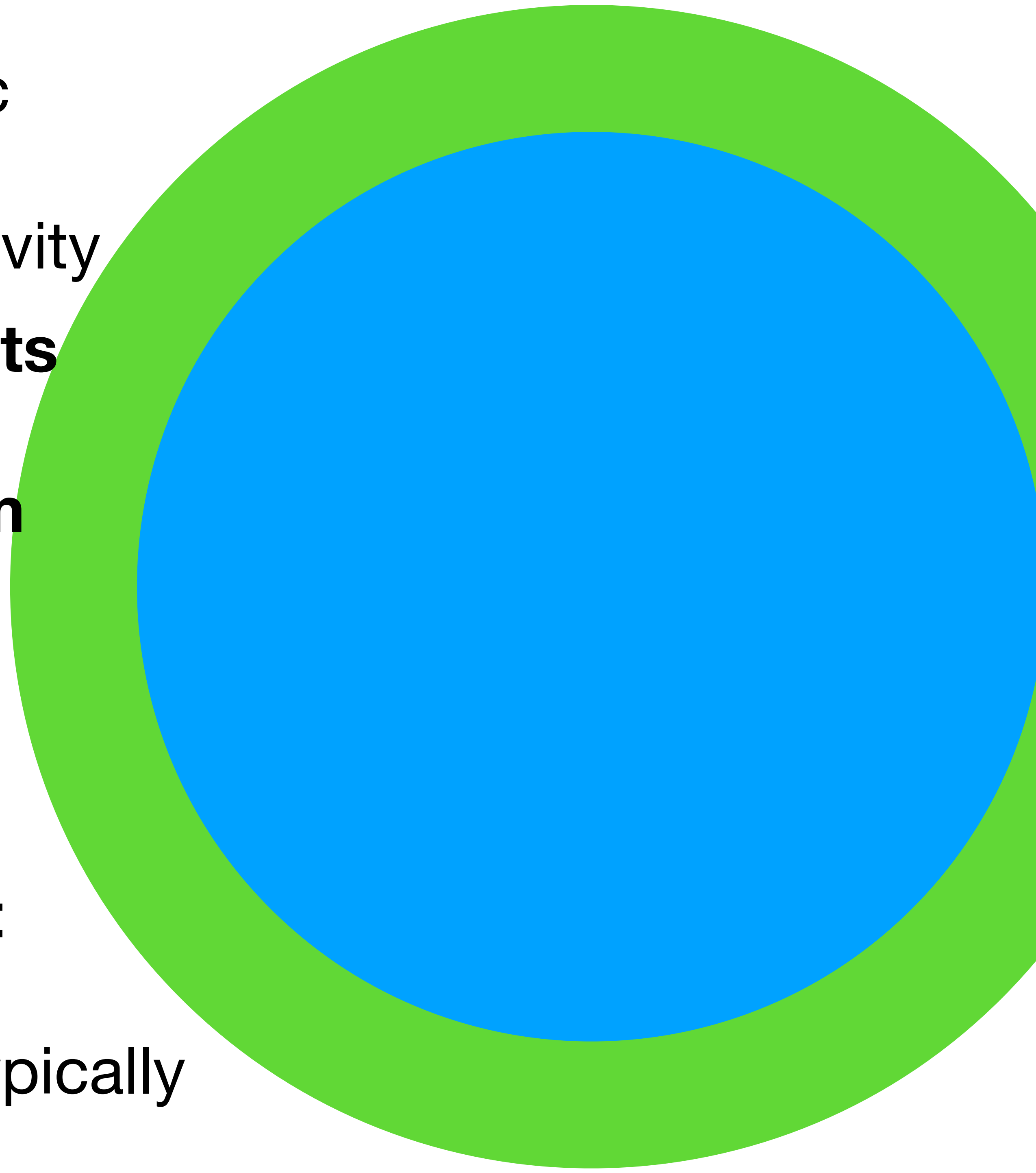

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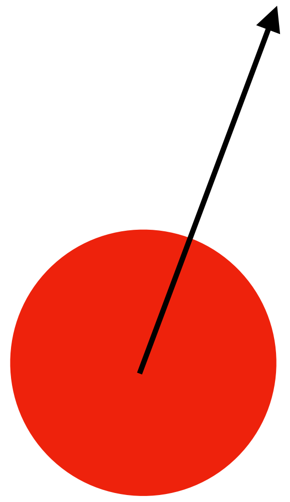

Important if happen. Impacts

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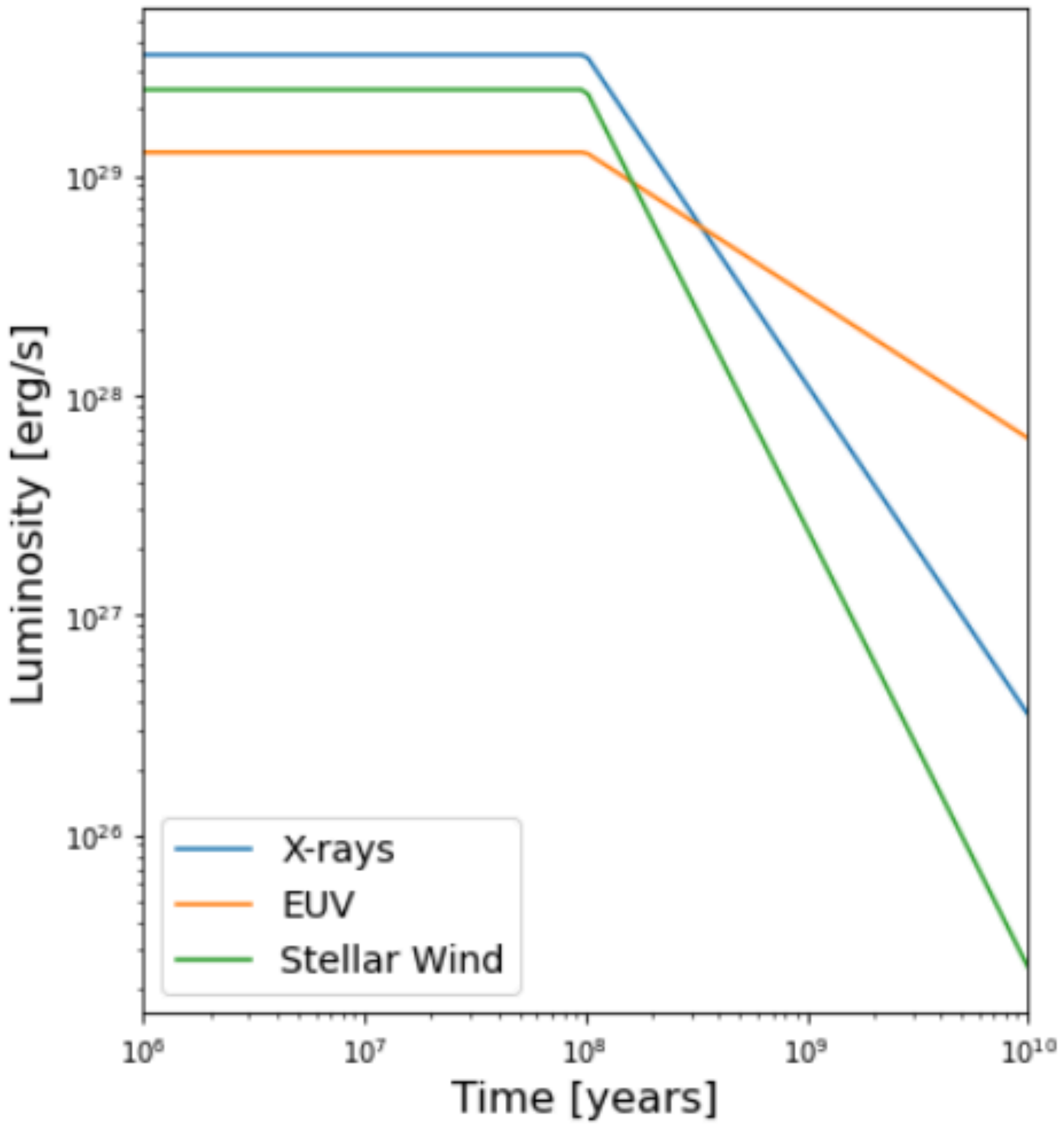
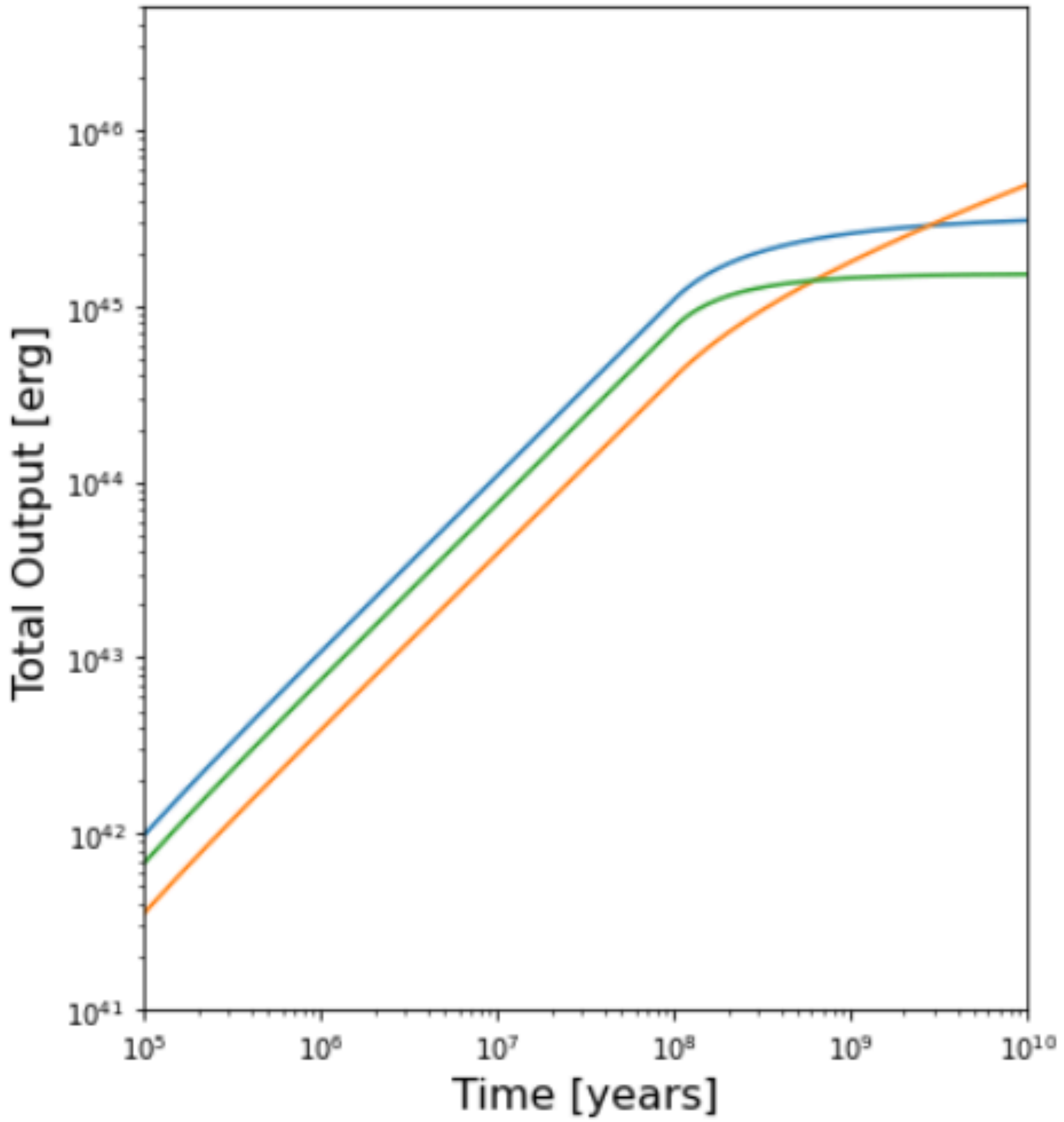
The energy required to unbind Earth's atmosphere in 10^9 years - 10^{34} erg

The physics of the different escape mechanisms tells you how efficiently you can use these different energy sources.

Energy scales over time





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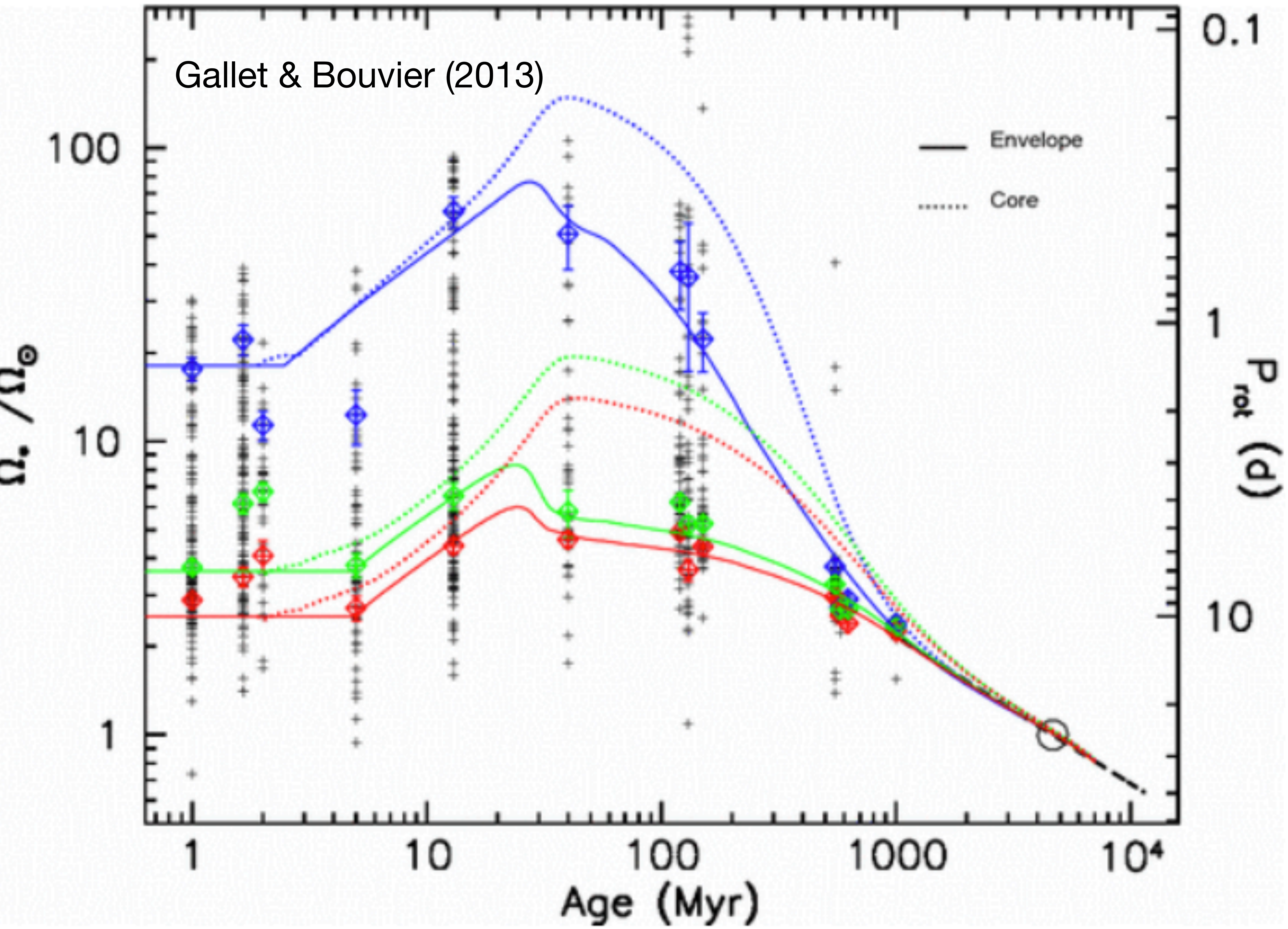

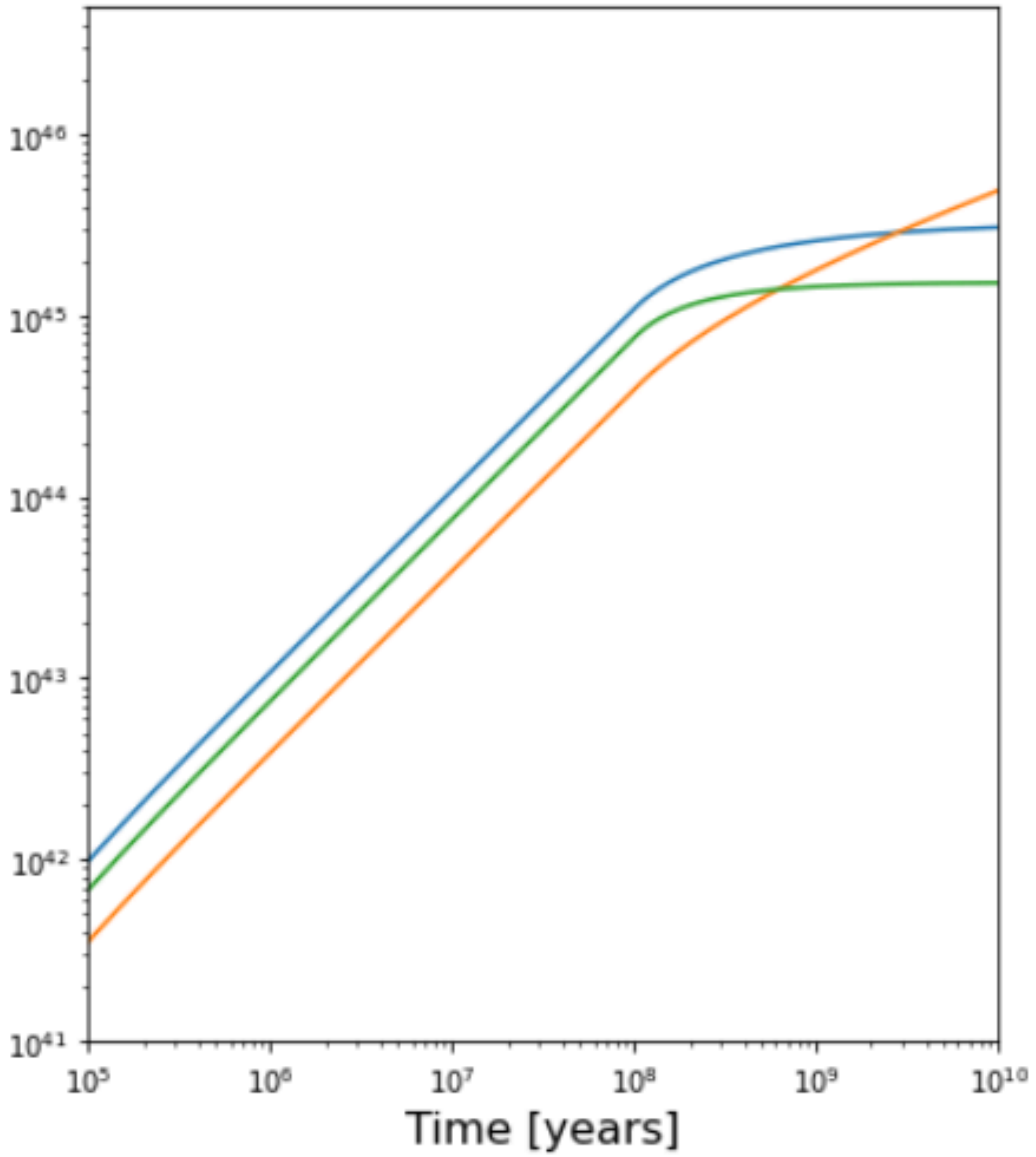

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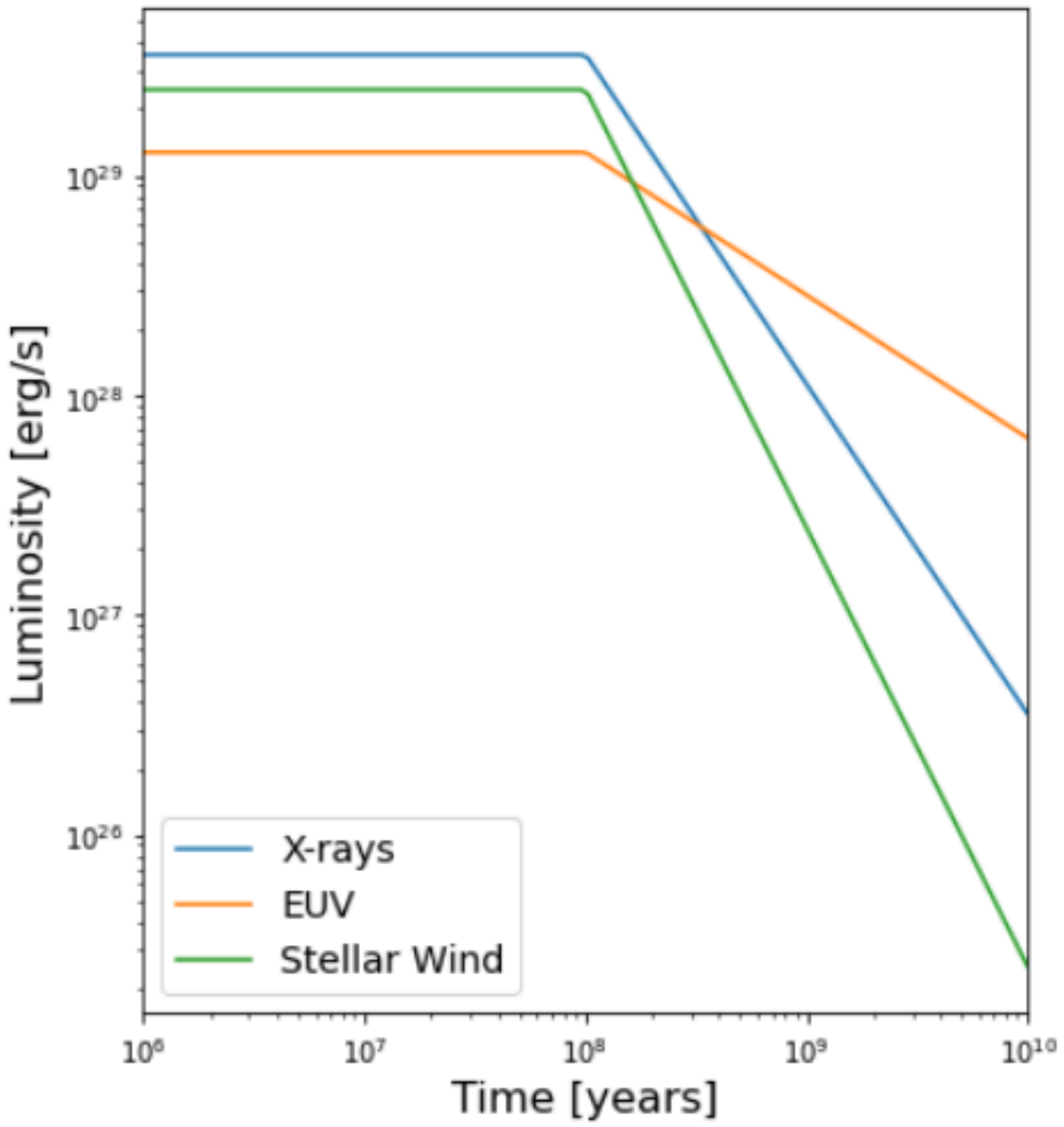

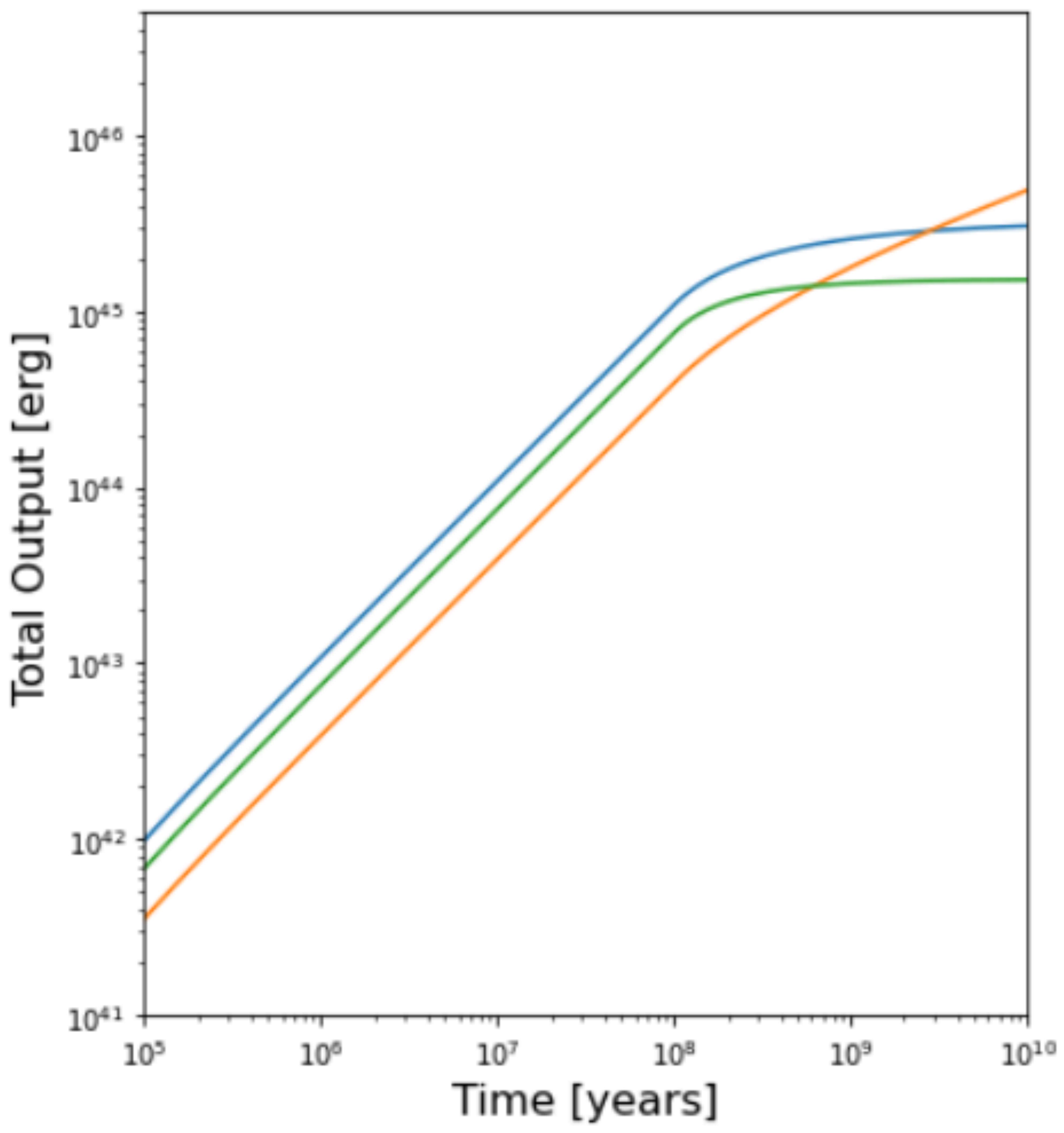

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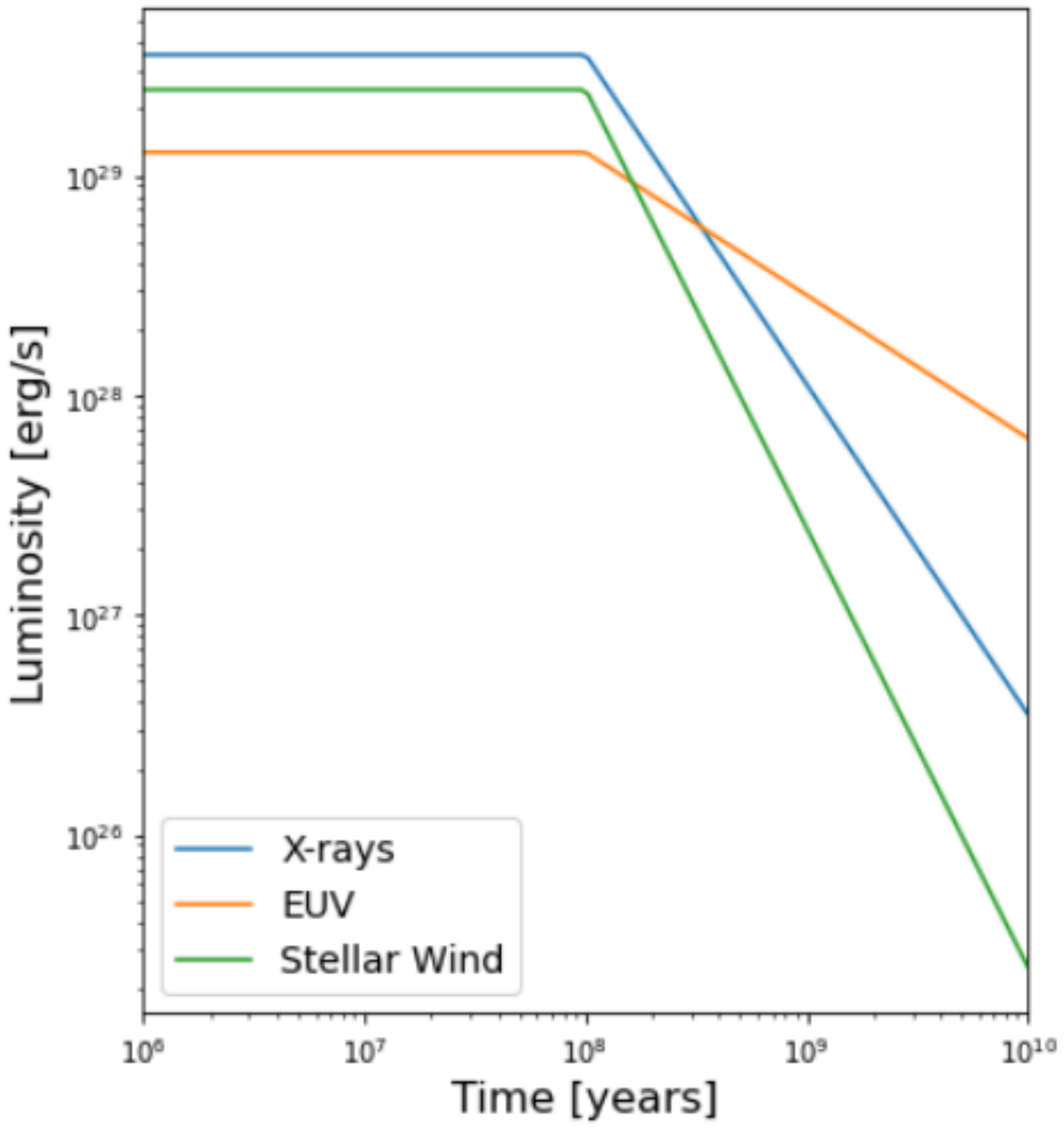

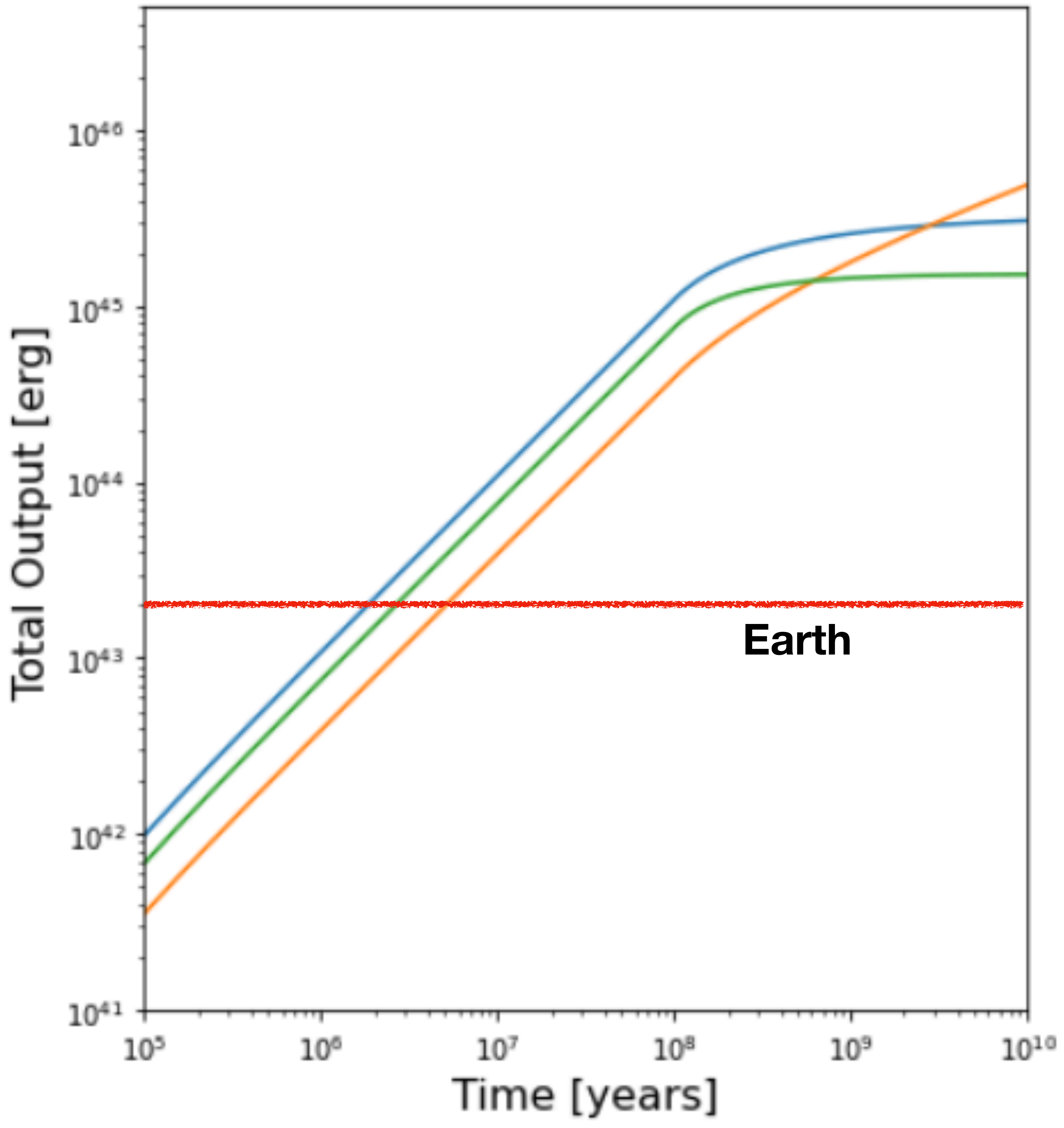

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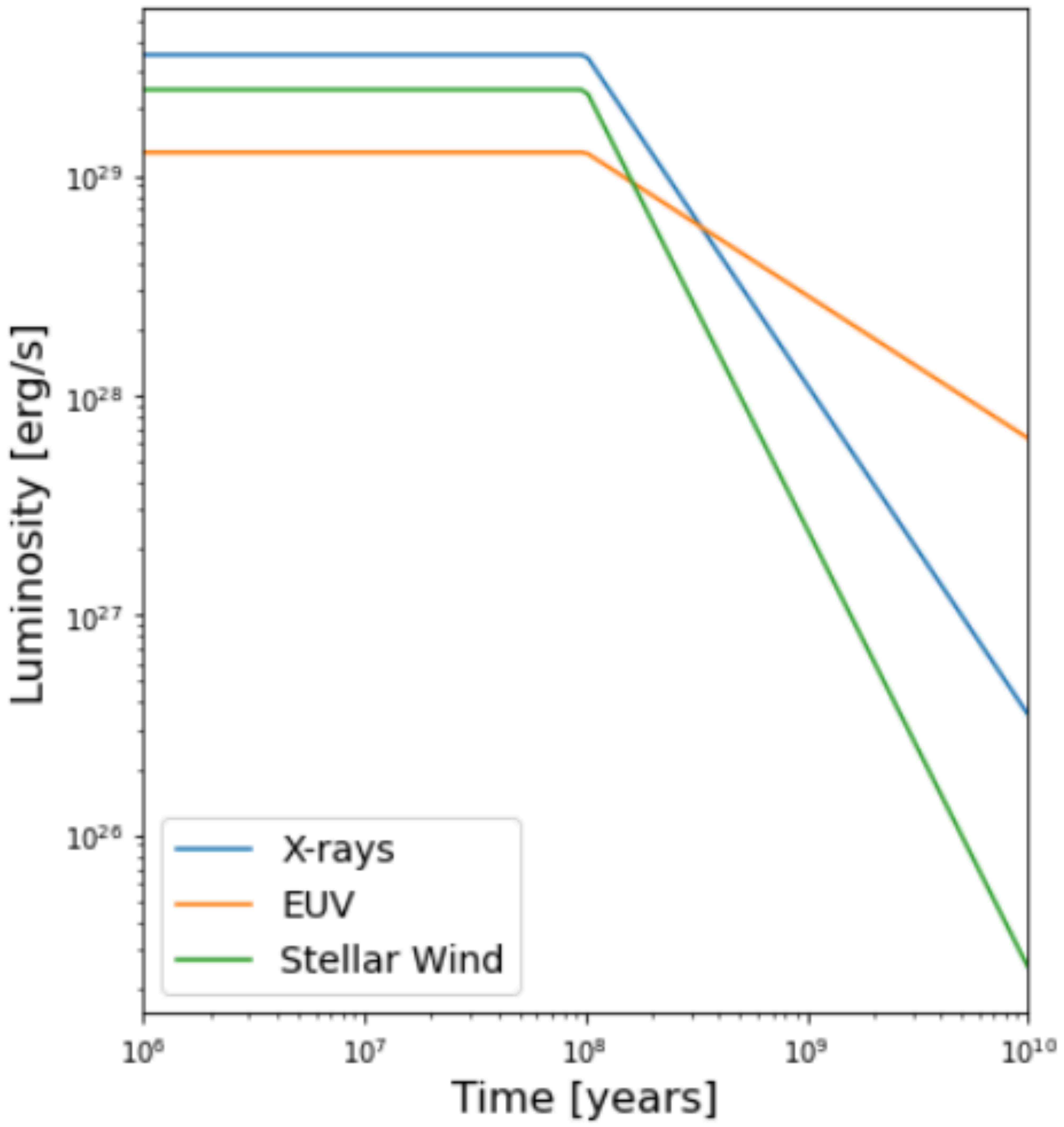

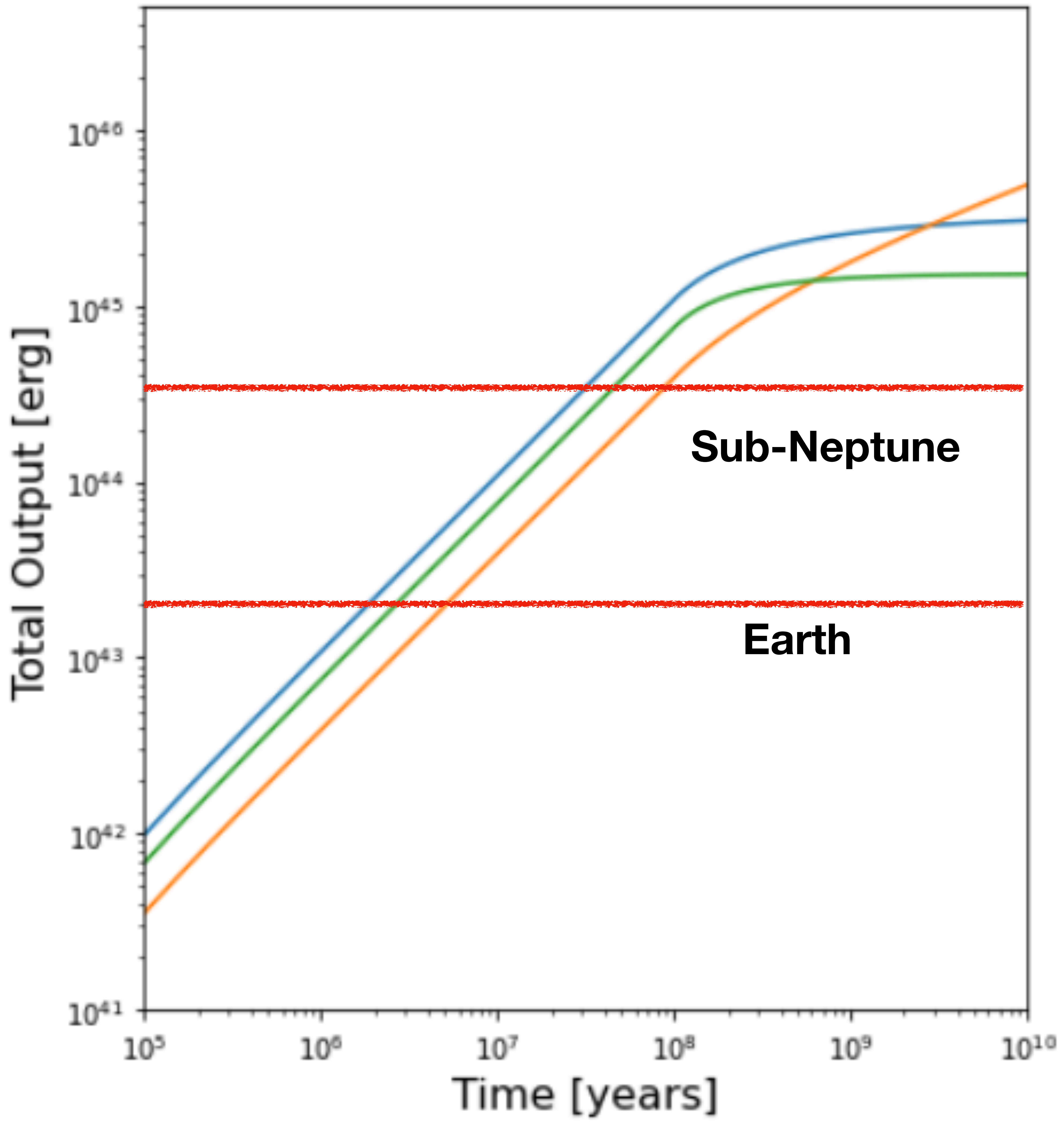

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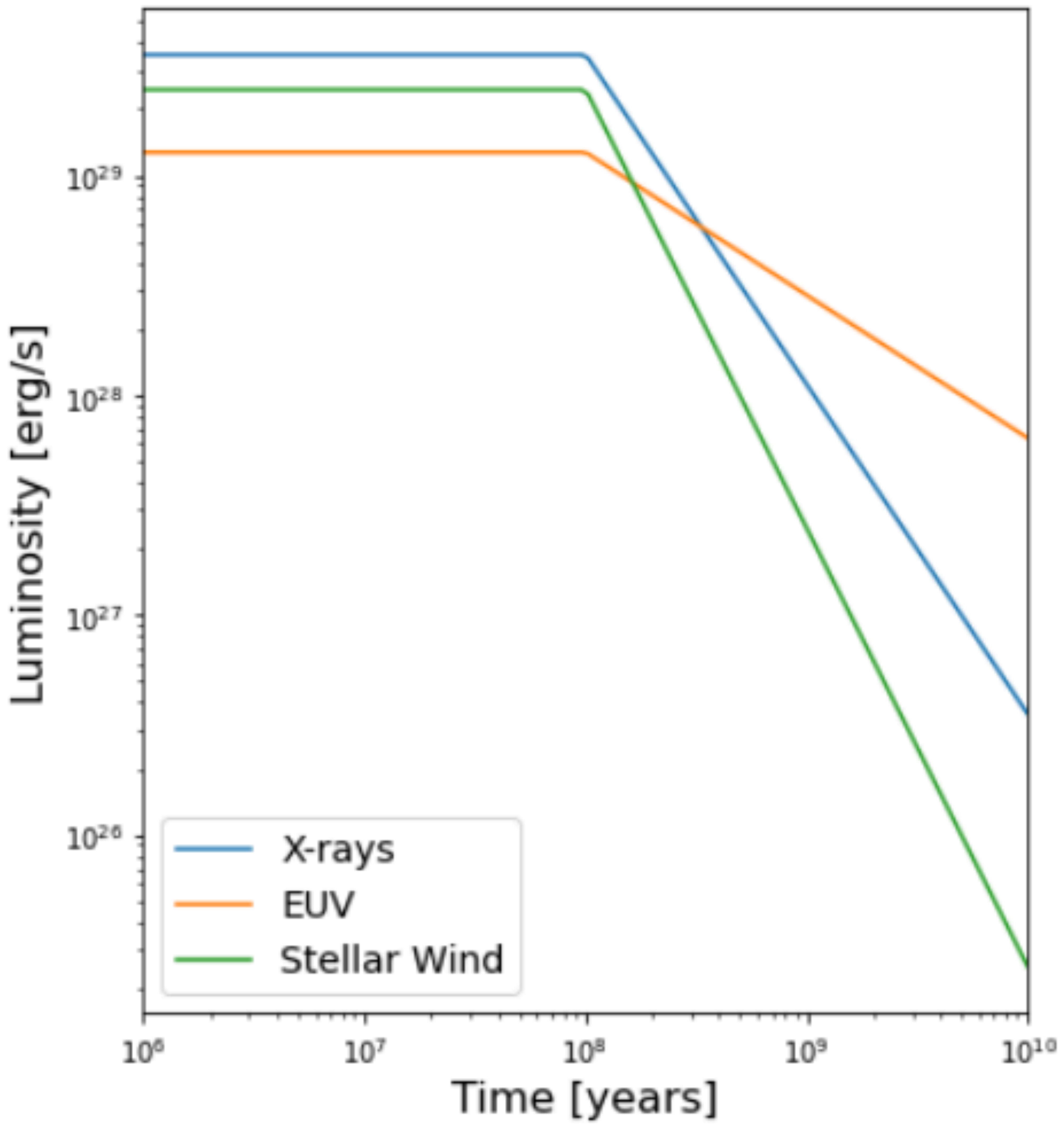
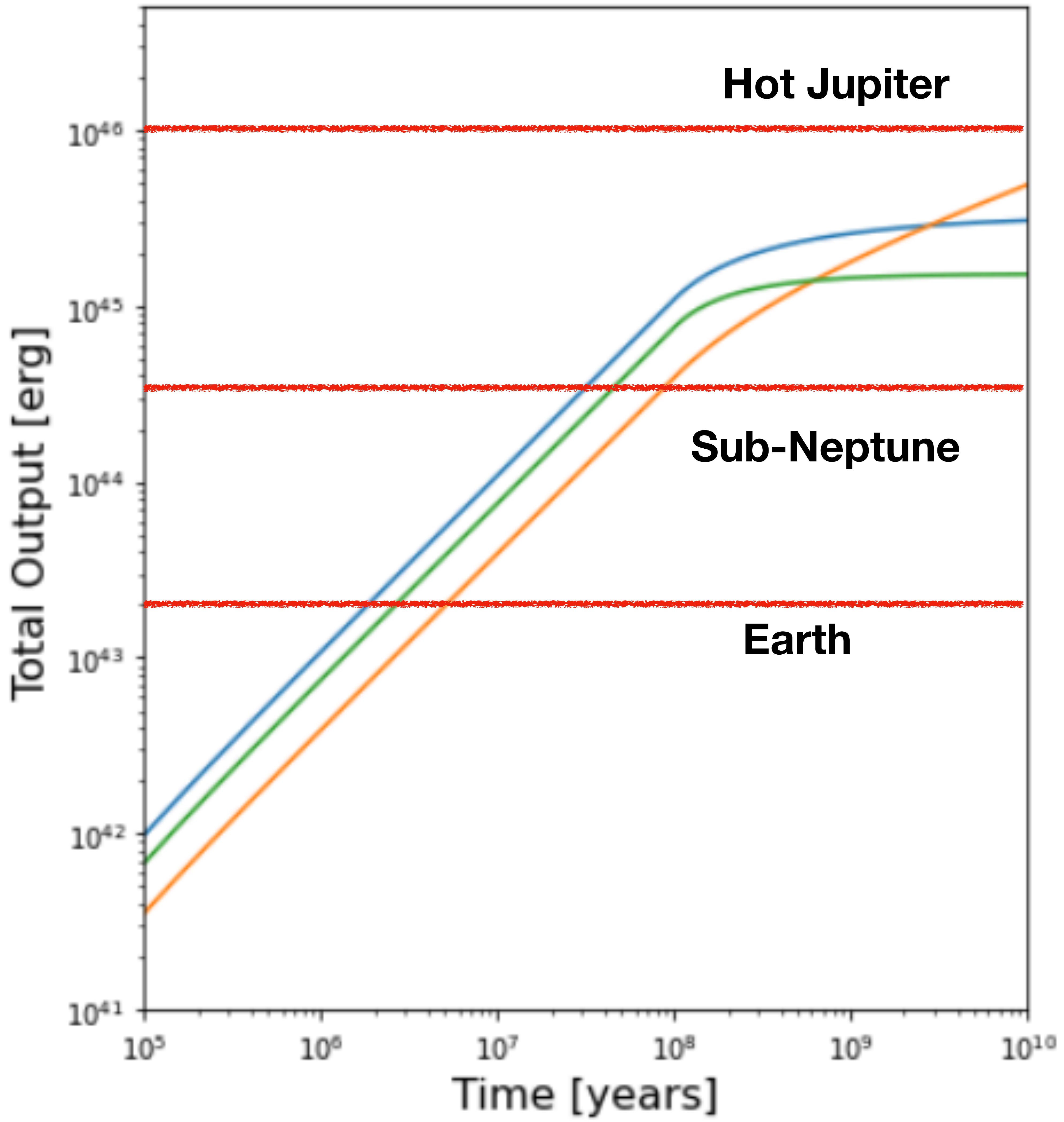
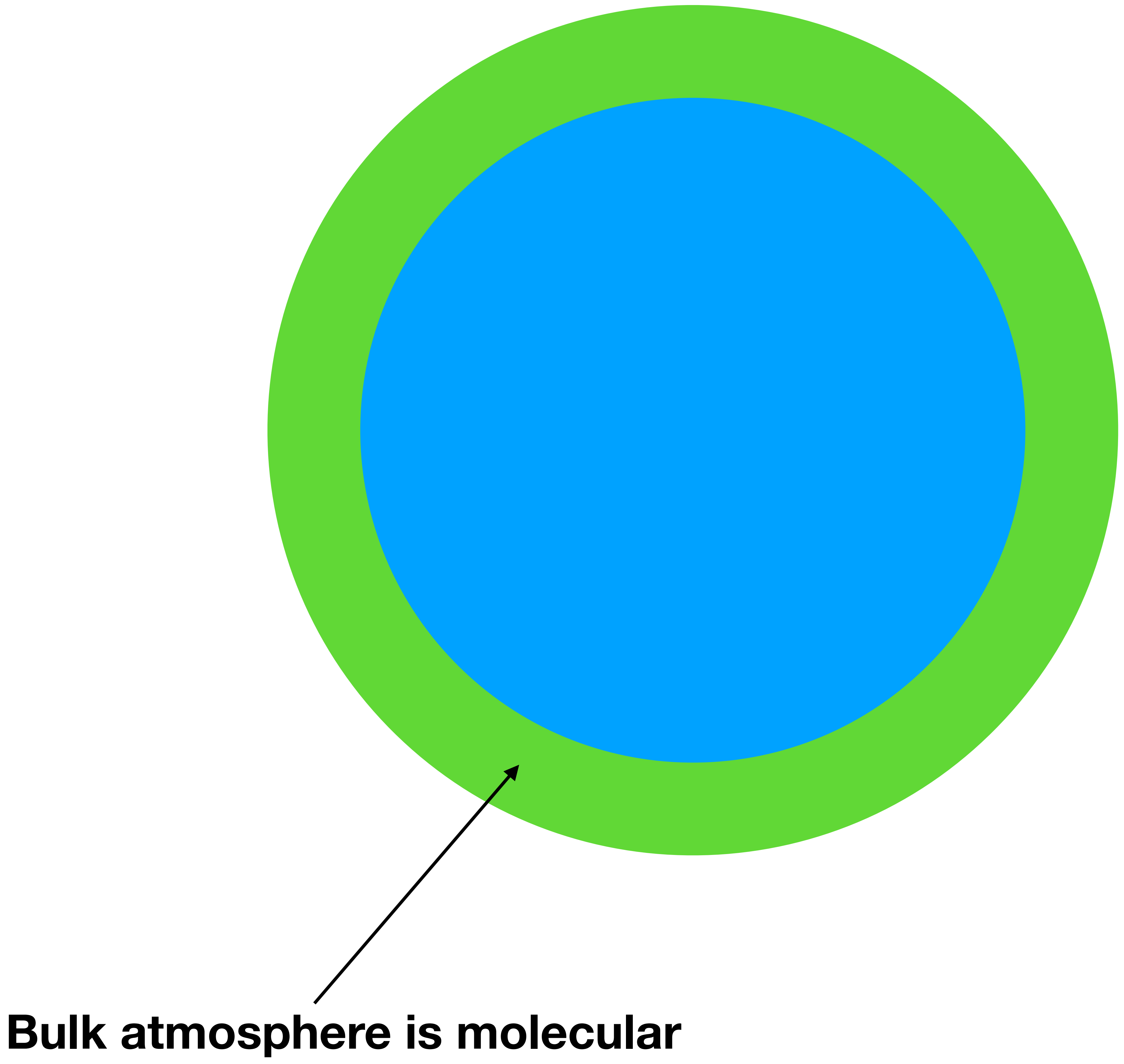




Properties of the upper atmosphere

$$T_{\rm eq} = T_* \sqrt{\frac{R_*}{2a}} \sim 1500\ {\rm K} \left(\frac{T_*}{5700\ {\rm K}}\right) \left(\frac{R_*}{R_\odot}\right)^{1/2} \left(\frac{a}{0.03\ {\rm AU}}\right)^{-1/2}$$



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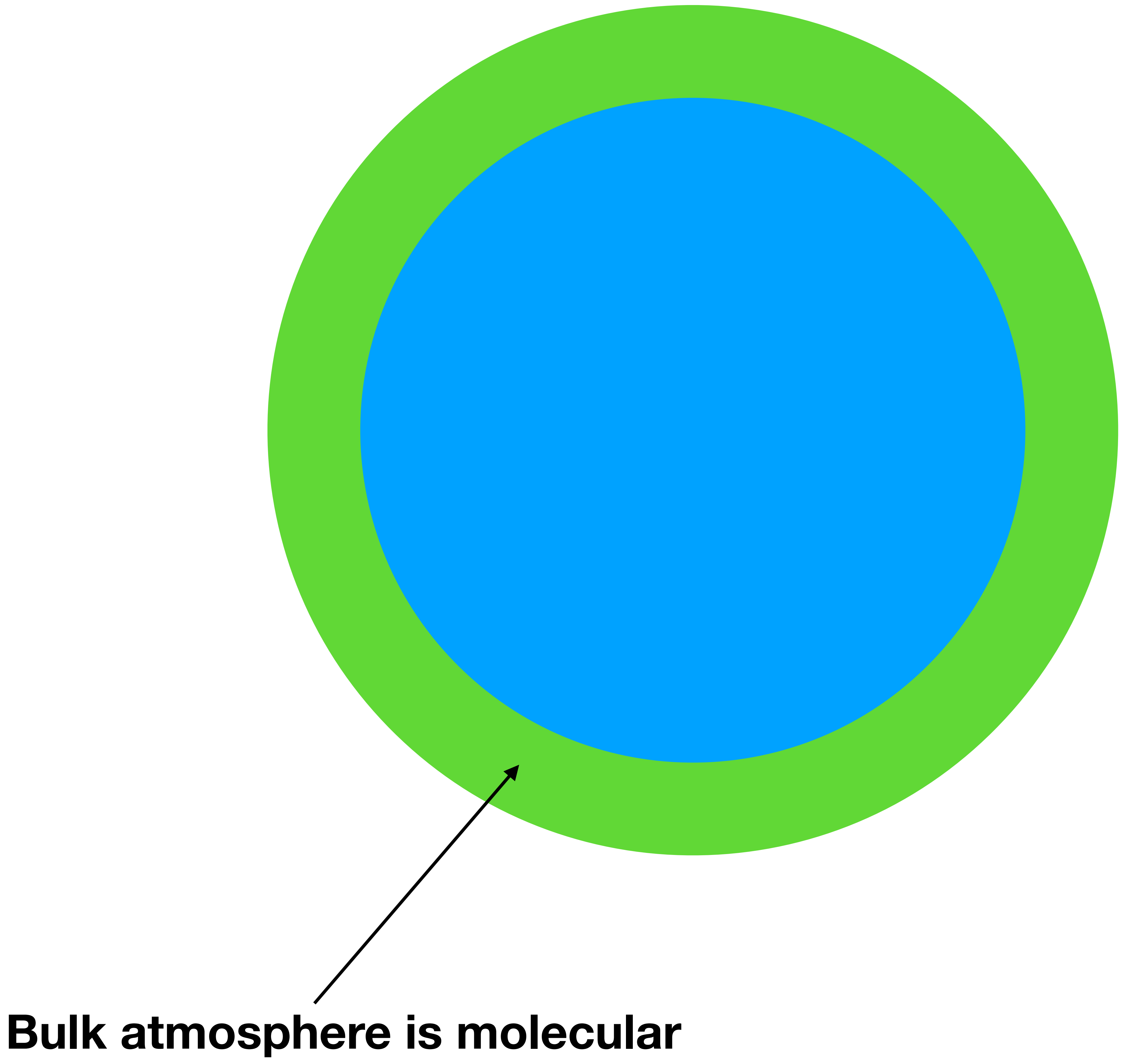

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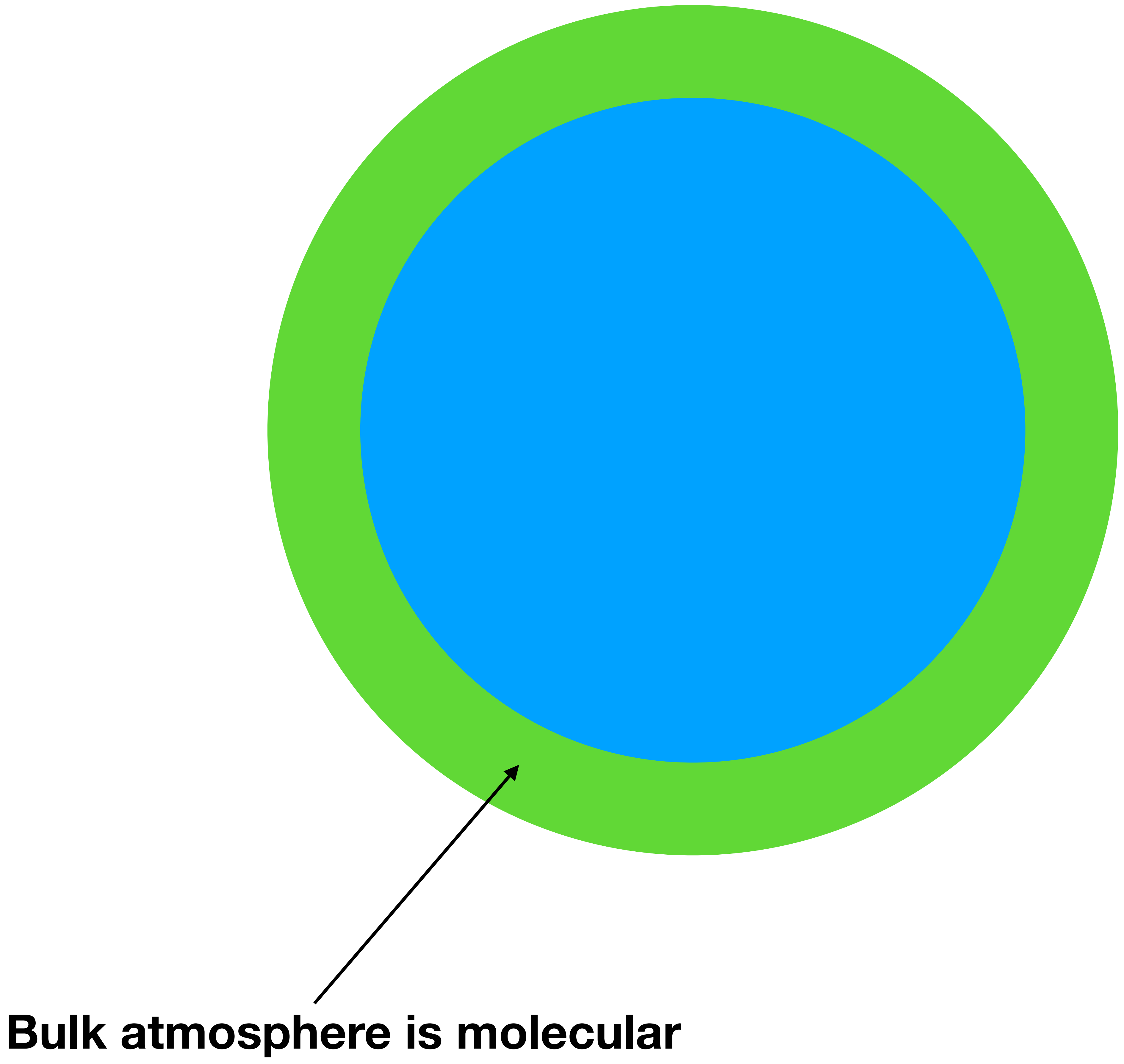

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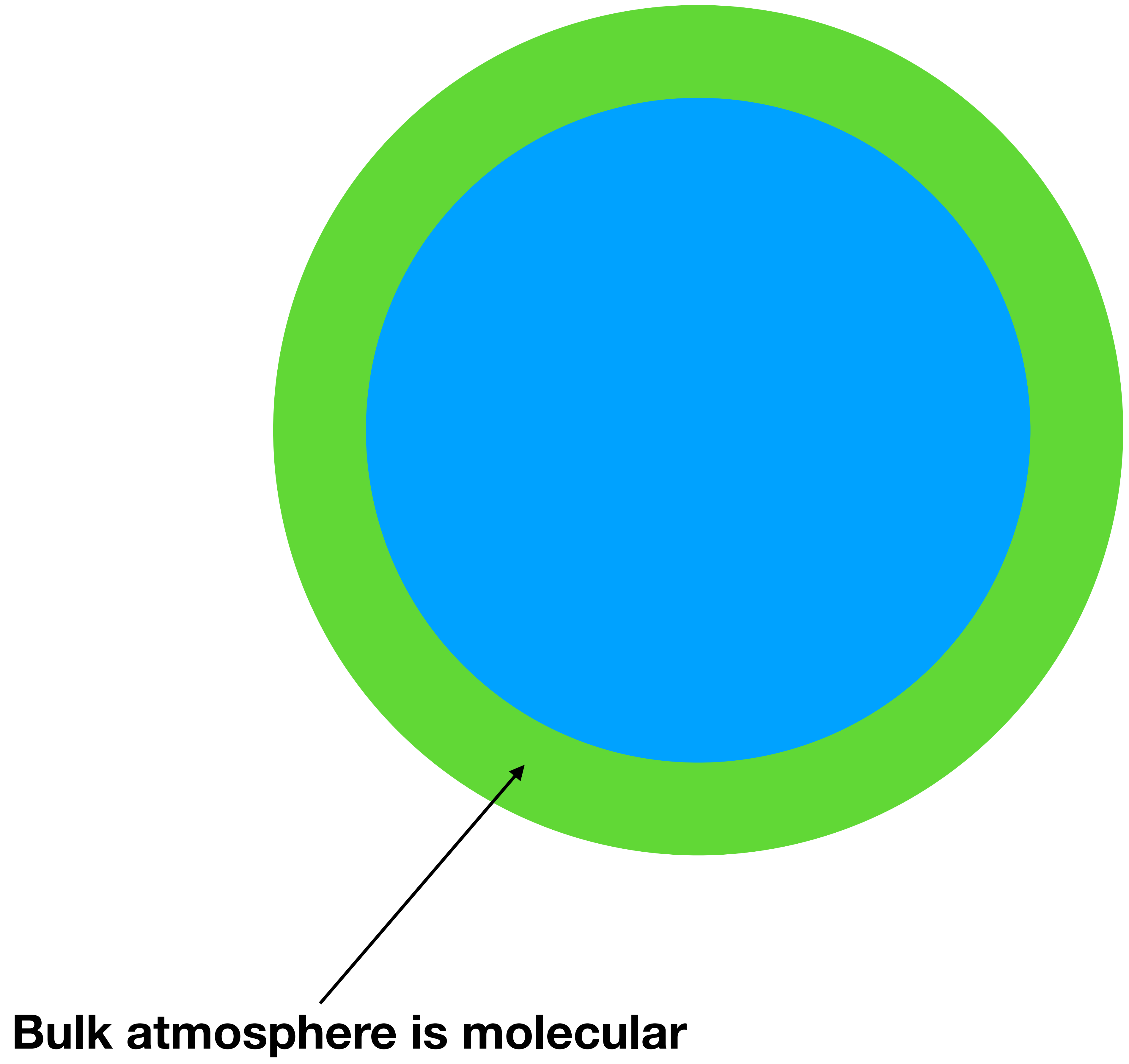

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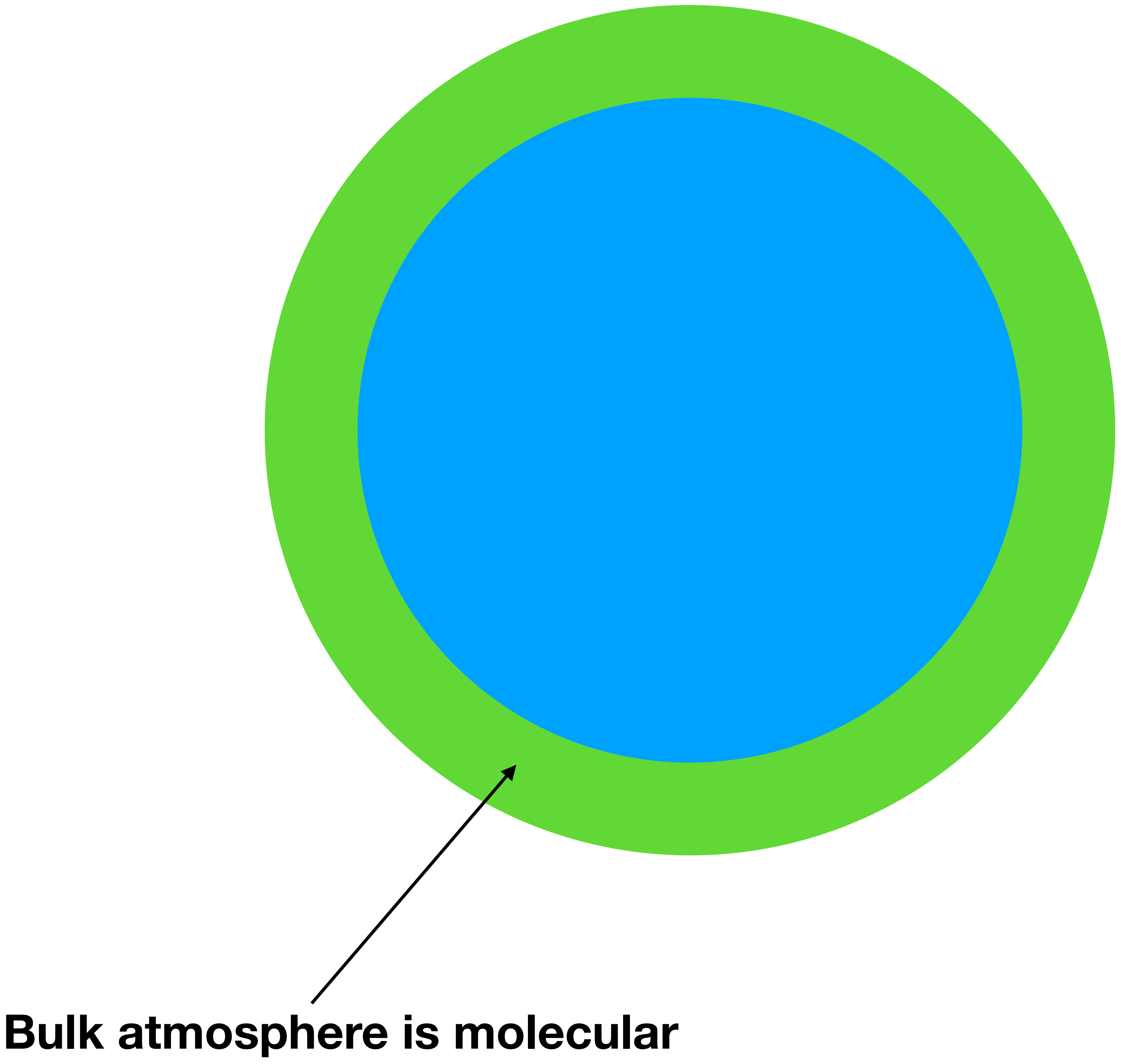

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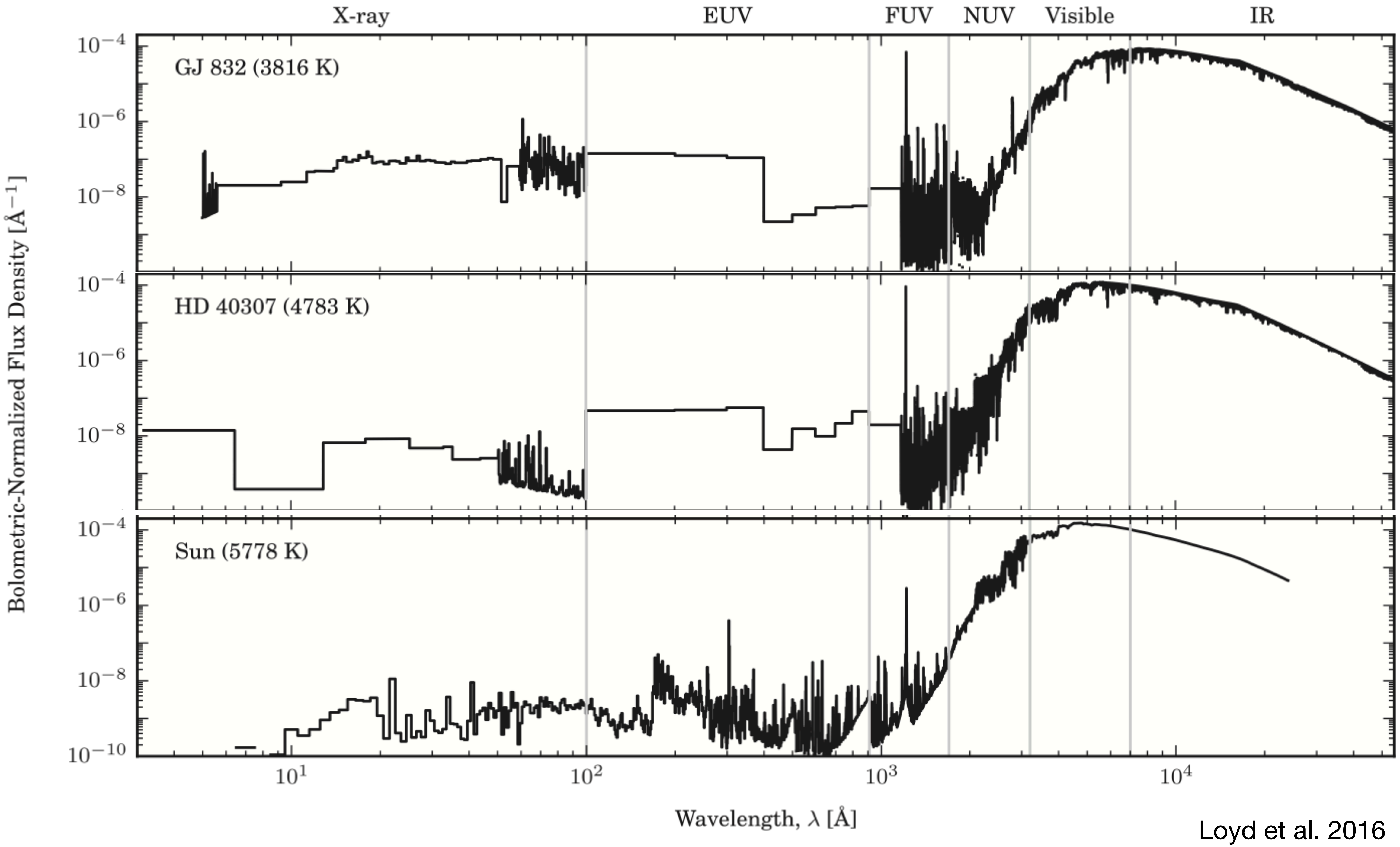
A star’s spectrum



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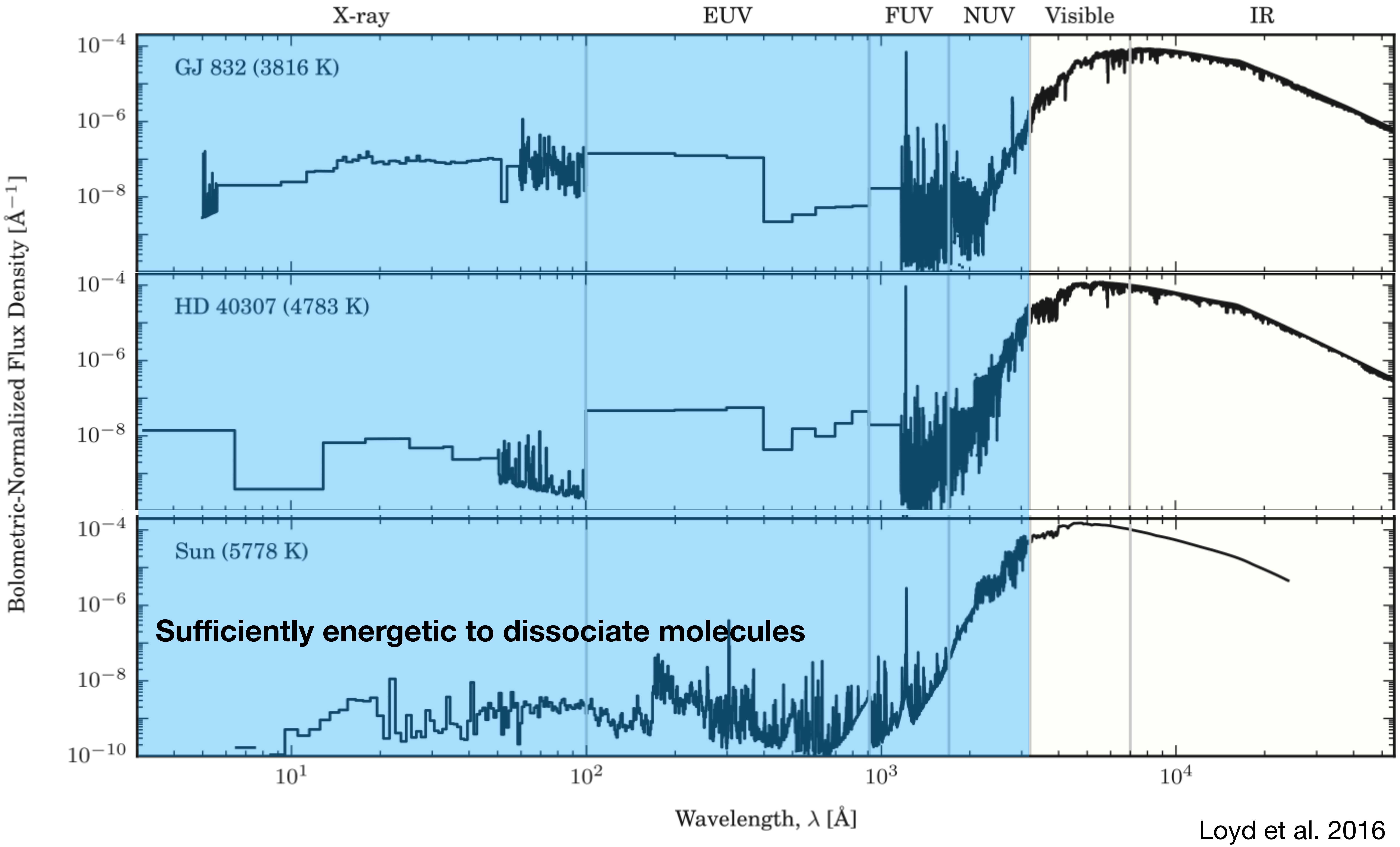

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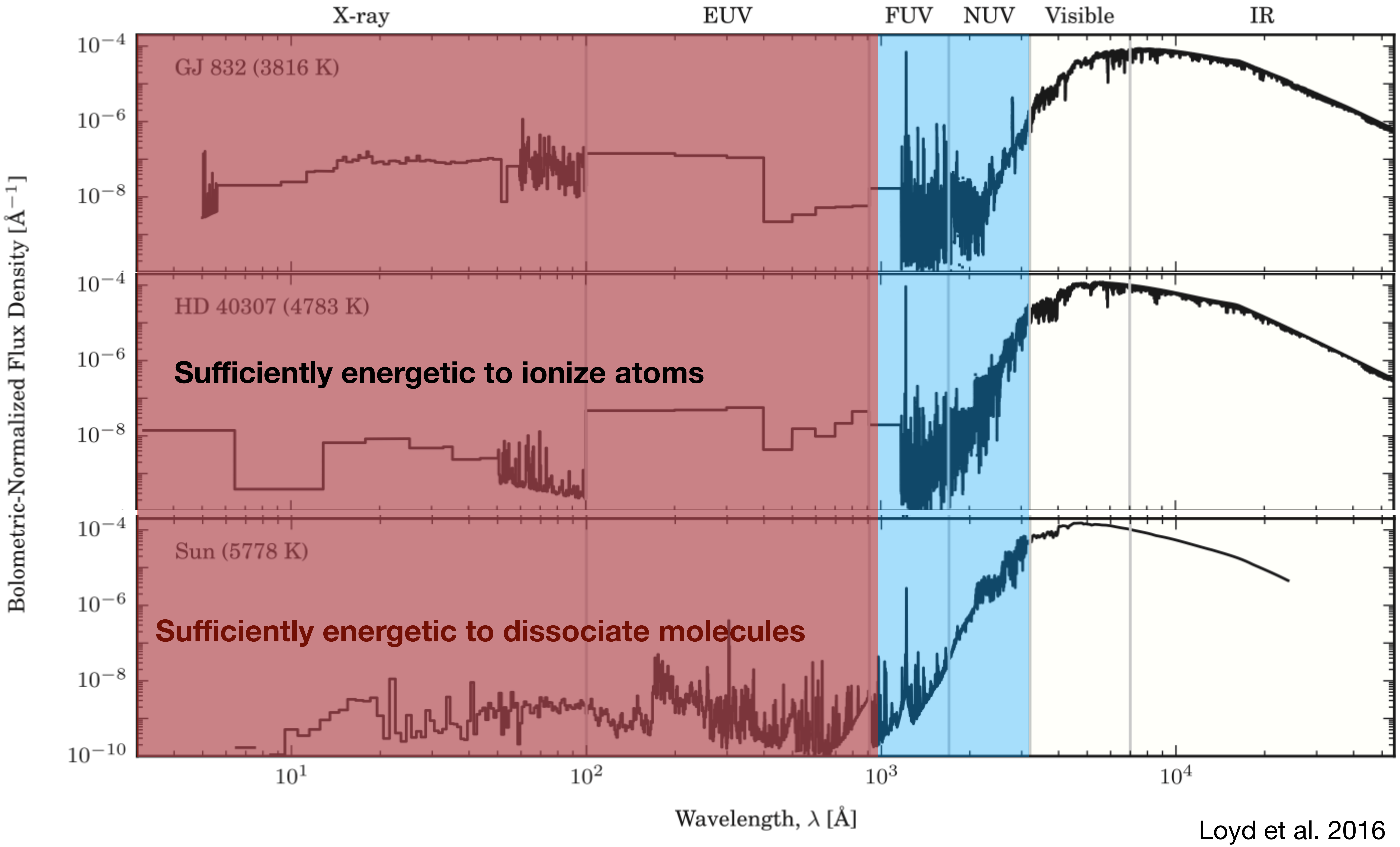

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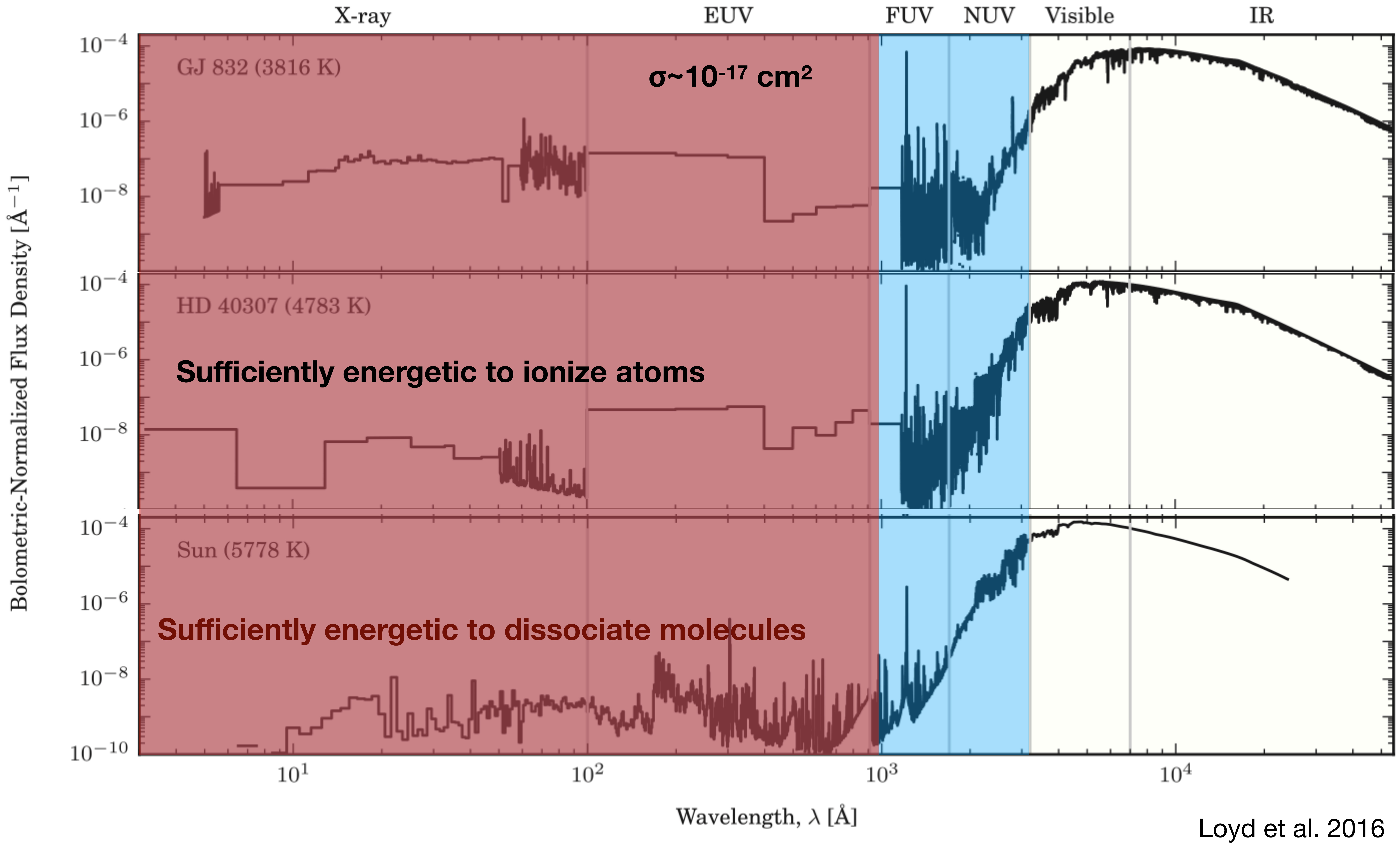

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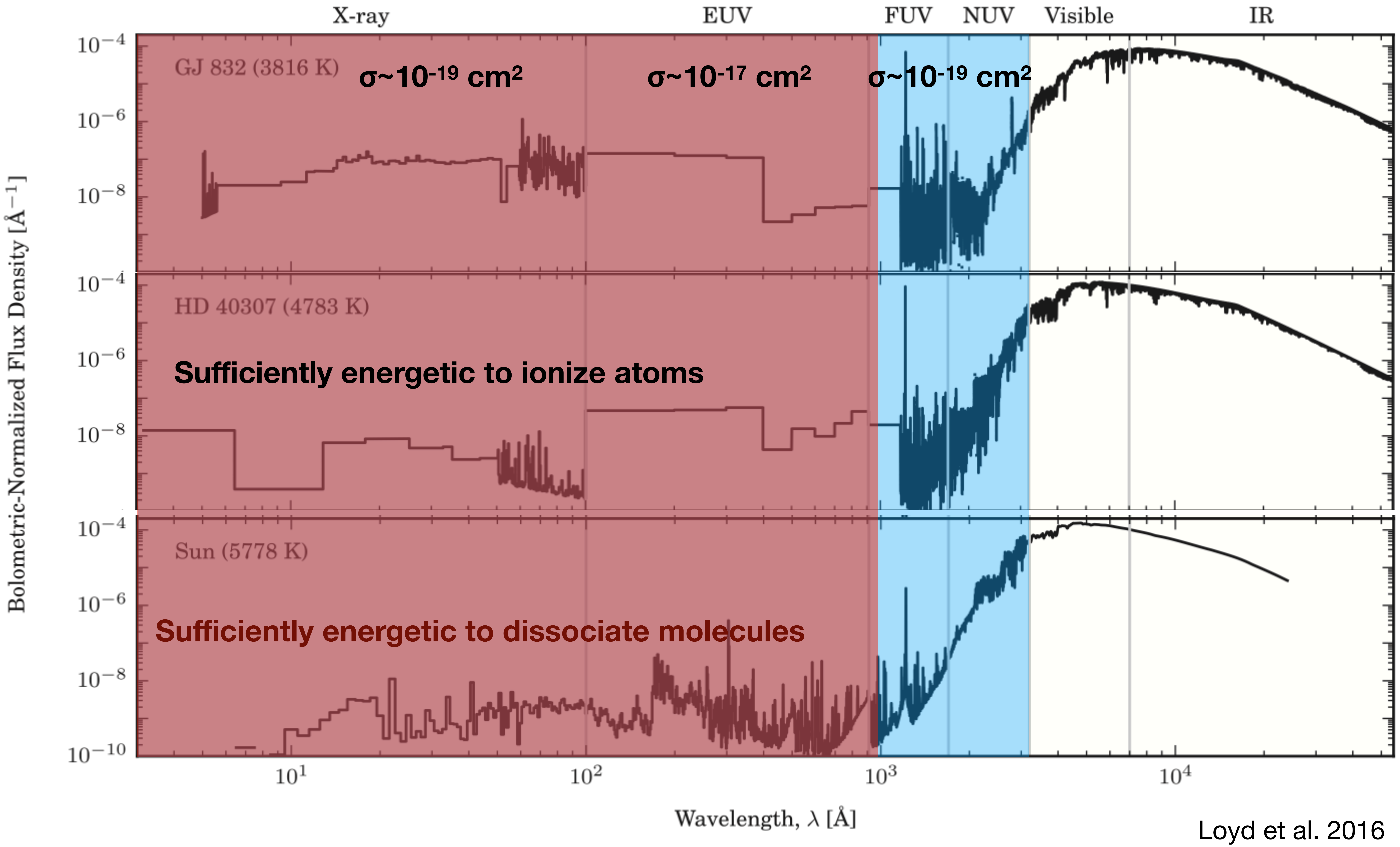

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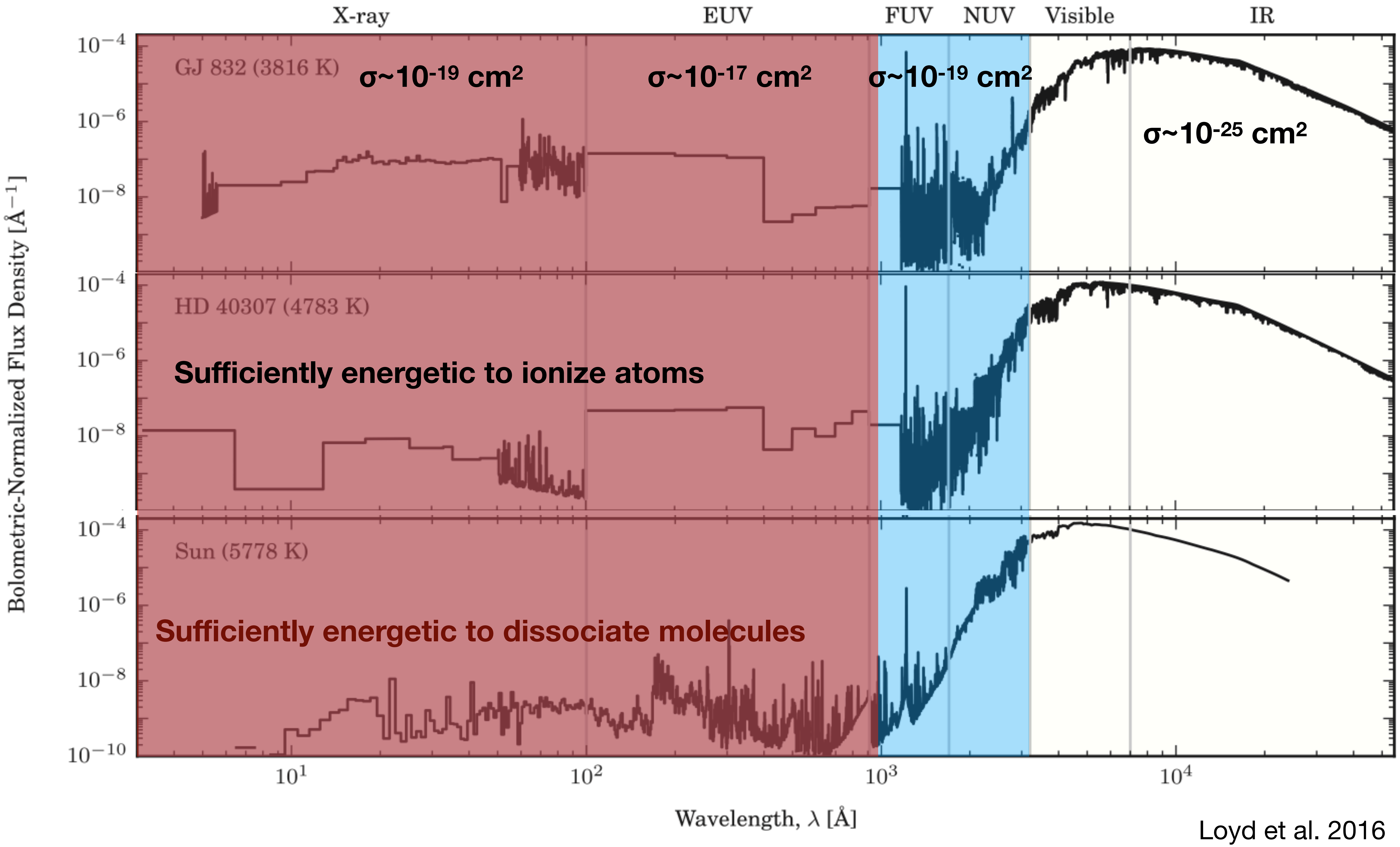

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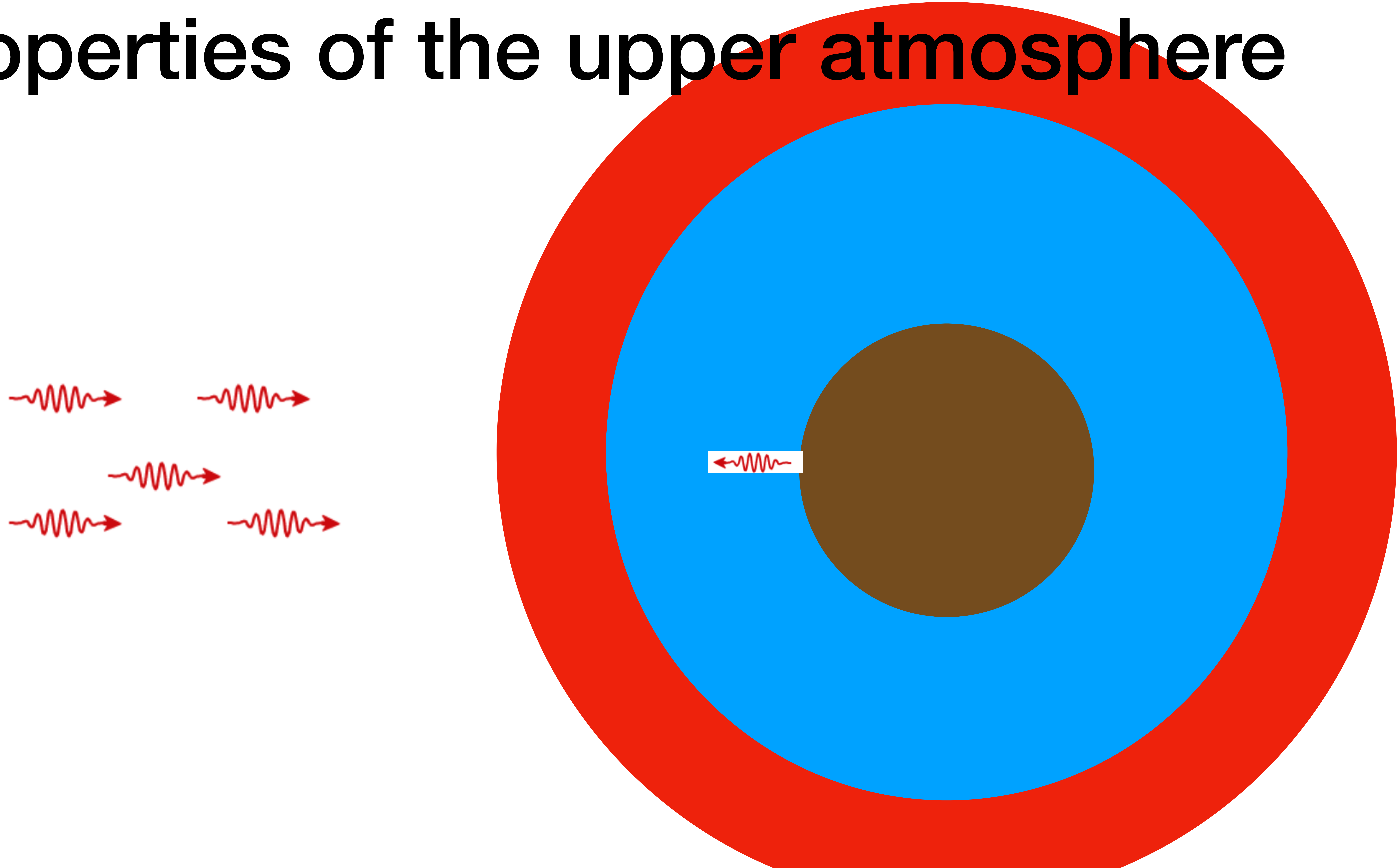

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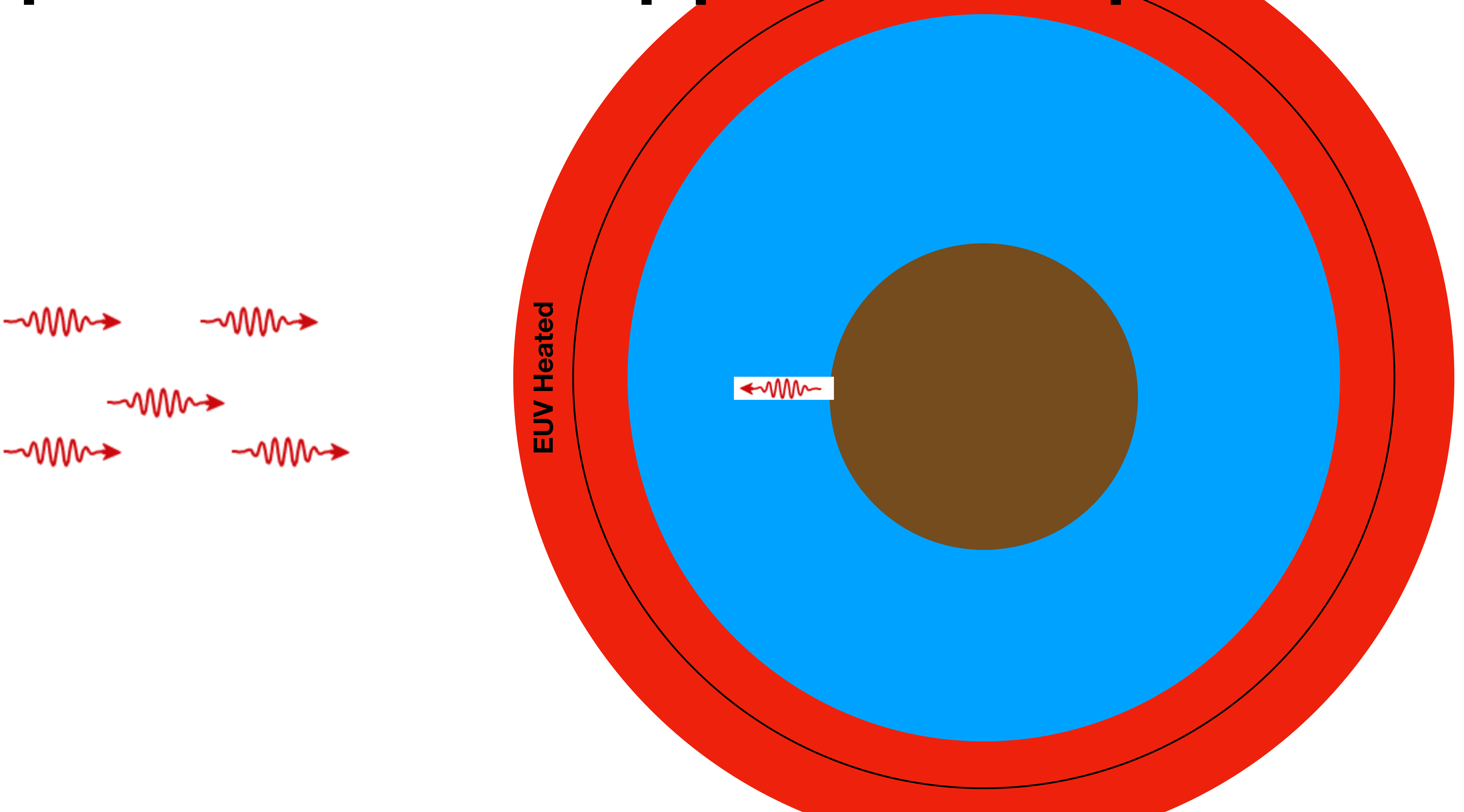

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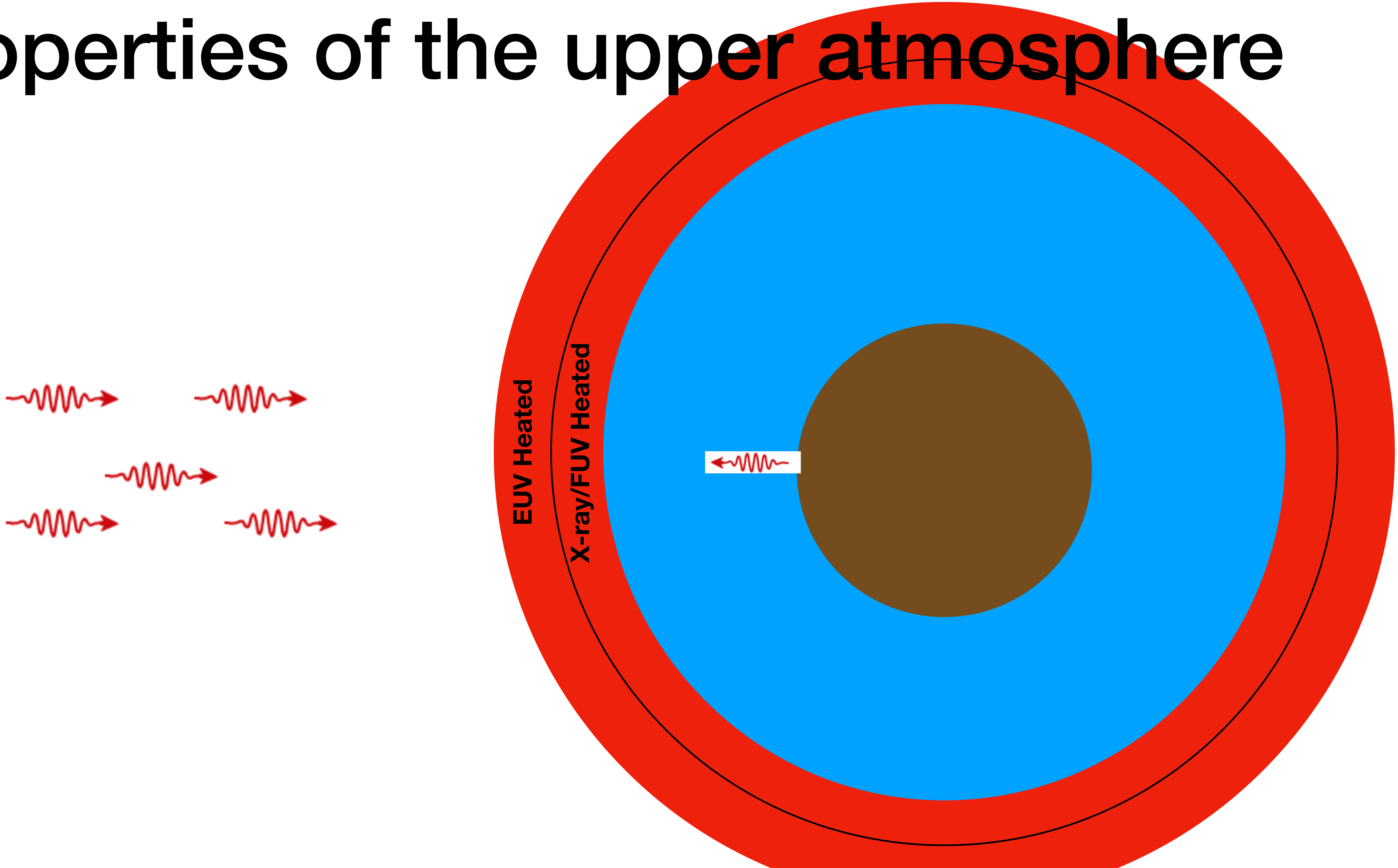

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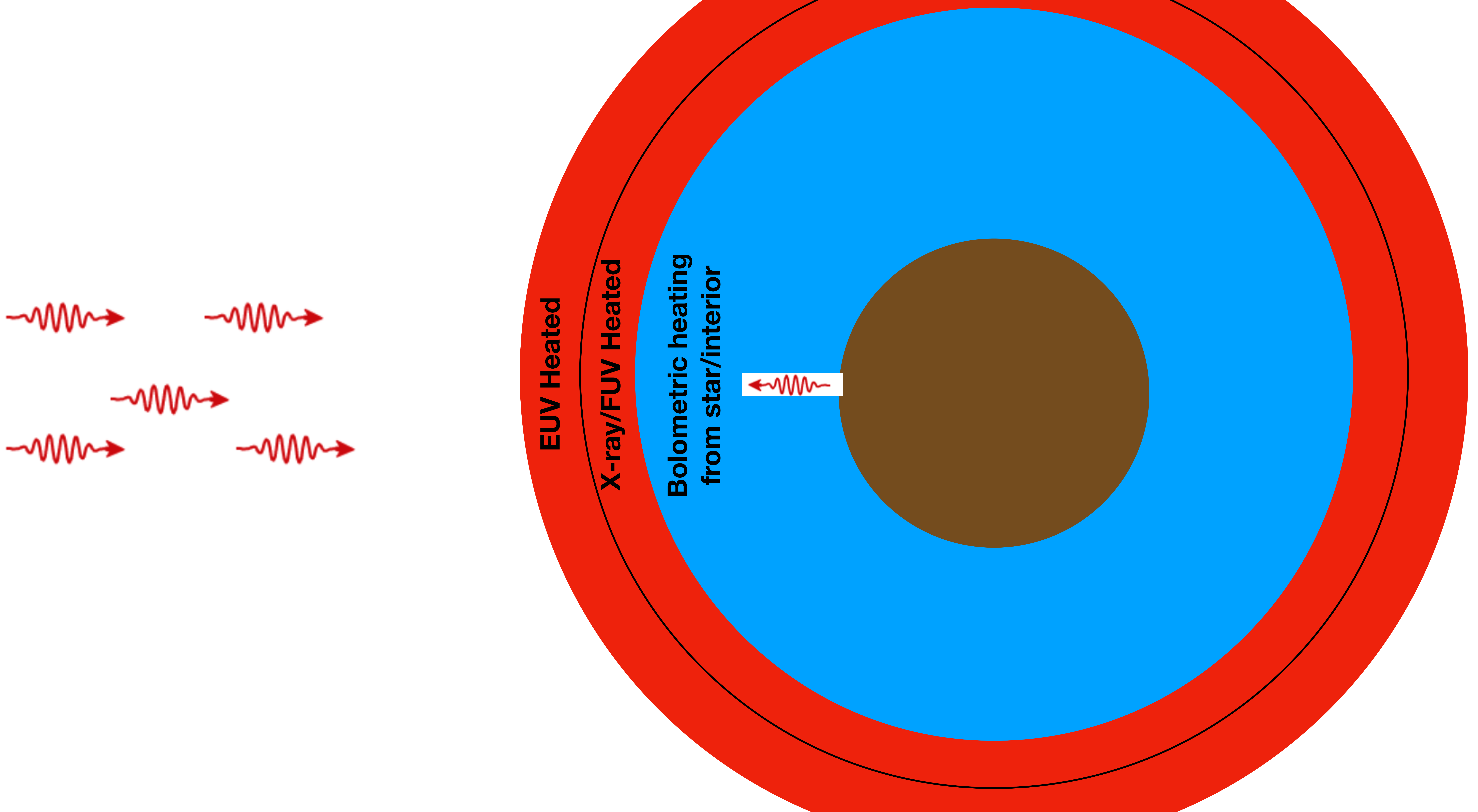

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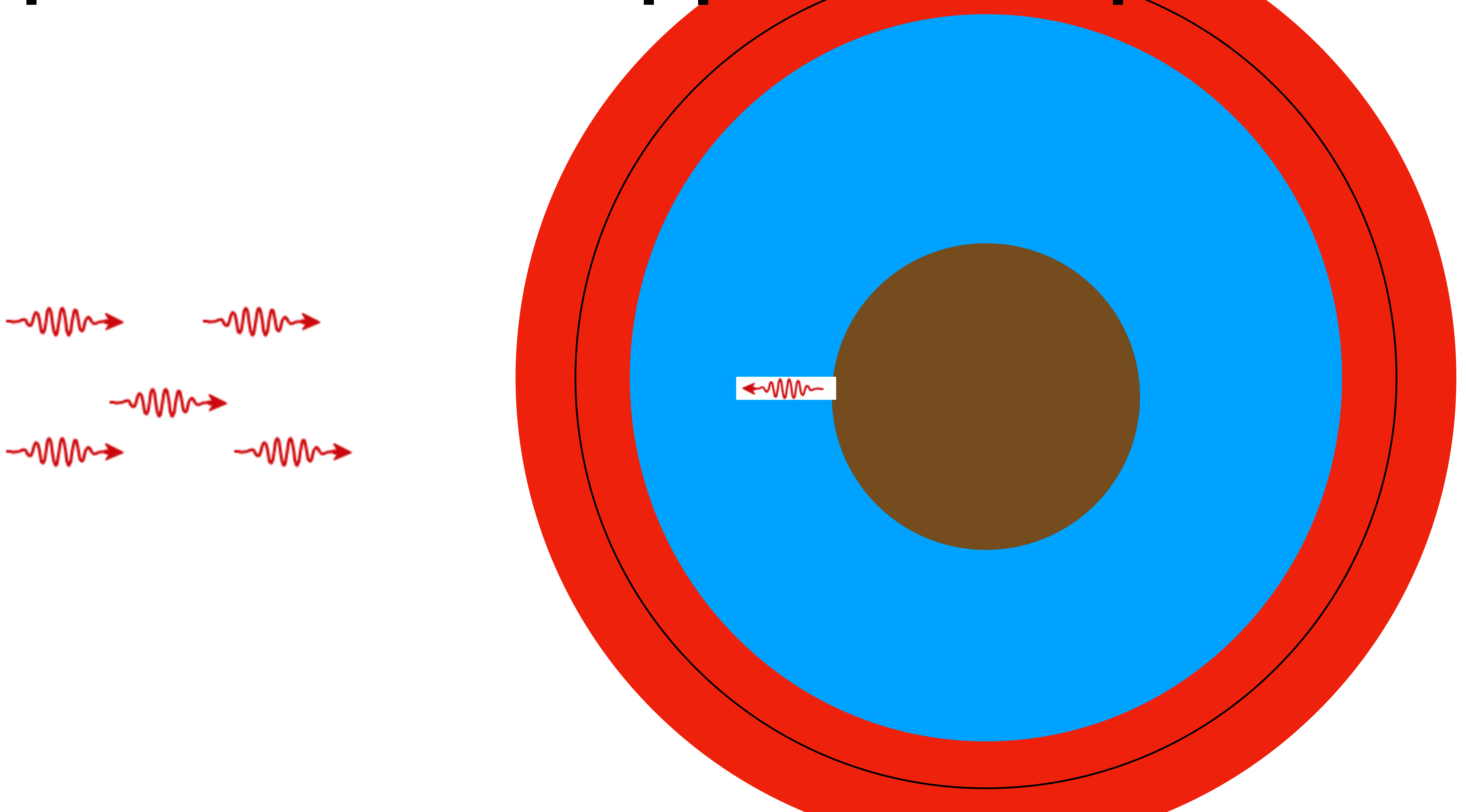

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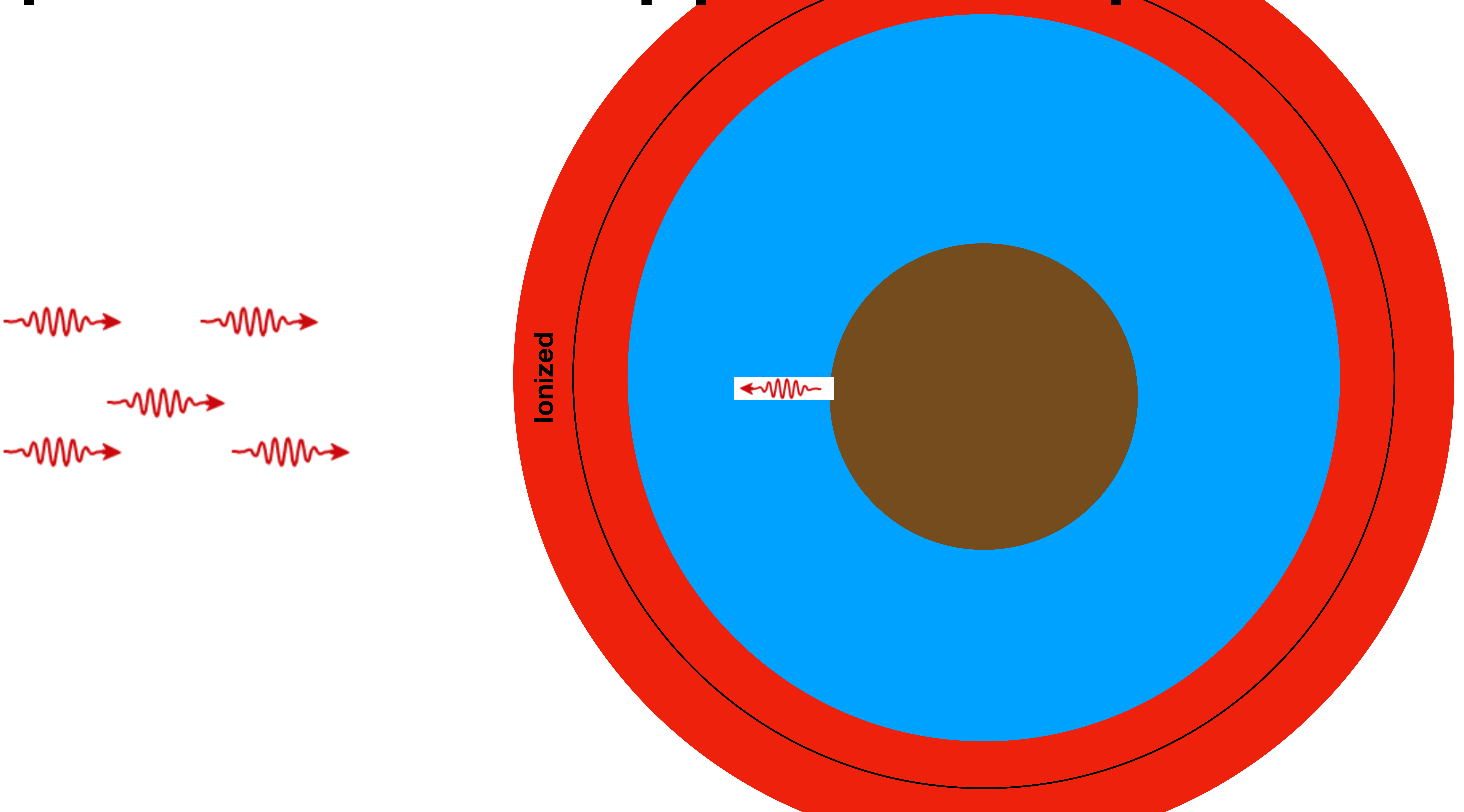

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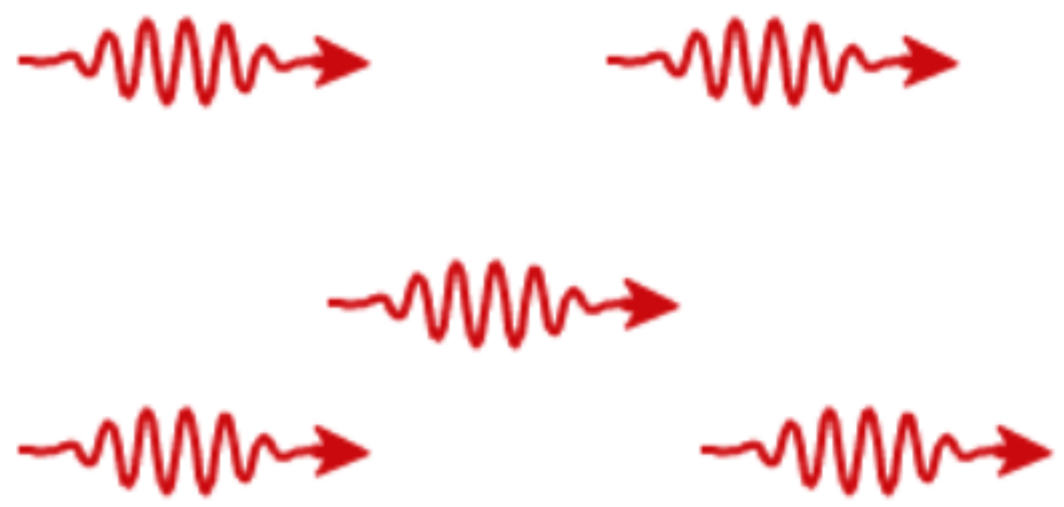

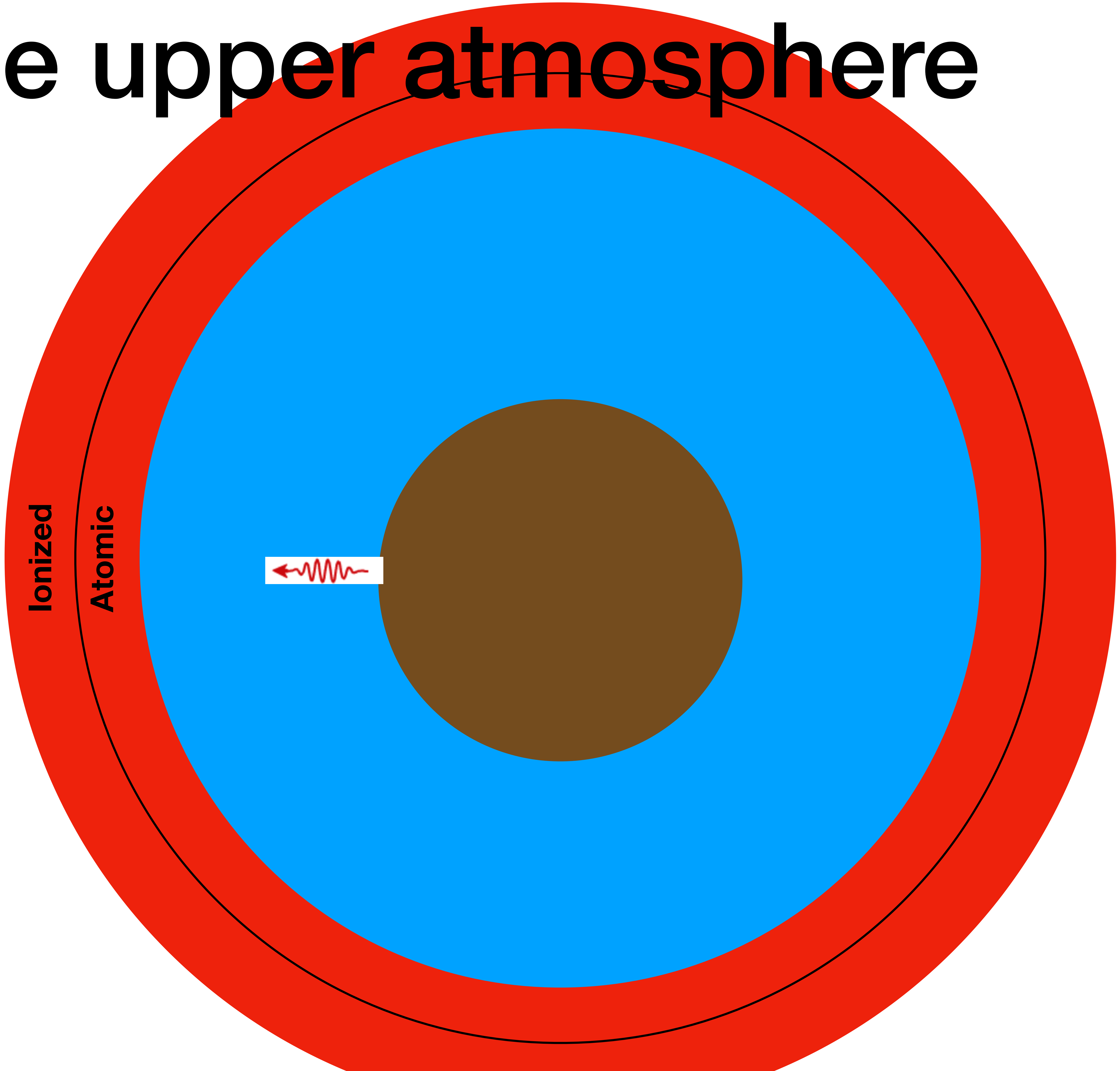

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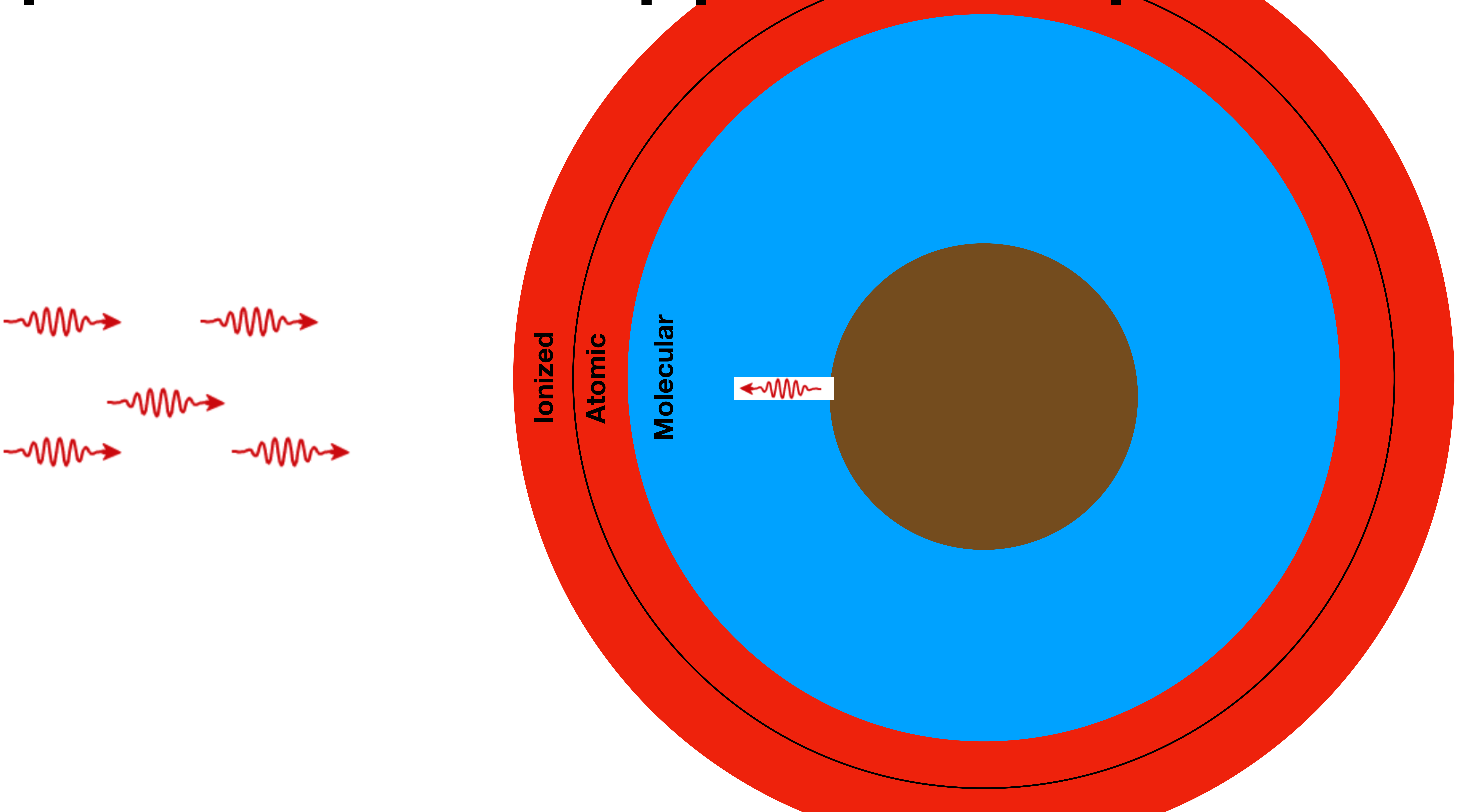

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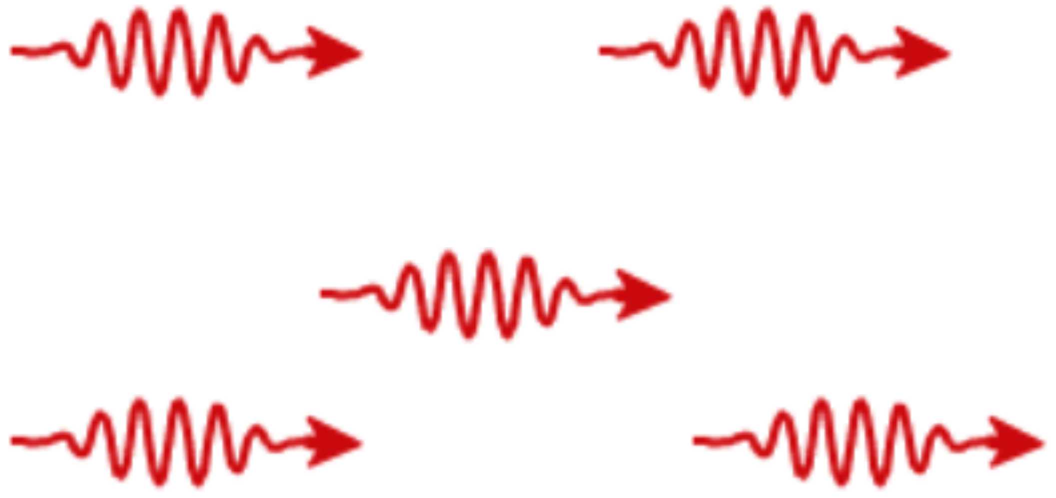

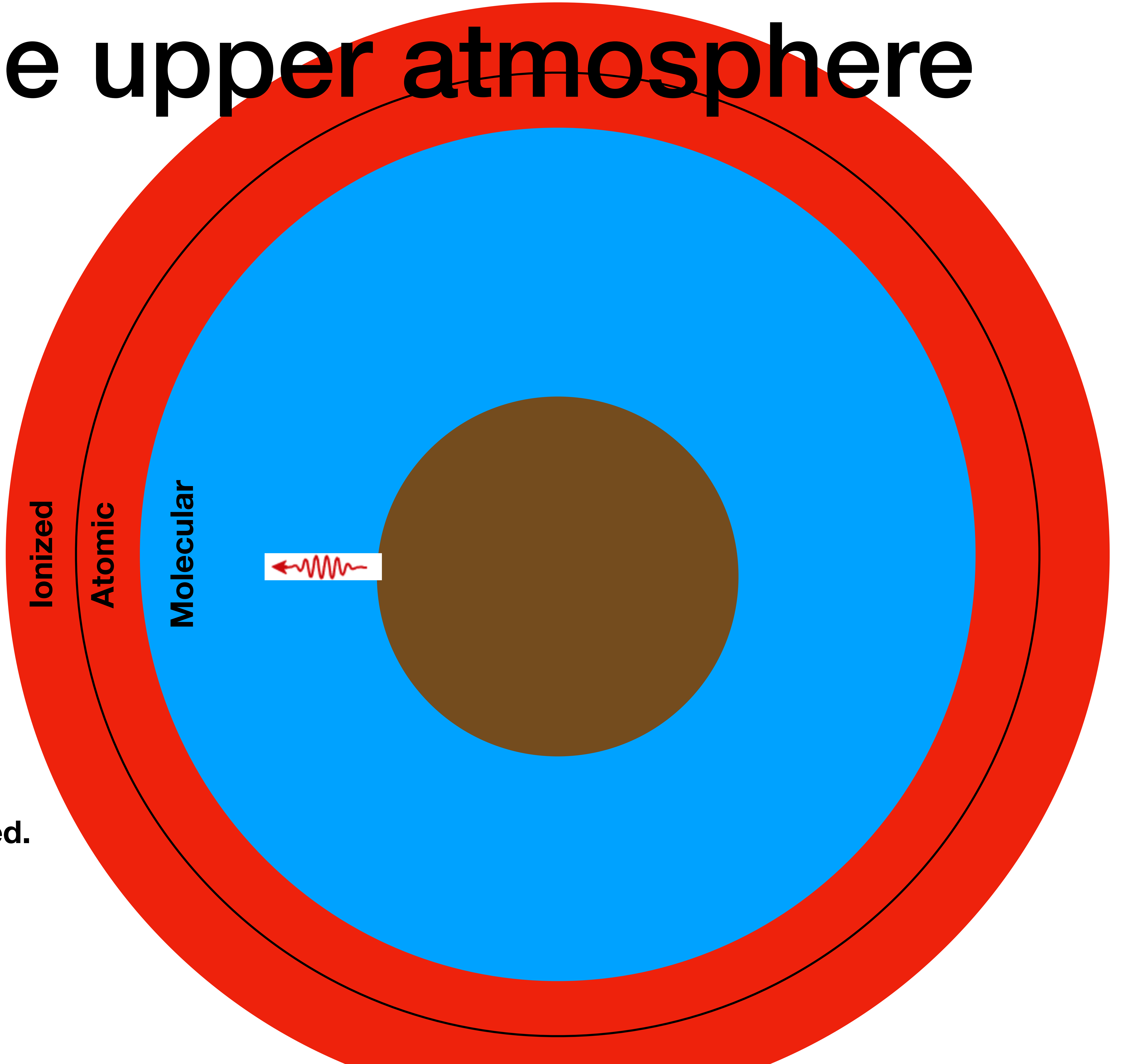

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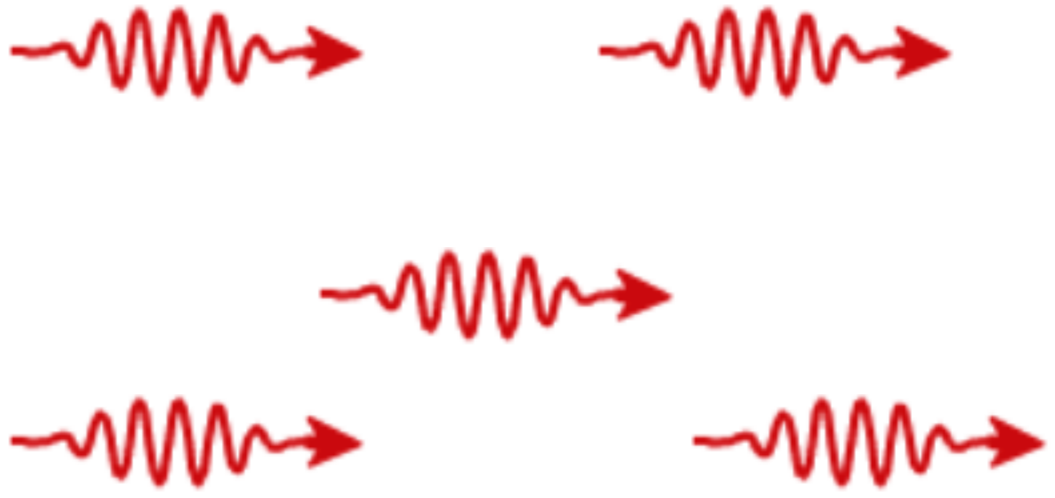

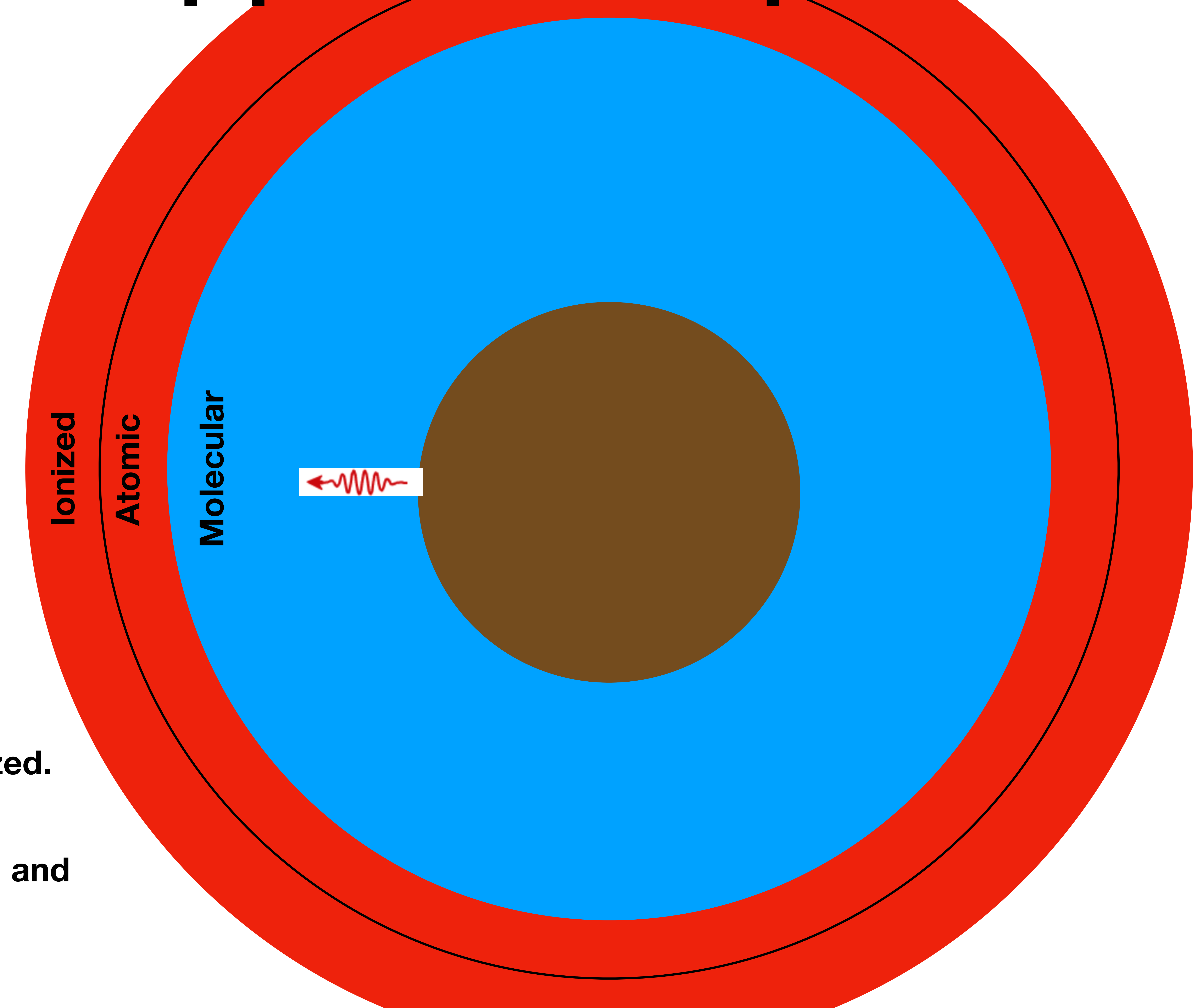

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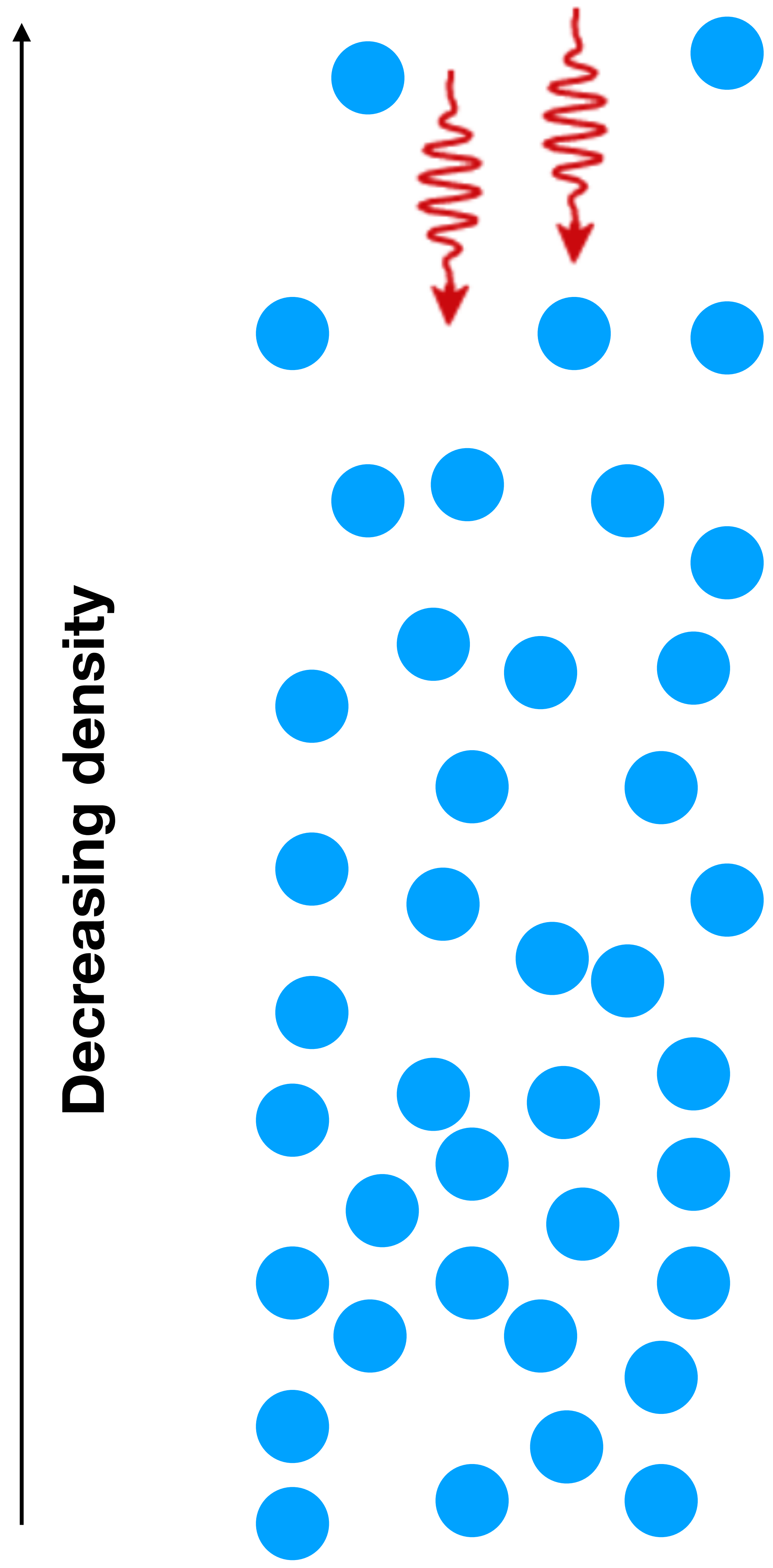
This has important consequences for both non-thermal and thermal escape.

The concept of the “exobase”



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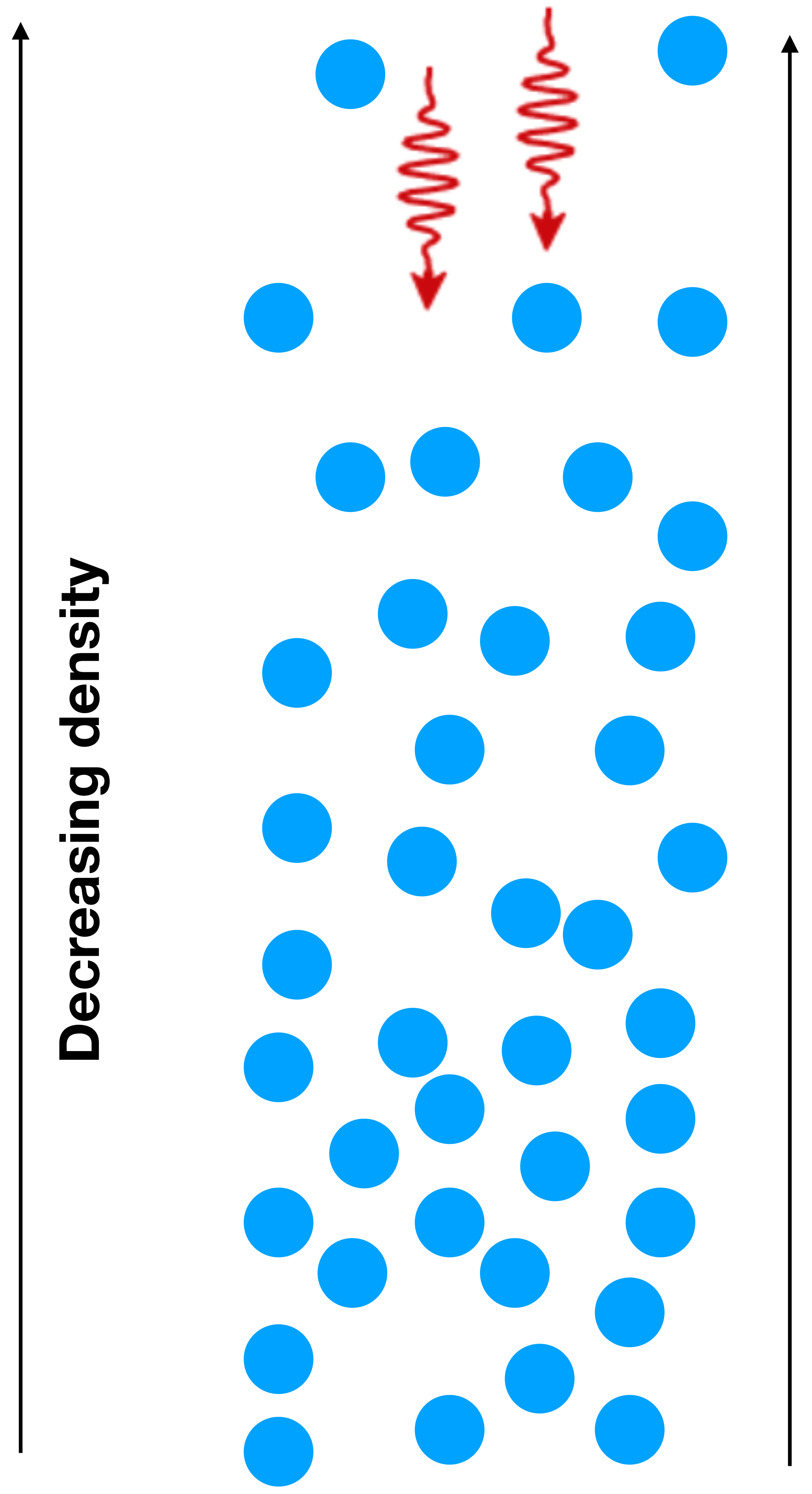

Collisions between particles become rarer.

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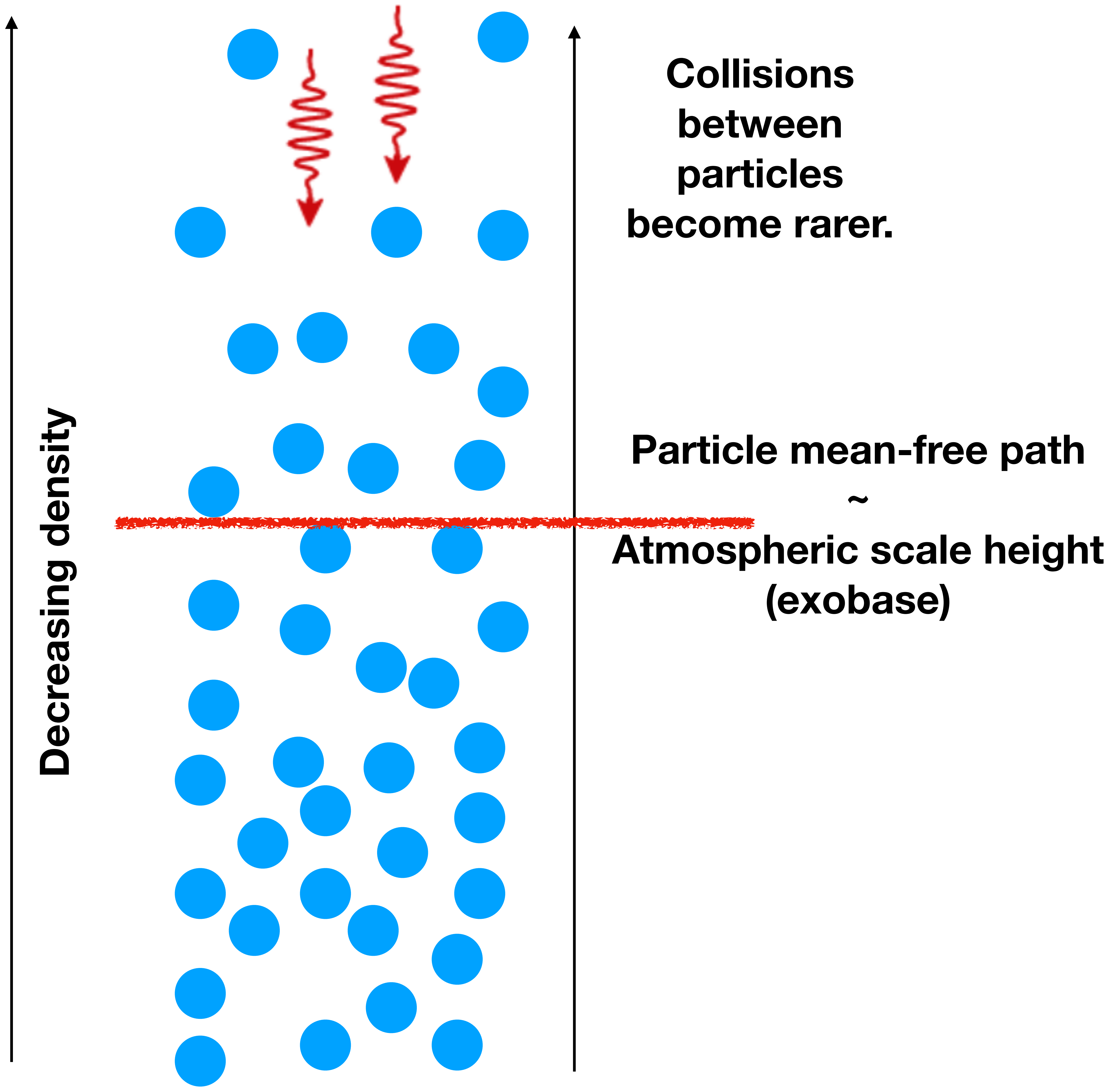

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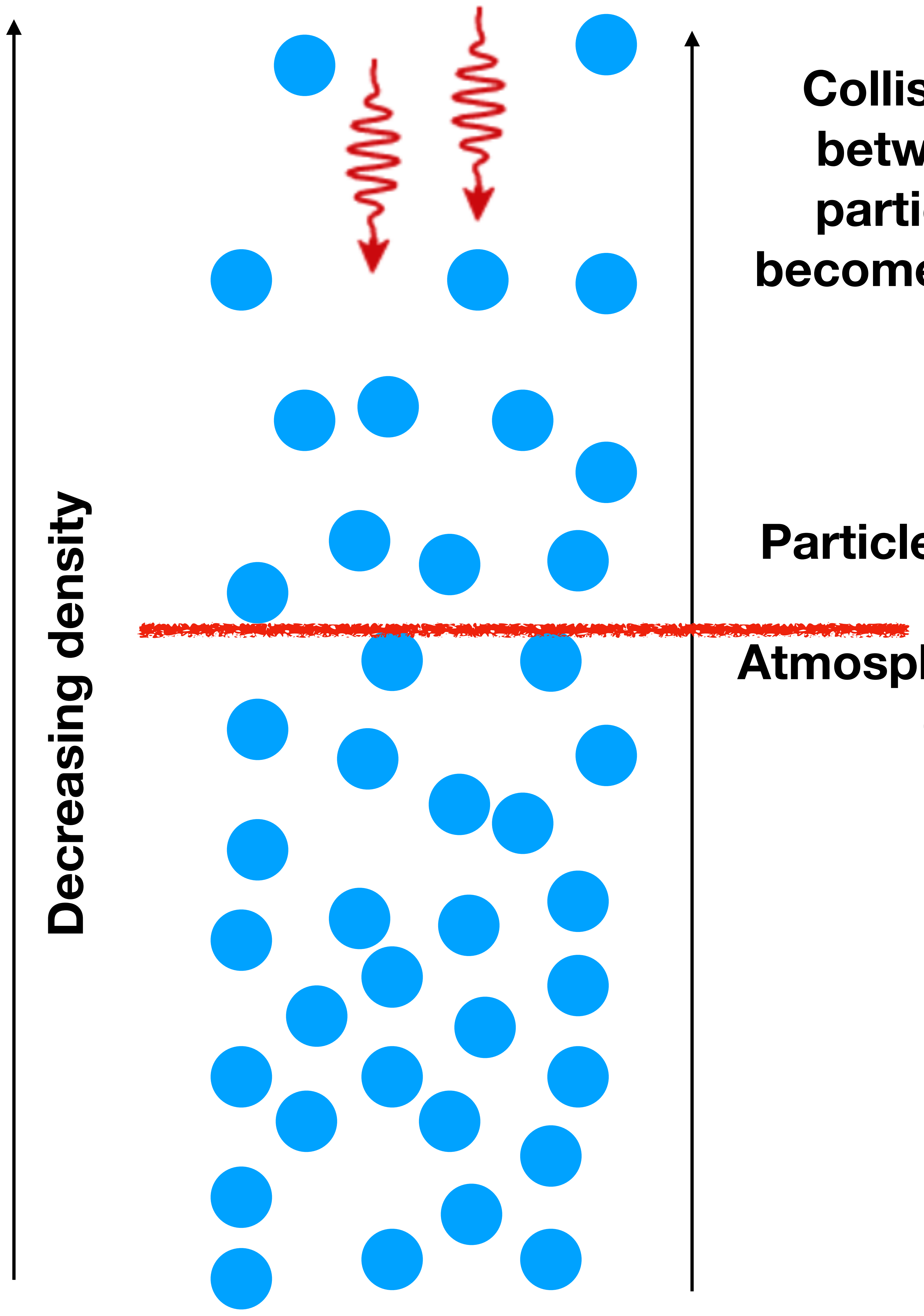

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Particle mean-free path ~ Atmospheric scale height (exobase)

Neutrals: σ_{col}~10^{-15} cm^2
Ions: σ_{col}~10^{-13} cm^2

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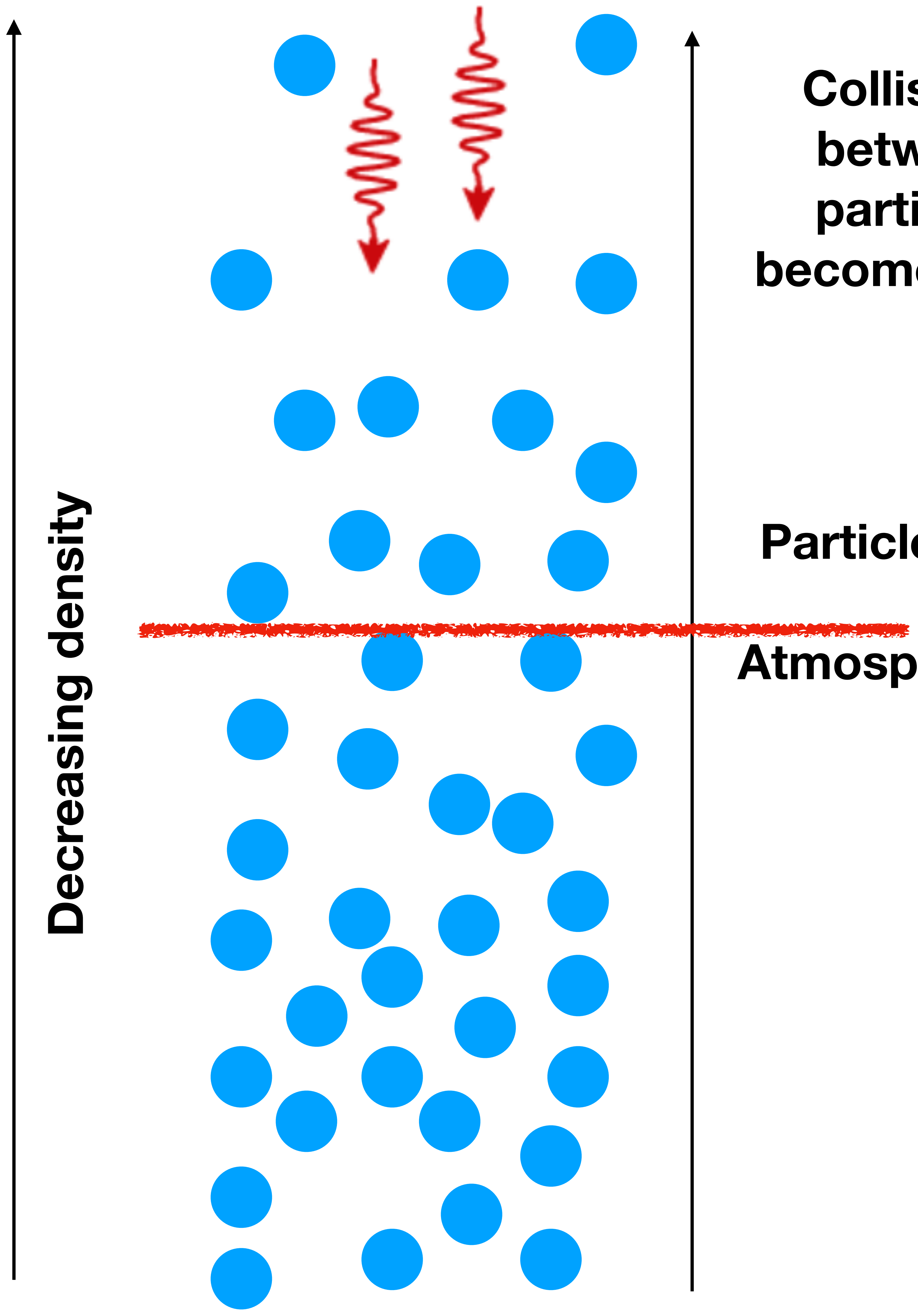

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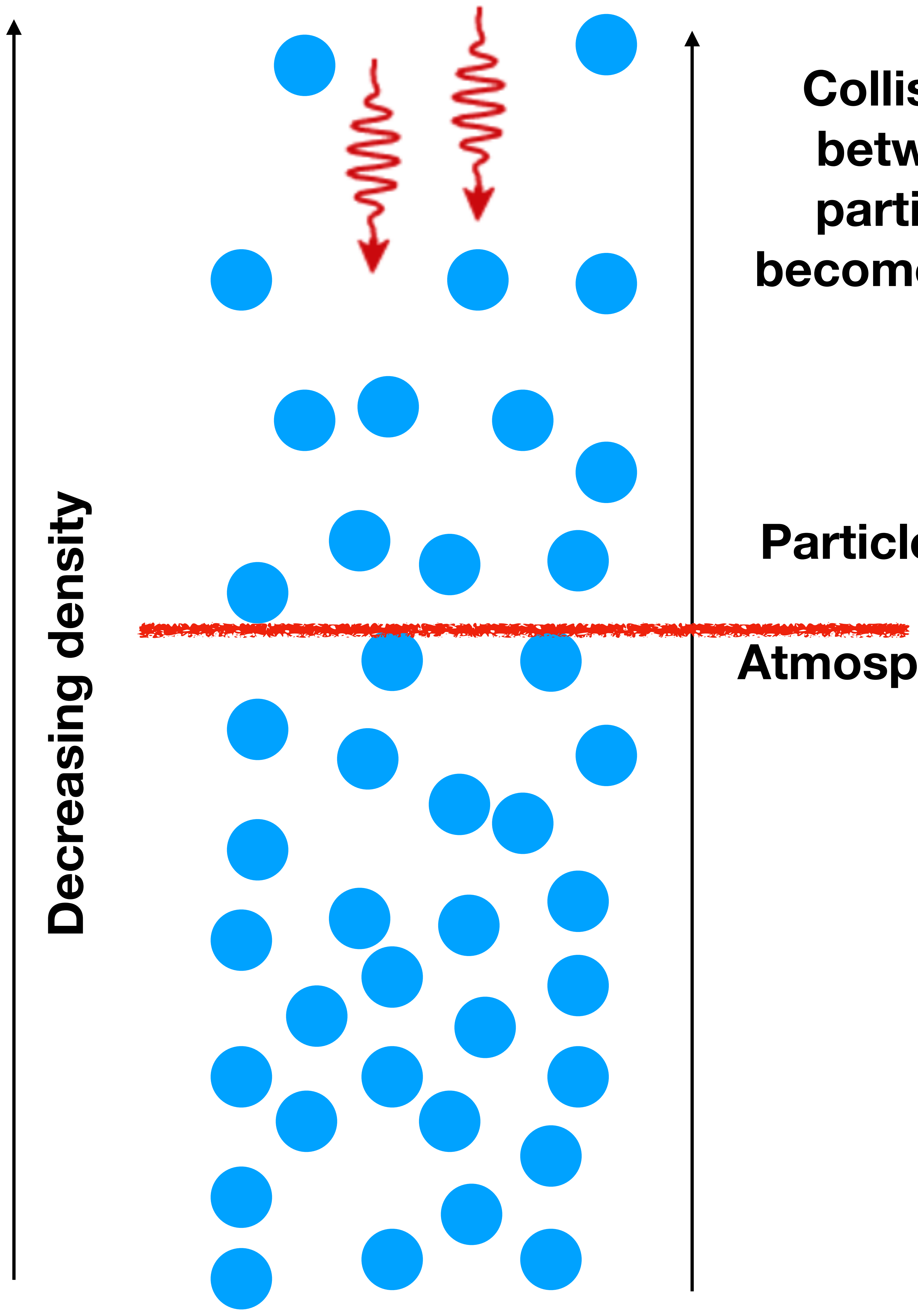

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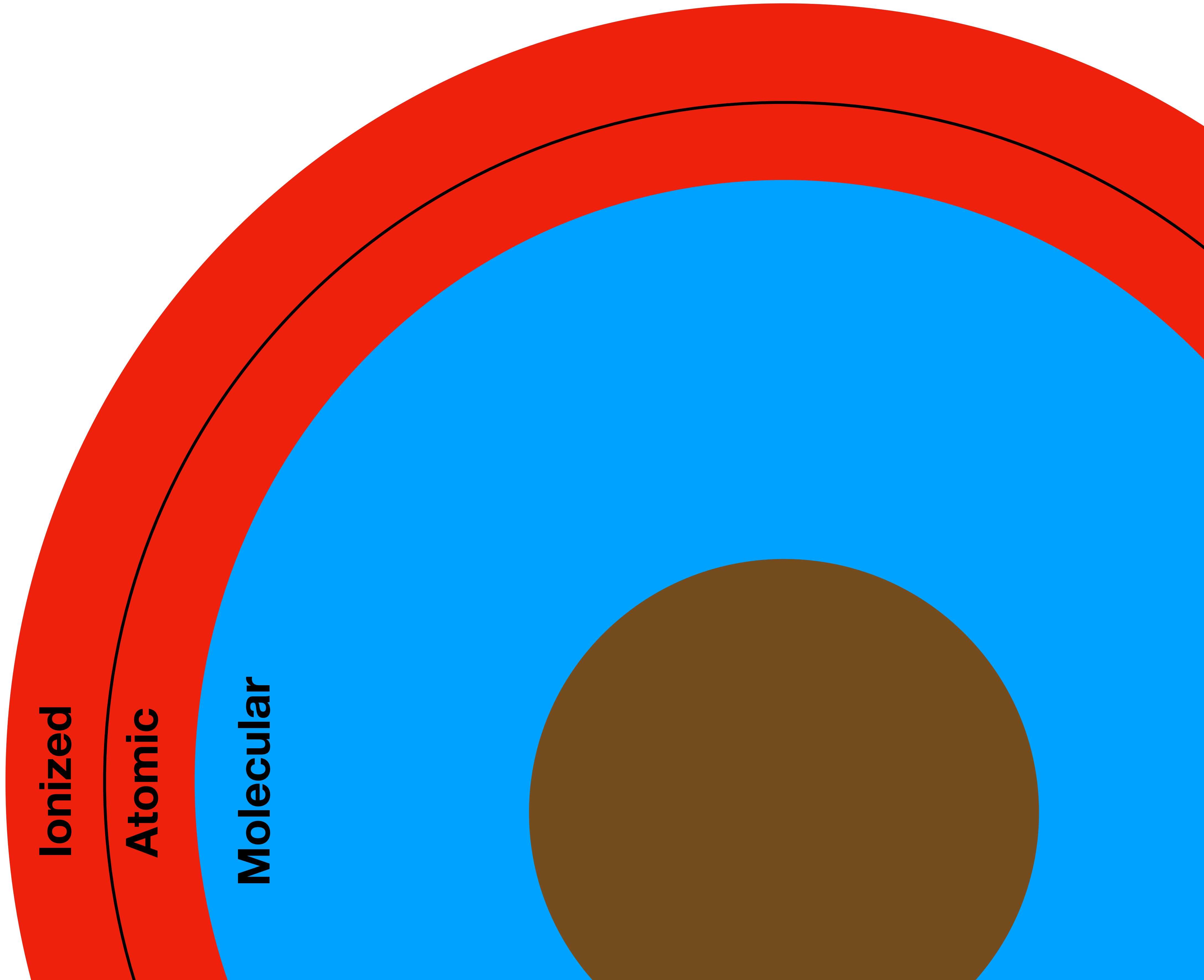

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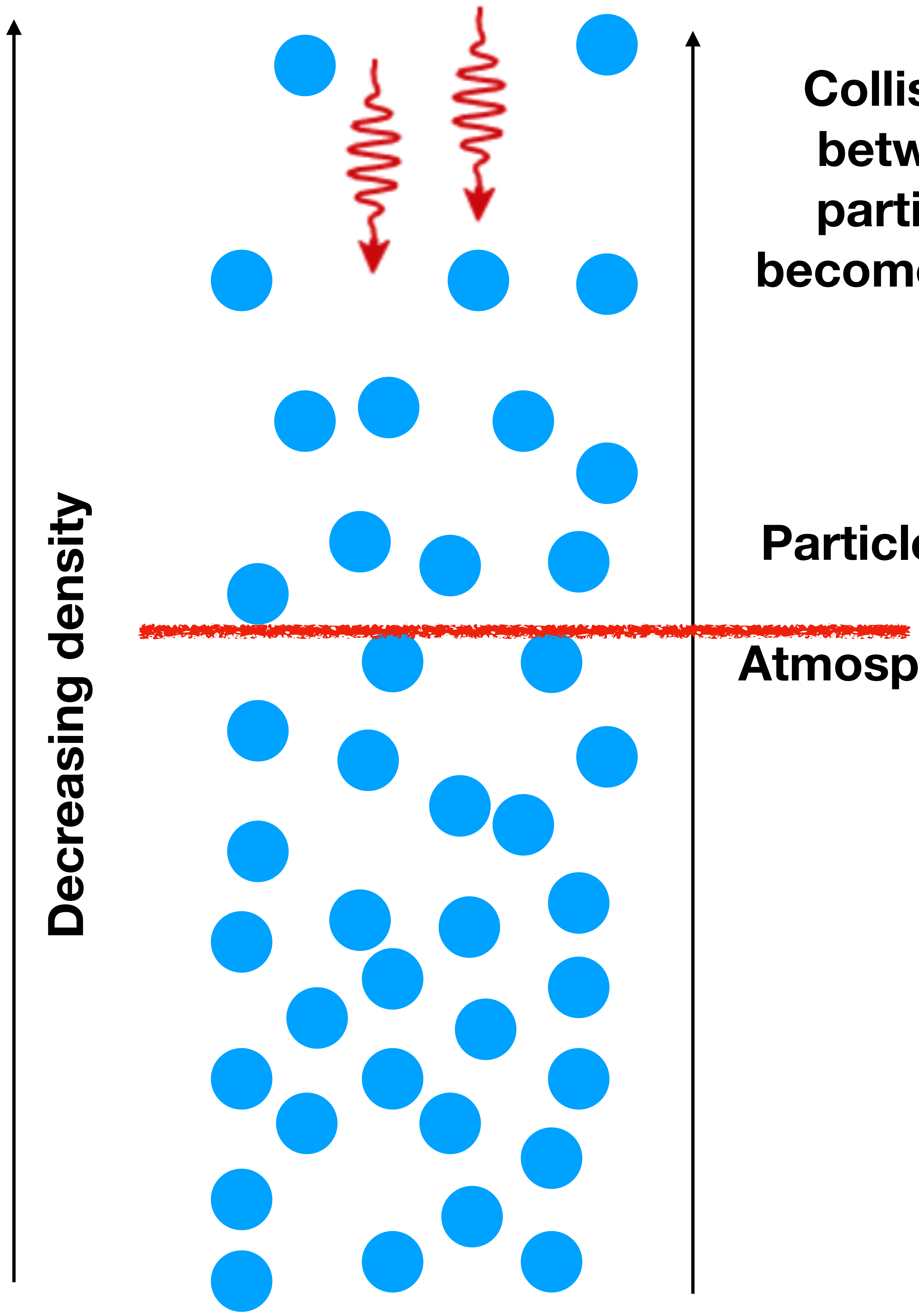

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Particle mean-free path
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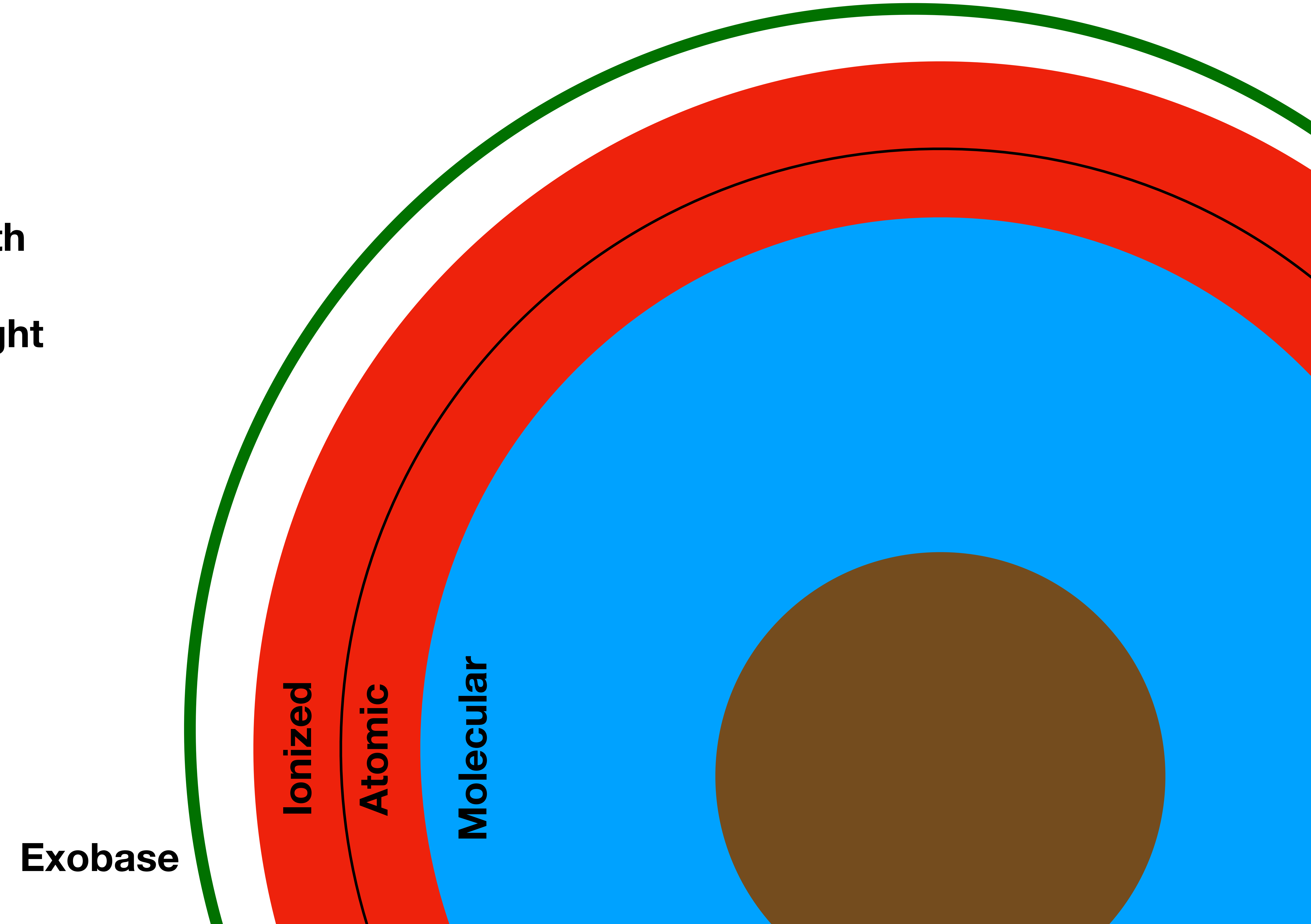
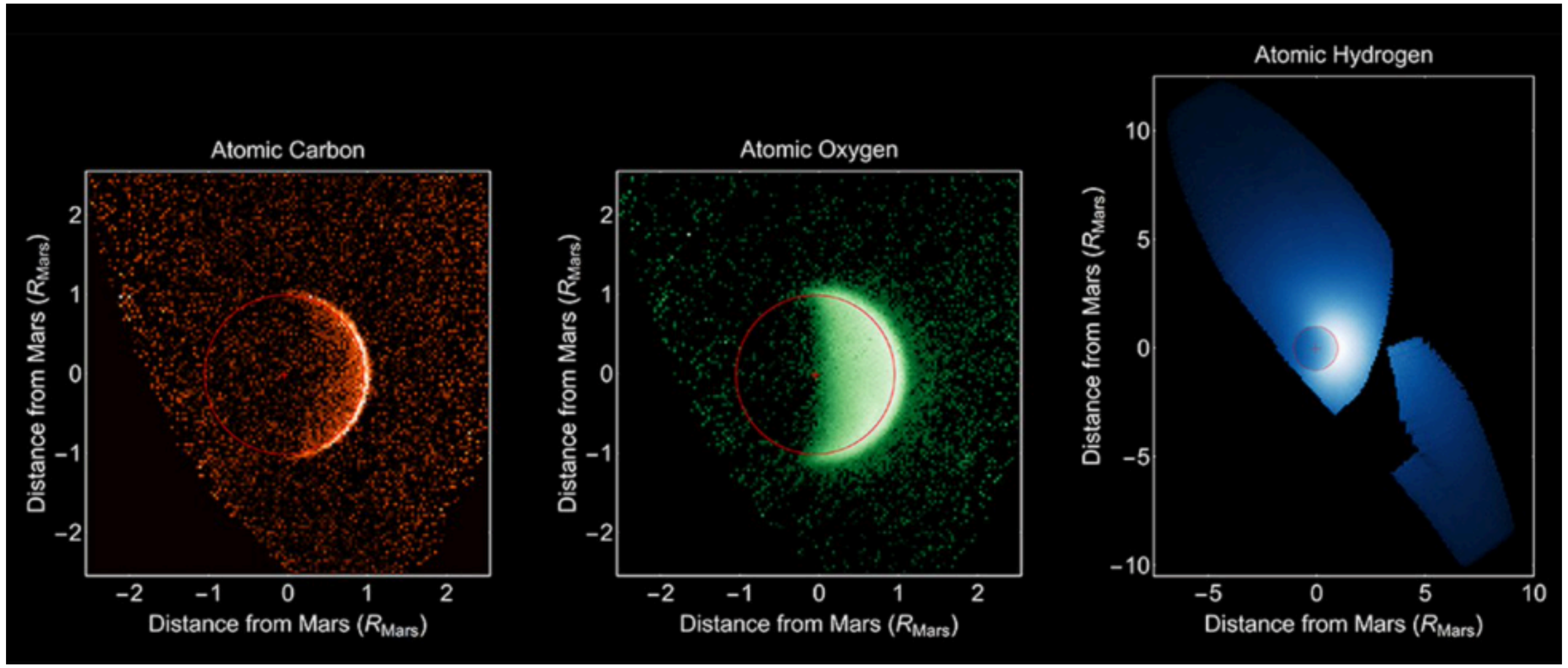
$>$

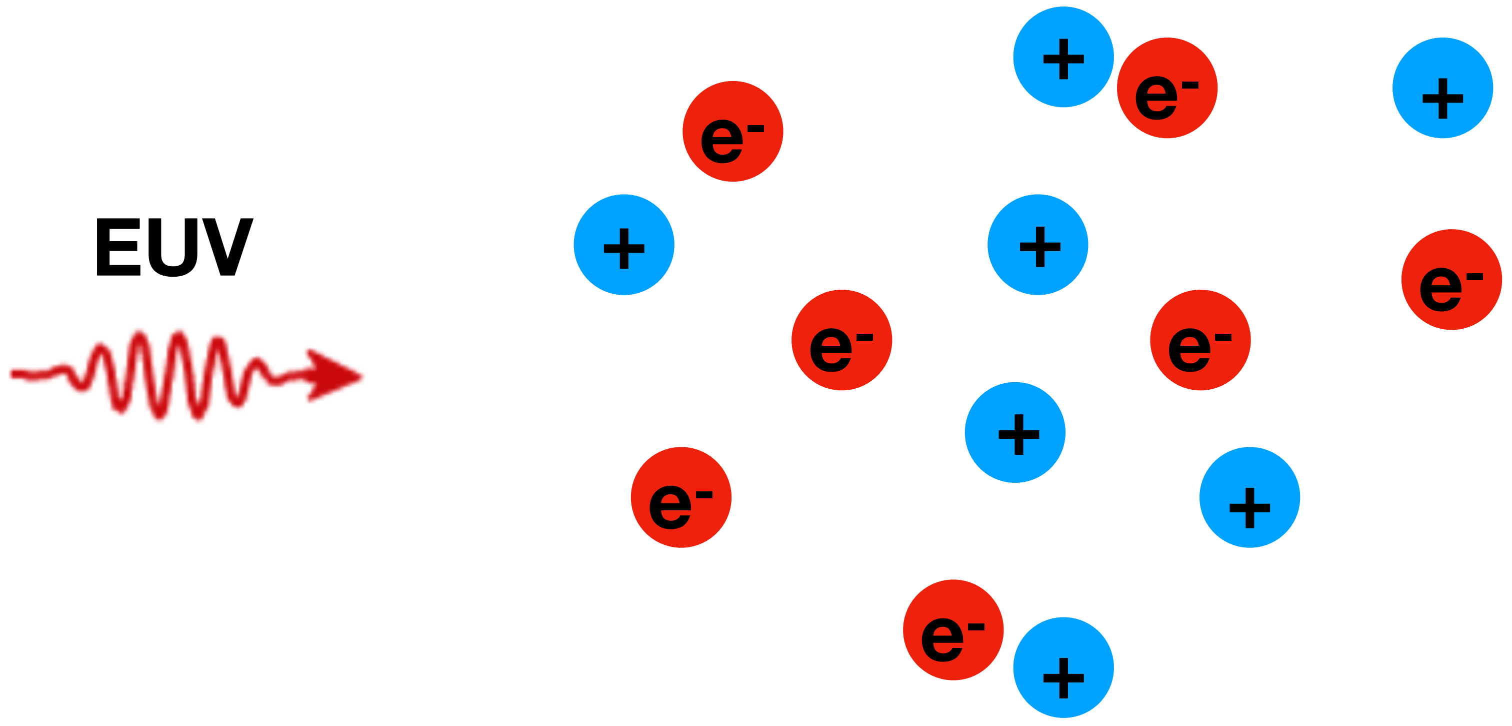
Photon absorption cross-sections



A dominant non-thermal escape processes: photochemical escape



Thought to be dominant on Mars today



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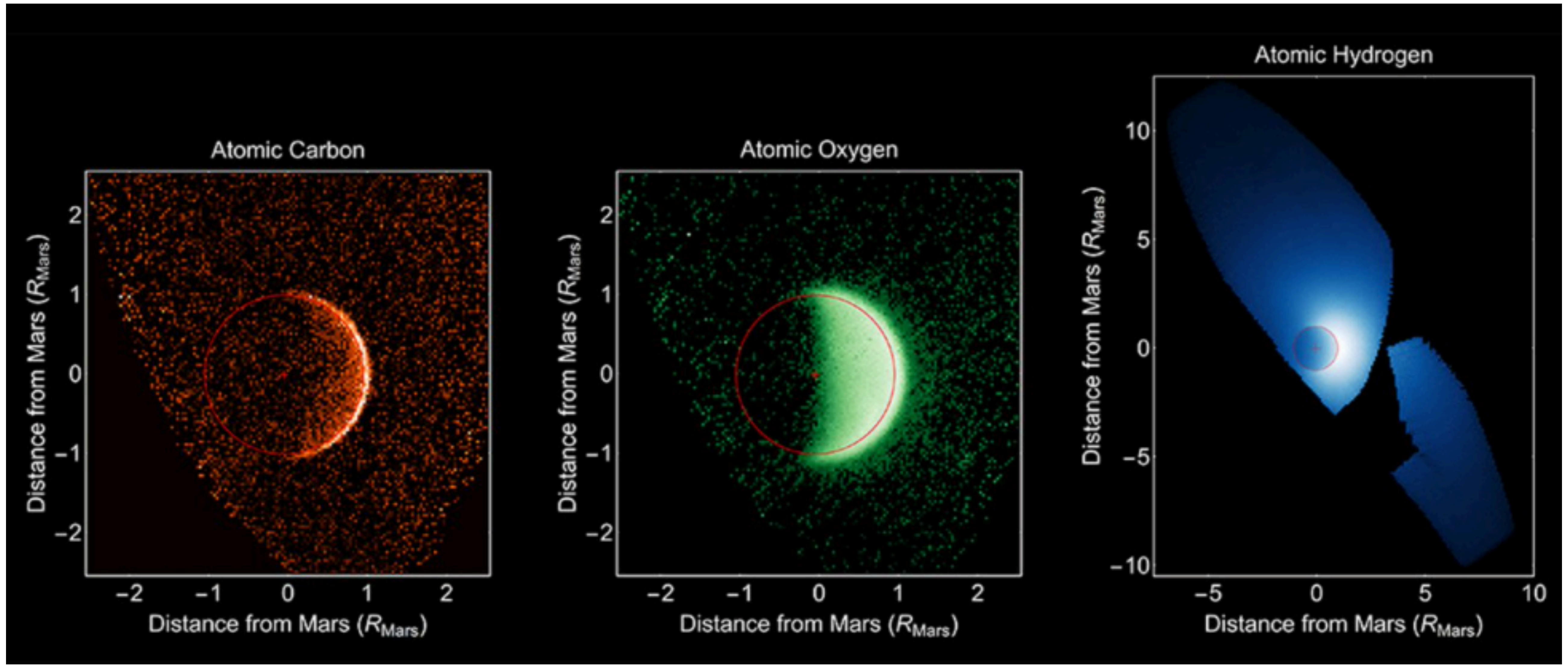

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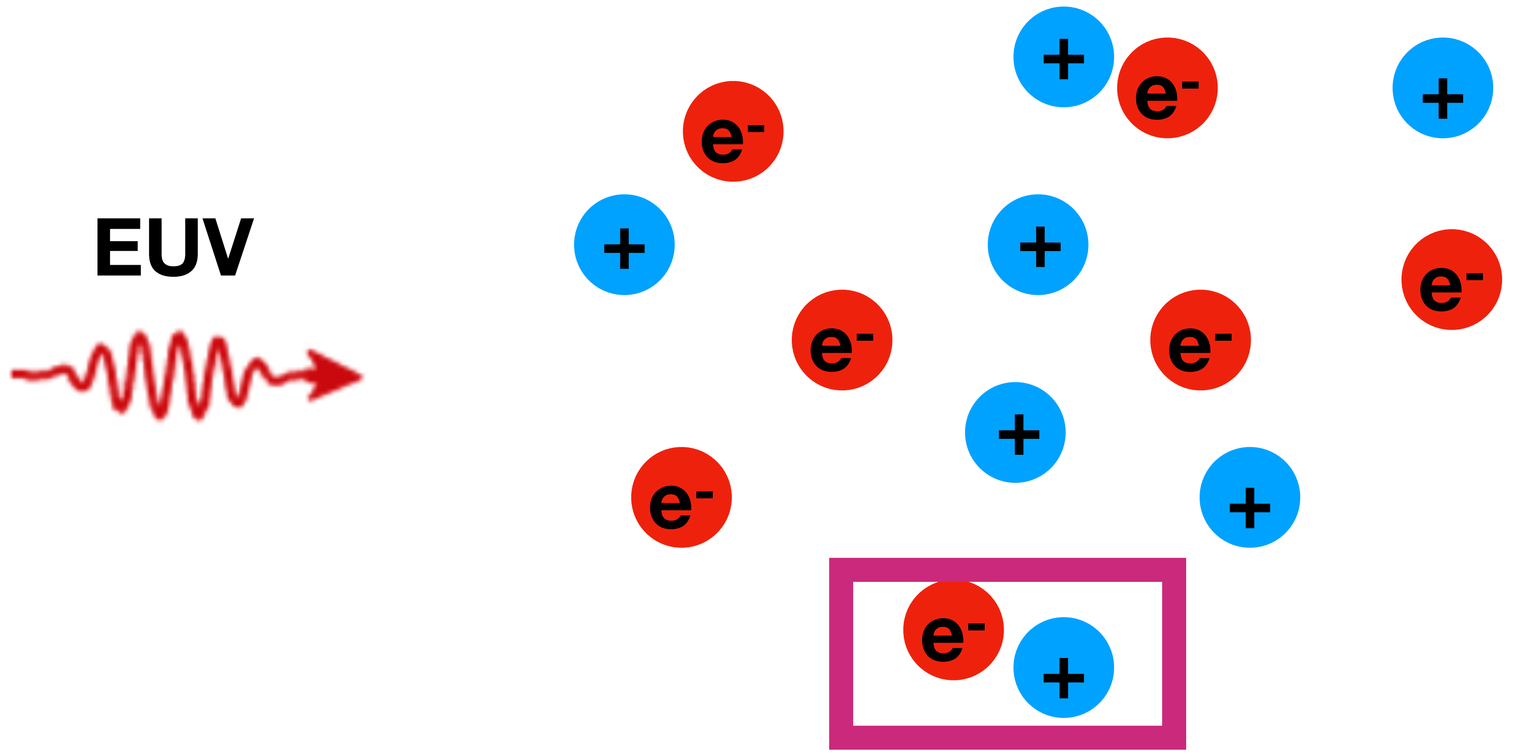

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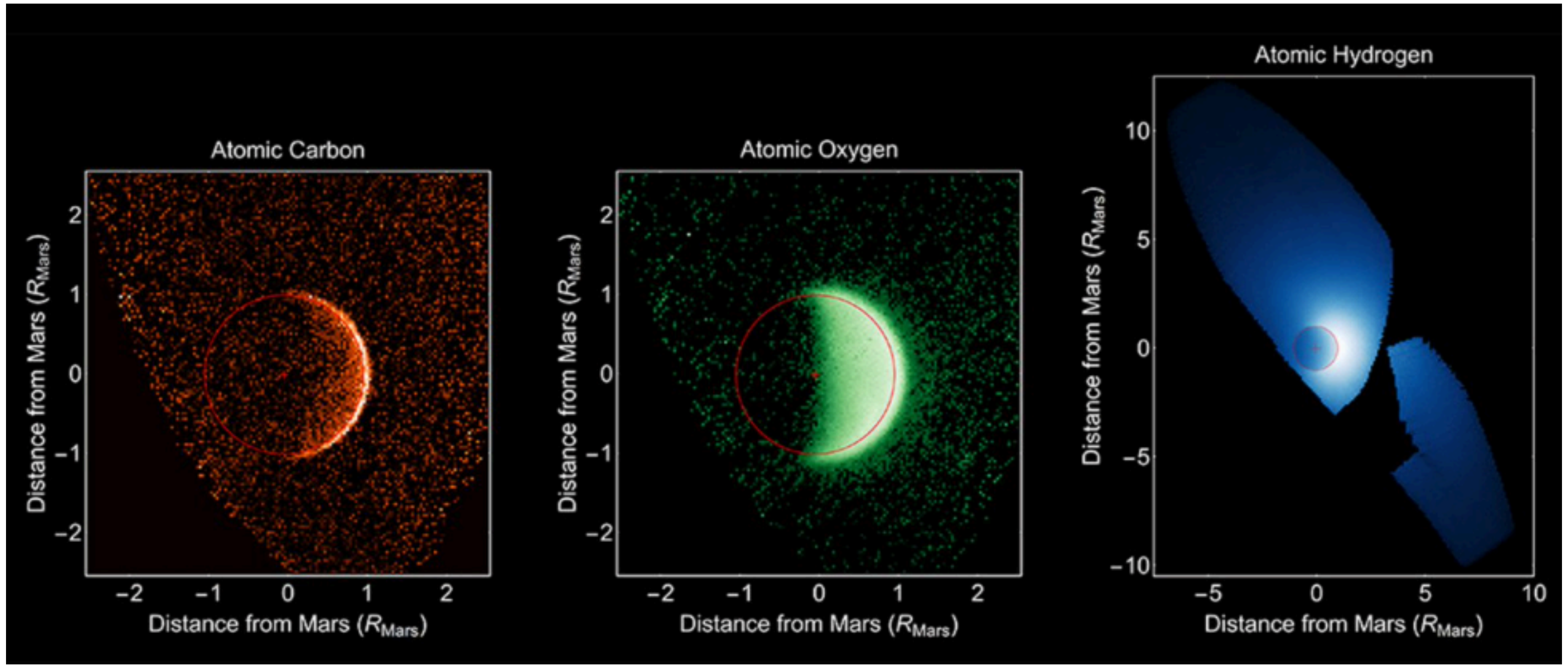

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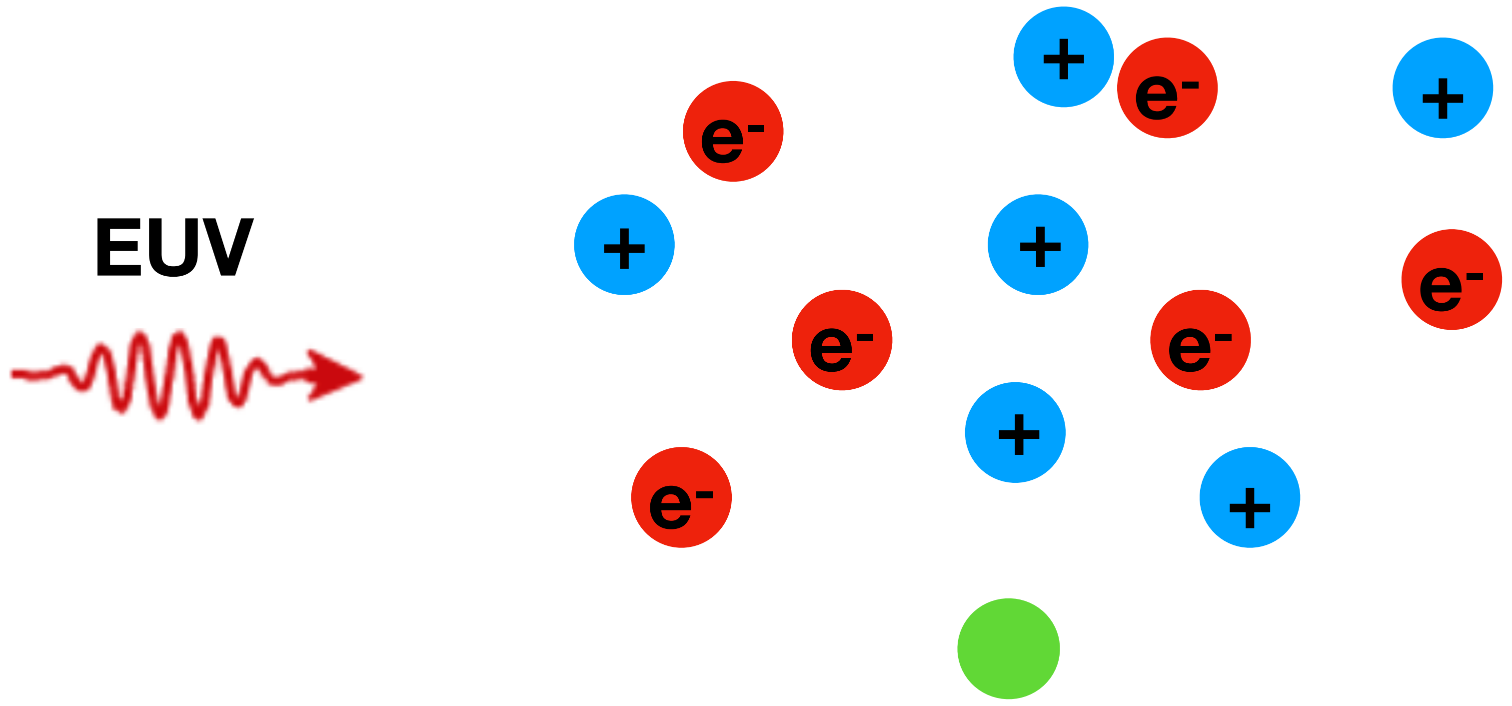

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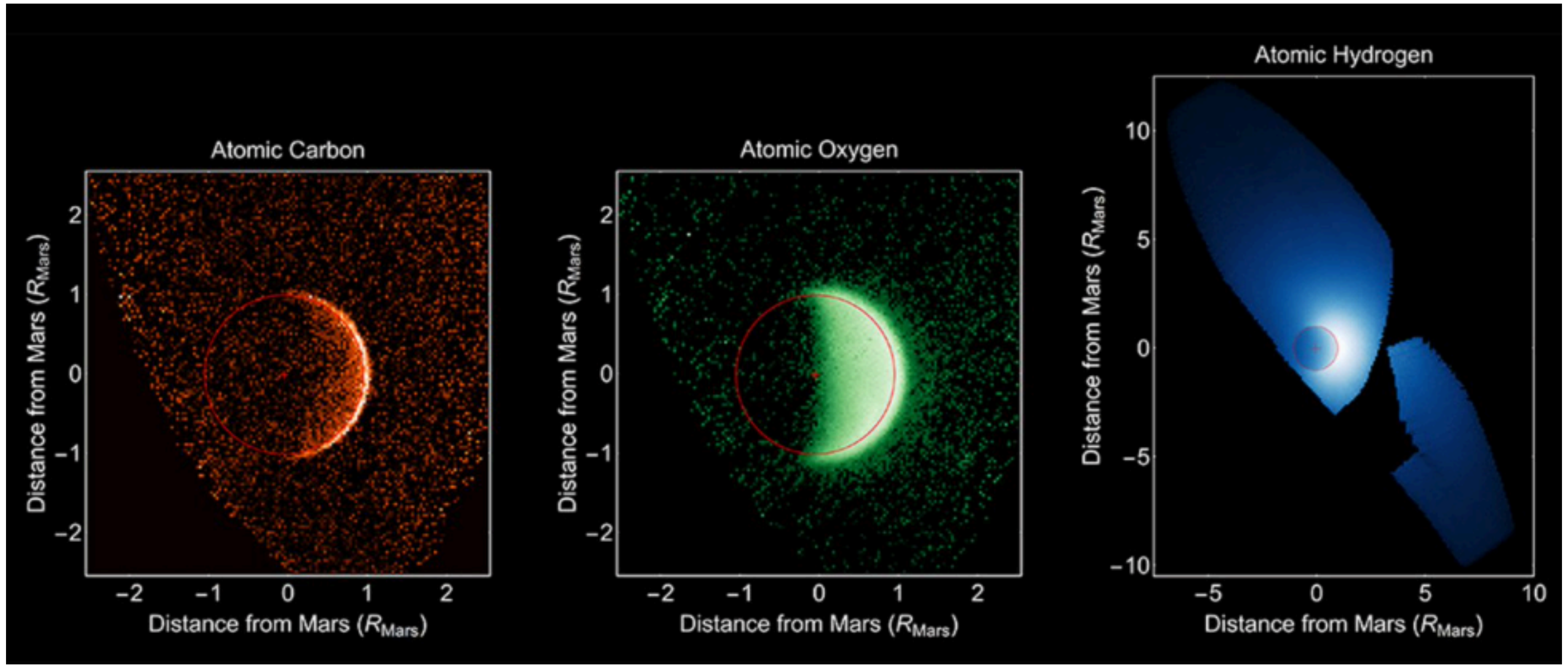

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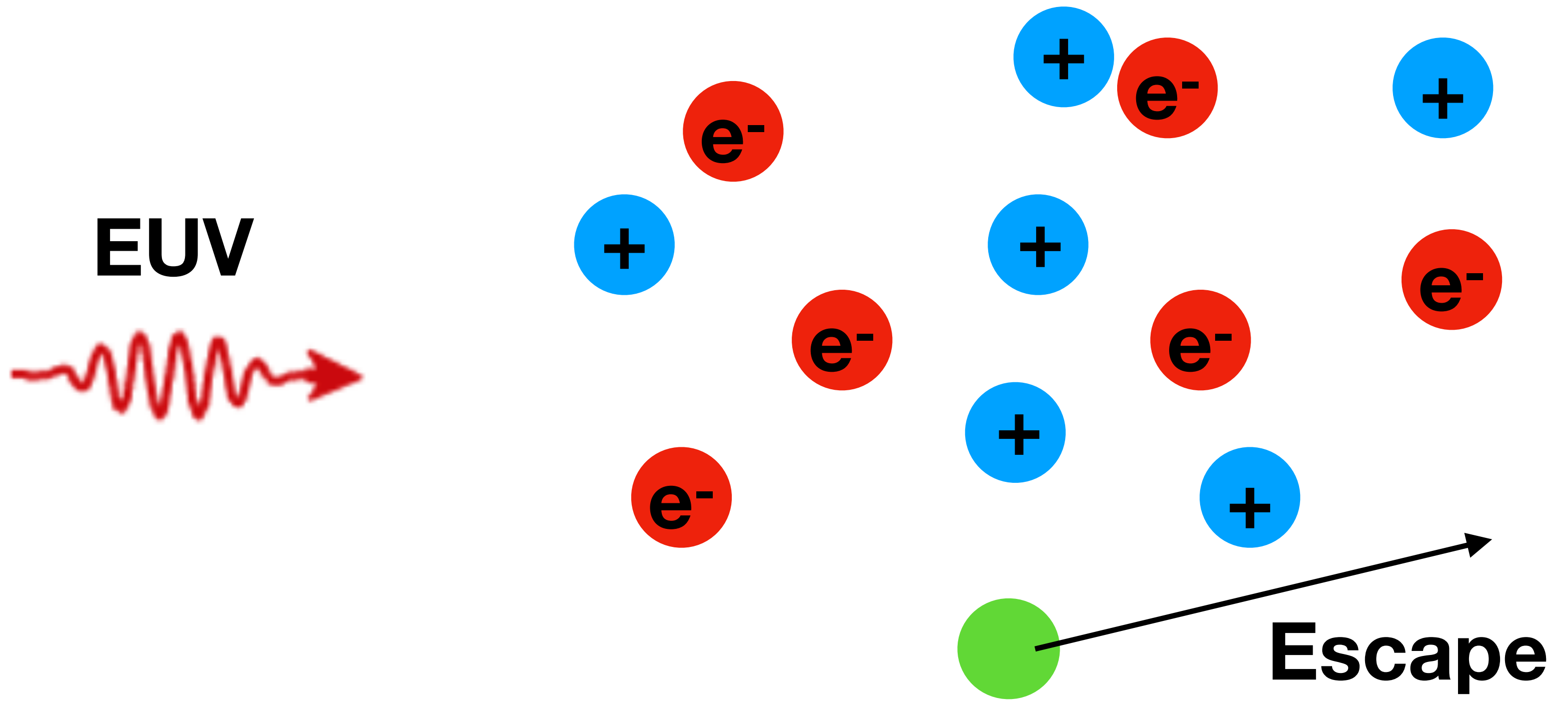

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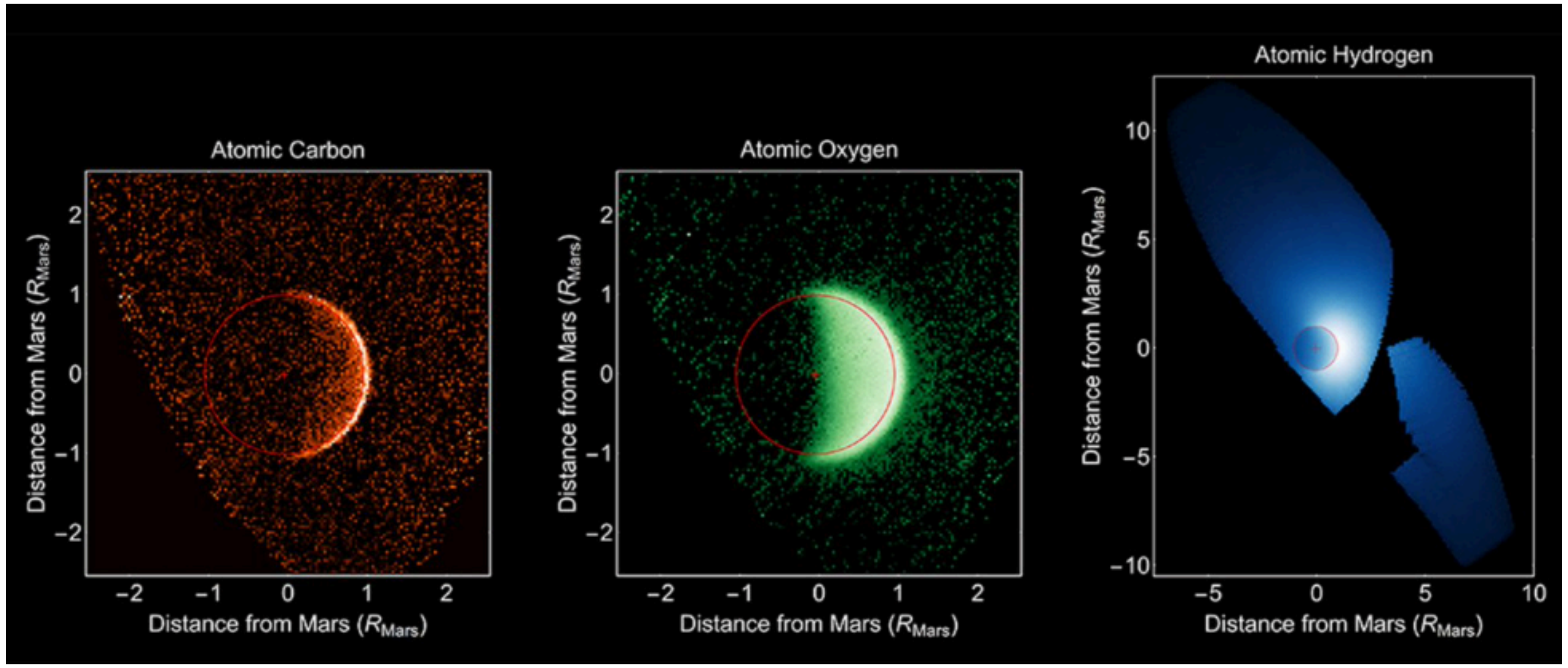

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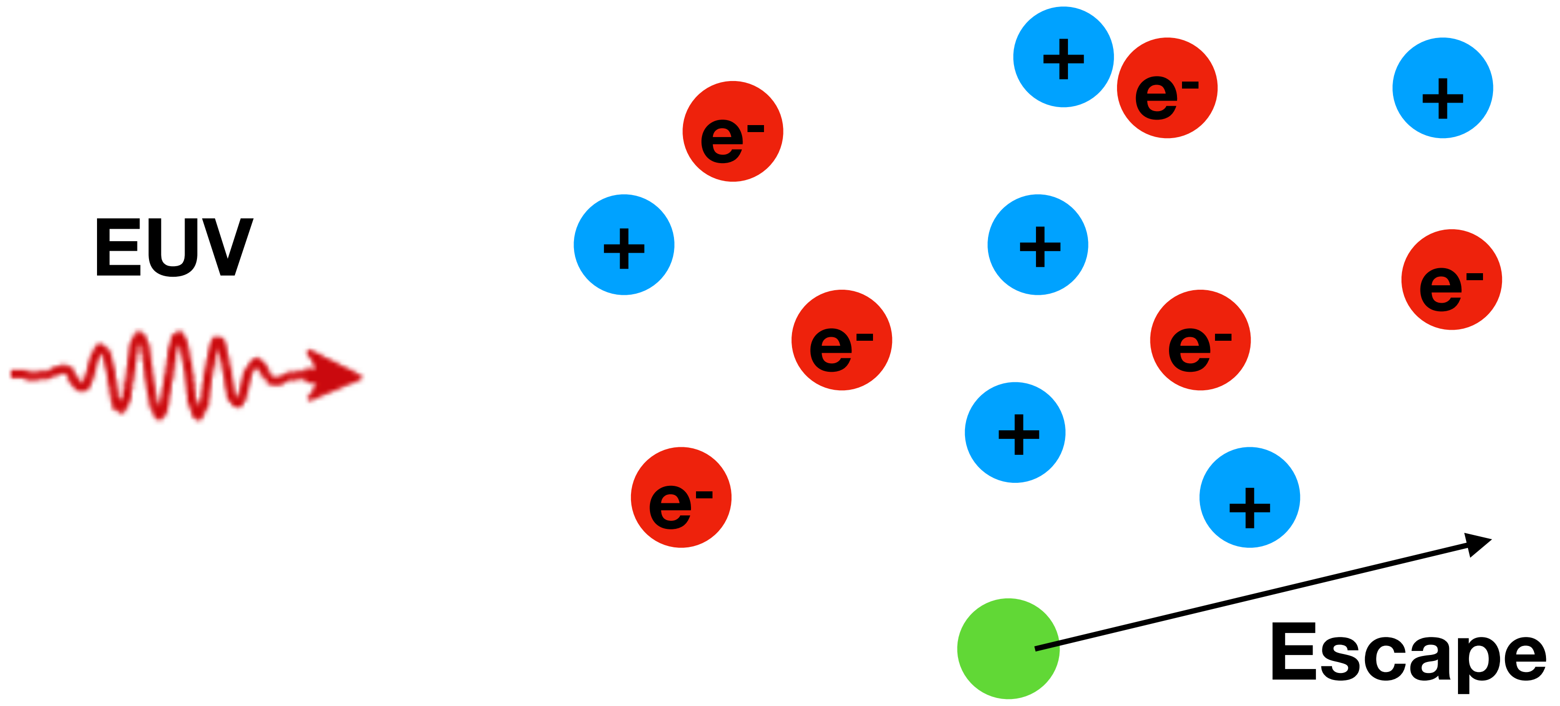

Why does this work?

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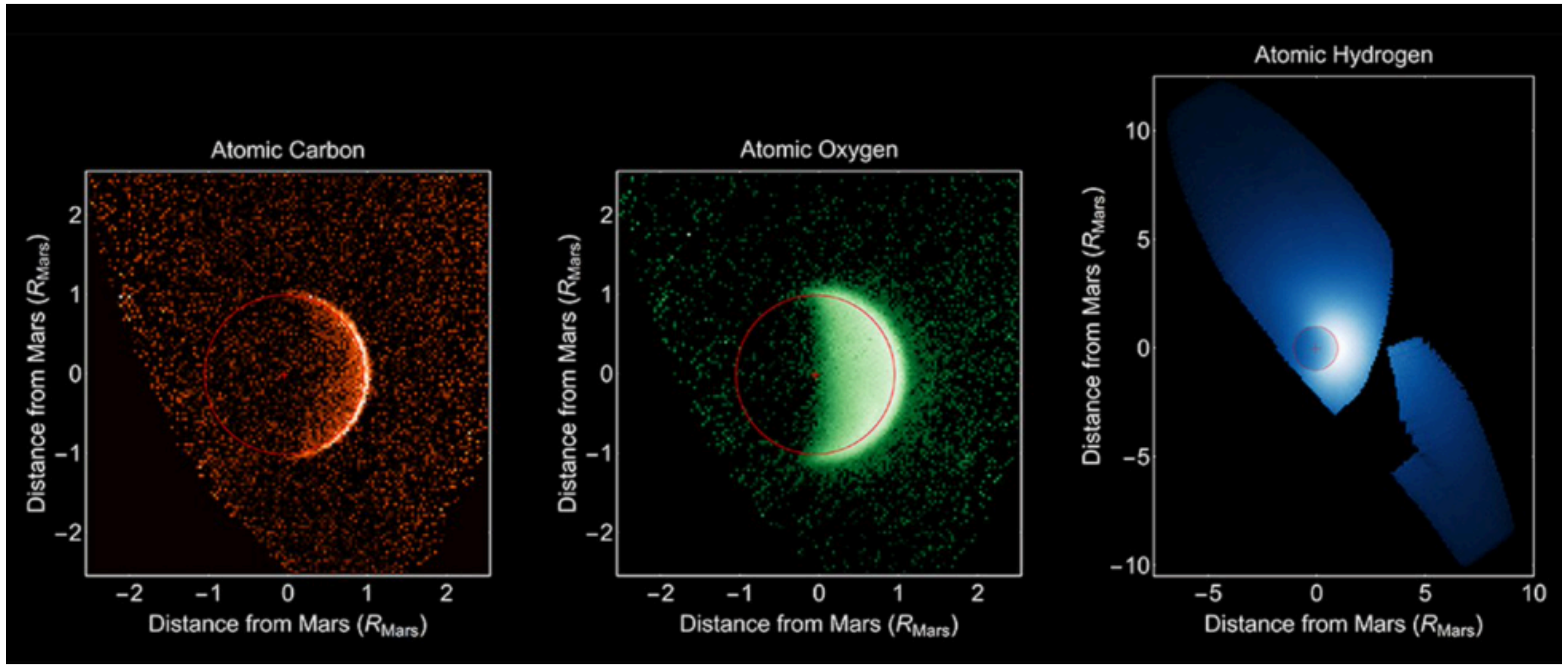

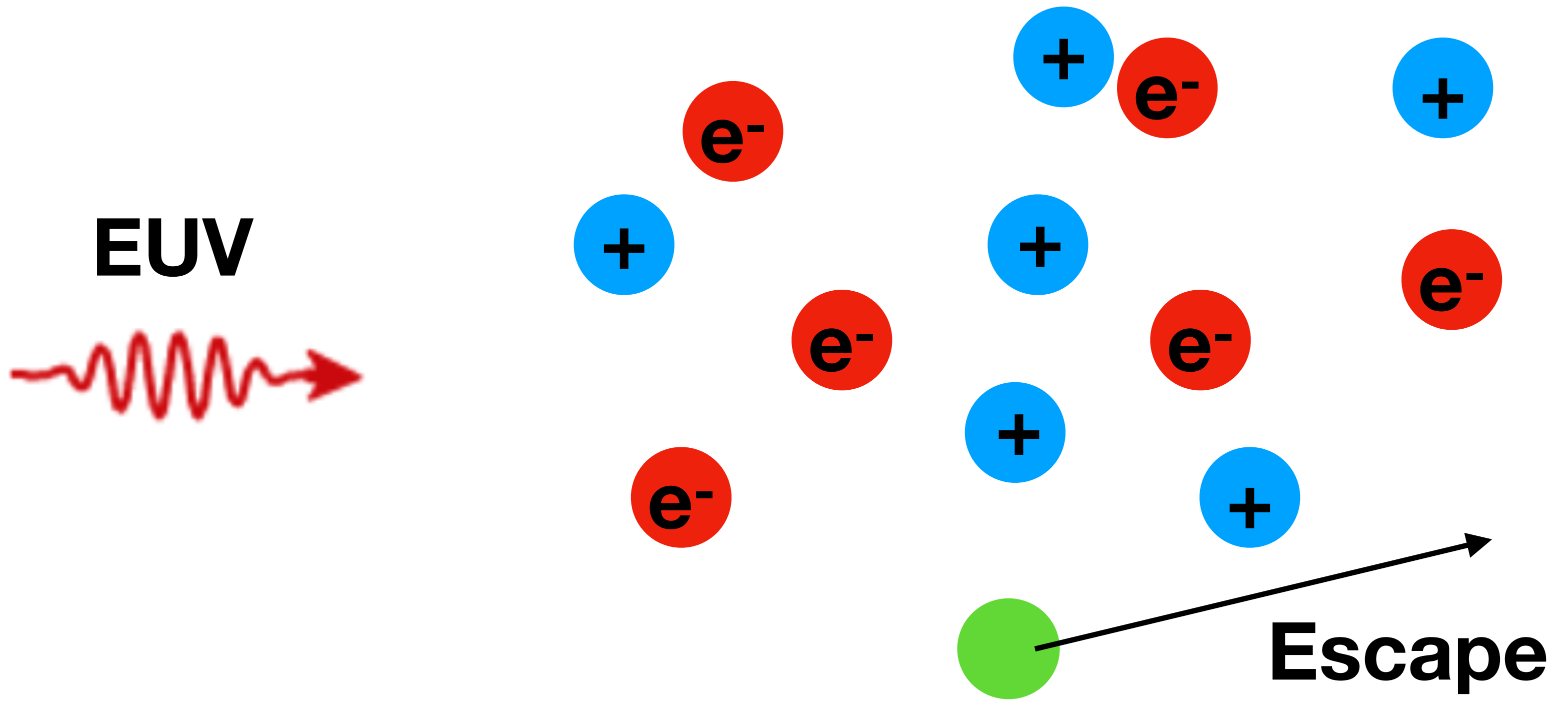

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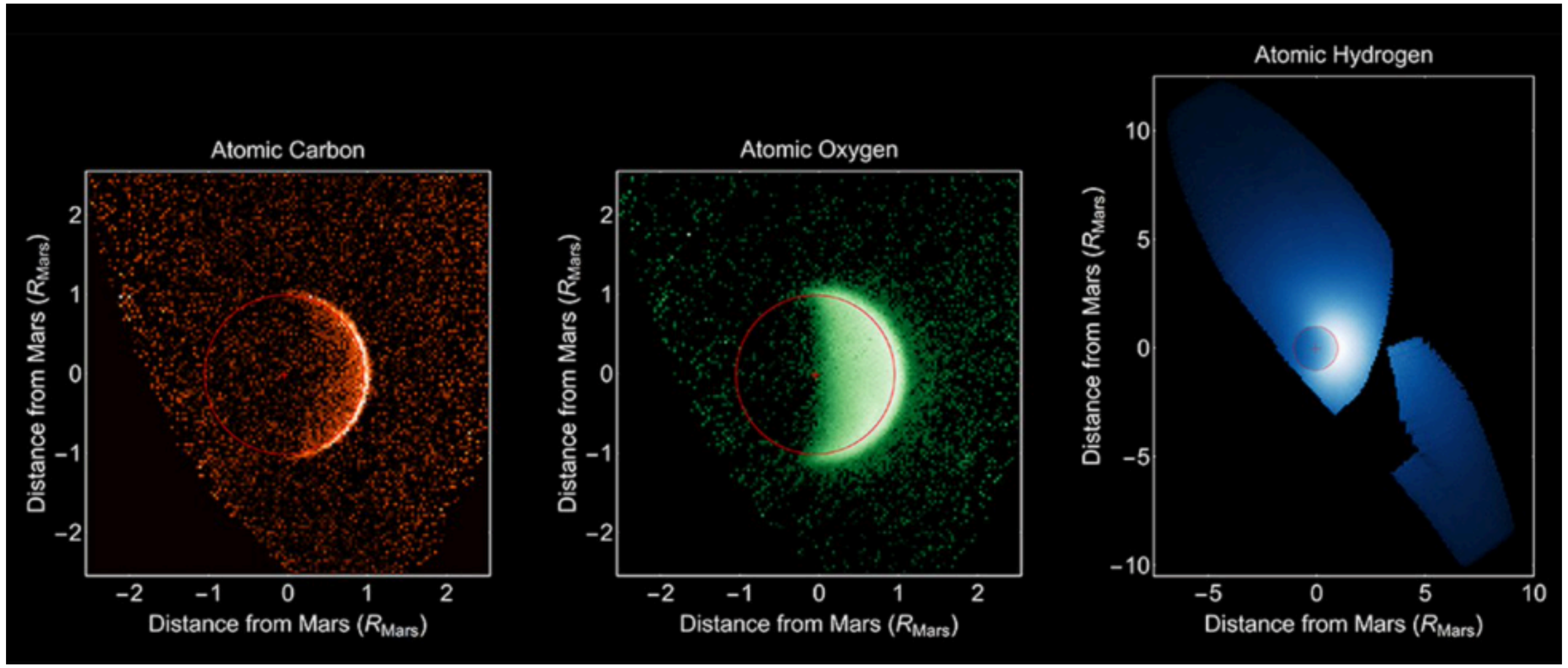

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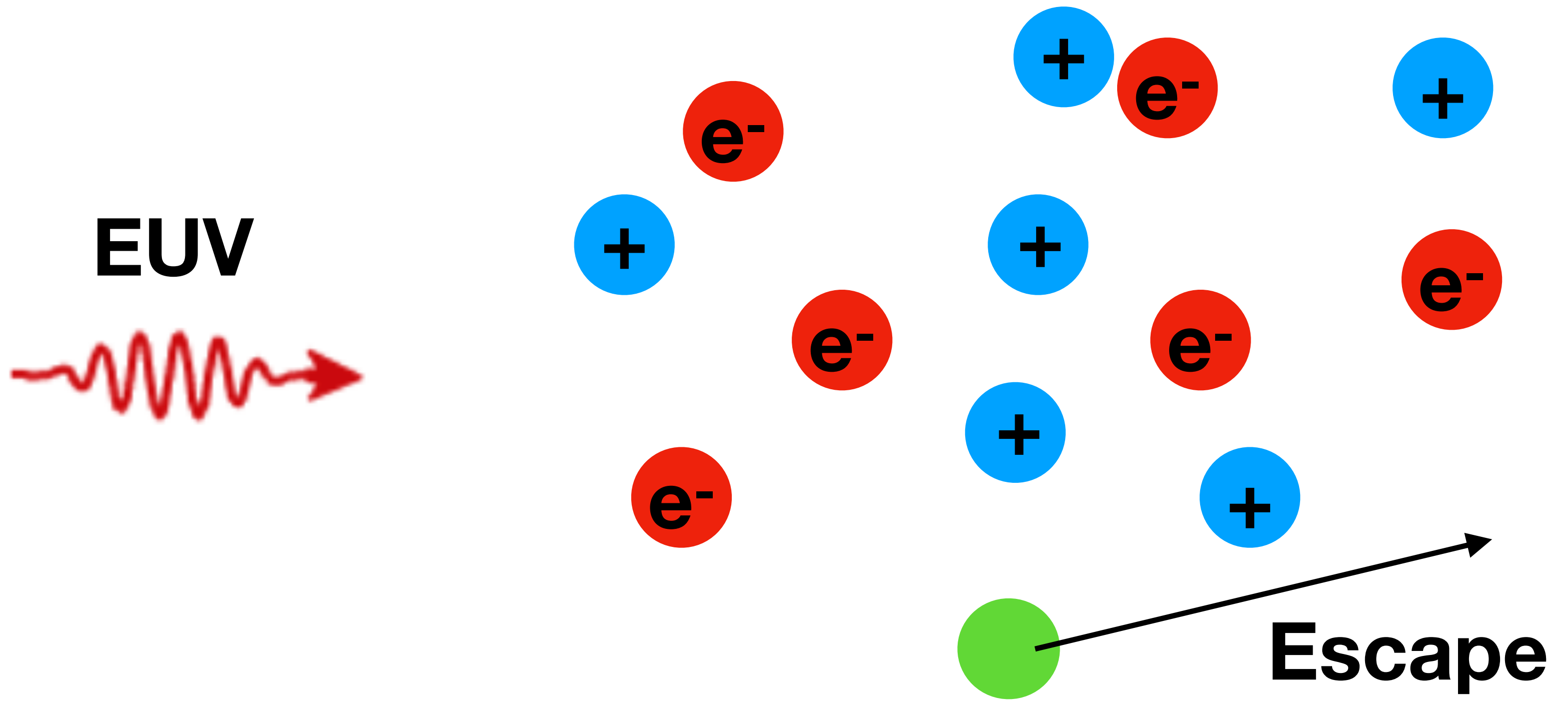

Why does this work?

Neutrals: σ_{col}~10^{-15} cm^2
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Once neutral, the particle has a much longer mean-free path and can become collisionless, and escape.

See Gronoff et al. (2022) for a recent review of many non-thermal escape processes

Thermal driven escape

$$T_{\rm eq} = T_* \sqrt{\frac{R_*}{2a}} \sim 1500\ {\rm K} \left(\frac{T_*}{5700\ {\rm K}}\right) \left(\frac{R_*}{R_\odot}\right)^{1/2} \left(\frac{a}{0.03\ {\rm AU}}\right)^{-1/2}$$

Bolometric heating cannot get close to the escape temperature.

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The concept of the escape temperature

$$\frac{GM_p \mu m_h}{R_p}$$

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The concept of the escape temperature

$$\frac{G M_p \mu m_h}{R_p} \sim k_b T_{\rm esc}$$

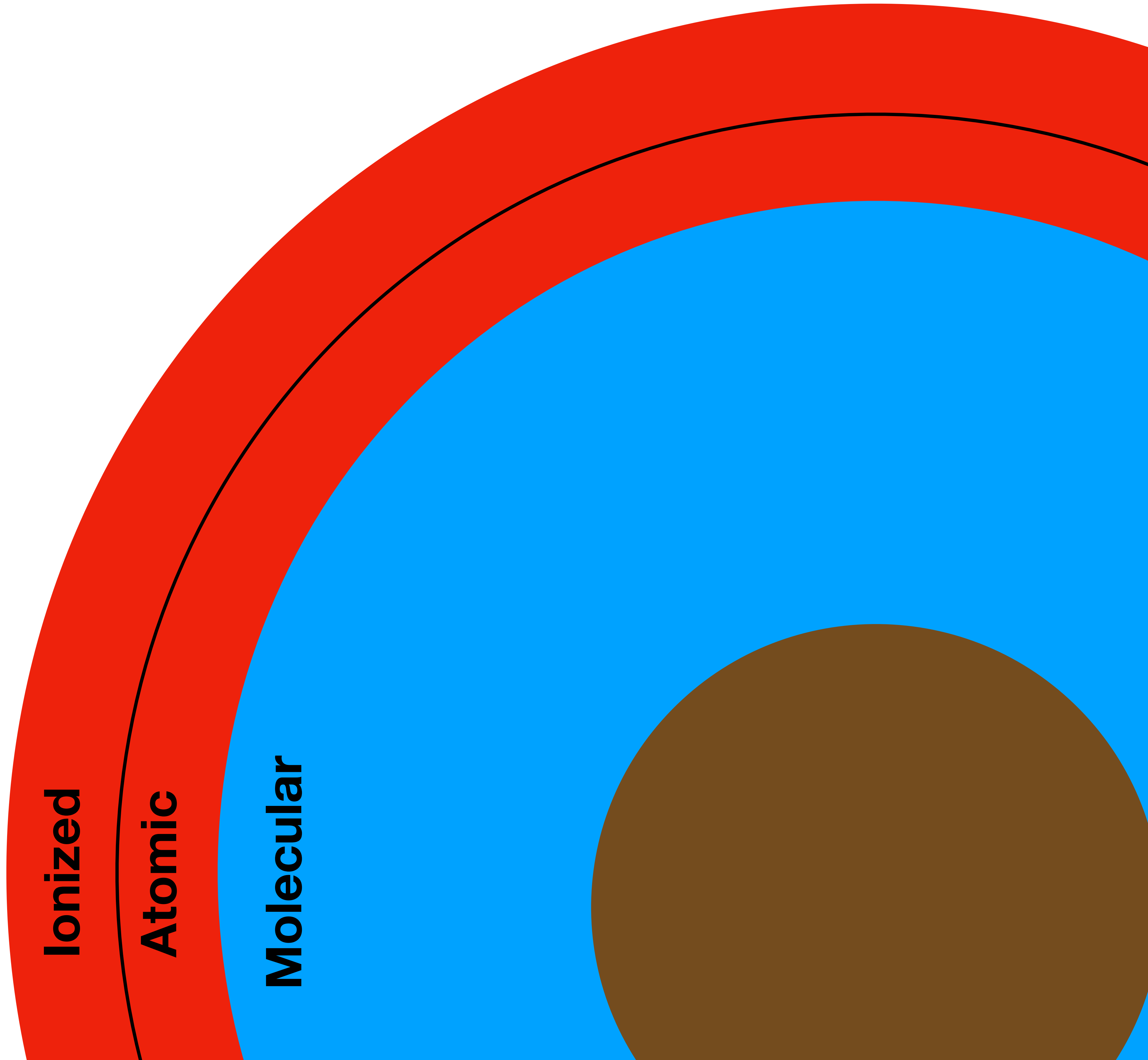
$$T_{\rm esc} \sim 8000 \text{ K } \mu \left(\frac{M_p}{1 \mathrm{M}_\oplus}\right) \left(\frac{R_p}{1 \mathrm{R}_\oplus}\right)^{-1}$$

Bolometric heating cannot get close to the escape temperature.

Heating and cooling

The gas temperature is set by balancing heating and cooling.

Considering just radiative processes now.



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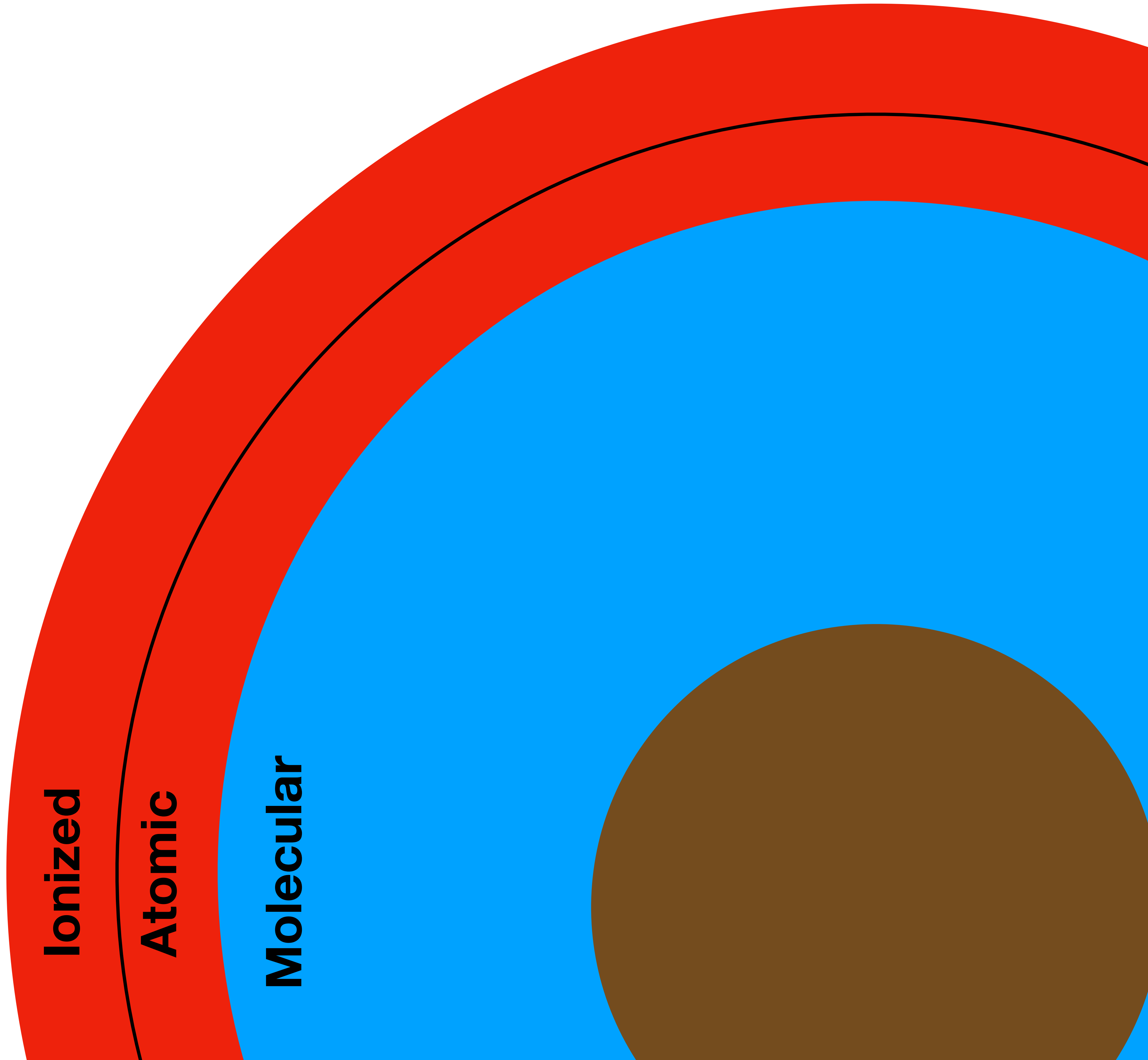

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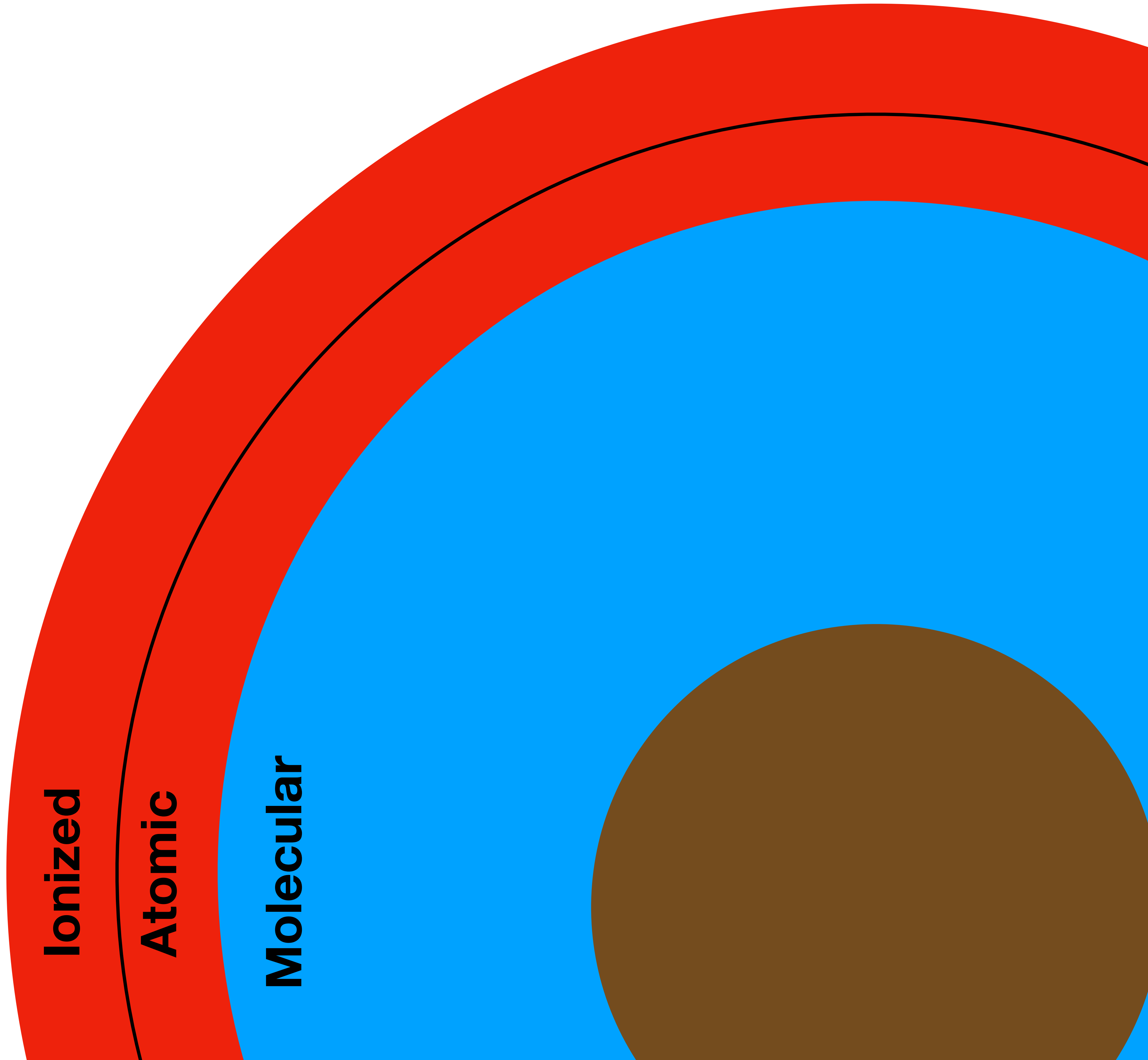

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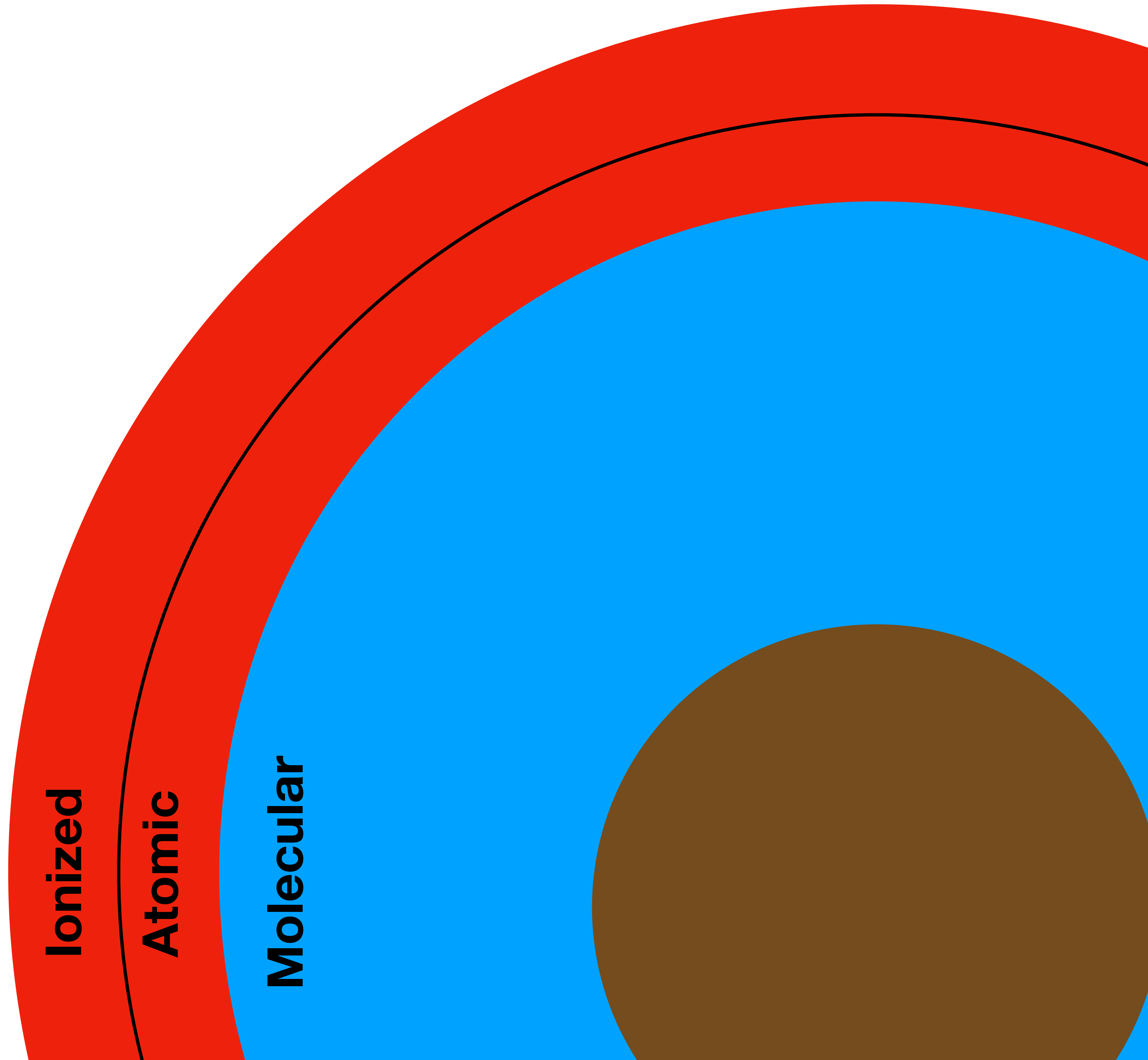

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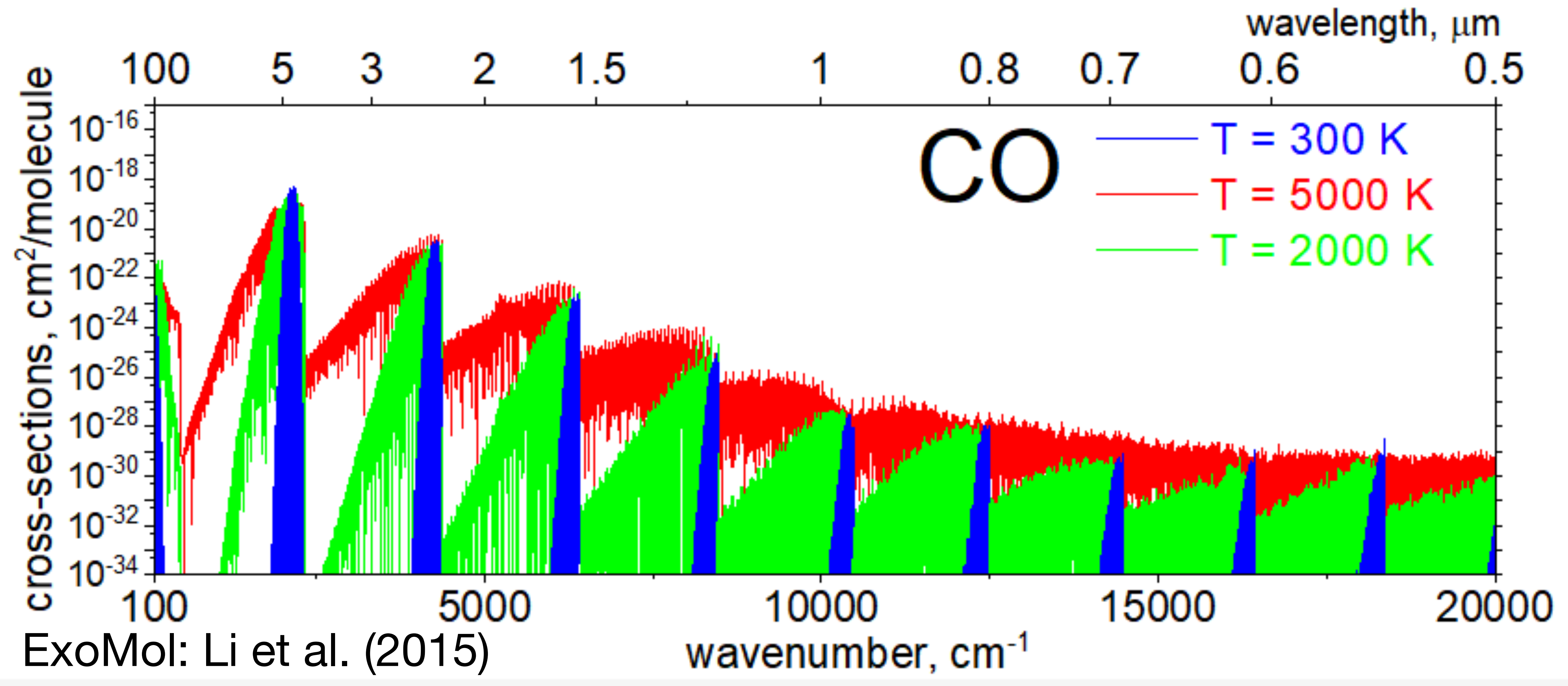

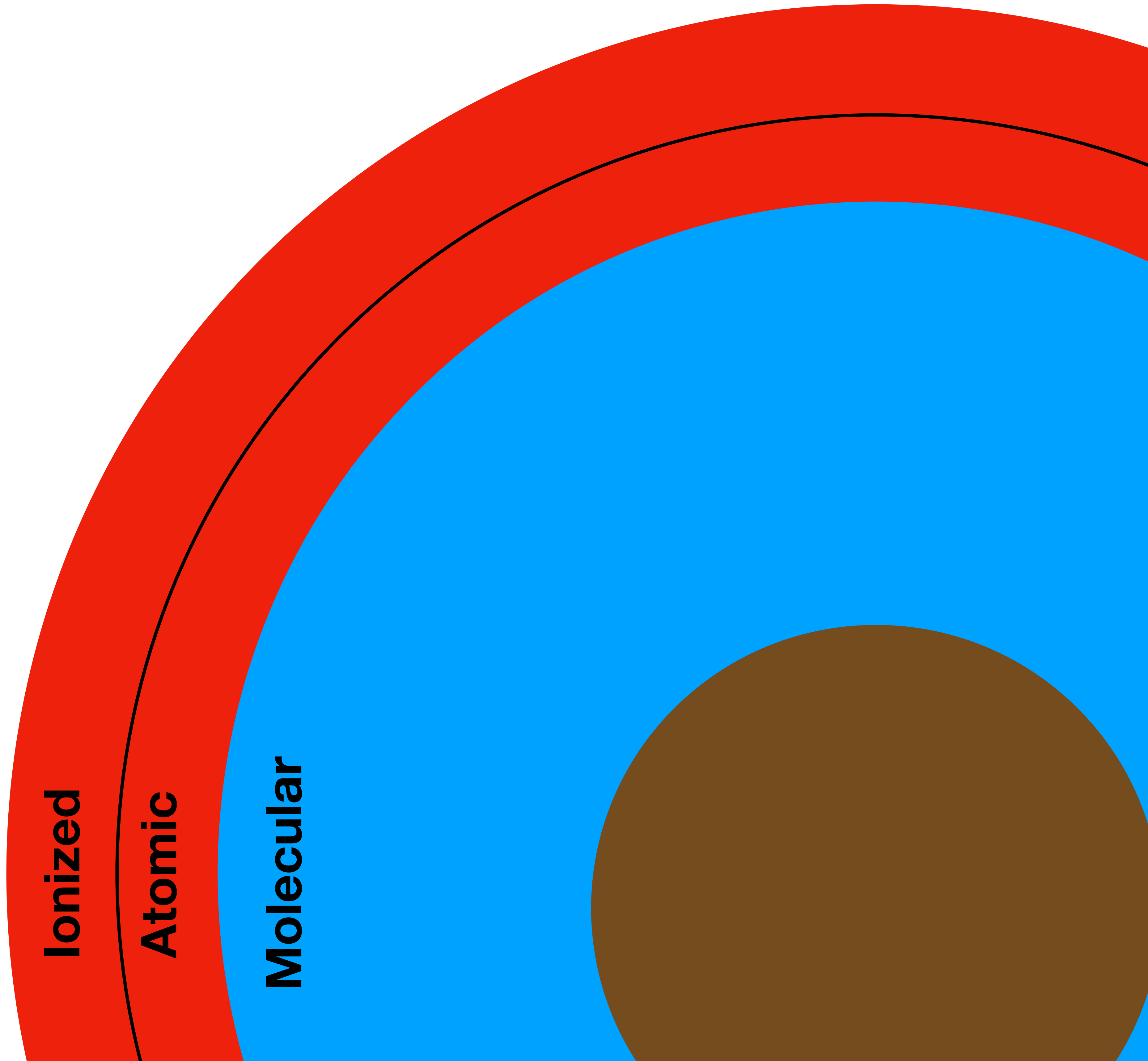

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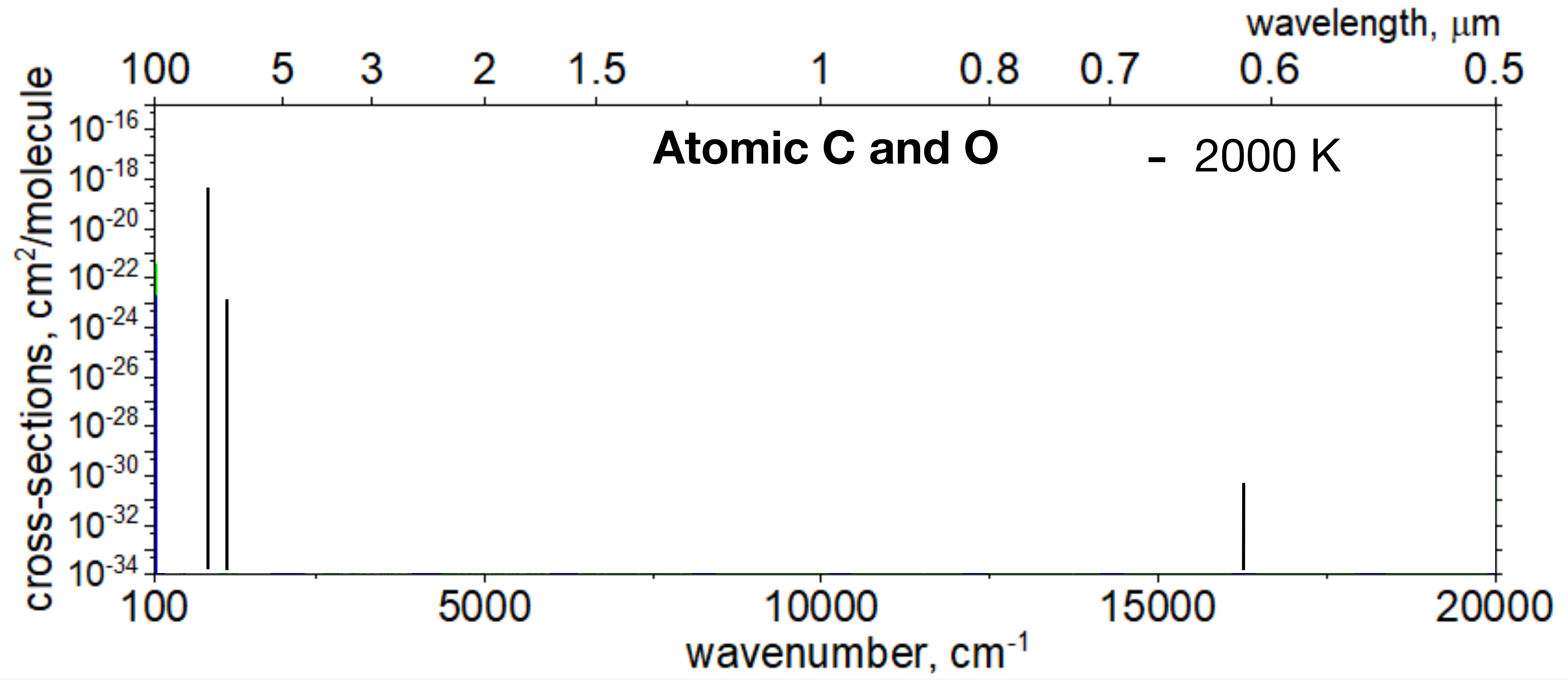

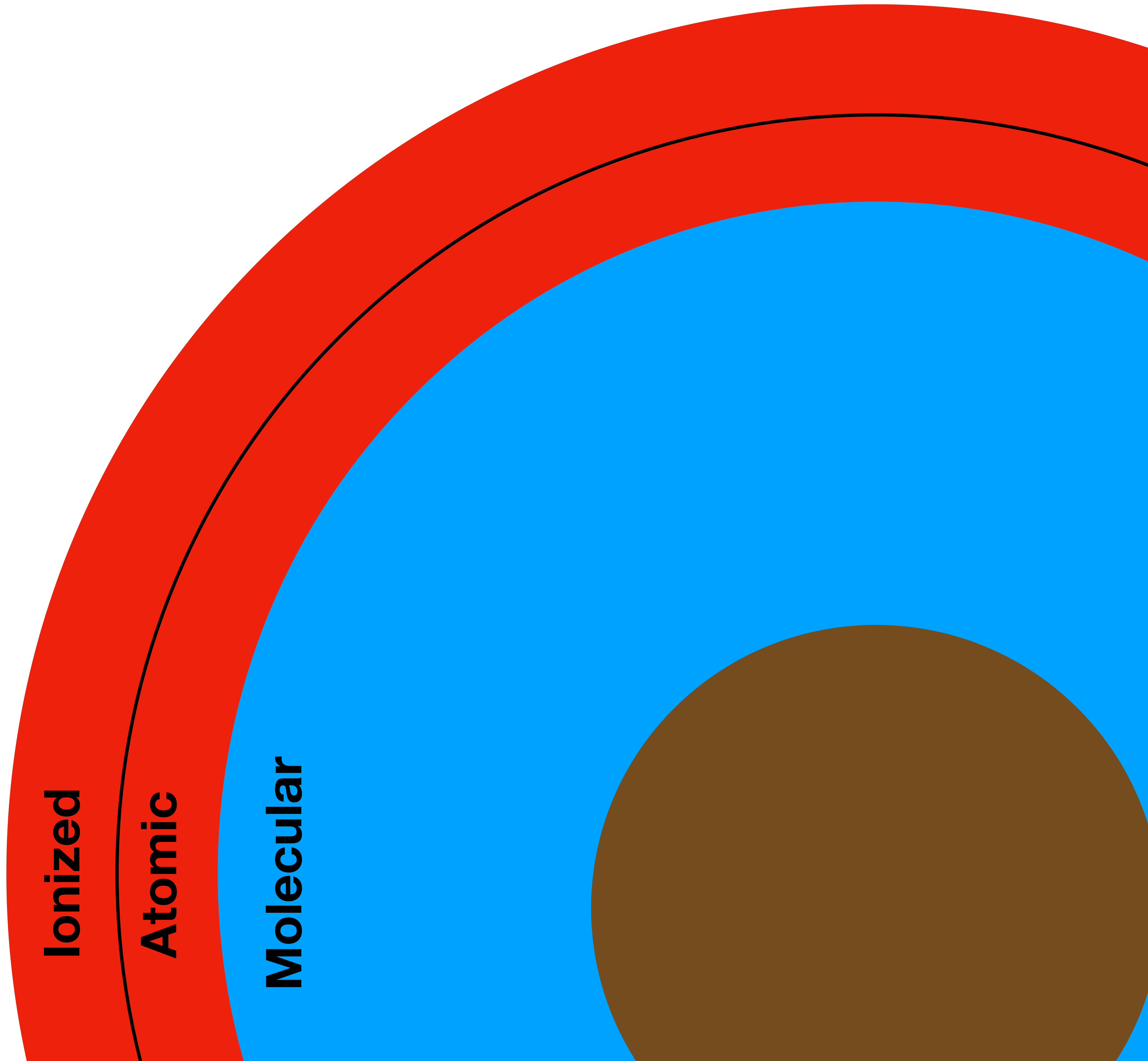

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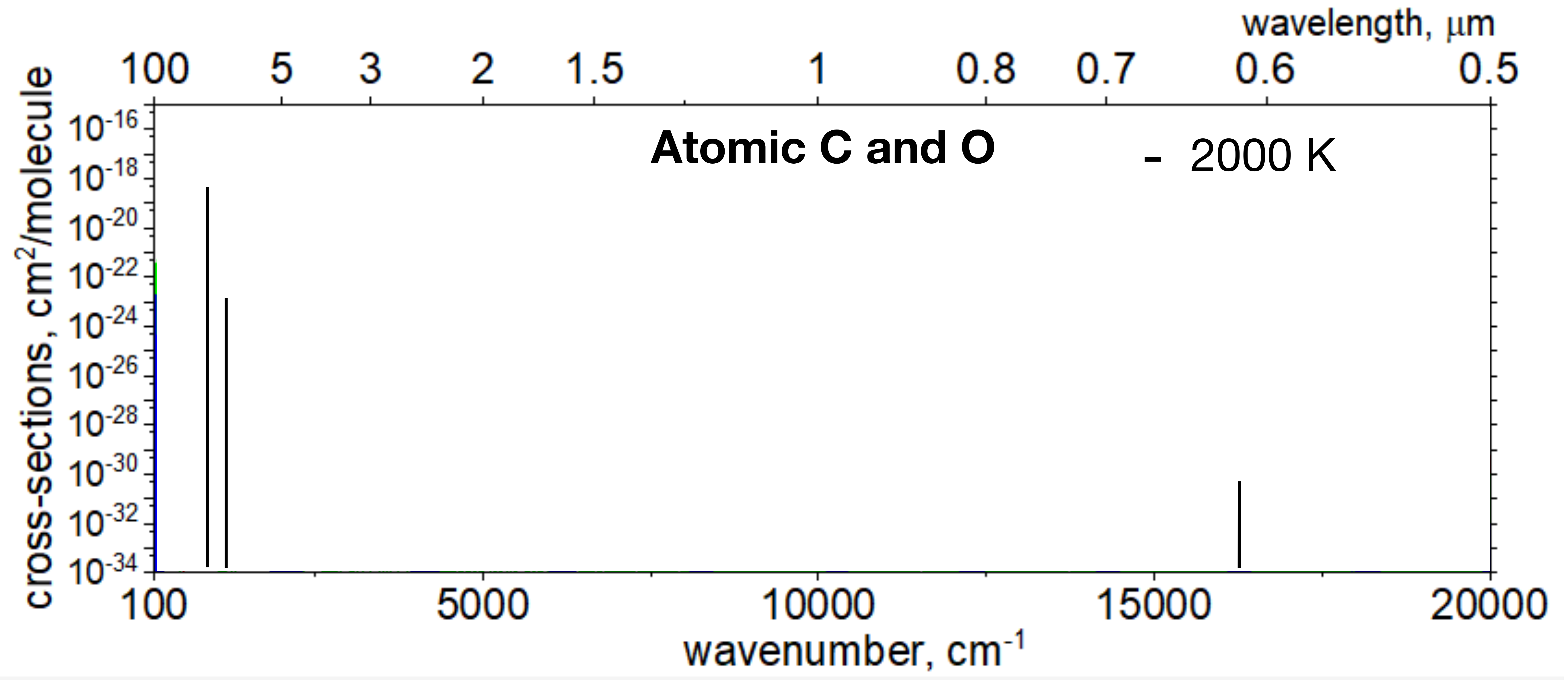

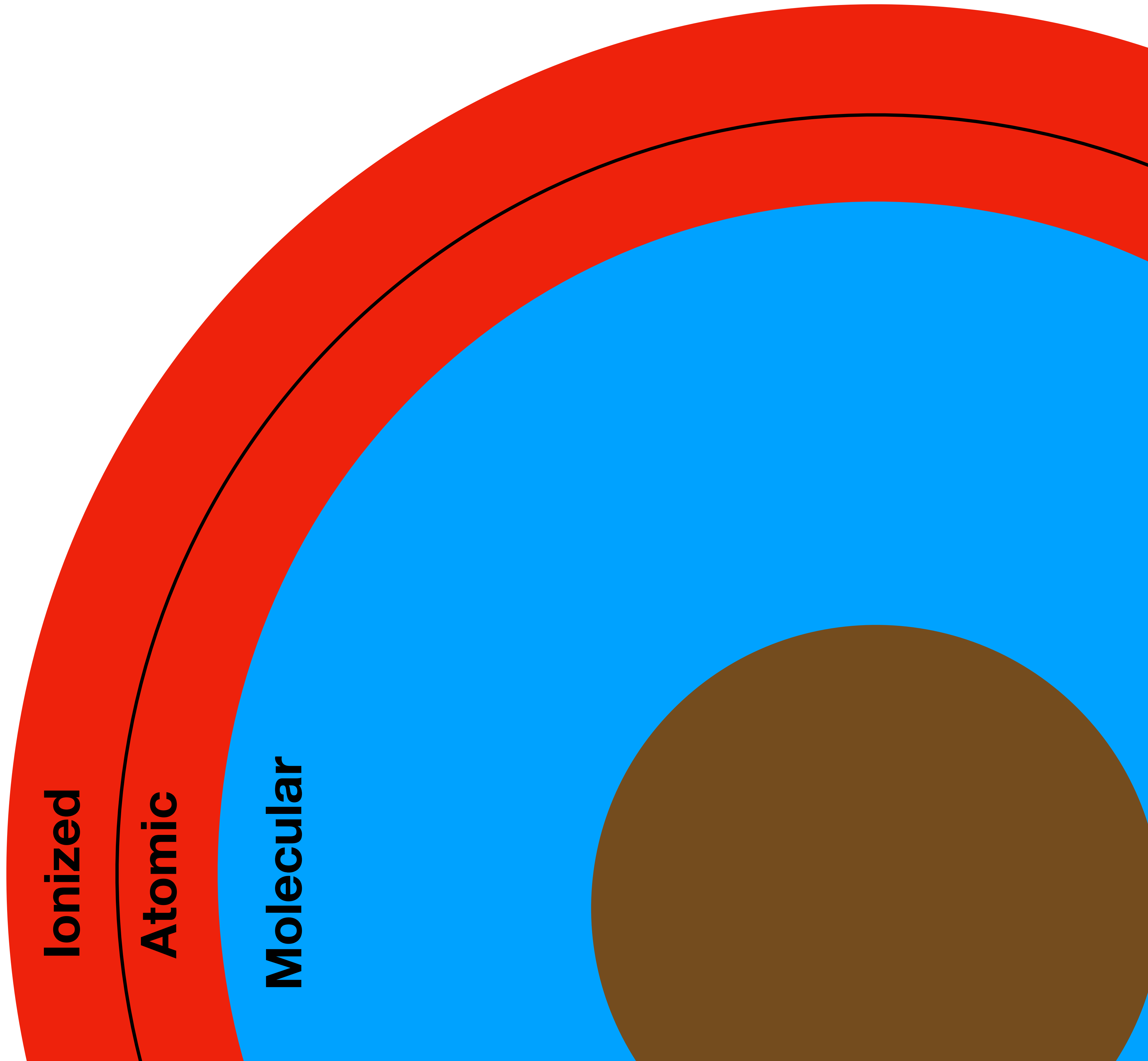

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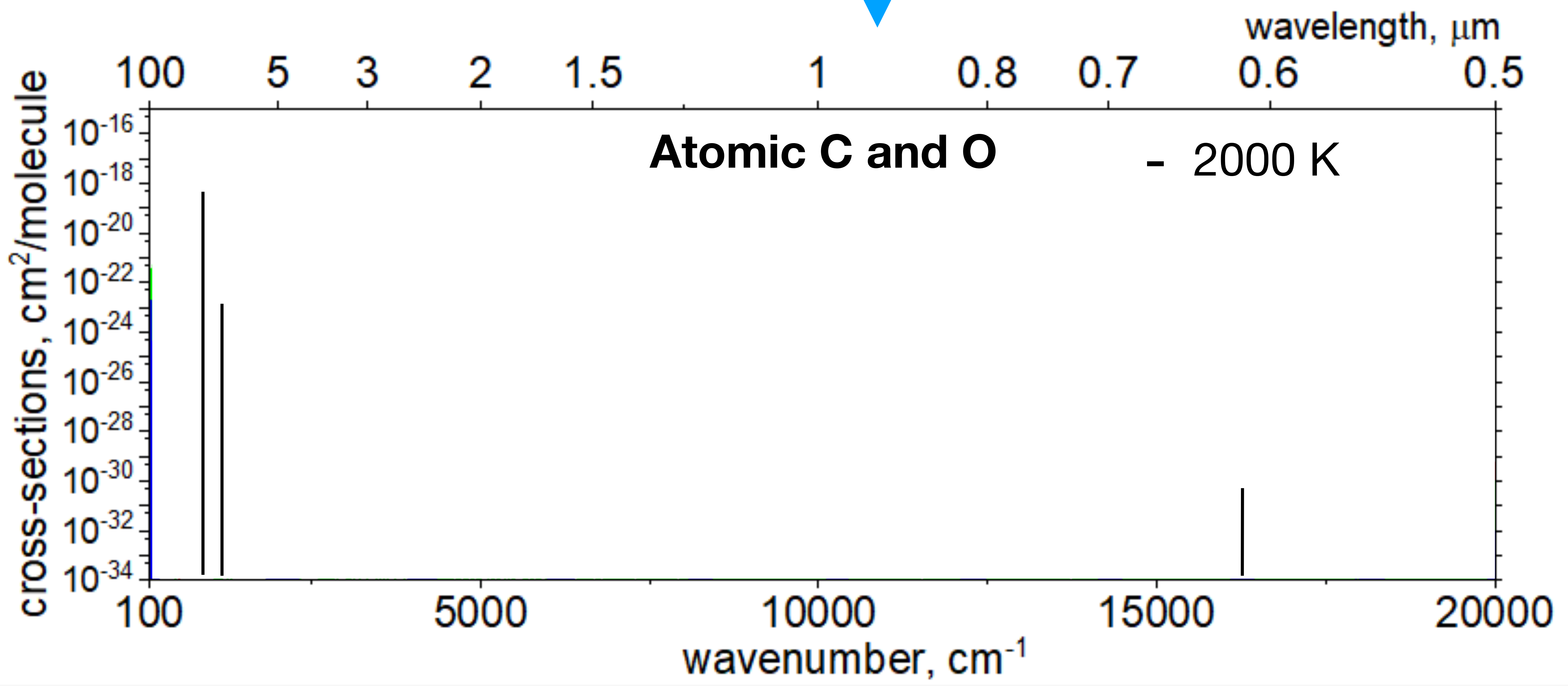

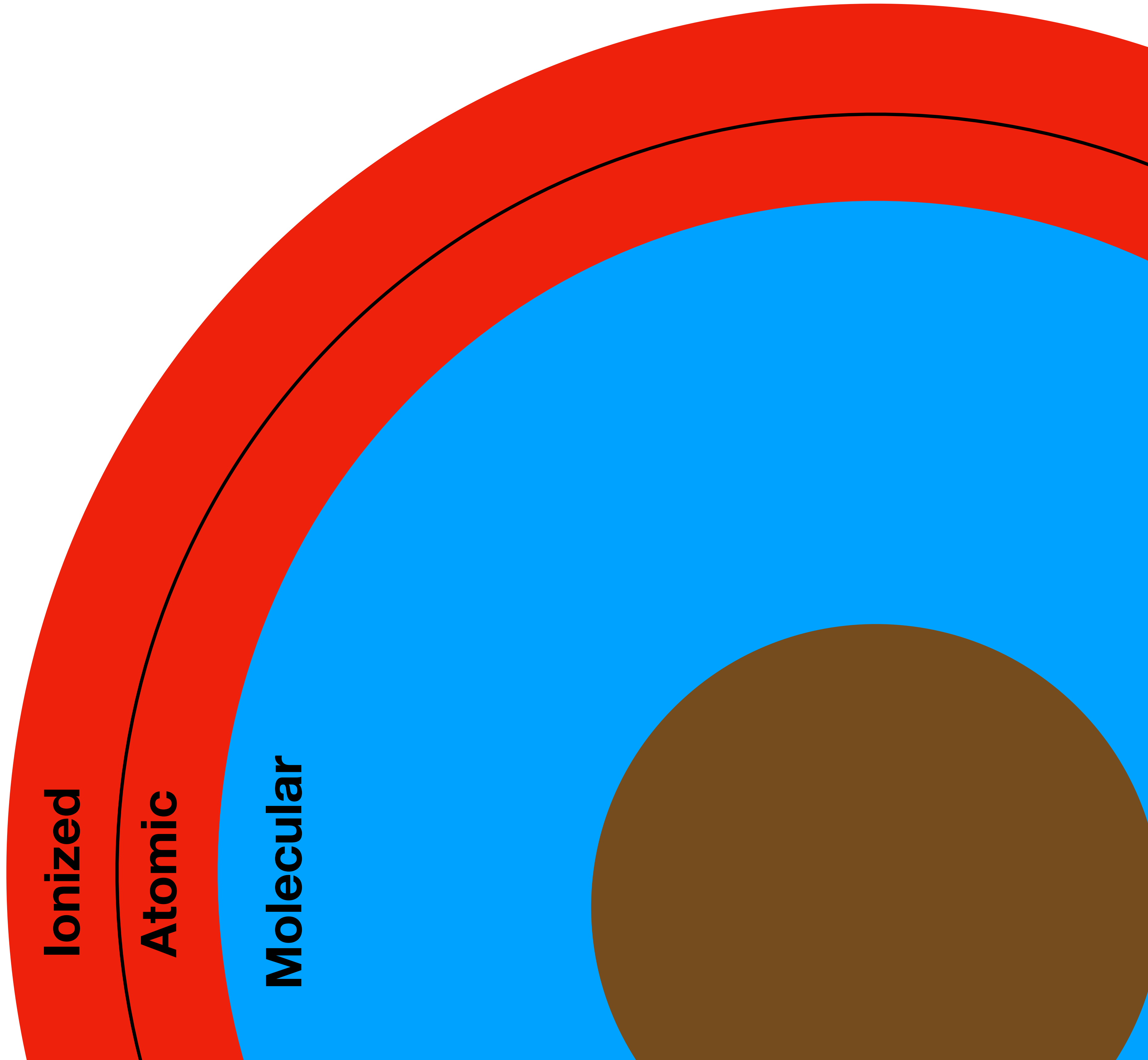

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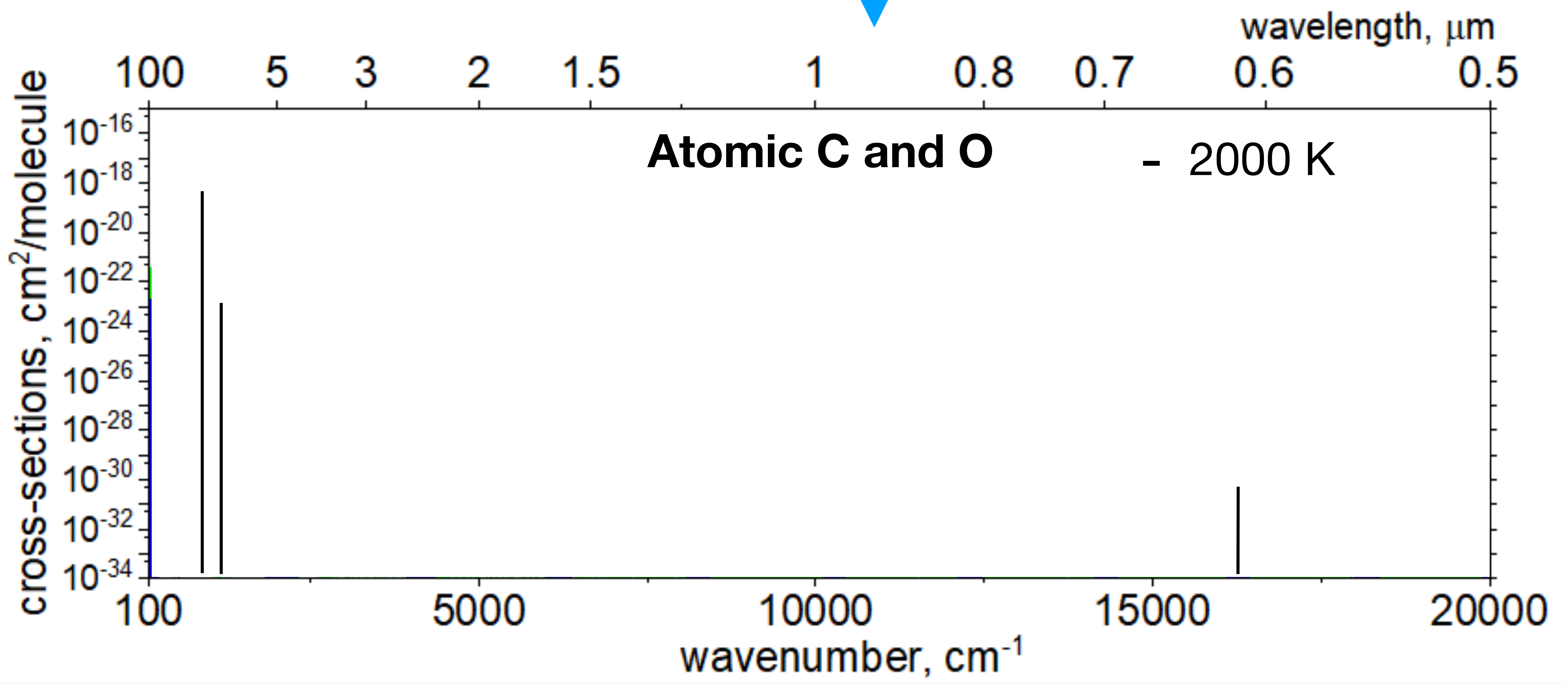
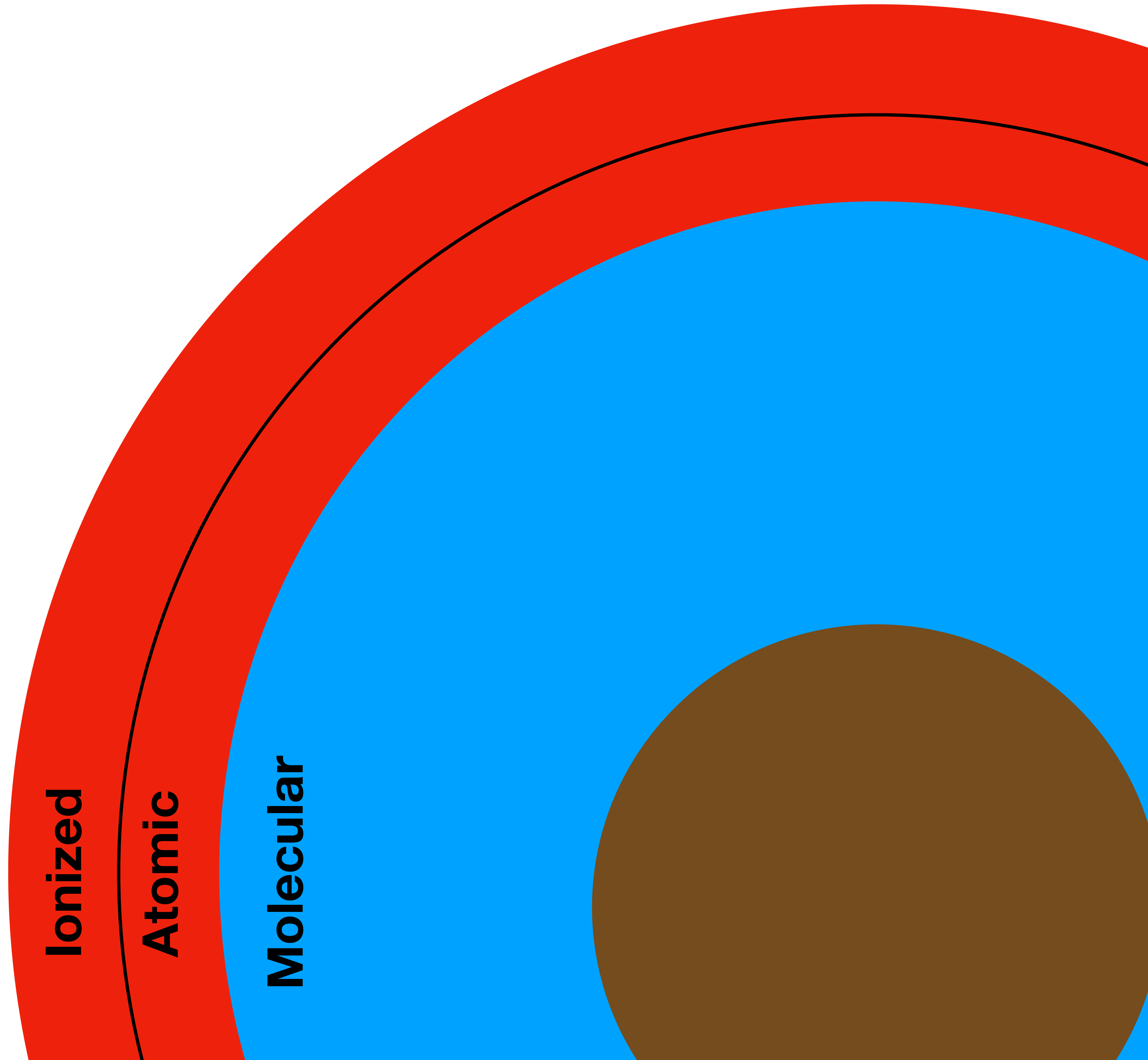


Cooling in atomic/ionized gas is very inefficient below 5,000-10,000 K



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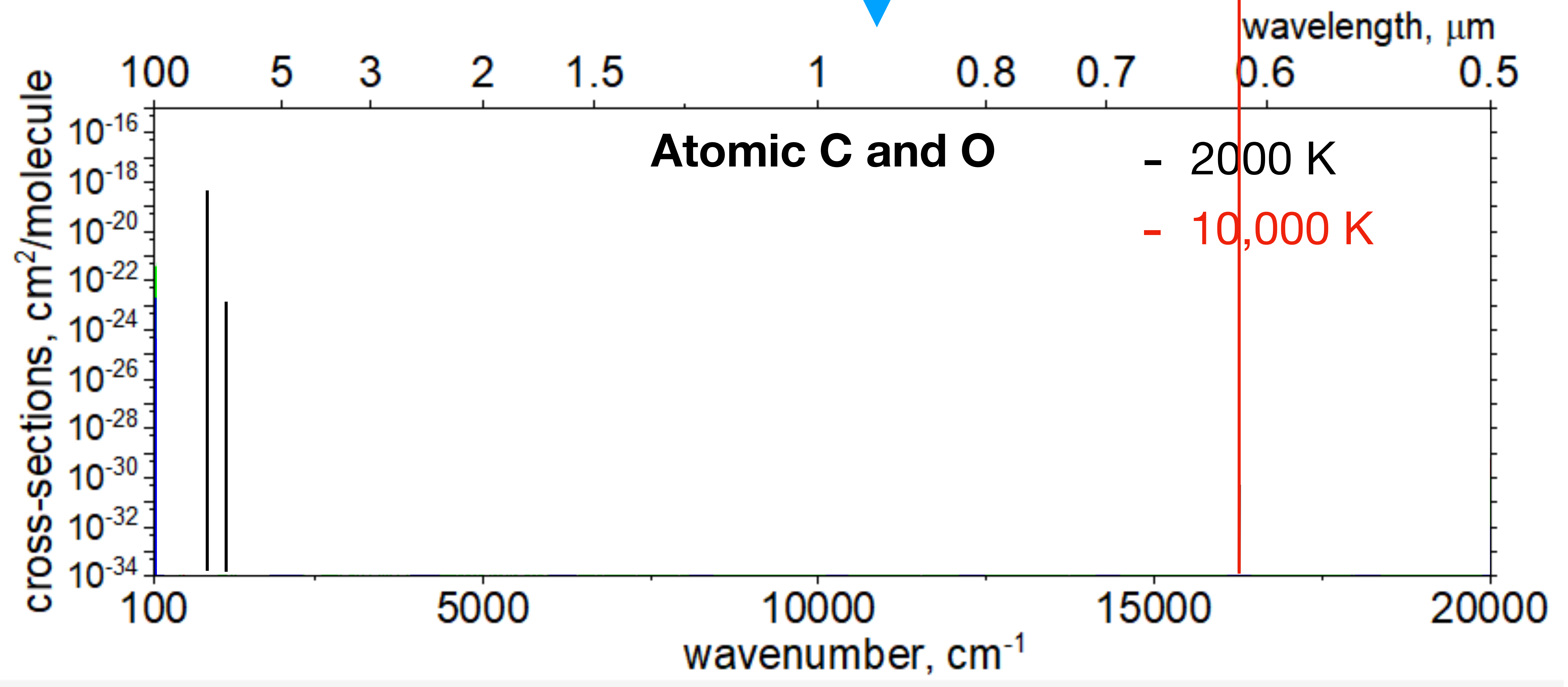

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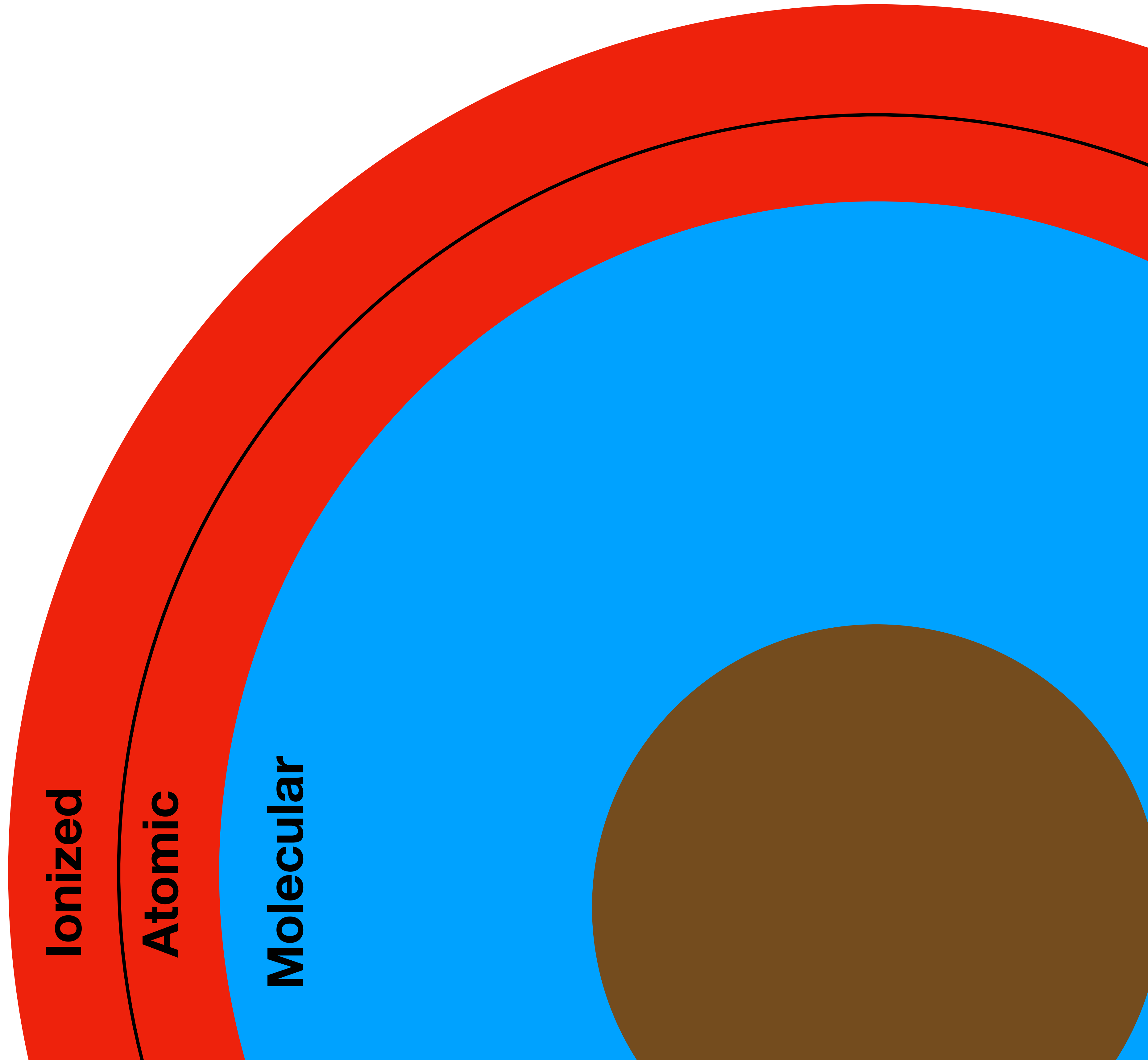

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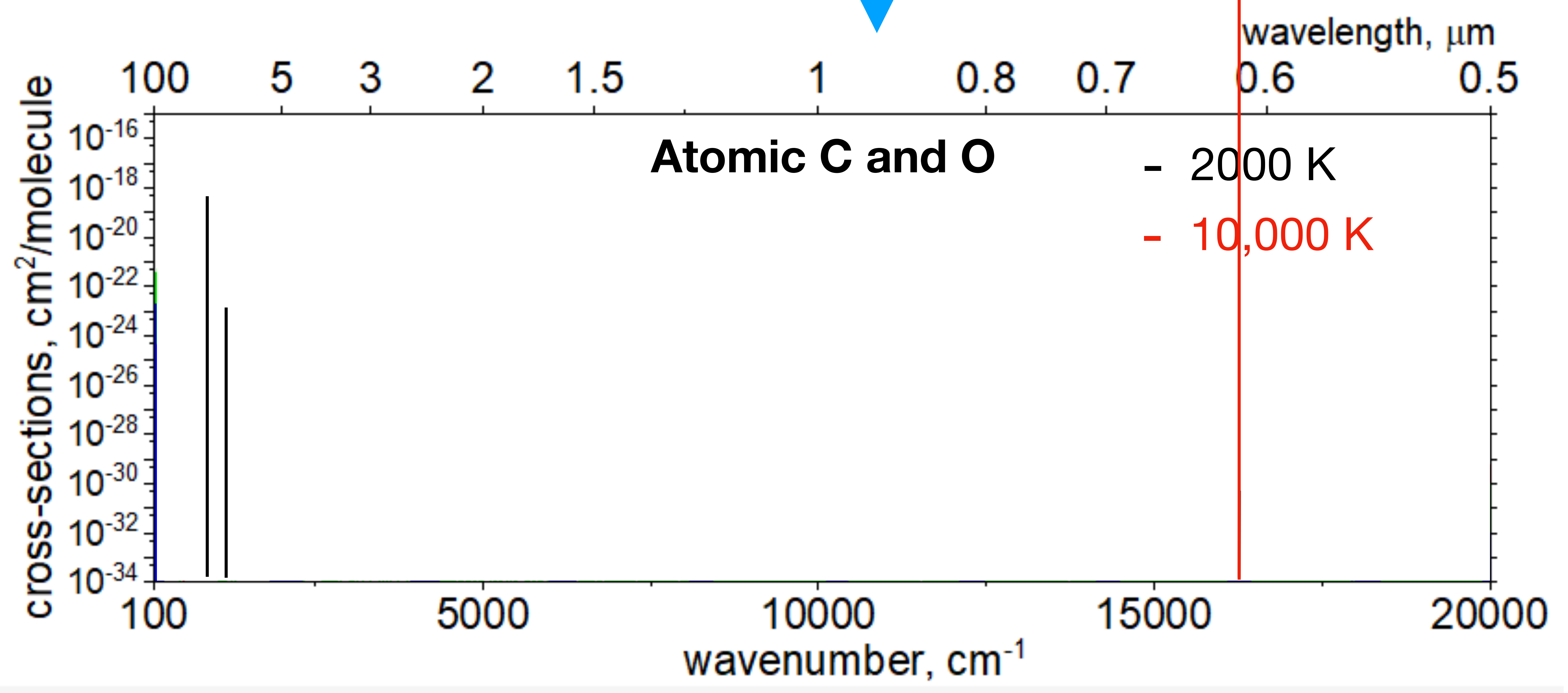

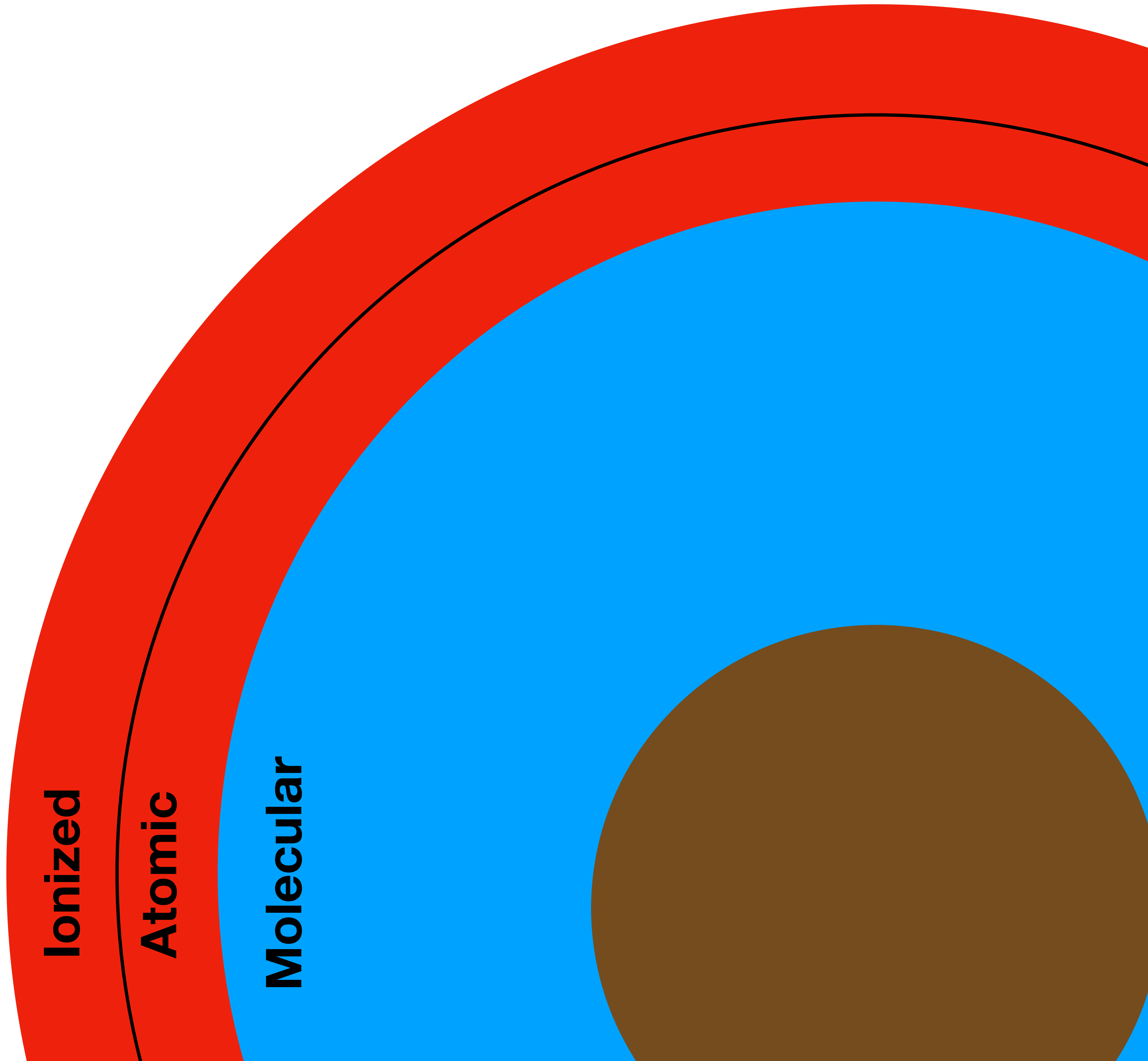

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Significantly hotter than equilibrium temperature

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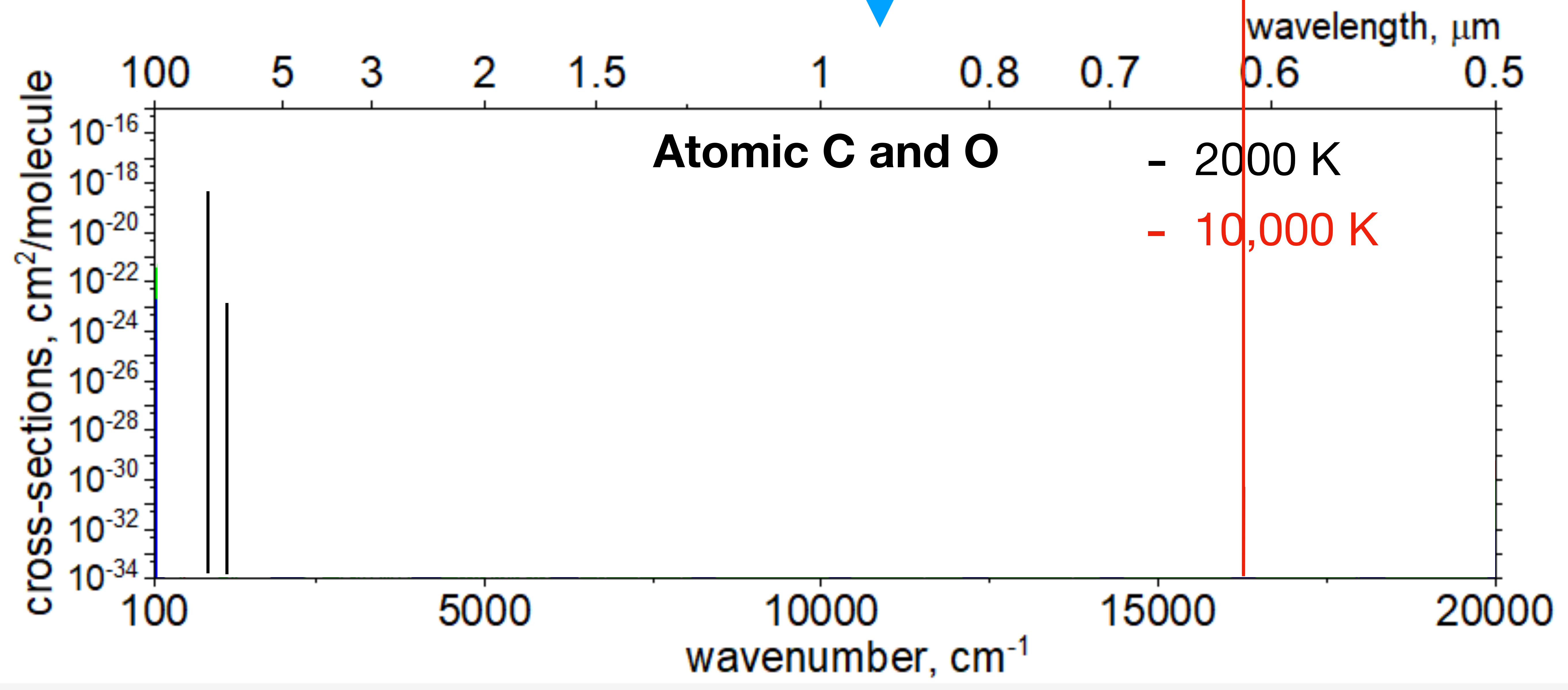
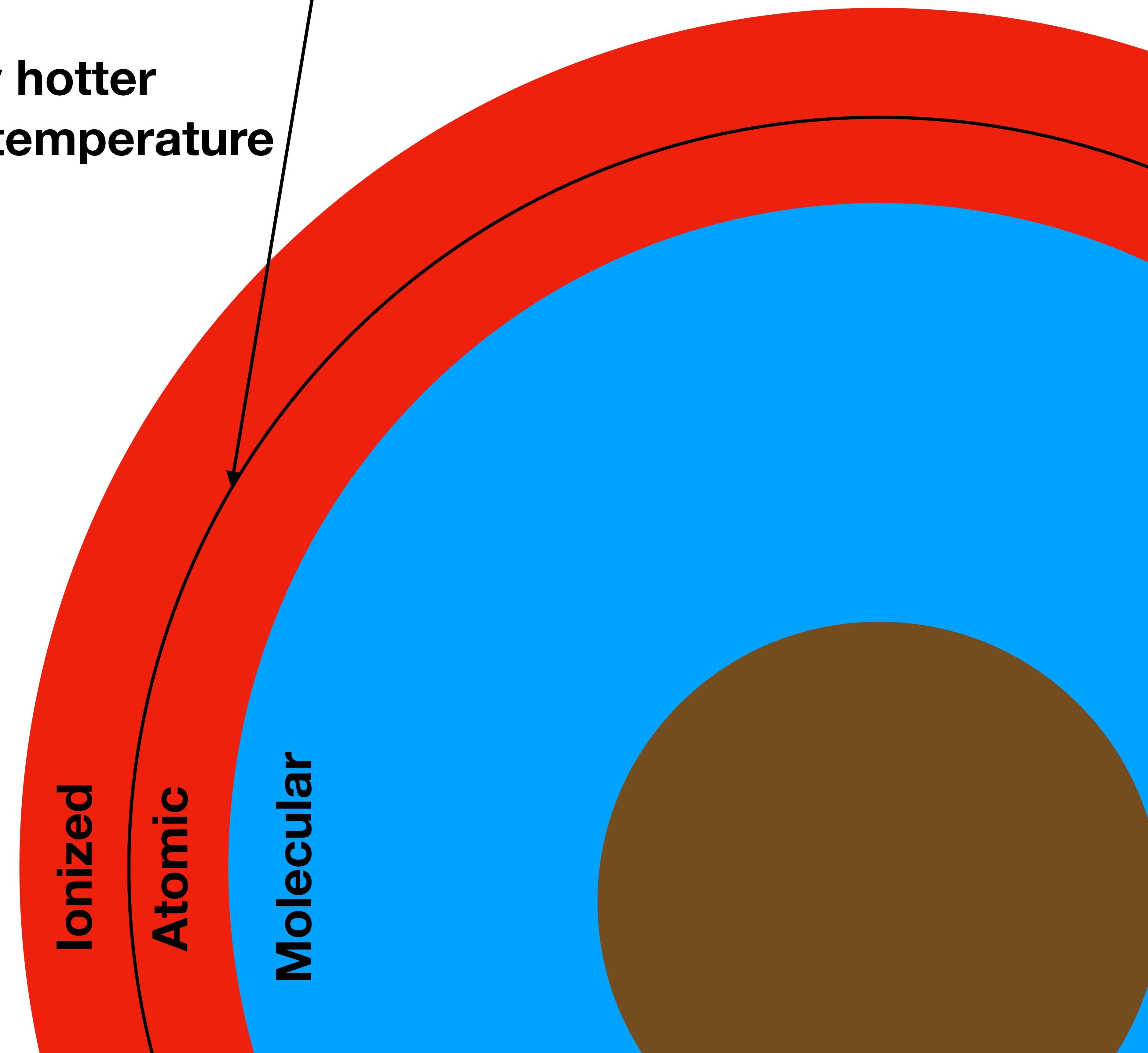
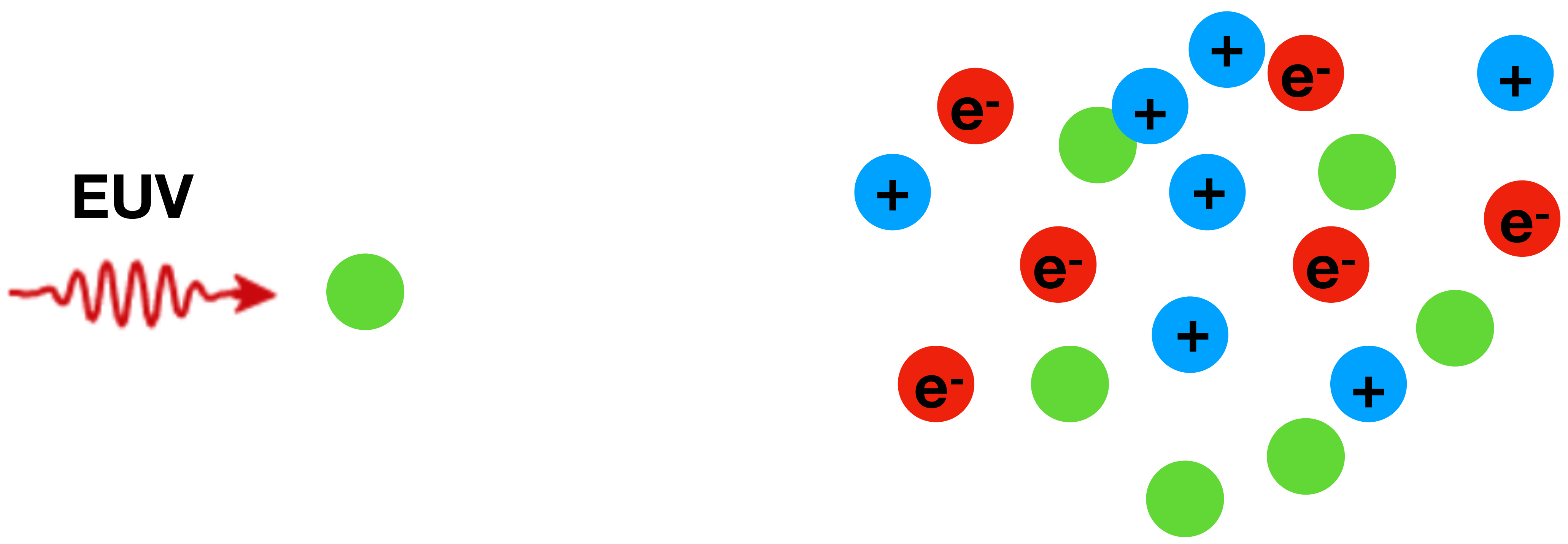




Heating and cooling in atomic/ionized regions



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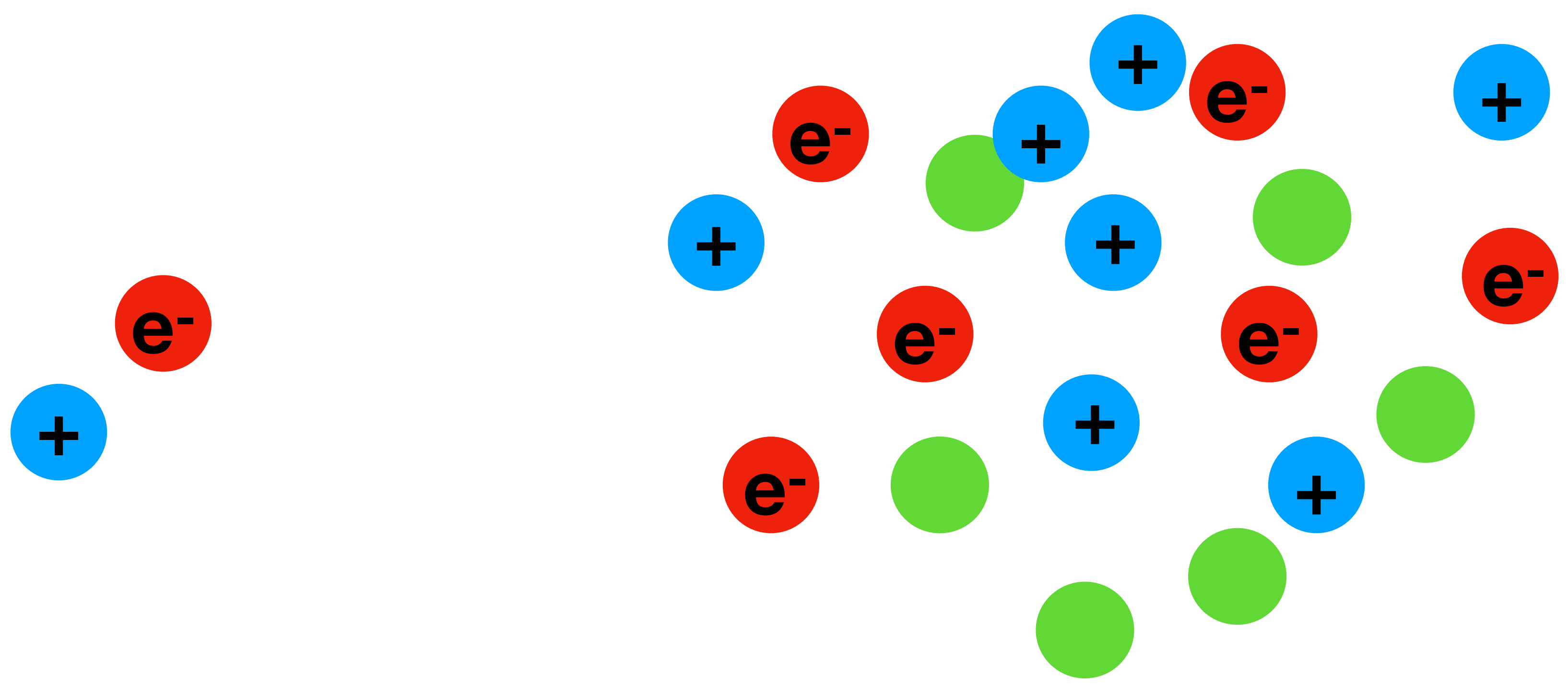

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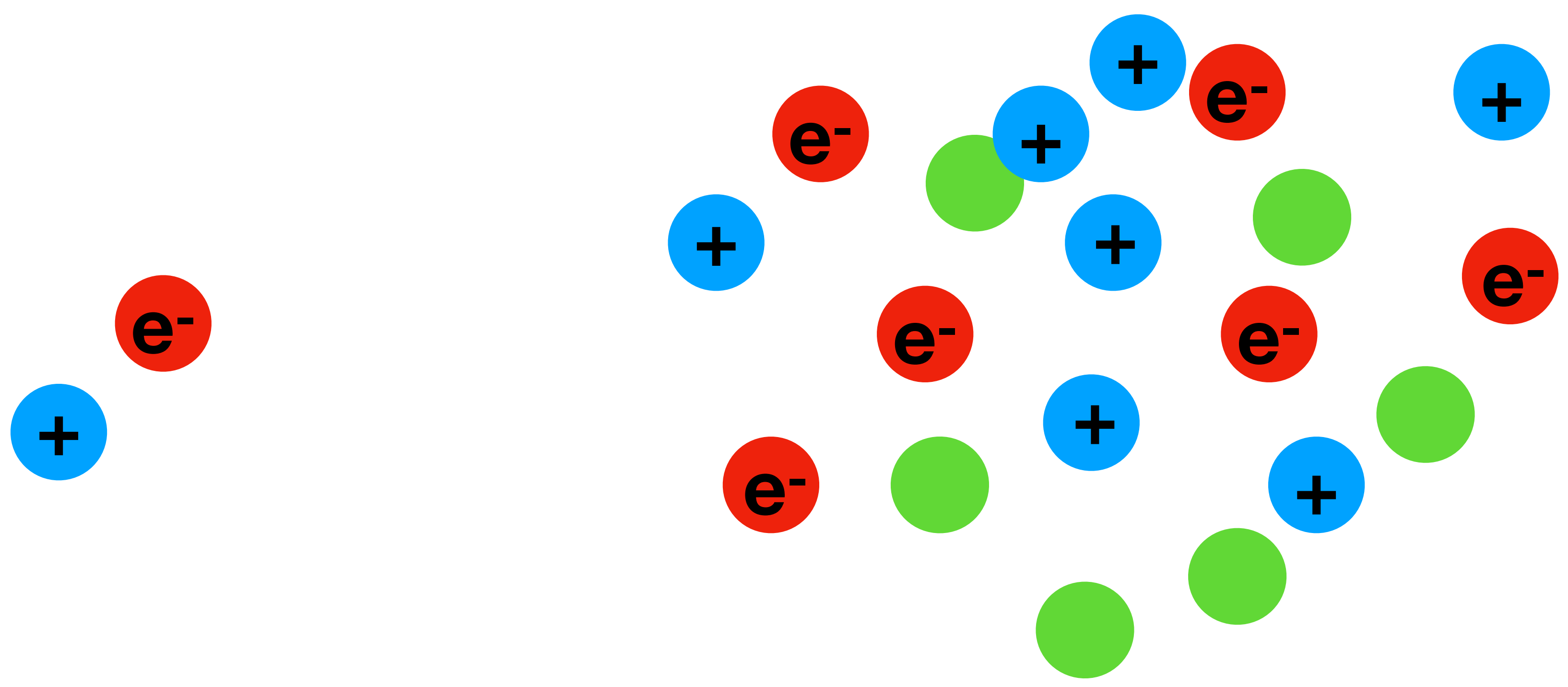

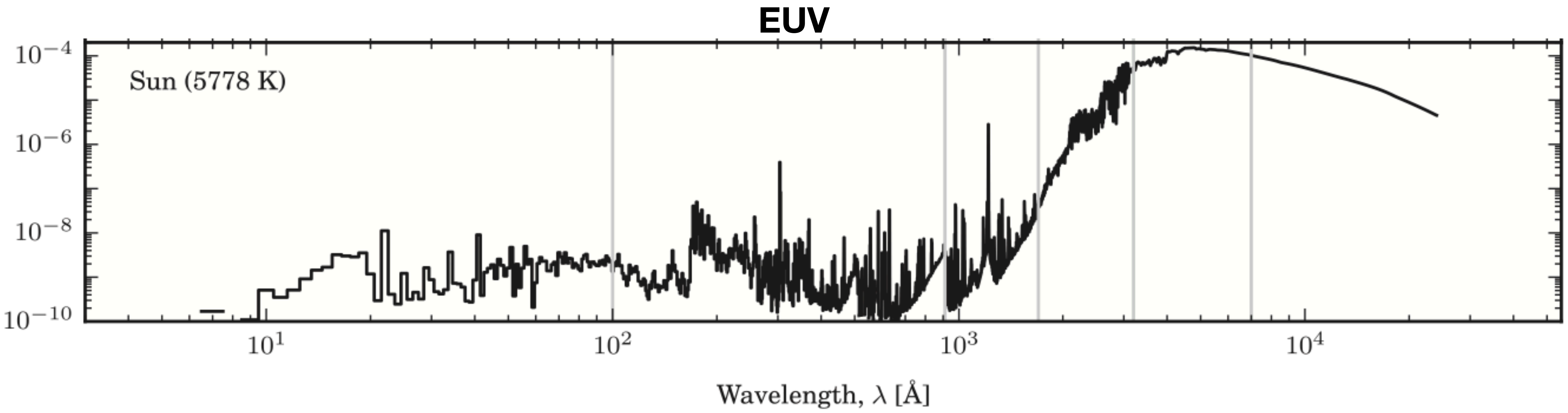

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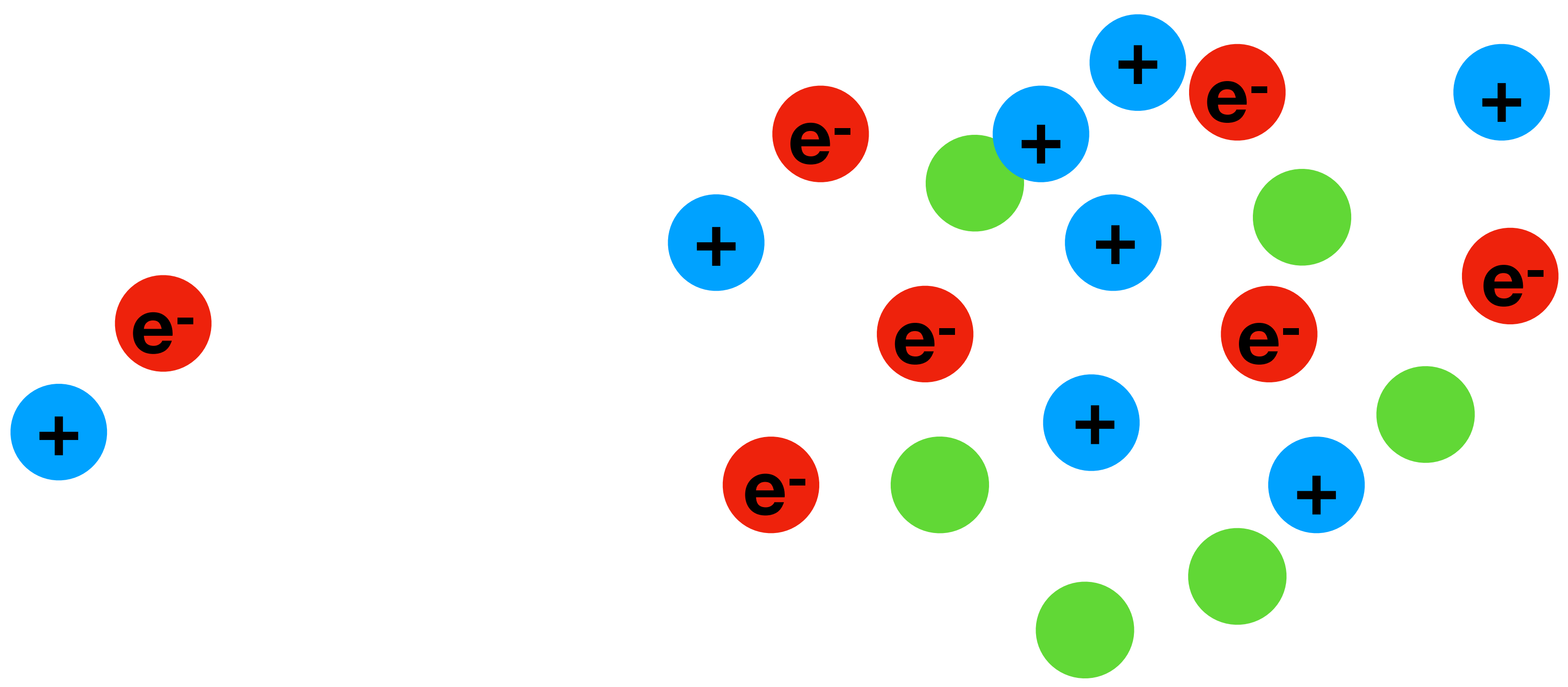

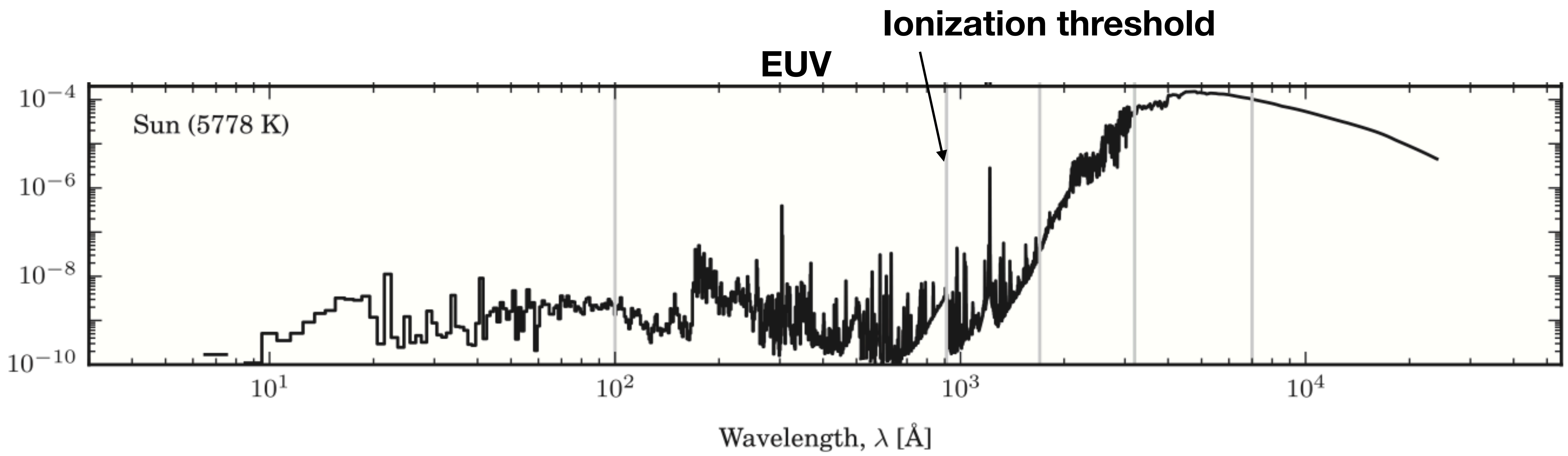

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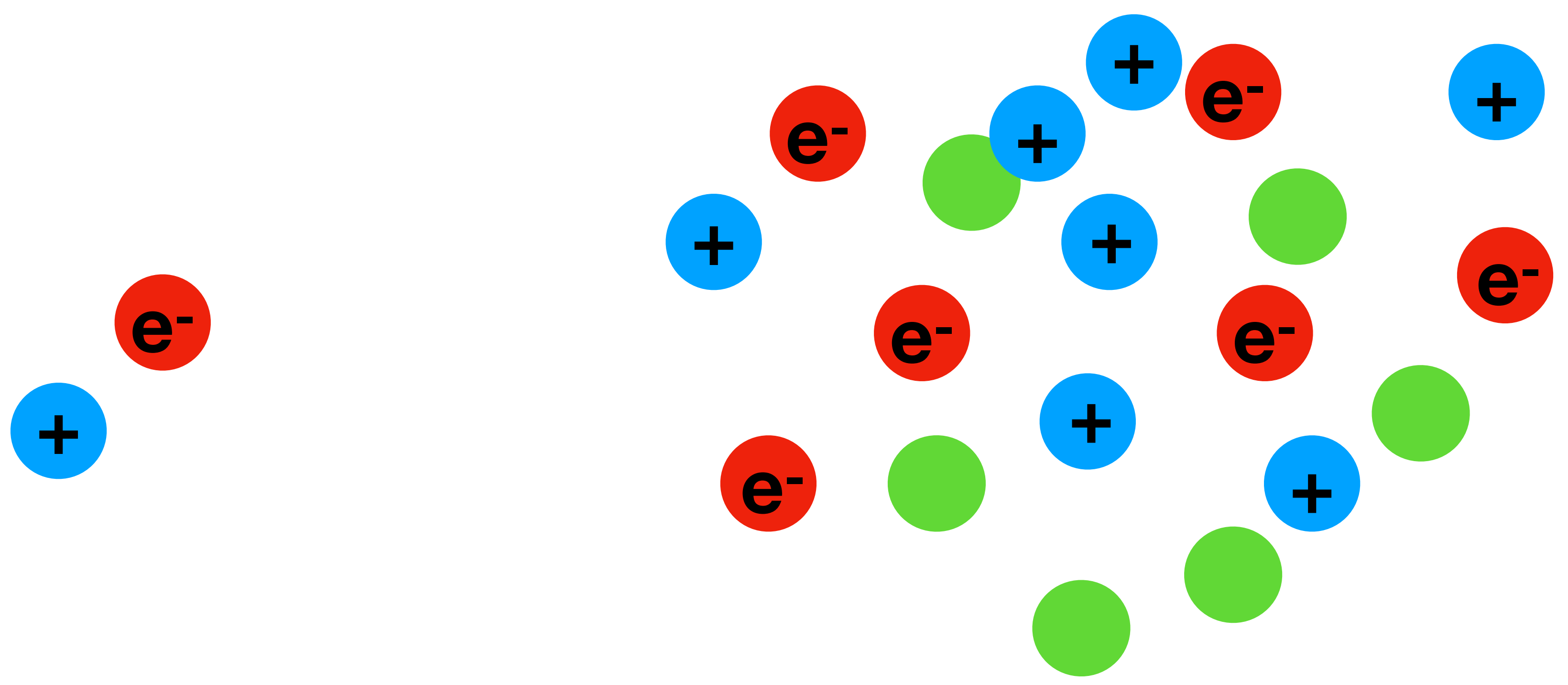
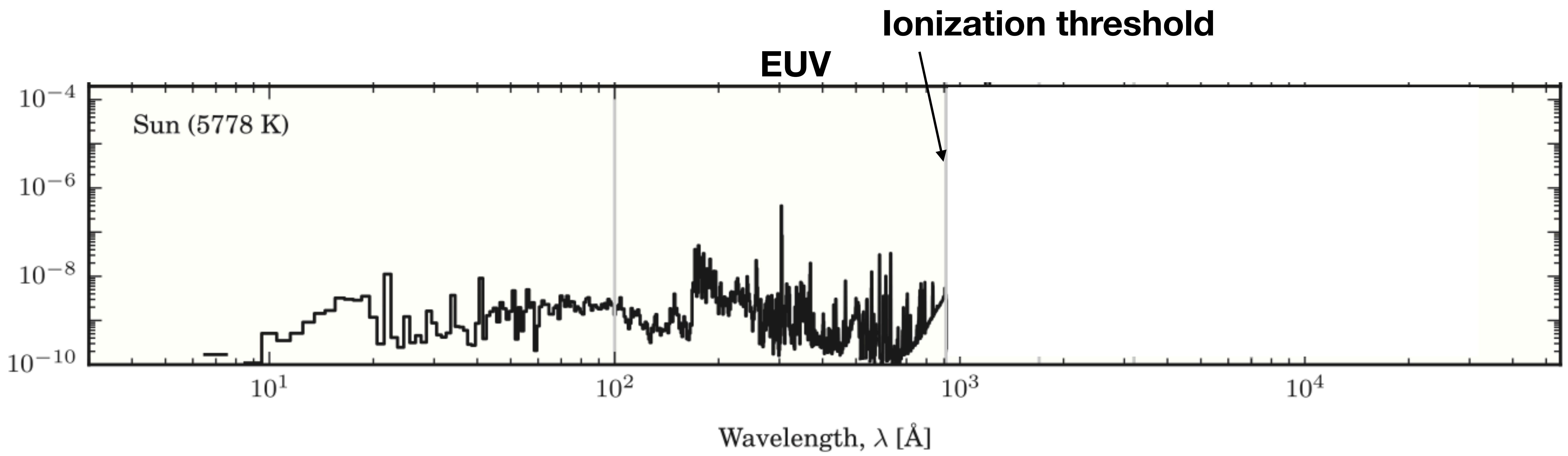
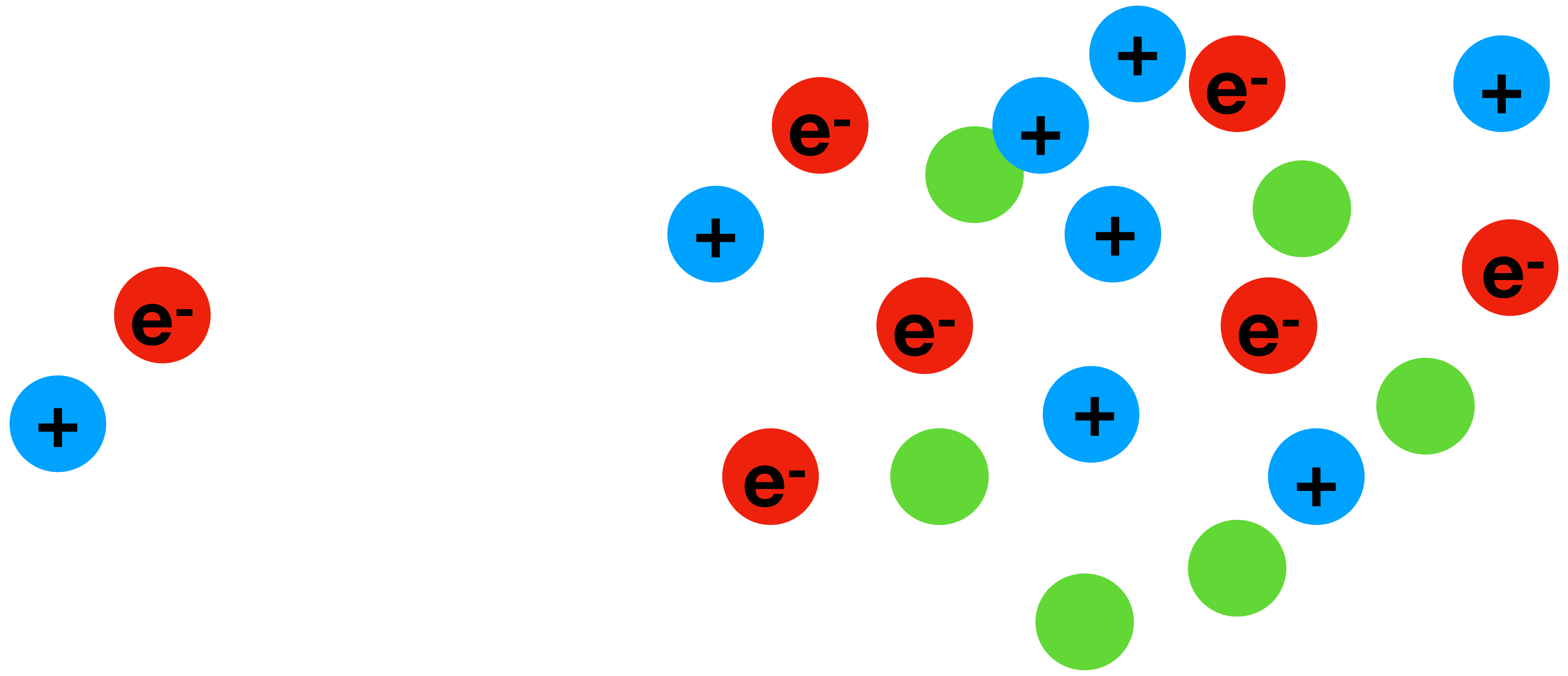
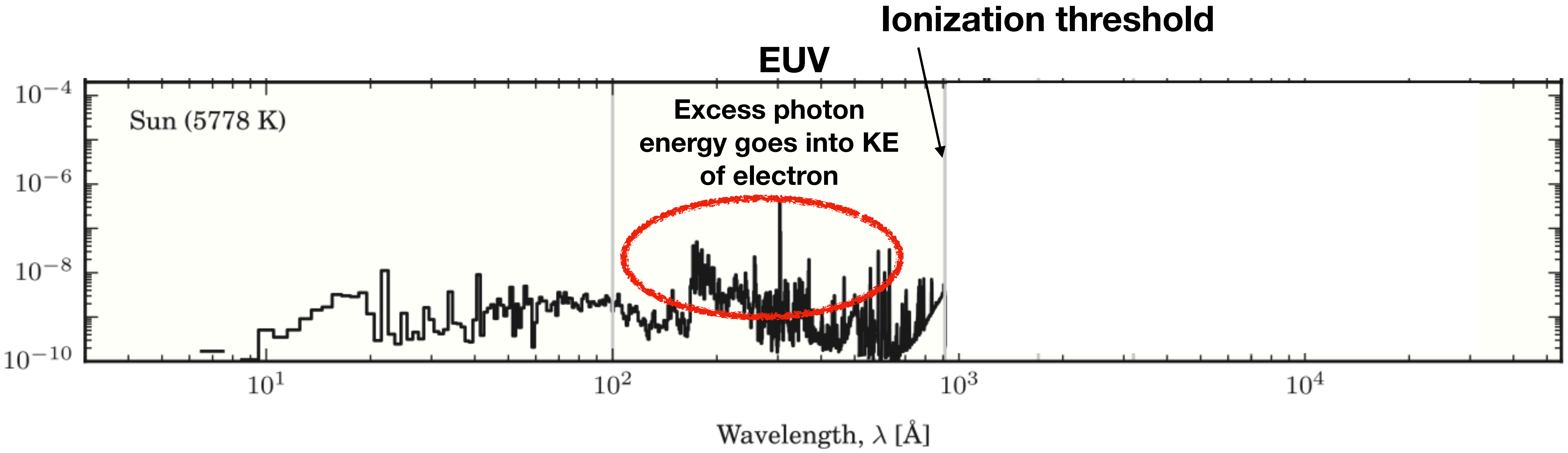




Heating and cooling in atomic/ionized regions





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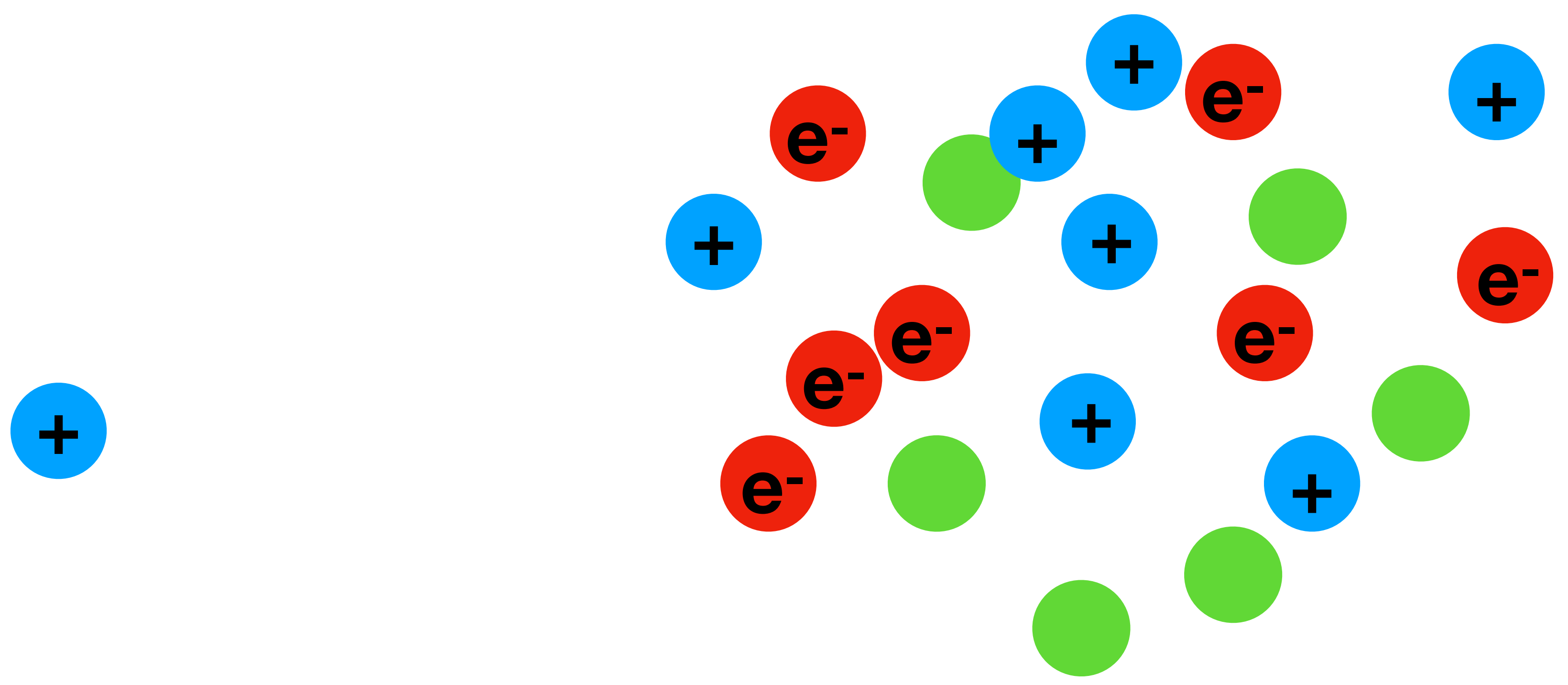

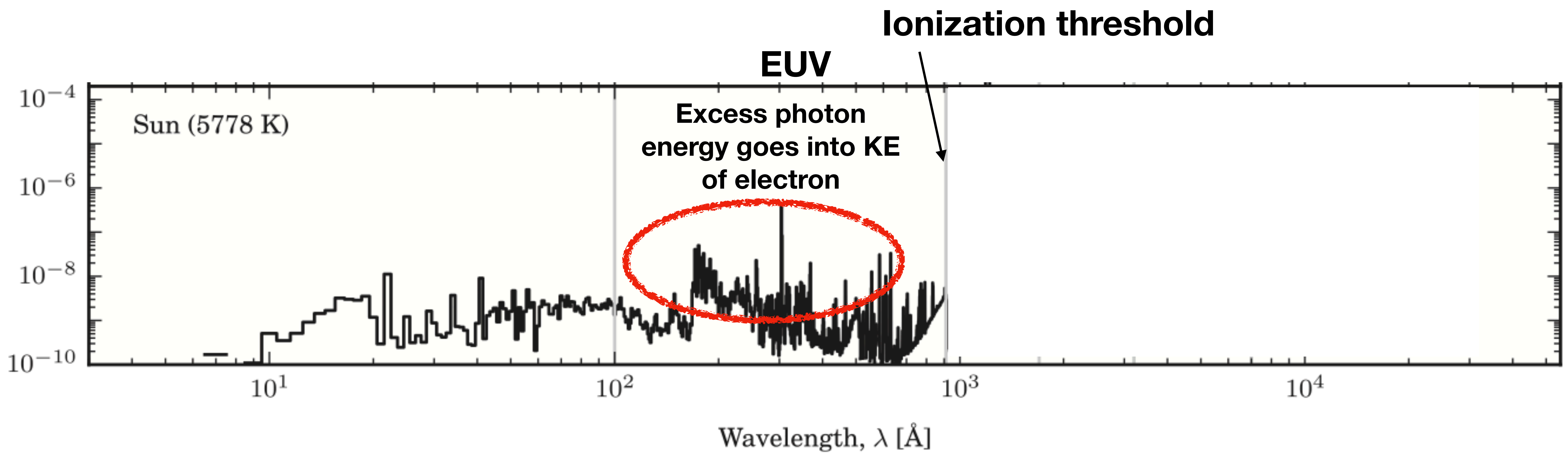

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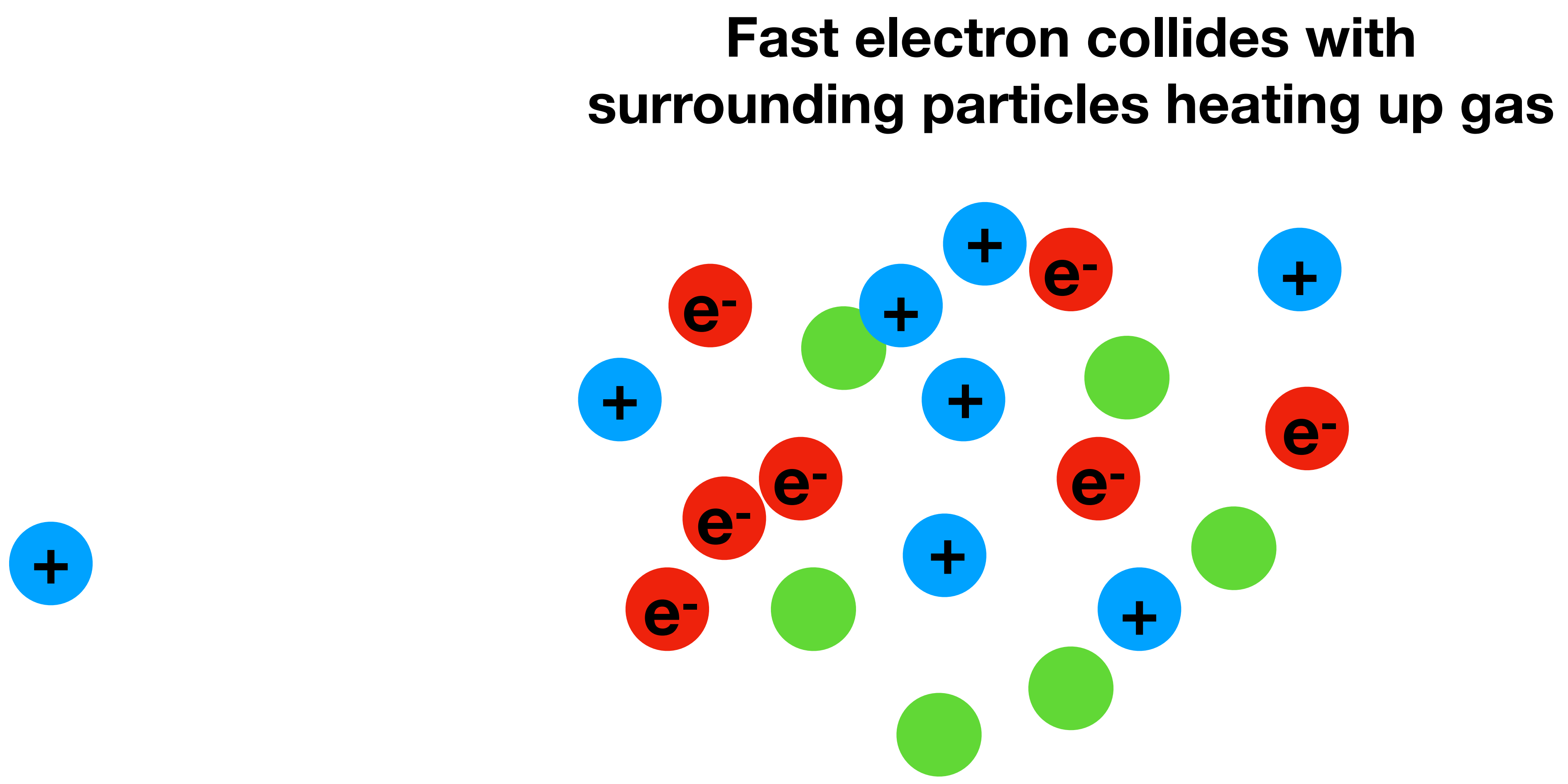

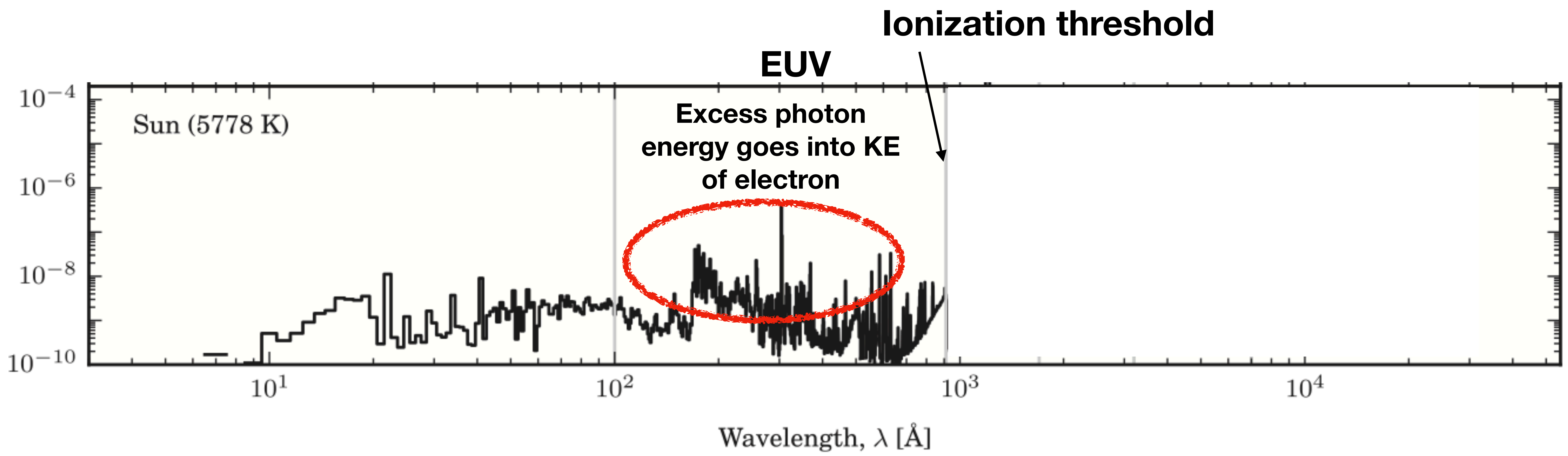

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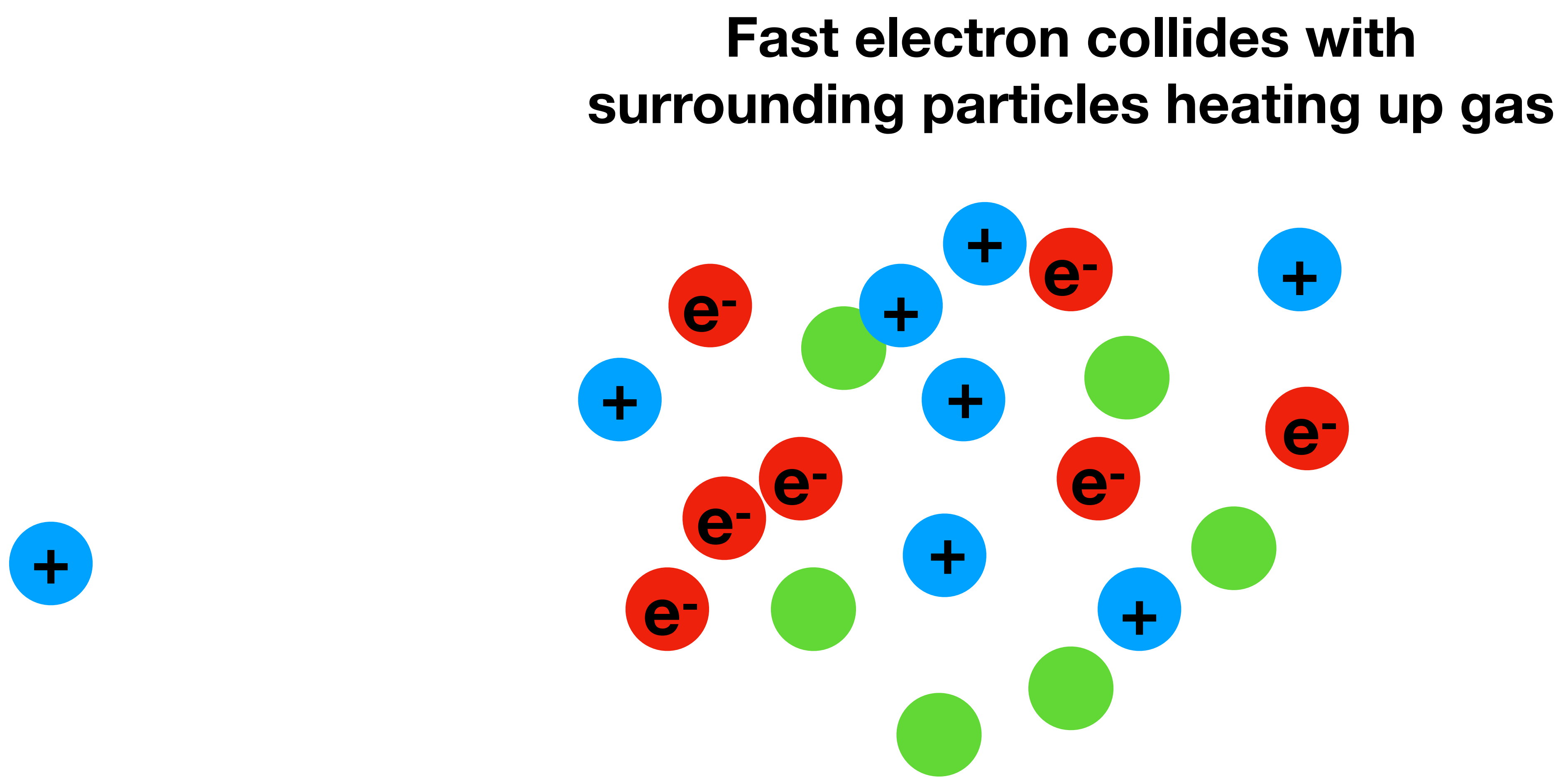
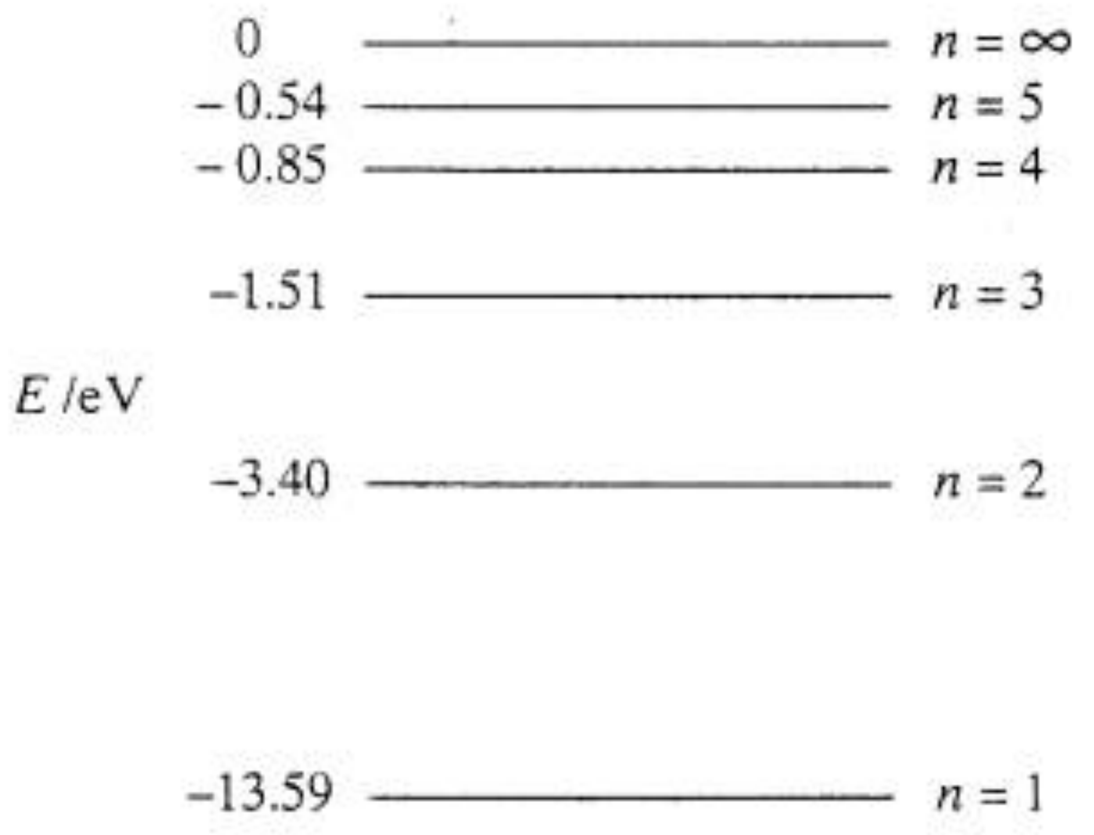
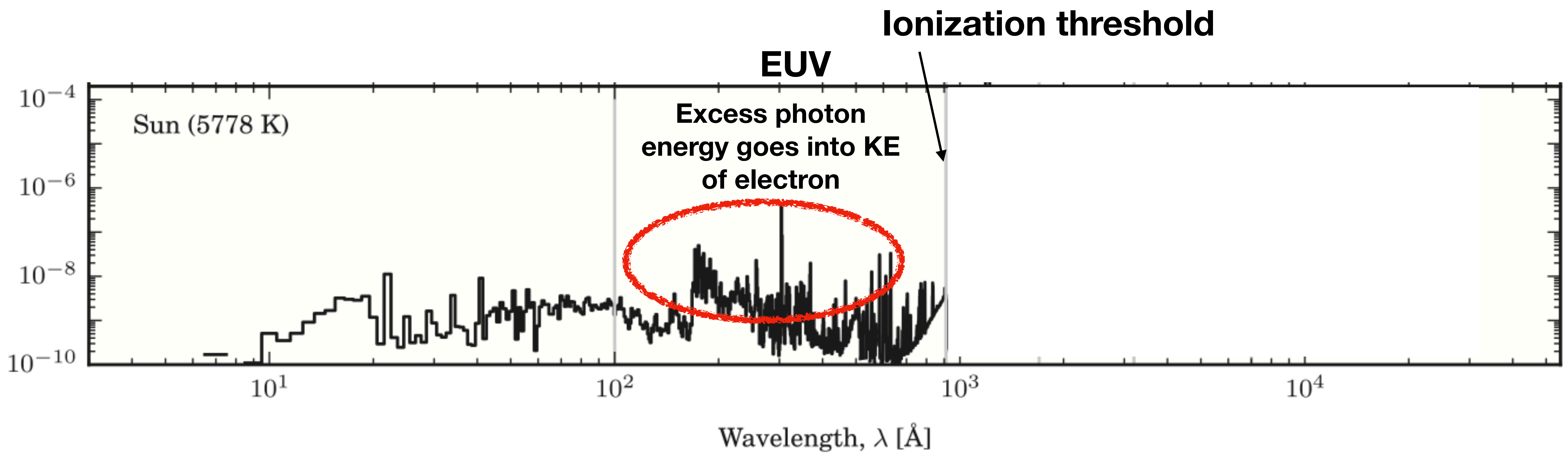


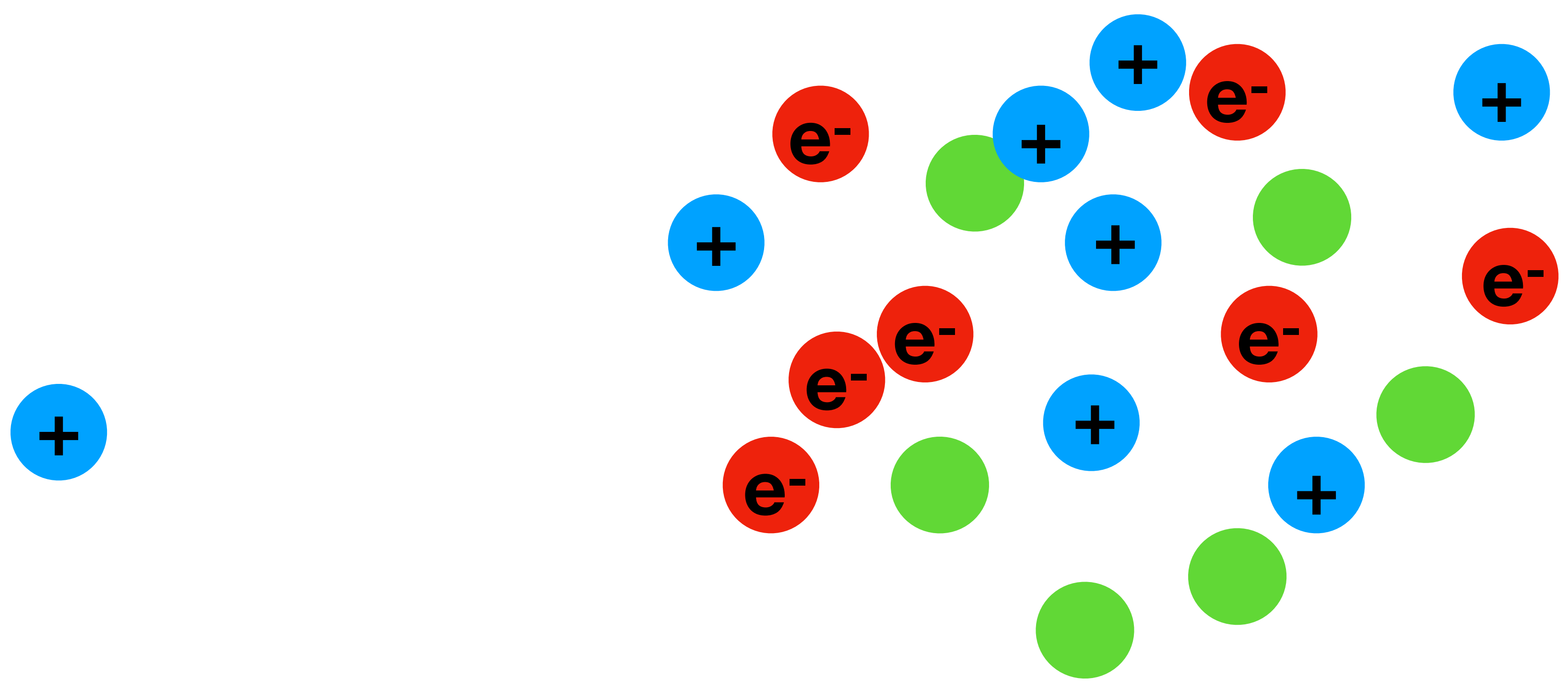


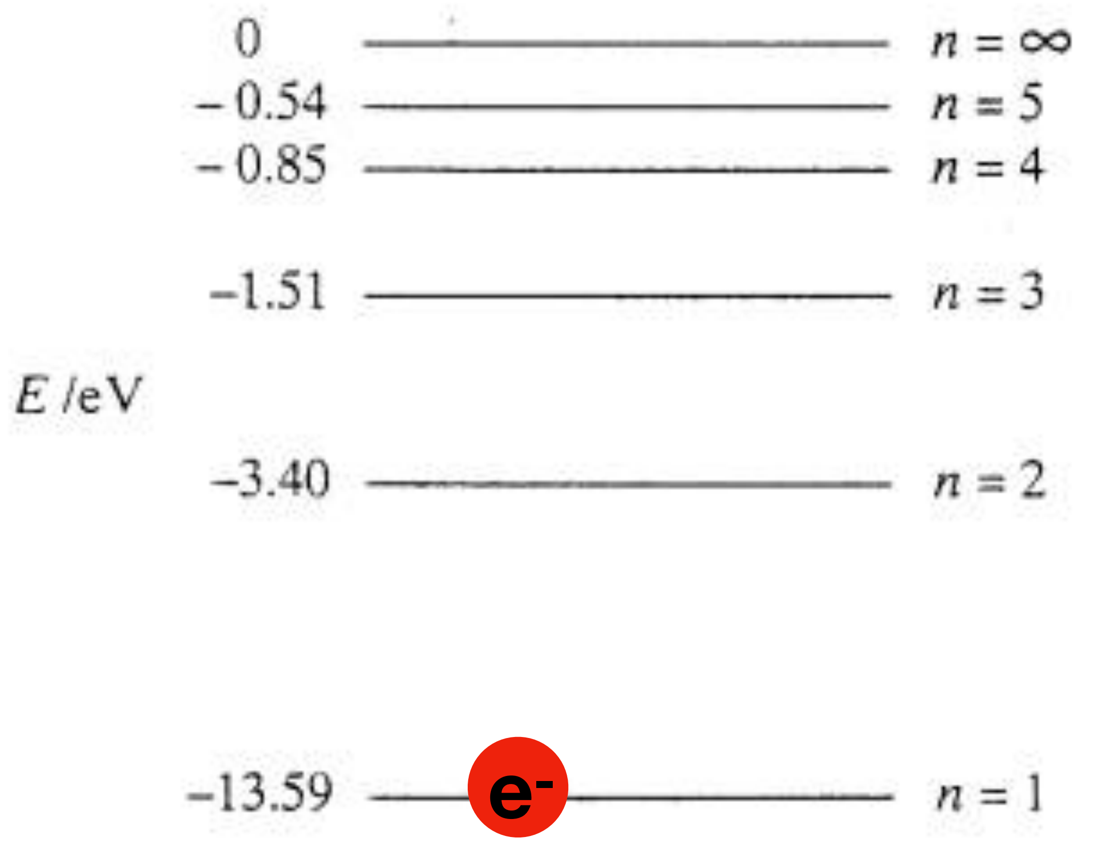
Energy levels of hydrogen



Heating and cooling in atomic/ionized regions

Fast electron collides with surrounding particles heating up gas





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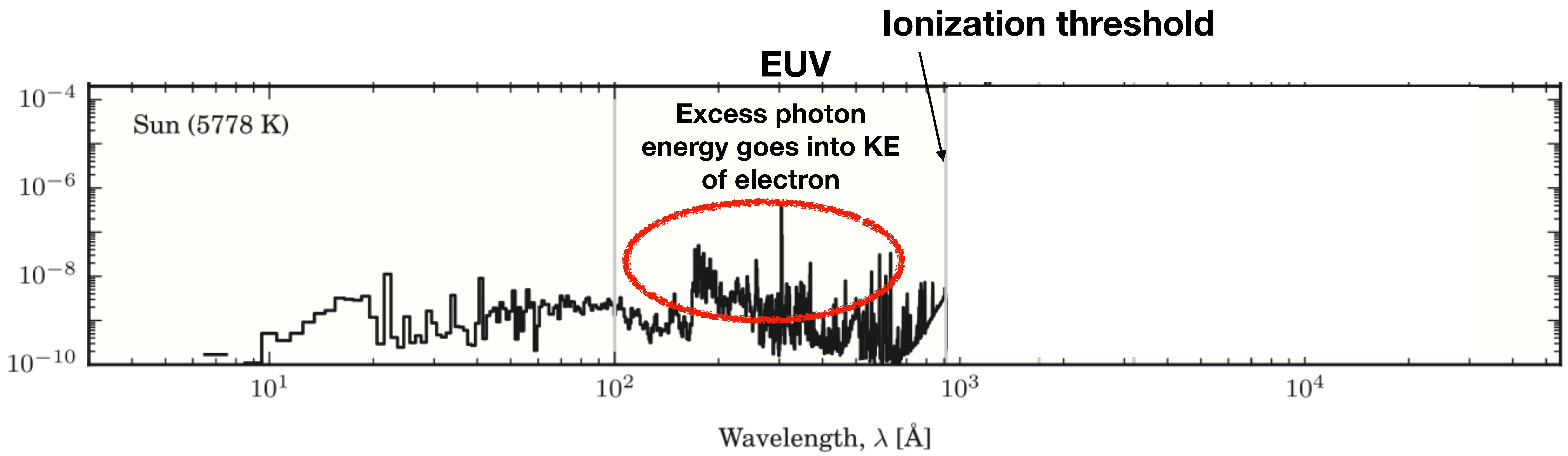

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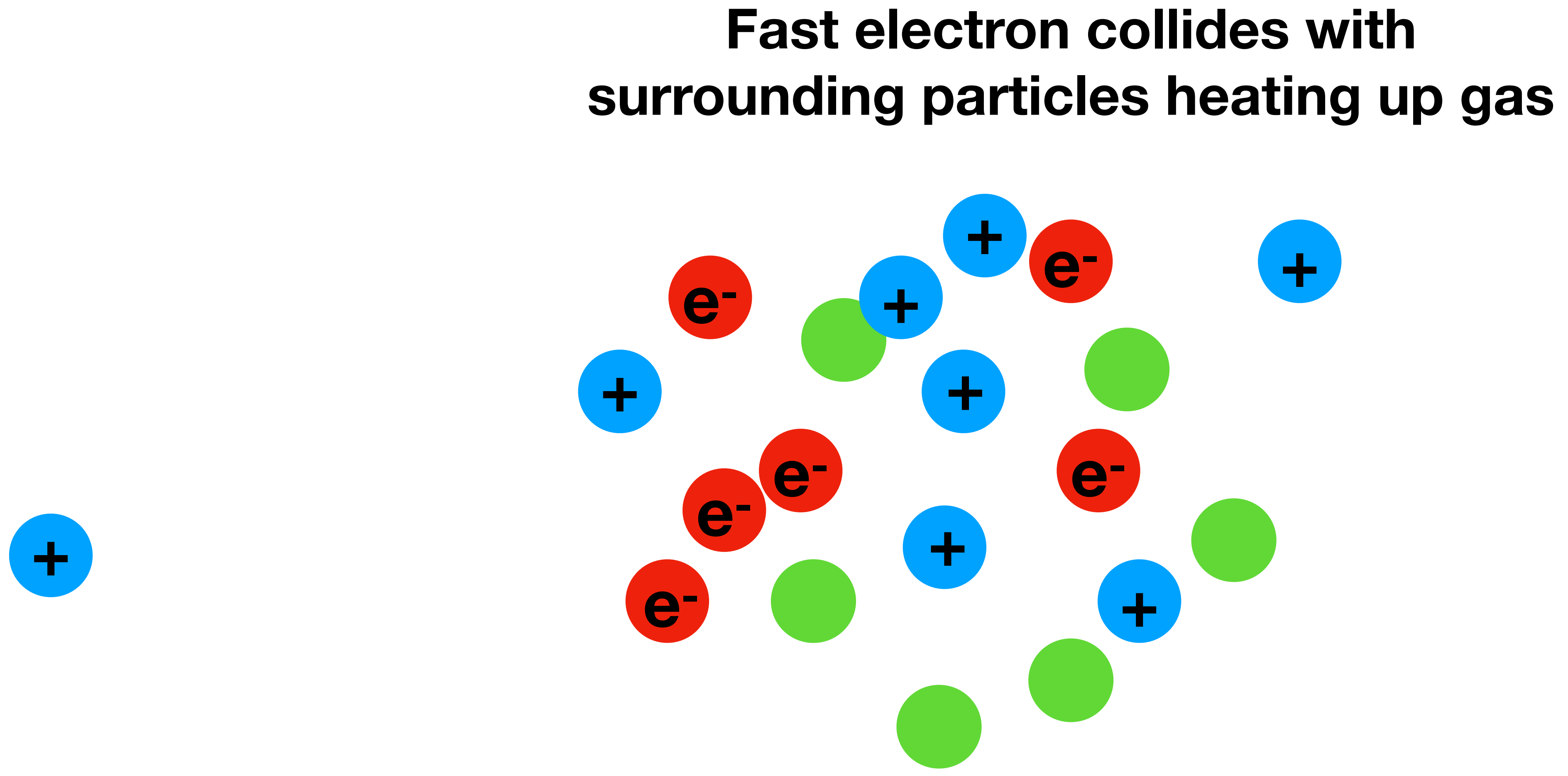

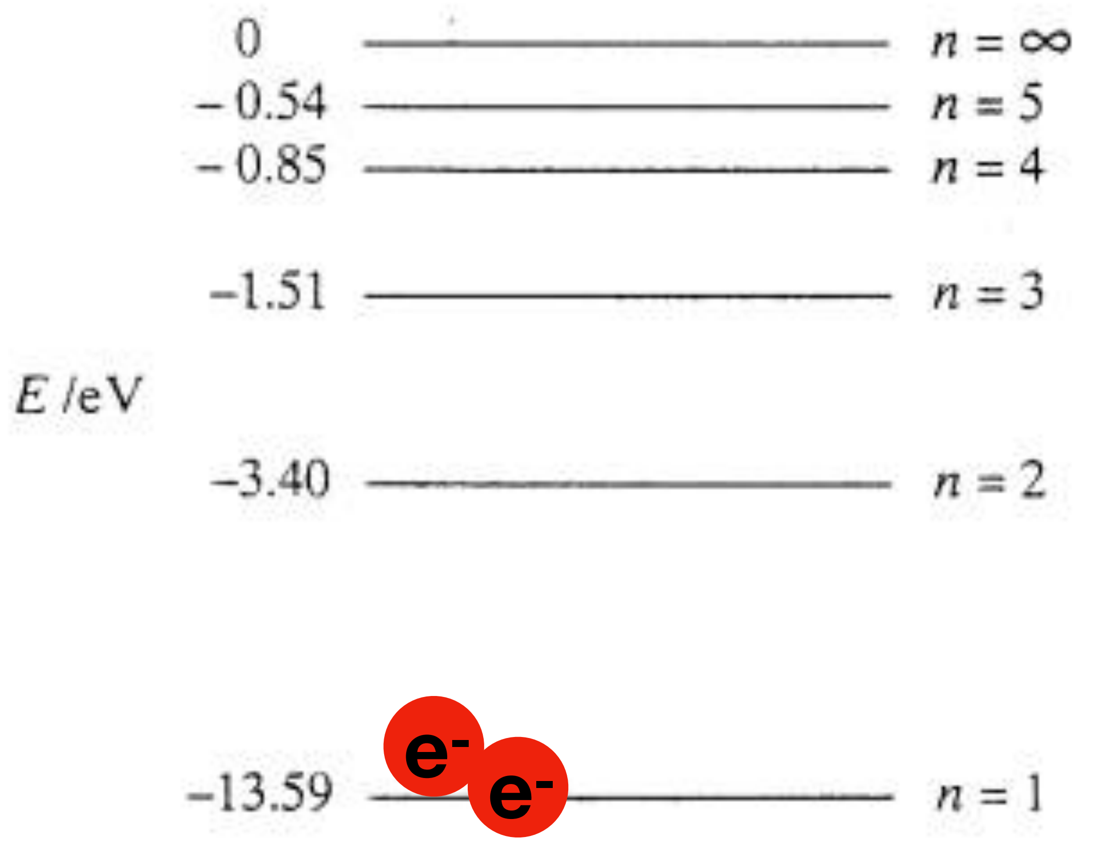

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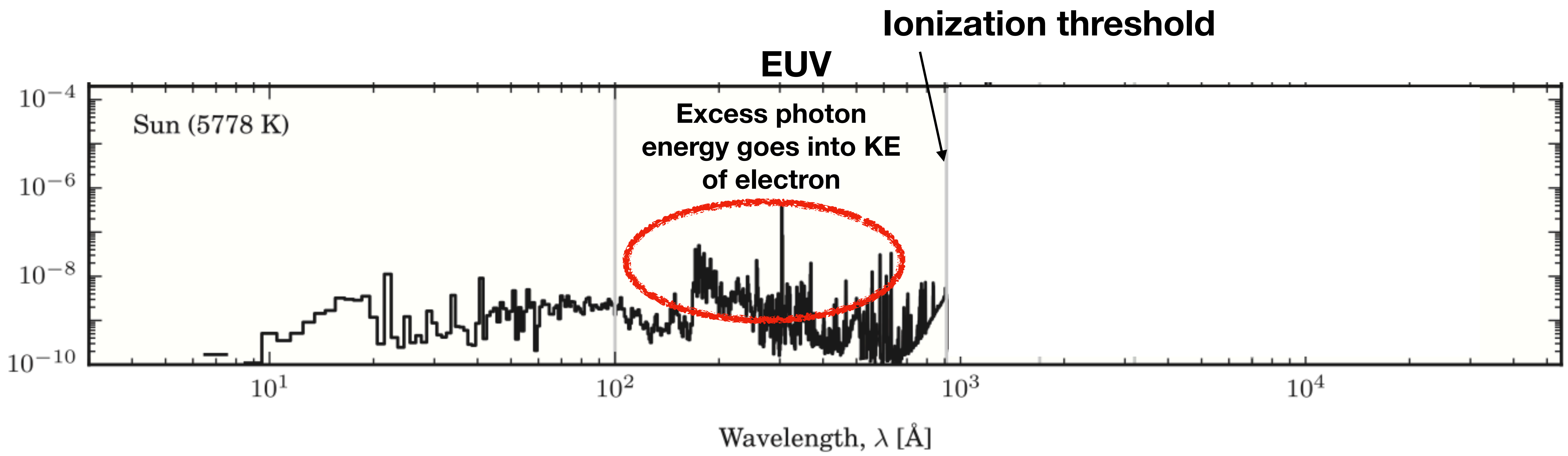

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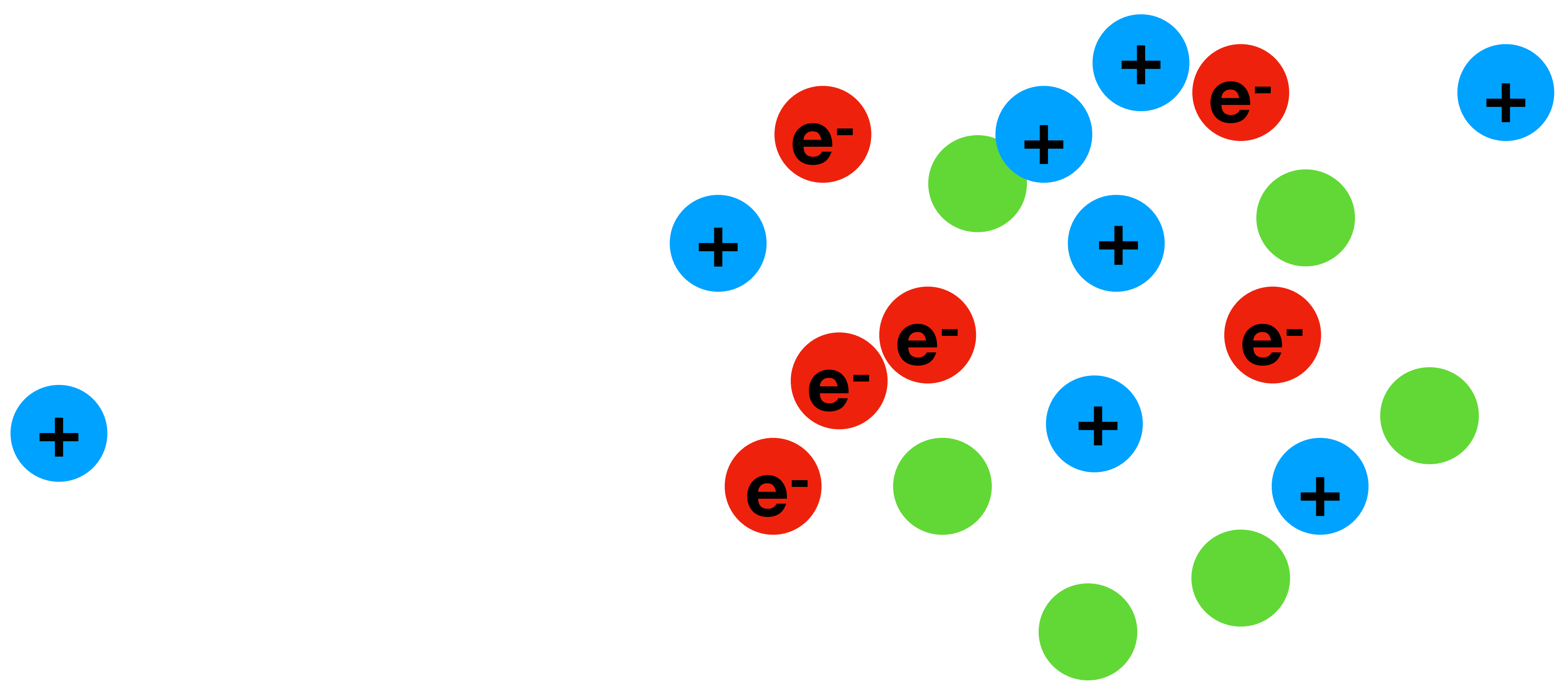
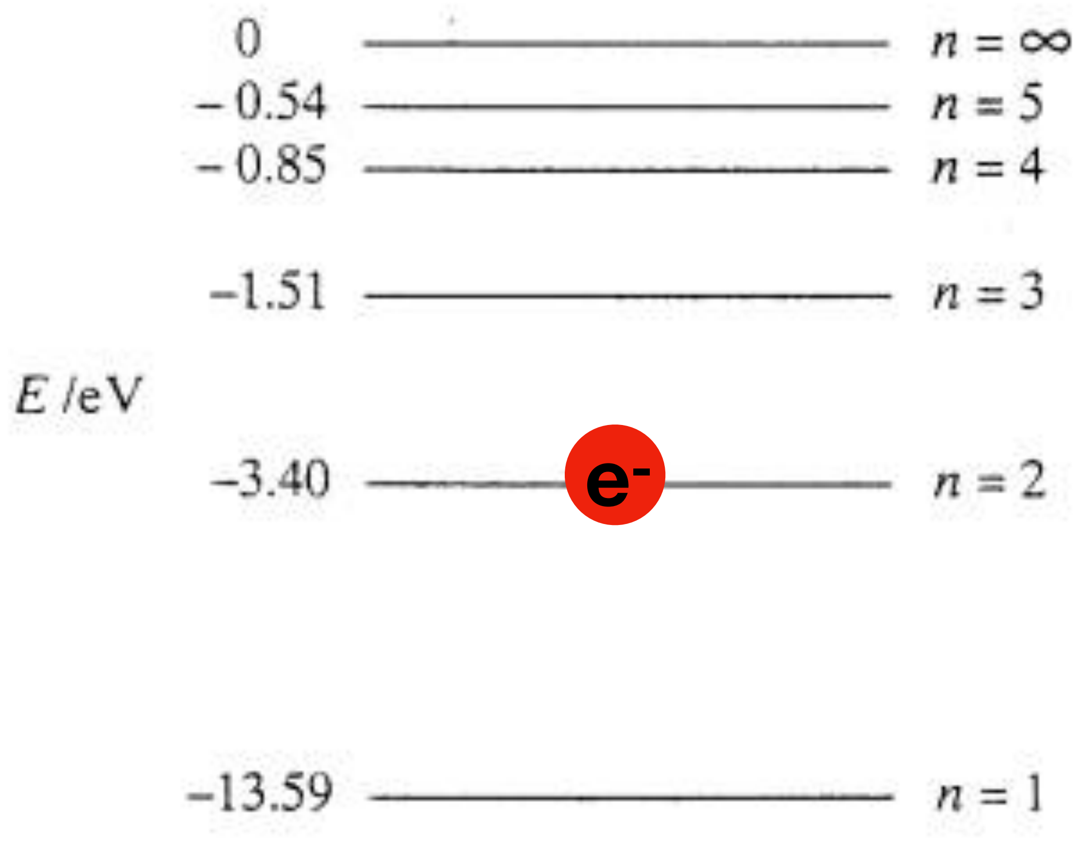
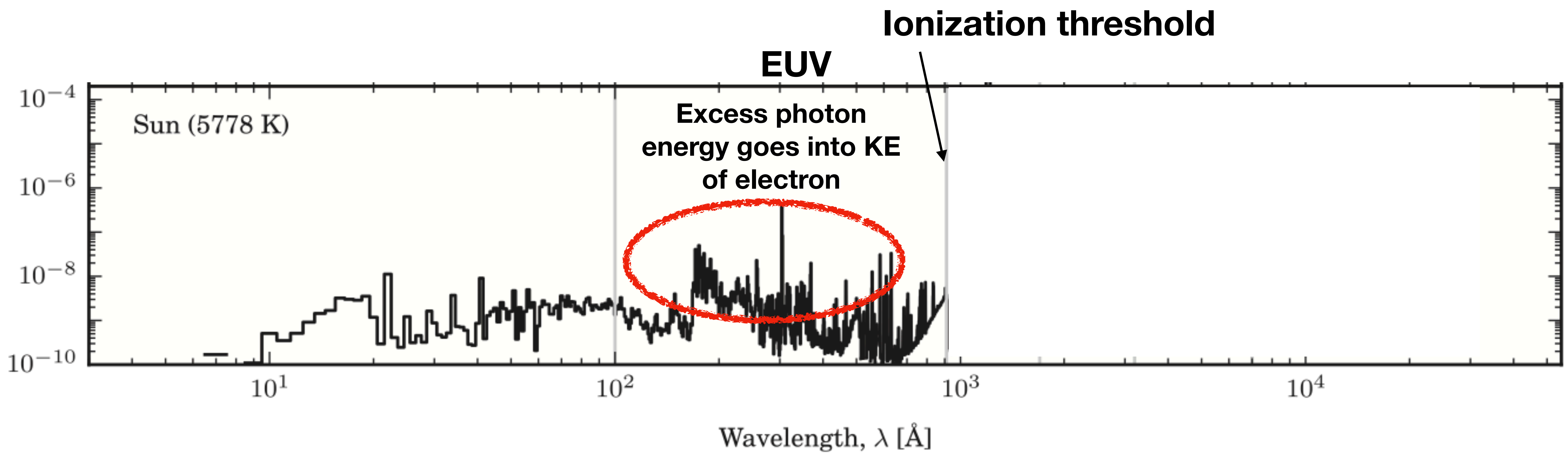




Energy levels of hydrogen



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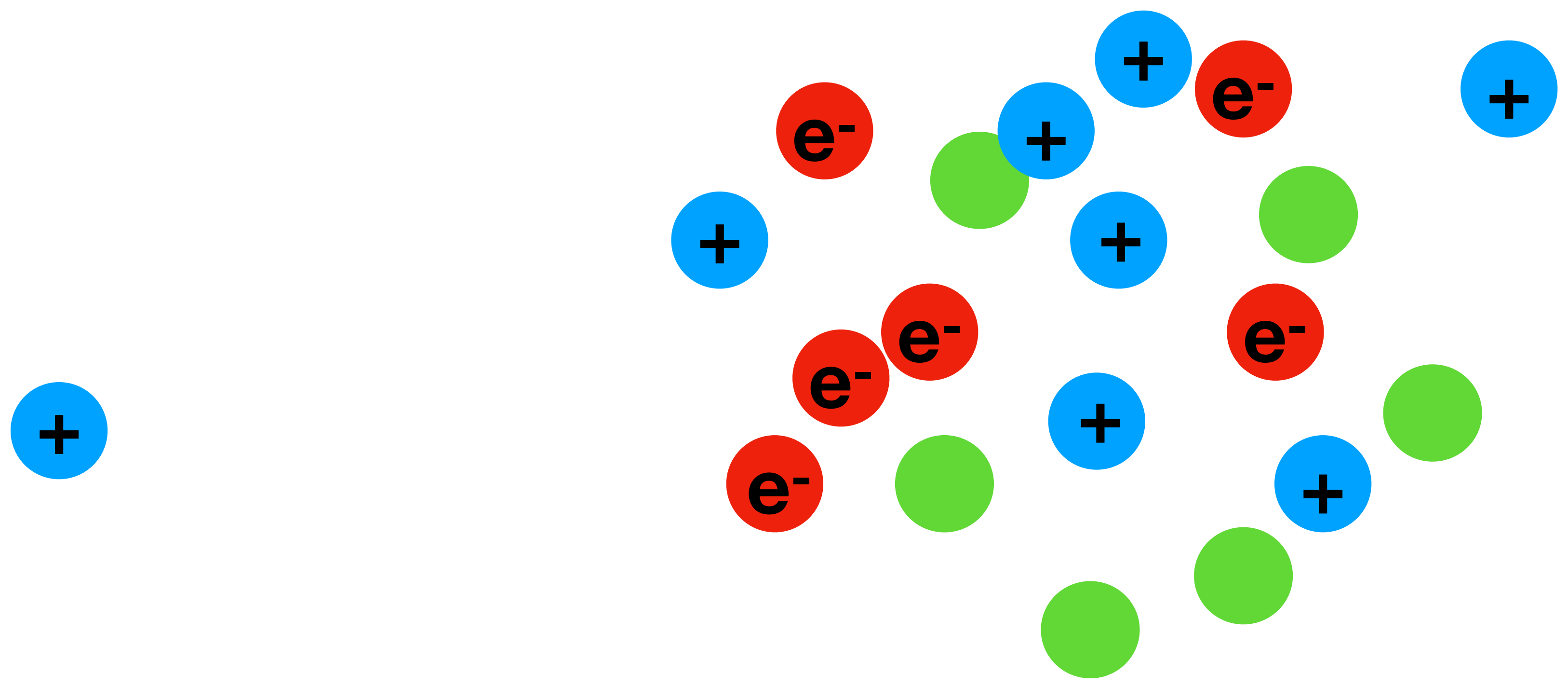
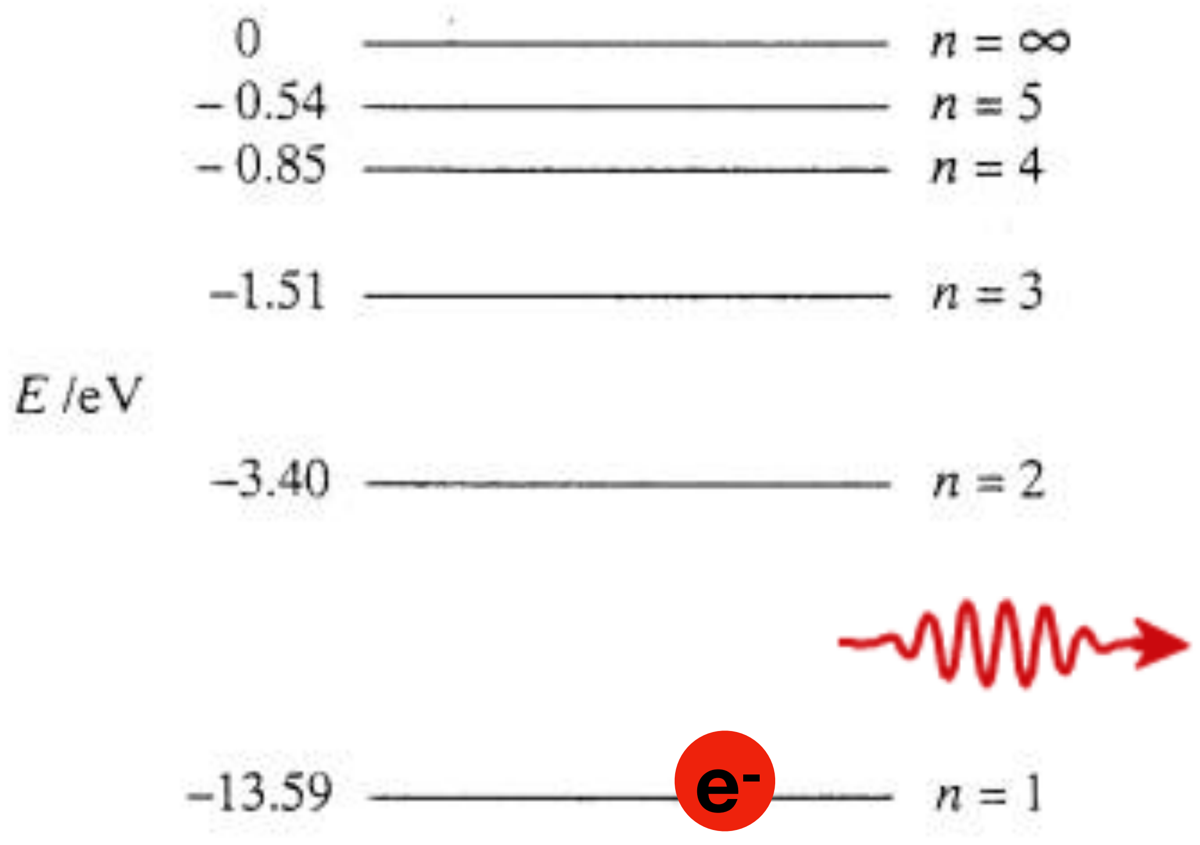


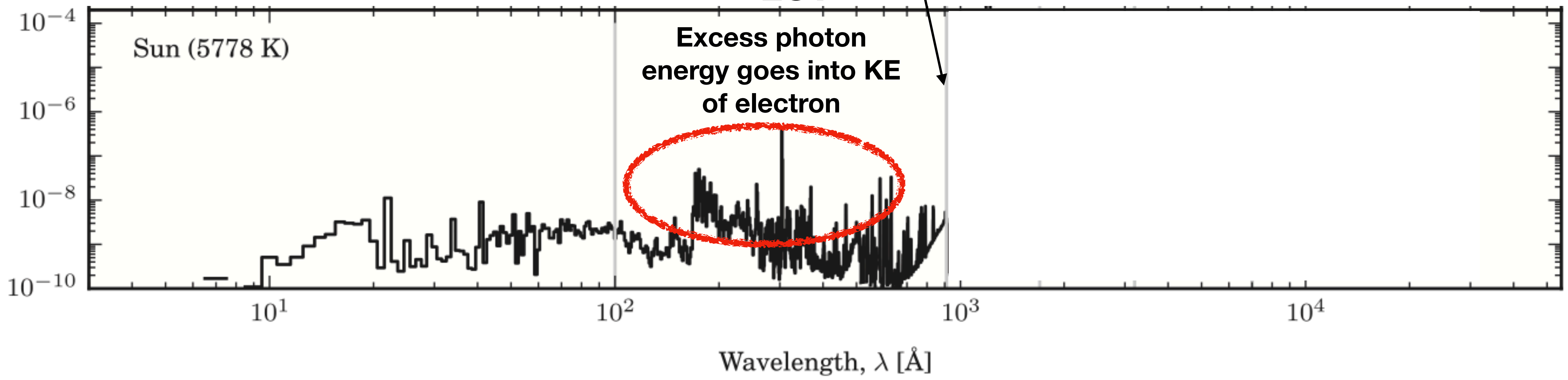


Photon escapes:
Gas cools

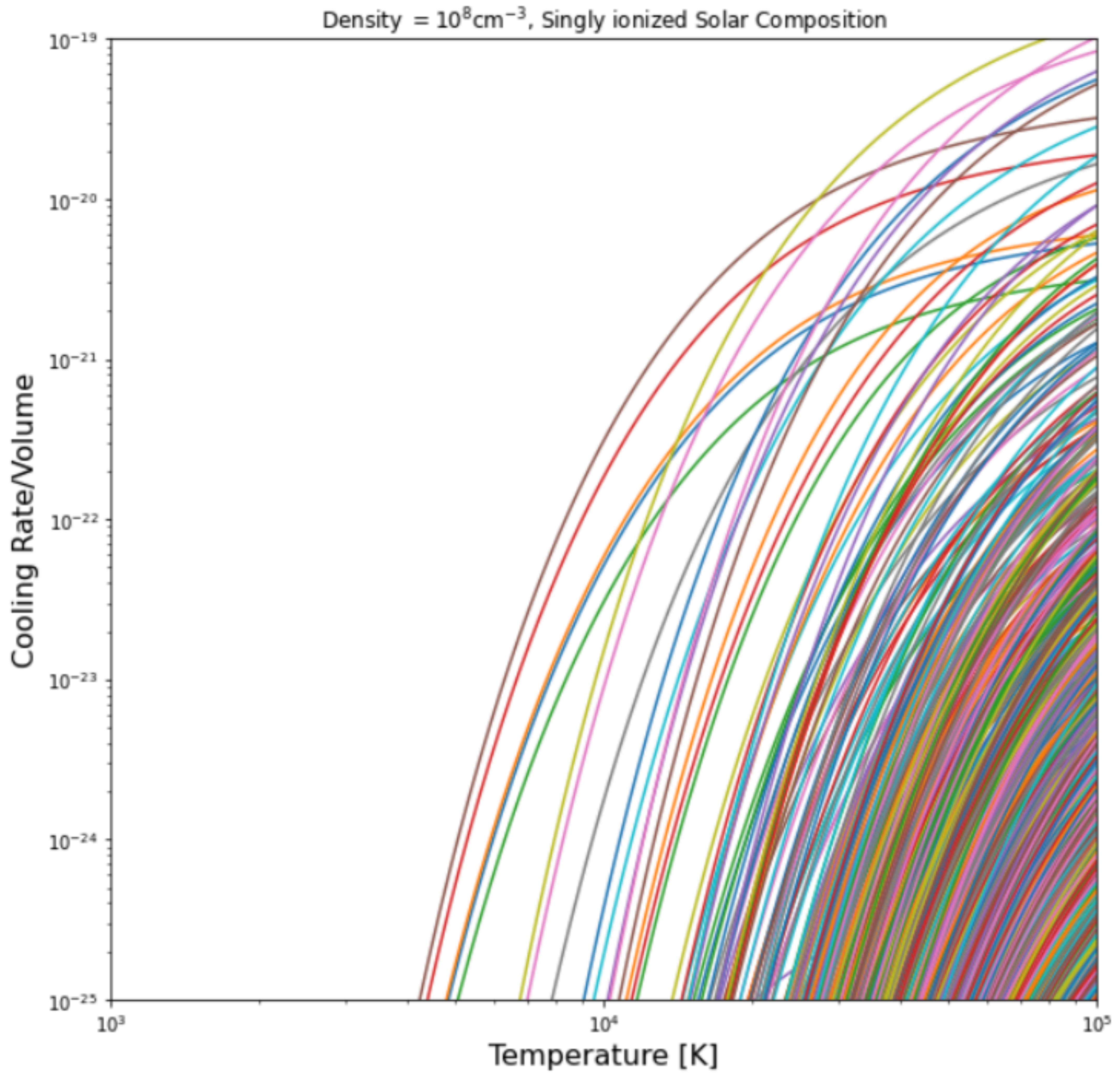
Energy levels of hydrogen

Ionization threshold

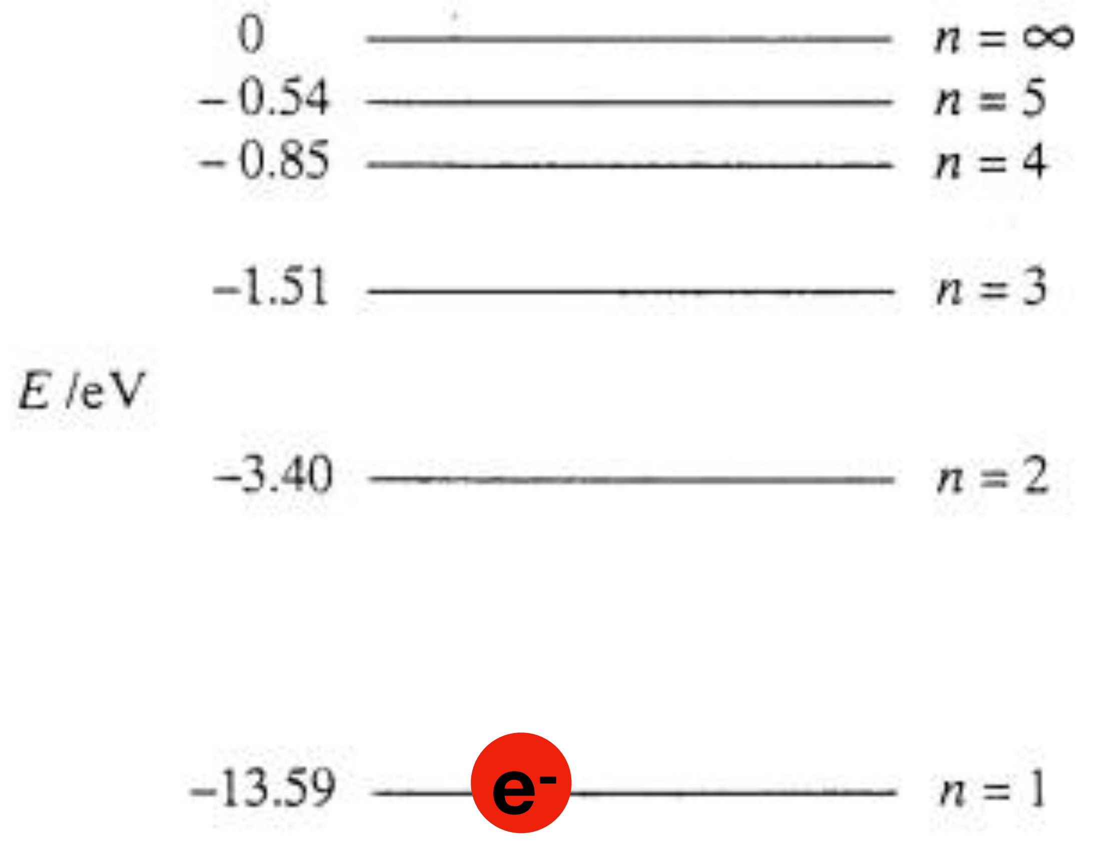
EUV



Cooling in atomic/ionic gas requires excitation of ground-state electrons



Calculated with the Chianti tool



Energy levels of hydrogen

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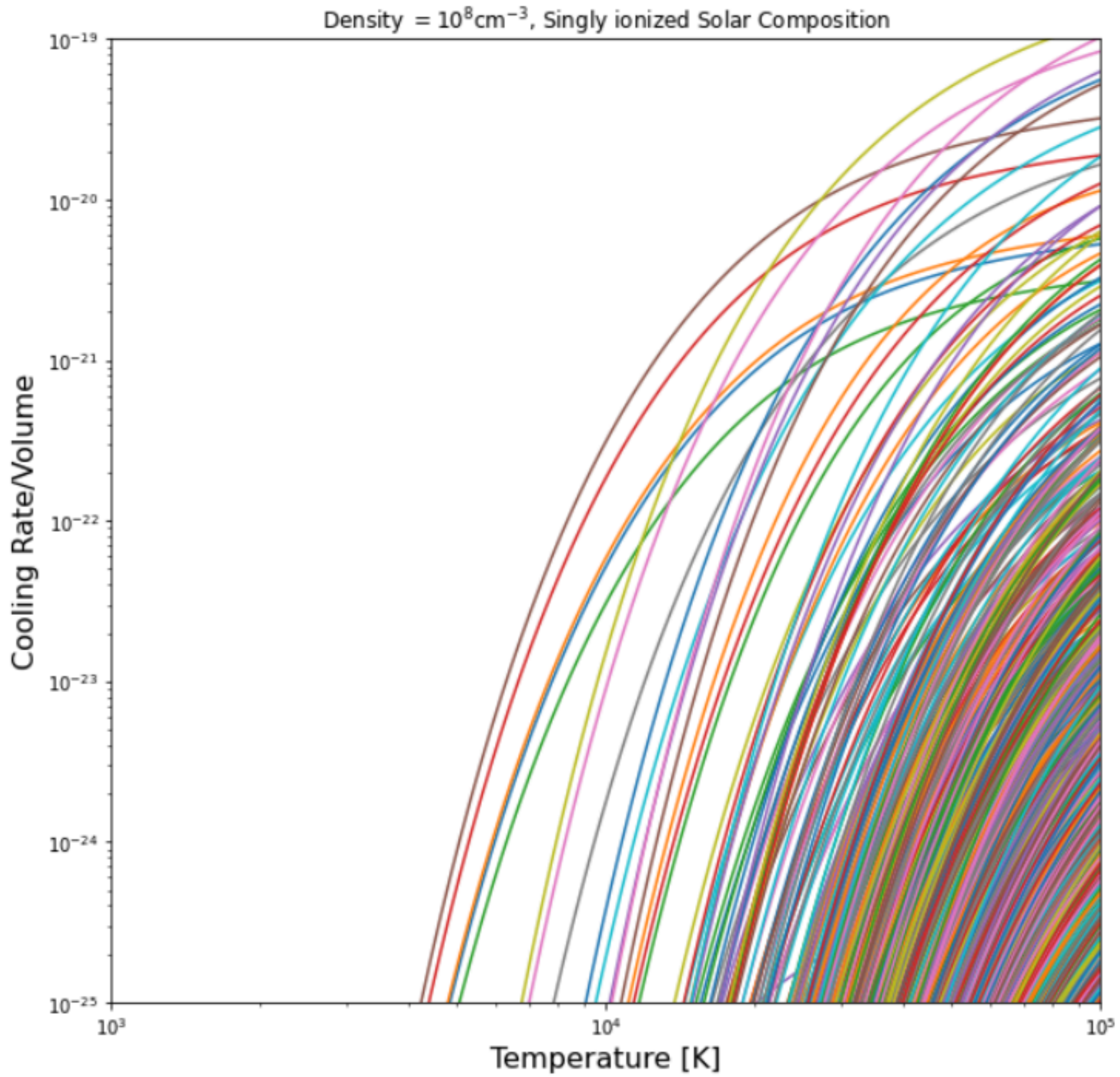

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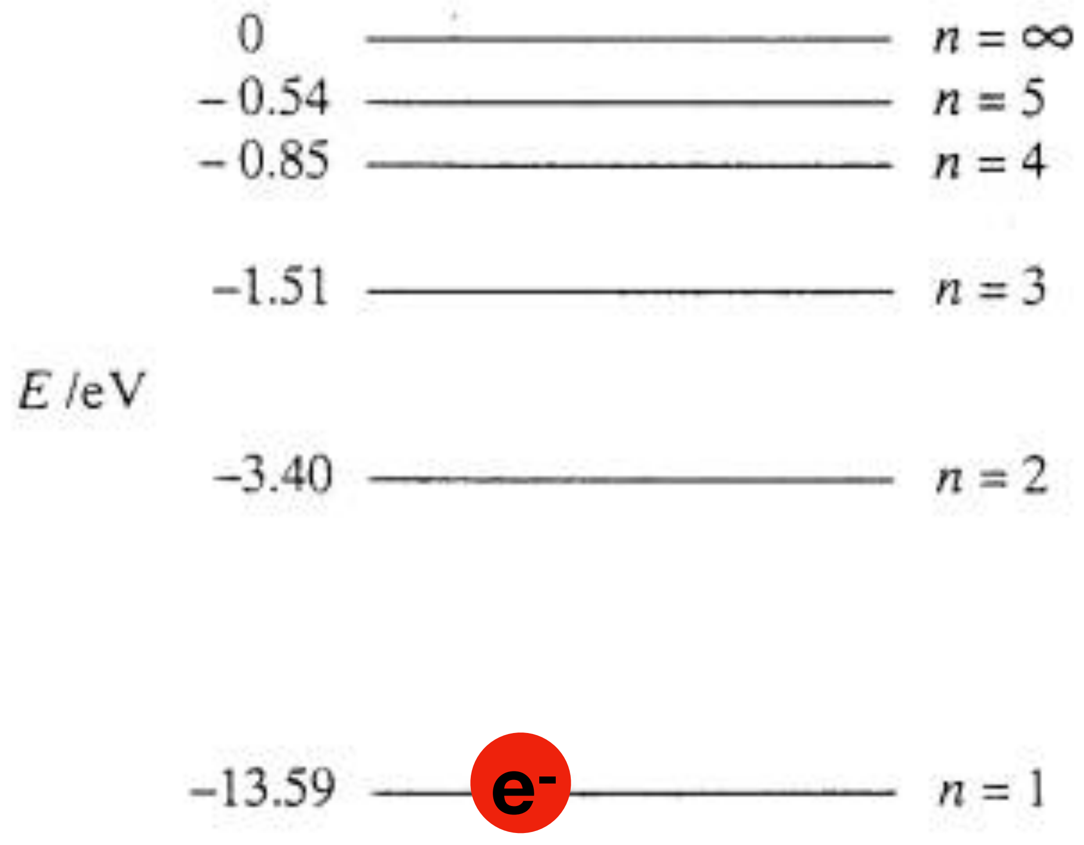

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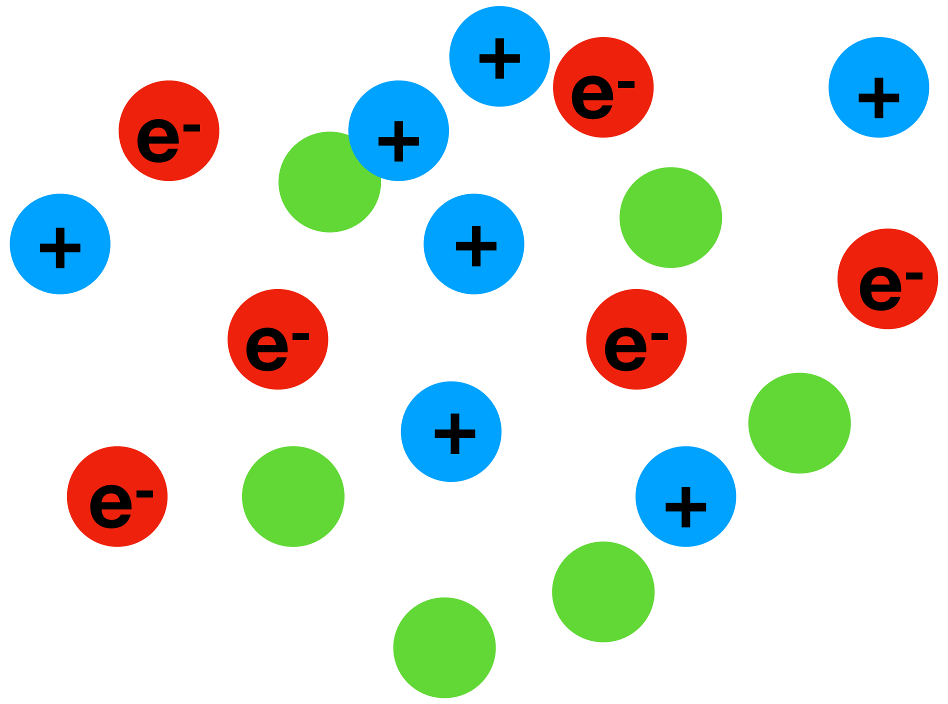

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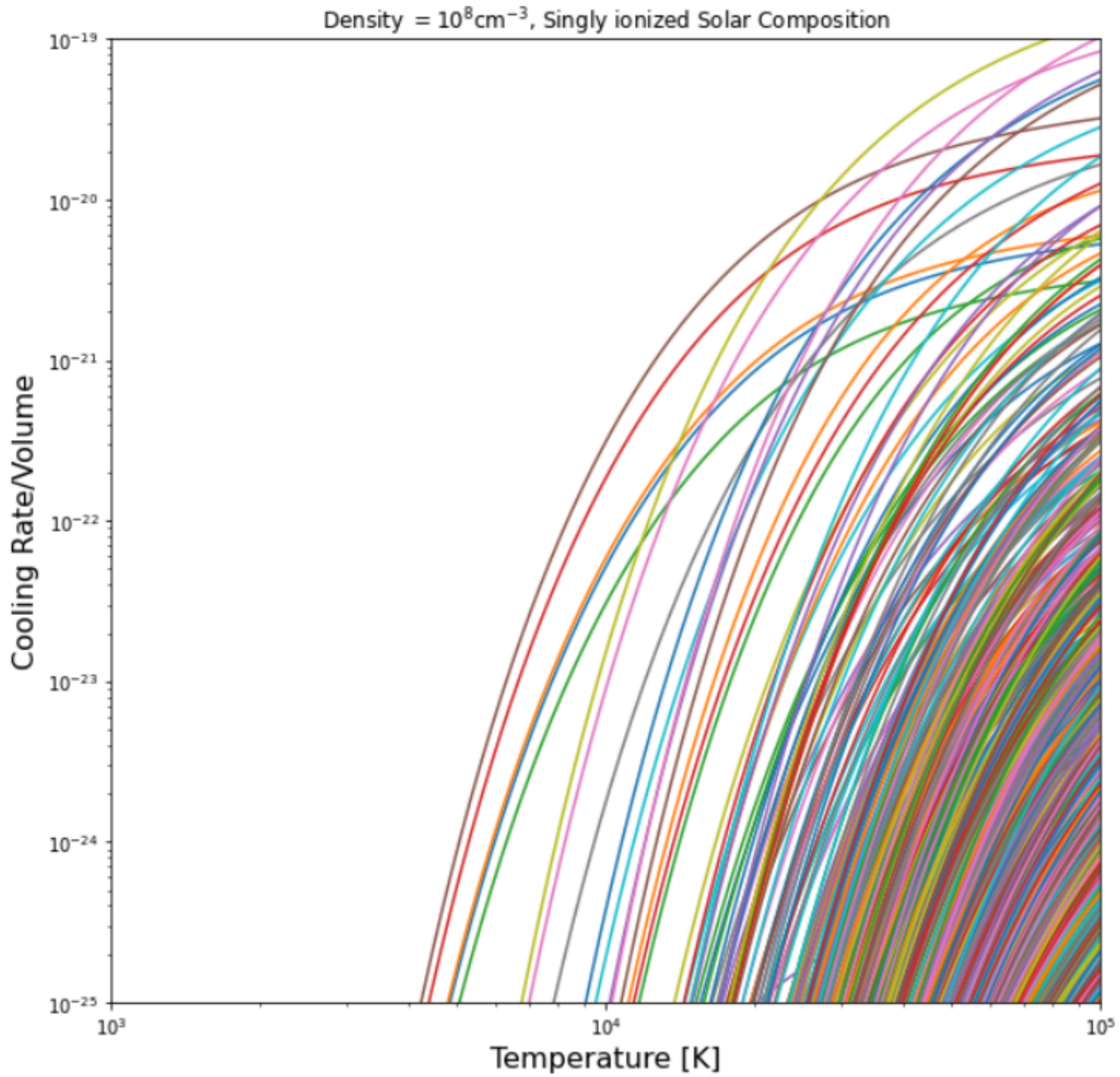

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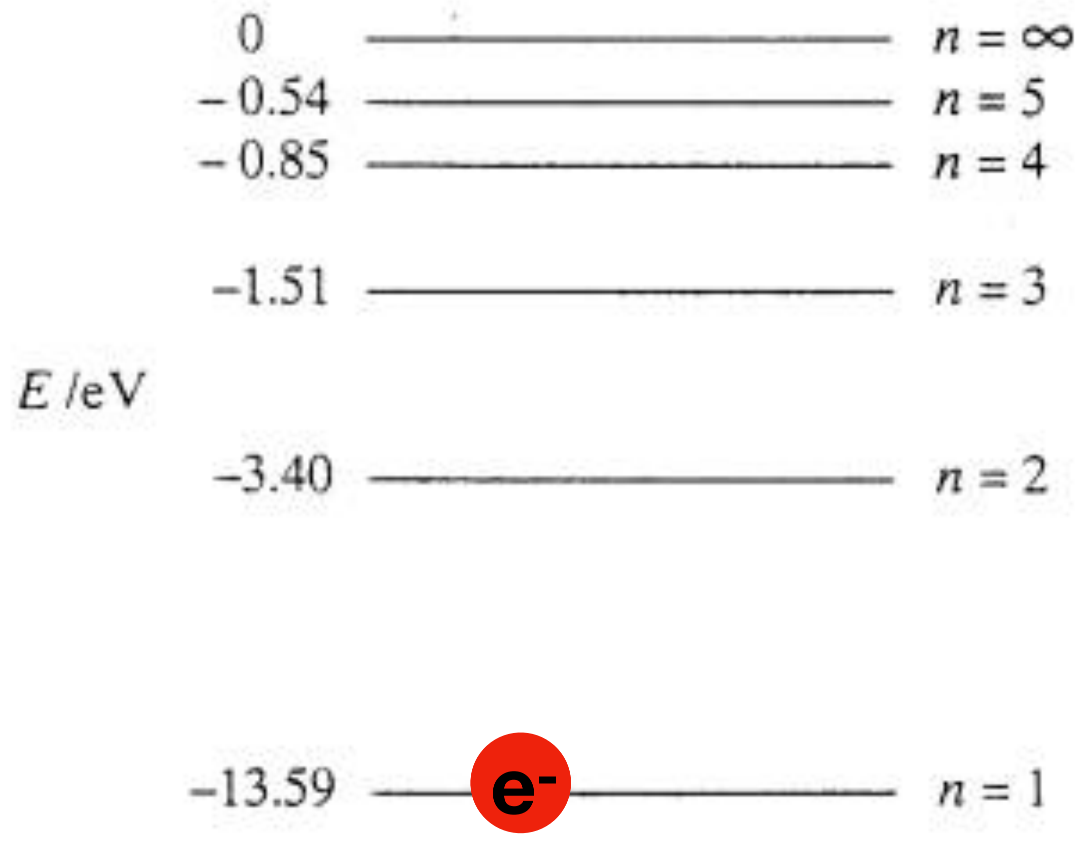

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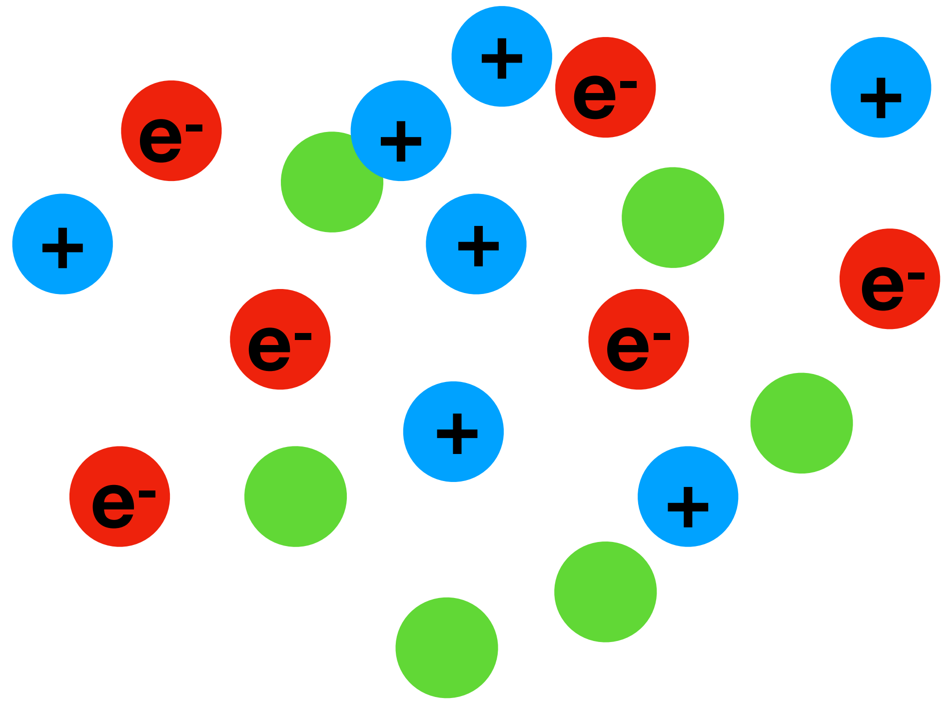

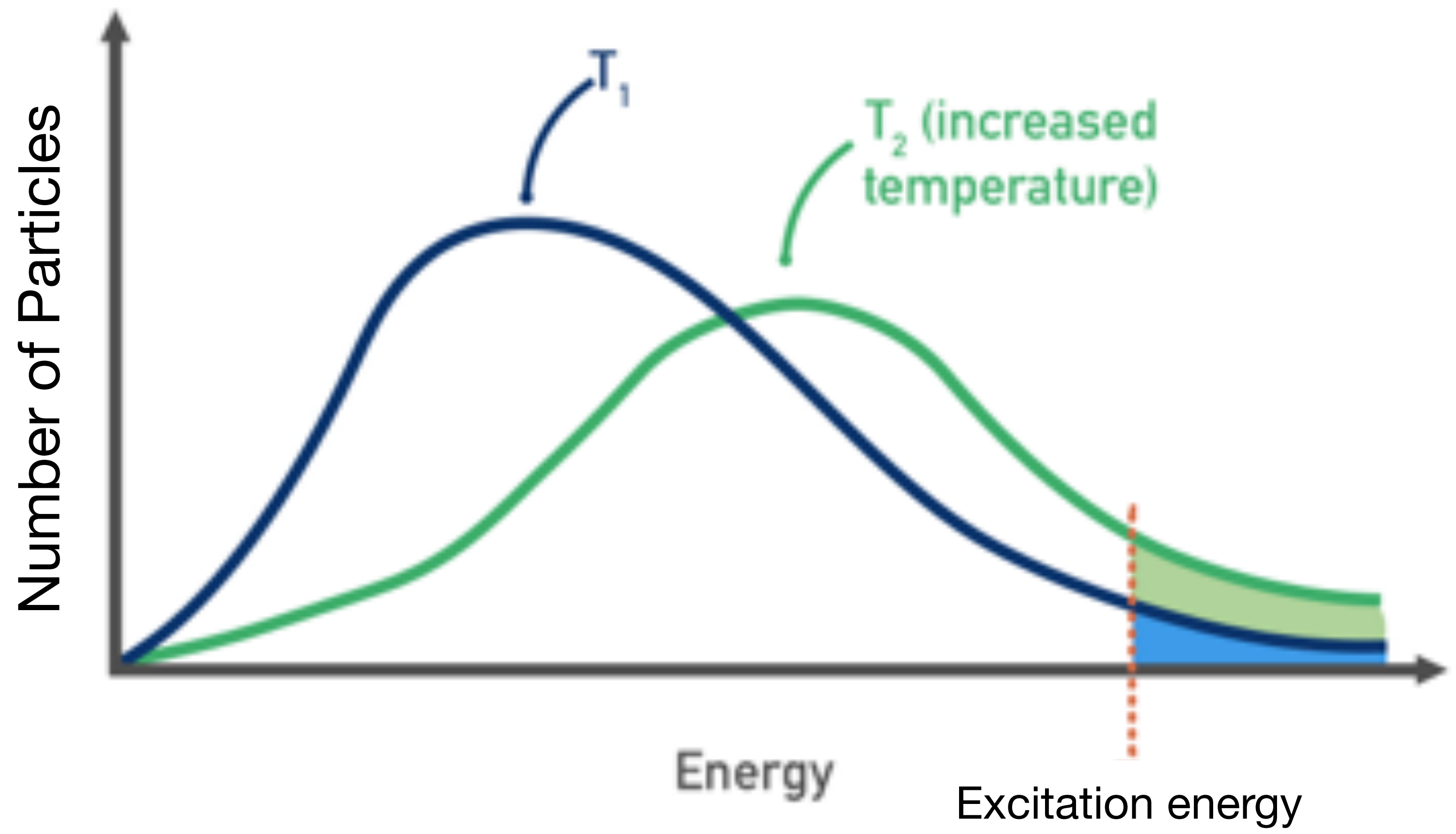

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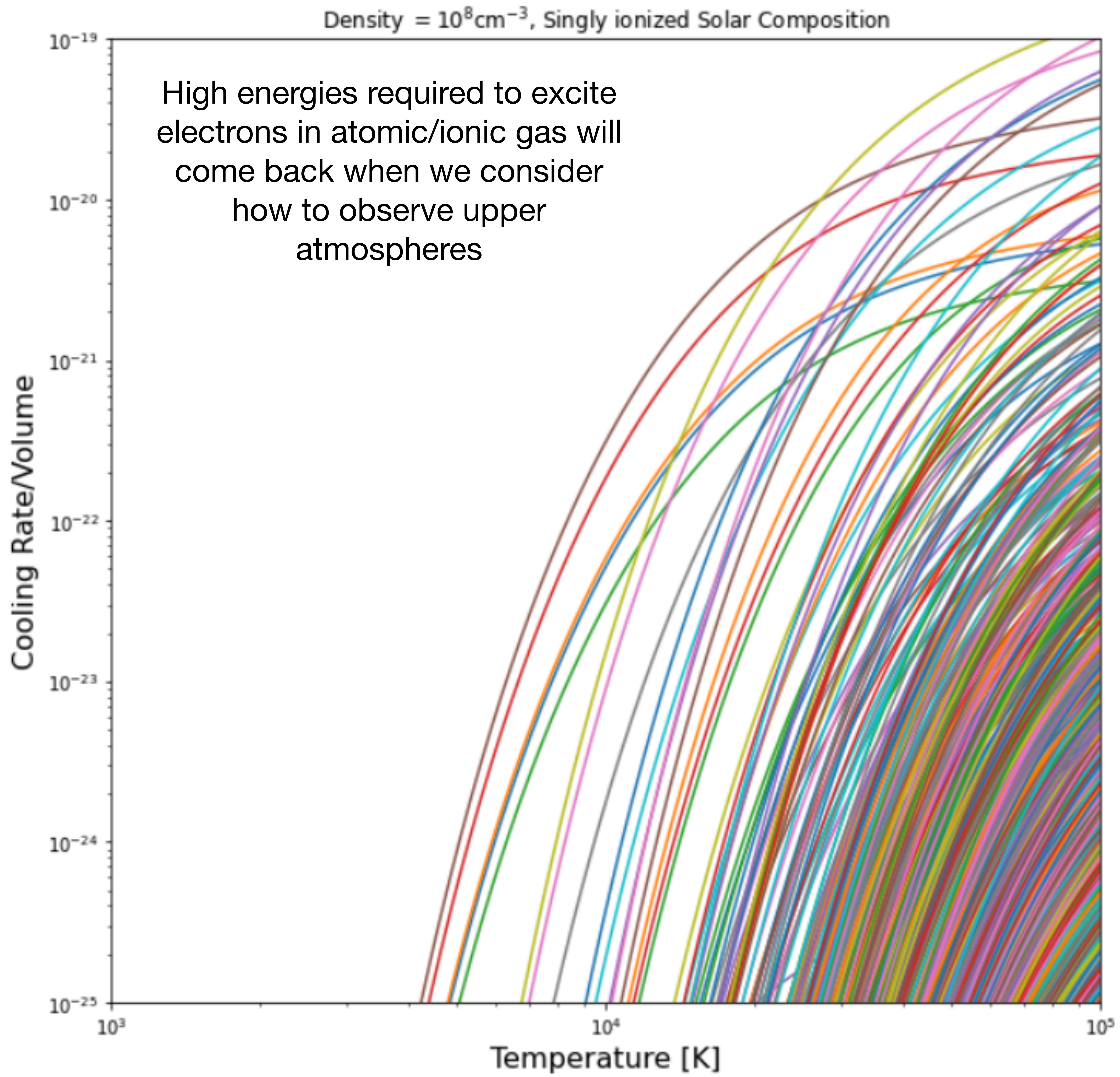

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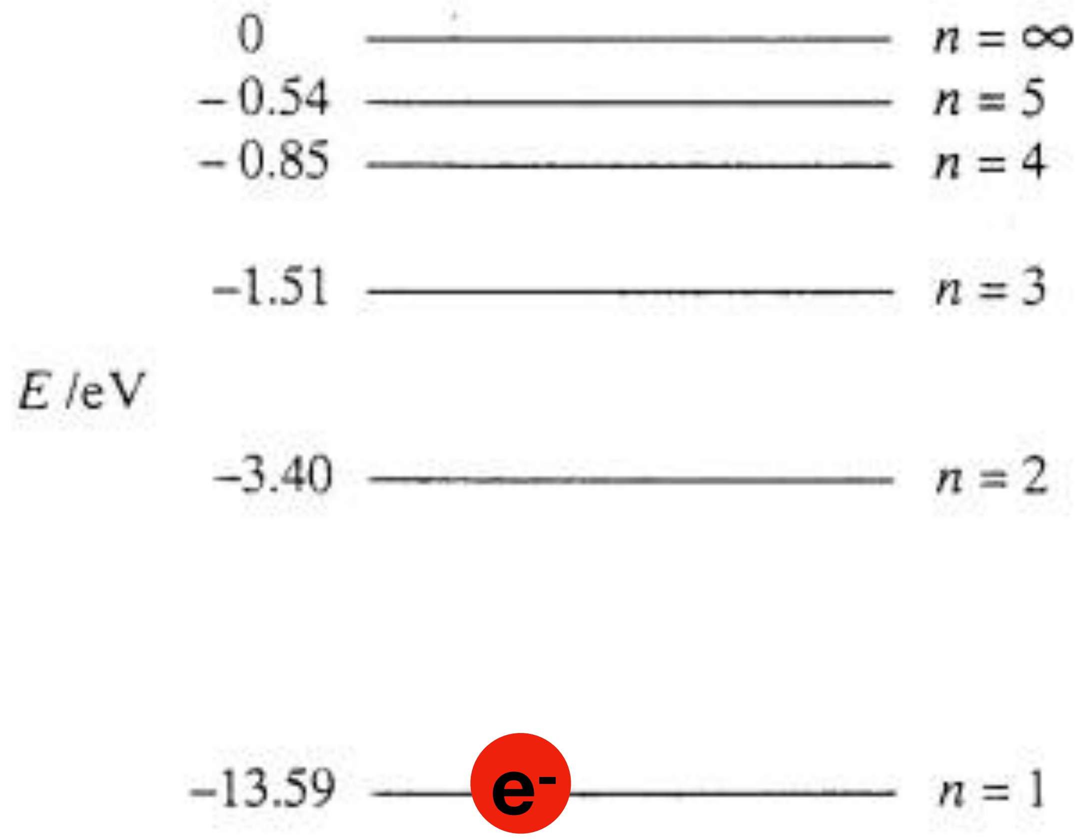

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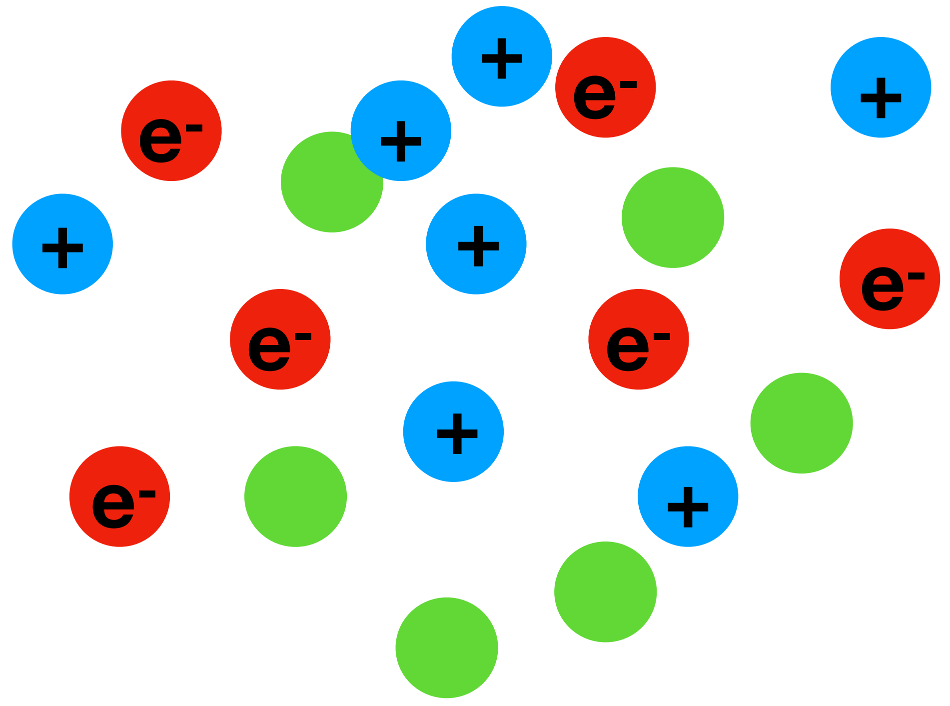
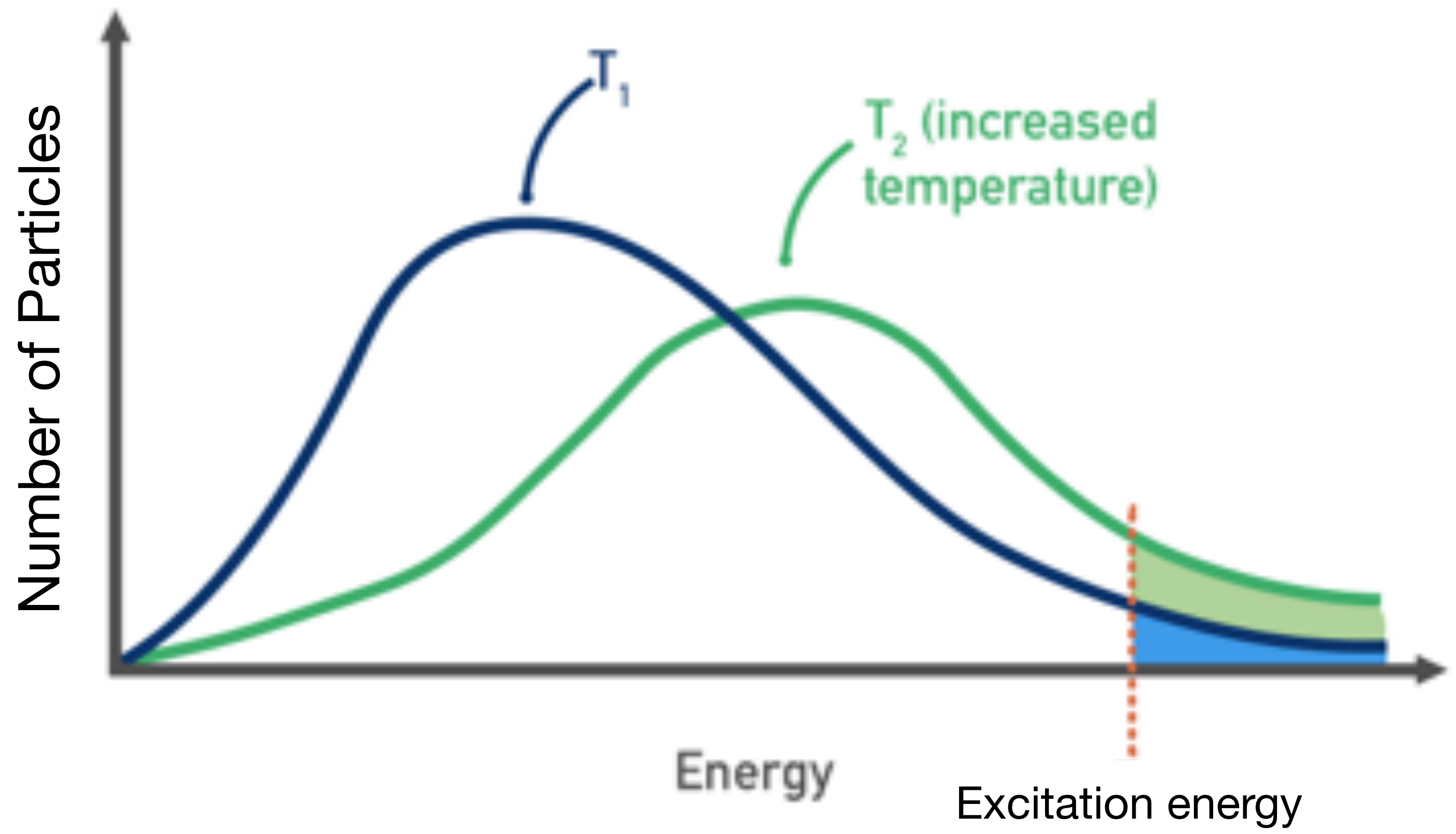
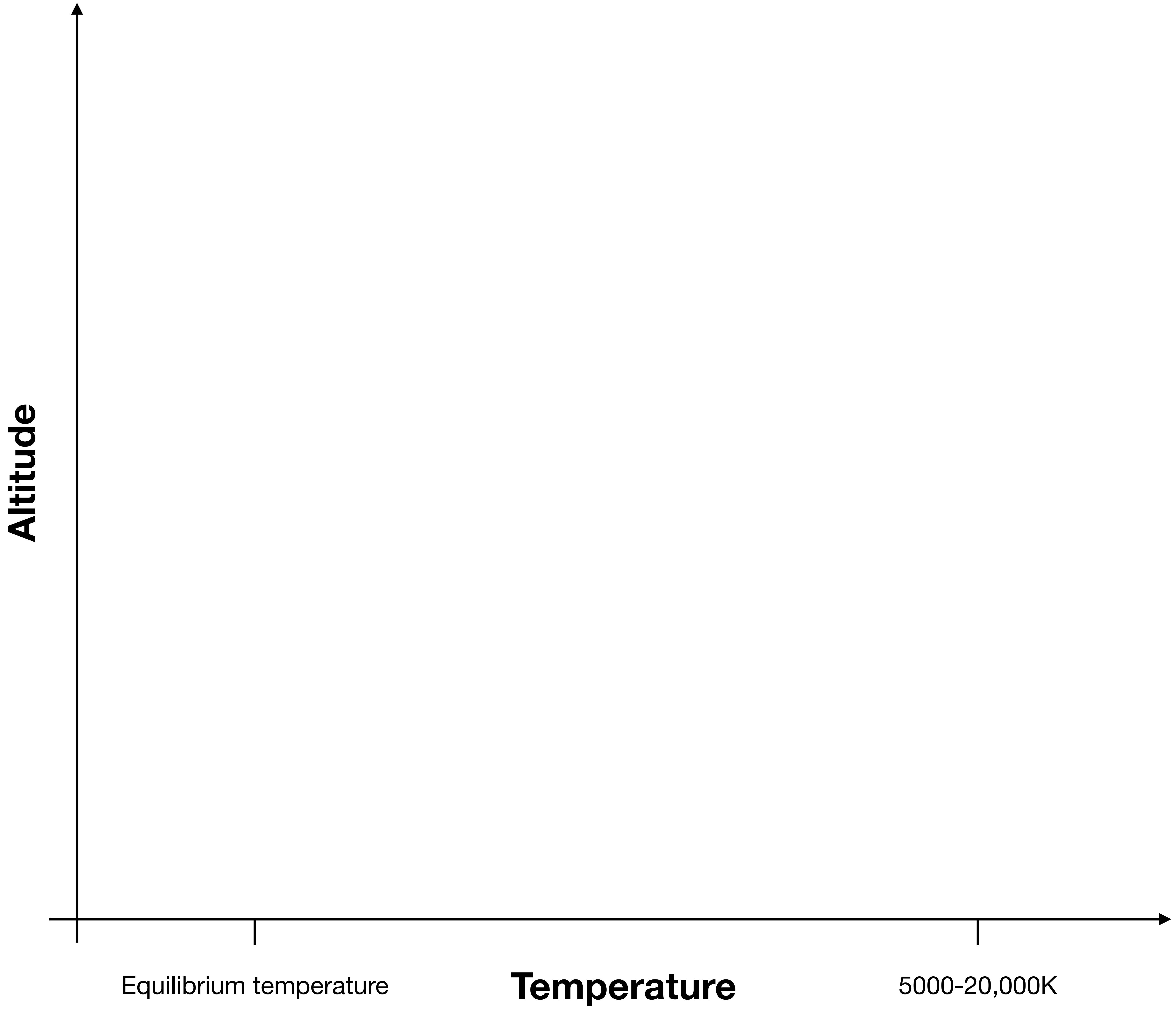




Thermal structure of an upper atmosphere



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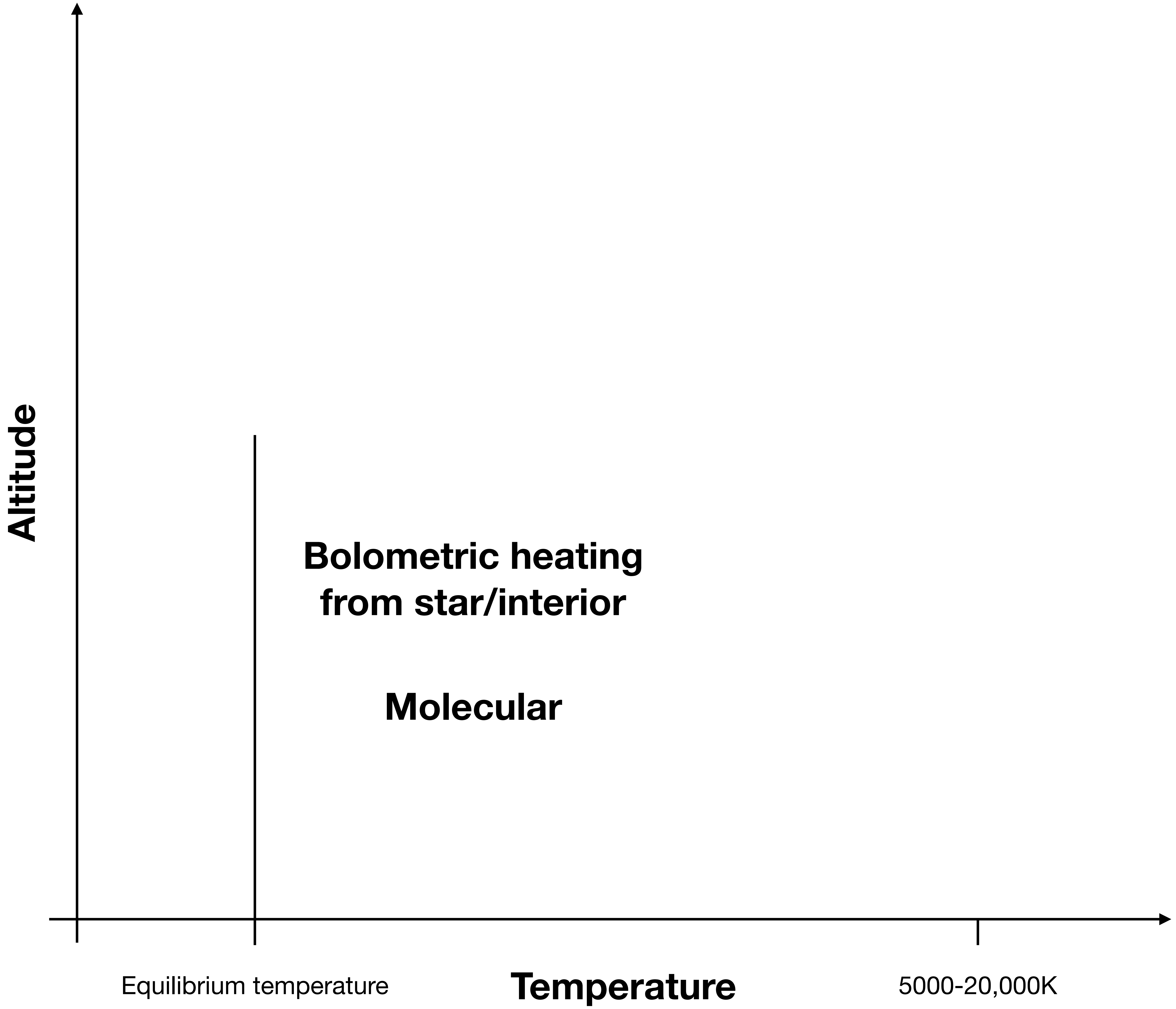

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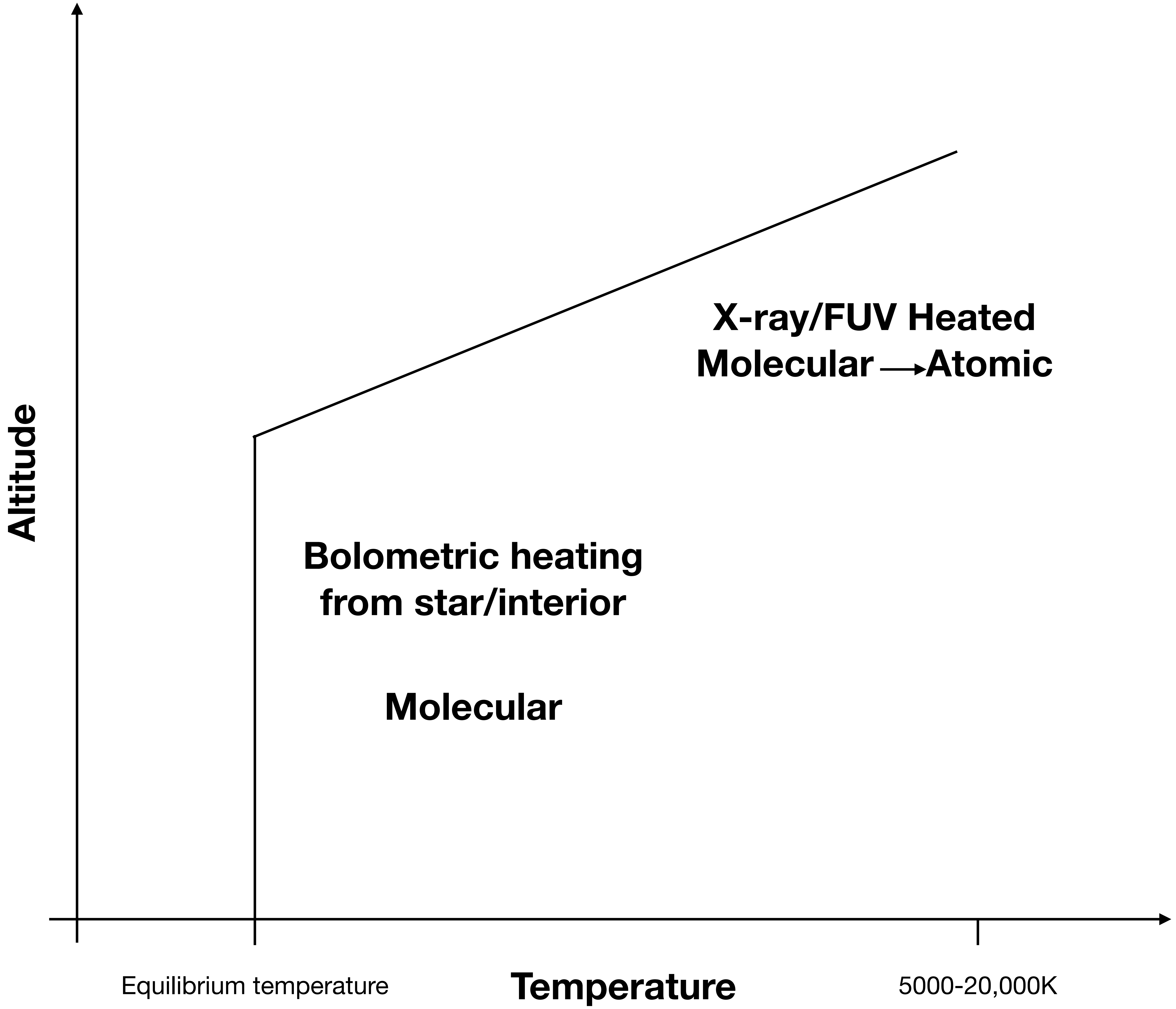

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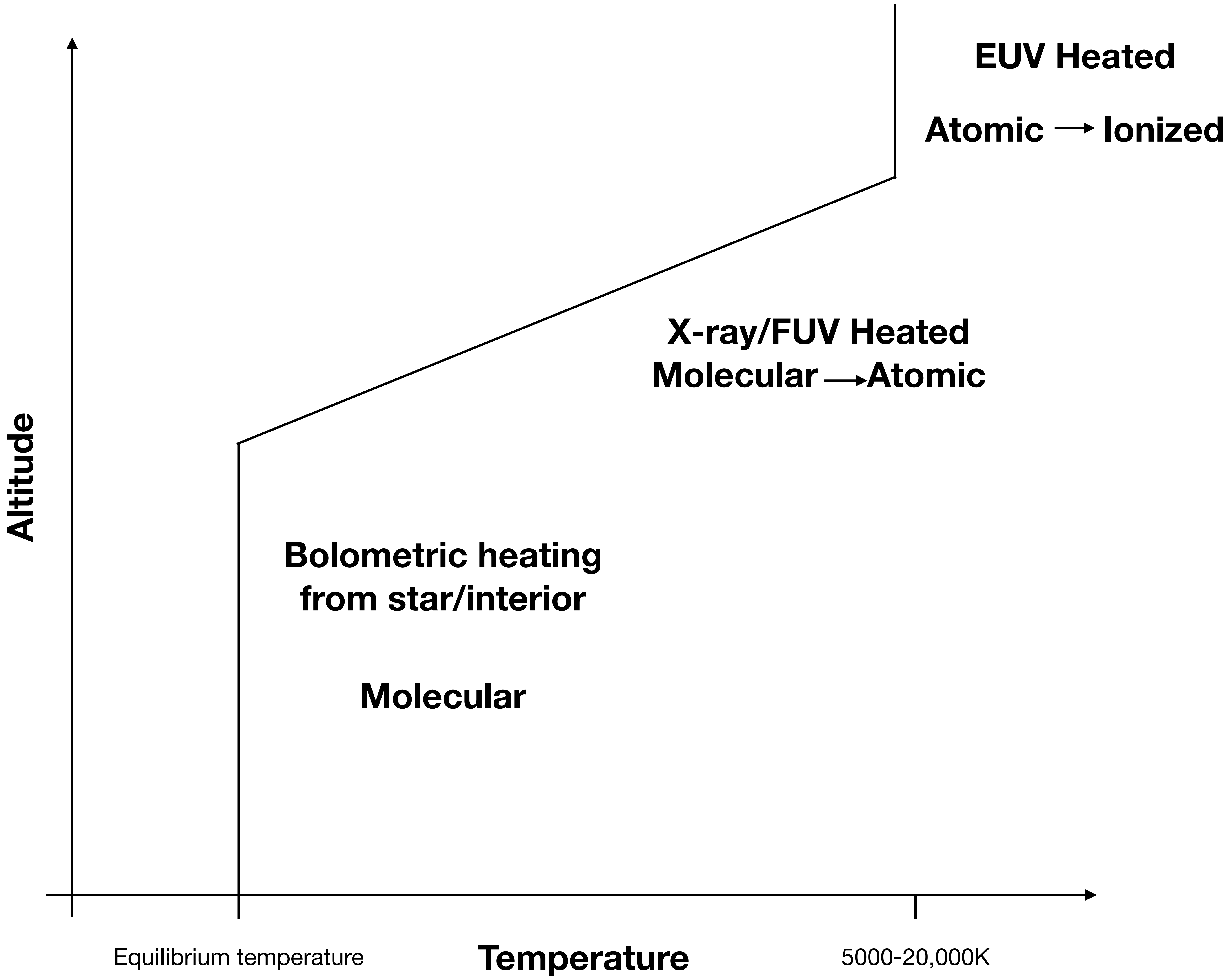

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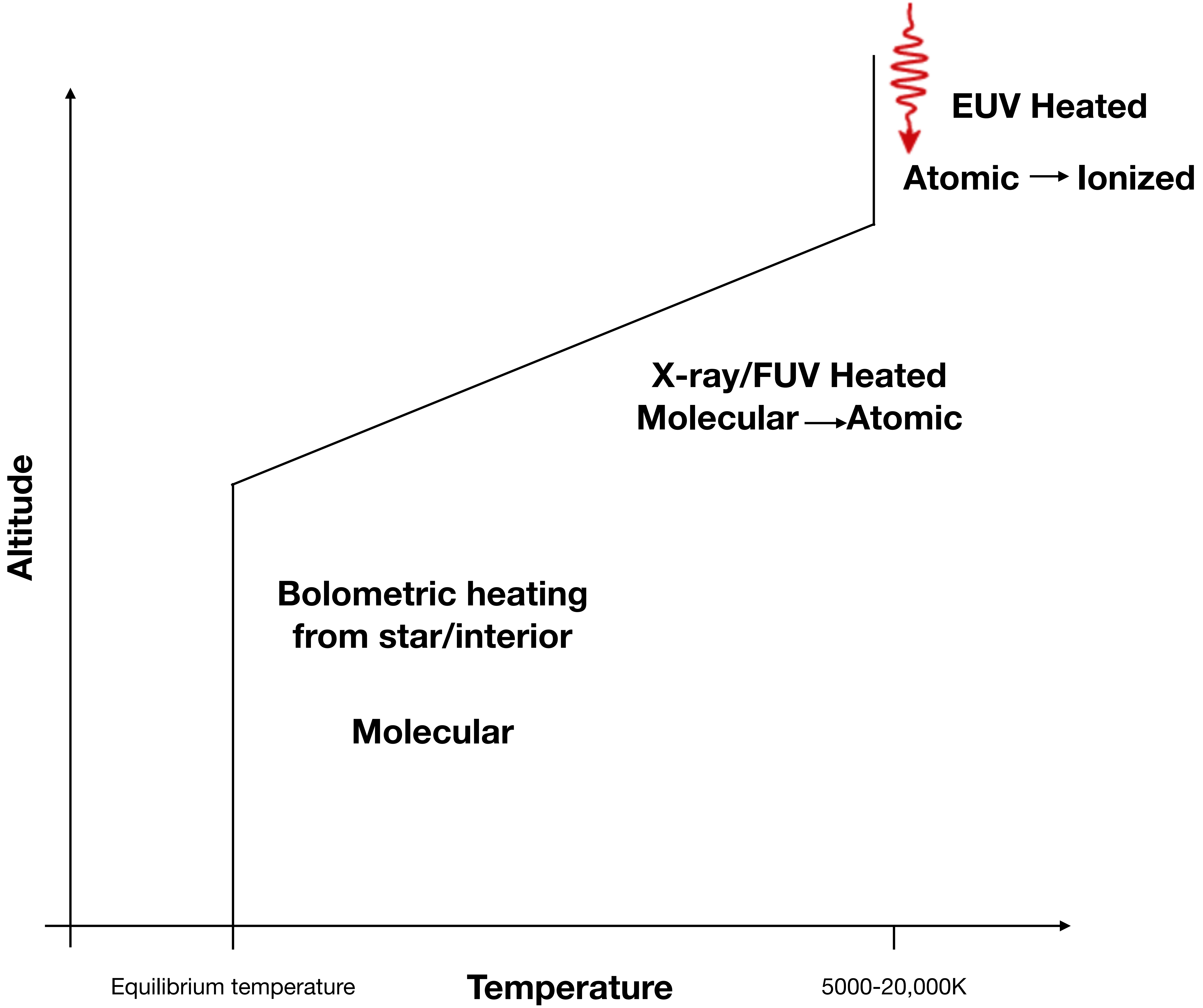

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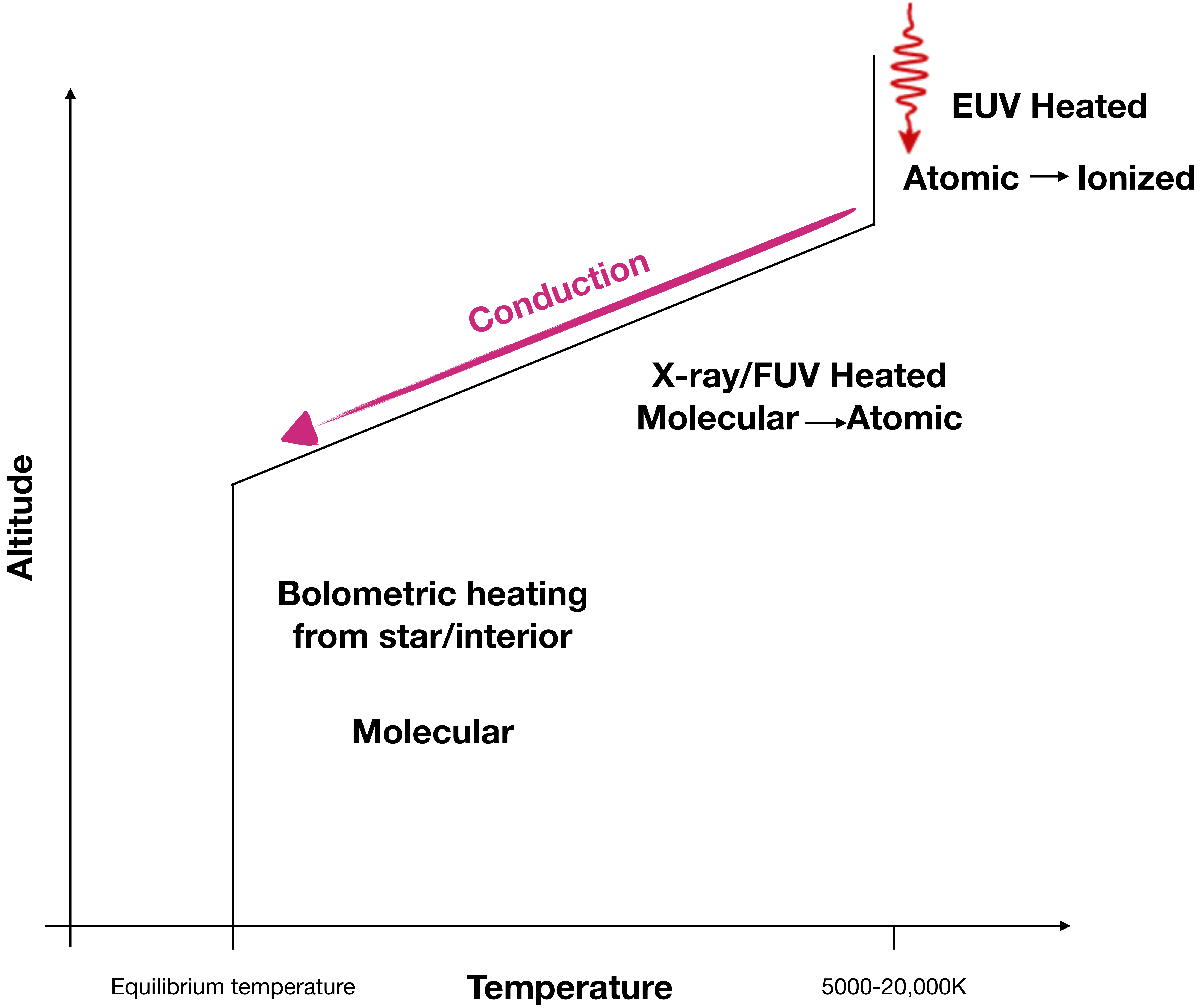

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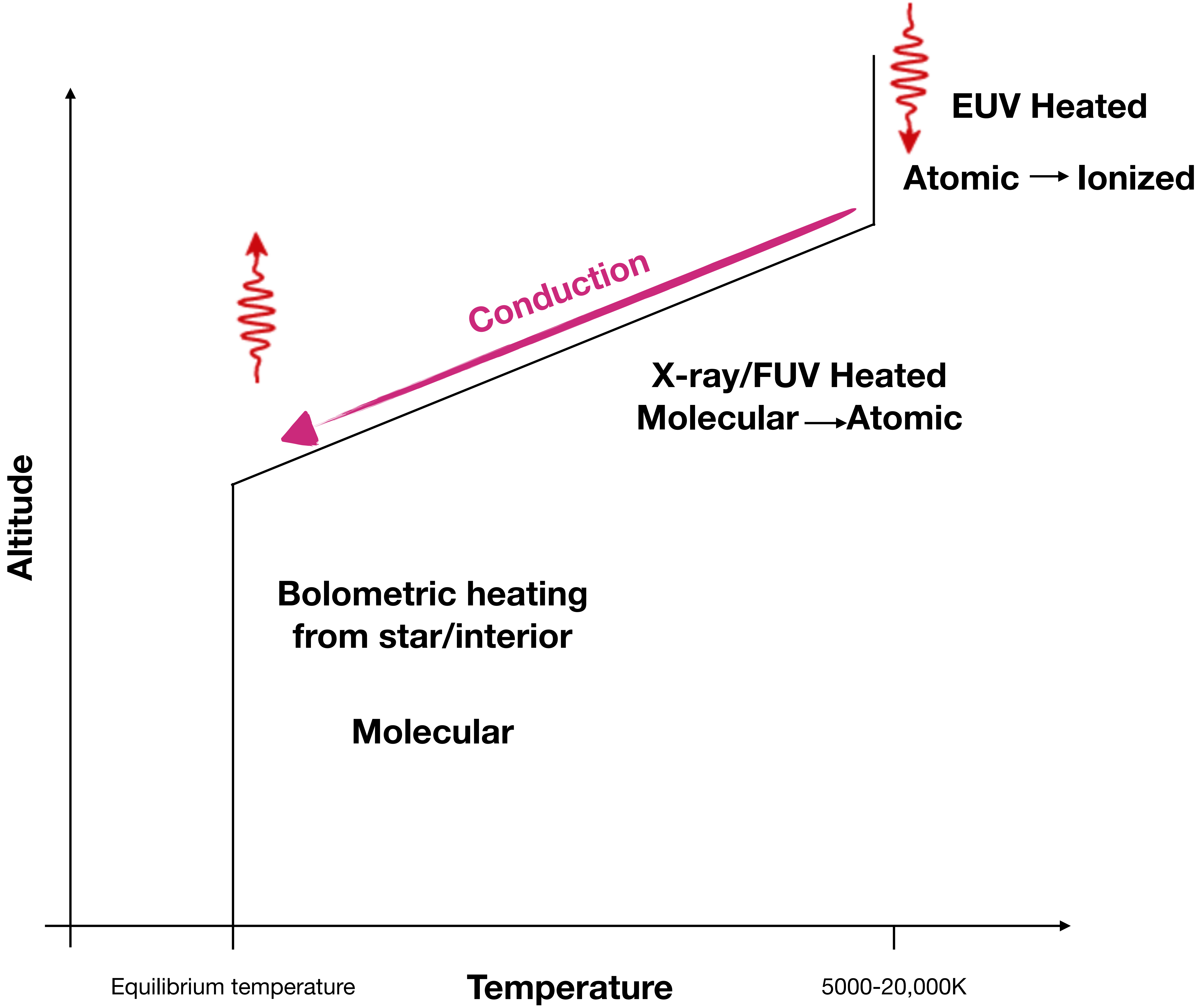

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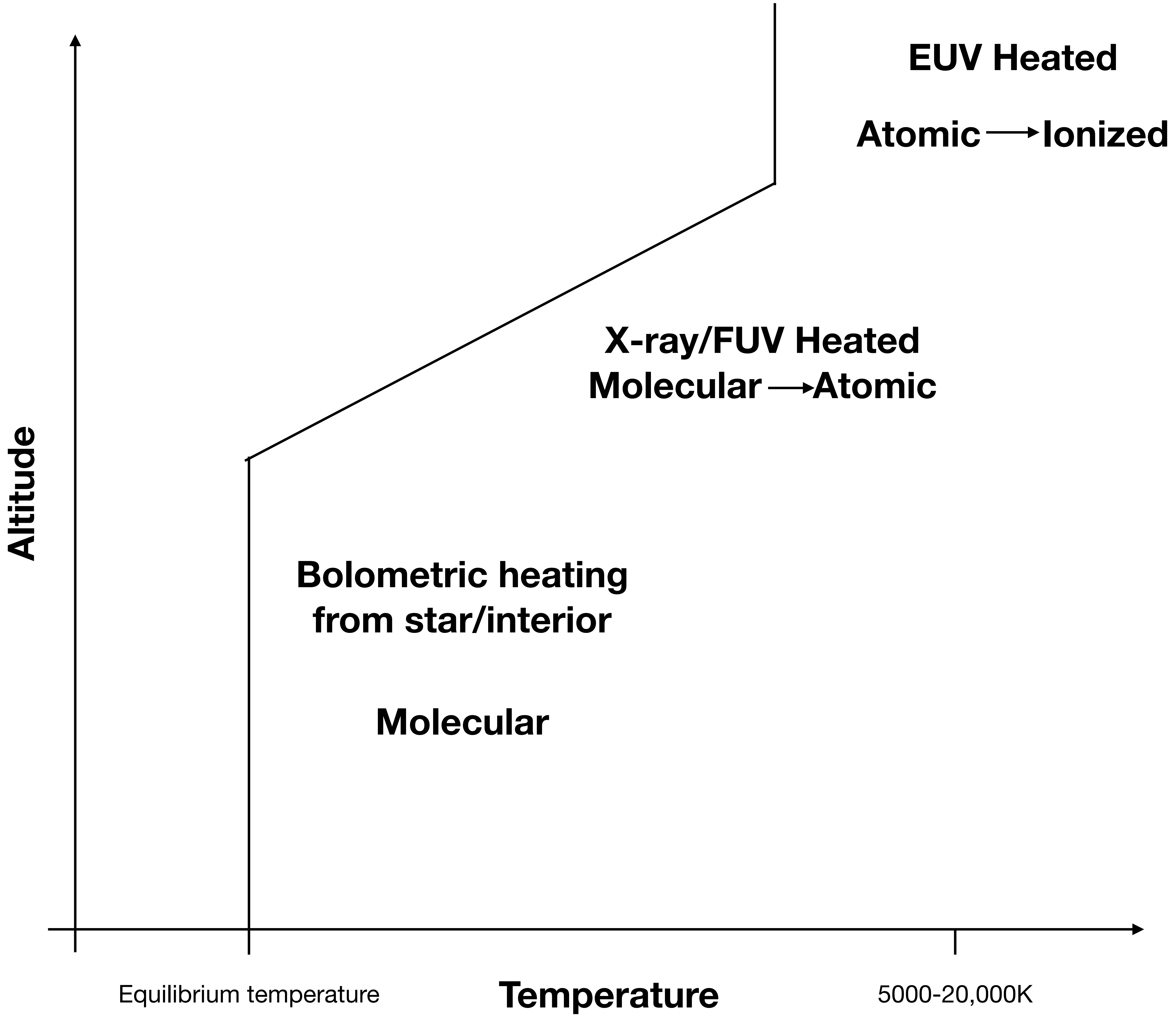

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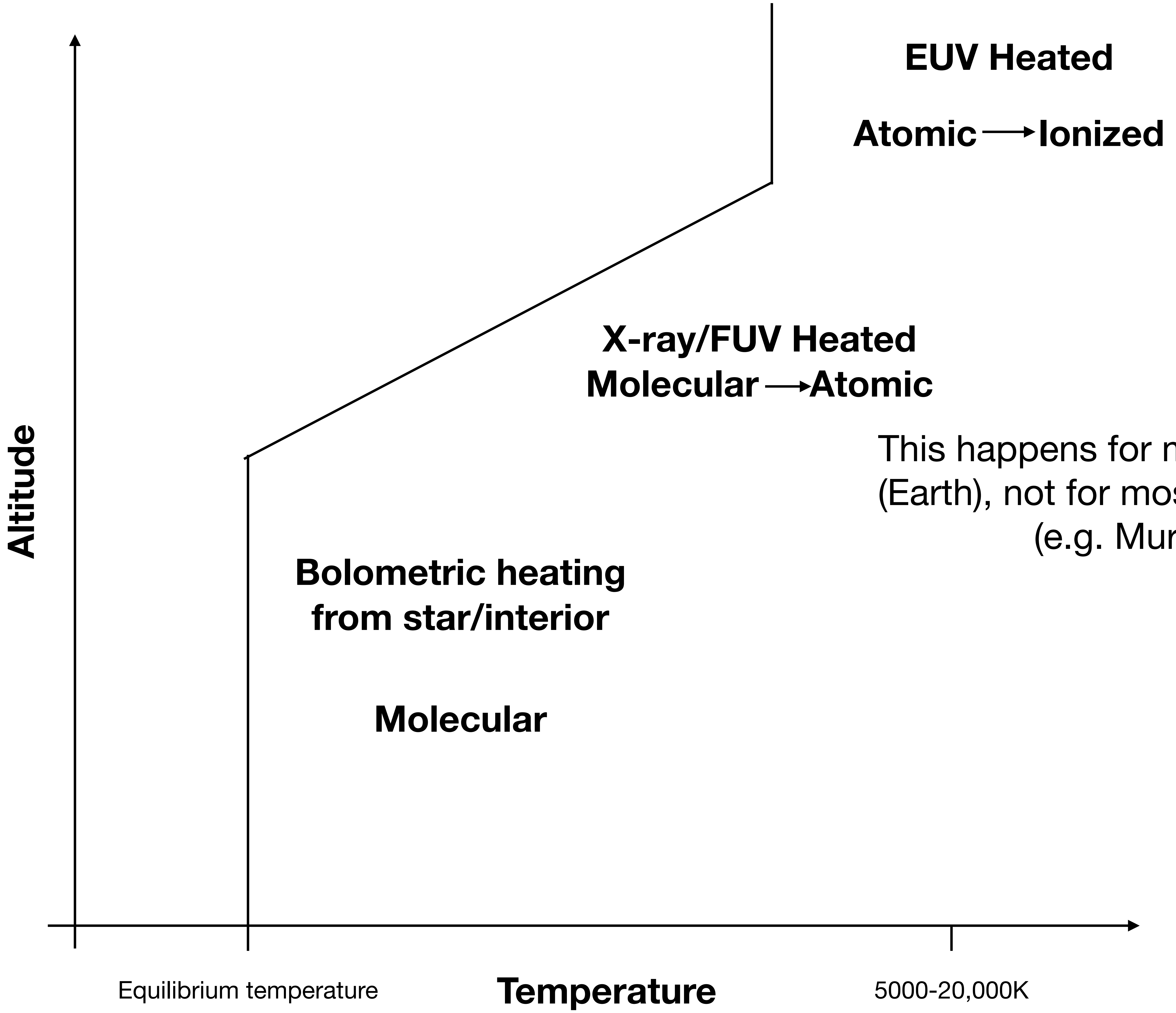

This happens for more weakly irradiated planets (Earth), not for most highly irradiated exoplanets (e.g. Murray-Clay et al. 2009)

Thermal driven escape

$$T_{\text{eq}} = T_* \sqrt{\frac{R_*}{2a}} \sim 1500\ \text{K} \left(\frac{T_*}{5700\ \text{K}}\right) \left(\frac{R_*}{R_\odot}\right)^{1/2} \left(\frac{a}{0.03\ \text{AU}}\right)^{-1/2}$$

The concept of the escape temperature

$$T_{\text{esc}} \sim 8000\ \text{K}\ \mu \left(\frac{M_p}{1\text{M}_\oplus}\right) \left(\frac{R_p}{1\text{R}_\oplus}\right)^{-1}$$

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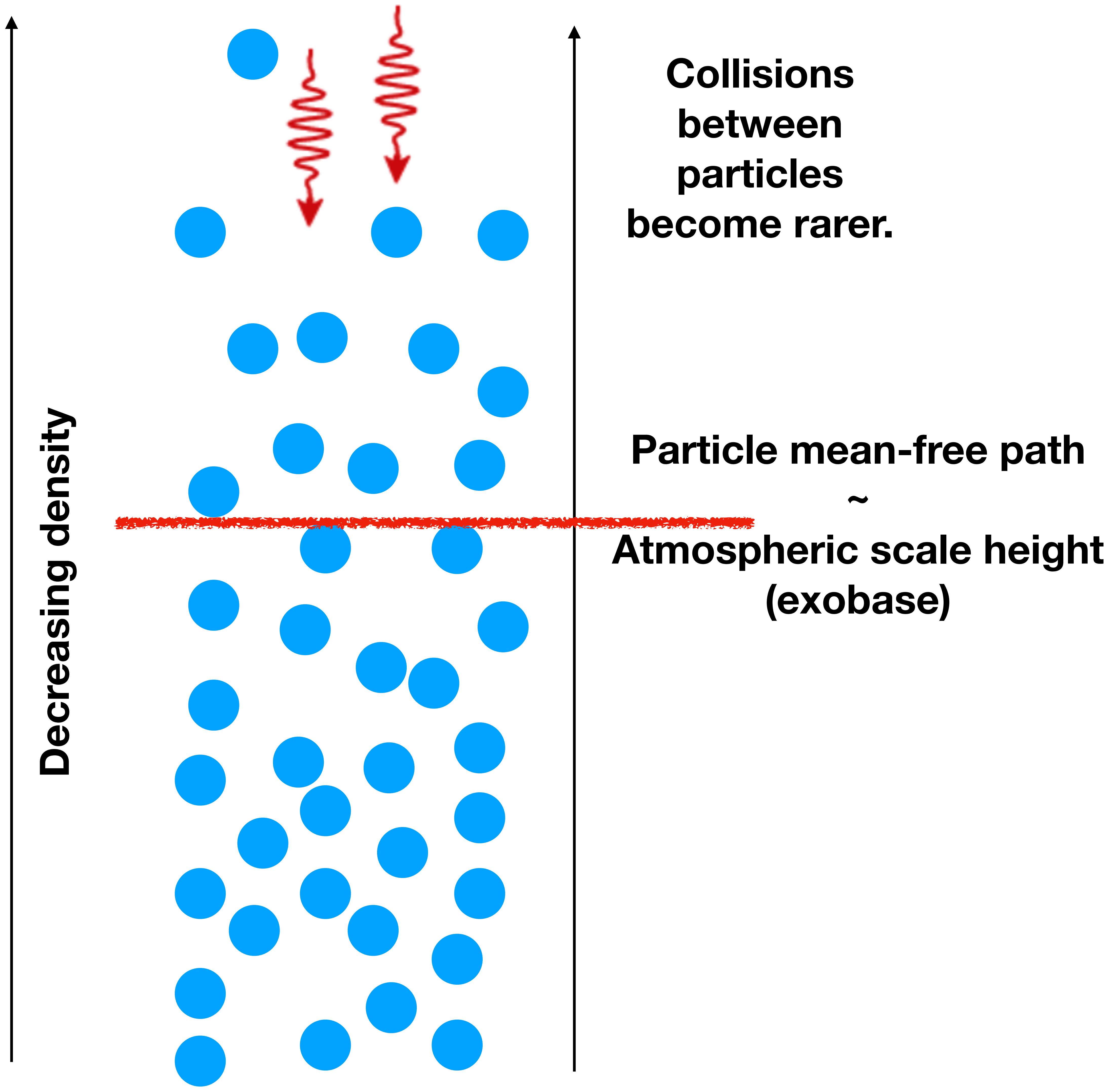
The concept of the escape temperature

The stellar UV/X-ray photons heat the upper atmospheres to temperatures approaching the escape temperature

$$T_{\rm esc} \sim 8000\ {\rm K}\ \mu \left(\frac{M_p}{1{\rm M}_\oplus}\right) \left(\frac{R_p}{1{\rm R}_\oplus}\right)^{-1}$$

Thermal escape regimes: collisional vs collisionless, an intuitive picture…



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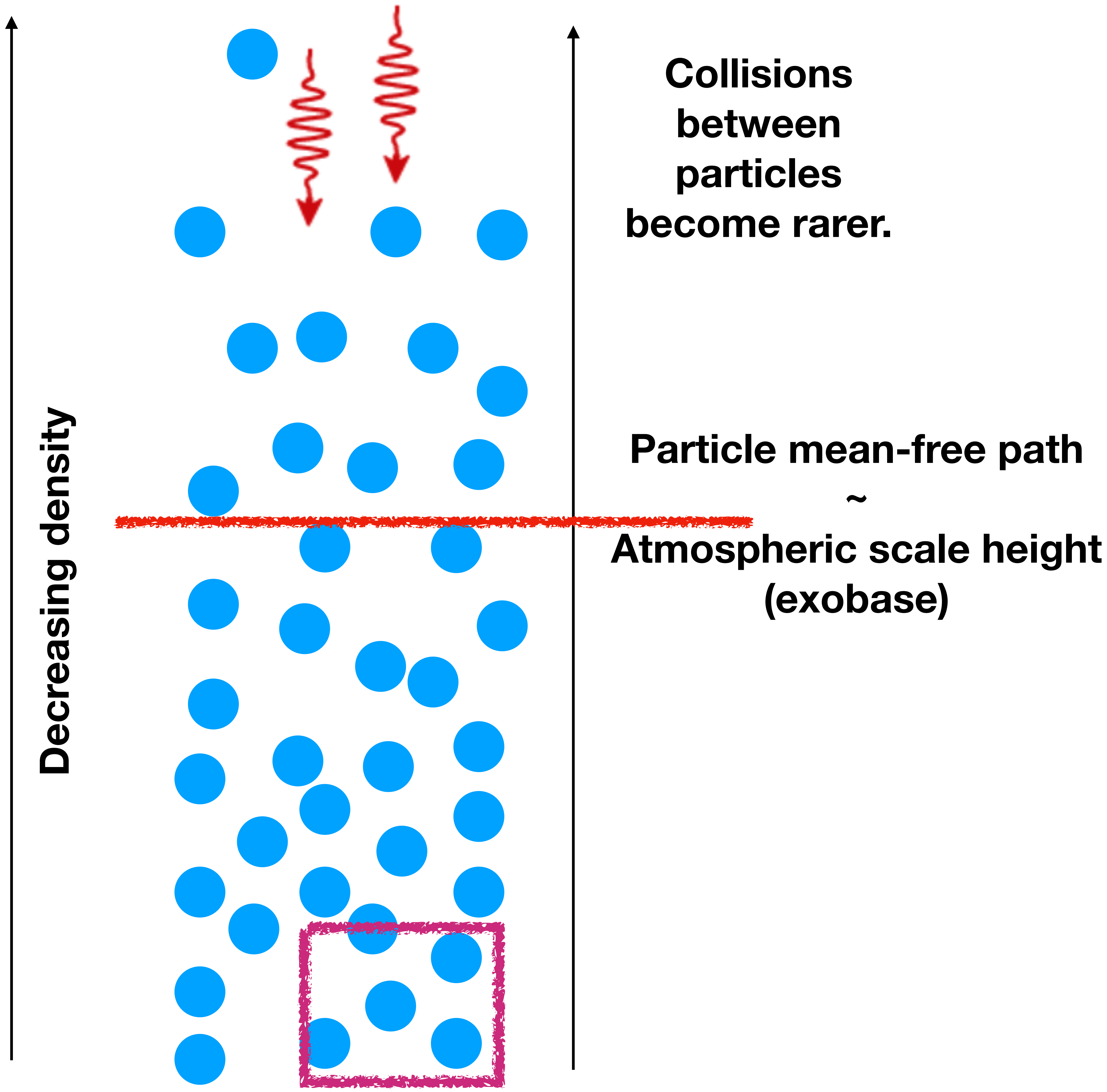

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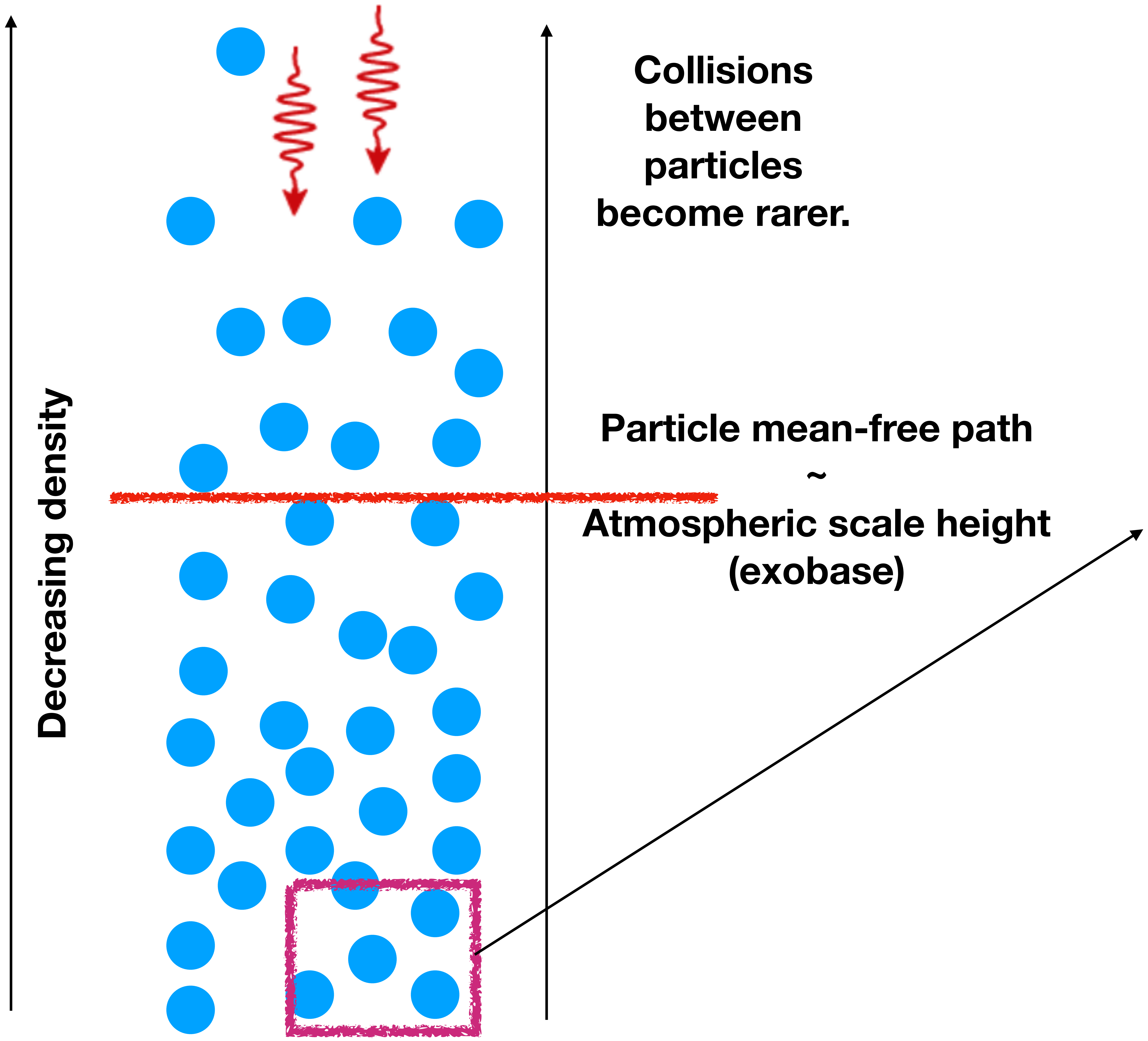

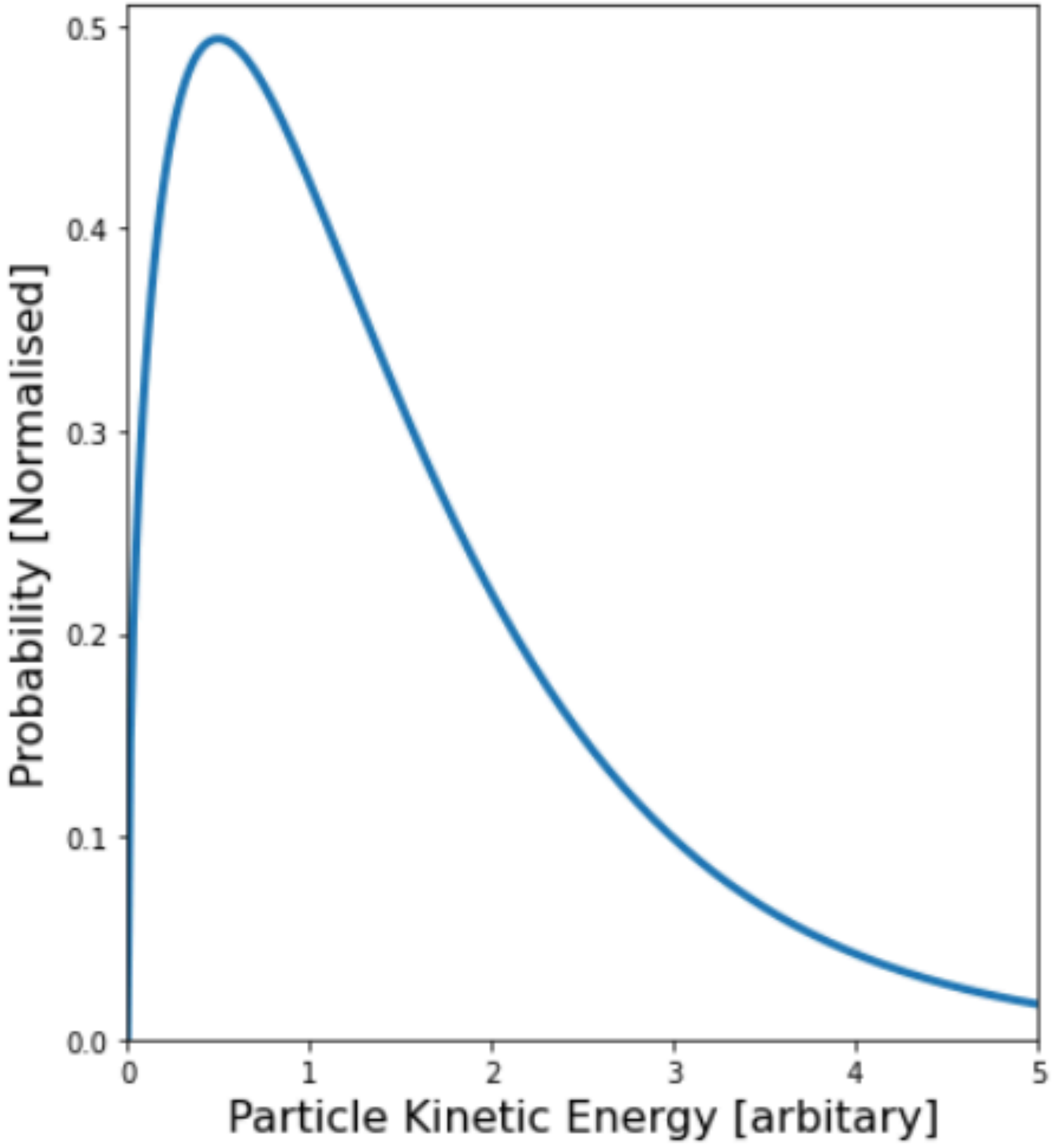

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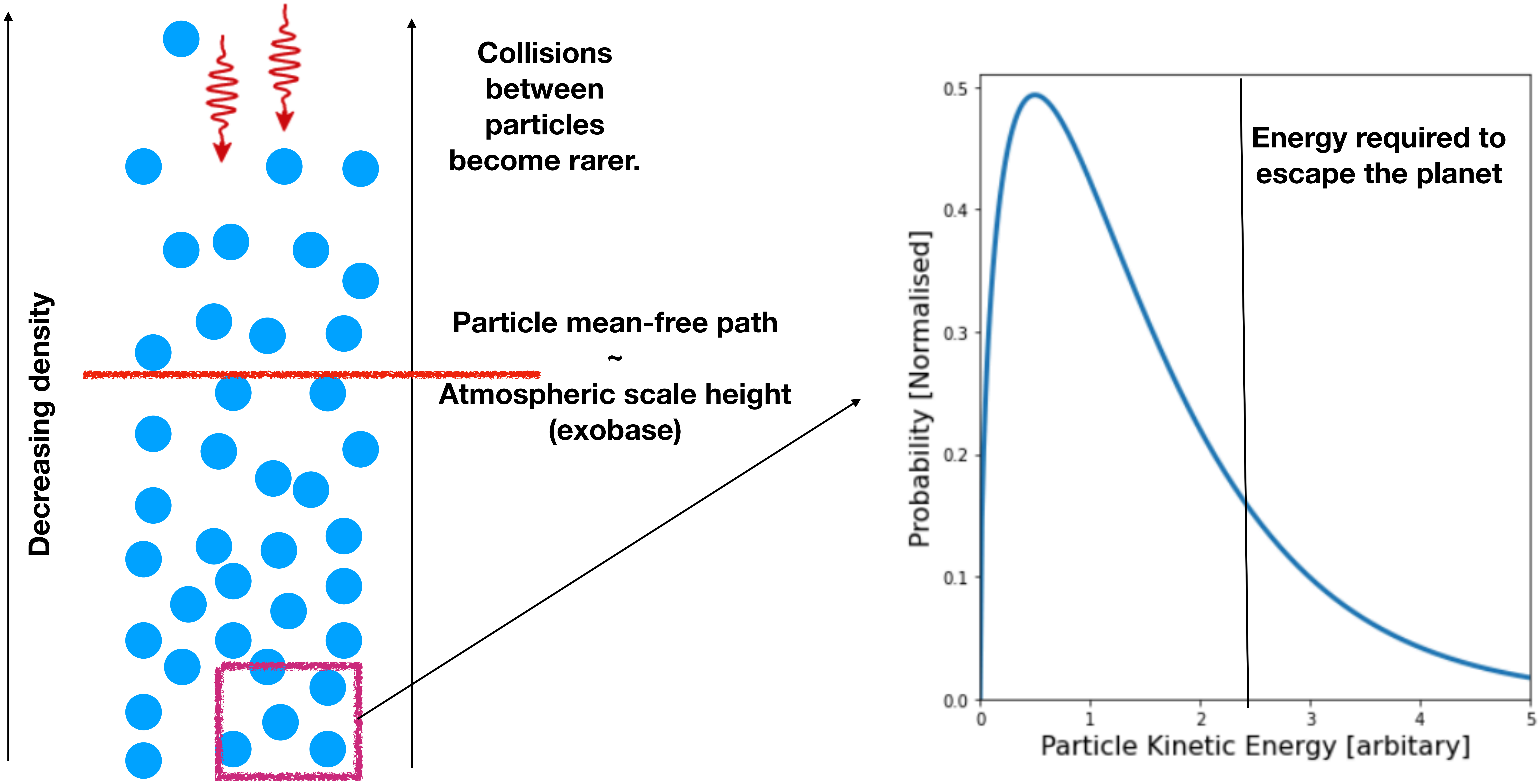

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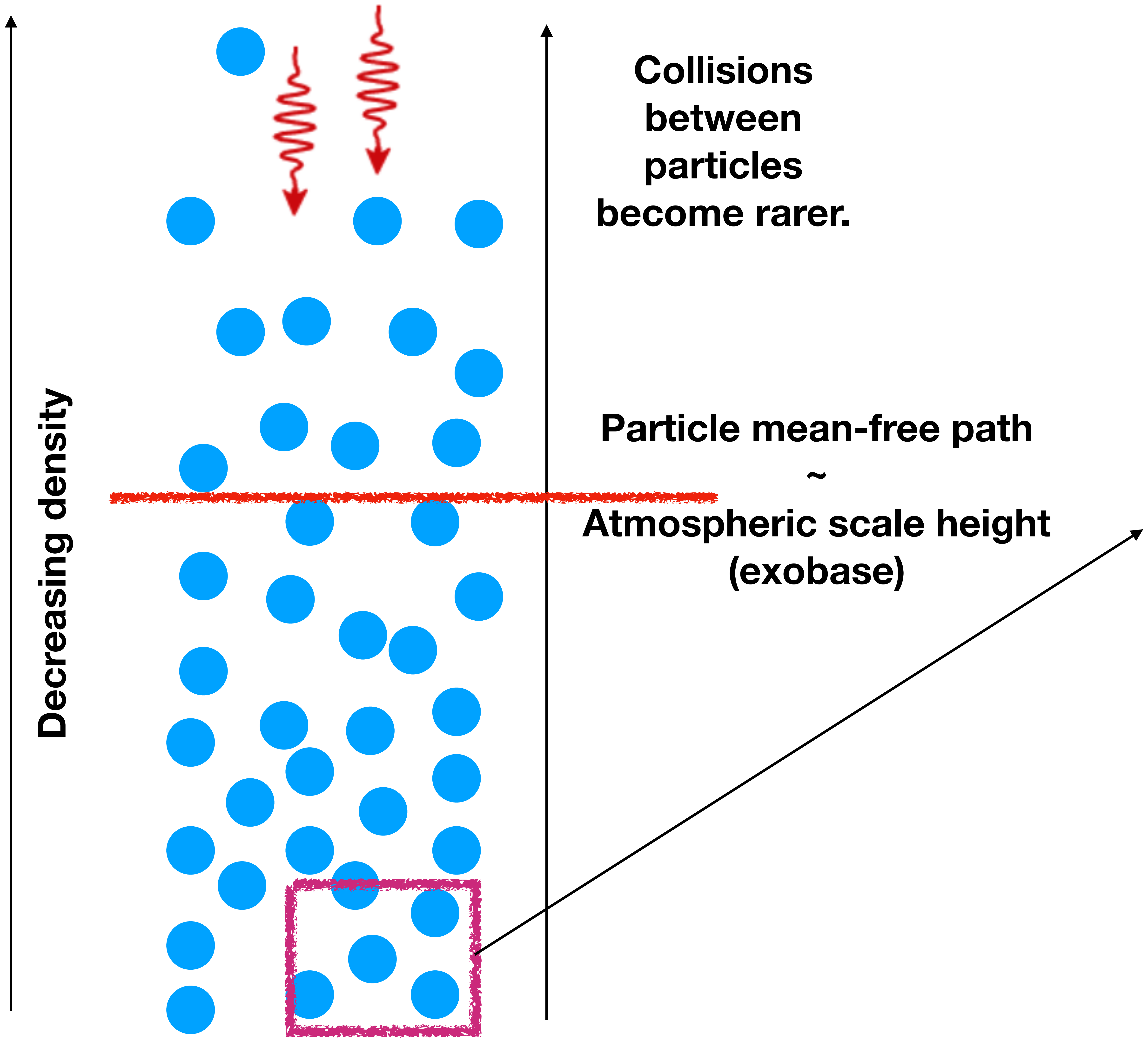

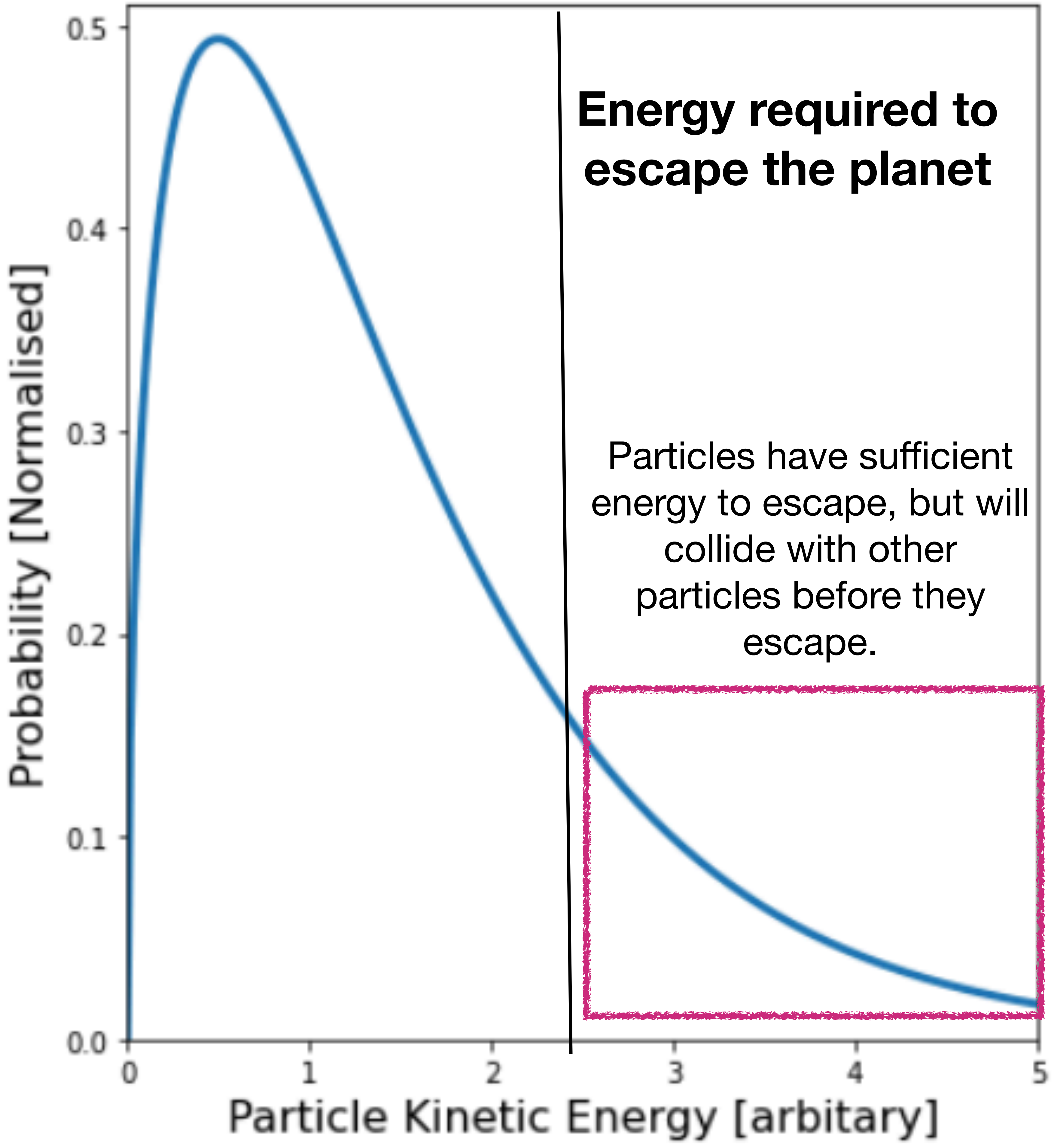

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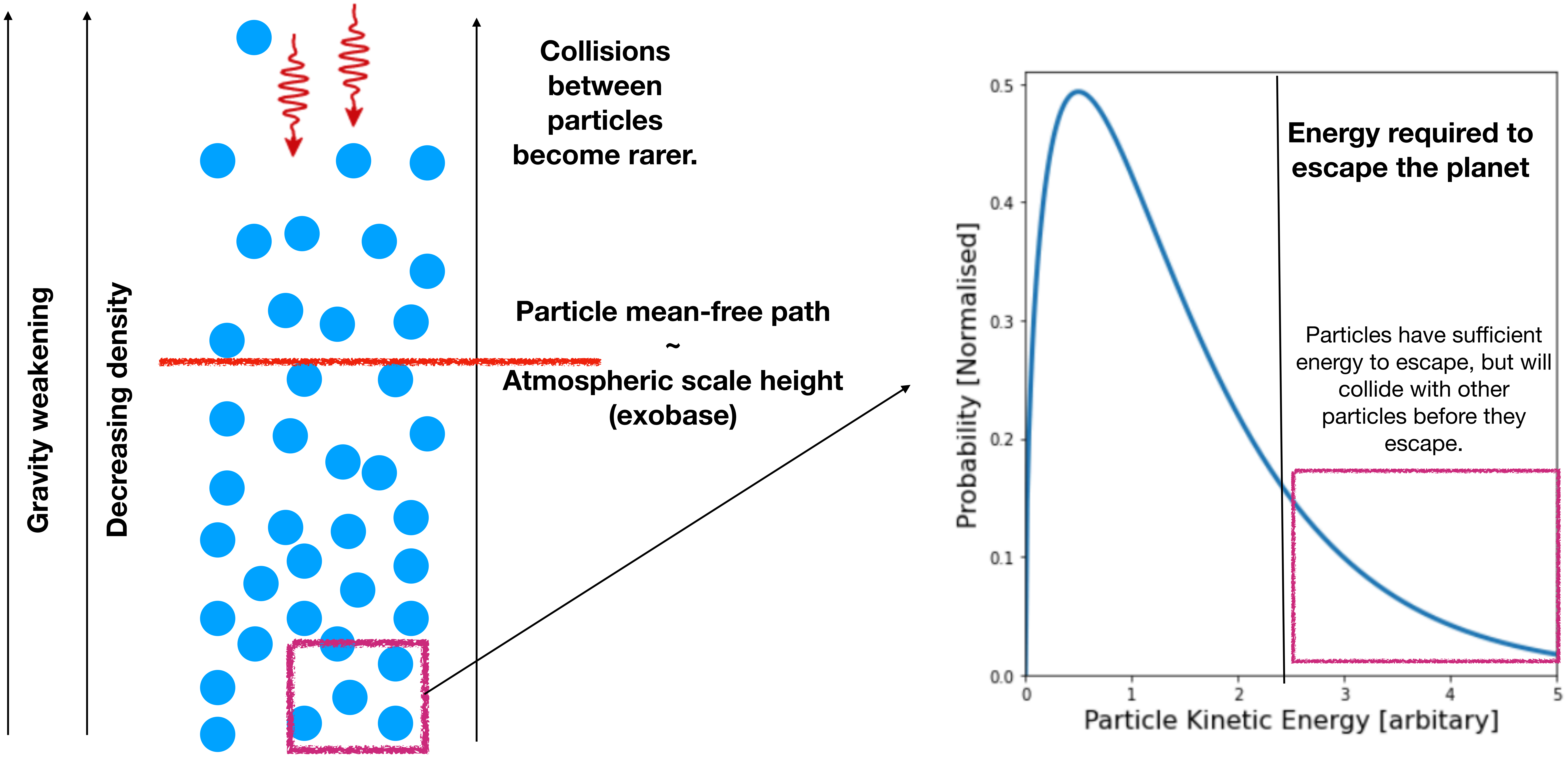

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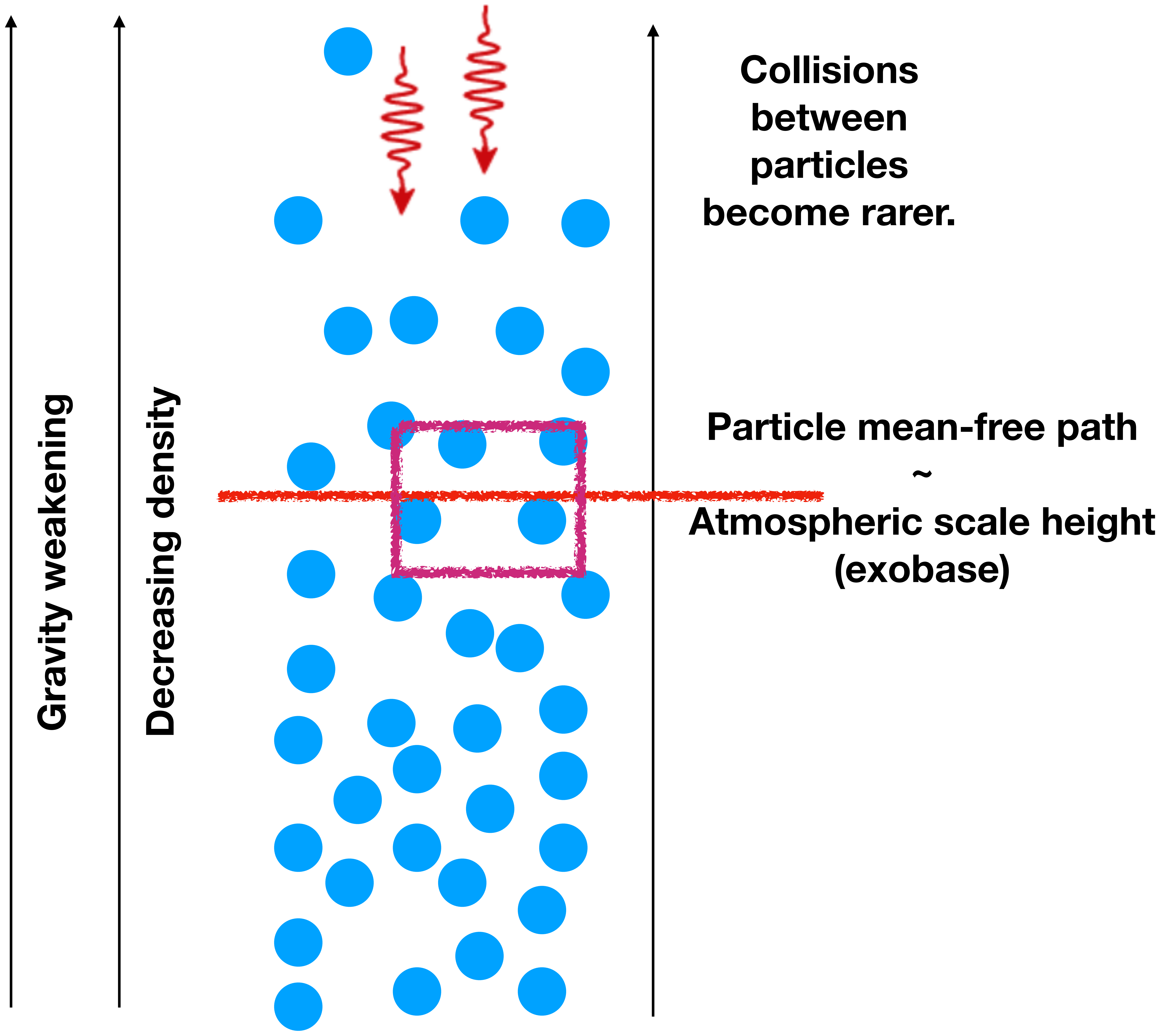

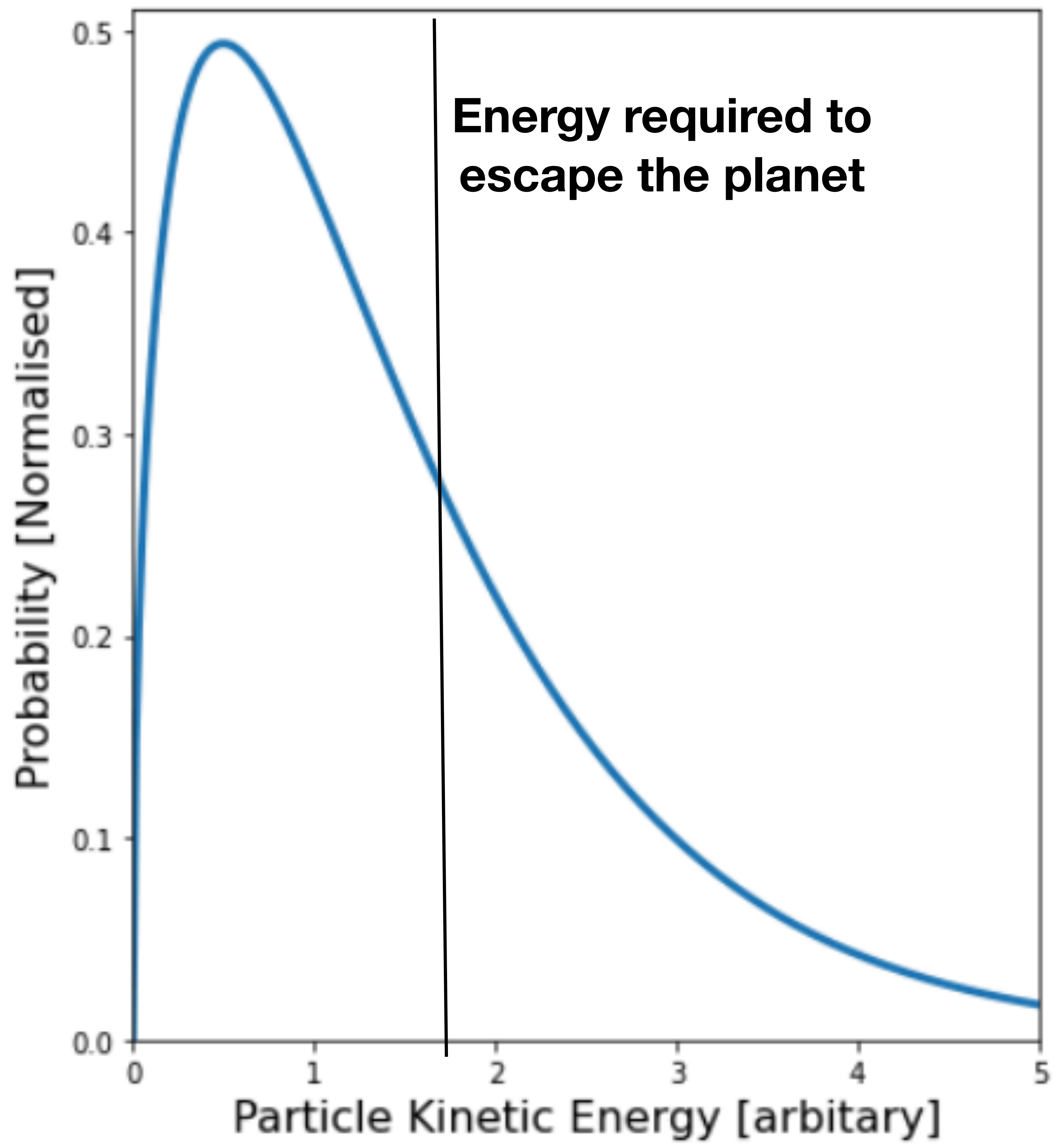

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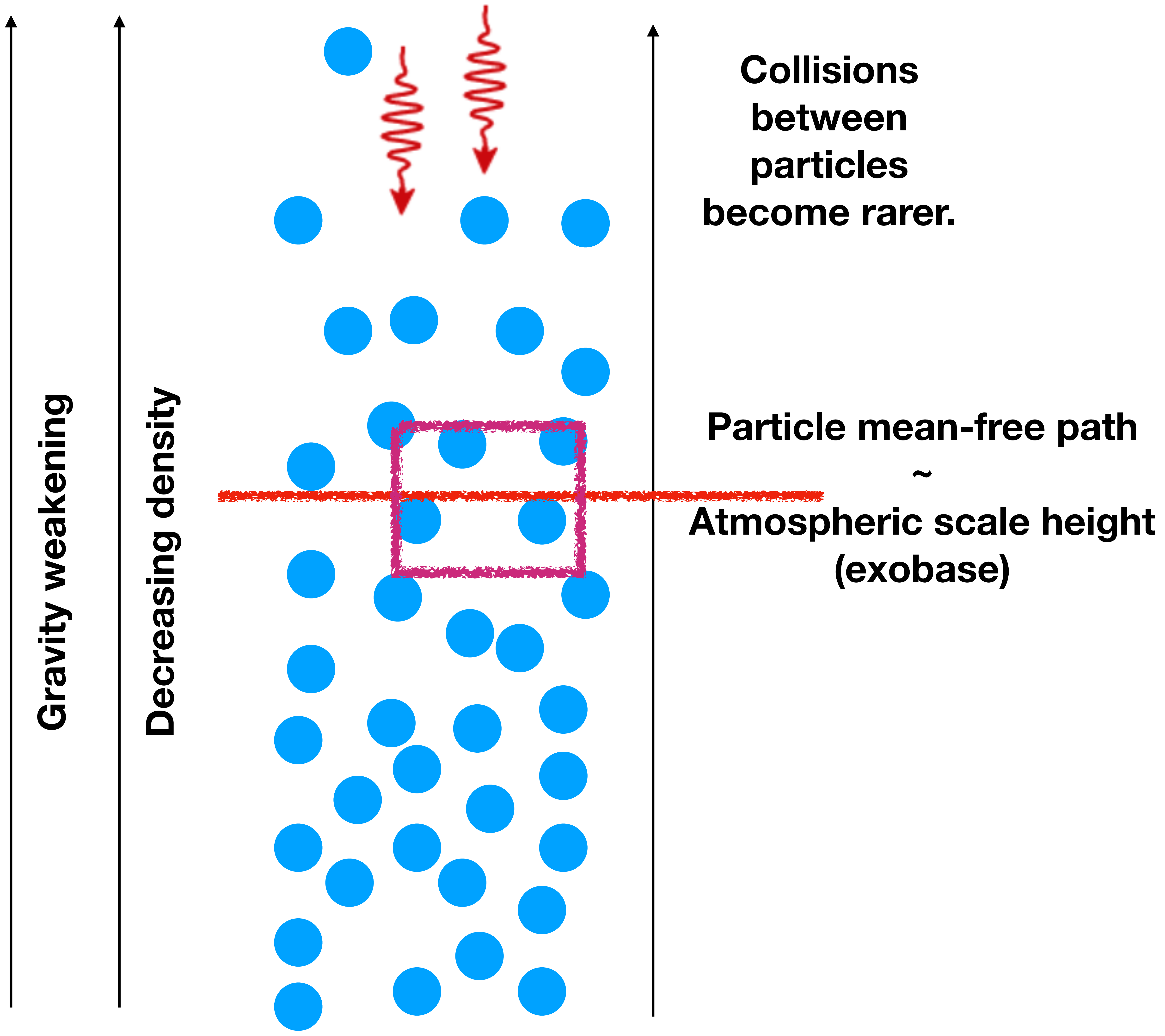

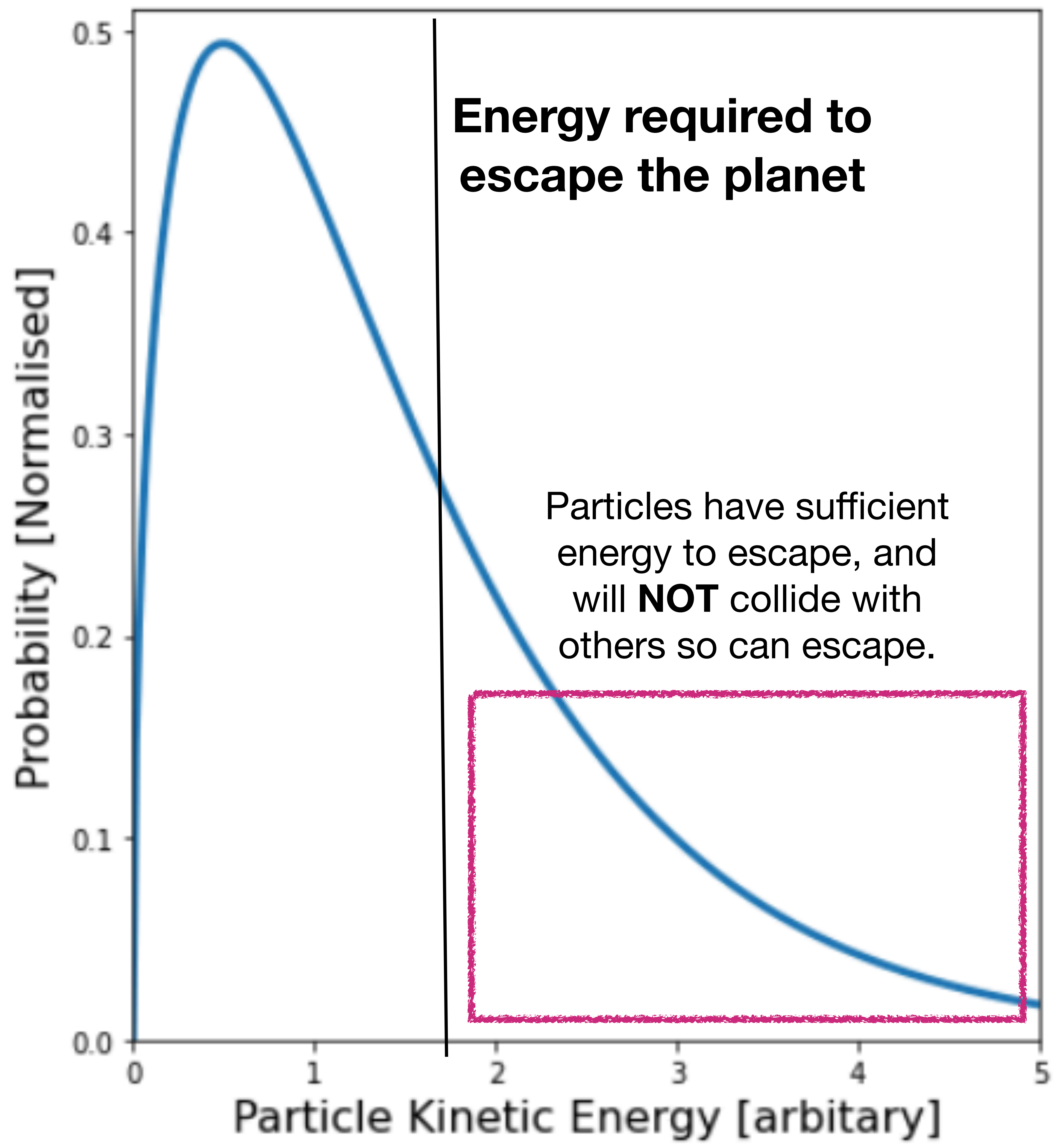

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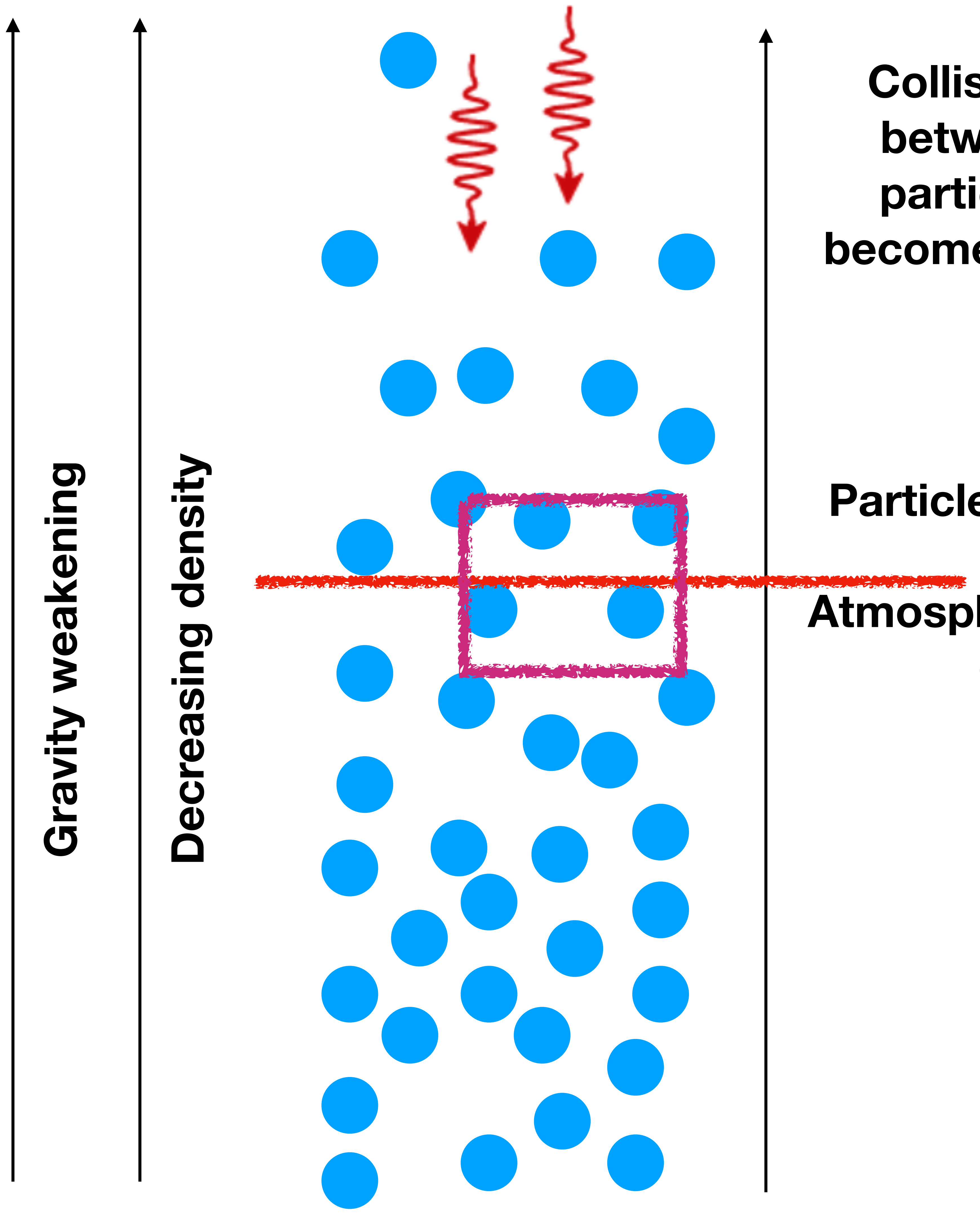
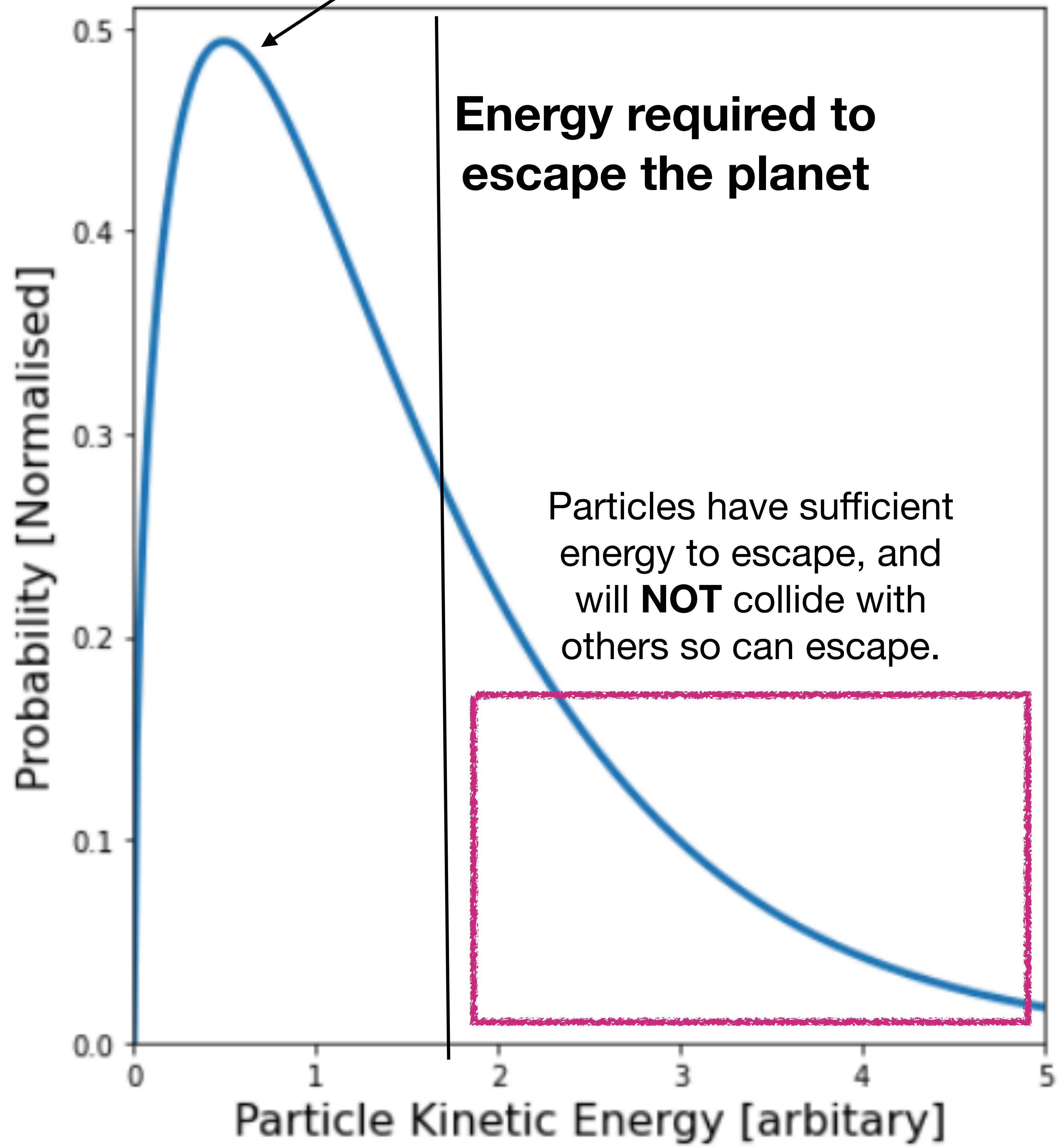


Collisions between particles become rarer.

Particle mean-free path ~ Atmospheric scale height (exobase)

Bulk of particles cannot escape**: Collisionless Jeans Escape**



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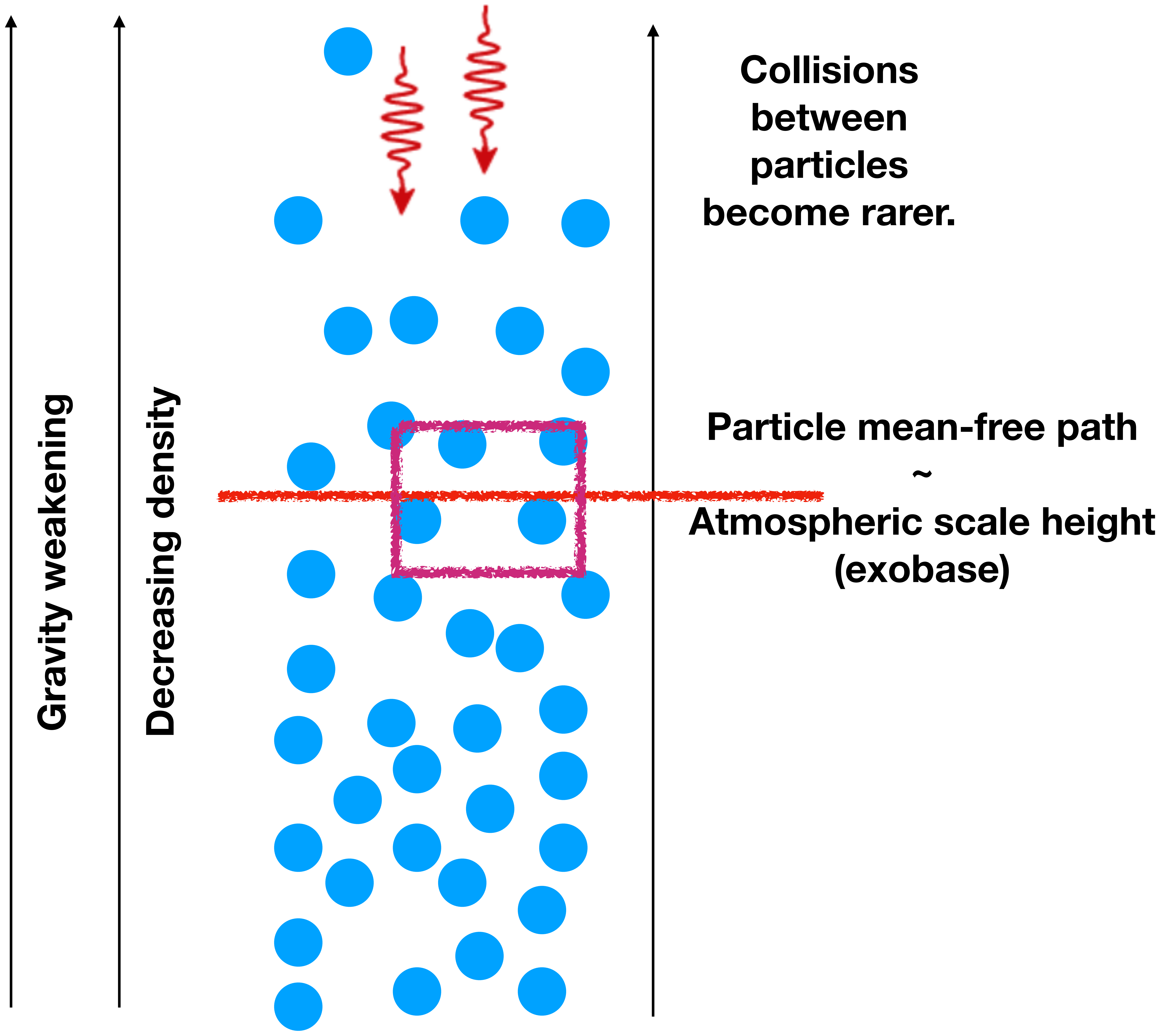

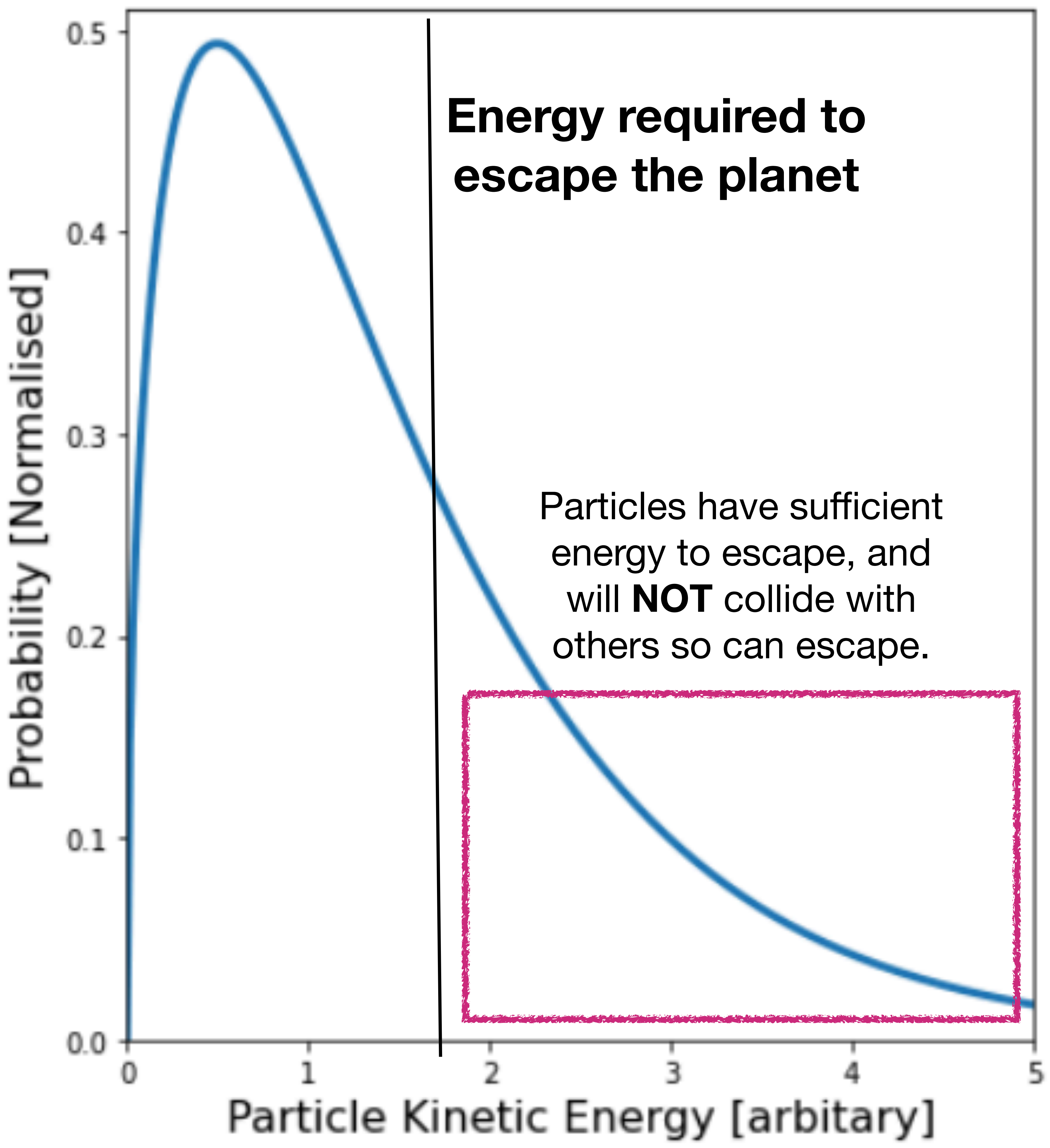

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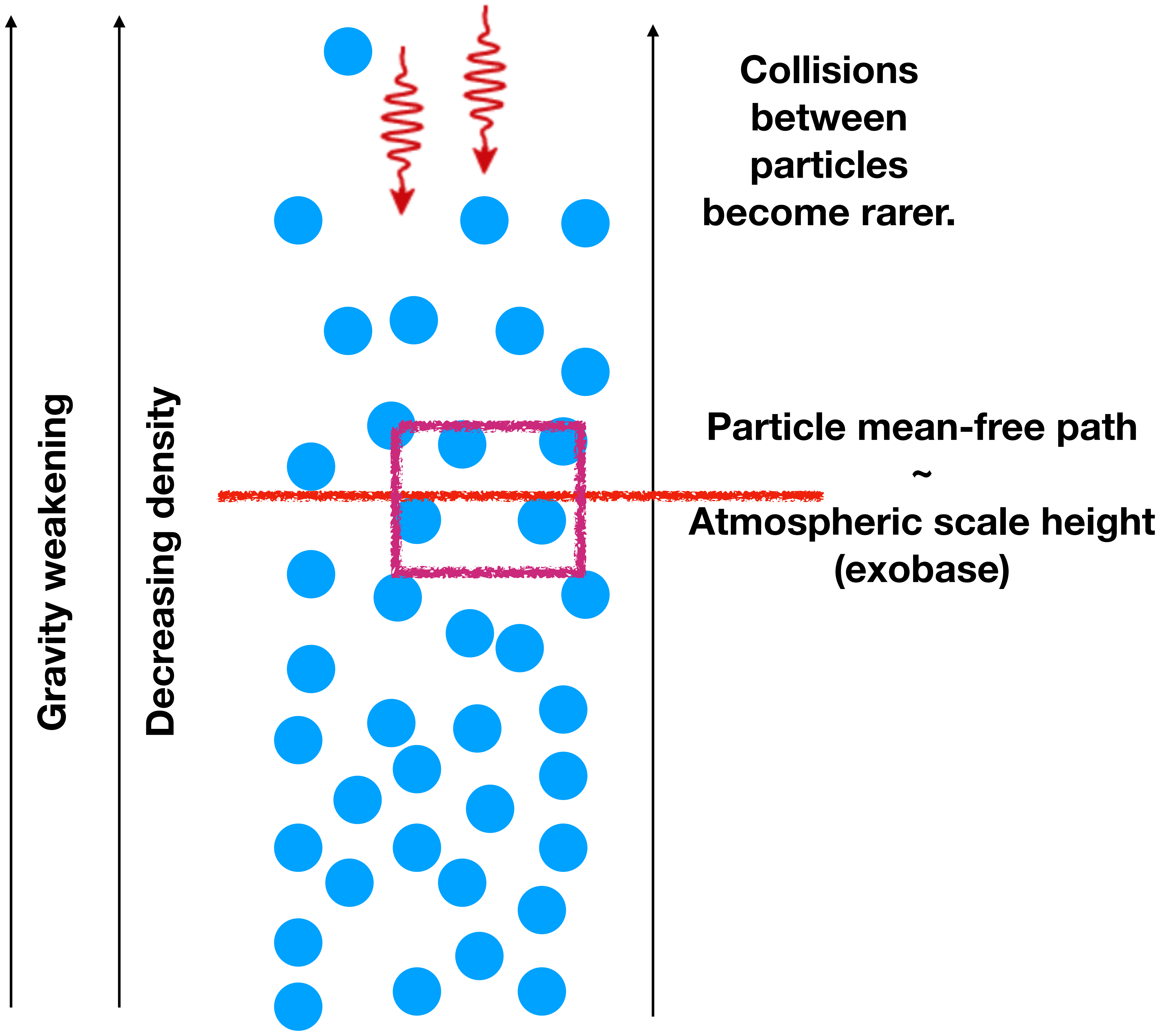

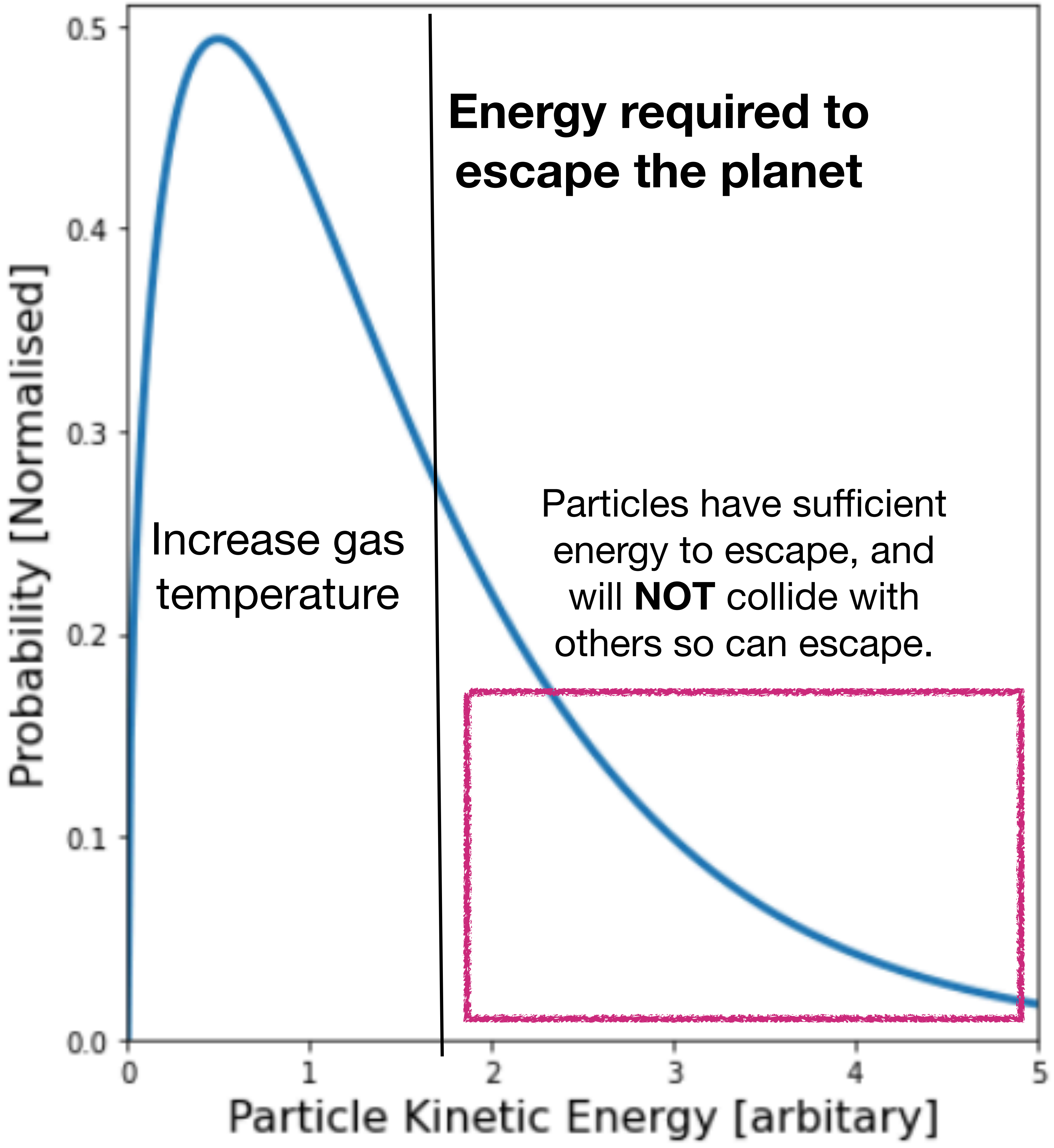

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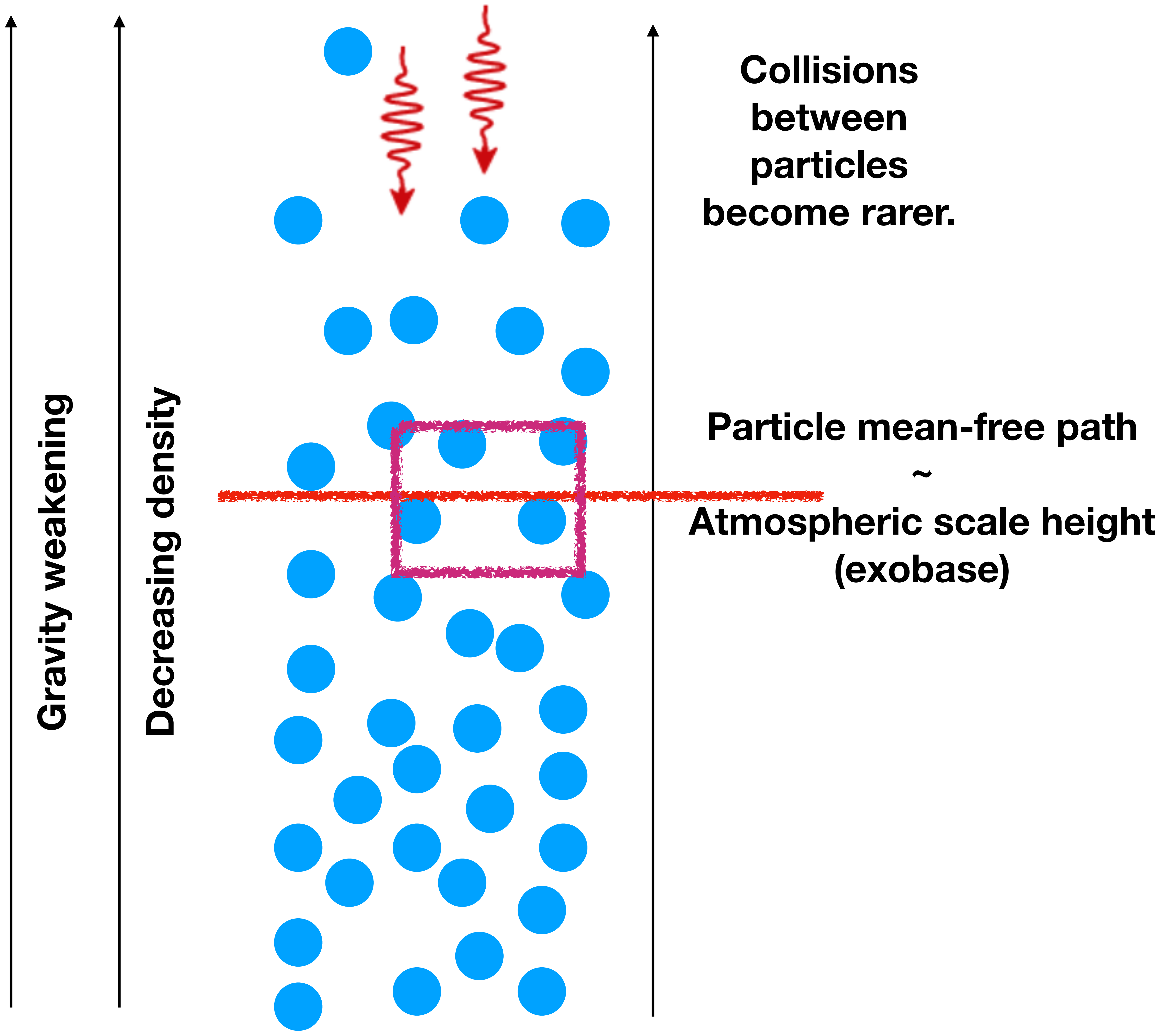

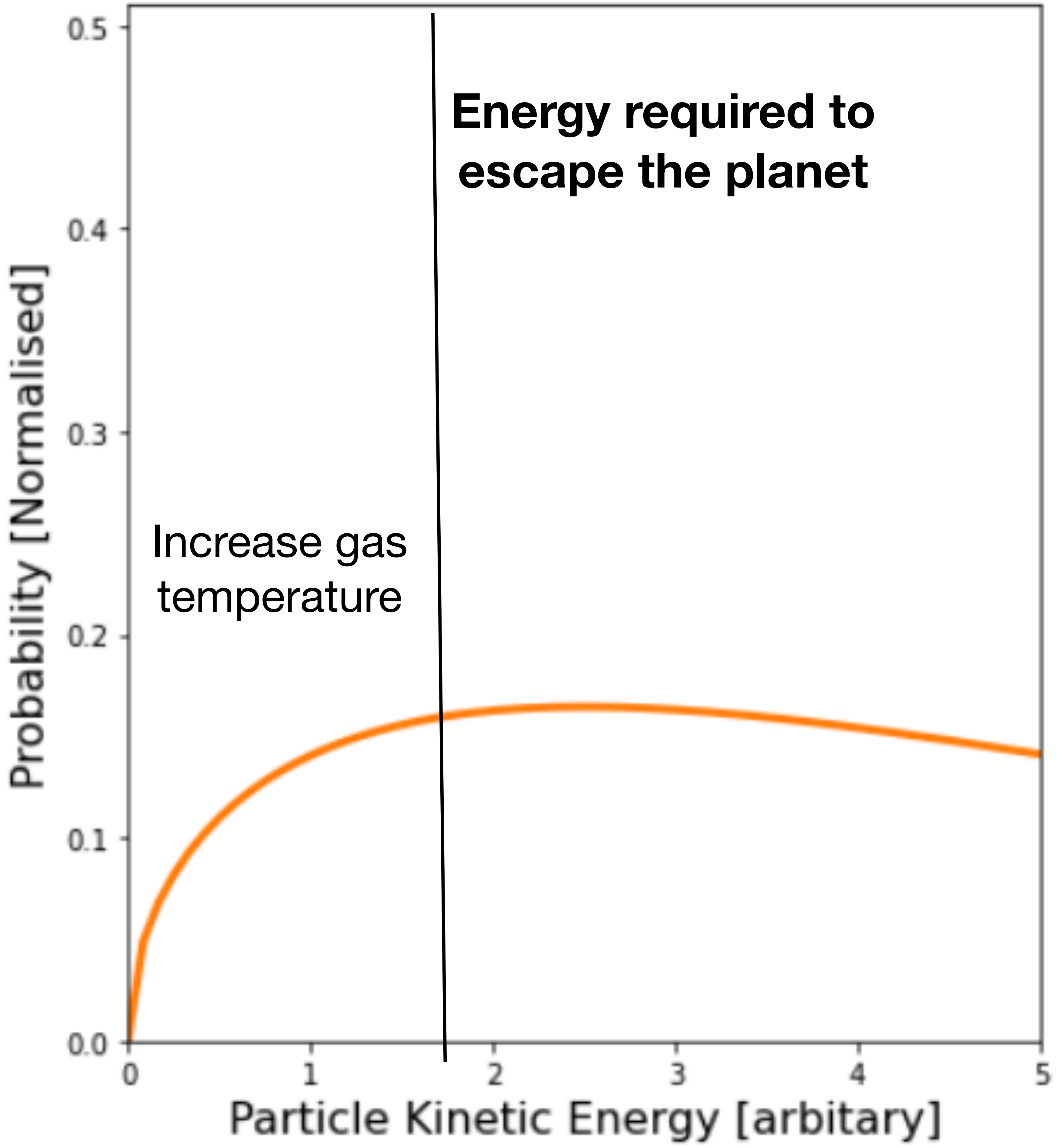

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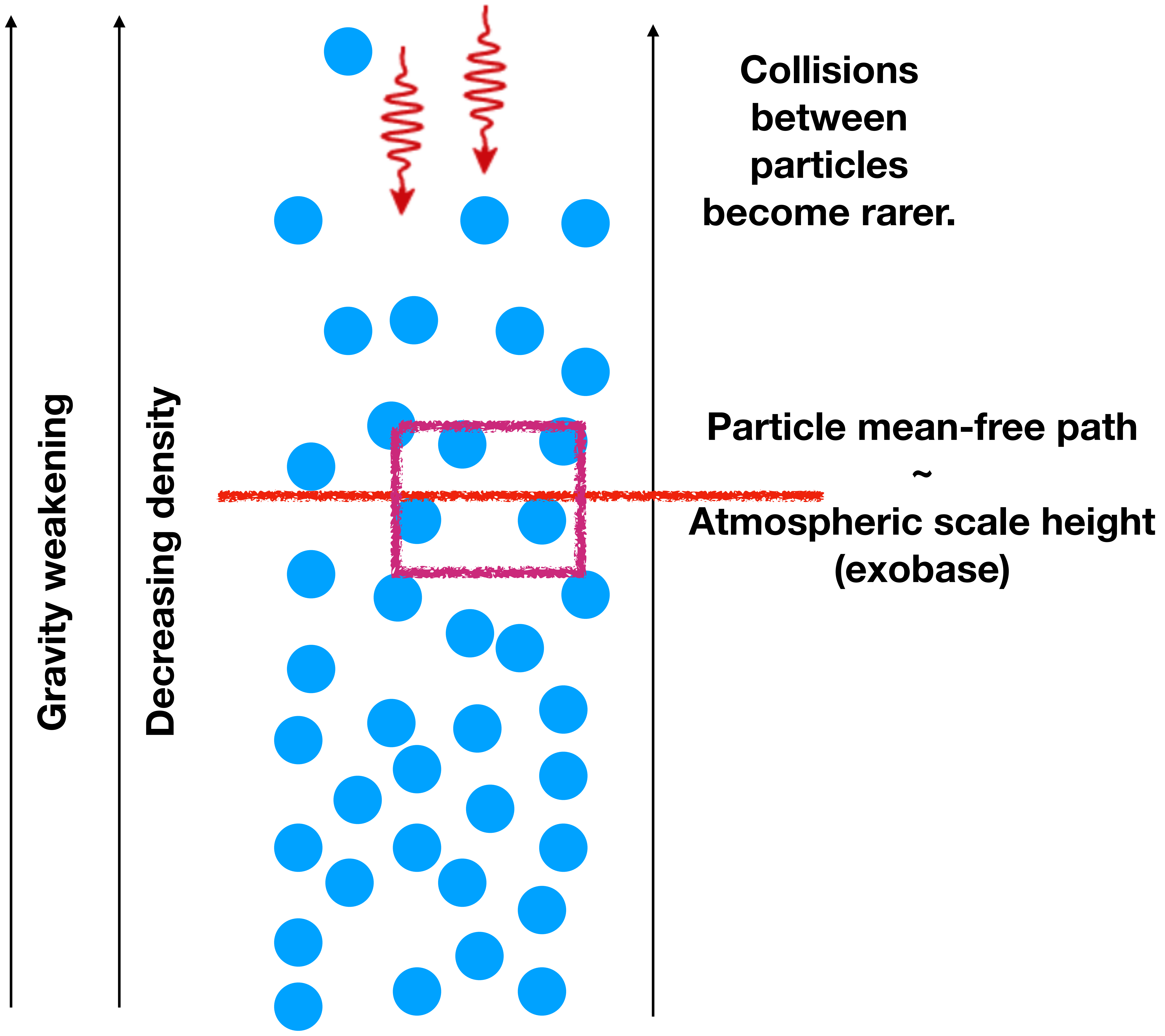
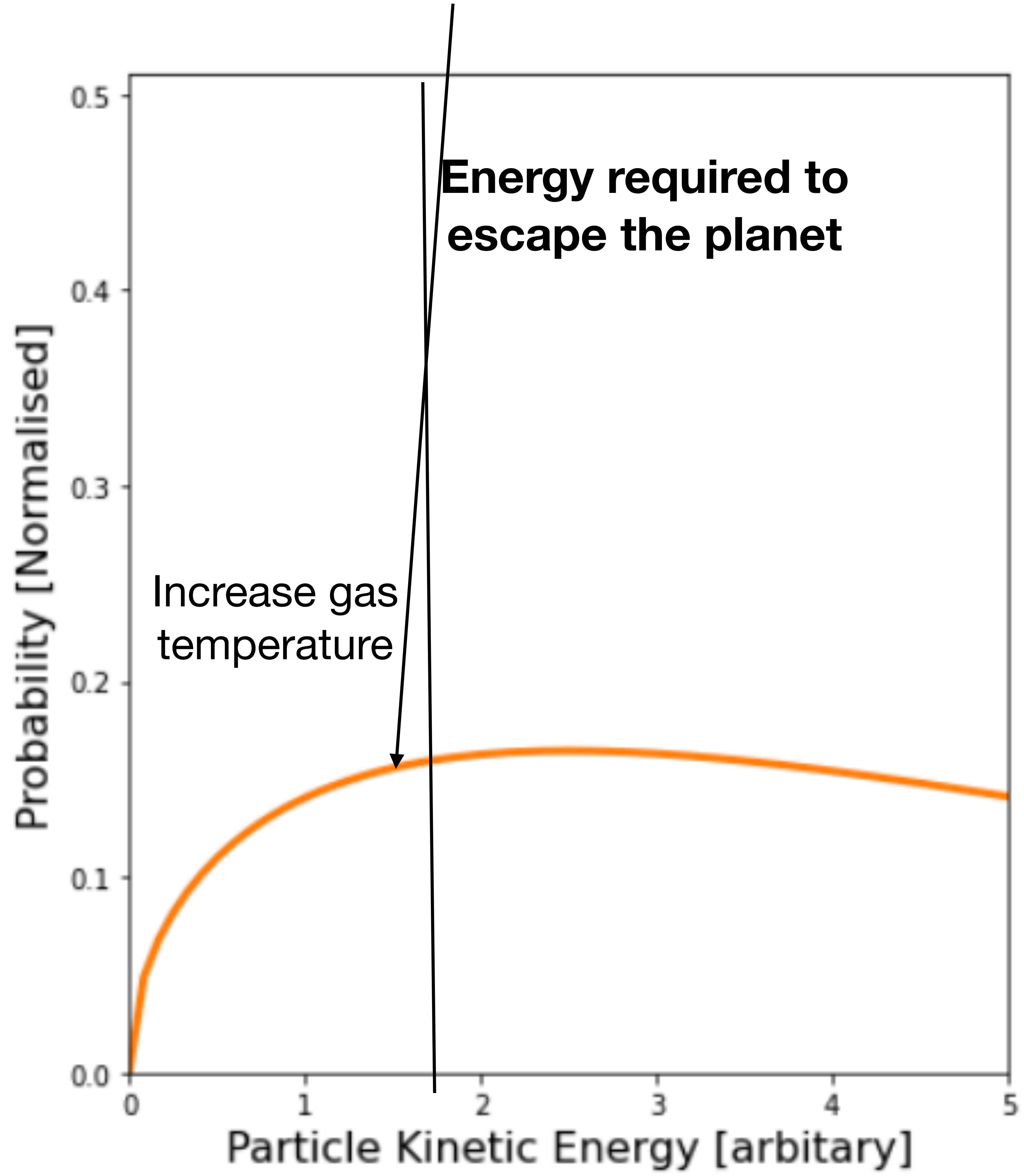


Bulk of particles can escape: **Collisional Hydrodynamic Escape**



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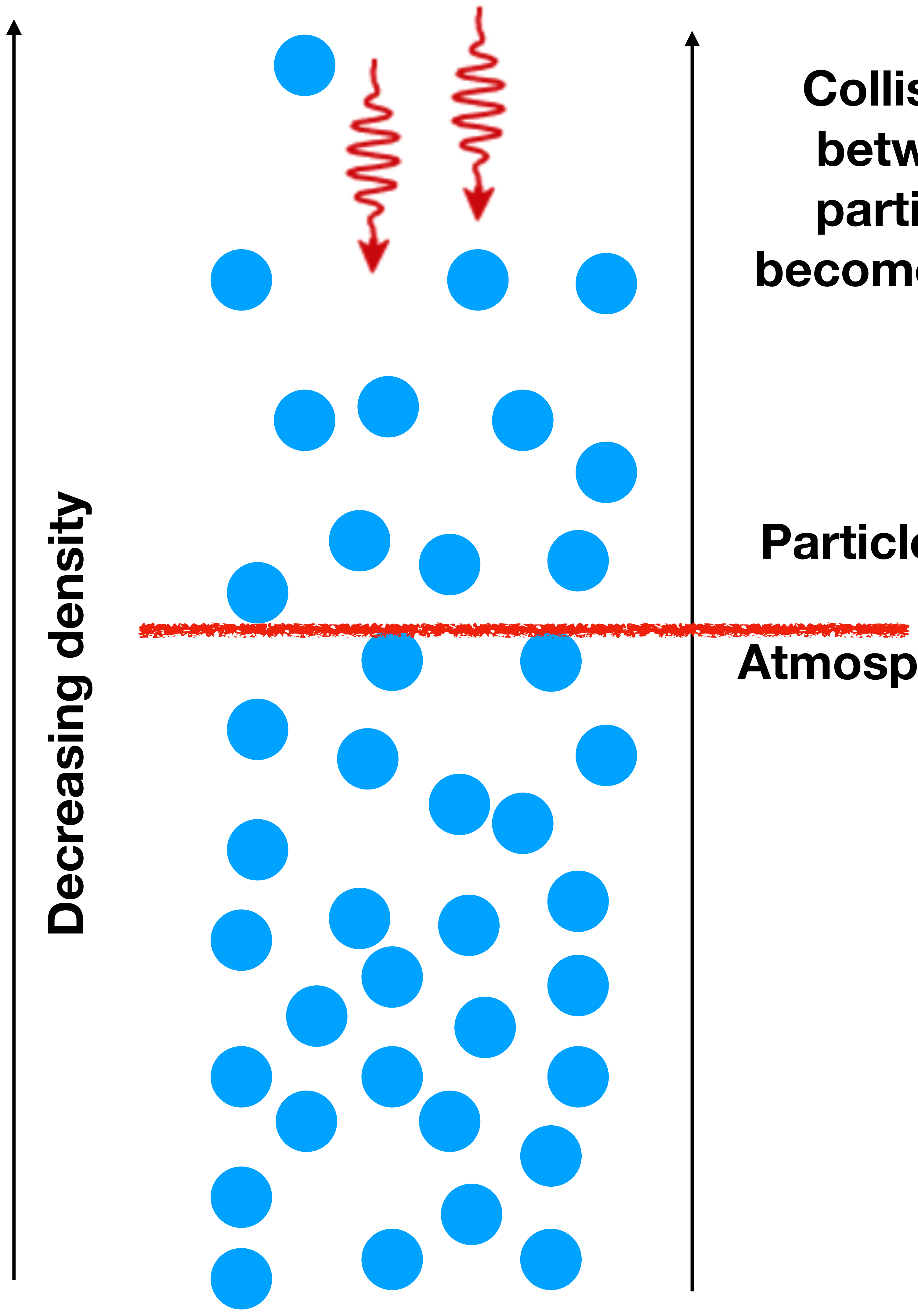

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Particle mean-free path
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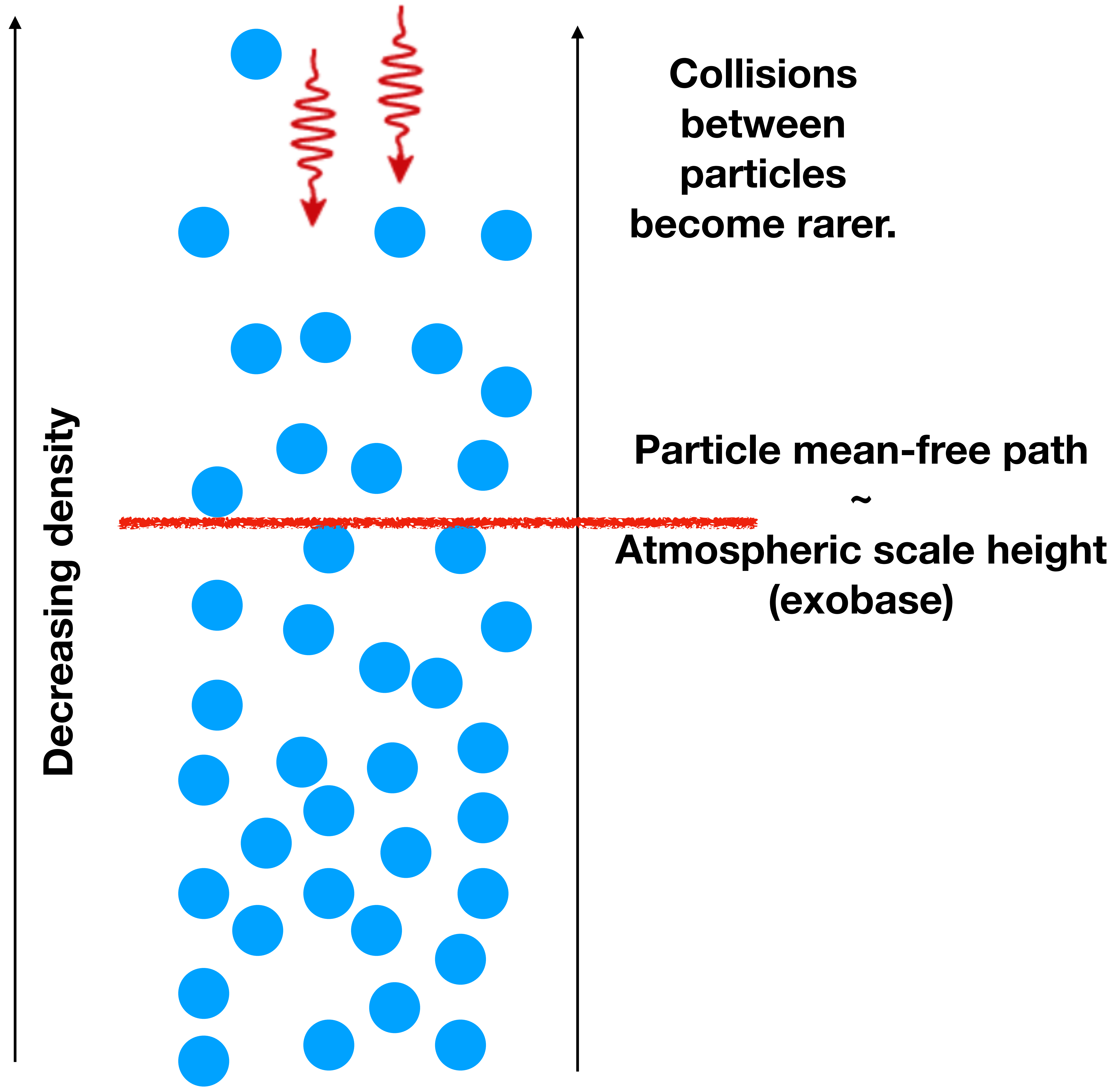
Atmospheric scale height (exobase)

Thermal escape regimes: collisional vs collisionless, an intuitive picture…



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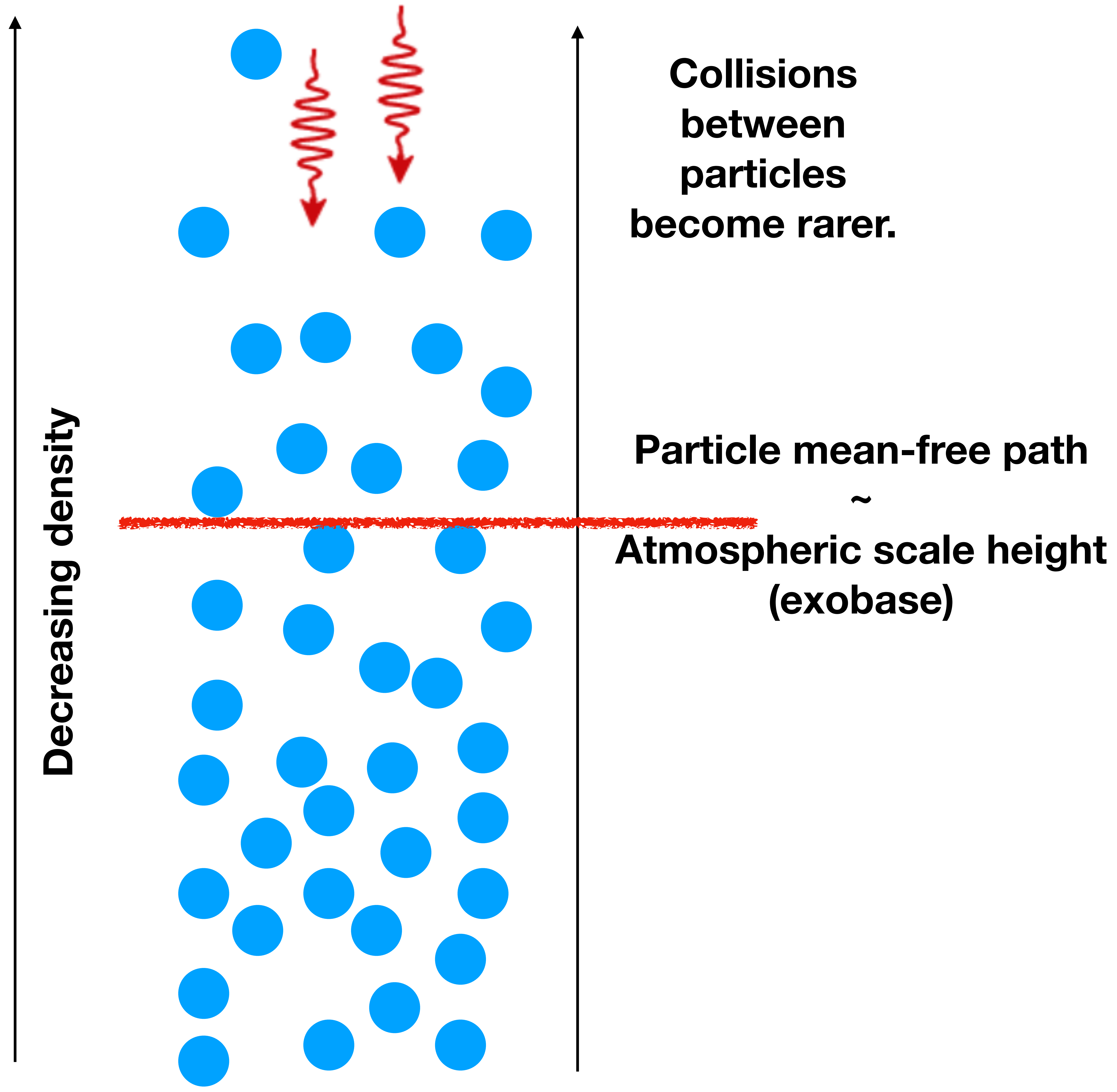

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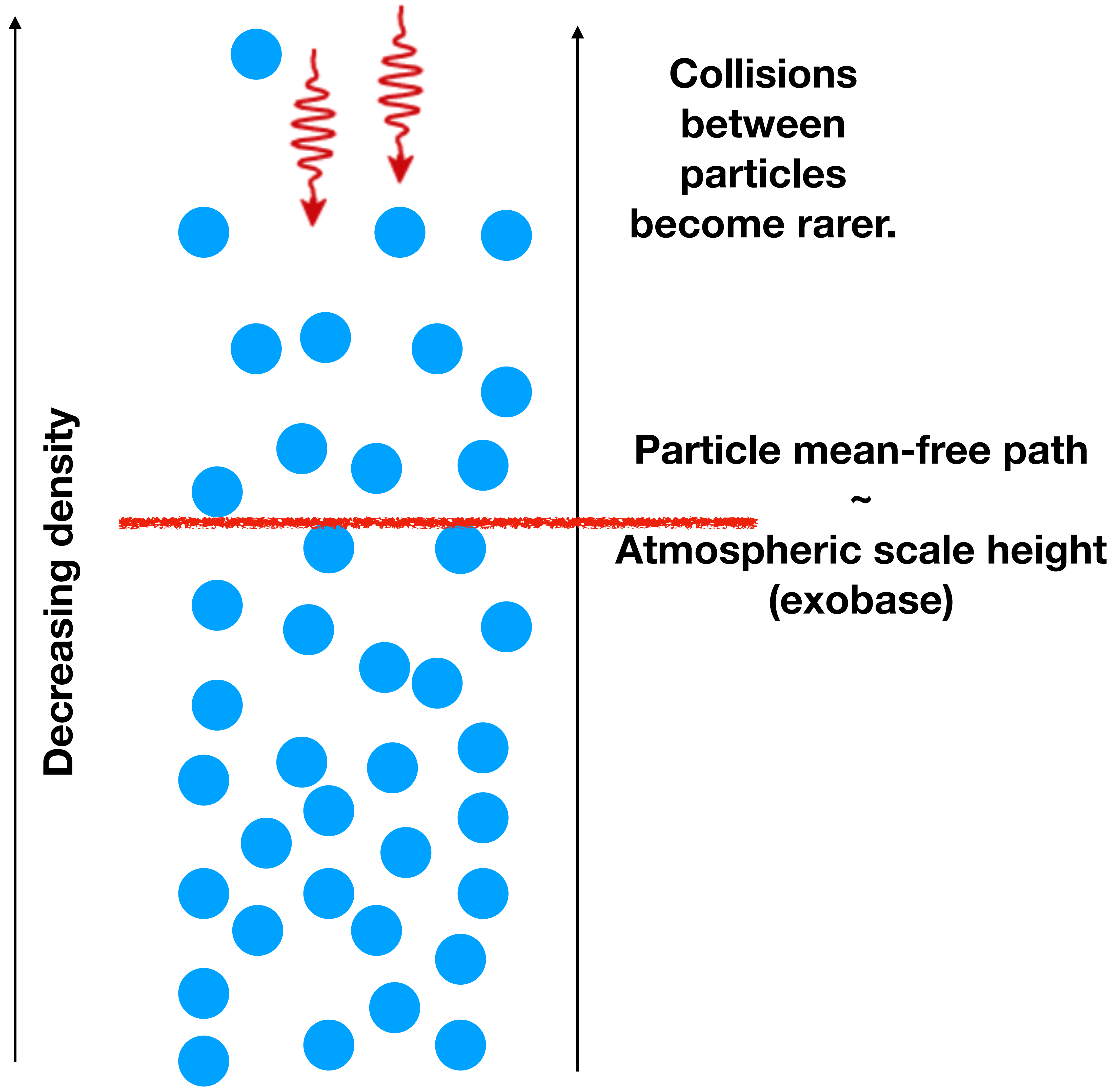

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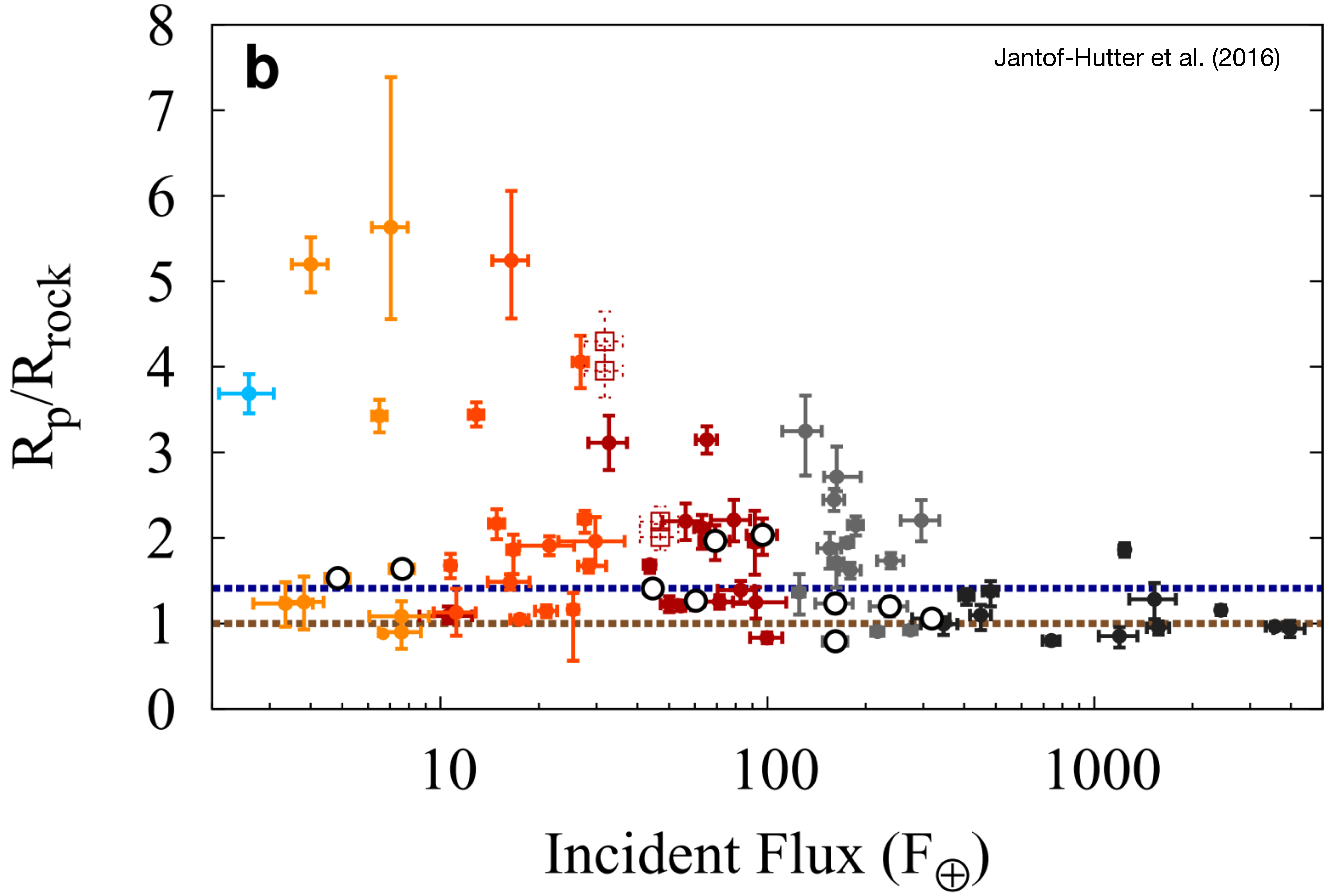
- Hydrodynamic escape occurs for hot, low-density planets with ionized regions.

Close-in Exoplanets



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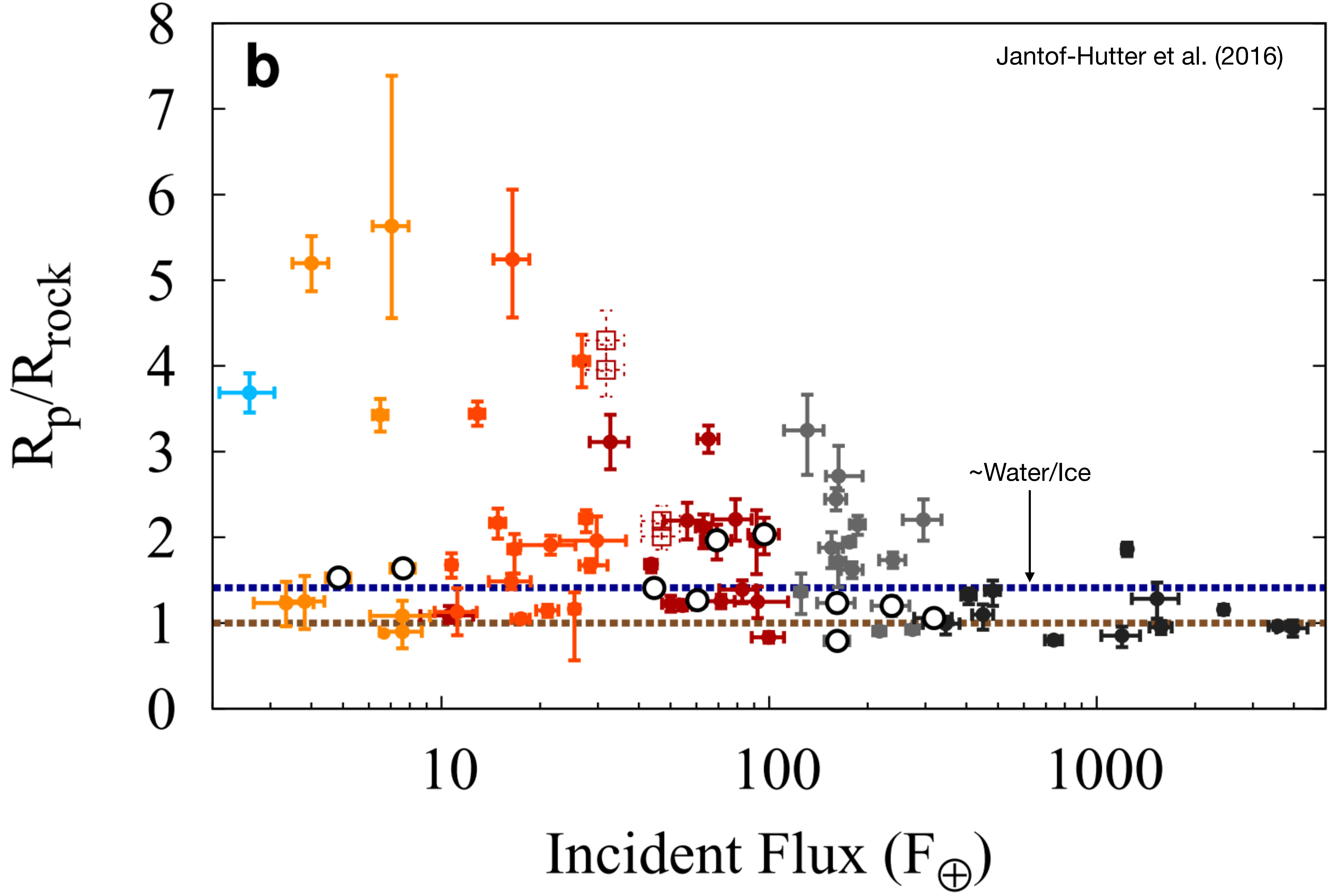

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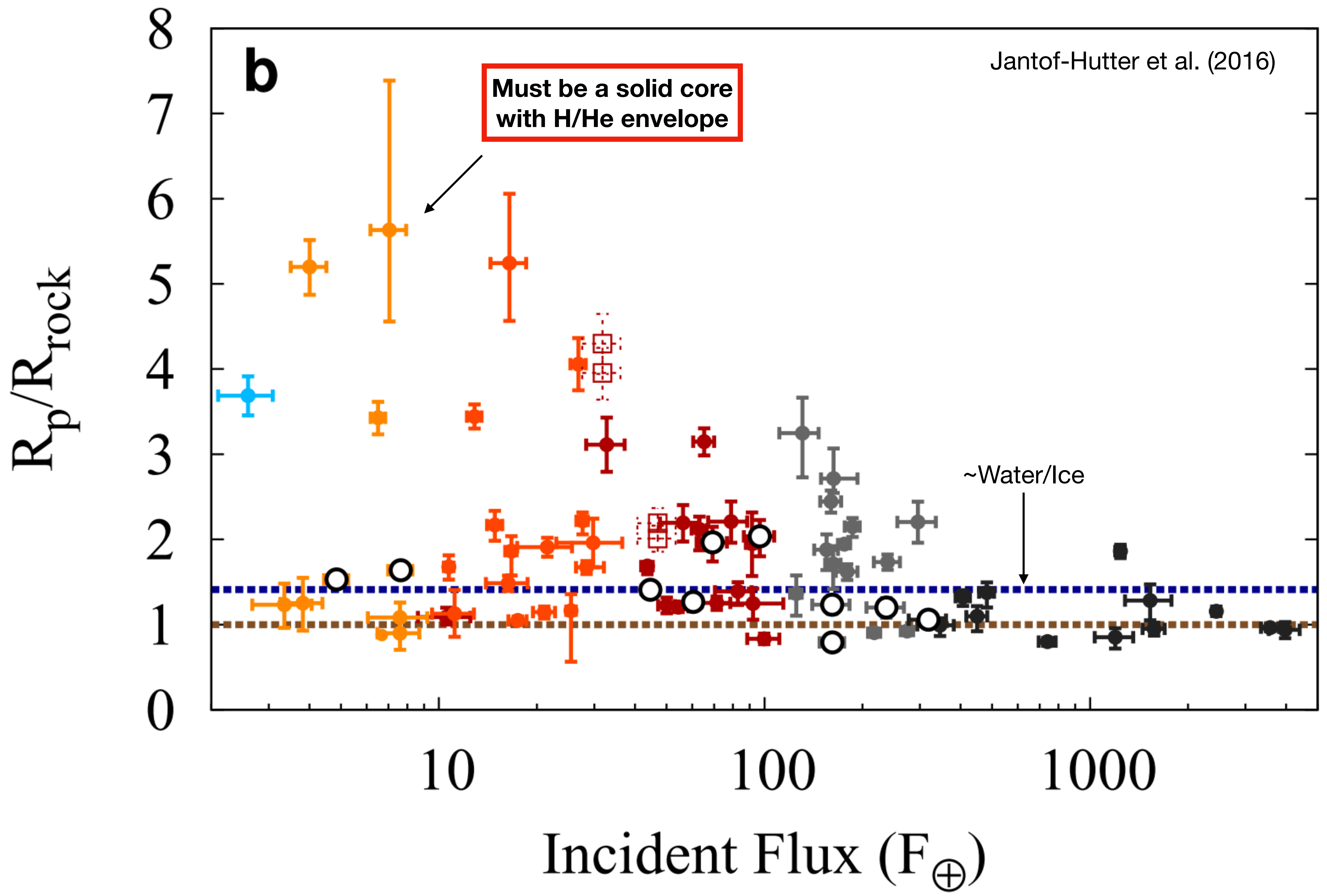

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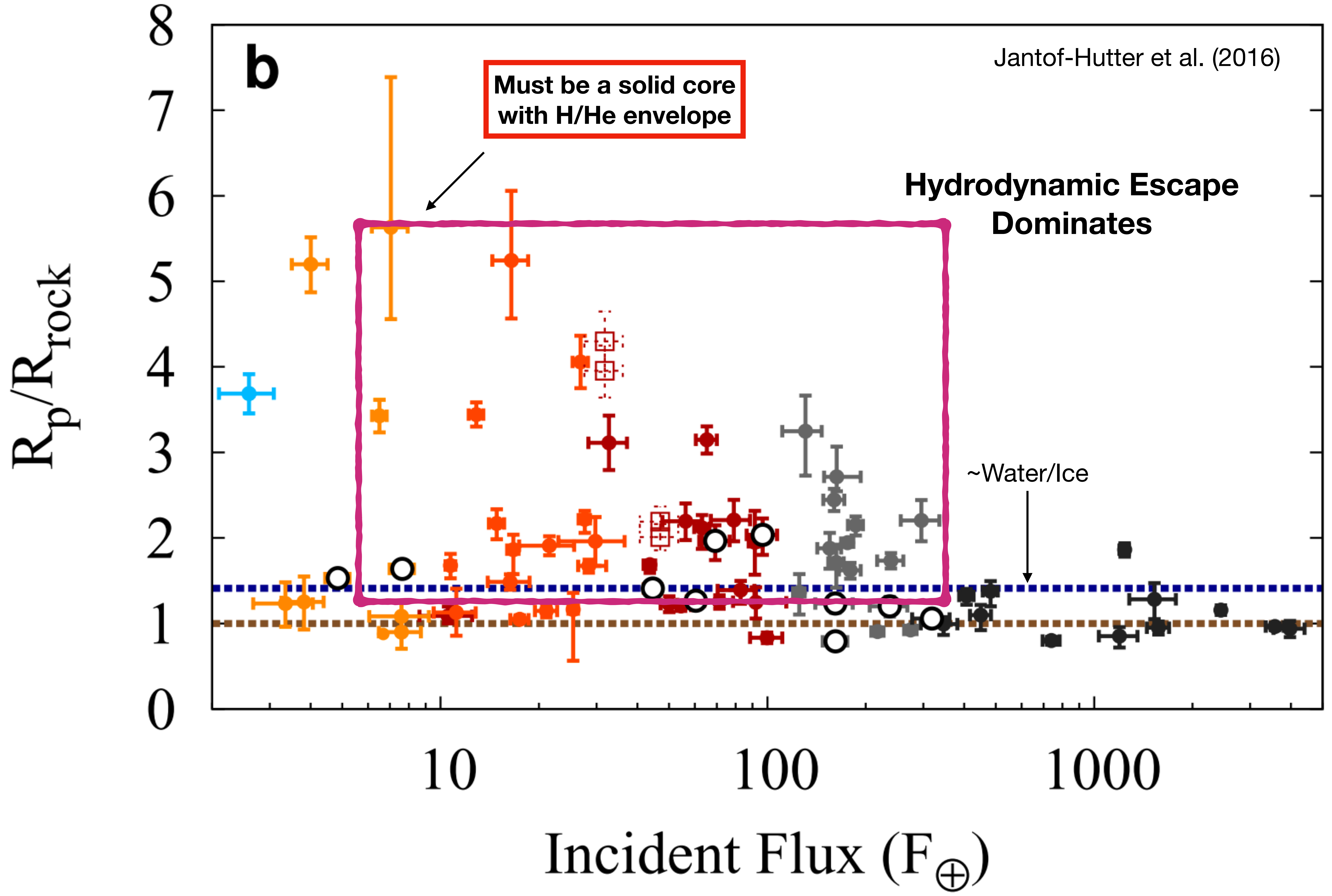


Break: questions?

Intuitive insights

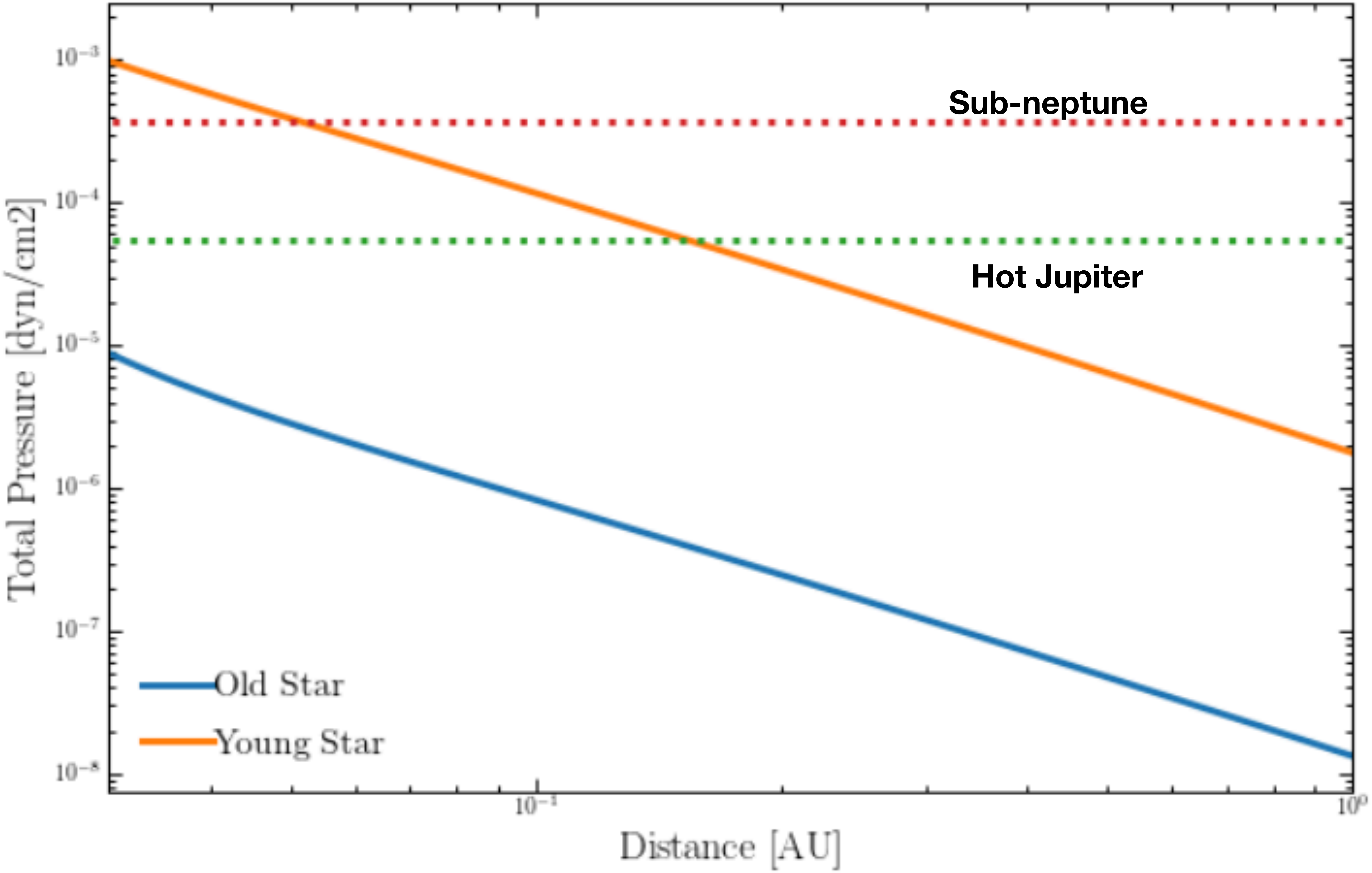
- Hydrodynamic escape roughly occurs when the thermal velocity of gas exceeds the escape velocity before the gas becomes collision less.
- Since hydrodynamic escape removes the bulk of the fluid, other escape processes cannot play a role.

Assumptions

- Assume gas can be treated as a continuum fluid.
- Gas particles follow the Maxwell-Boltzmann distribution.
- Check *a posteriori* that approximation holds: collisional mean-free path is smaller than the fluid scale length.

Hydrodynamic escape: must overcome any external pressure

Stellar wind vs planet pressure



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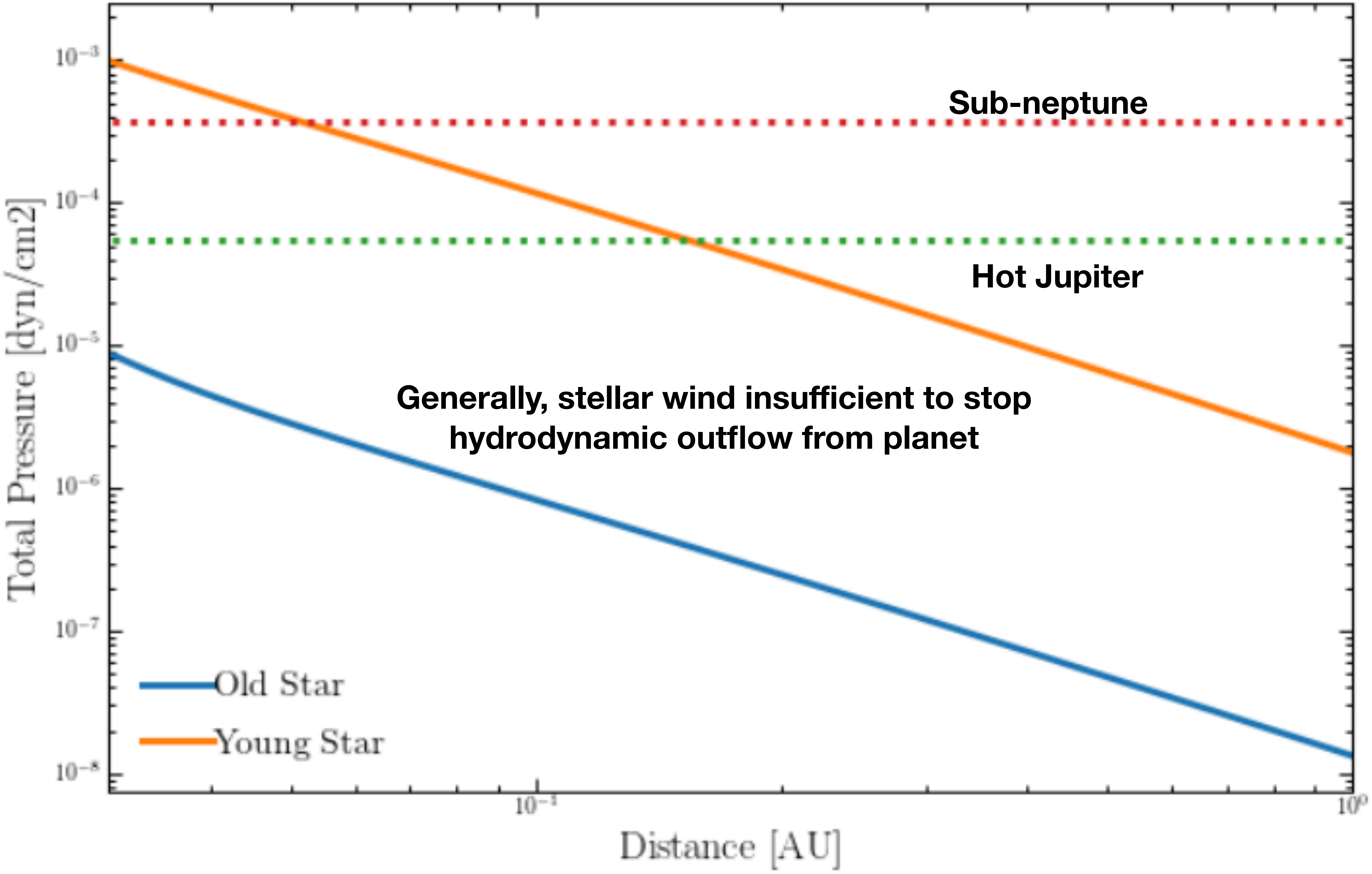
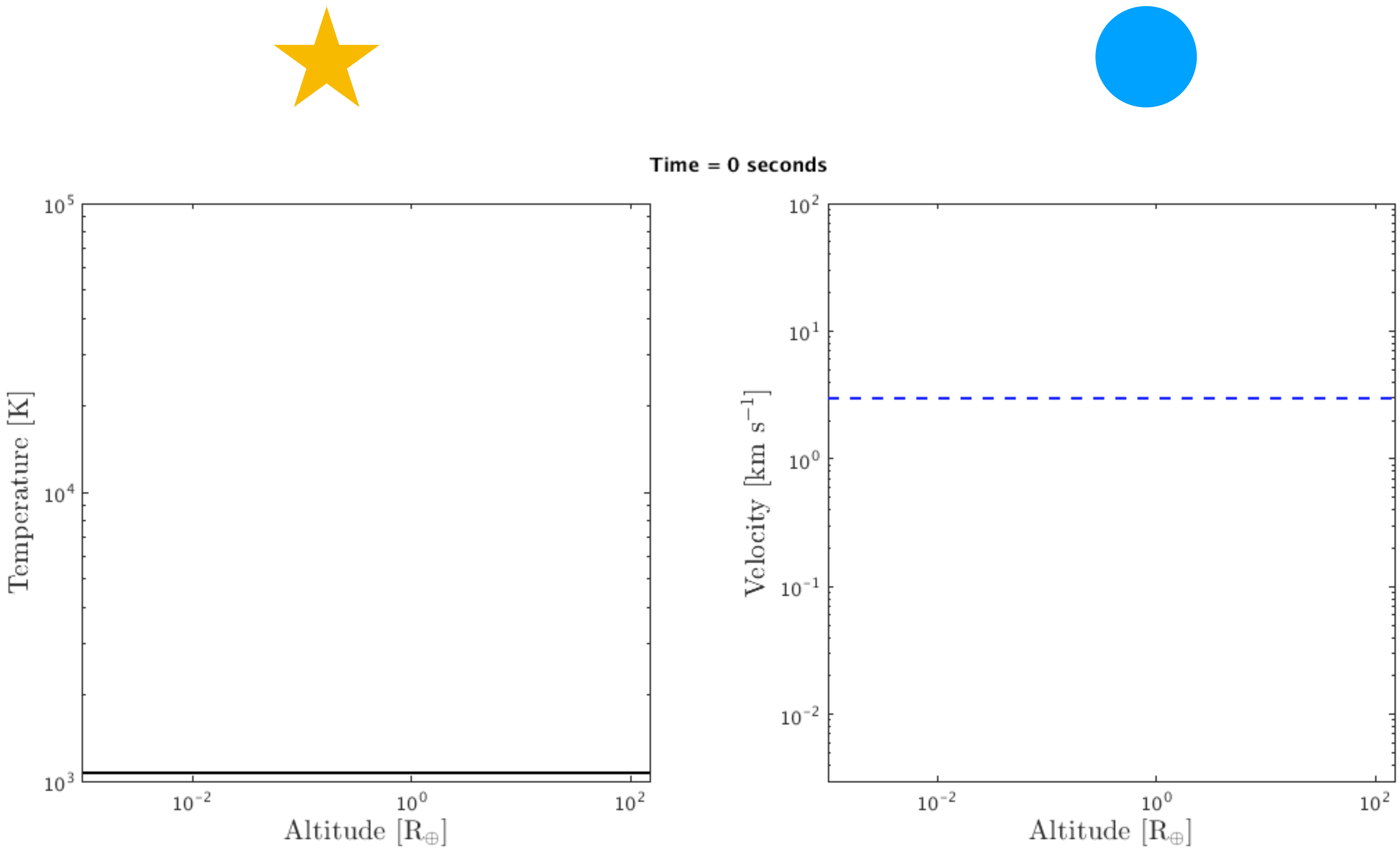


A hydrodynamic approach



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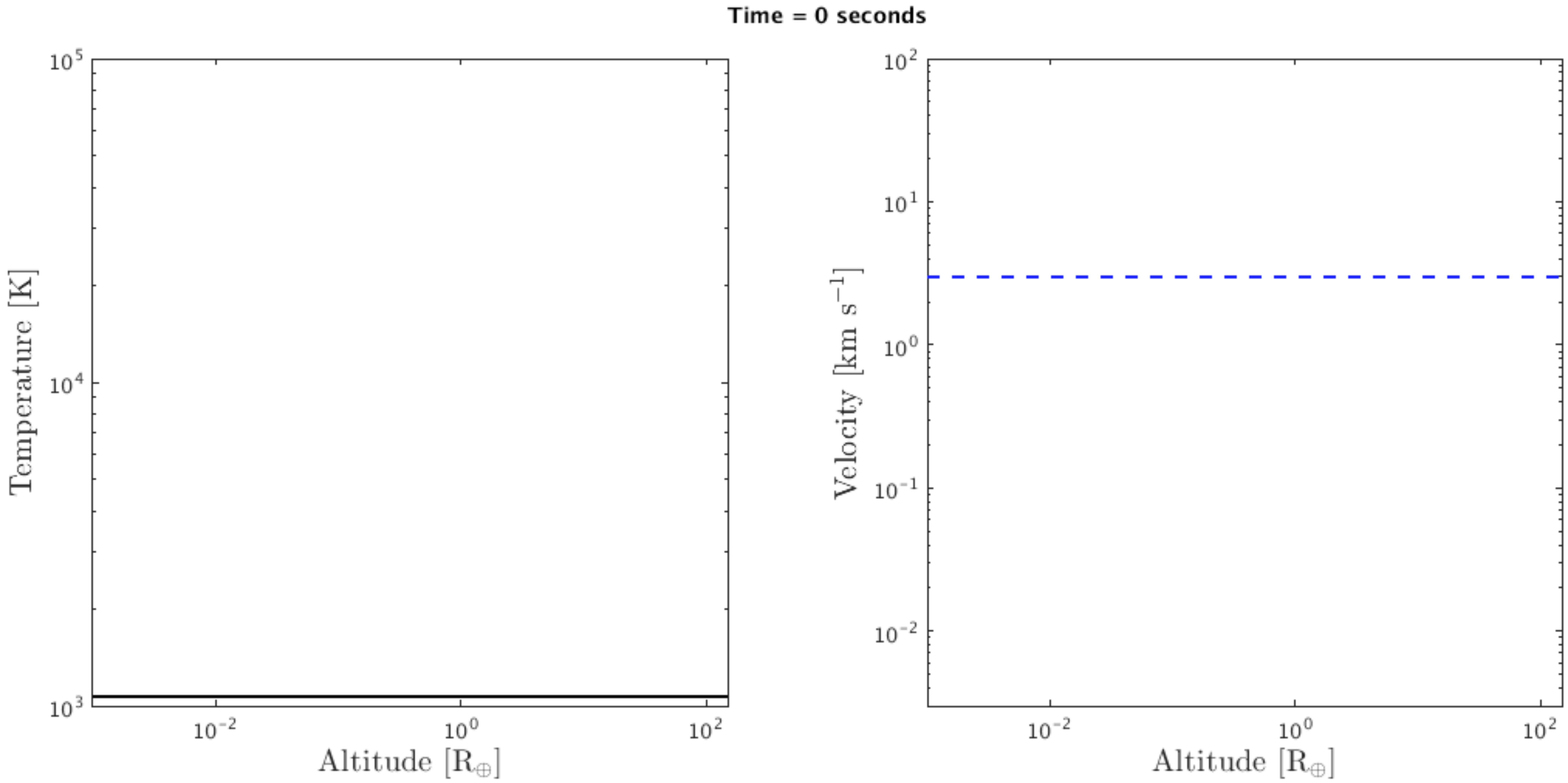

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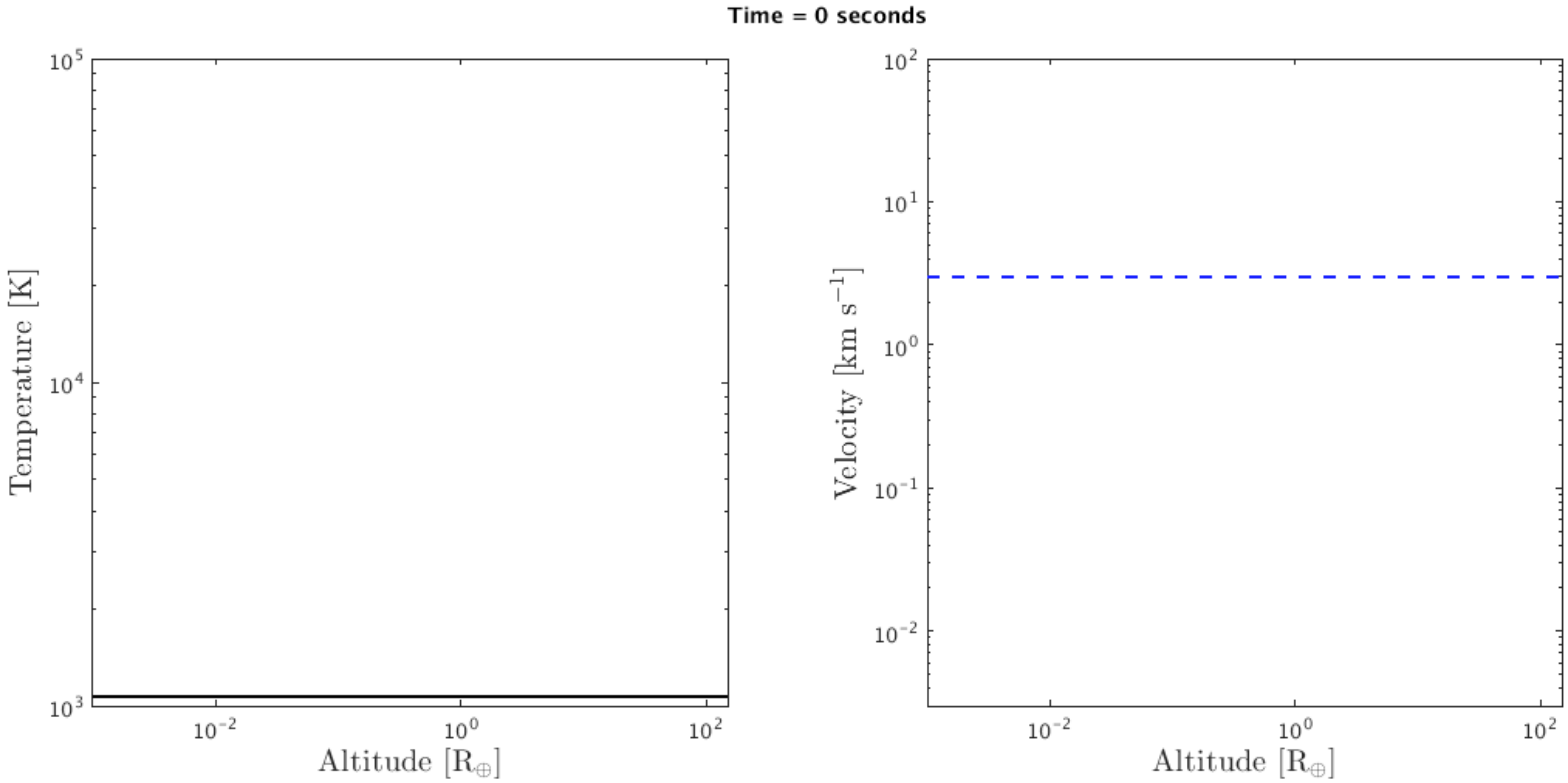

Importance of sonic-point

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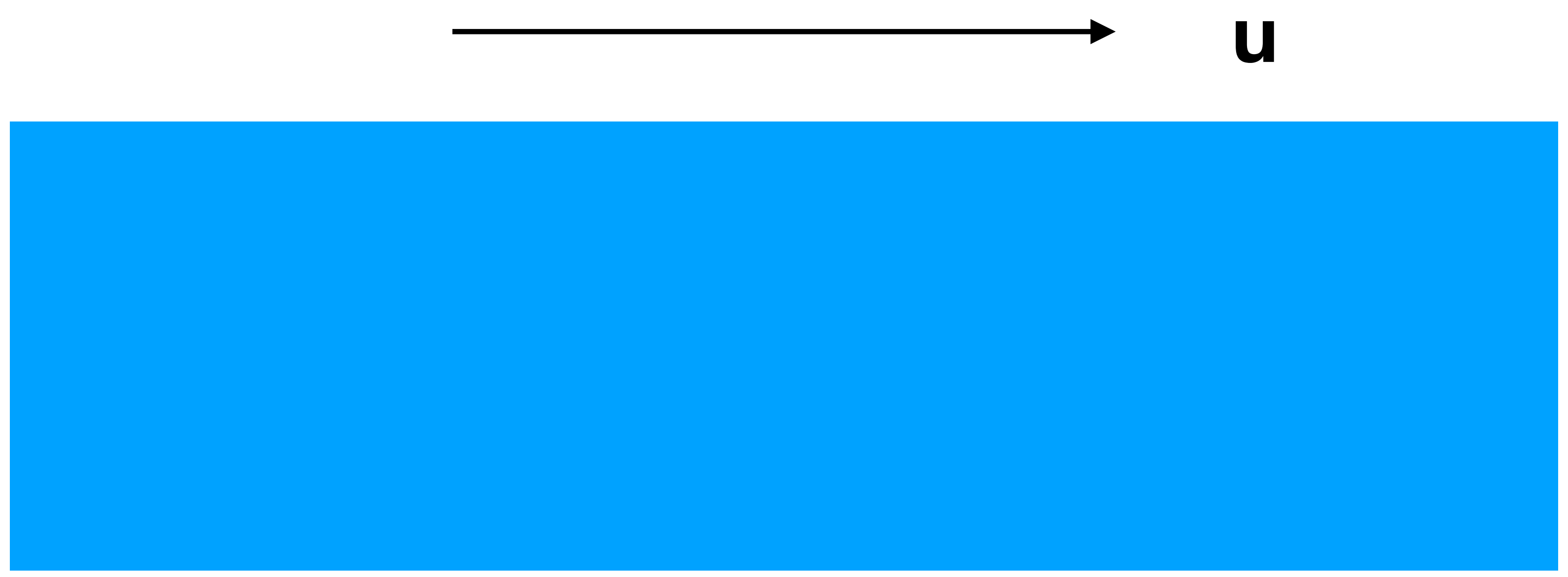

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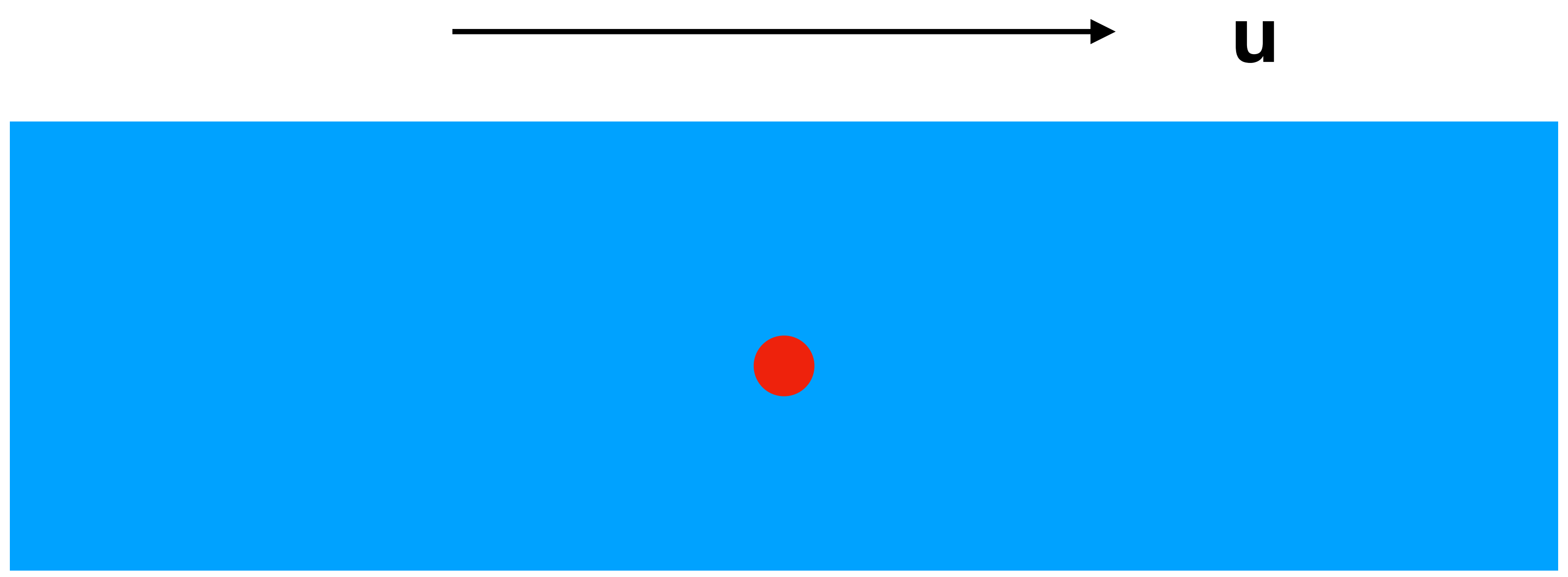

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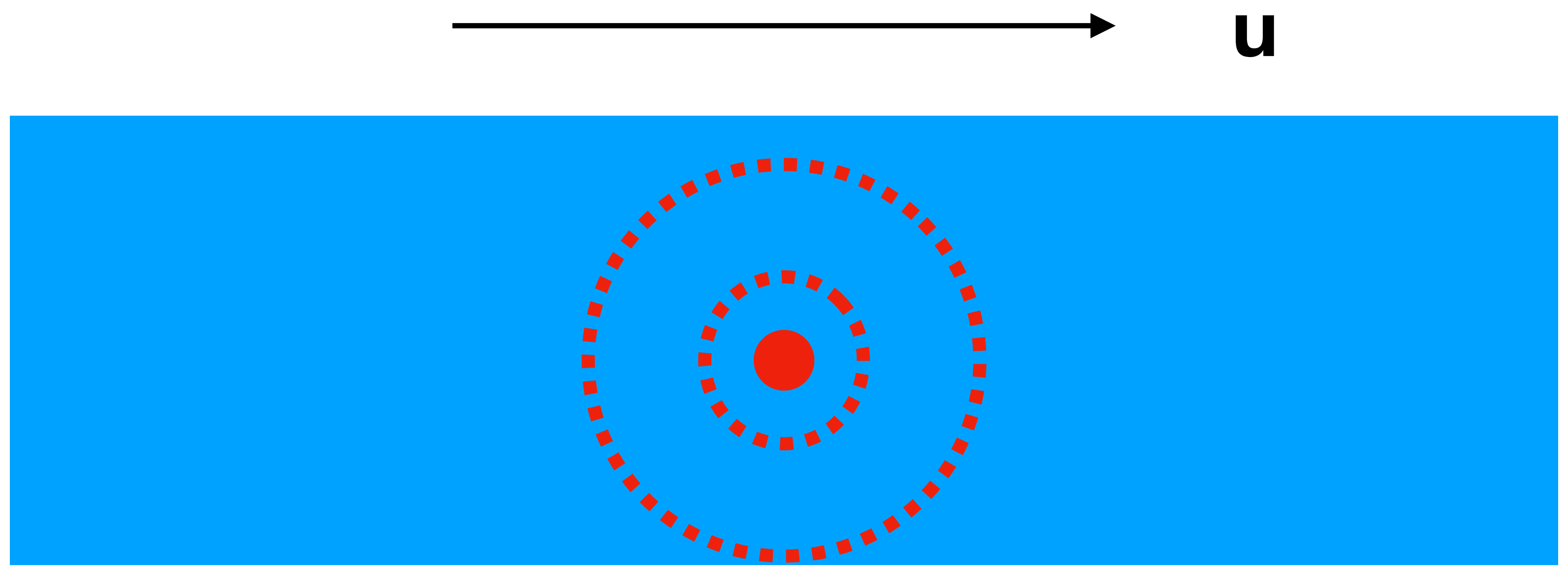

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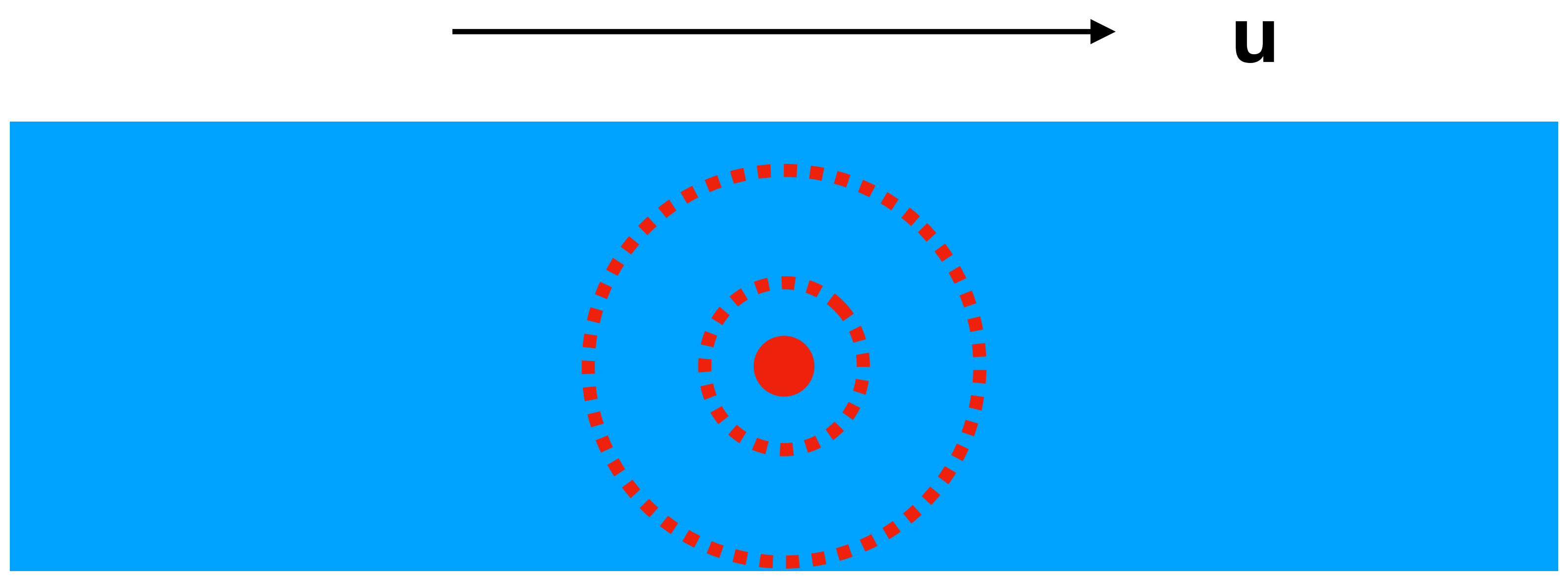

Disturbance moves at the sound-speed (in the co-moving frame)

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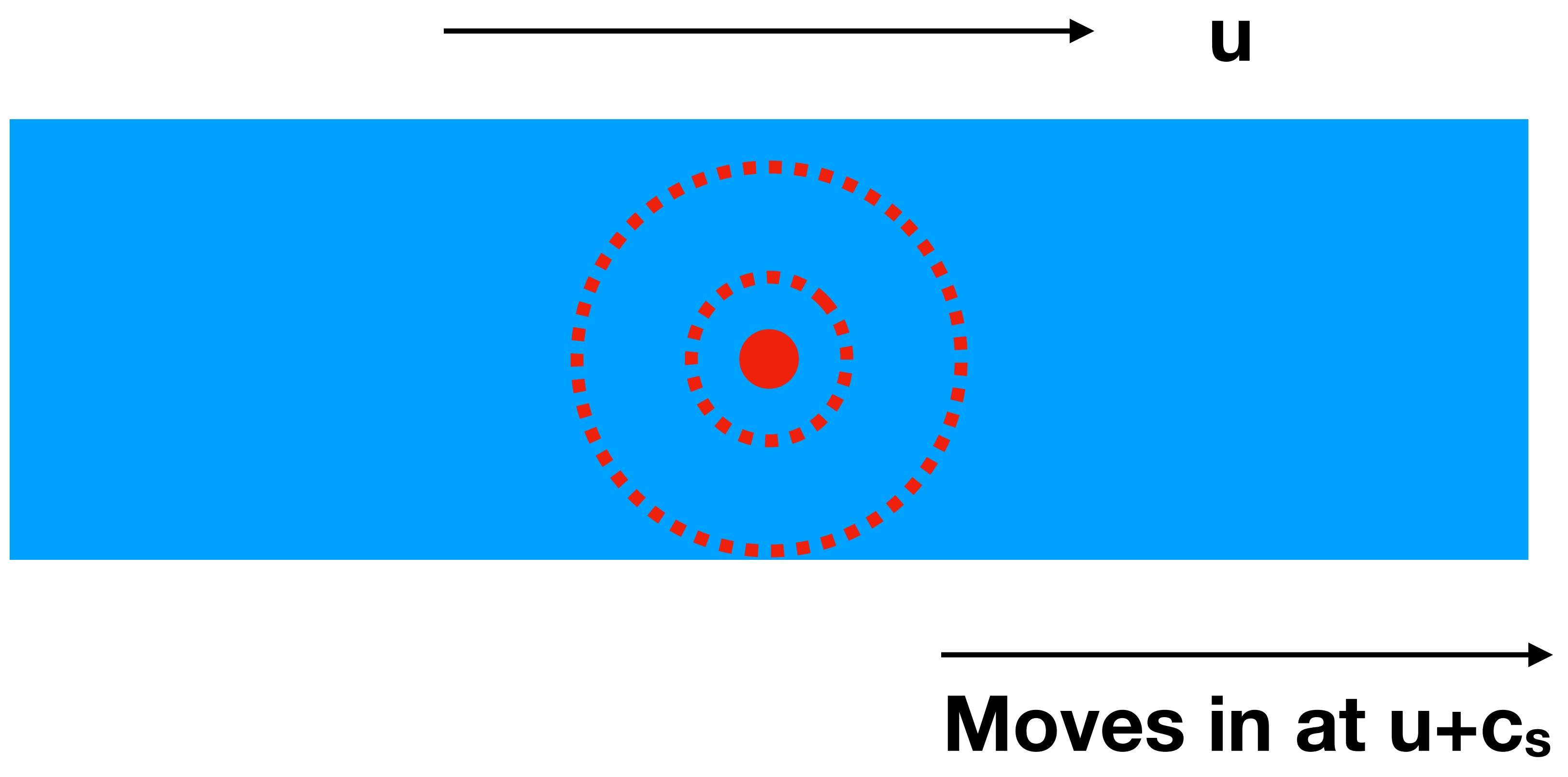

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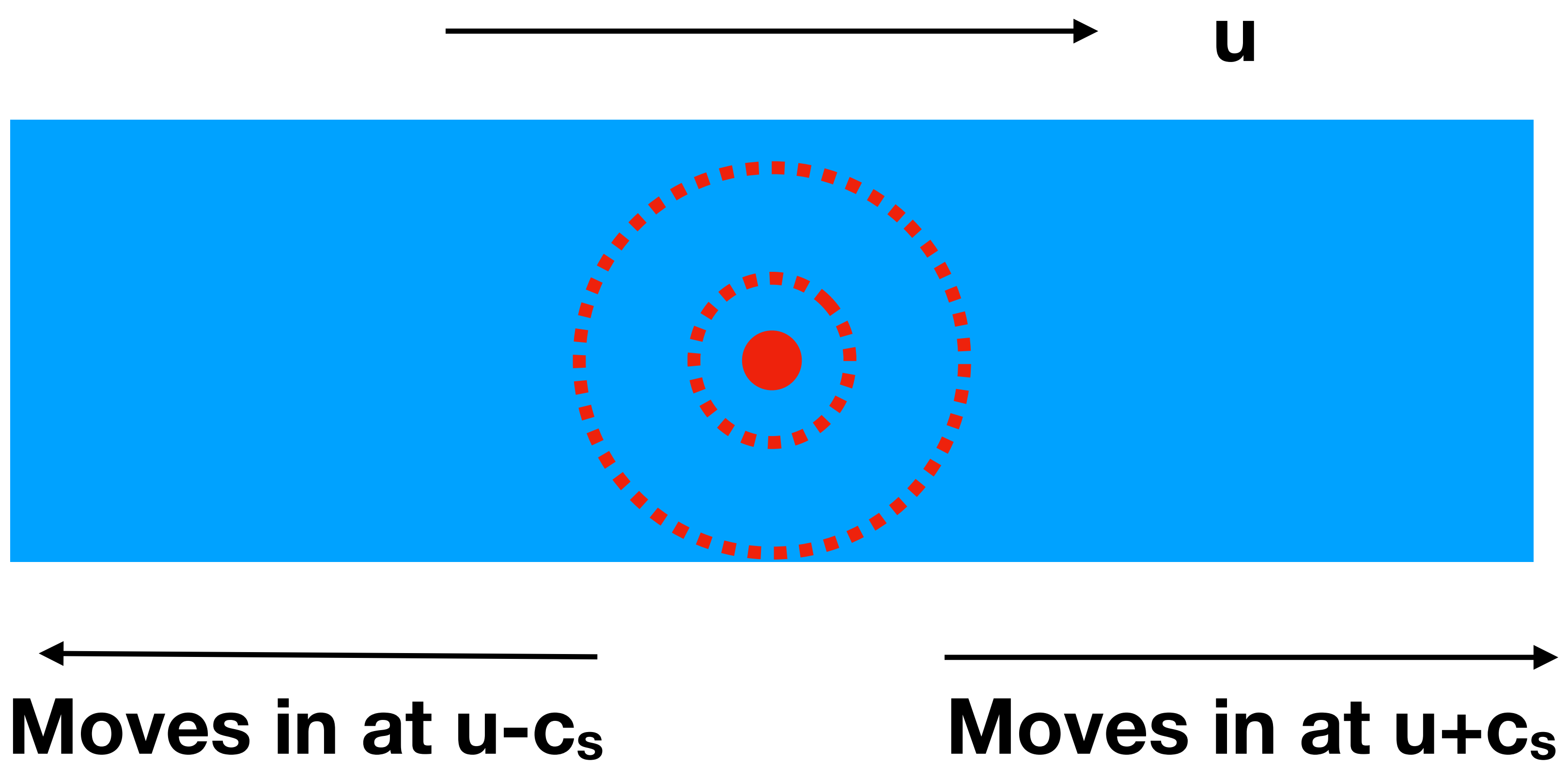

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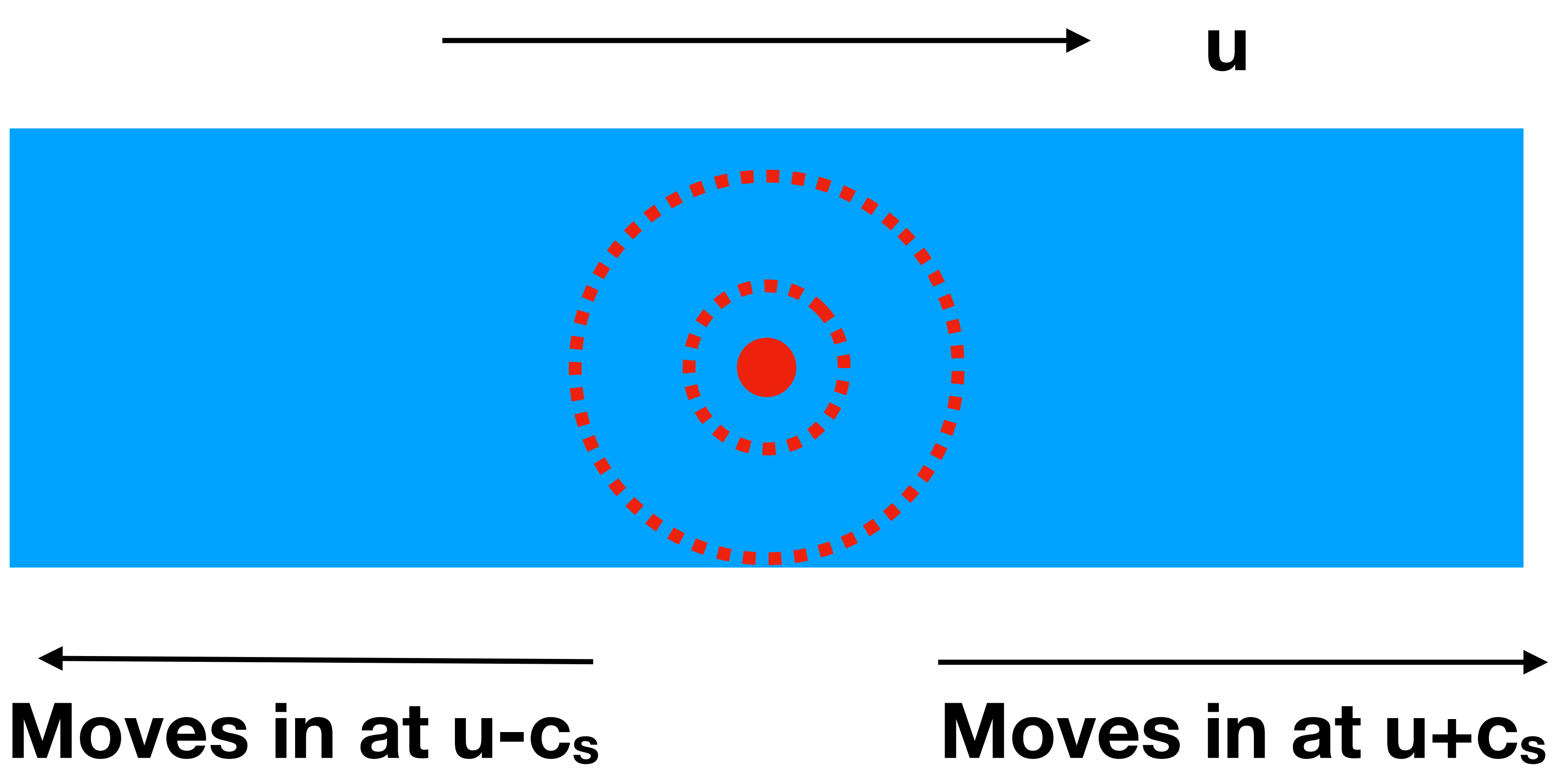

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So if $u>c_s$, information of this perturbation cannot propagate upstream (toward the planet)

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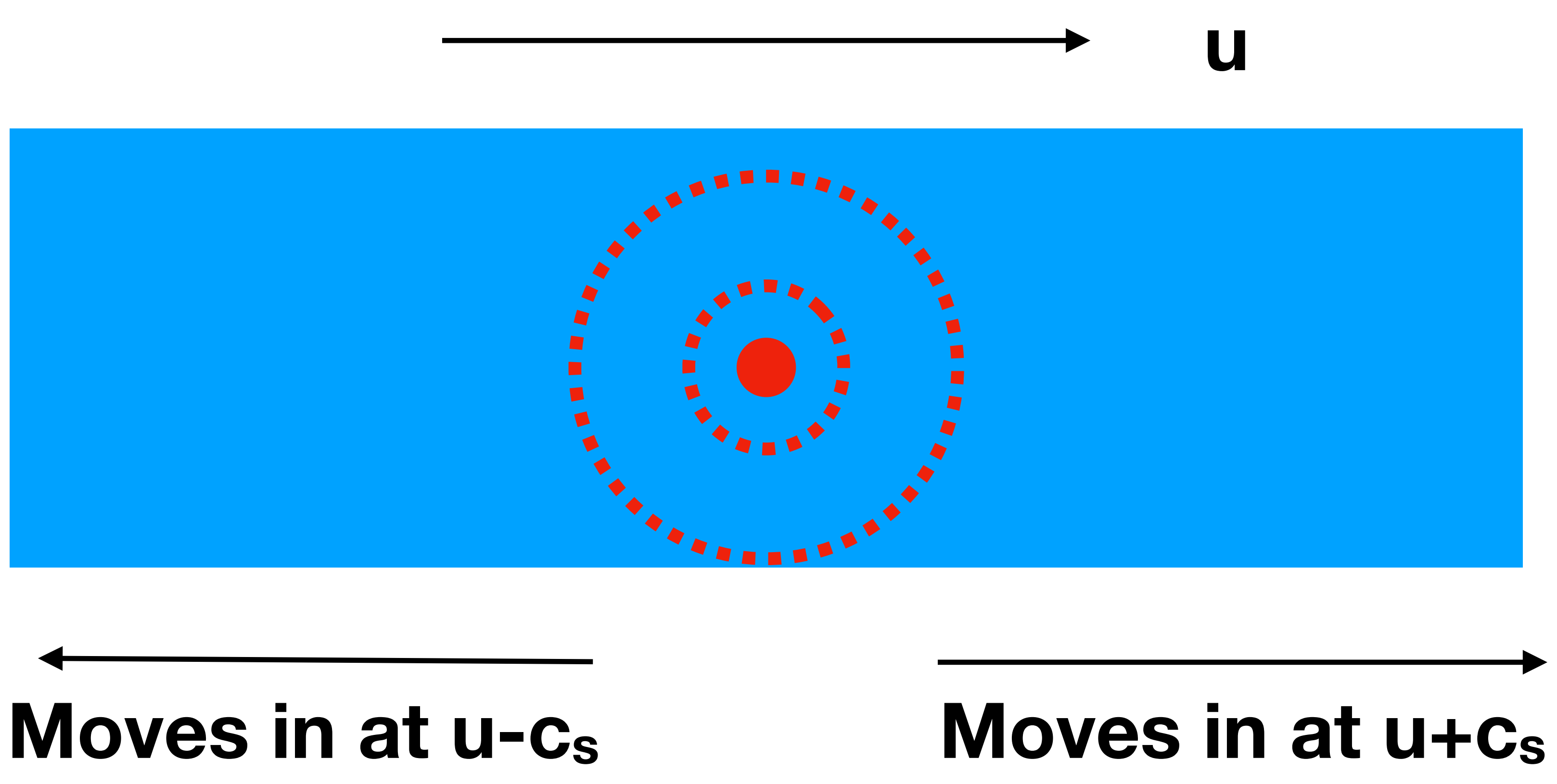


Disturbance moves at the sound-speed (in the co-moving frame)

So if $u>c_s$, information of this perturbation cannot propagate upstream (toward the planet)

So anything that happens outside the sonic point cannot affect the outflow or the mass-loss rate.

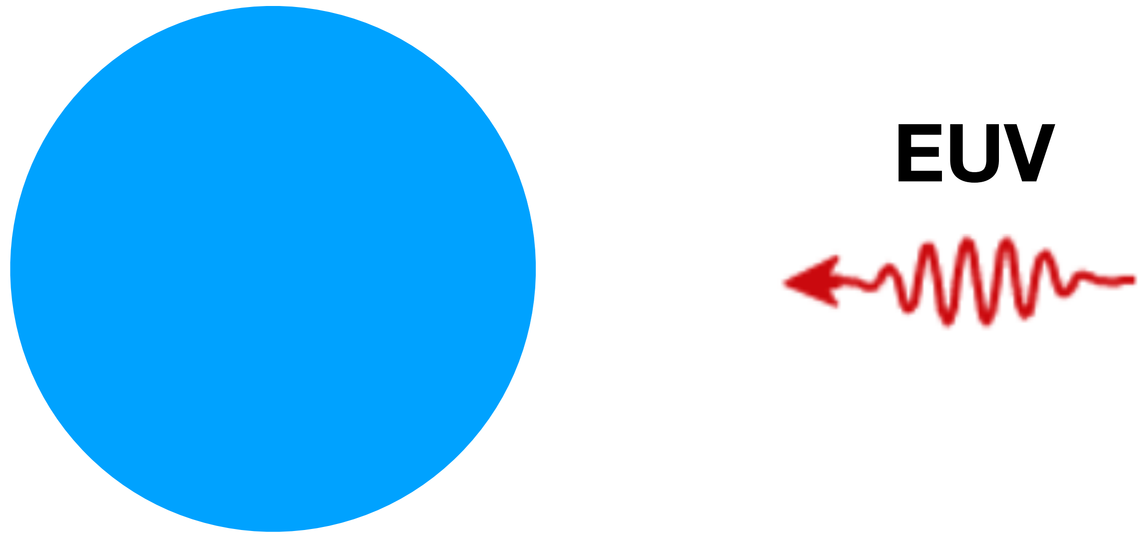
Transition between hydrodynamic and Jeans escape

- An outflow that becomes collisionless after the sonic point has no effect on the hydrodynamic outflow.

- An outflow that becomes collisionless before the sonic point can no longer accelerate gas parcels to higher velocities ($u<v_{esc}$), so bulk outflow cannot escape: Jeans Escape.

- The transition between Jeans Escape and hydrodynamic escape is the flow becomes collisionless at the sonic point of the hydrodynamic outflow.

“Energy-limited” photo evaporation



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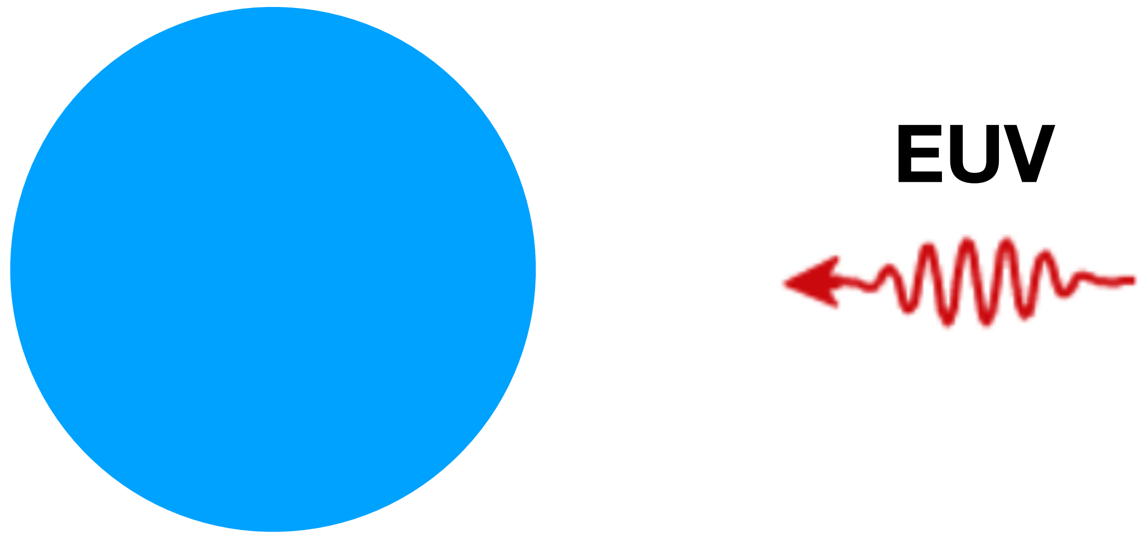

$$\pi R_{XUV}^2 F_* \Delta t$$

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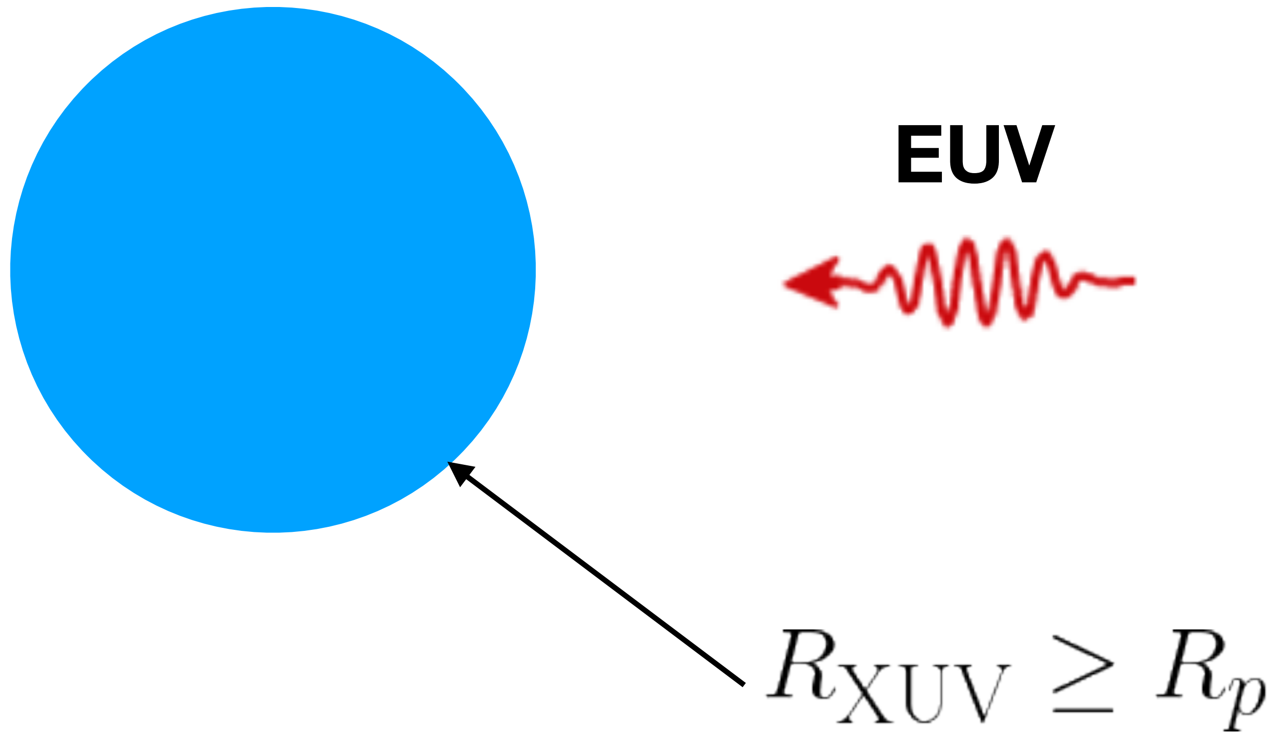

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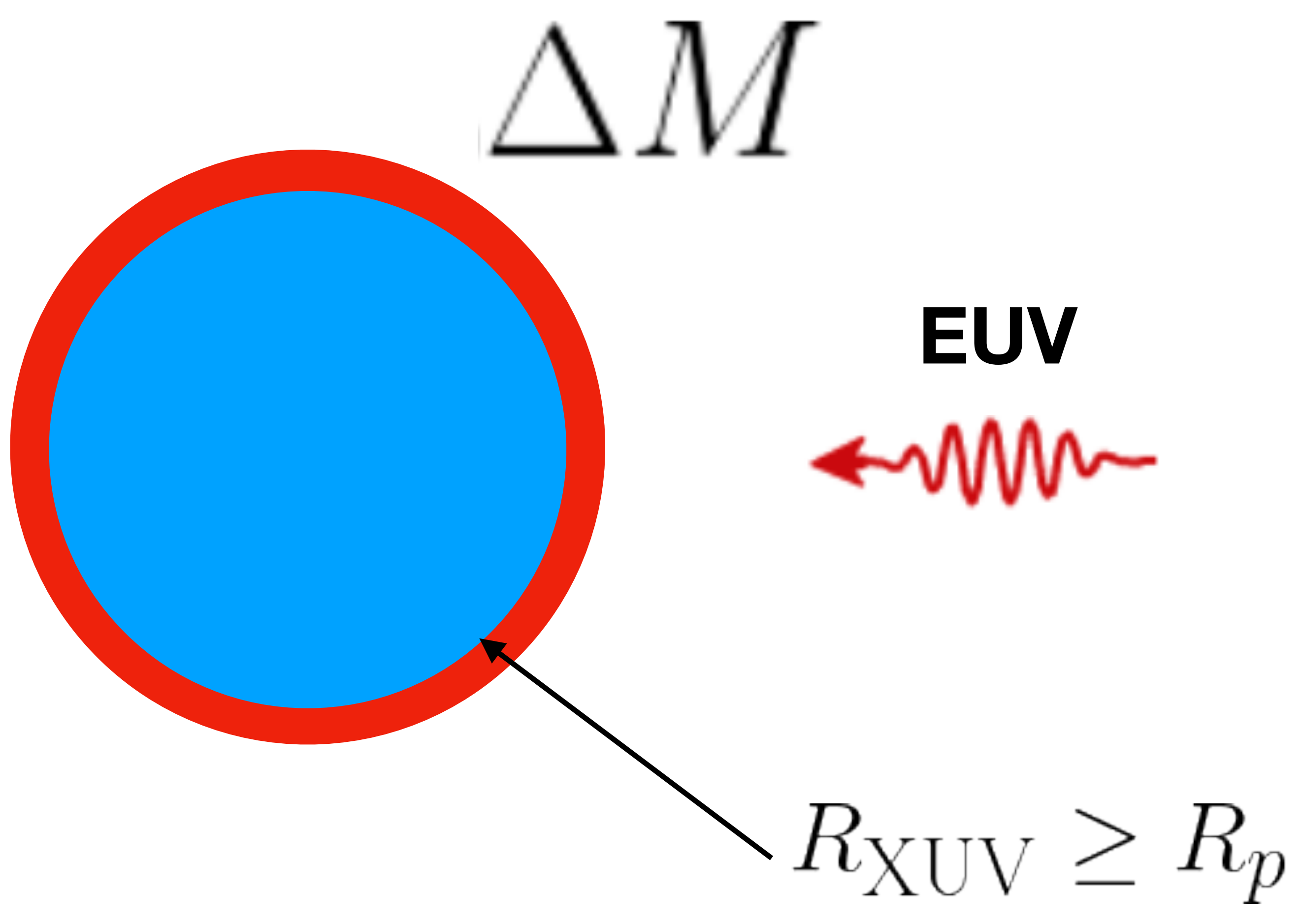

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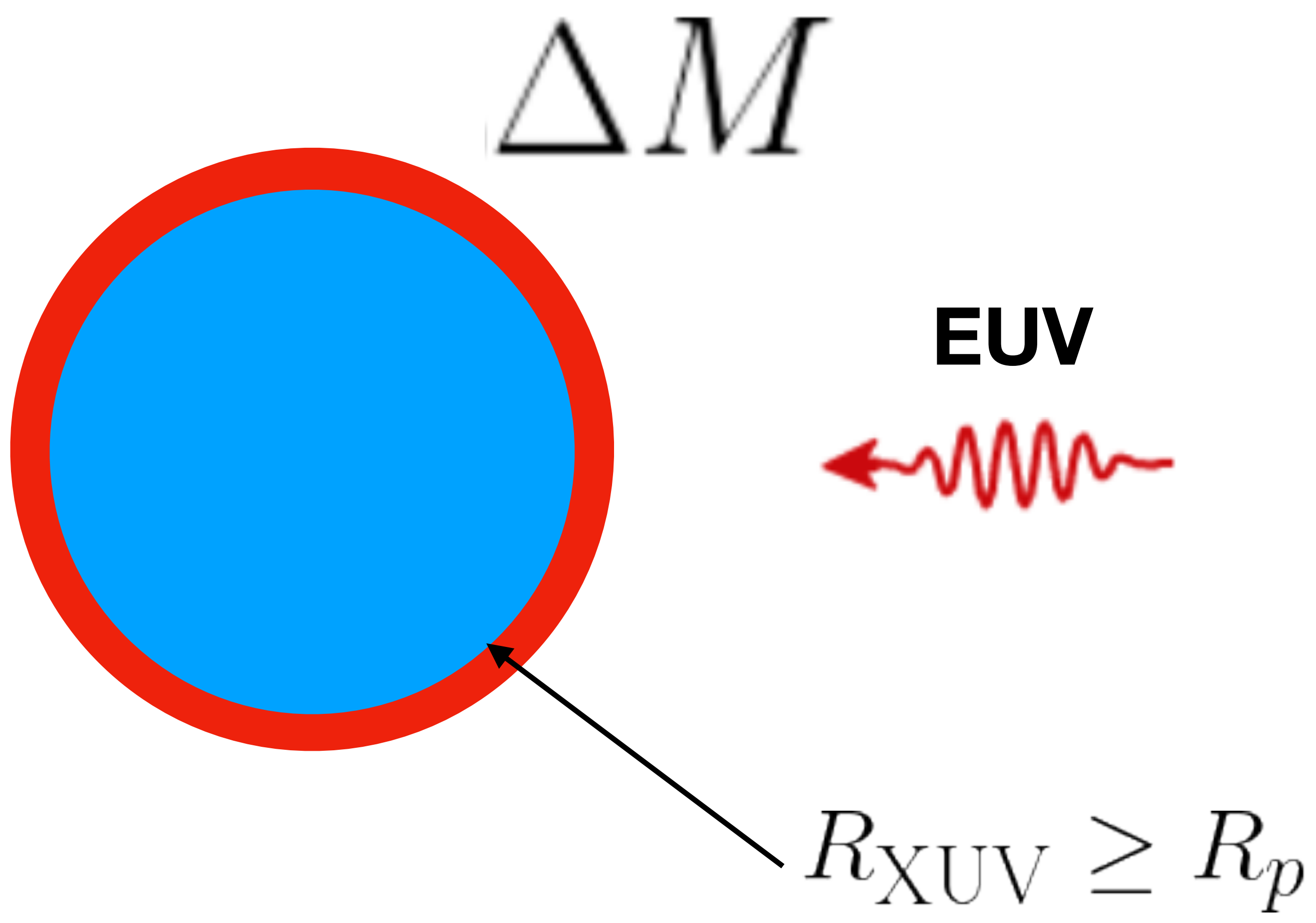

$$\pi R_{XUV}^2 F_* \Delta t \sim \frac{G M_p \Delta M}{R_{\rm XUV}}$$

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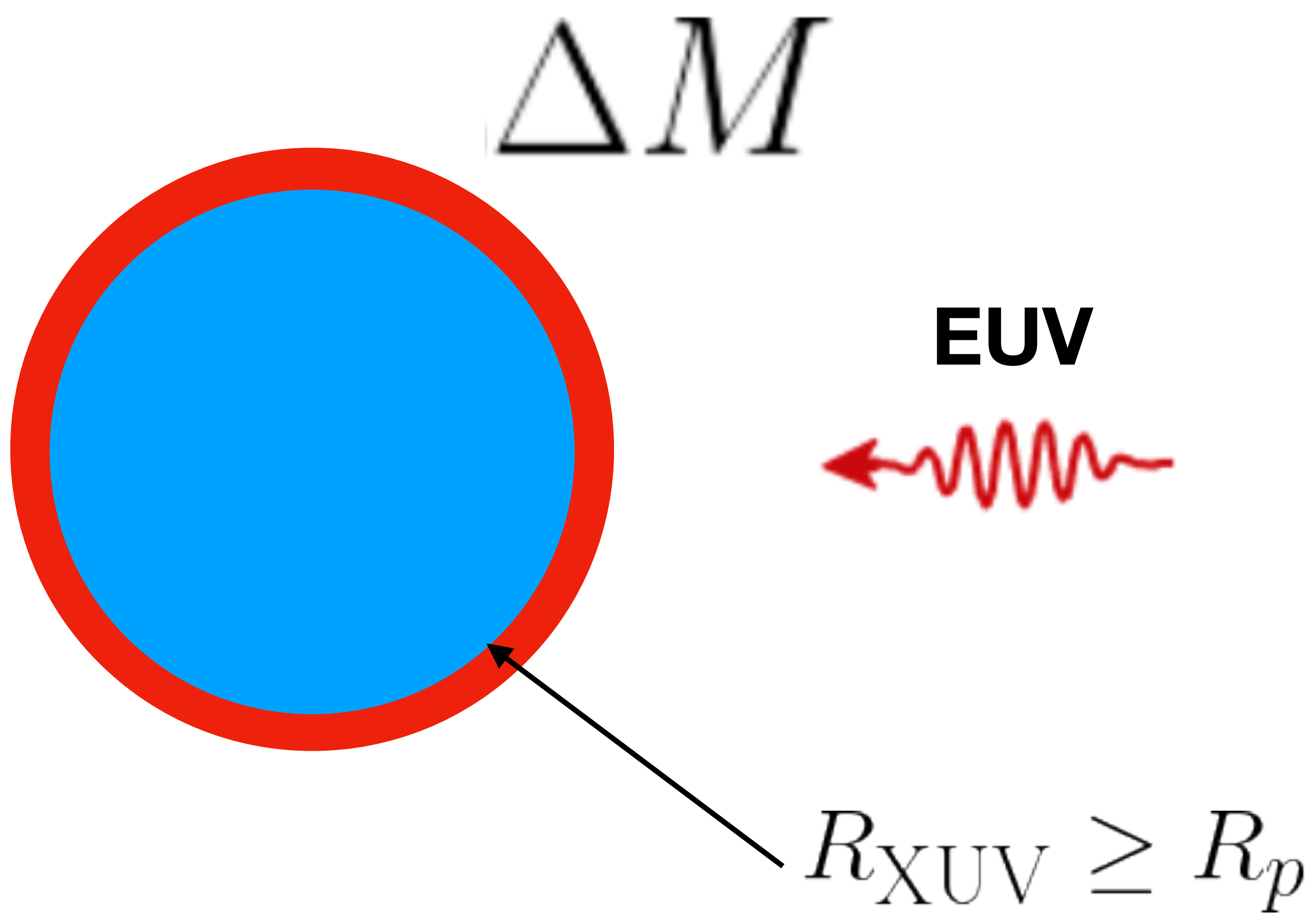

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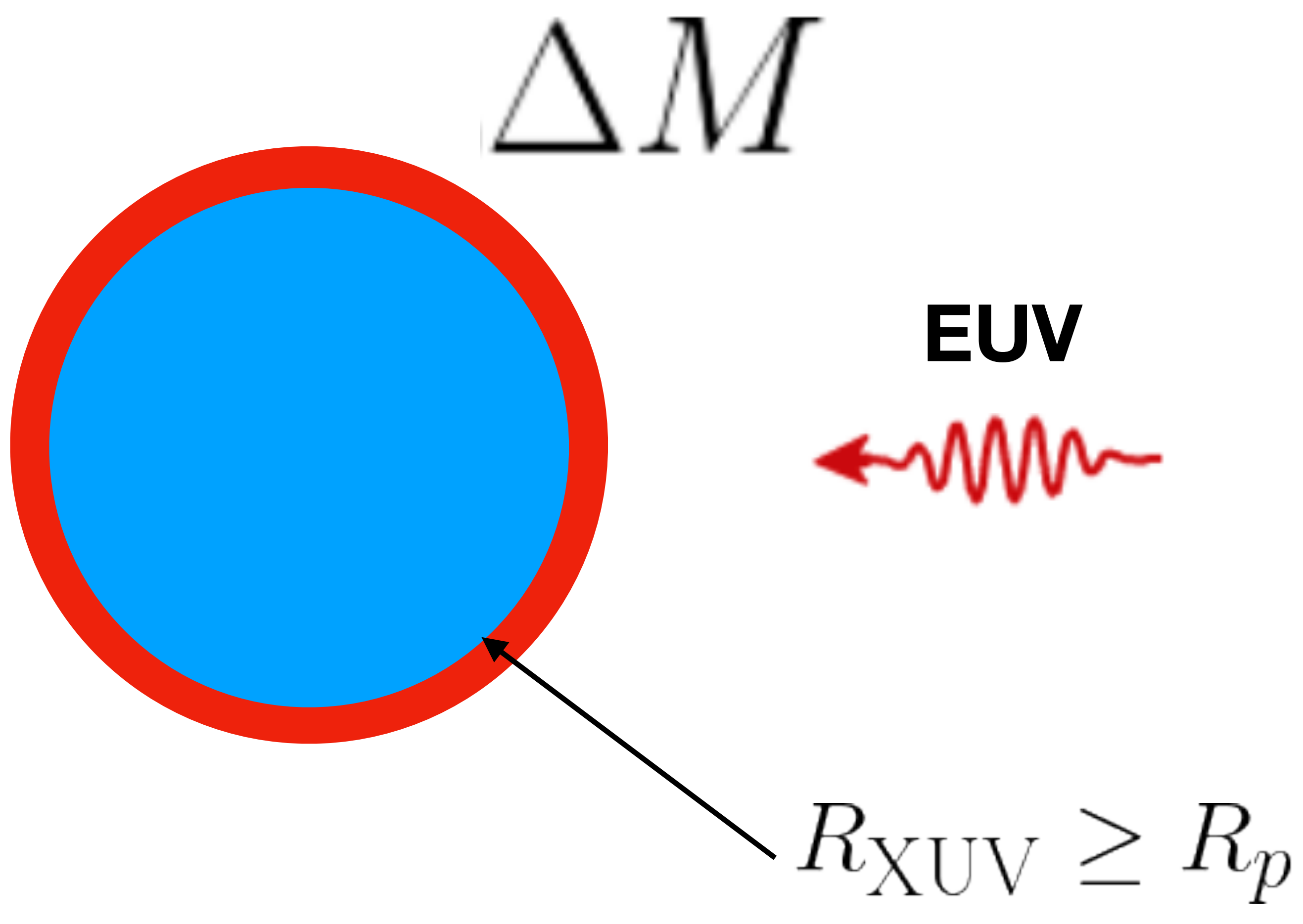

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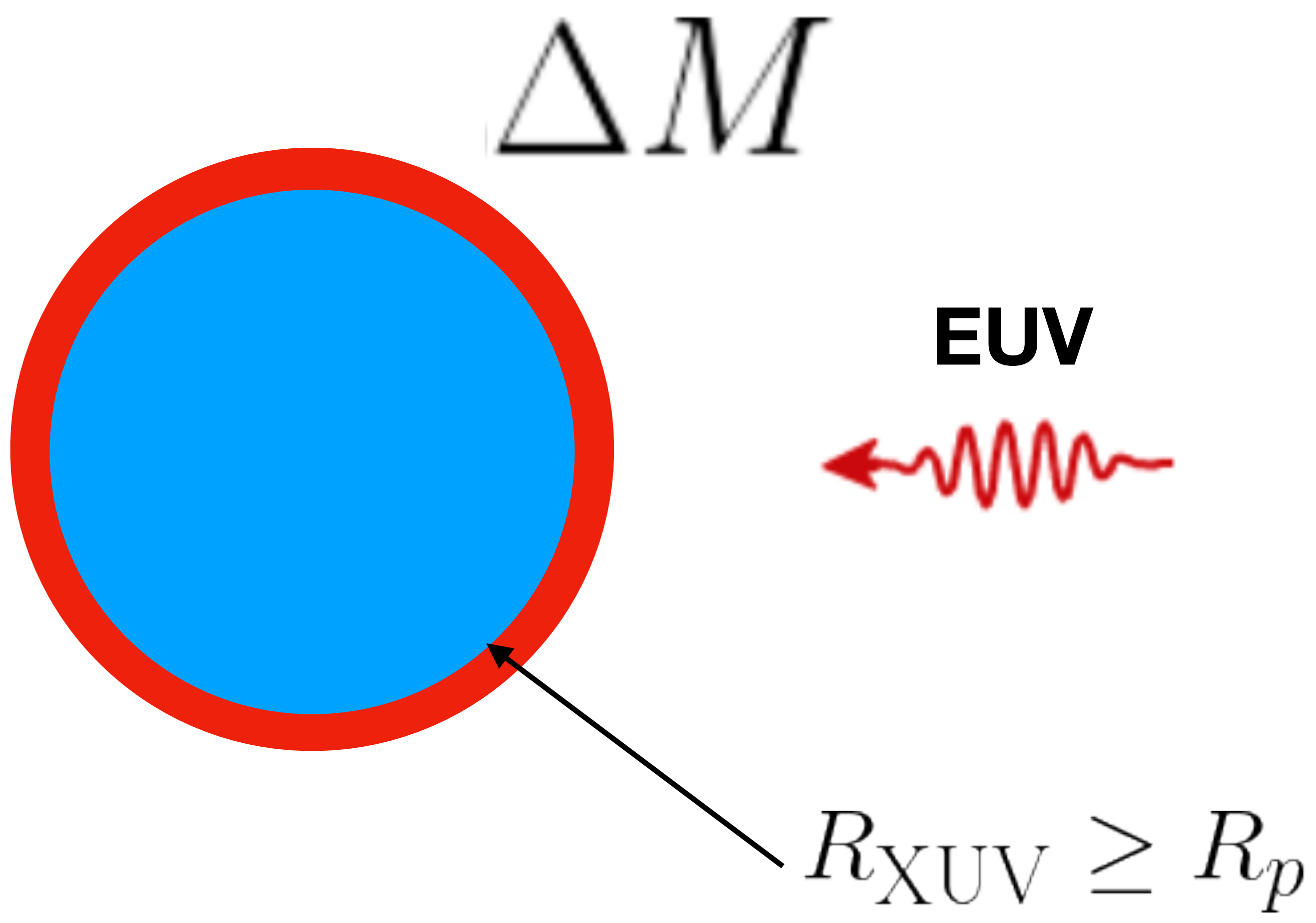

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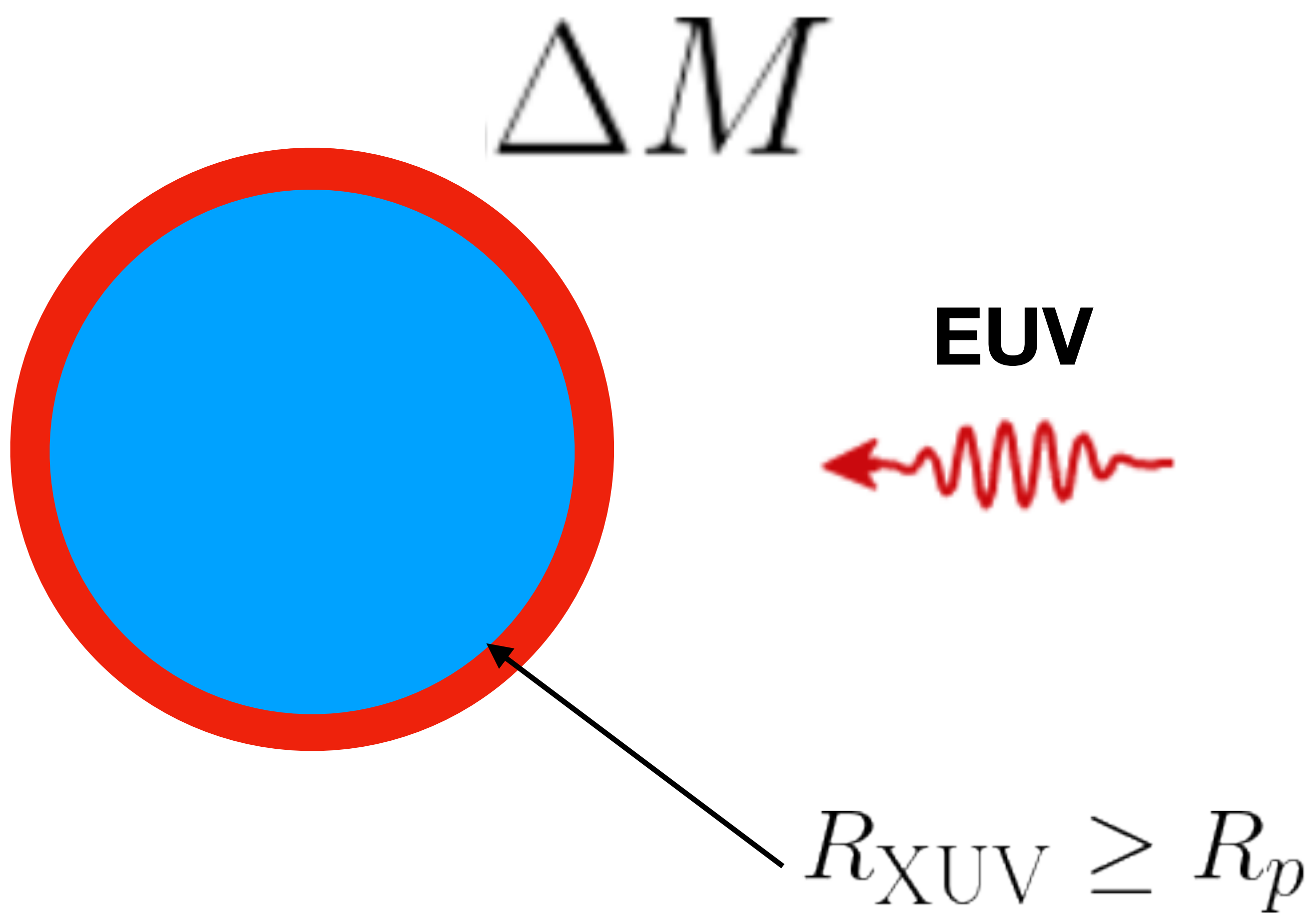

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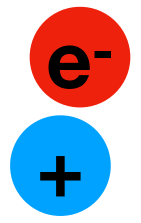

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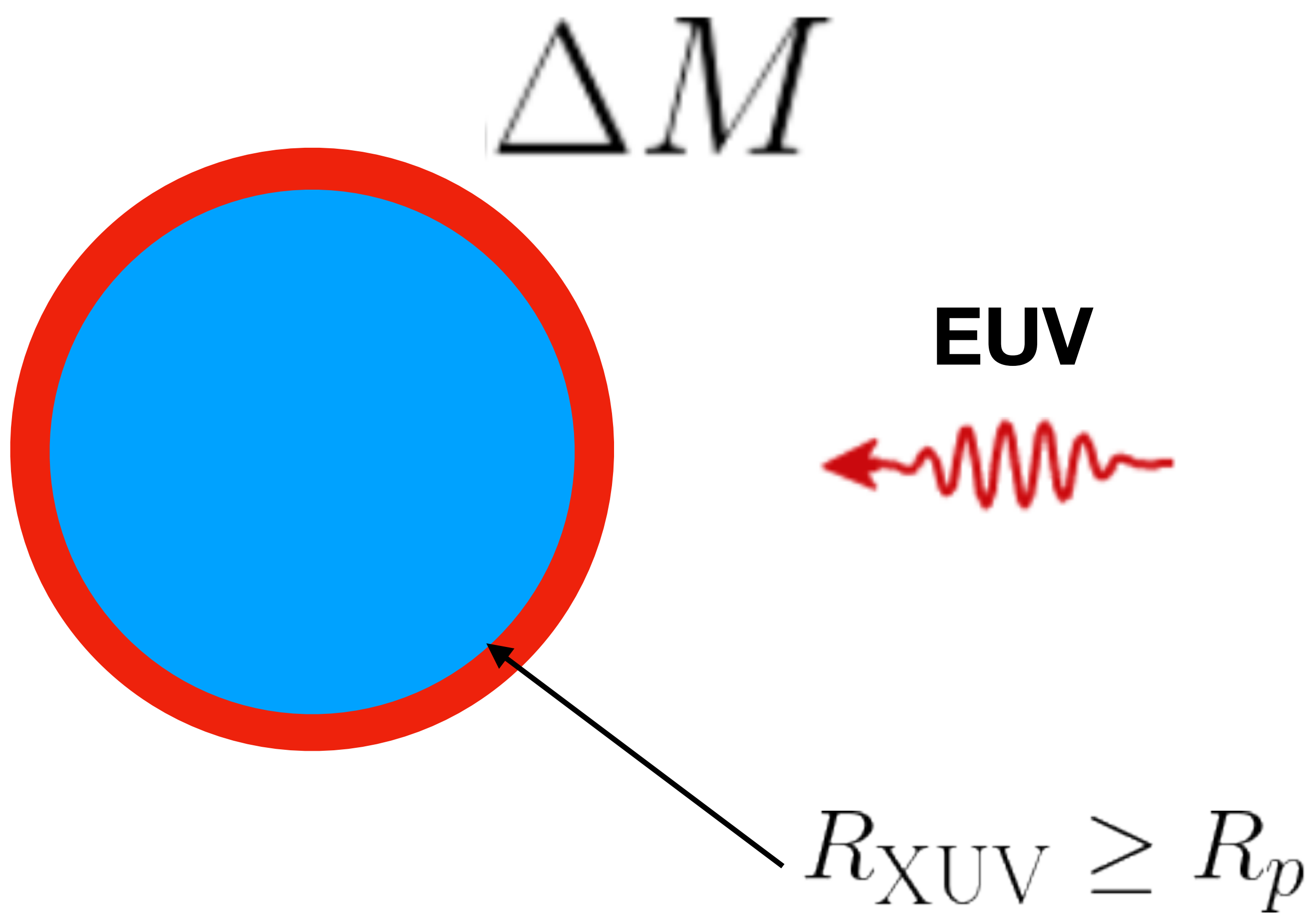

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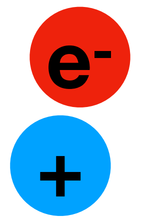

You lose 13.6eV of a photons energy to ionization.

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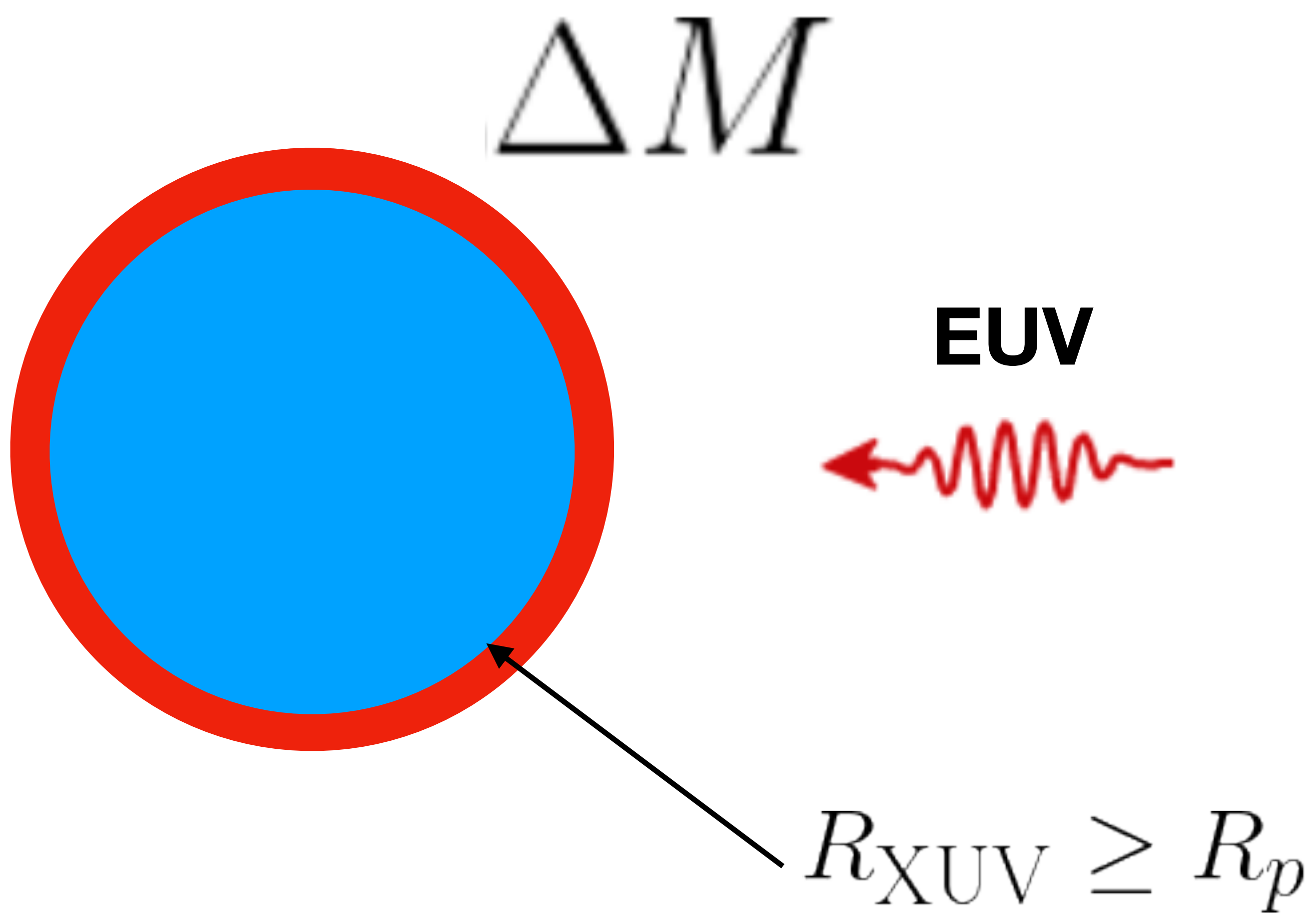

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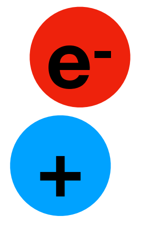

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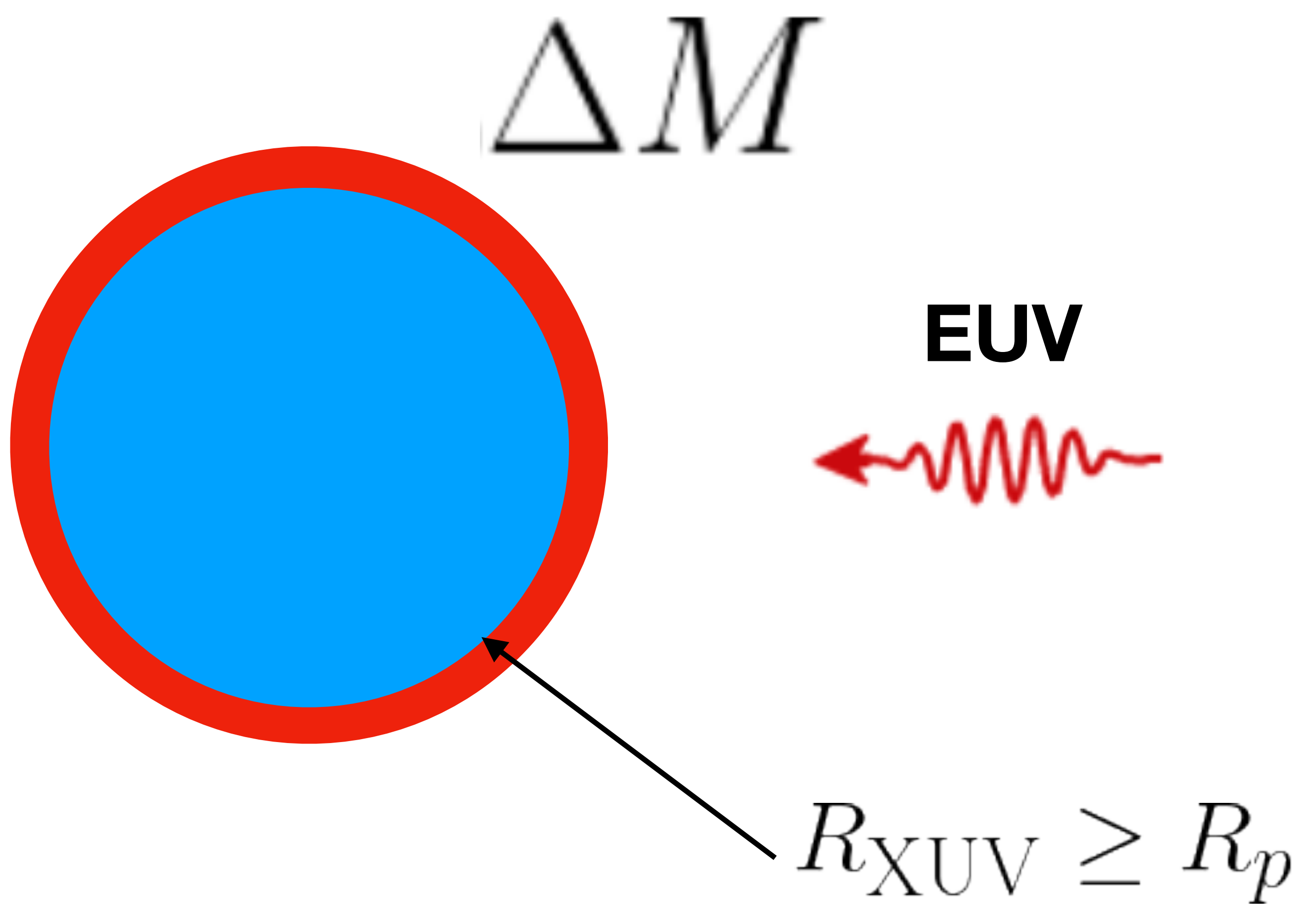

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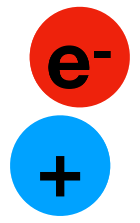

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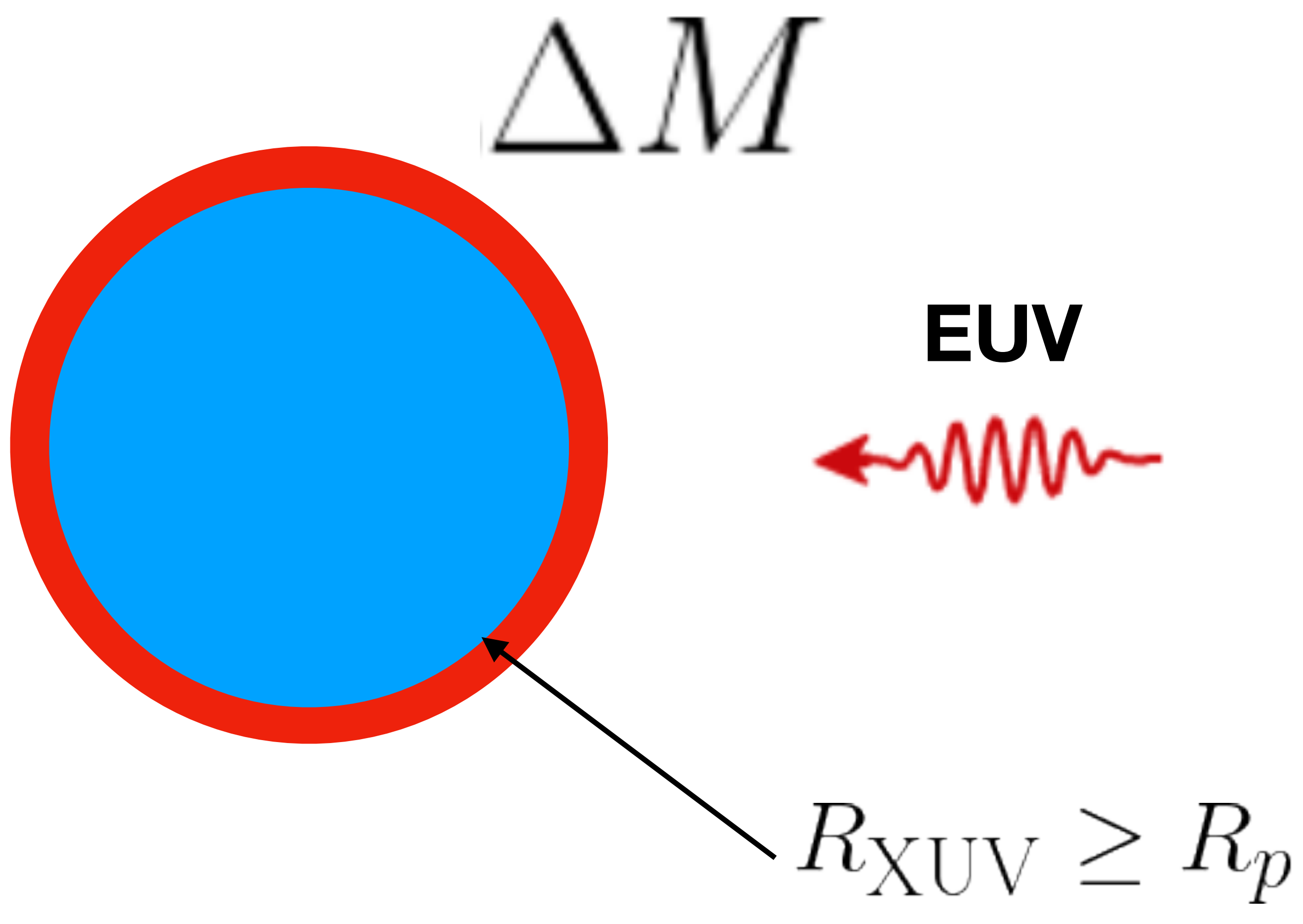

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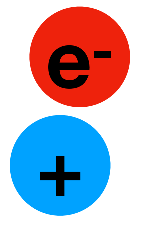

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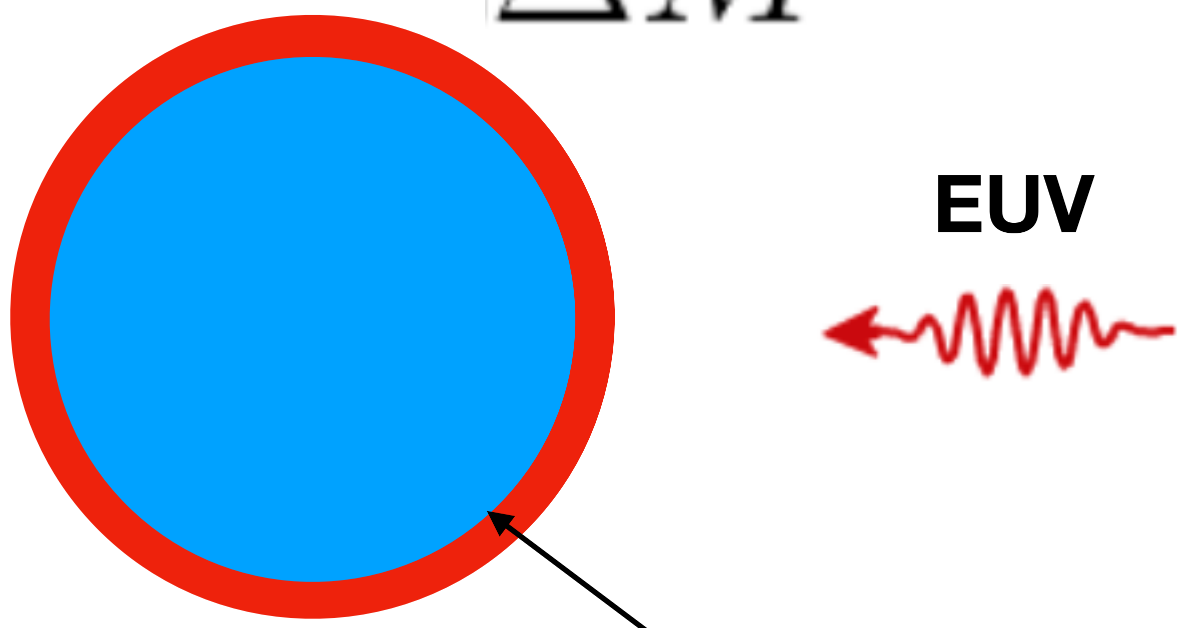
ΔM



$R_{\rm XUV} \geq R_p$

$$\pi R_{XUV}^2 F_* \Delta t \sim \frac{G M_p \Delta M}{R_{\rm XUV}}$$

Still lose energy to radiative processes

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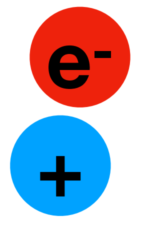

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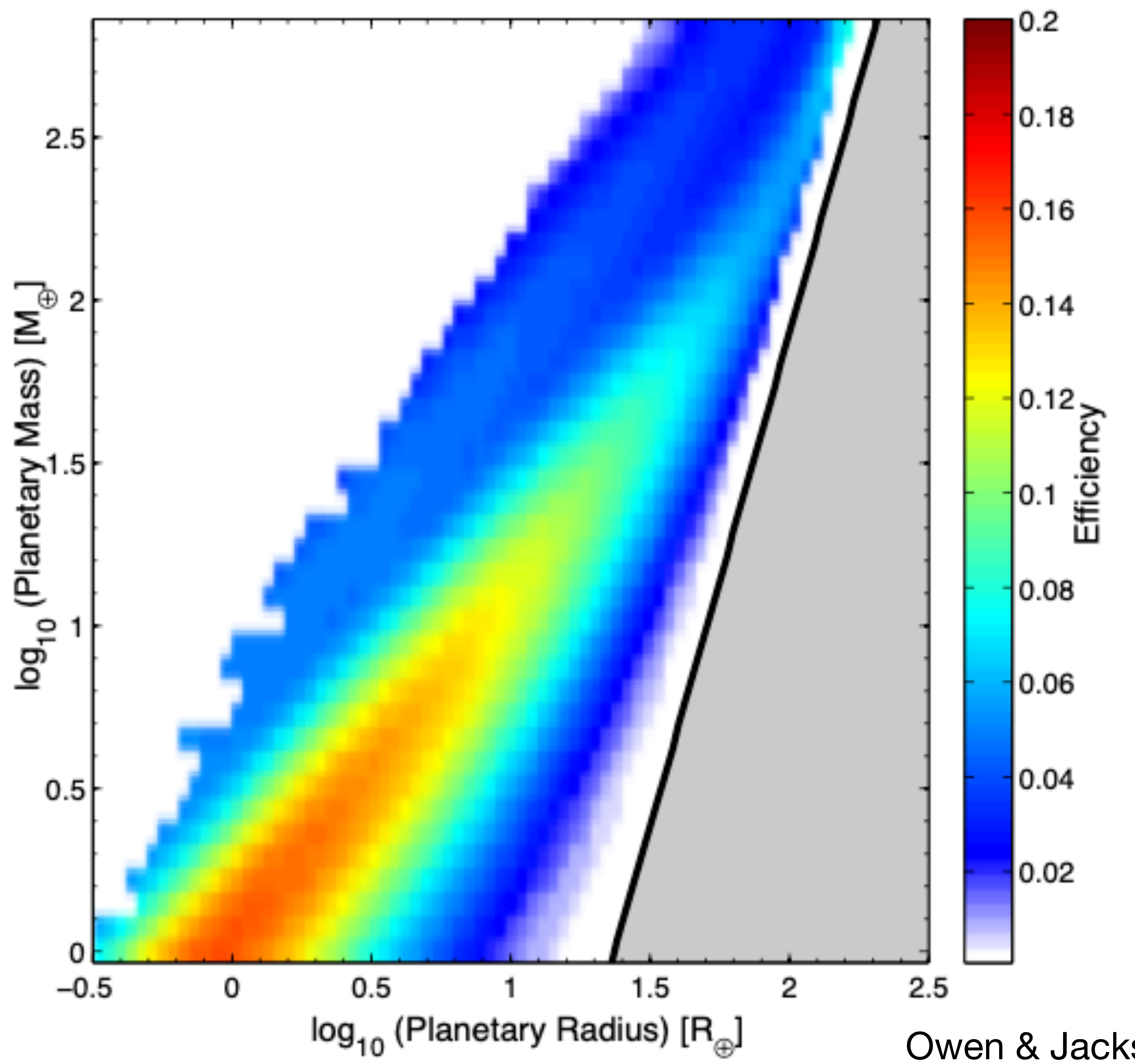
Efficiency across parameter space

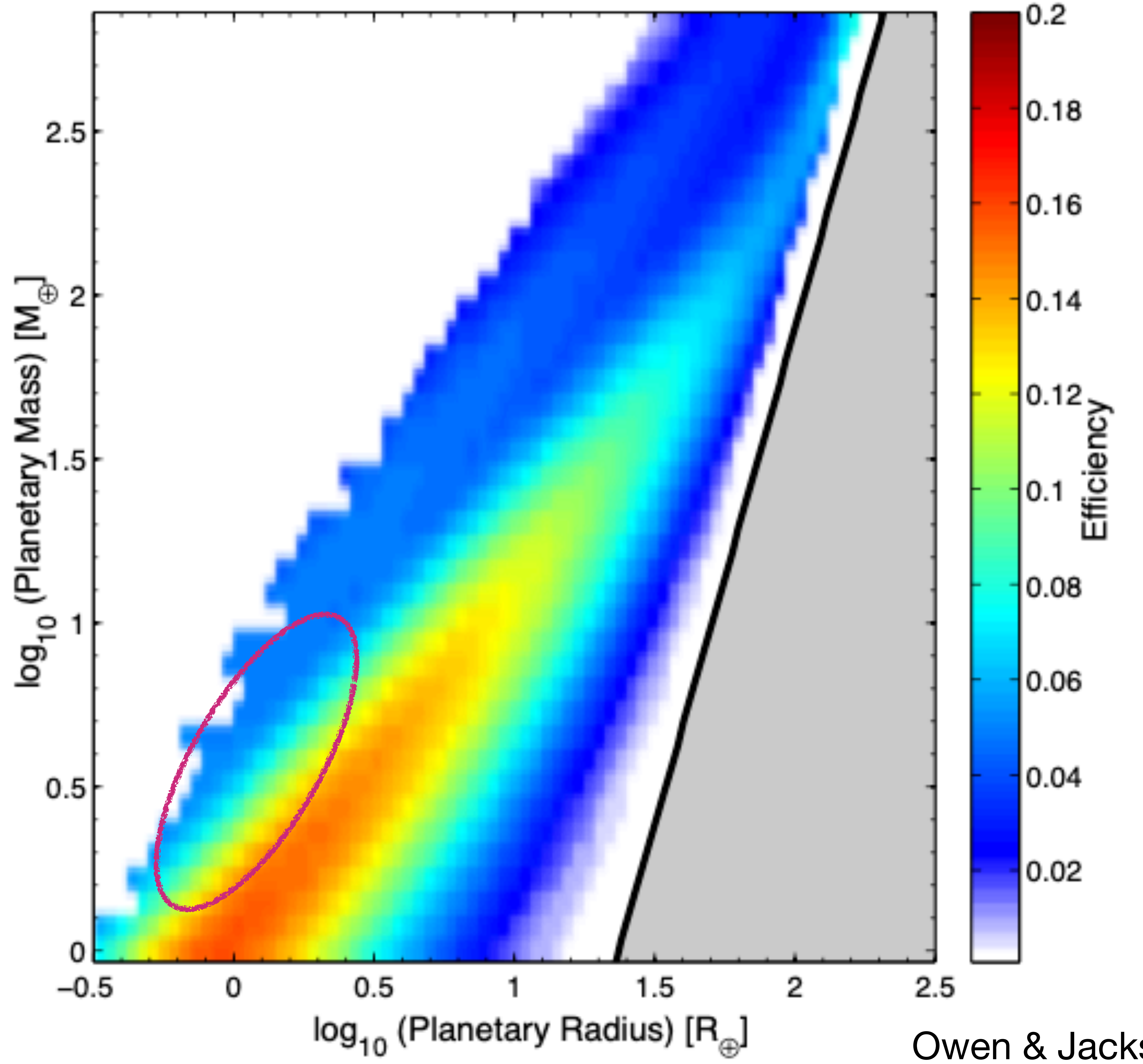


Owen & Jackson (2012)

Efficiency across parameter space

Radiative process:

Takes a finite time to escape planet: time to cool.



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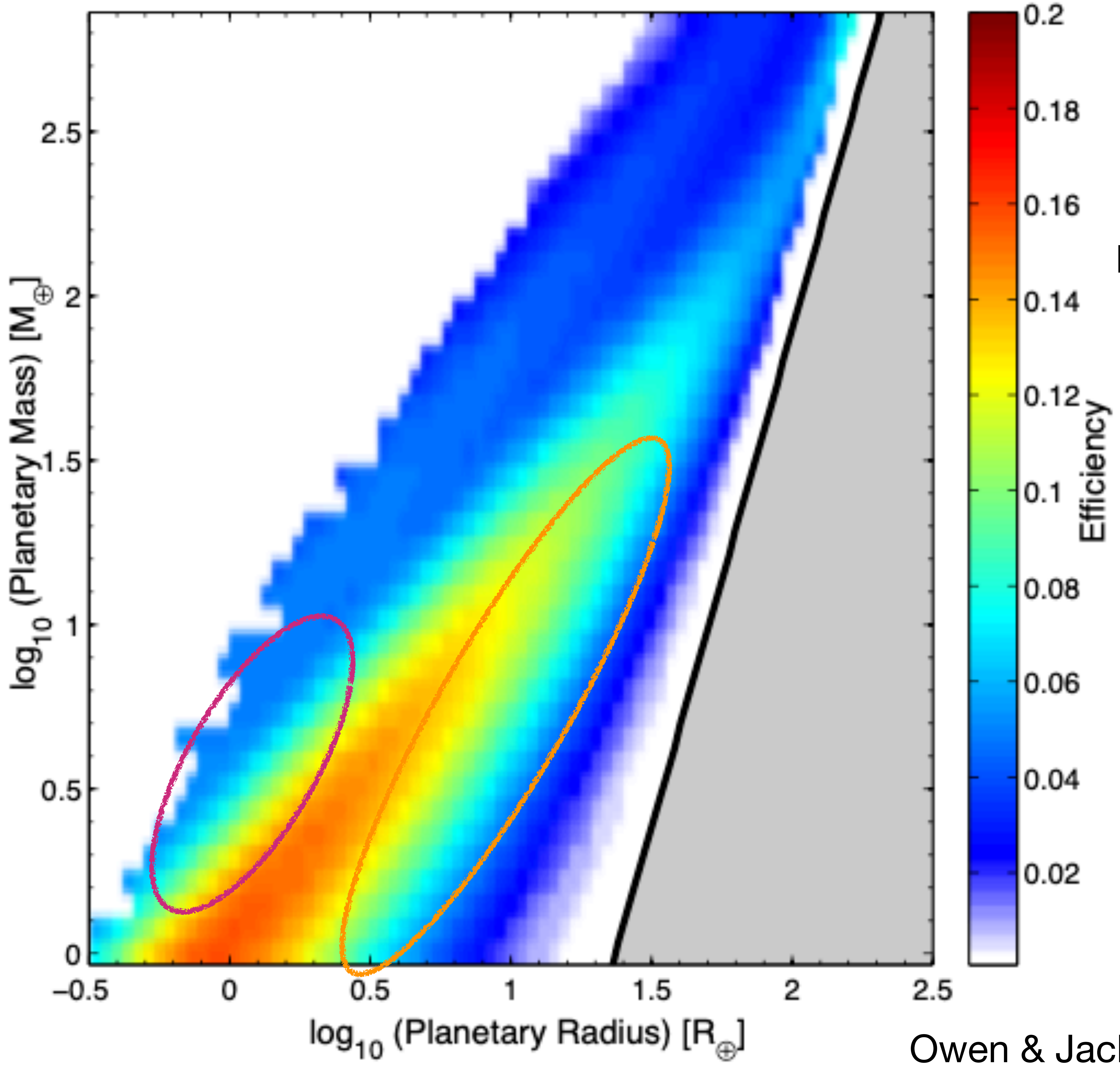

"Hydrodynamic processes"

Excess thermal + kinetic energy from heating

Owen & Jackson (2012)

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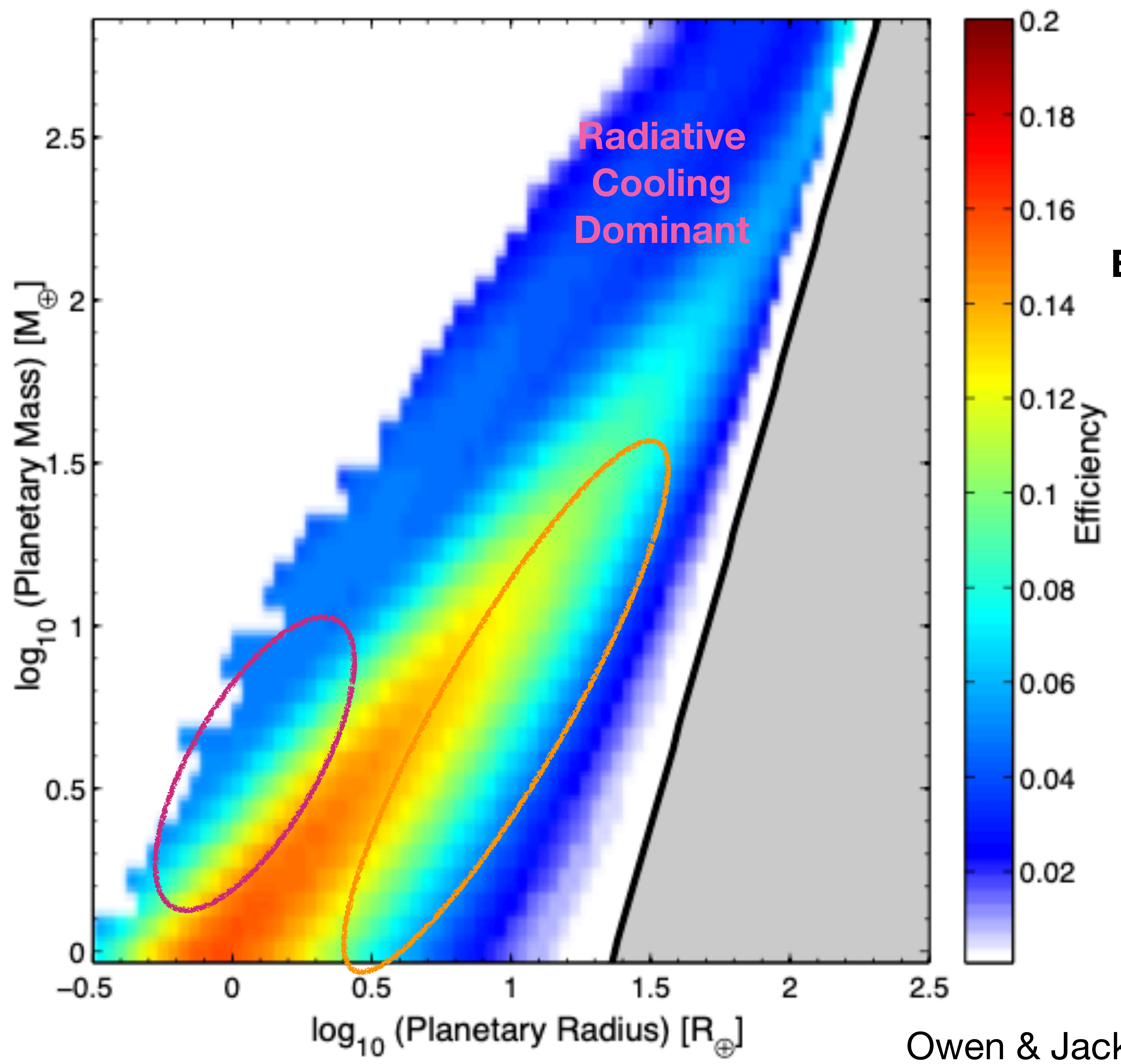

"Hydrodynamic processes"

Excess thermal + kinetic energy from heating

Owen & Jackson (2012)

Where to go?

A&A 619, A151 (2018)
https://doi.org/10.1051/0004-6361/201833737

Astronomy & Astrophysics

Grid of upper atmosphere models for 1–40 $M_\oplus$ planets: application to CoRoT-7 b and HD 219134 b,c

D. Kubyshkina[1], L. Fossati[1], N. V. Erkaev[2,3], C. P. Johnstone[4], P. E. Cubillos[1], K. G. Kislyakova[4,1], H. Lammer[1], M. Lendl[1], and P. Odert[1,5]

Extending a grid of hydrodynamic planetary upper atmosphere models

Daria I. Kubyshkina[1] and Luca Fossati[2]

[1] *Trinity College Dublin*
Dubline-2 College Green
Dublin, Ireland
[2] *Space Research Institute*
8042 Graz, Austria

Evolution

What do exoplanets do without escape?

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$$|U| \sim \frac{GM^2}{R}$$

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$$|U| \sim \frac{GM^2}{R} \qquad \sim Nk_BT$$

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$$T \sim \frac{GM\mu m_h}{k_BR} \sim 8000\,\mathrm{K}\;\mu\left(\frac{M}{1\ \mathrm{M}_\oplus}\right)\left(\frac{R}{1\ \mathrm{R}_\oplus}\right)^{-1}$$

What do exoplanets do without escape?

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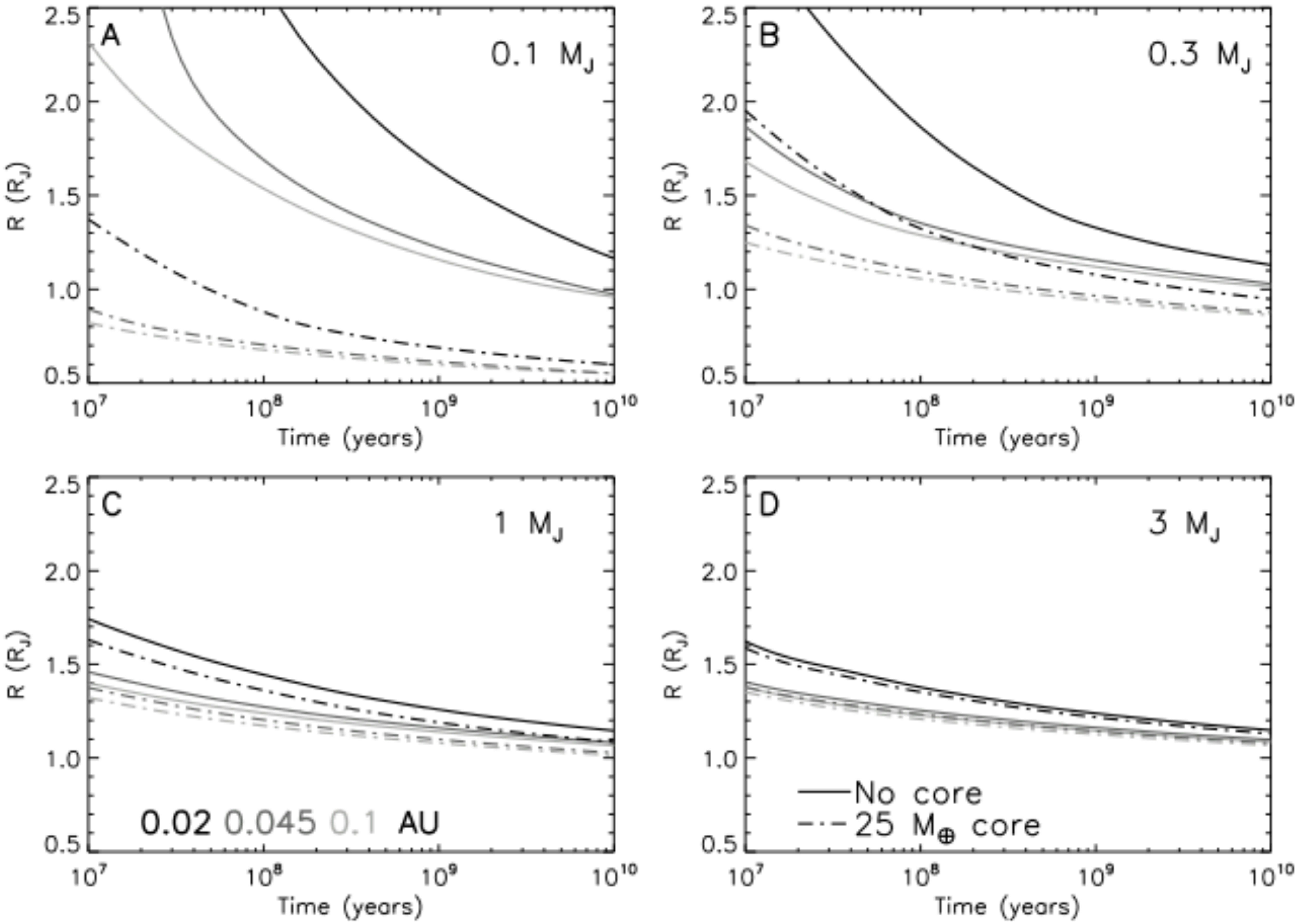
Exoplanets are born hot, and they cool over time.

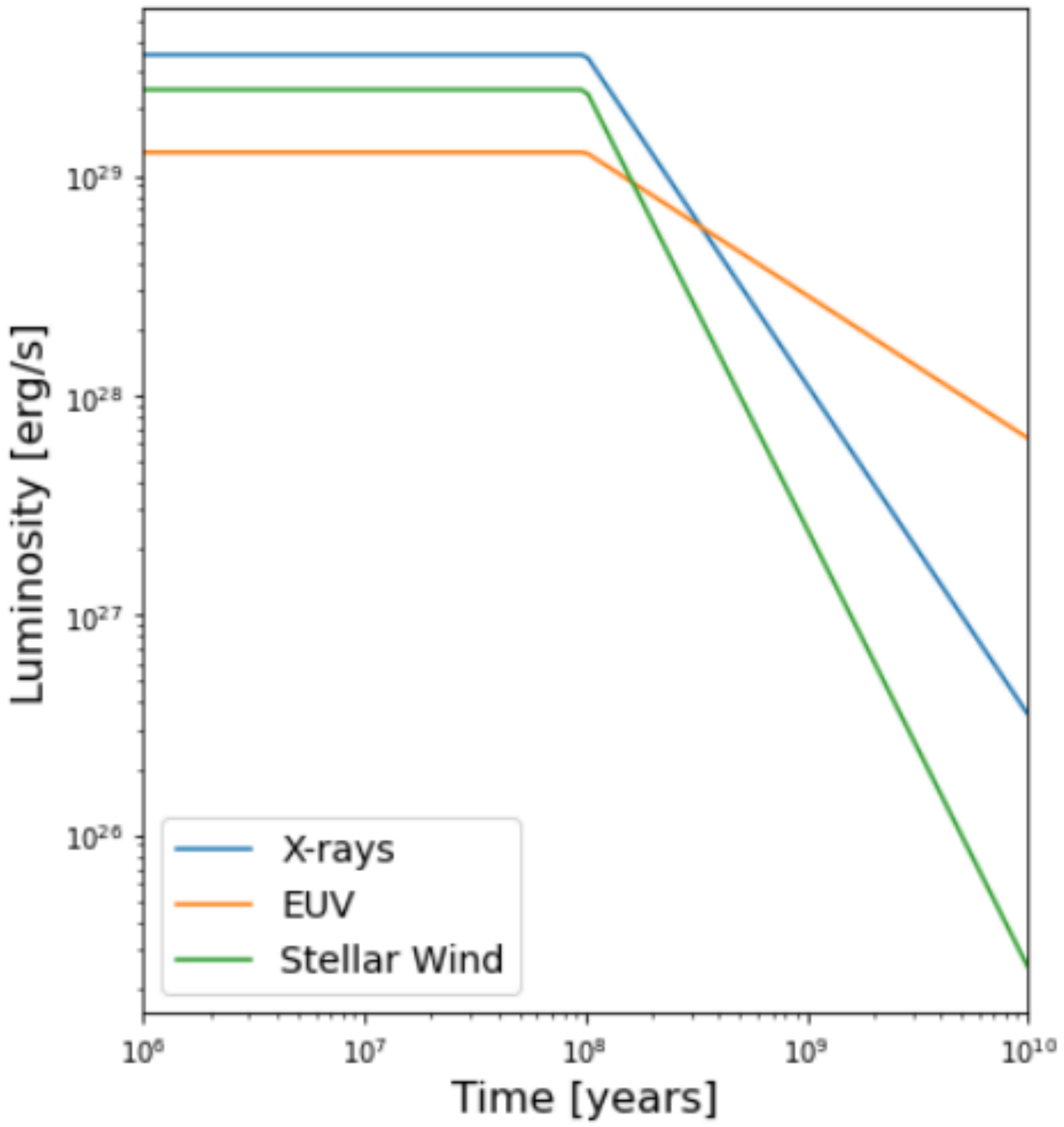
What do exoplanets do without escape?

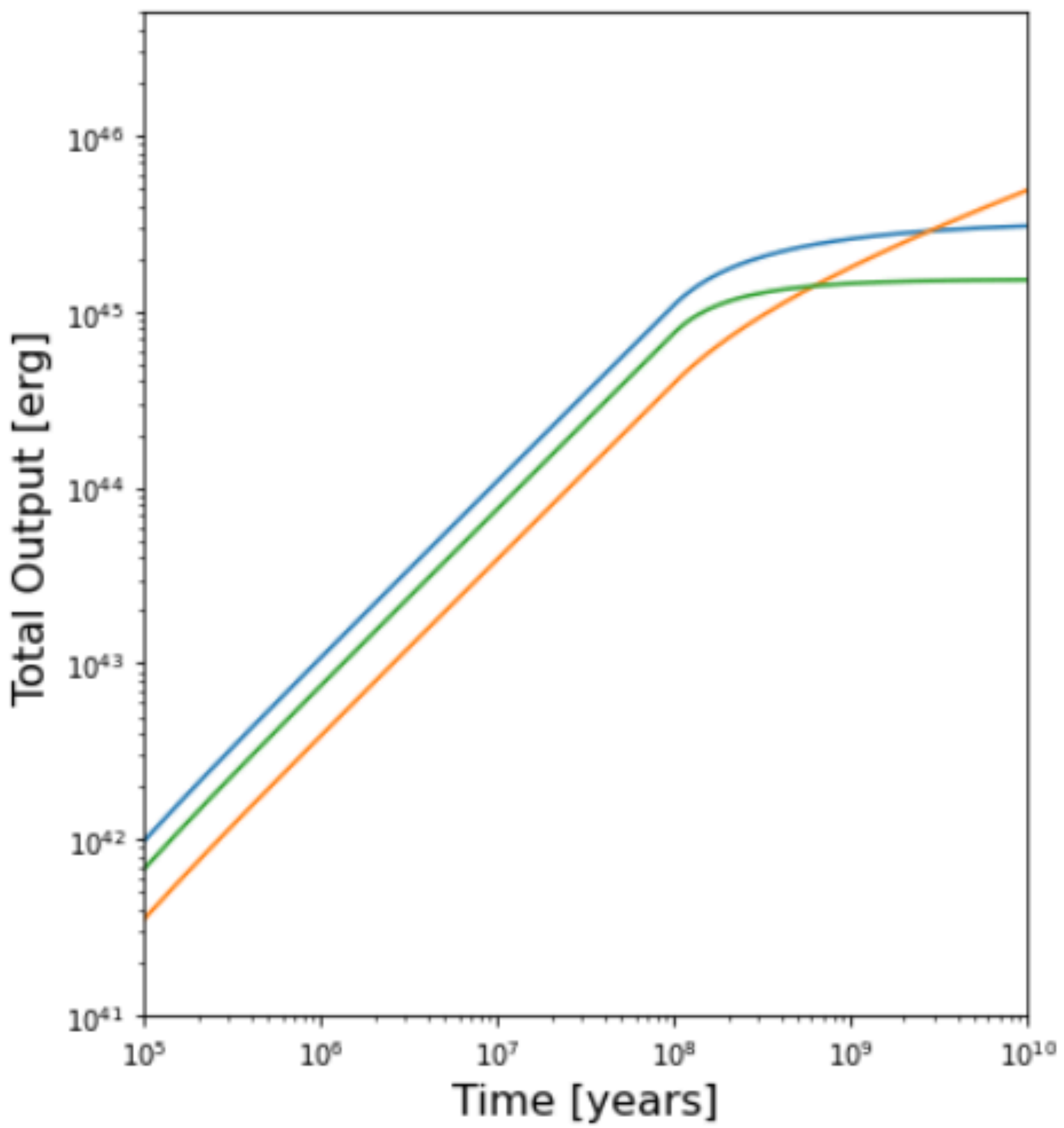
Fortney & Nettelmann (2010)



Planets with primordial atmospheres contract significantly over their lifetimes

Reminder - earlier





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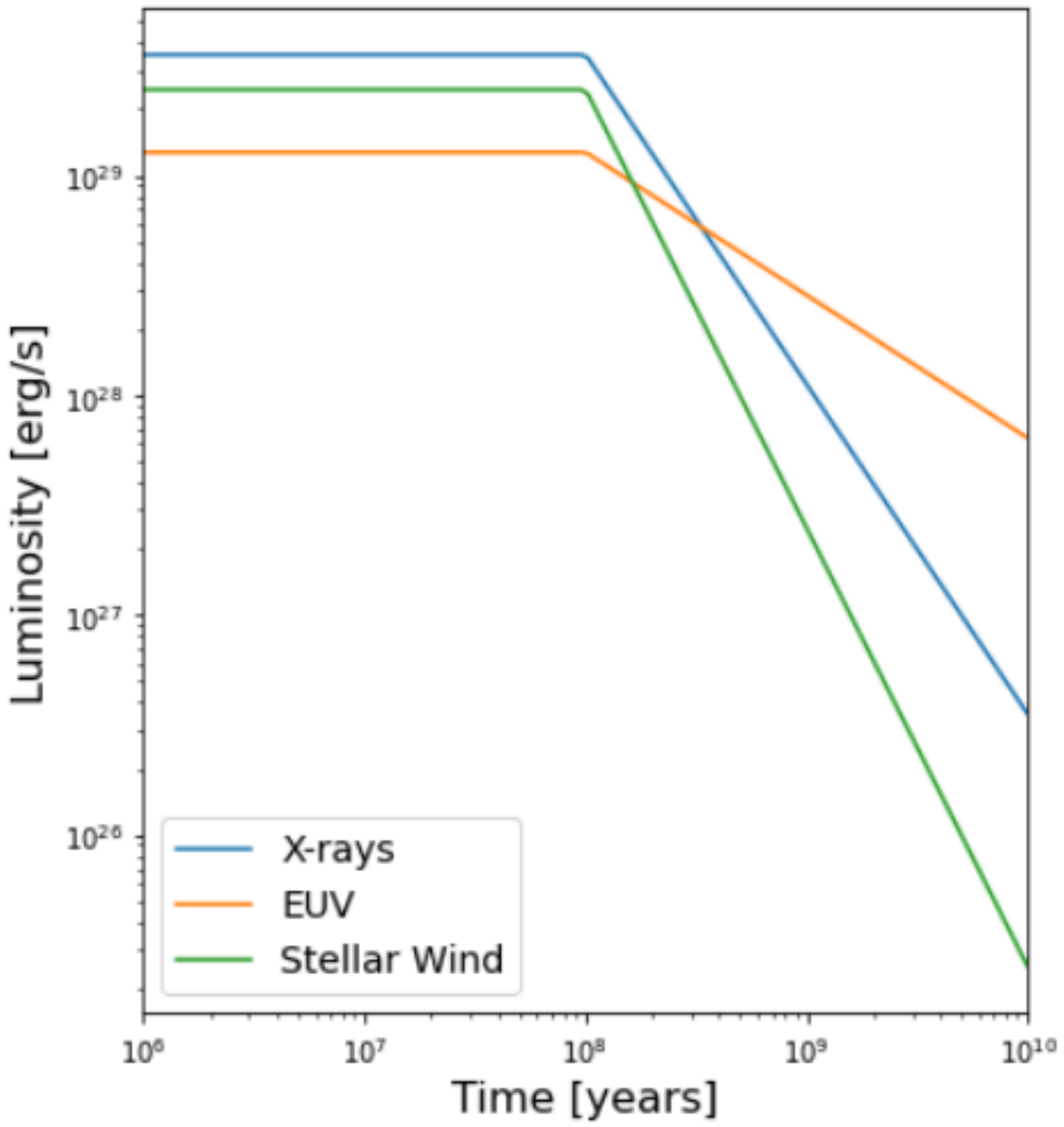
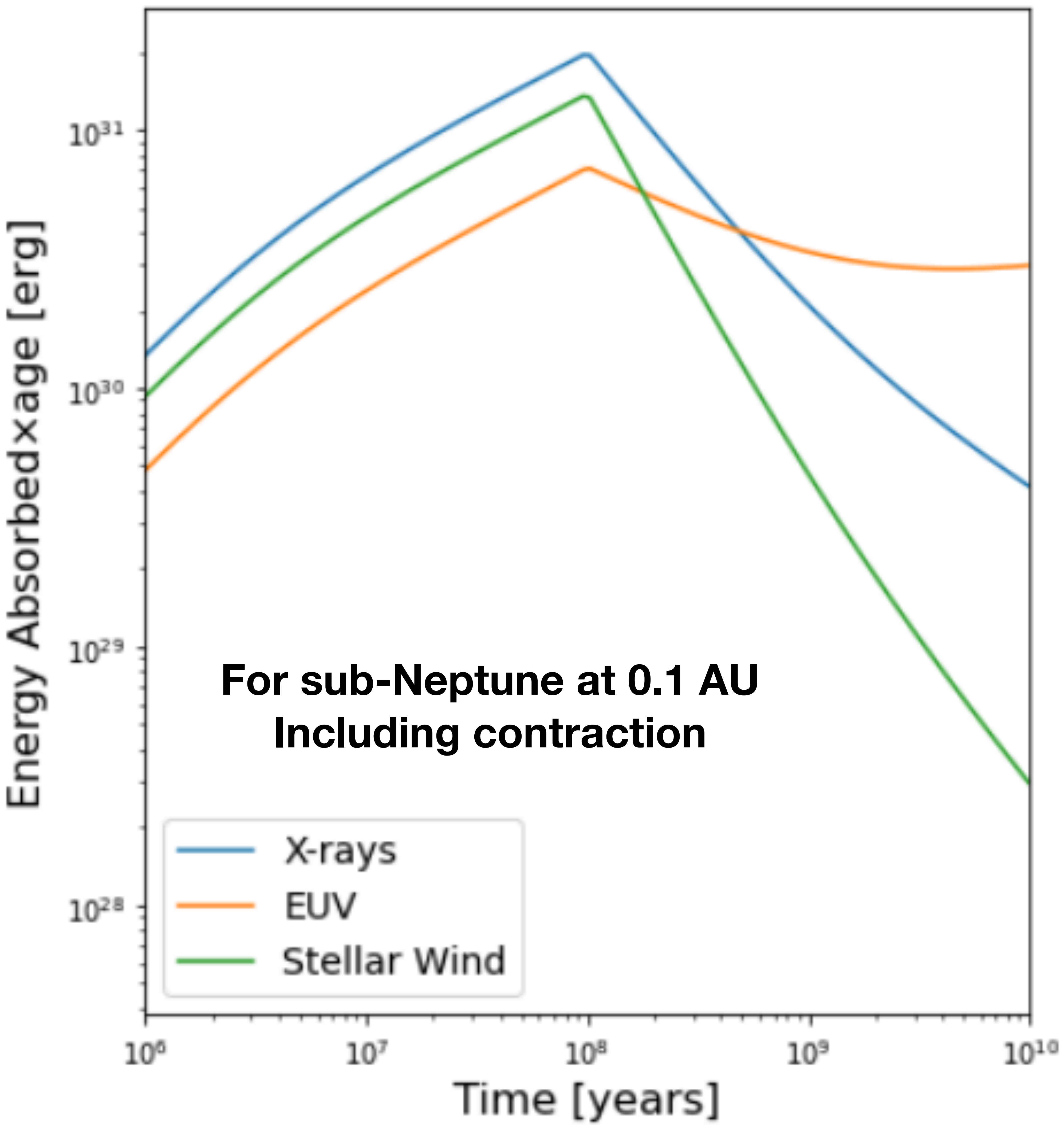
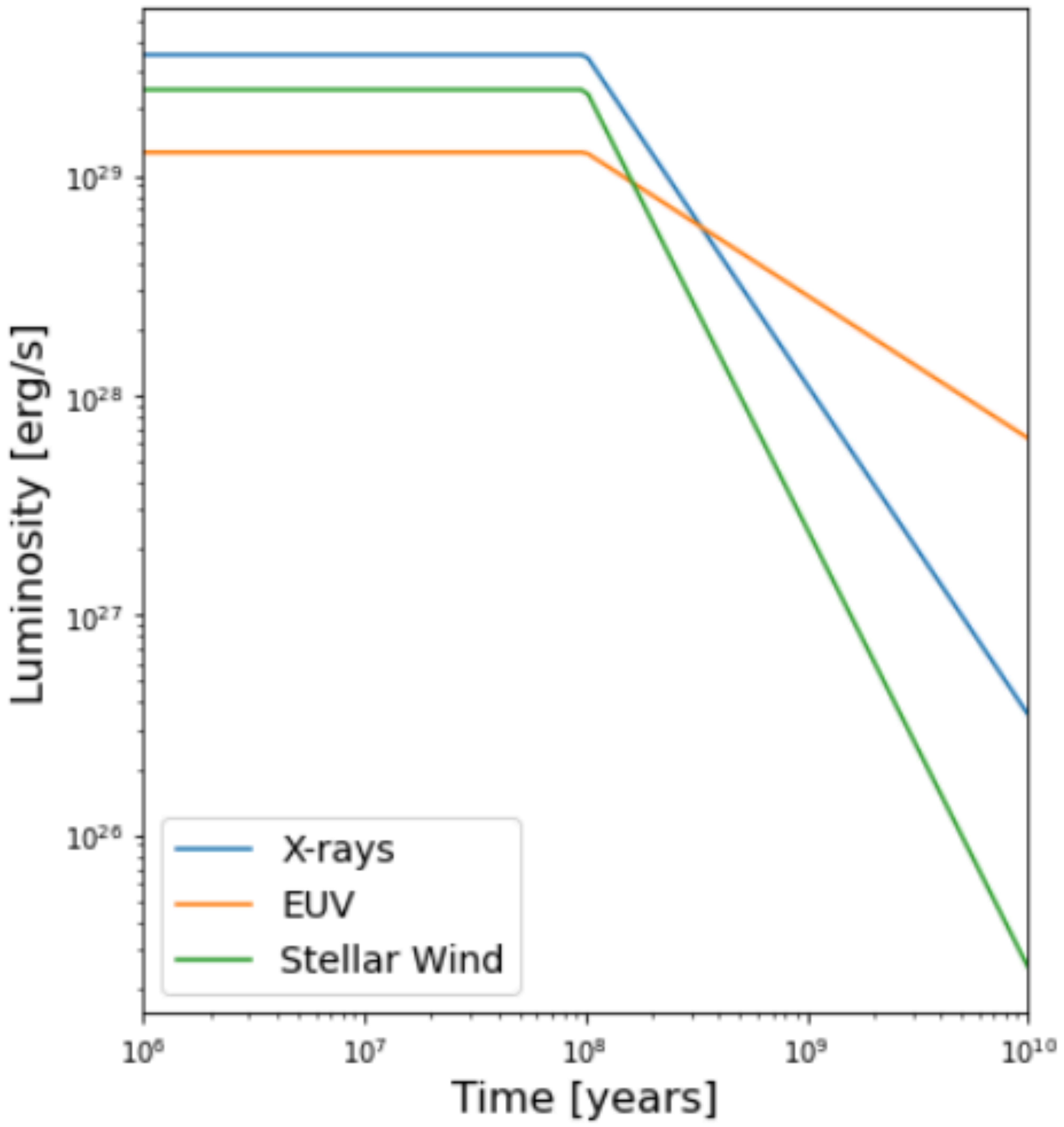
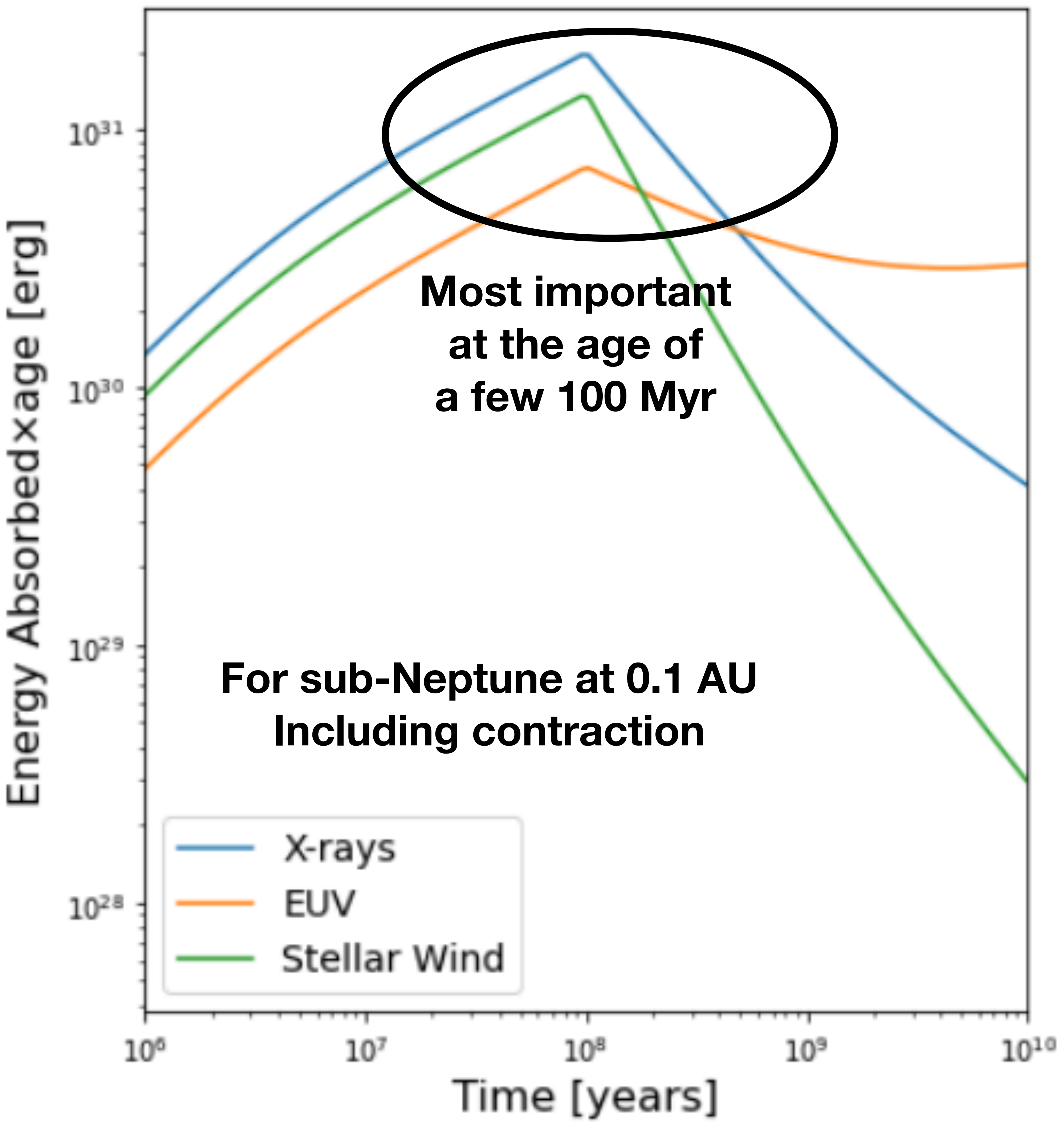


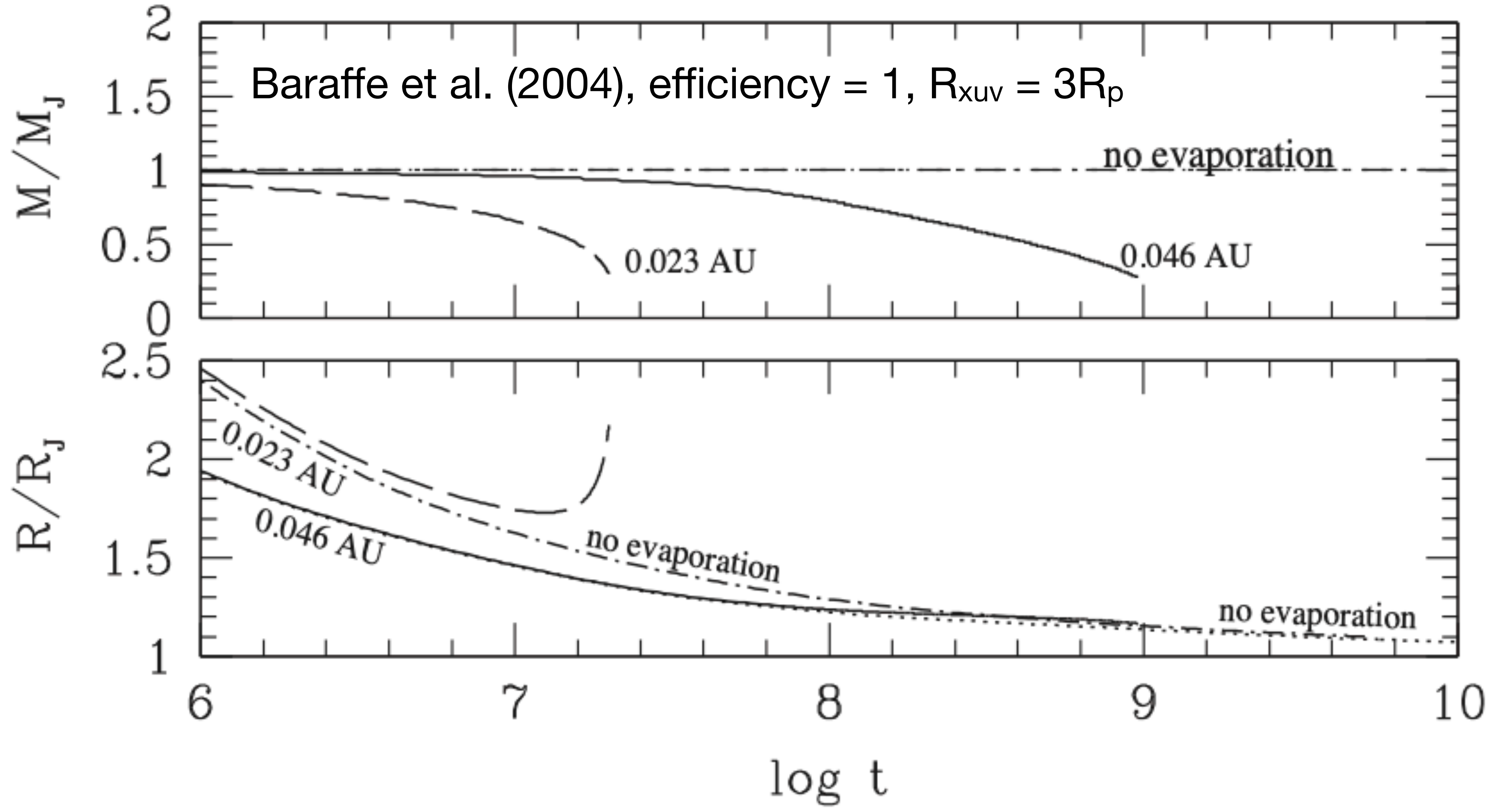


Reminder - earlier

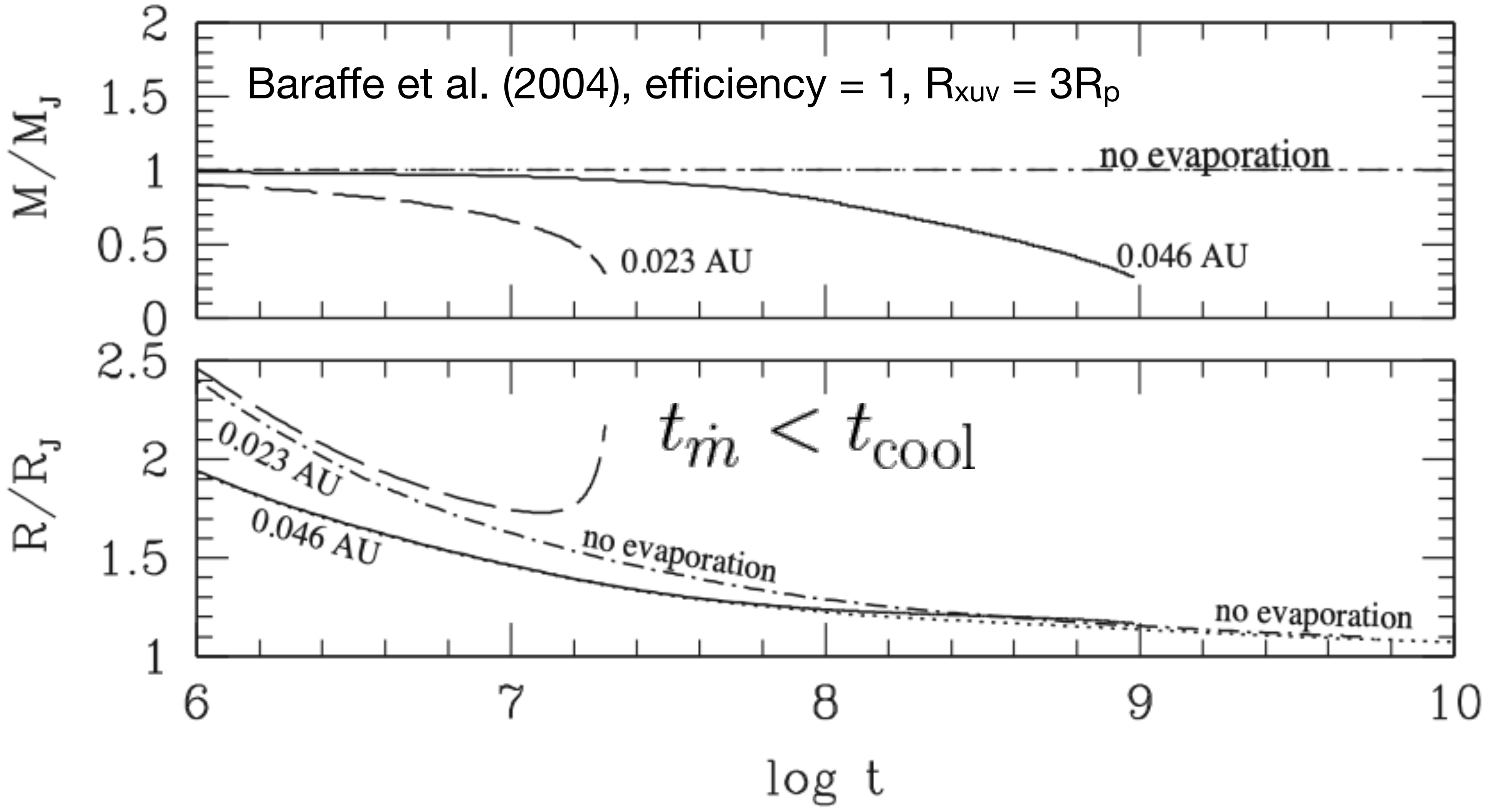




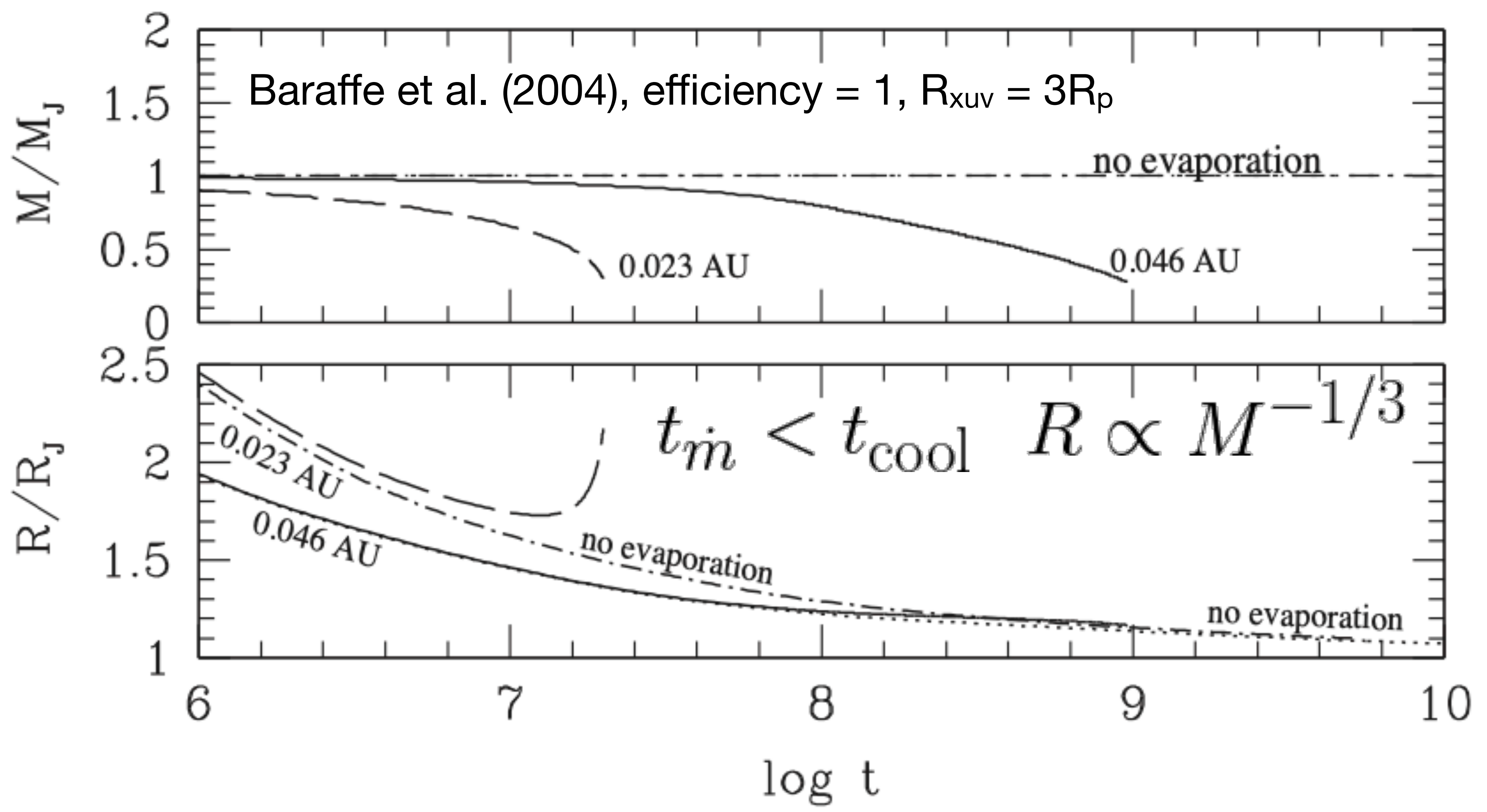
Hot Jupiters



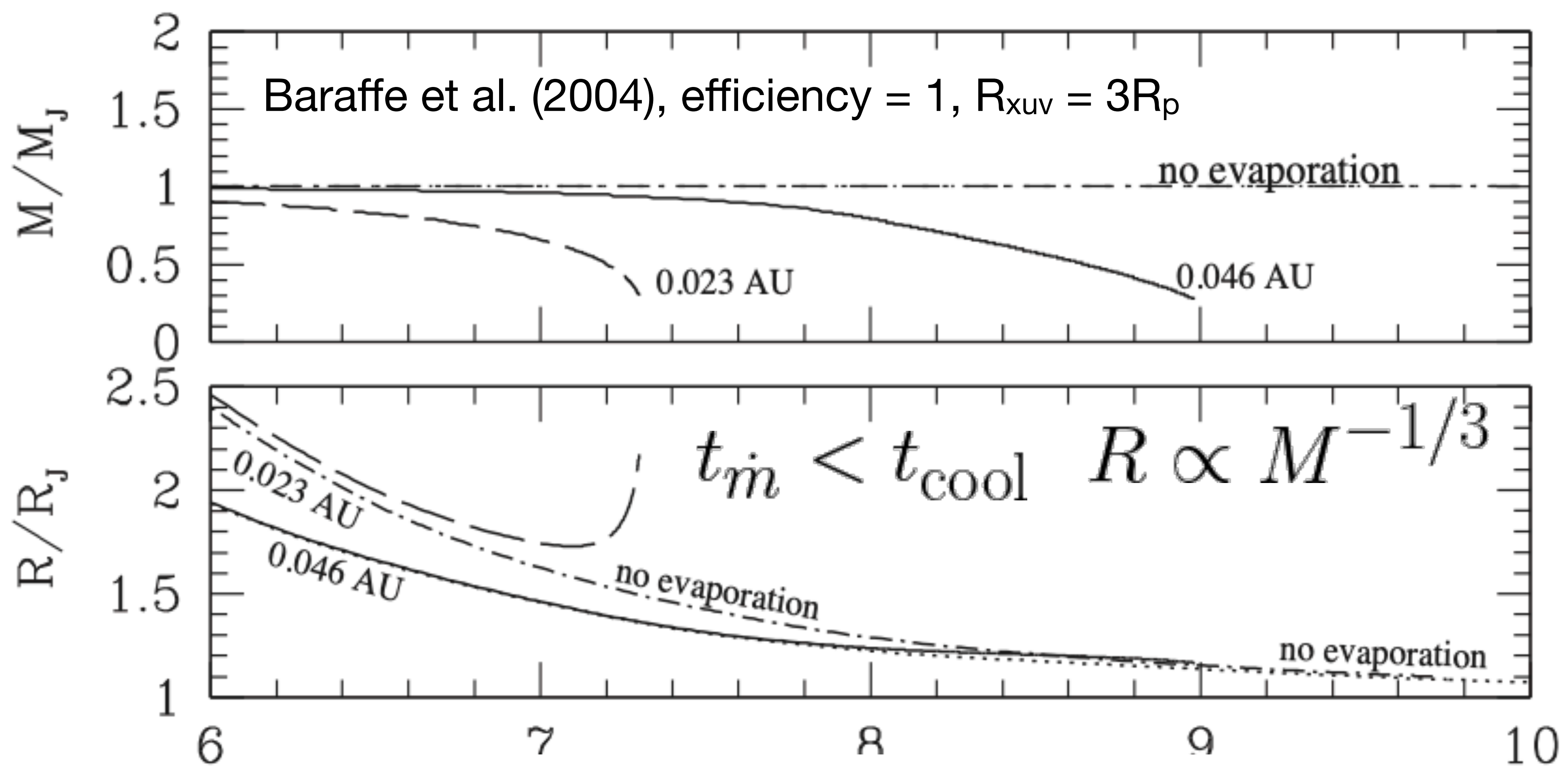
Hot Jupiters



Hot Jupiters



Hot Jupiters



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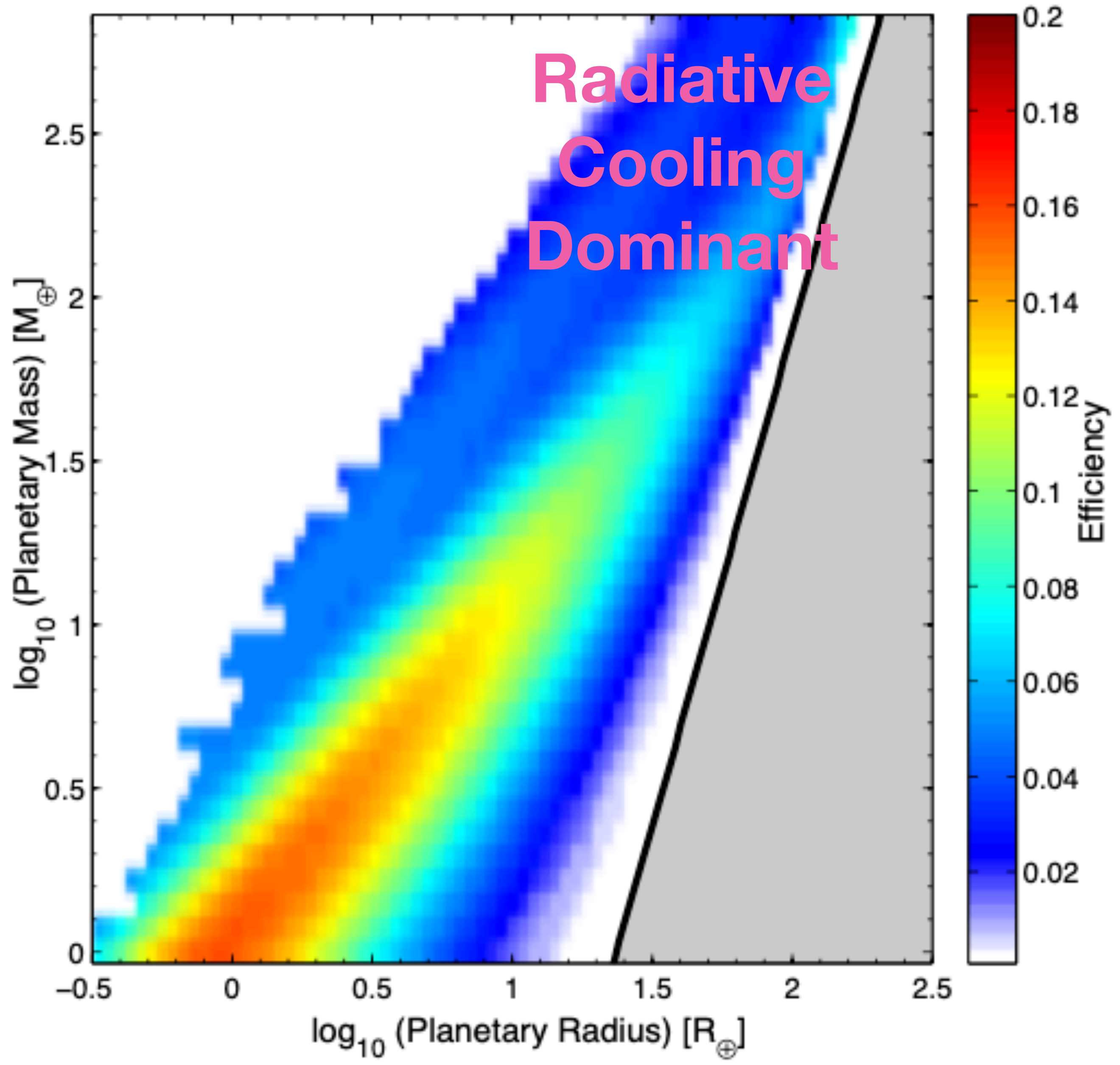
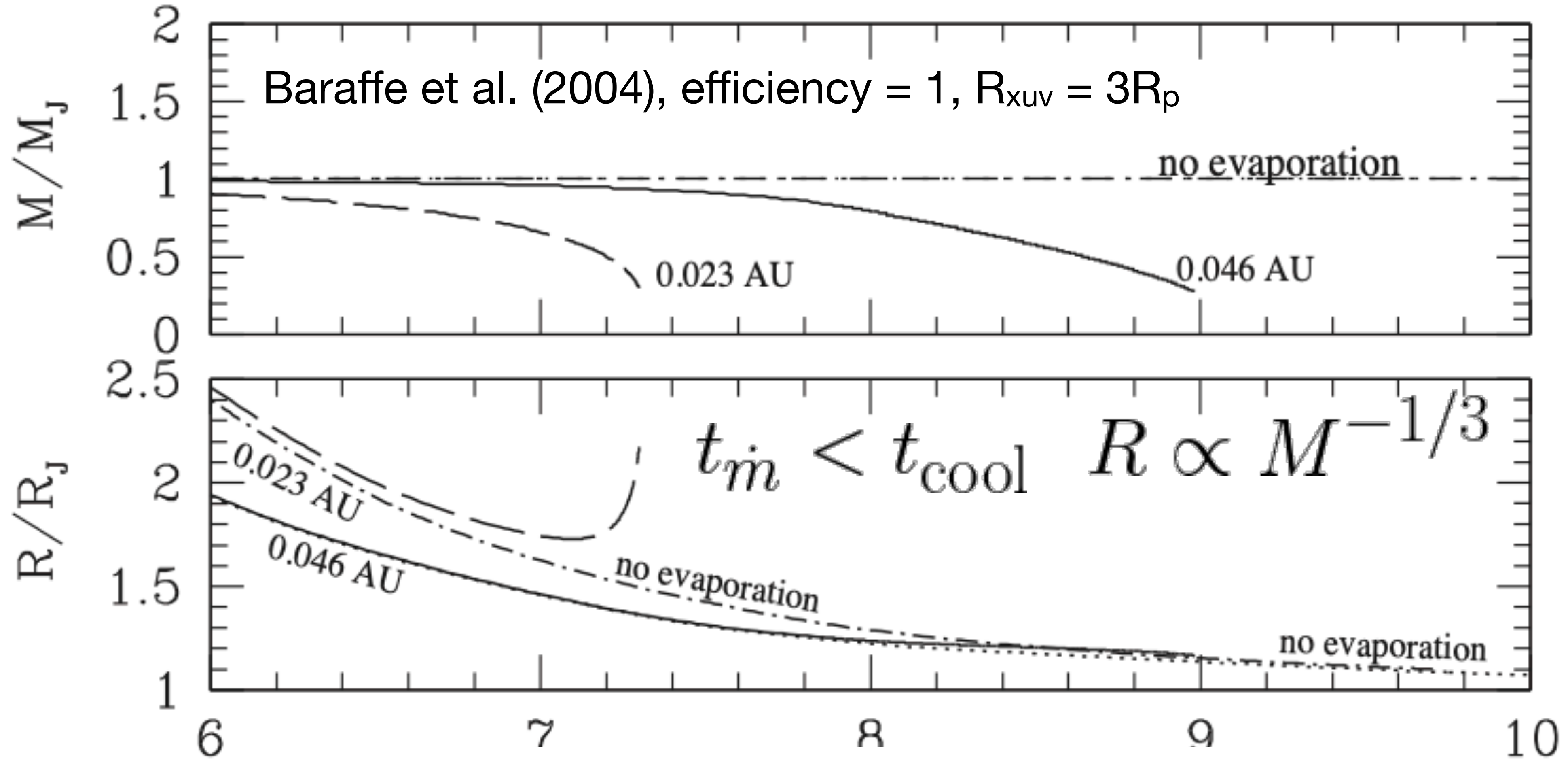


Hot Jupiters



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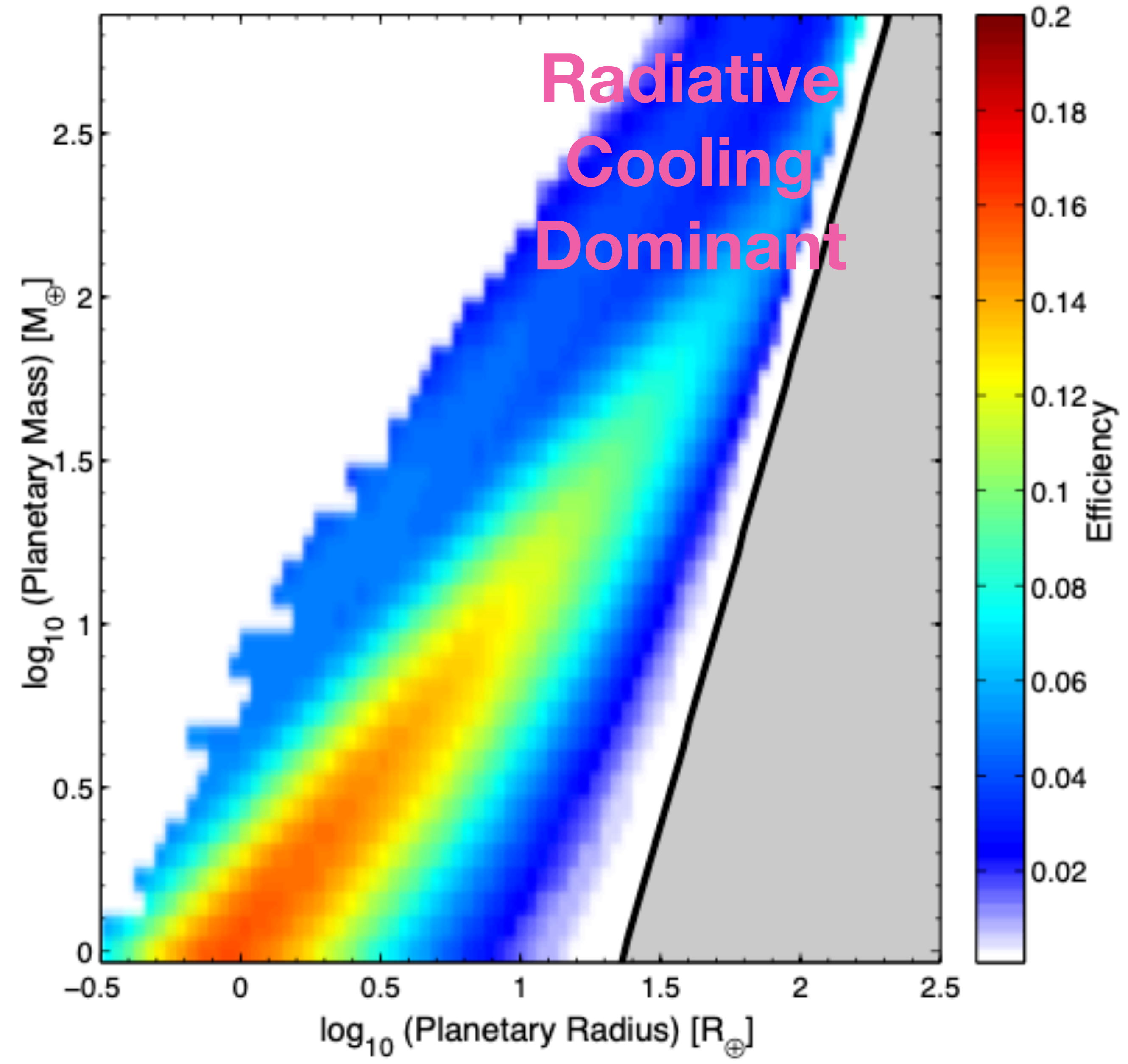
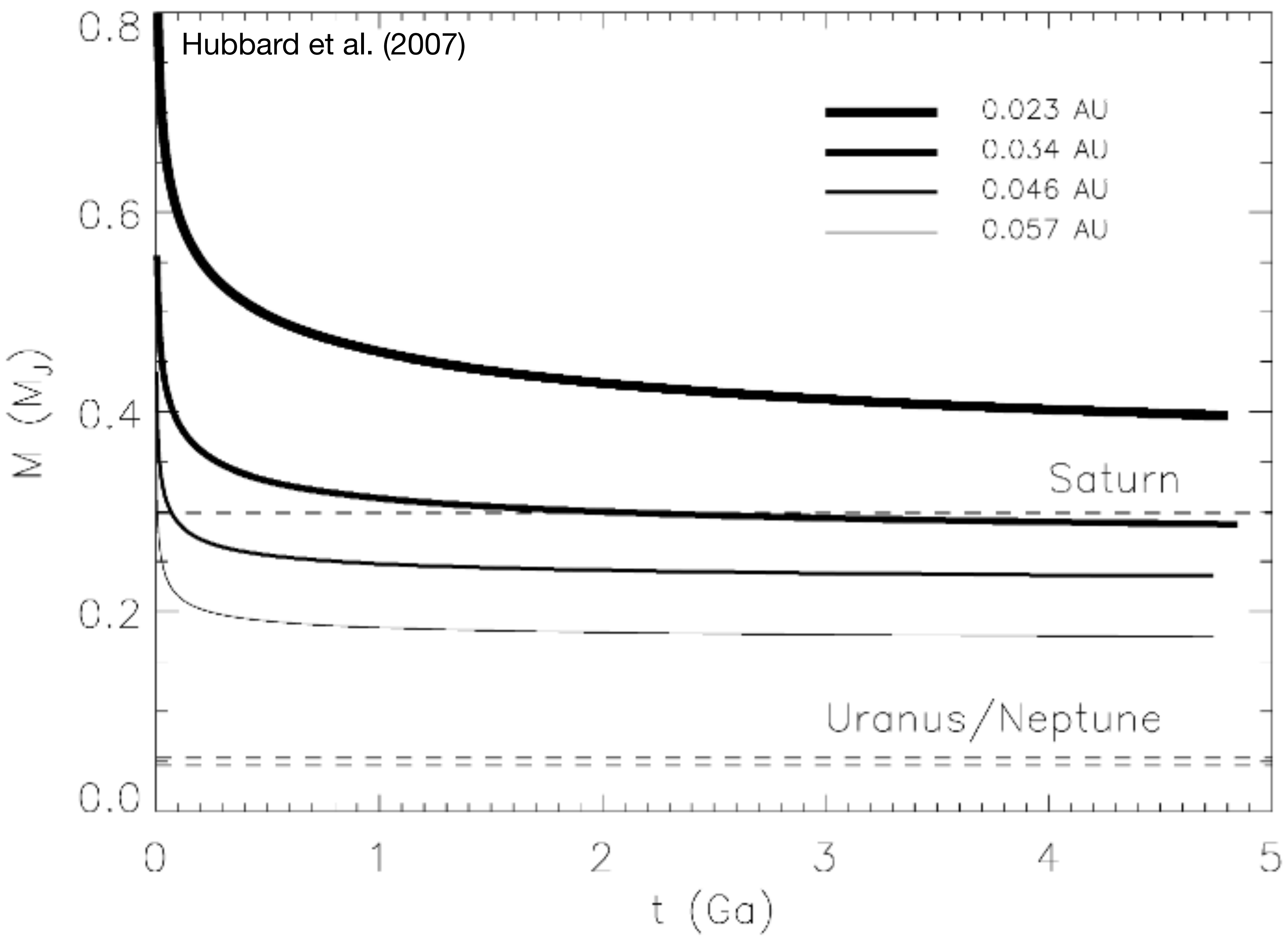
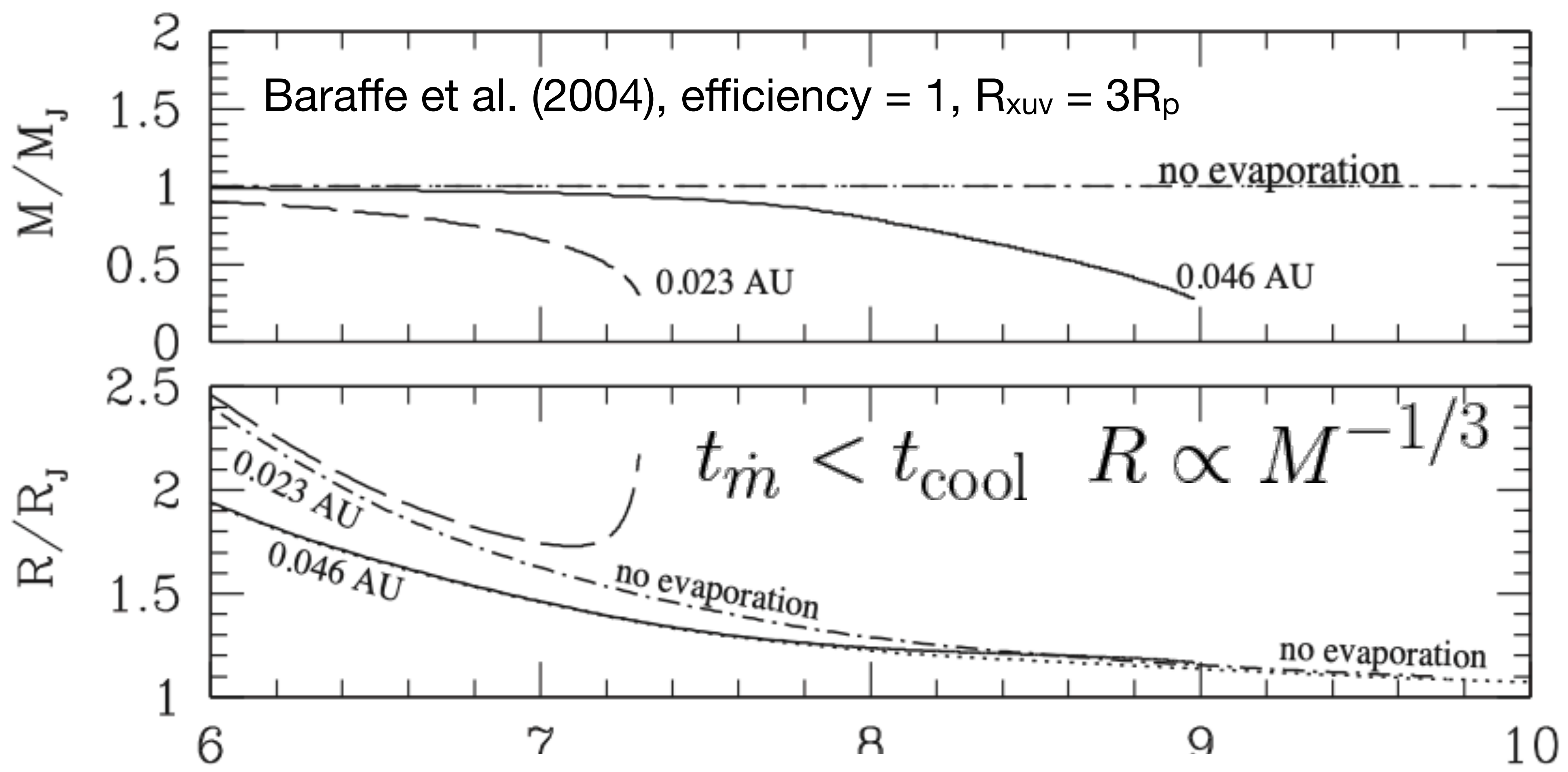


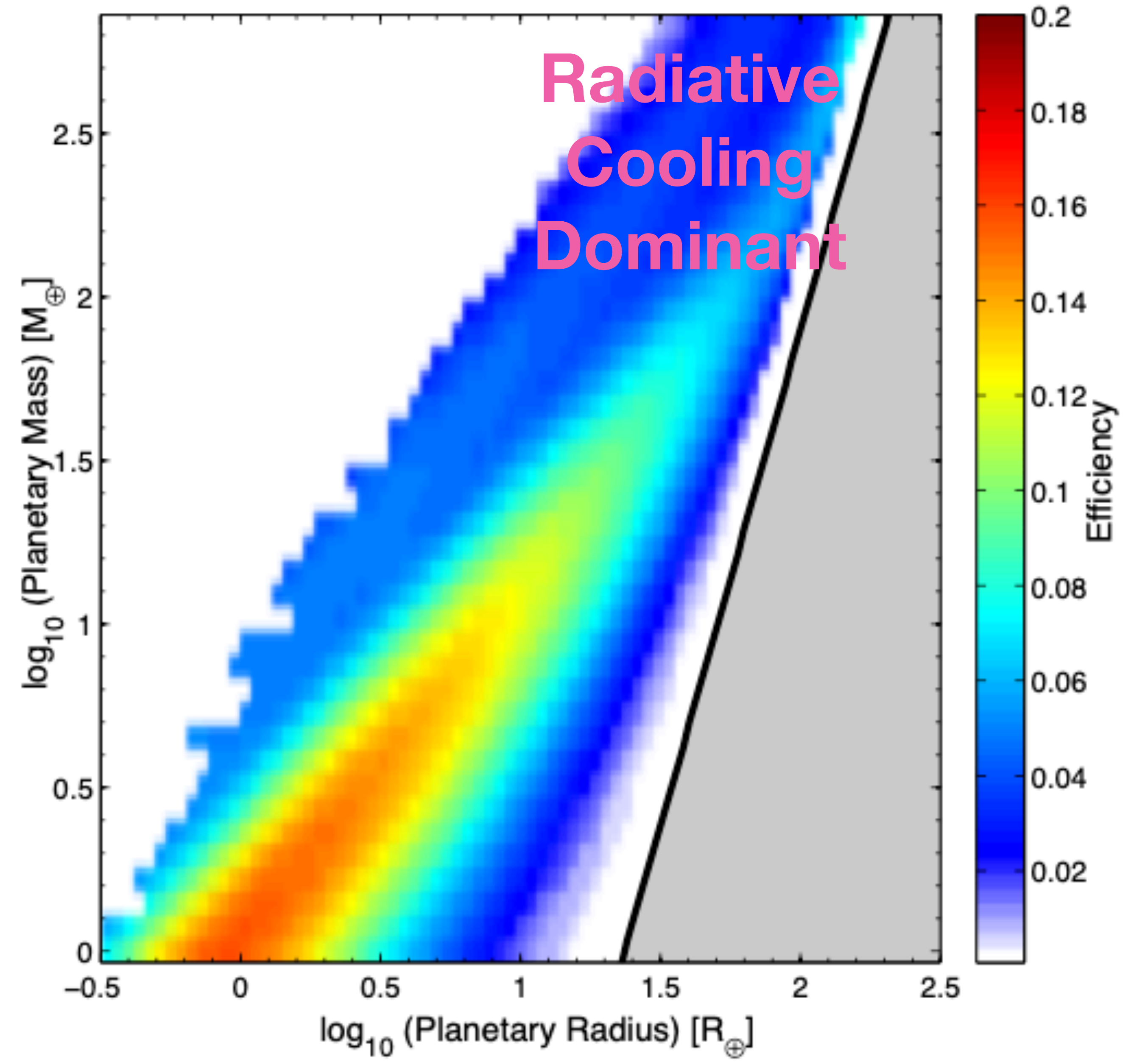


Giant planets are stable against atmospheric loss, without other processes

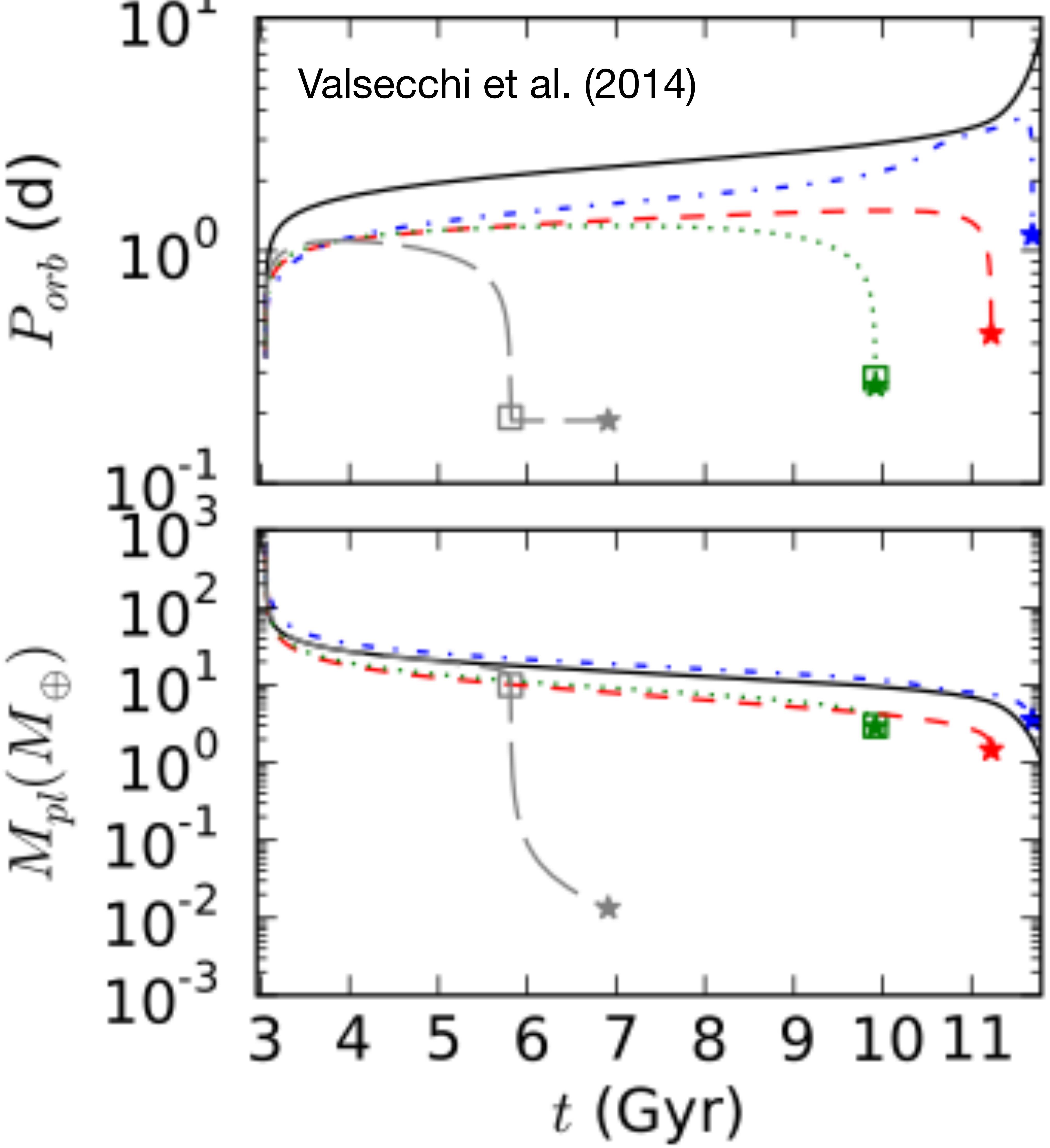
Hot Jupiters



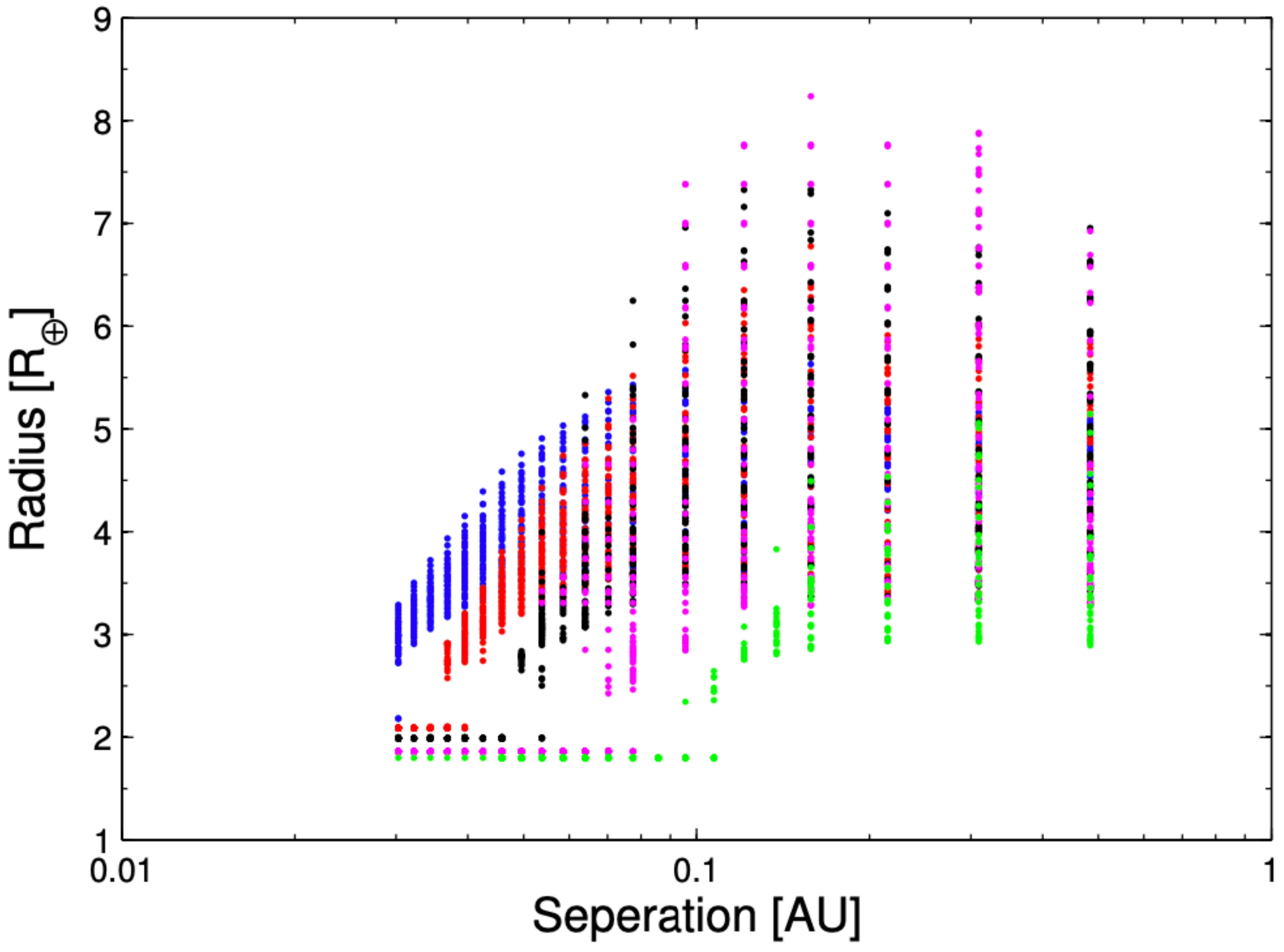
Earlier:

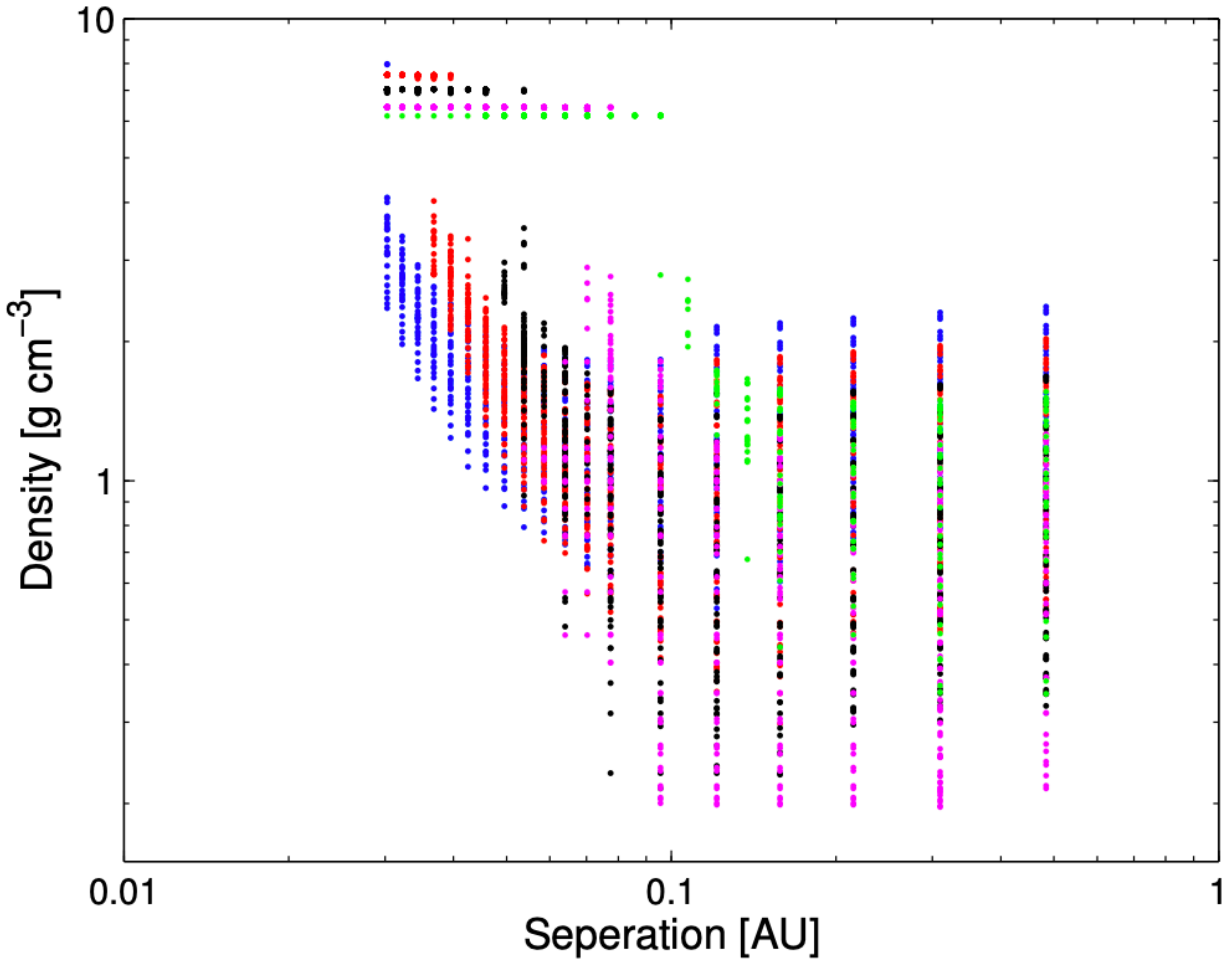


Including high-e migration, photoevaporation and Roche Lobe overflow.



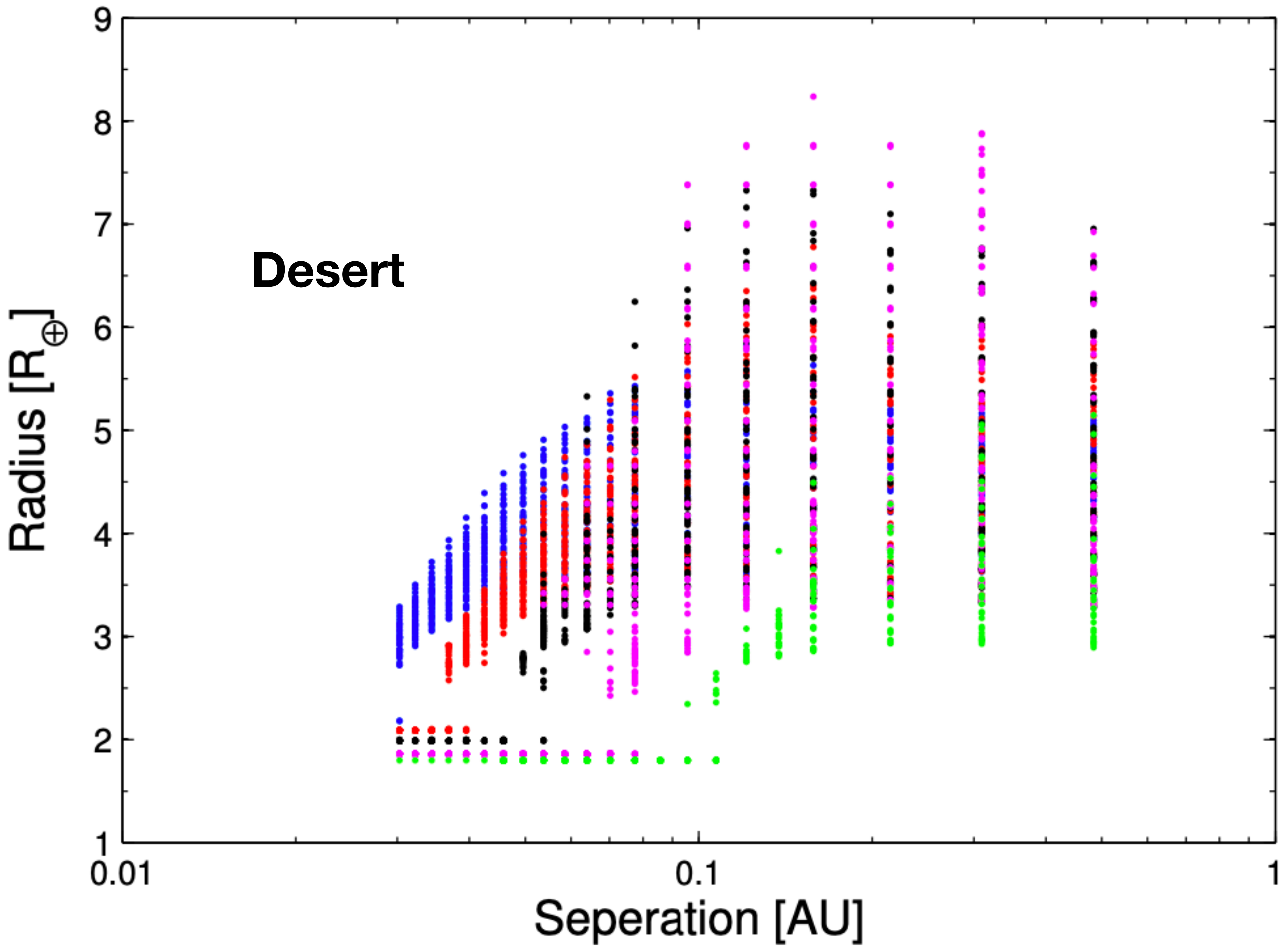
Population-level work on atmospheric escape

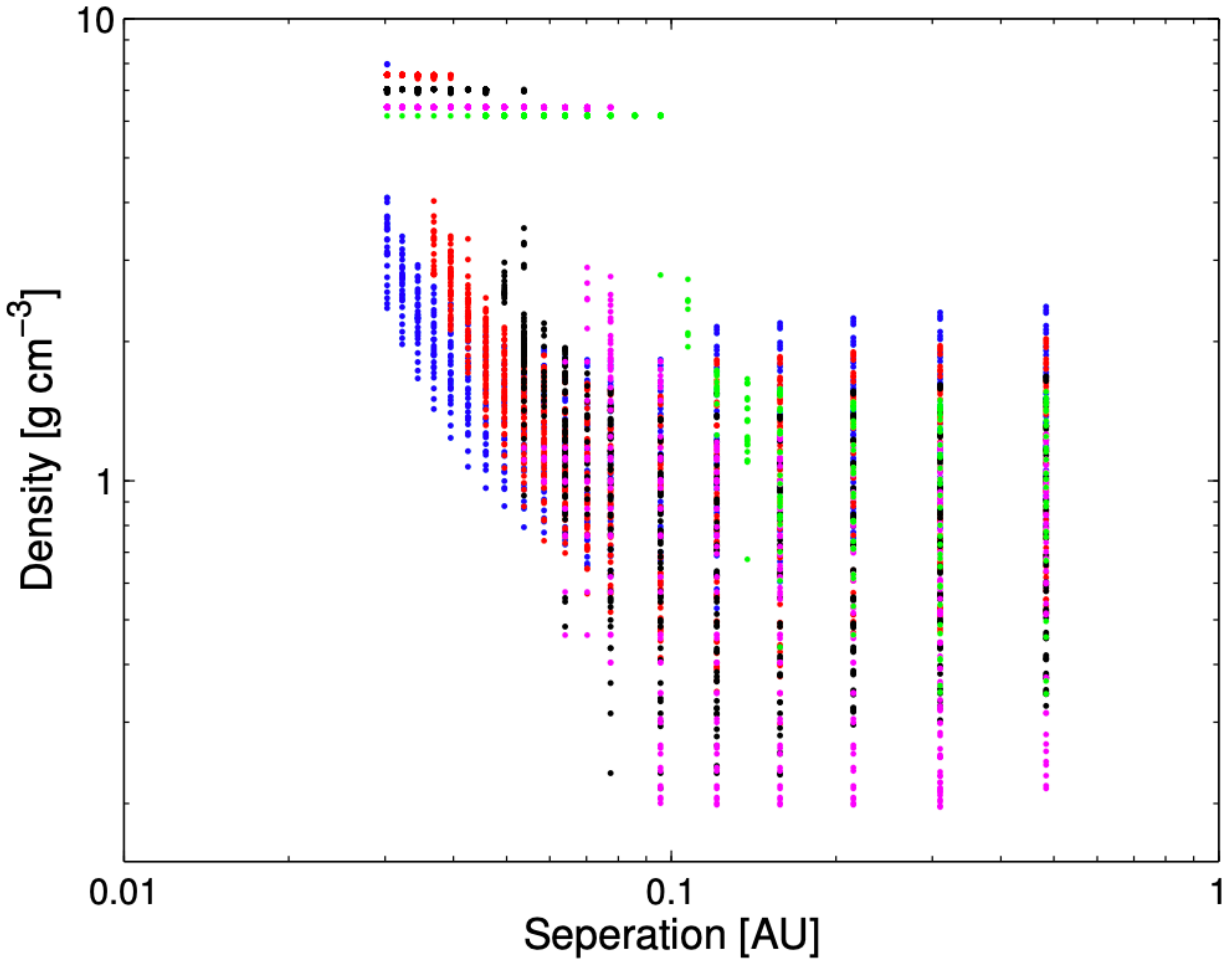




Owen & Wu (2013)

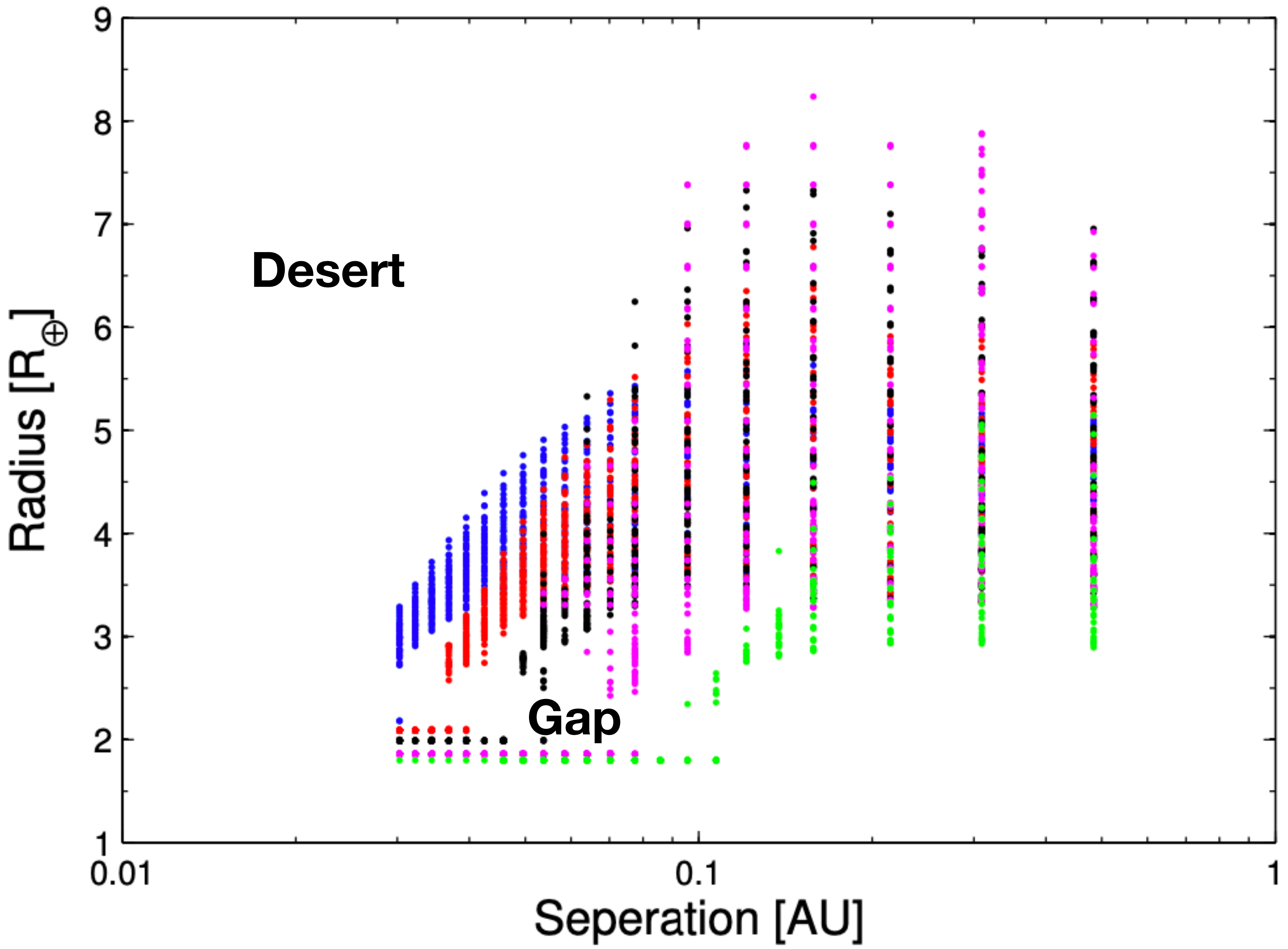
Population-level work on atmospheric escape

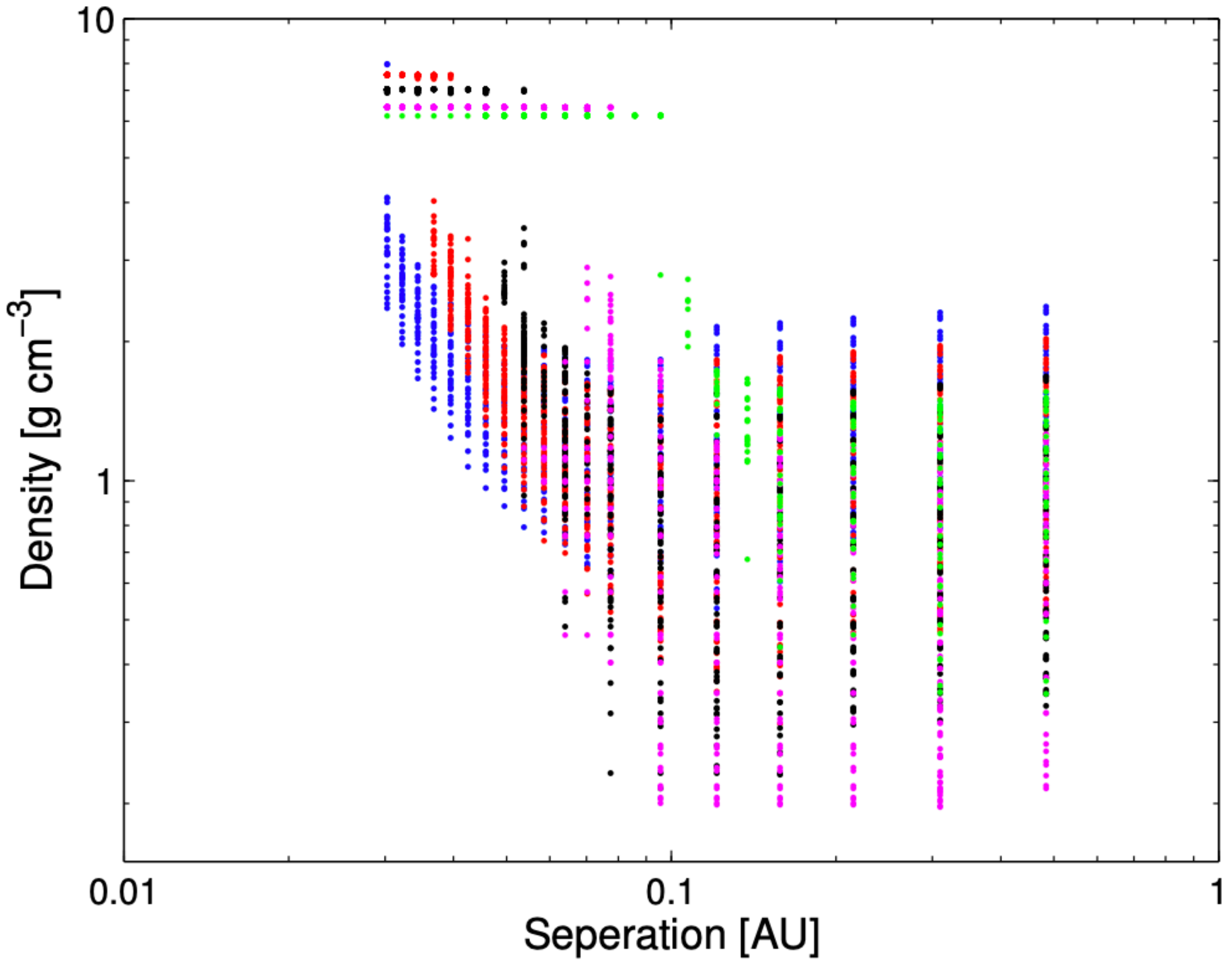




Owen & Wu (2013)

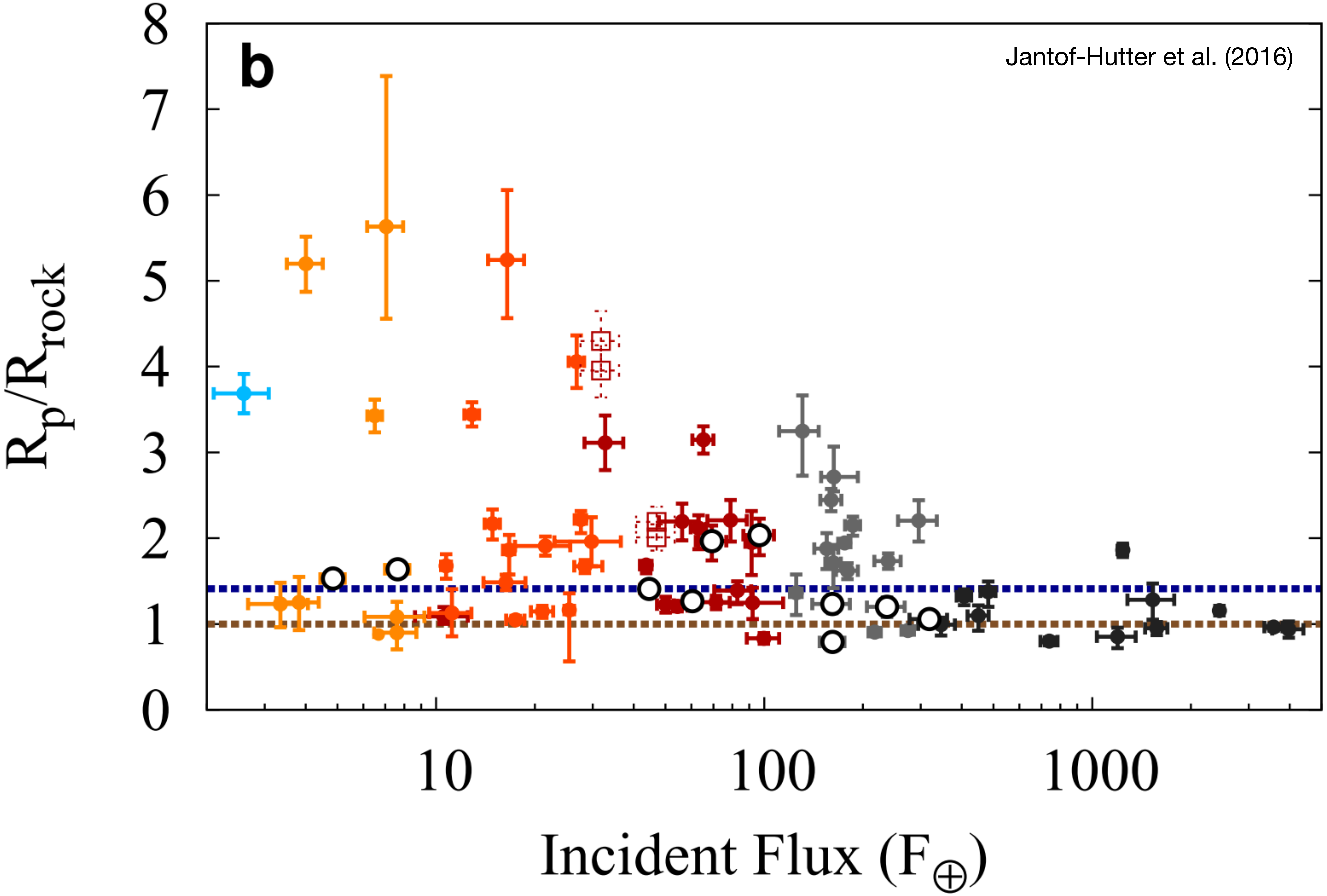
Population-level work on atmospheric escape





Owen & Wu (2013)

Some sub-Neptunes must have primordial atmospheres



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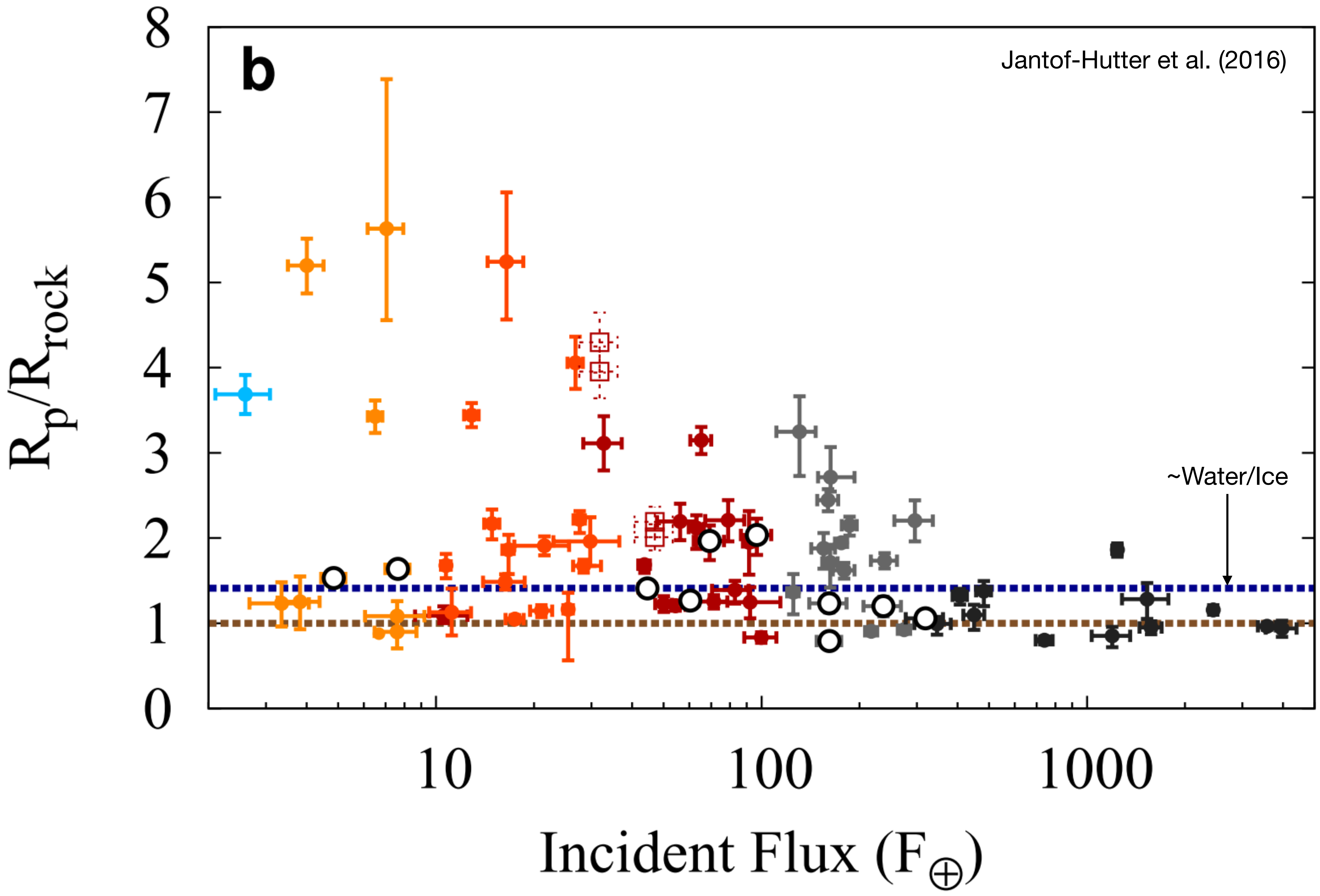
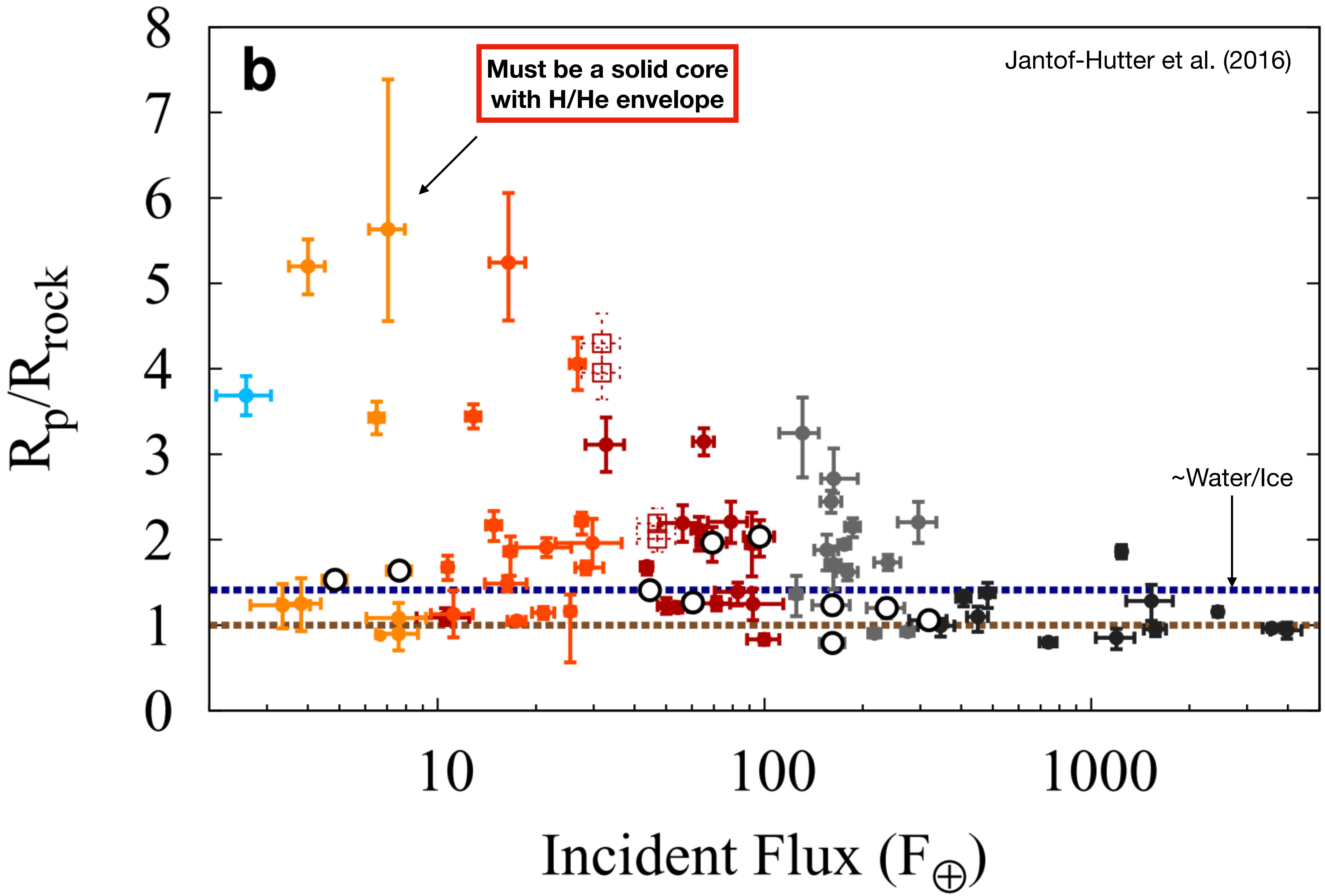


Some sub-Neptunes must have primordial atmospheres



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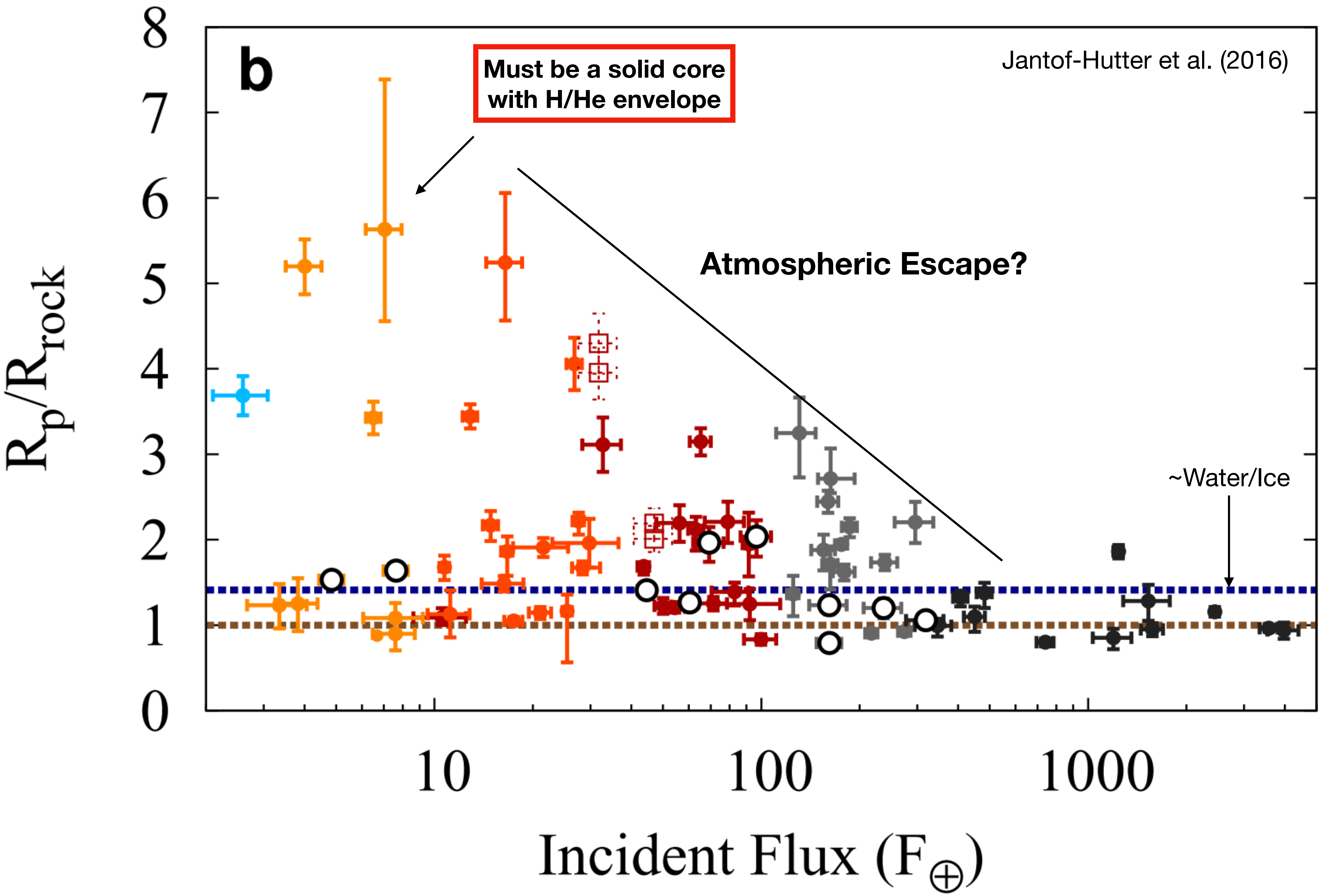

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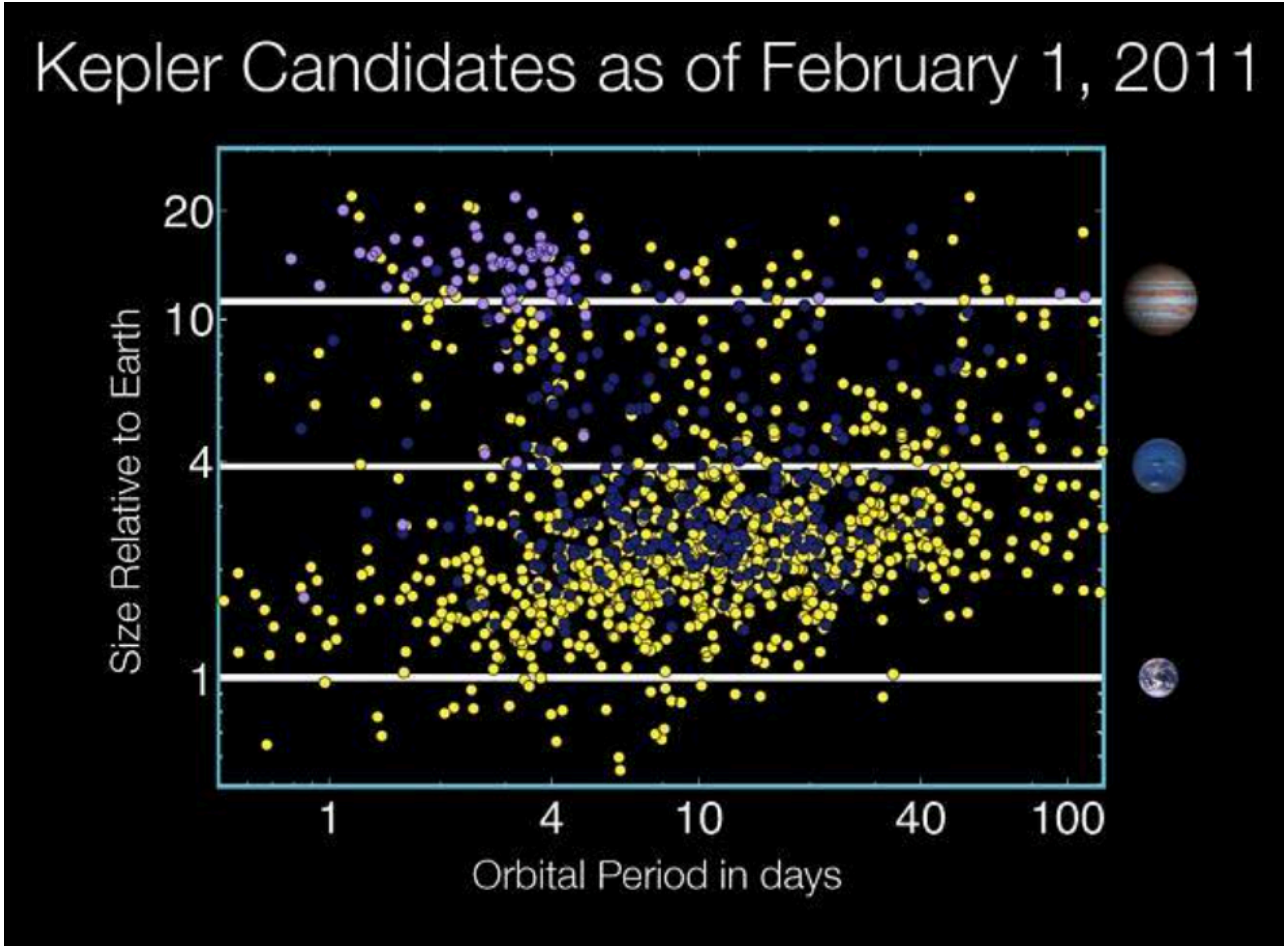
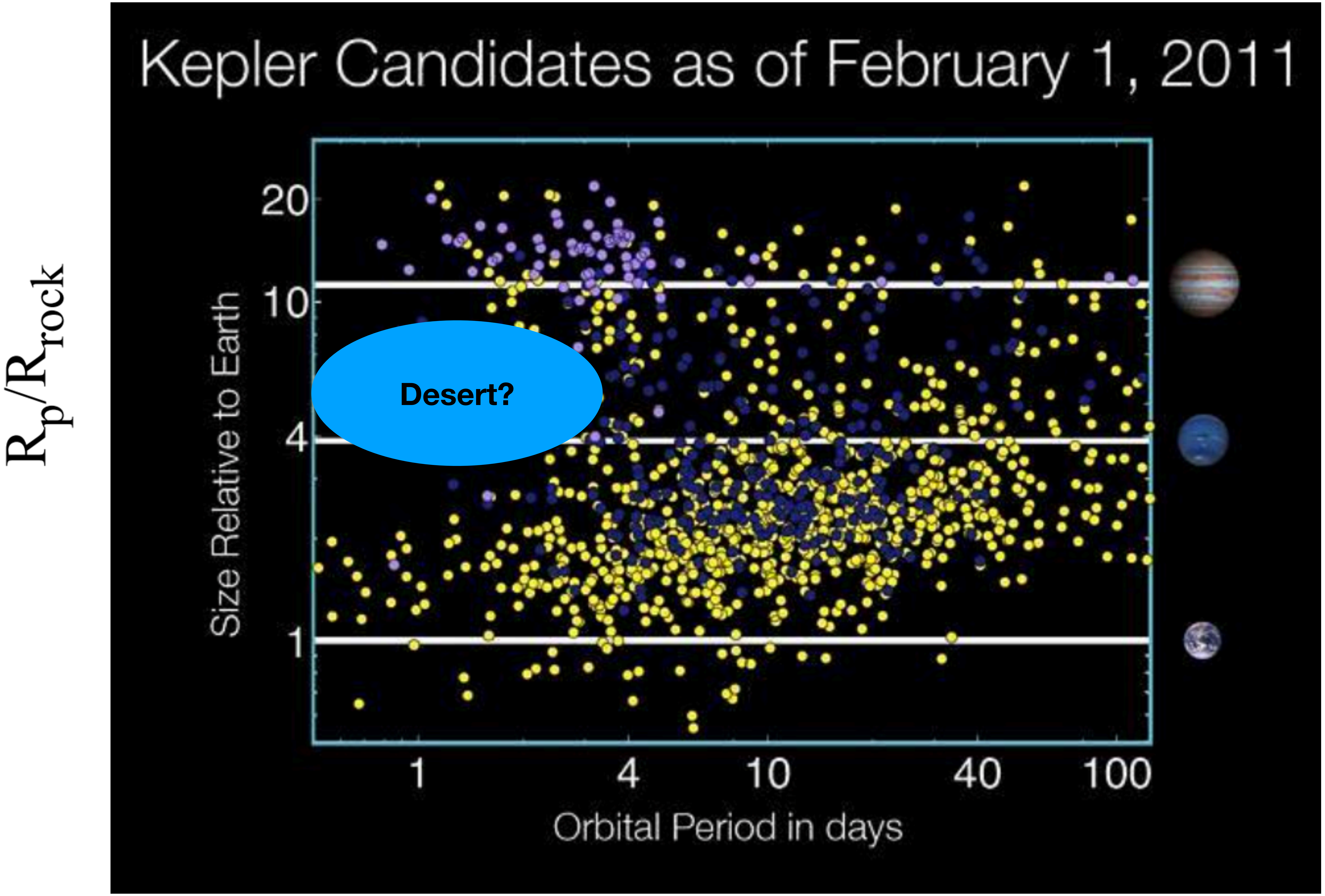
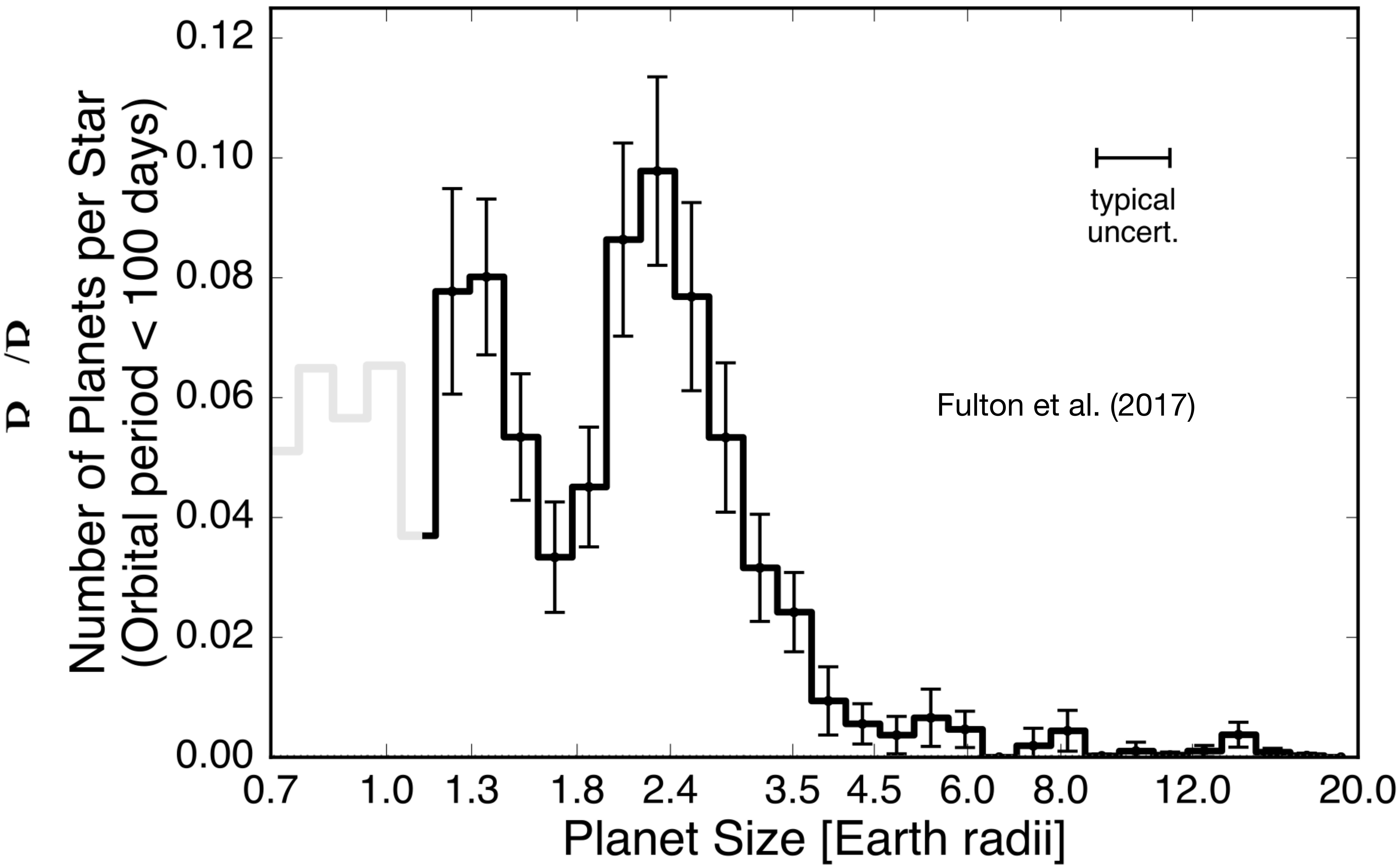


R_p/R_{rock}

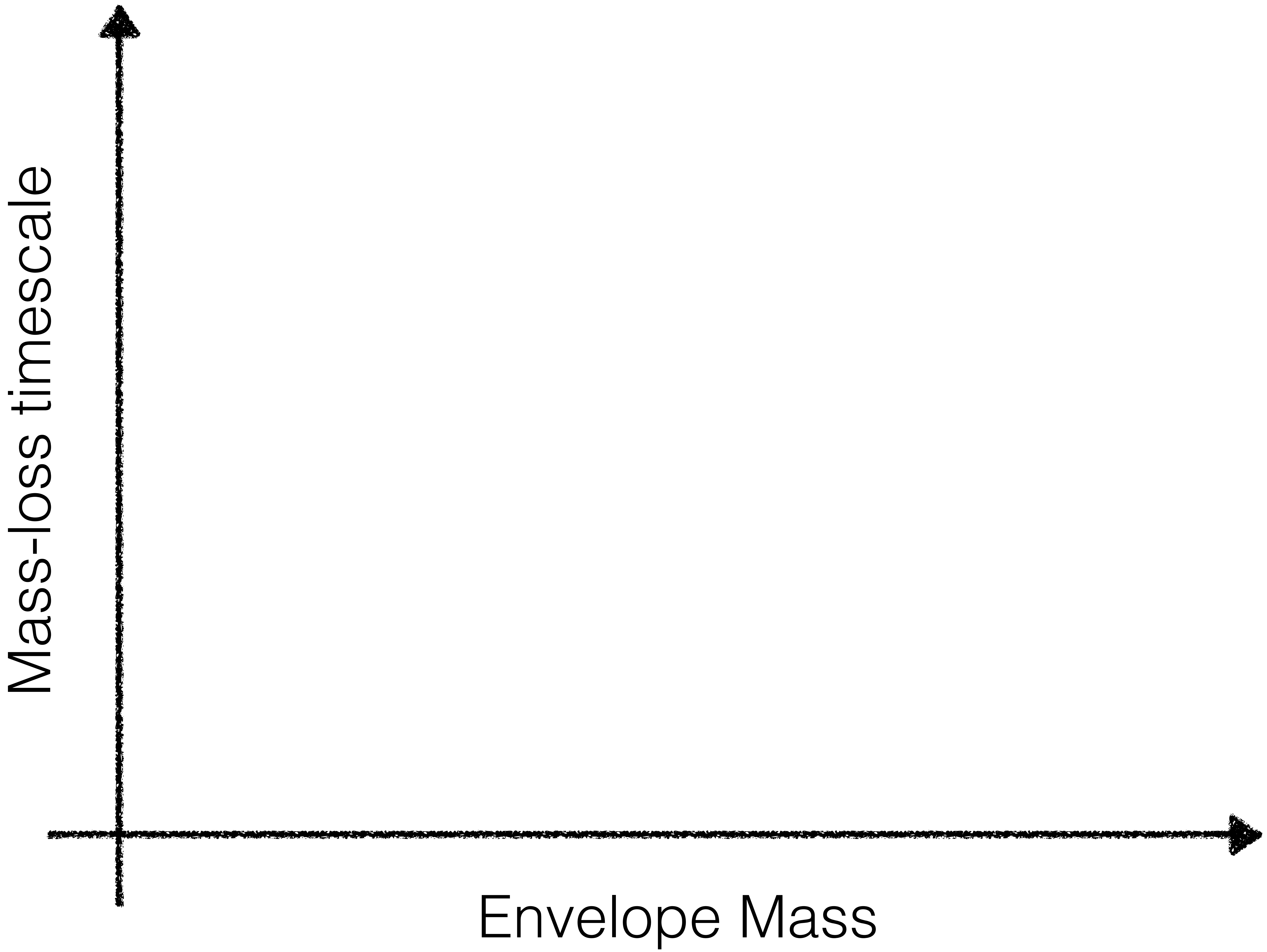
Some sub-Neptunes must have primordial atmospheres

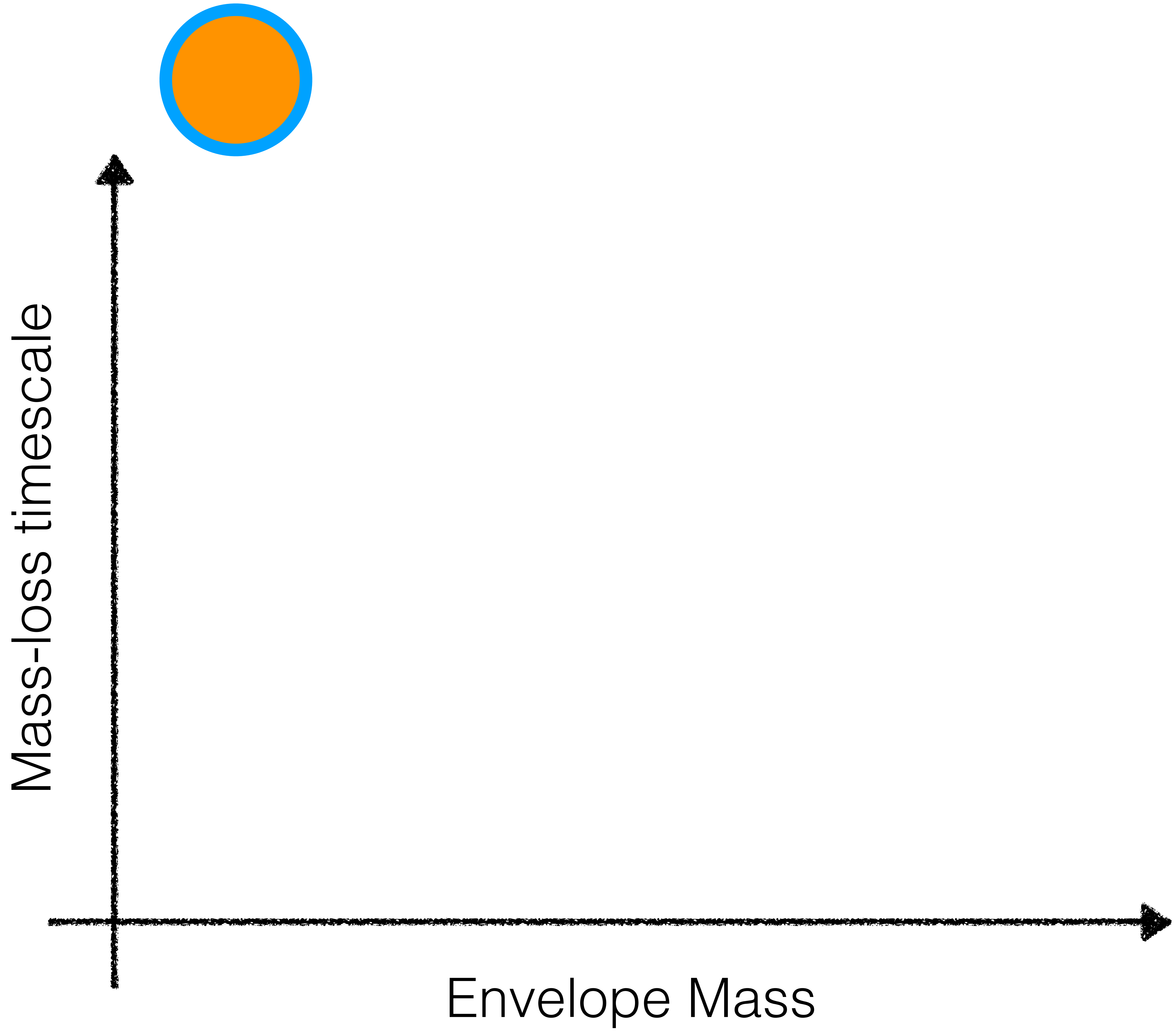


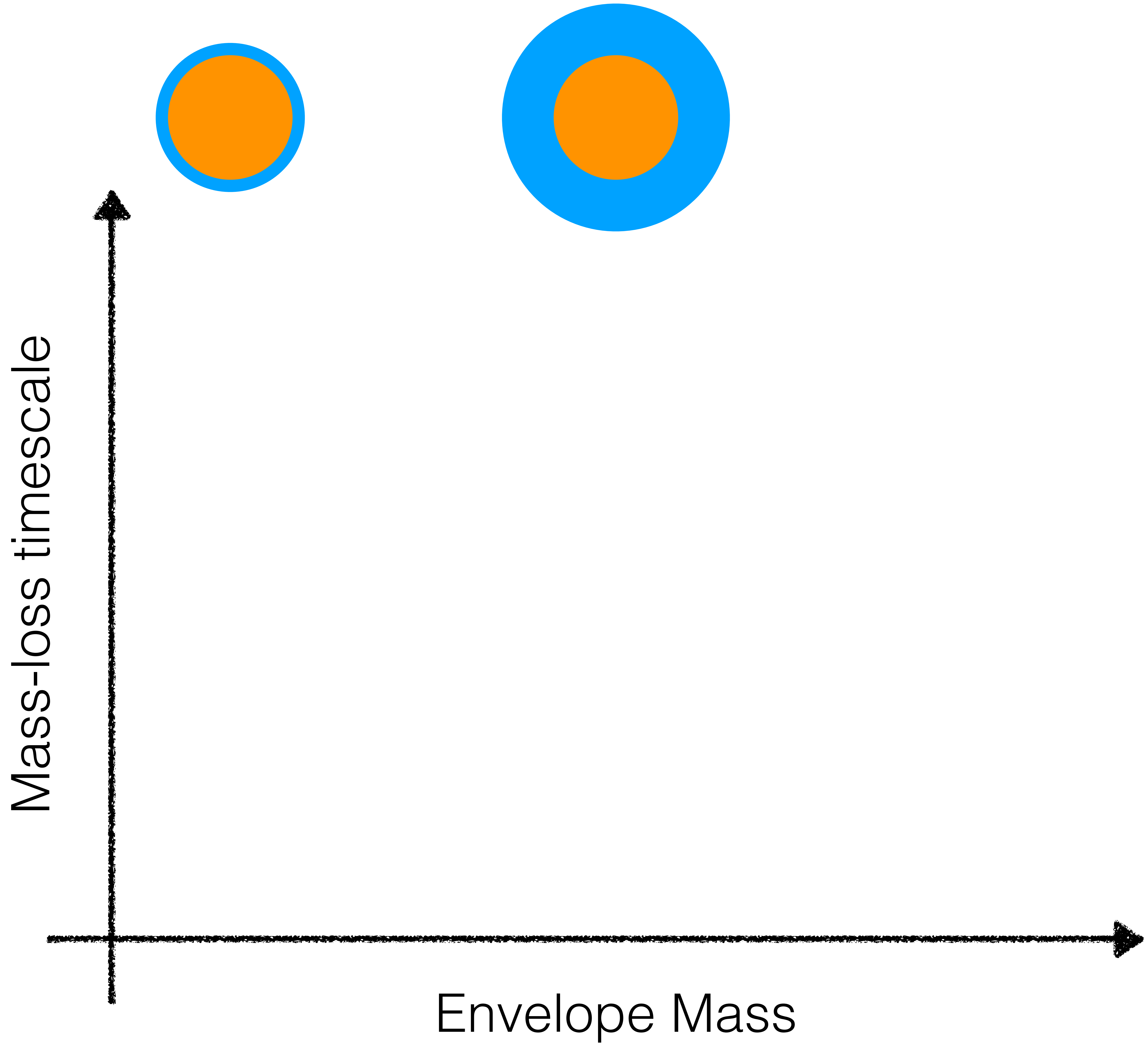
Some sub-Neptunes must have primordial atmospheres



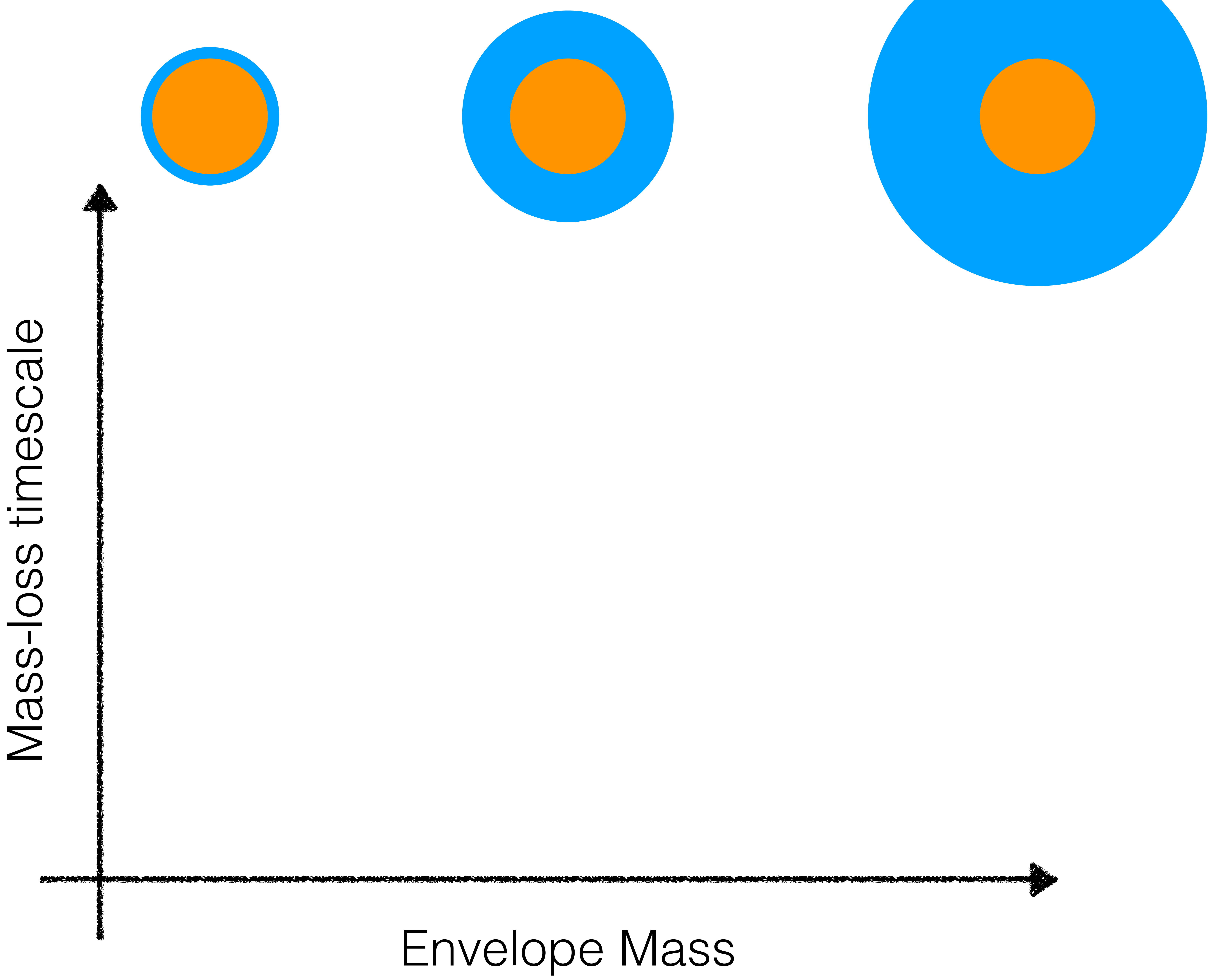
Why do you get an occurrence valley?

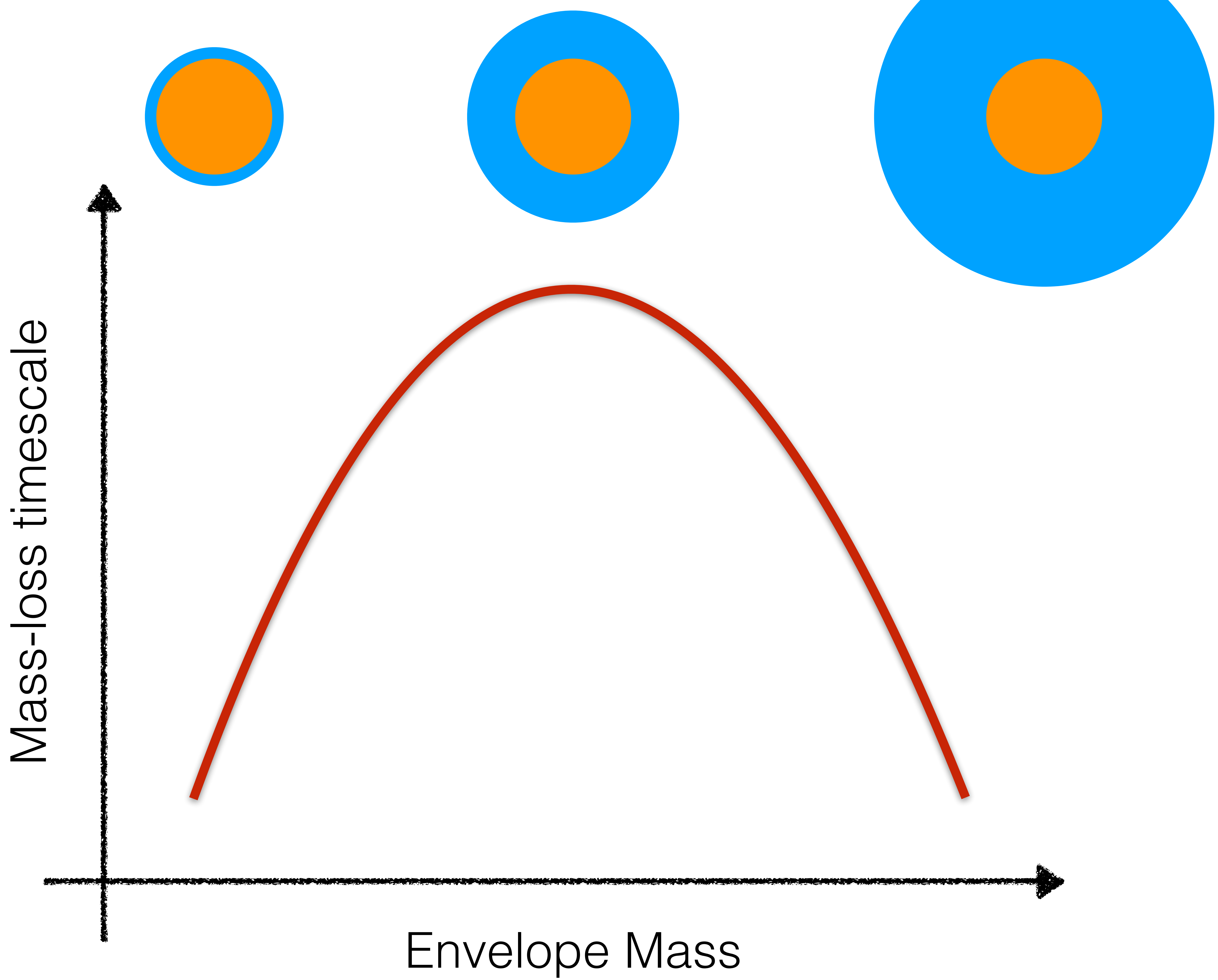

Mass-loss timescale
Envelope Mass

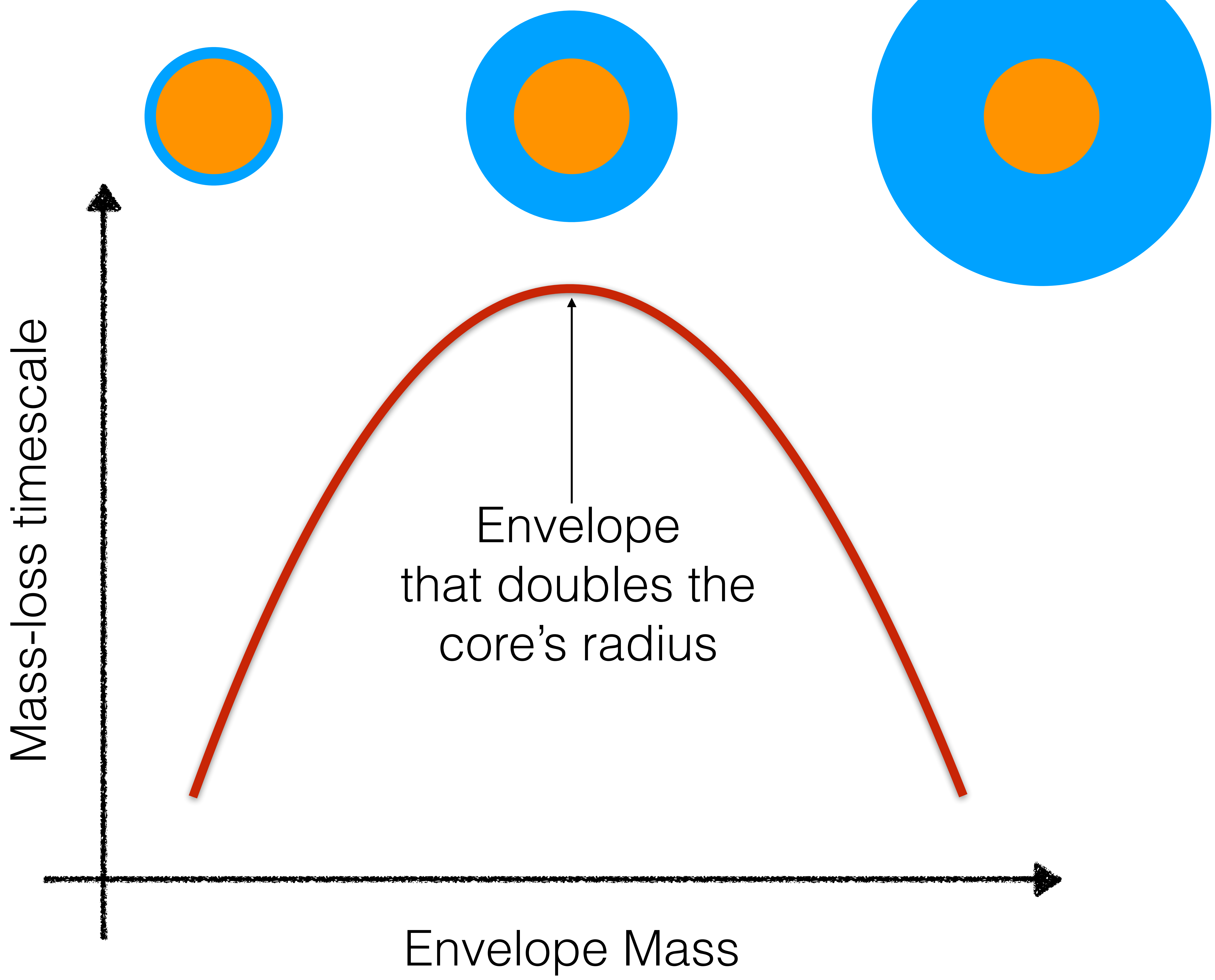

Mass-loss timescale
Envelope Mass

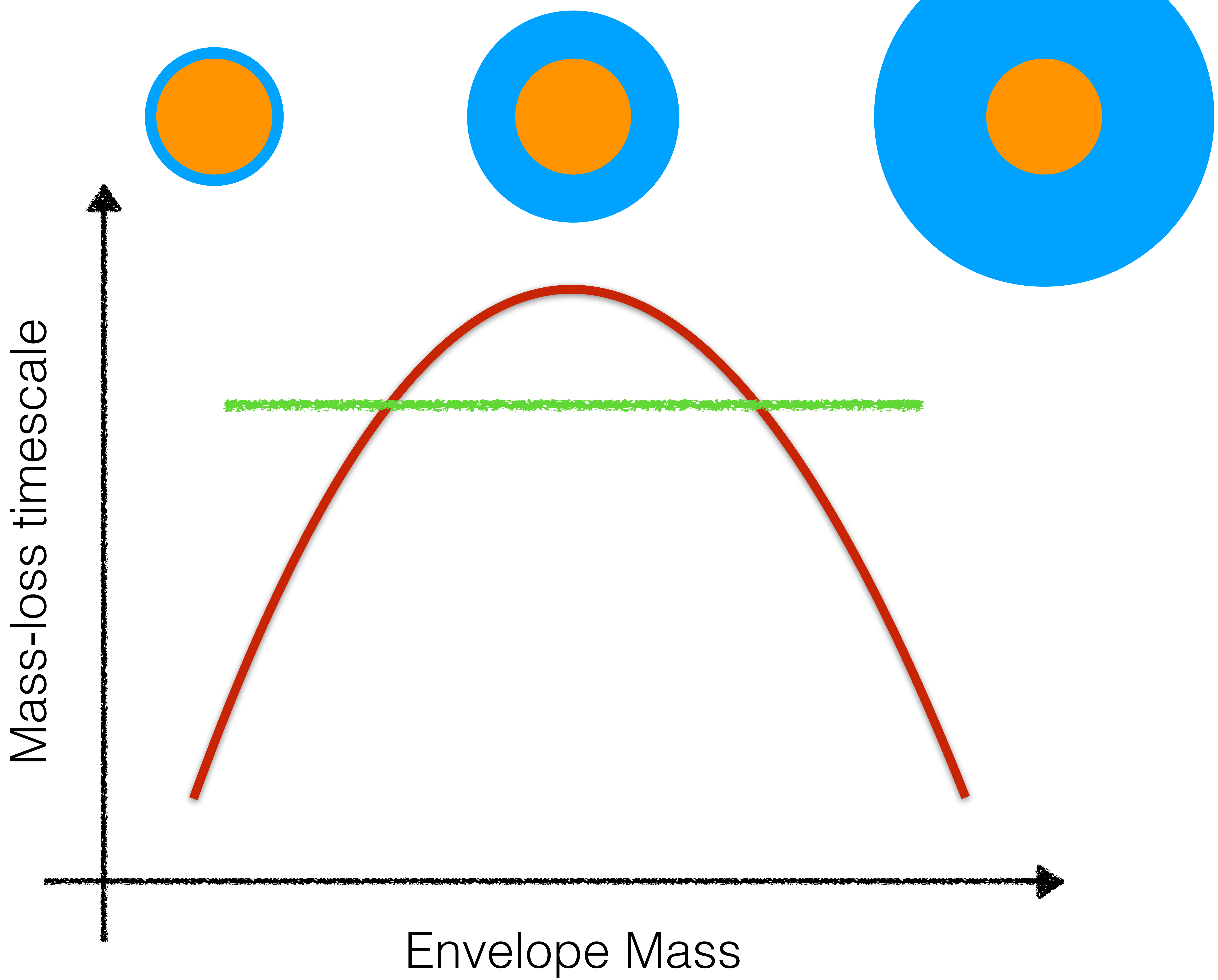


Mass-loss timescale
Envelope Mass

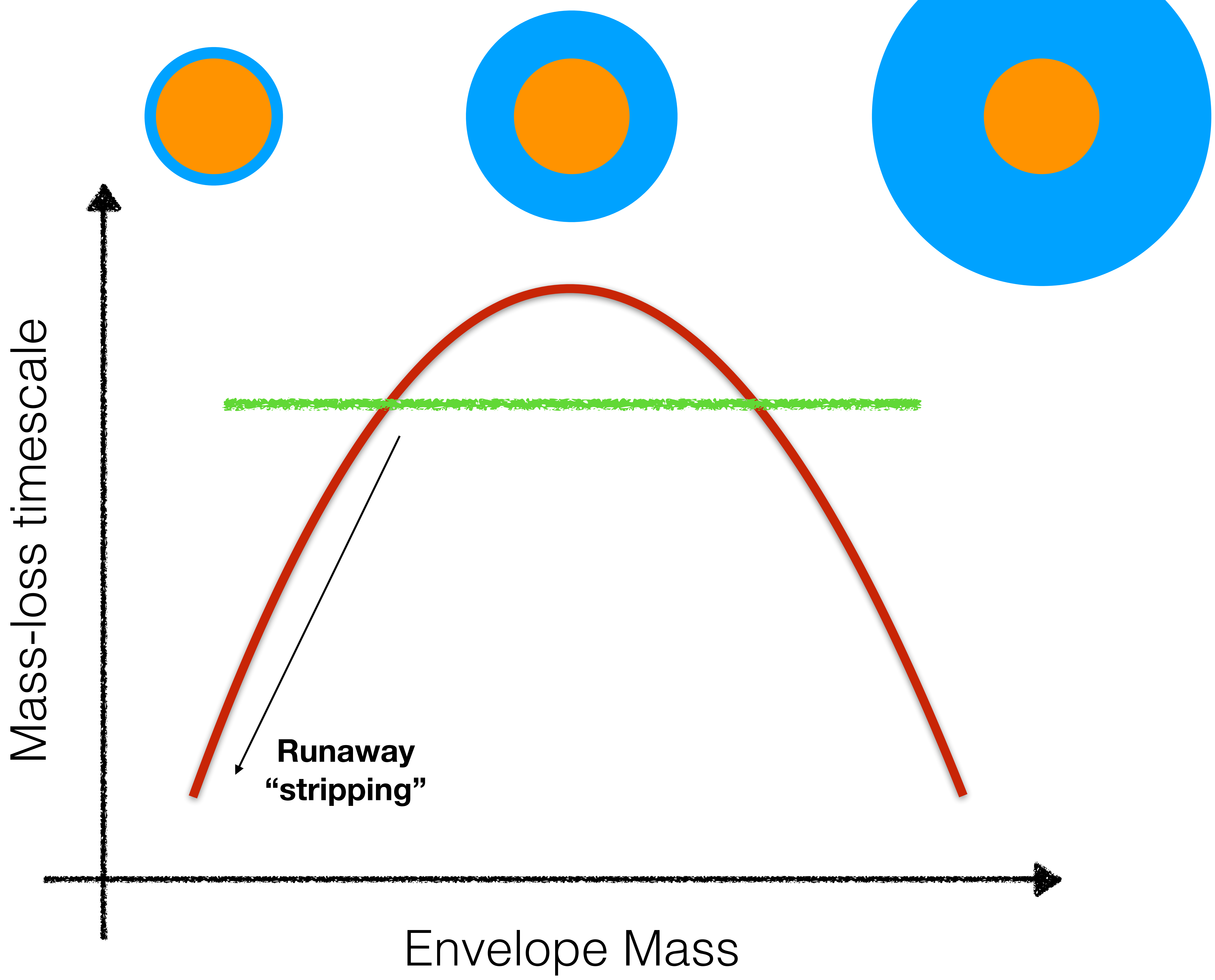

Mass-loss timescale
Envelope Mass

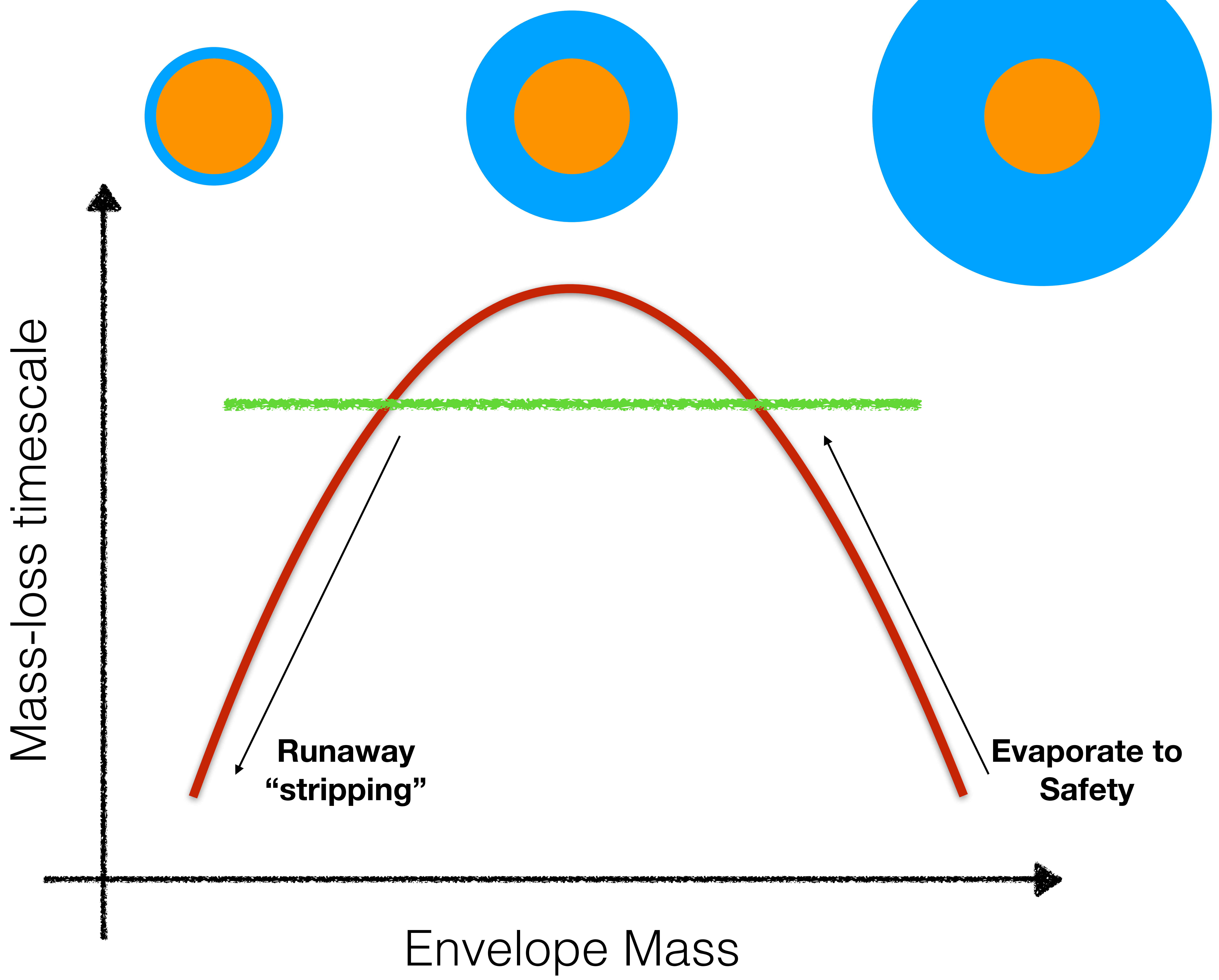

Mass-loss timescale
Envelope Mass


Mass-loss timescale
Envelope
that doubles the
core's radius
Envelope Mass

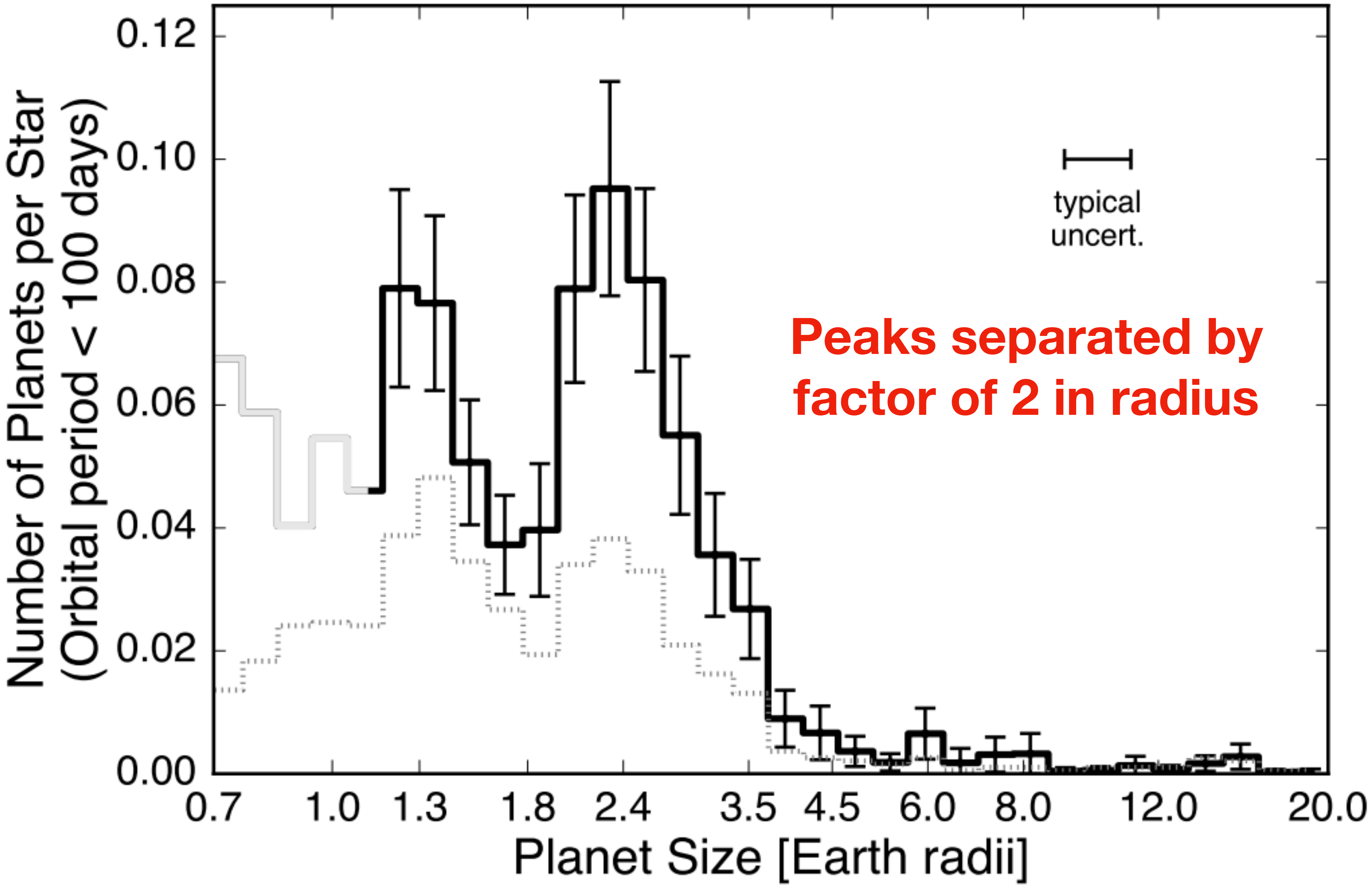


Mass-loss timescale
Envelope Mass


Mass-loss timescale
Runaway
“stripping”
Envelope Mass

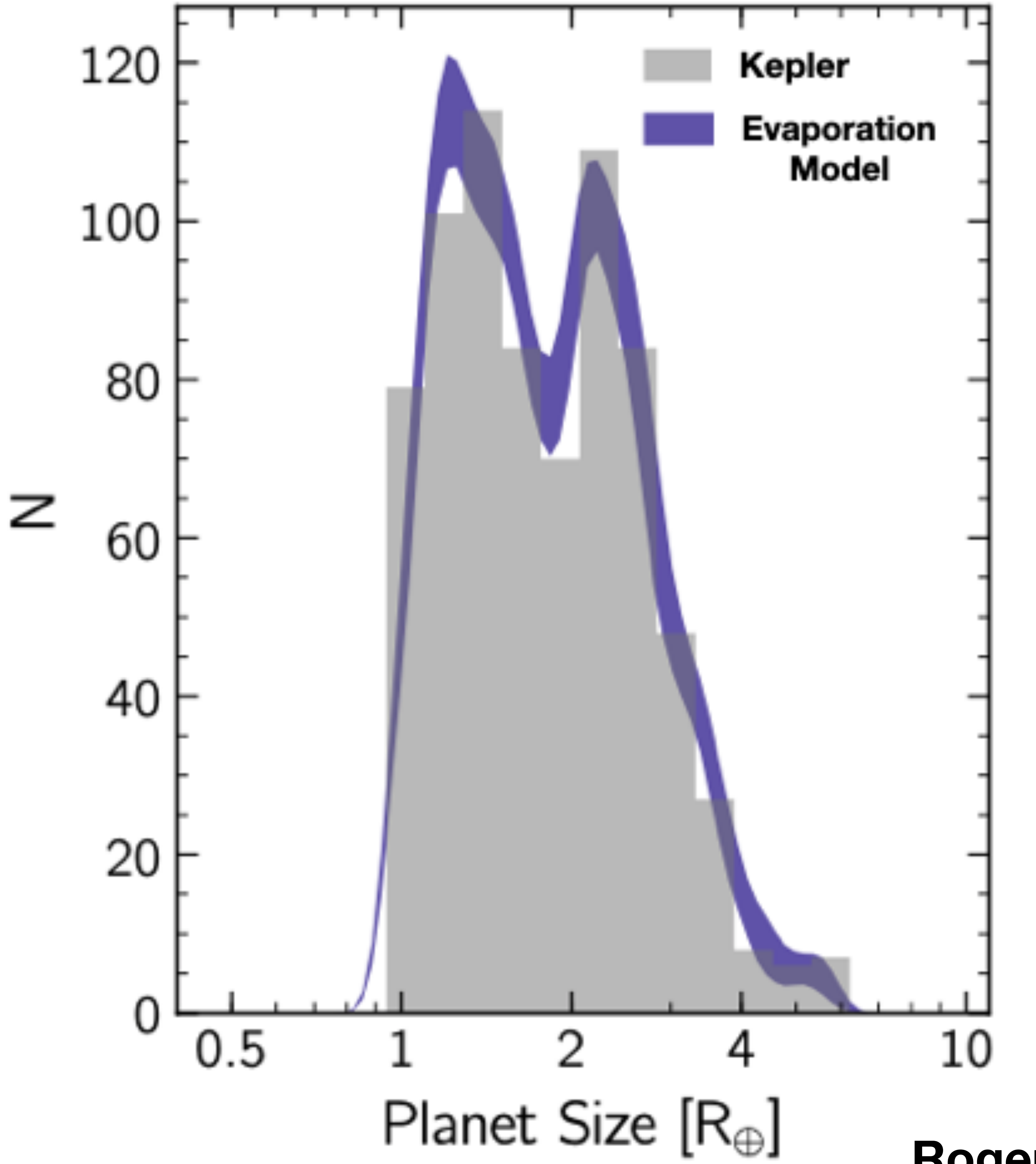

Mass-loss timescale
Runaway
"stripping"
Evaporate to
Safety
Envelope Mass

The Radius Gap/Valley



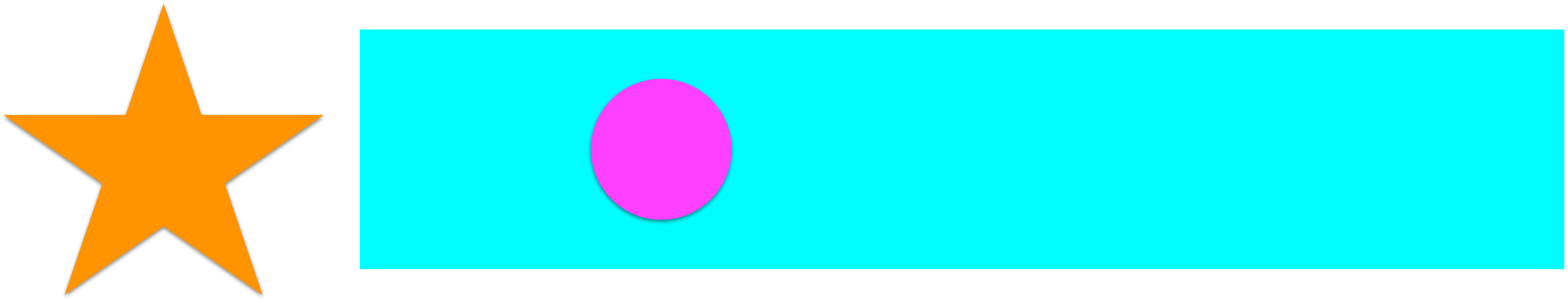
Fulton et al. 2017

Model comparison



Rogers & Owen (2021)

The Birth of Primordial Sub-Neptune Atmosphere



$t_{cool} \sim$ Myr

‘Boil-off’

The Birth of Primordial Sub-Neptune Atmosphere

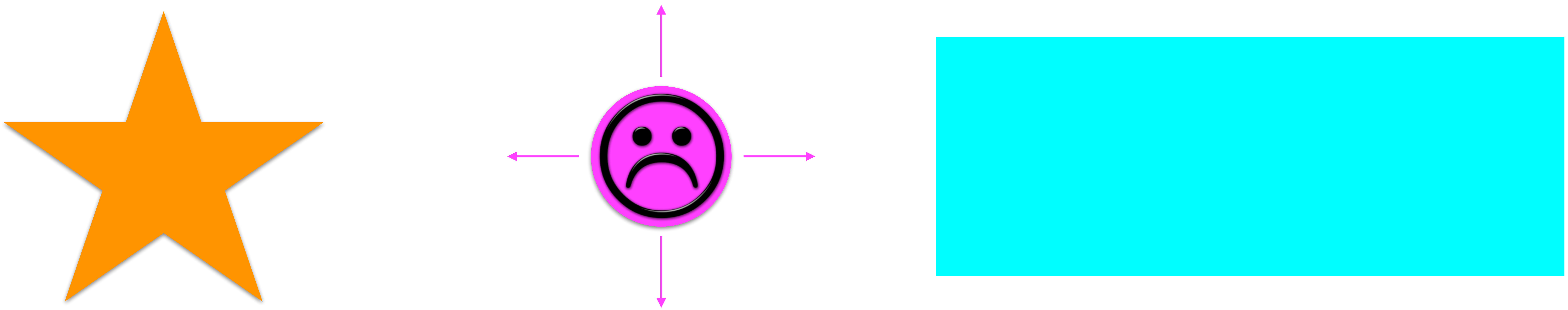
$t_{clear} < 0.1$ Myr

$t_{cool} \sim$ Myr

'Boil-off'

The Birth of Primordial Sub-Neptune Atmosphere

$t_{clear} < 0.1$ Myr



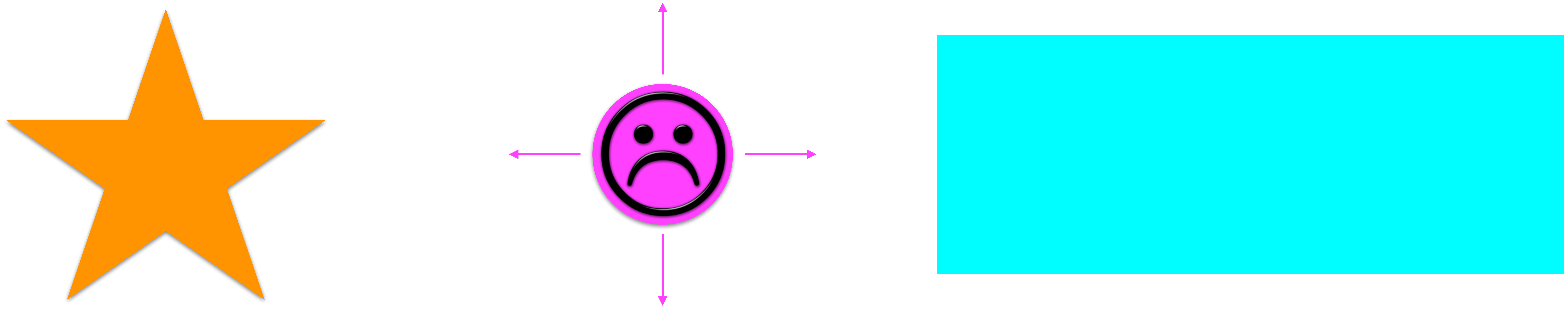
$t_{cool} \sim$ Myr

‘Boil-off’

The Birth of Primordial Sub-Neptune Atmosphere

First stage of mass-loss: “Boil-off”

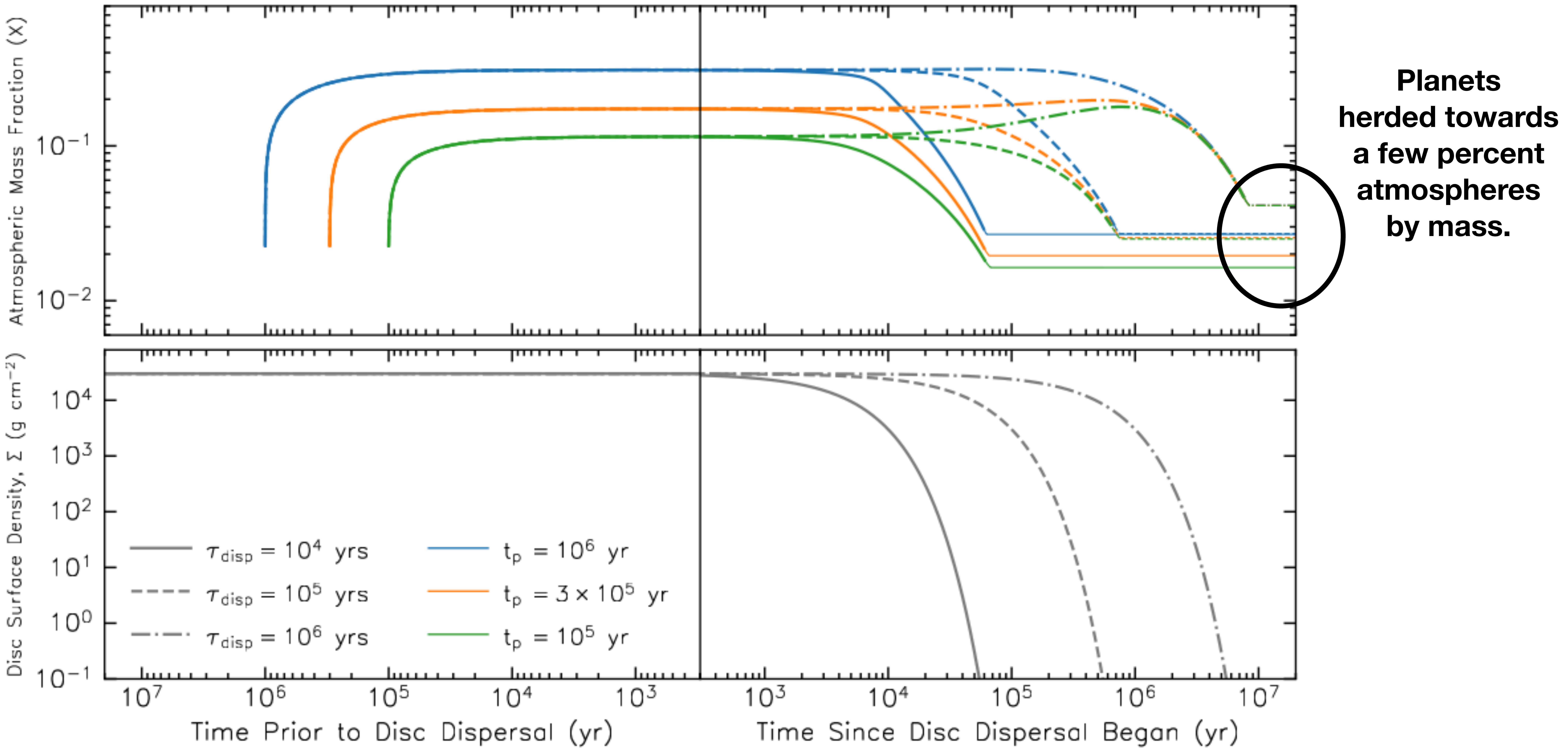
$t_{clear} < 0.1$ Myr



$t_{cool} \sim$ Myr

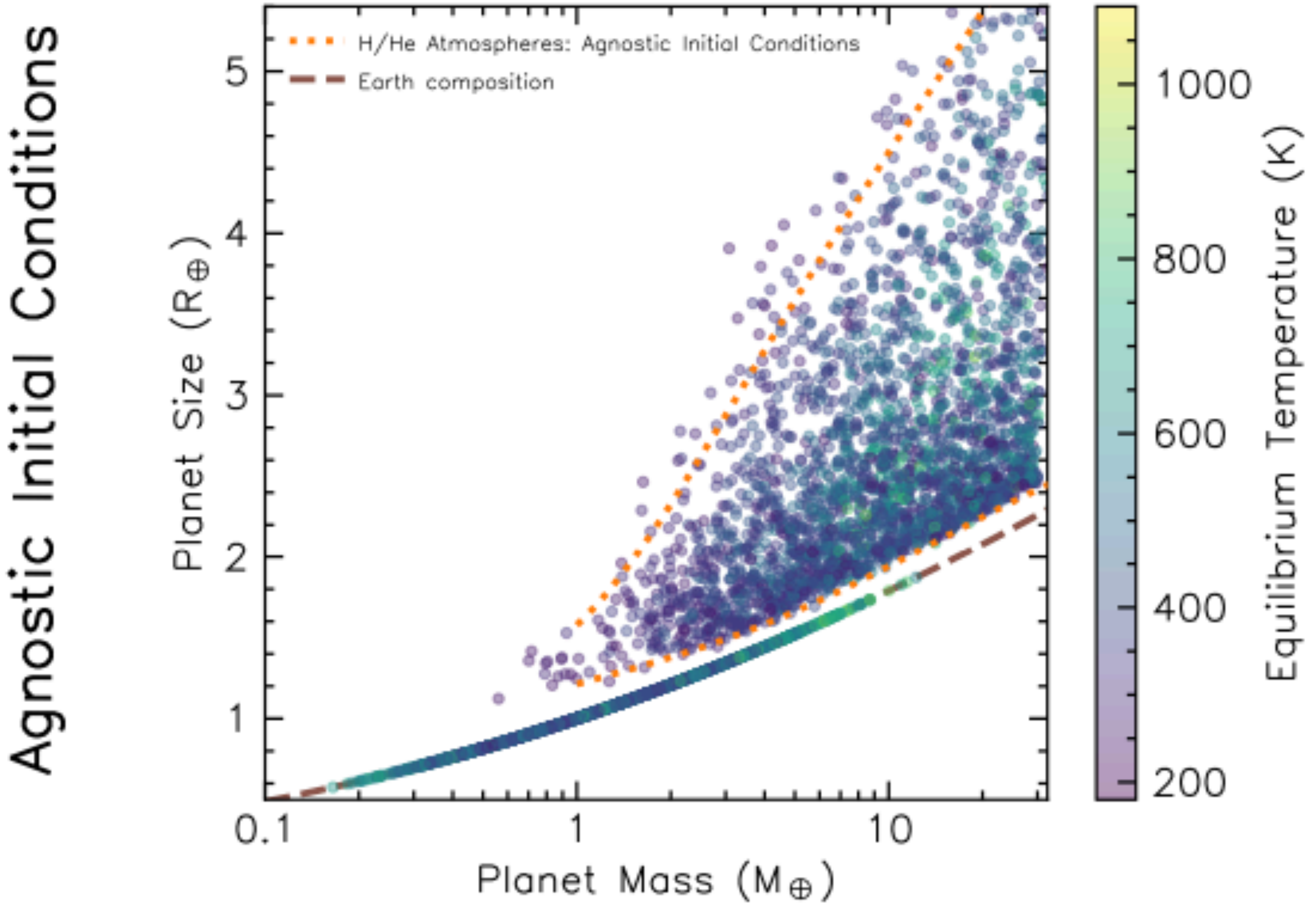
‘Boil-off’

Boil-off in action

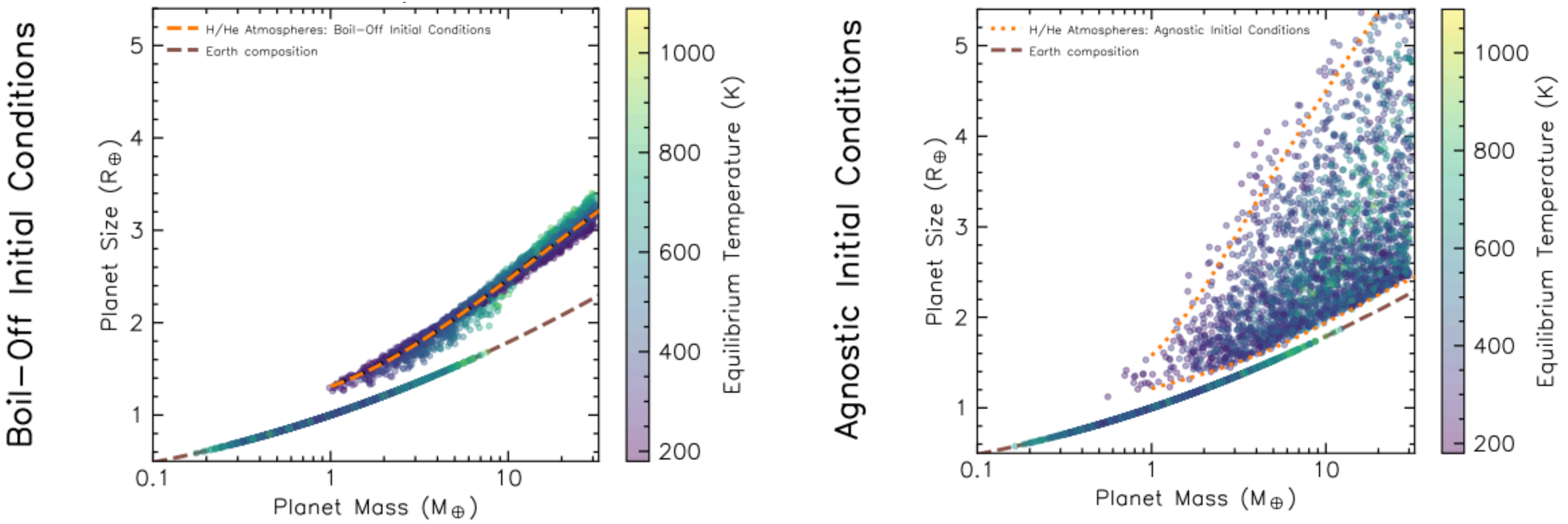


James Rogers (UCLA), Rogers et al. (2023)

Degeneracy in M-R space

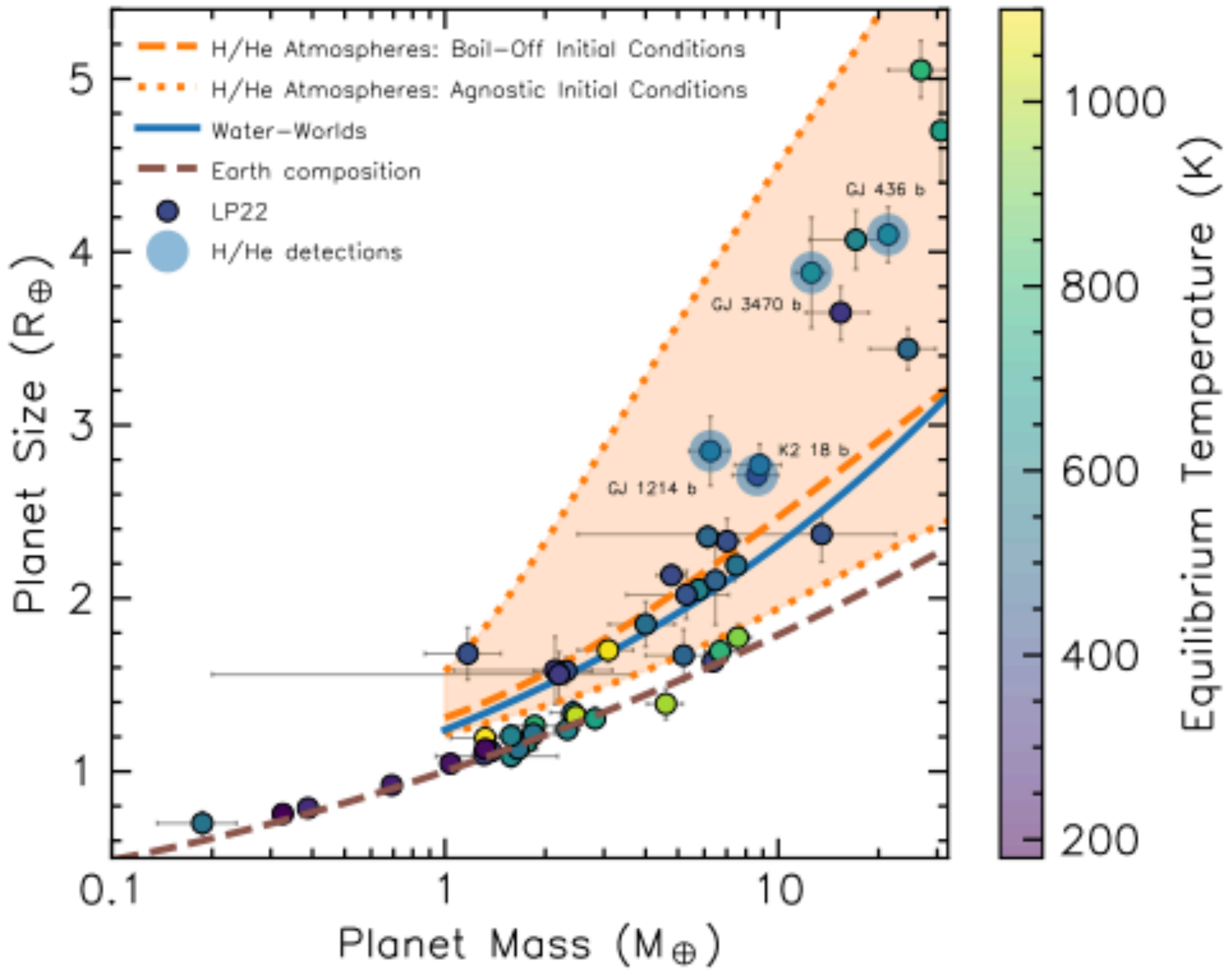


Degeneracy in M-R space



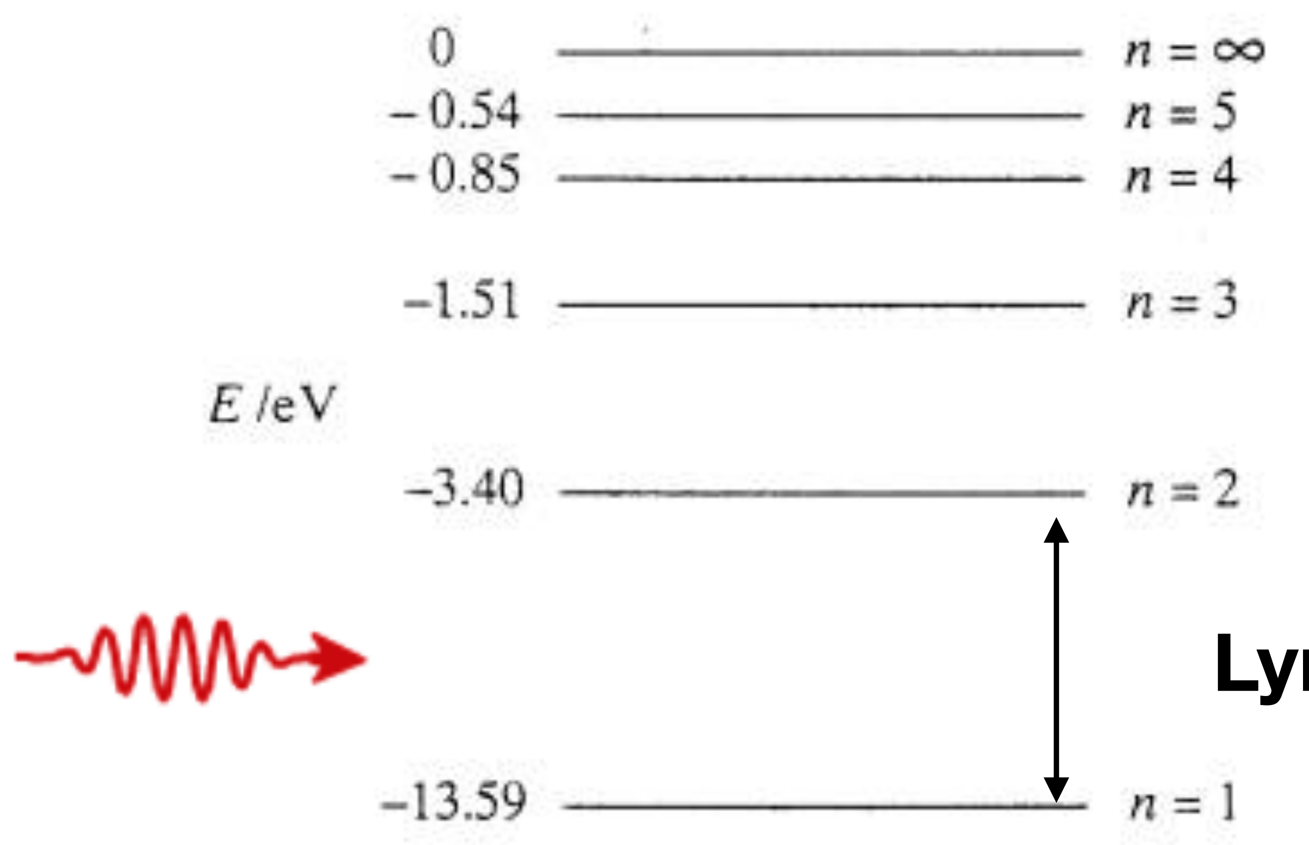
Degeneracy in M-R space

Observations



Break: questions?

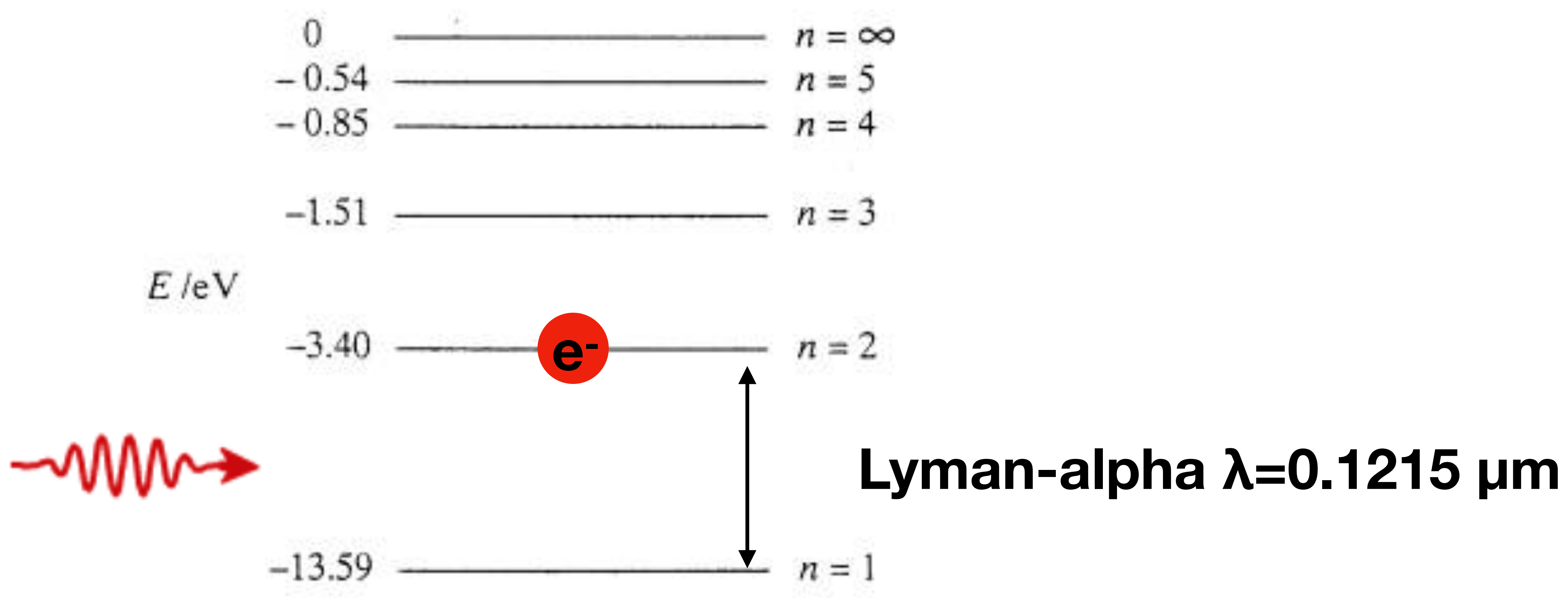
Lyman-alpha observations



Lyman-alpha λ=0.1215 μm

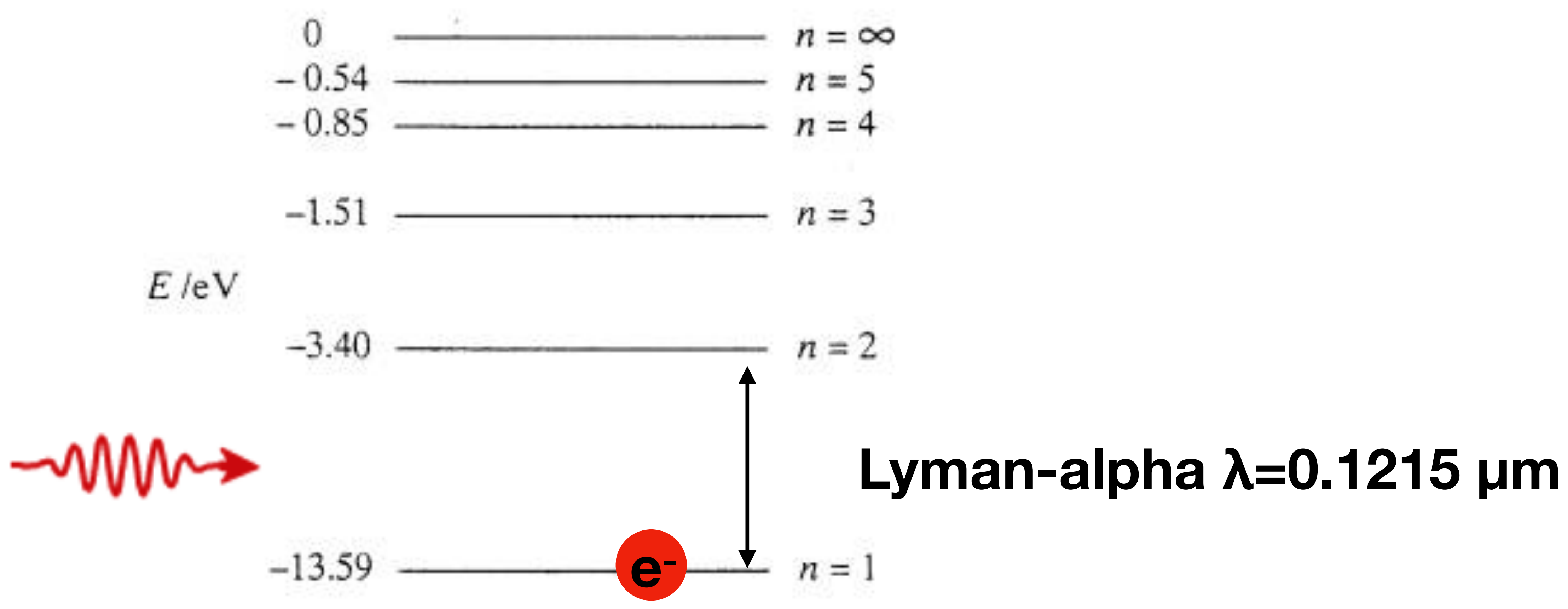
Hydrogen Energy Levels

Lyman-alpha observations



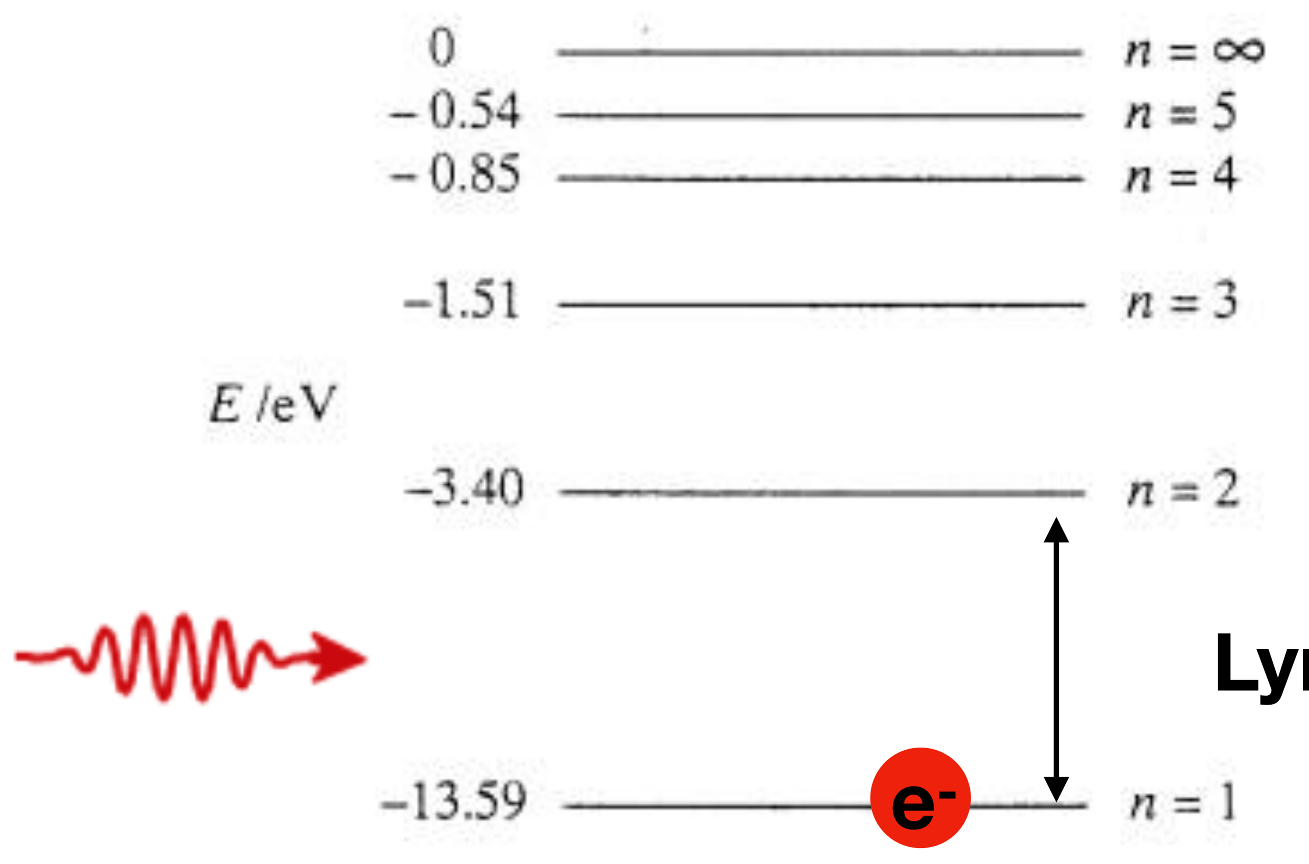
Hydrogen Energy Levels

Lyman-alpha observations



Hydrogen Energy Levels

Lyman-alpha observations



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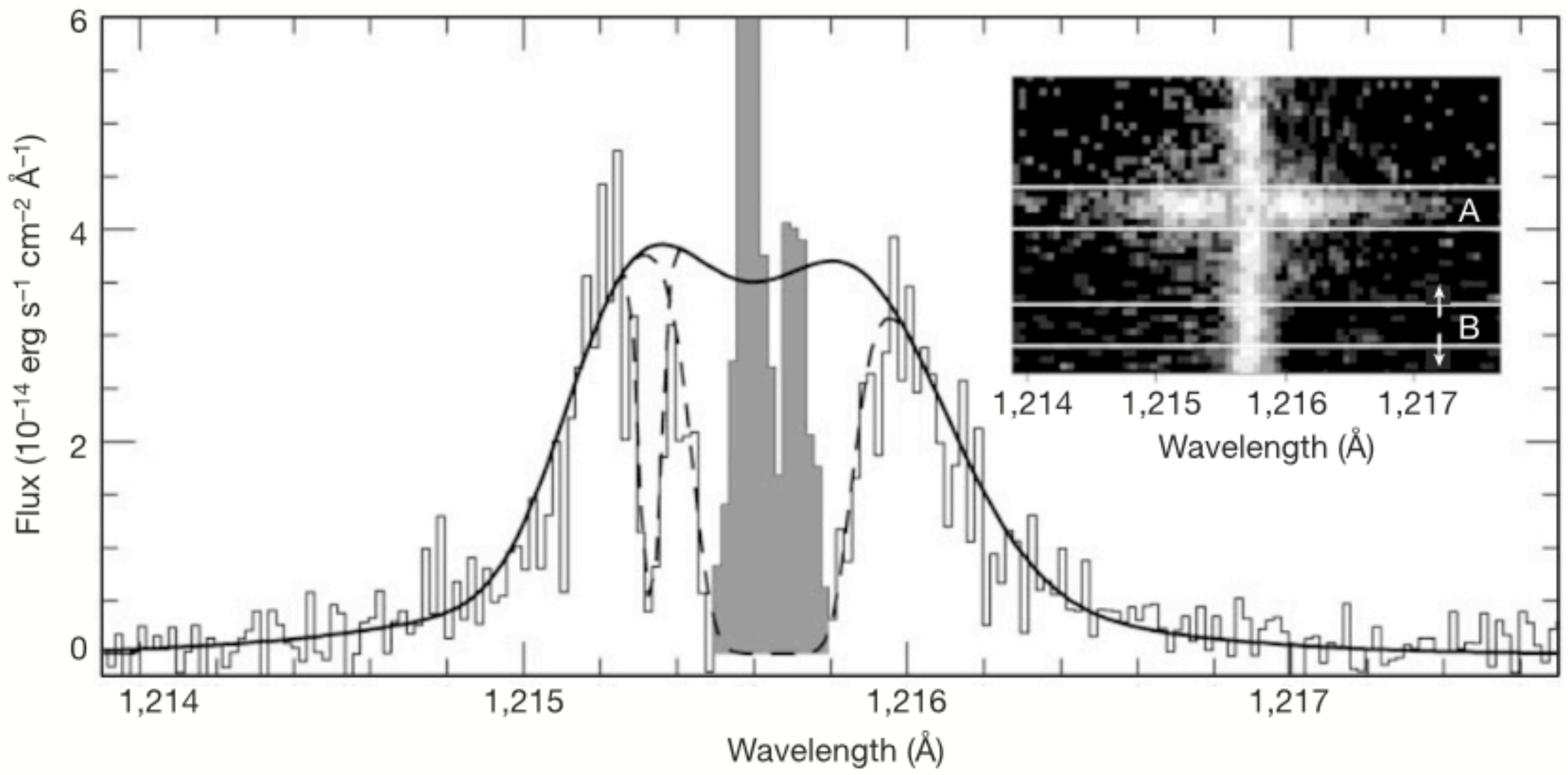
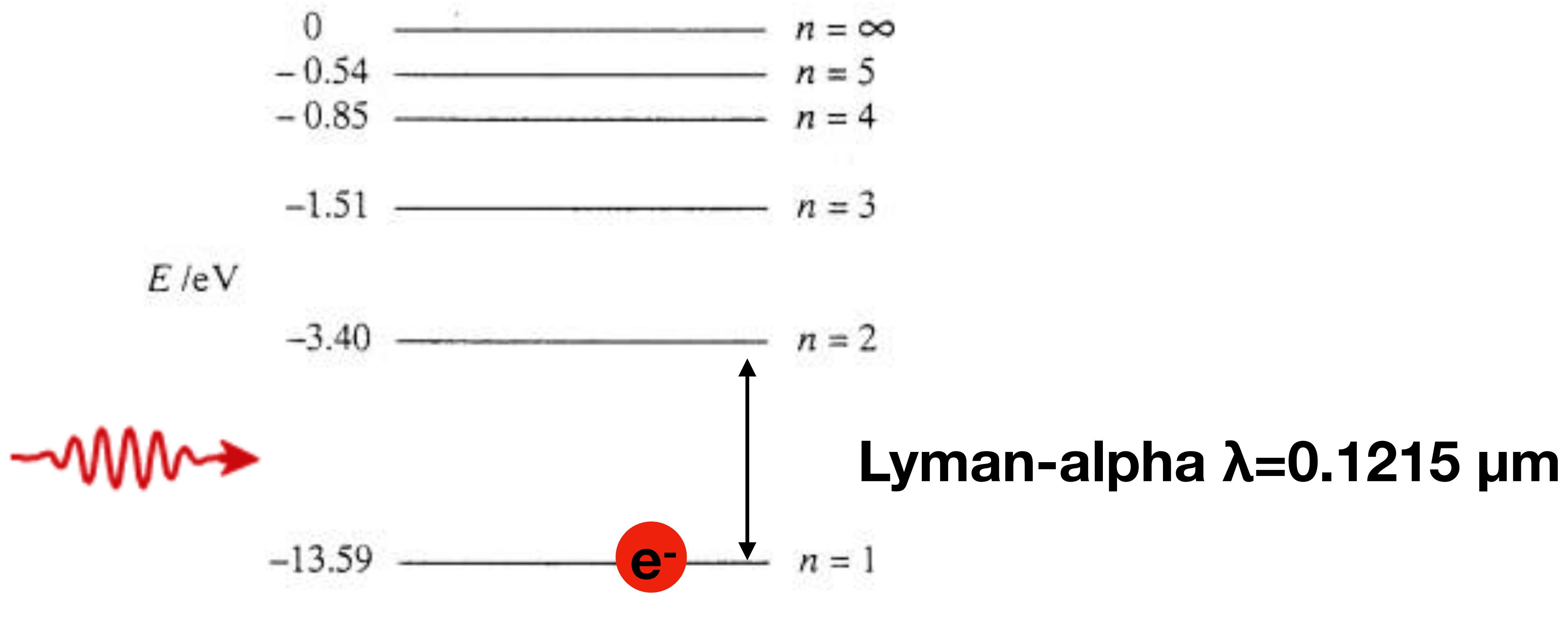
Hydrogen Energy Levels

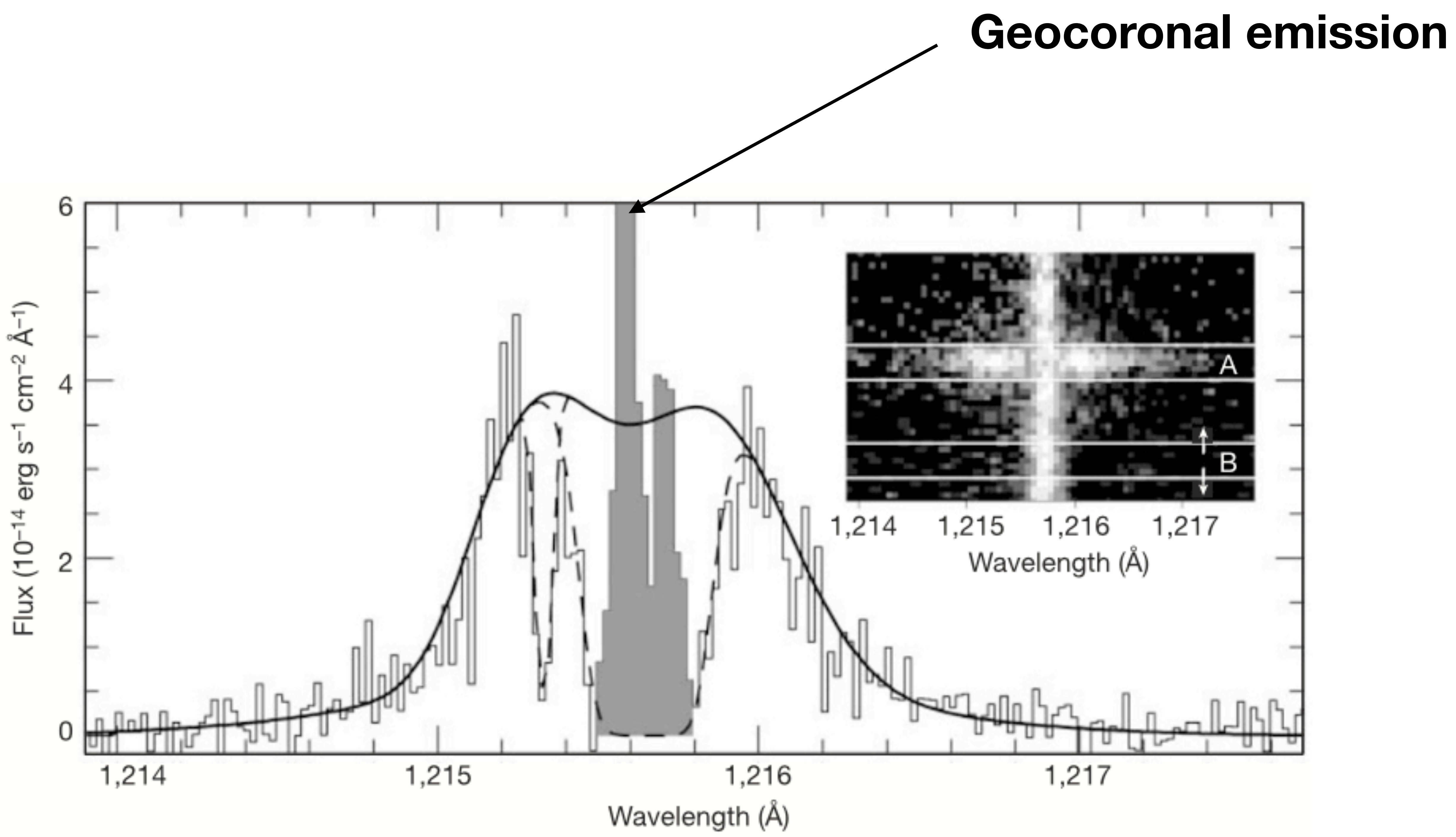


HD 209458b Vidal Madjar et al. (2003)

Lyman-alpha observations



Hydrogen Energy Levels



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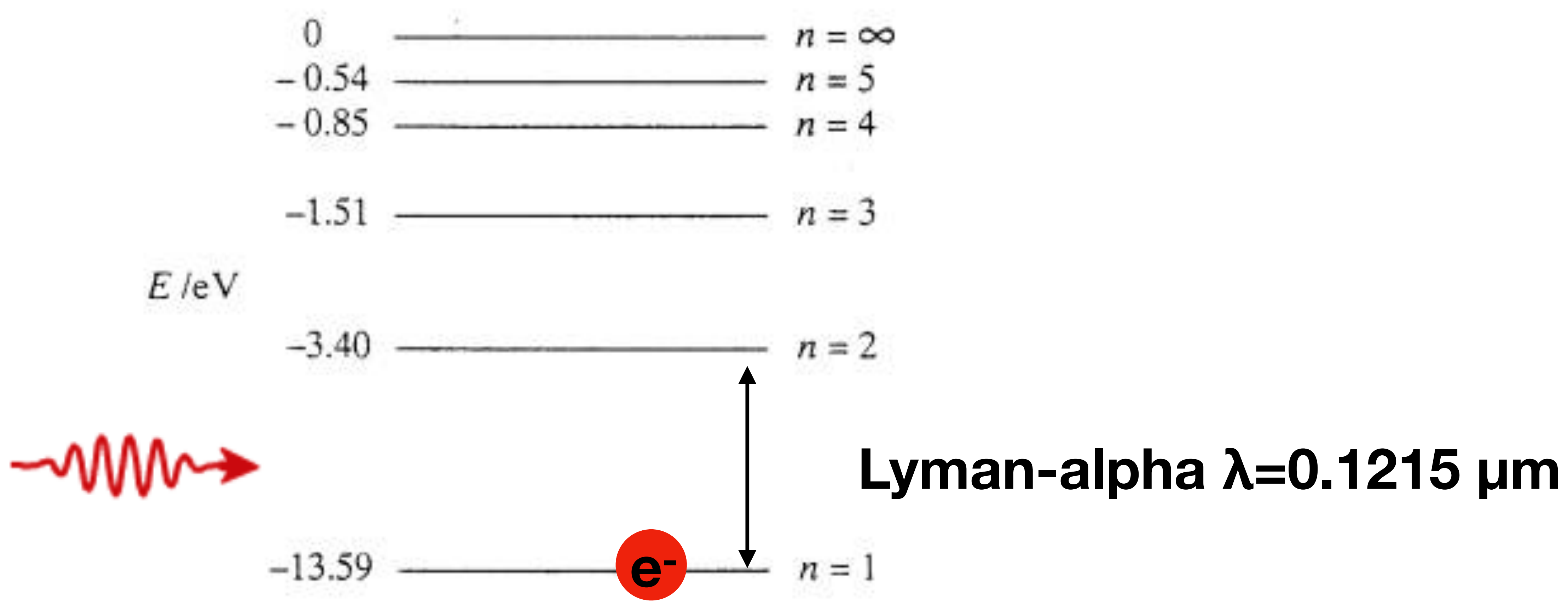
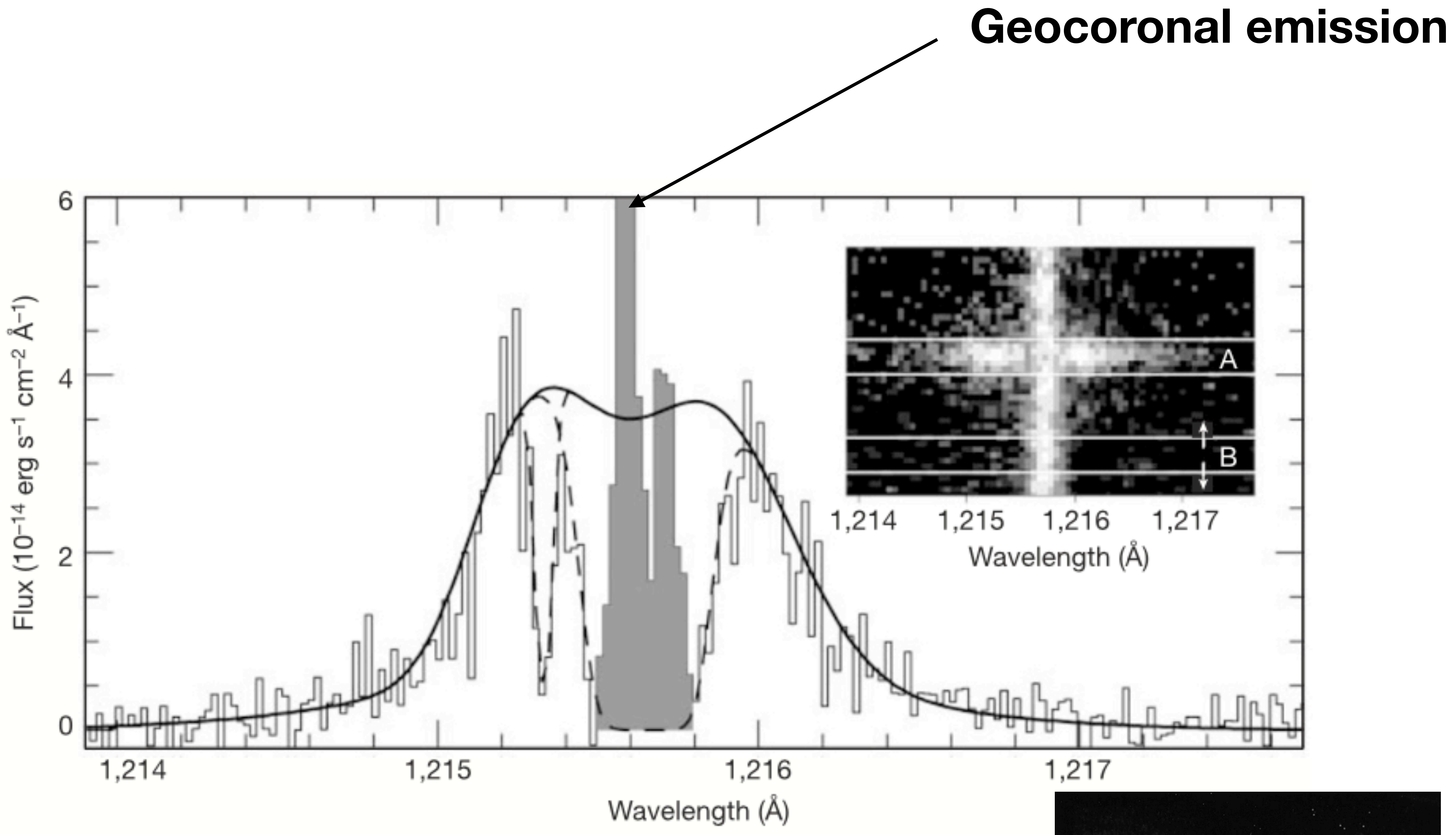
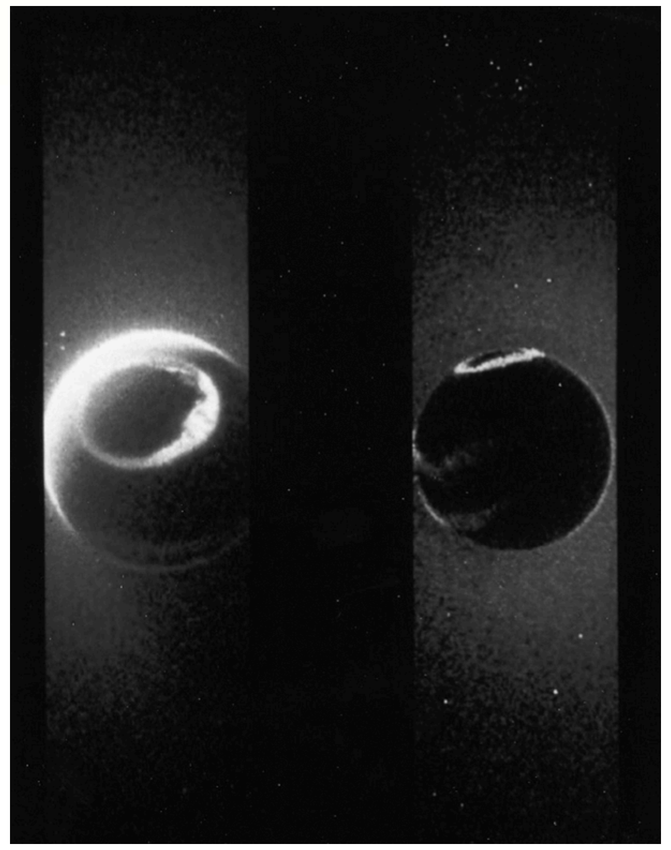


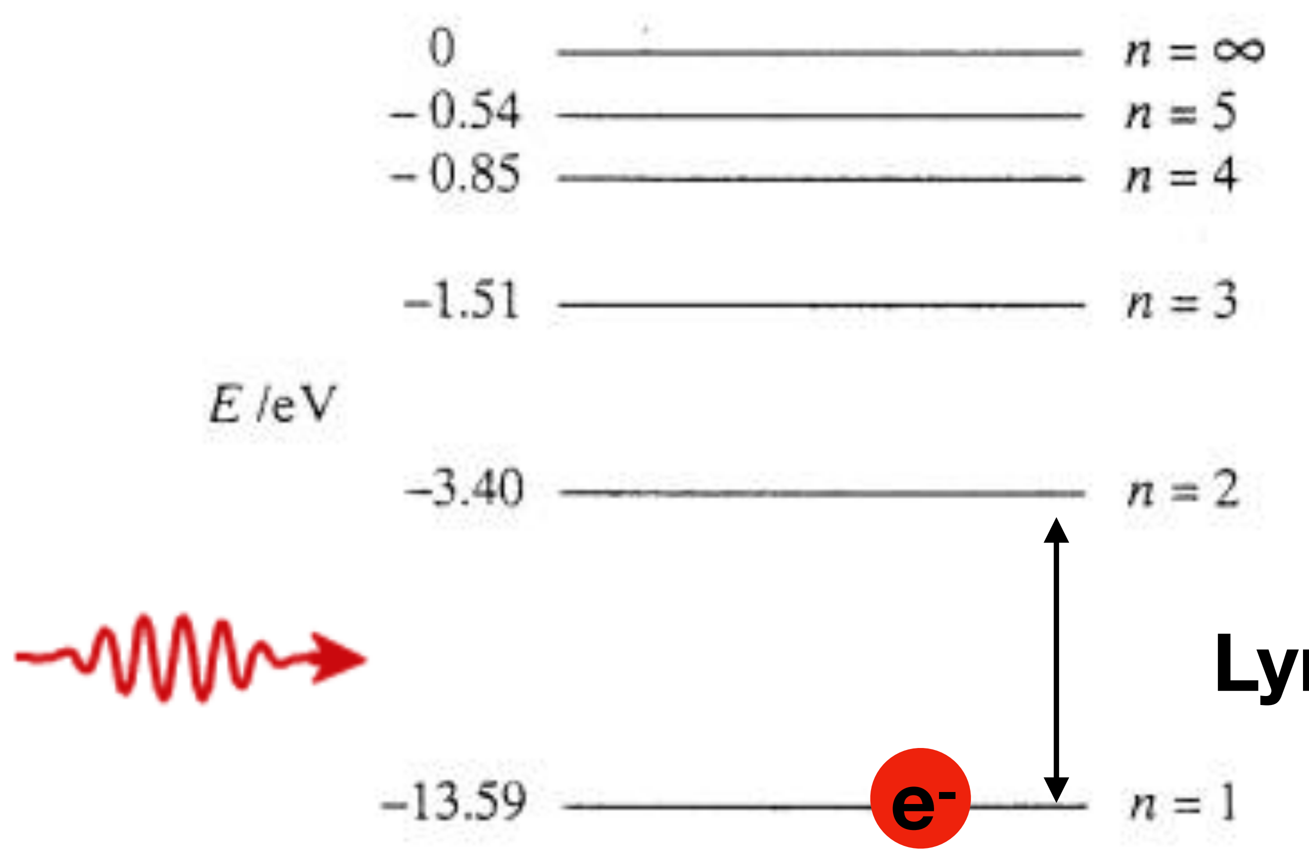
Hydrogen Energy Levels



HD 209458b Vidal Madjar et al. (2003)



Lyman-alpha observations

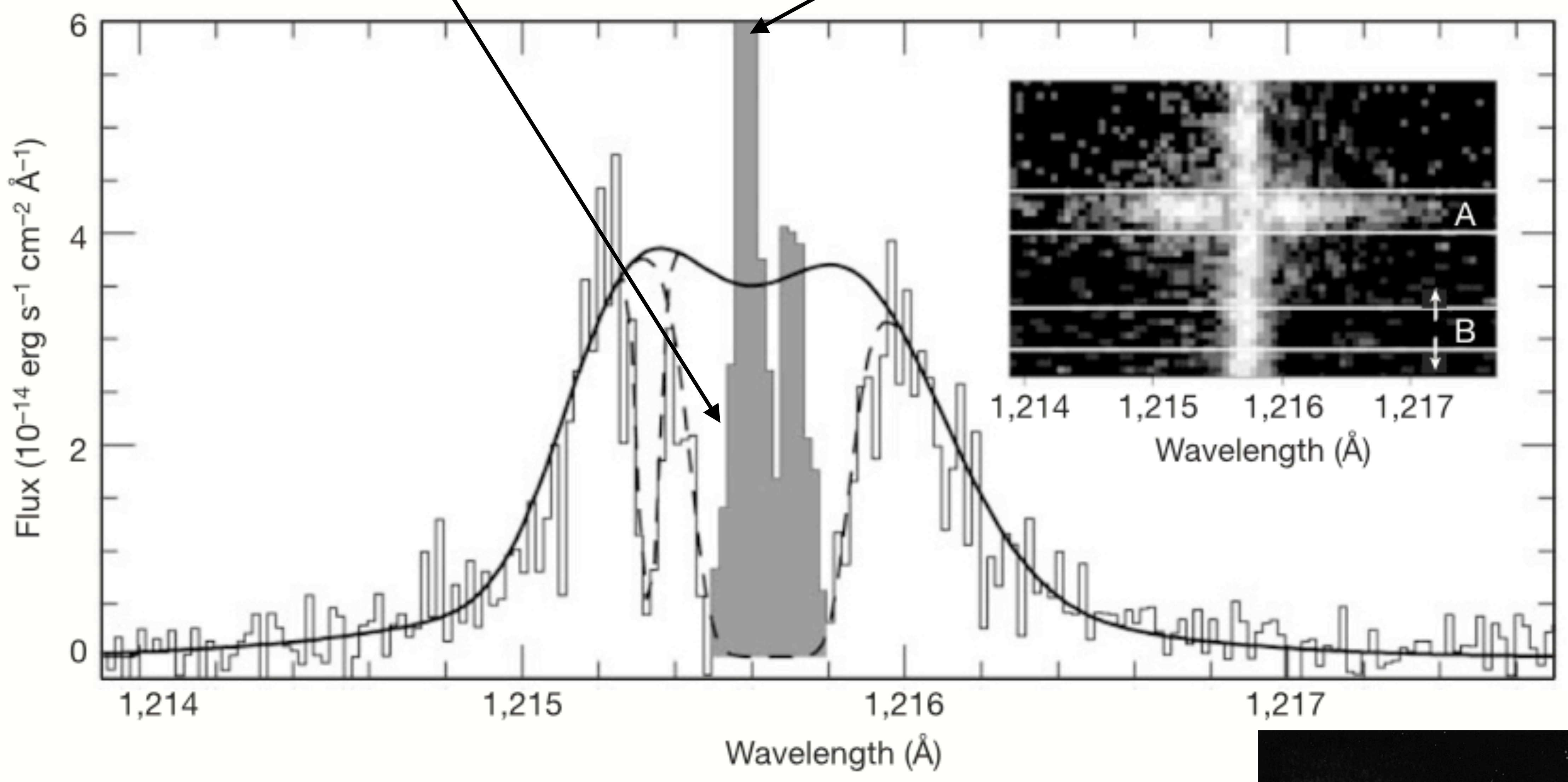


Lyman-alpha λ=0.1215 μm

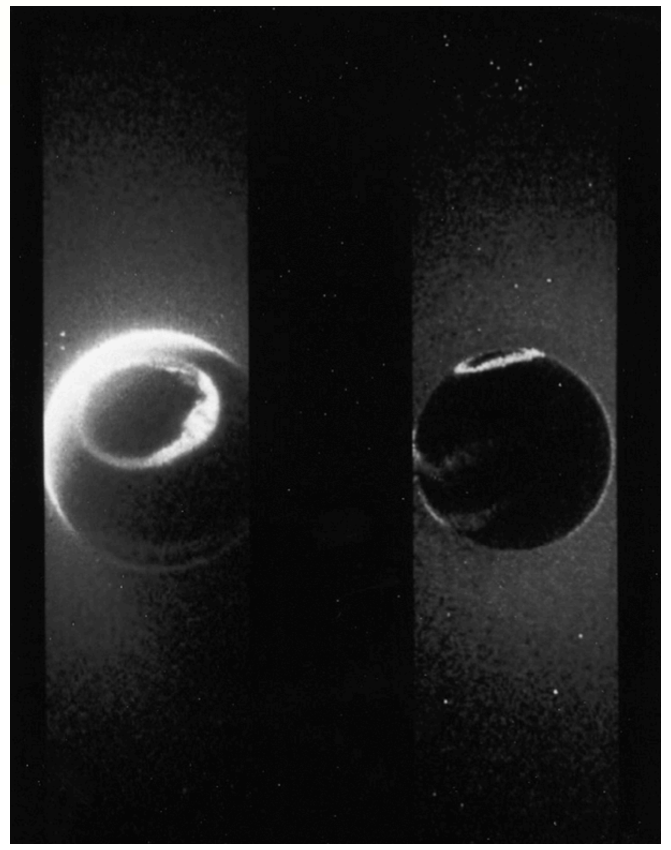
Hydrogen Energy Levels

ISM absorption

Geocoronal emission

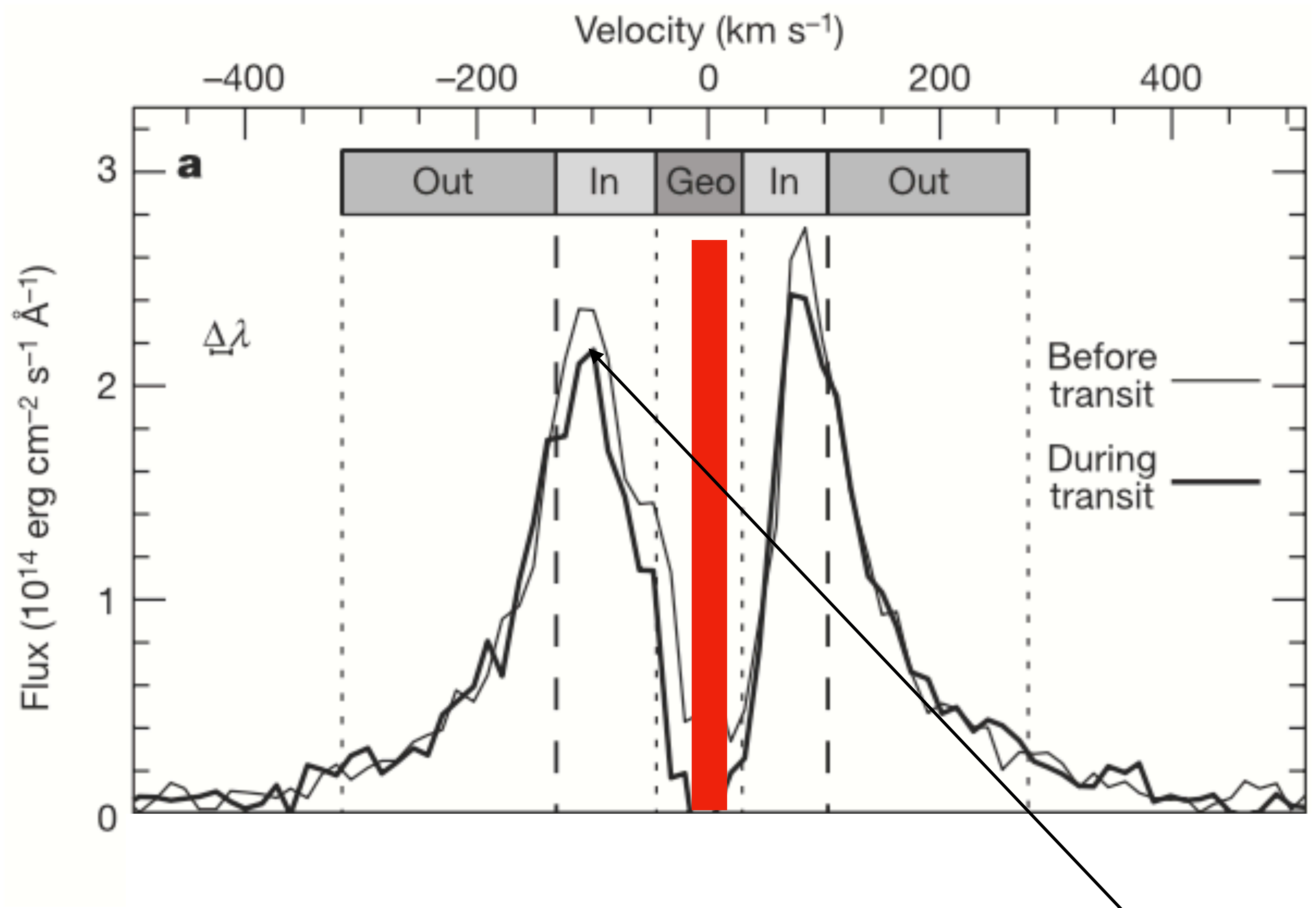


HD 209458b Vidal Madjar et al. (2003)



HD209458 b - Lyman-alpha

Typical velocity of outflows is ~10 km/s



We see absorption at ~100 km/s

HD209458 b - Lyman-alpha

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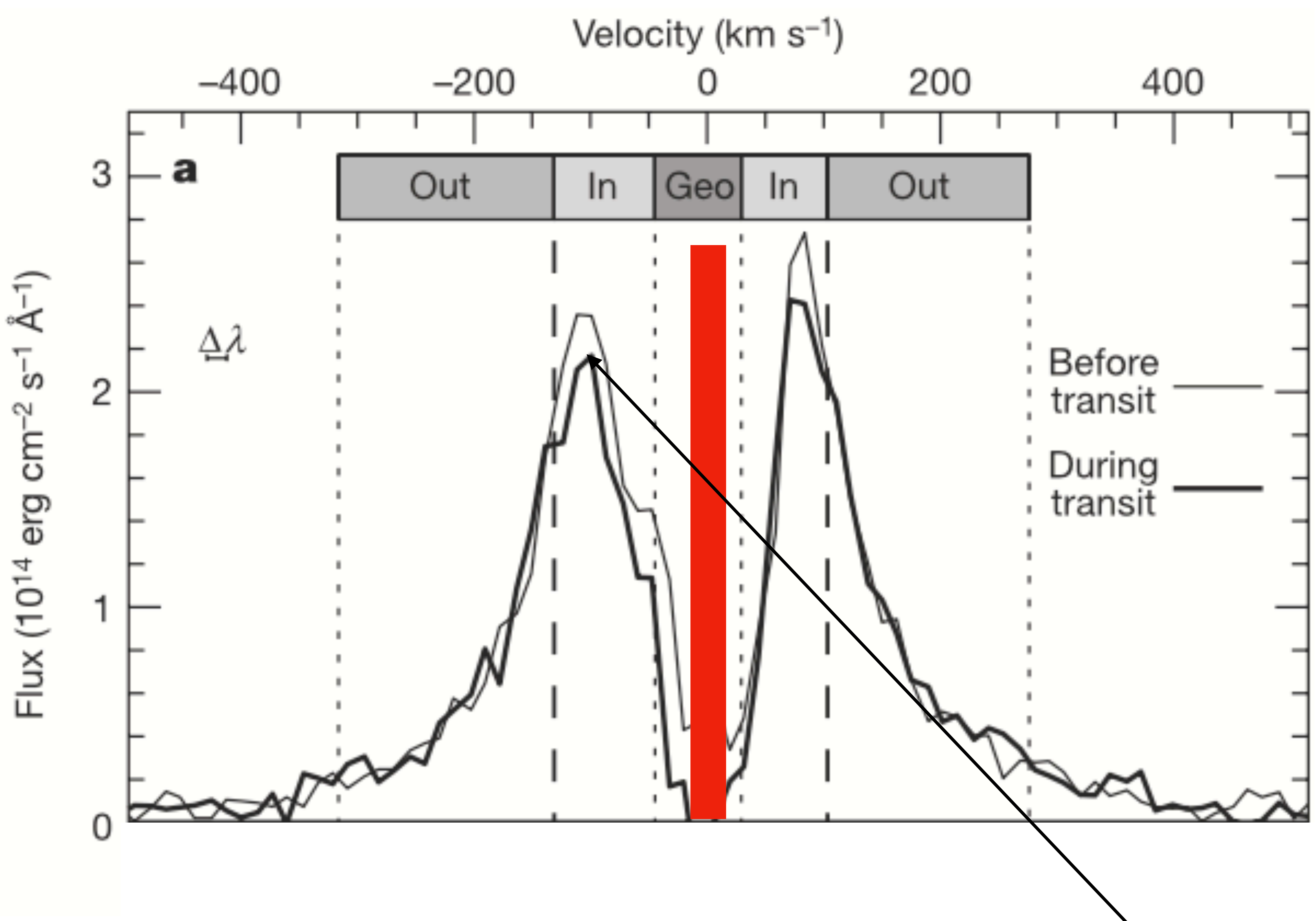

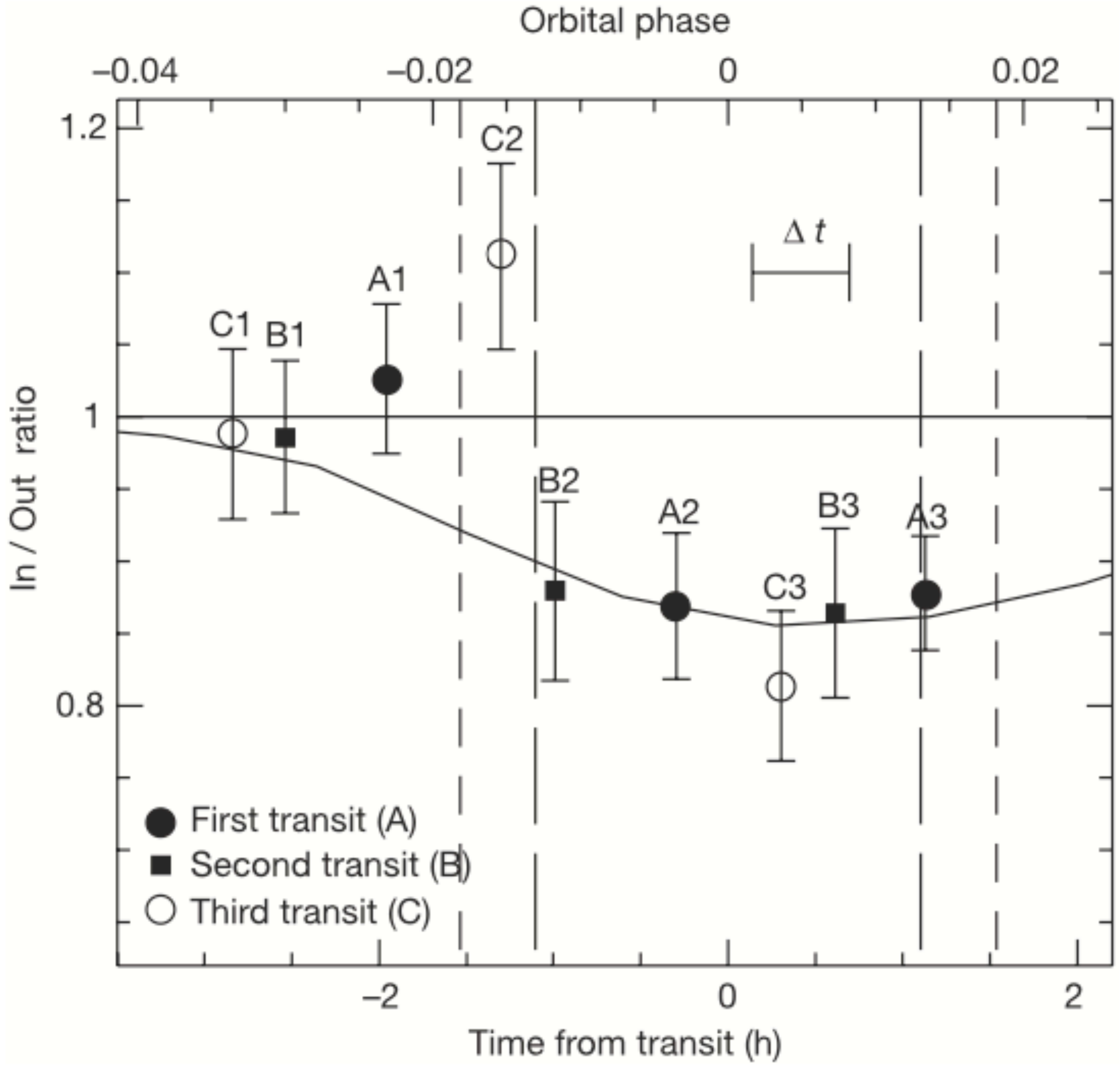

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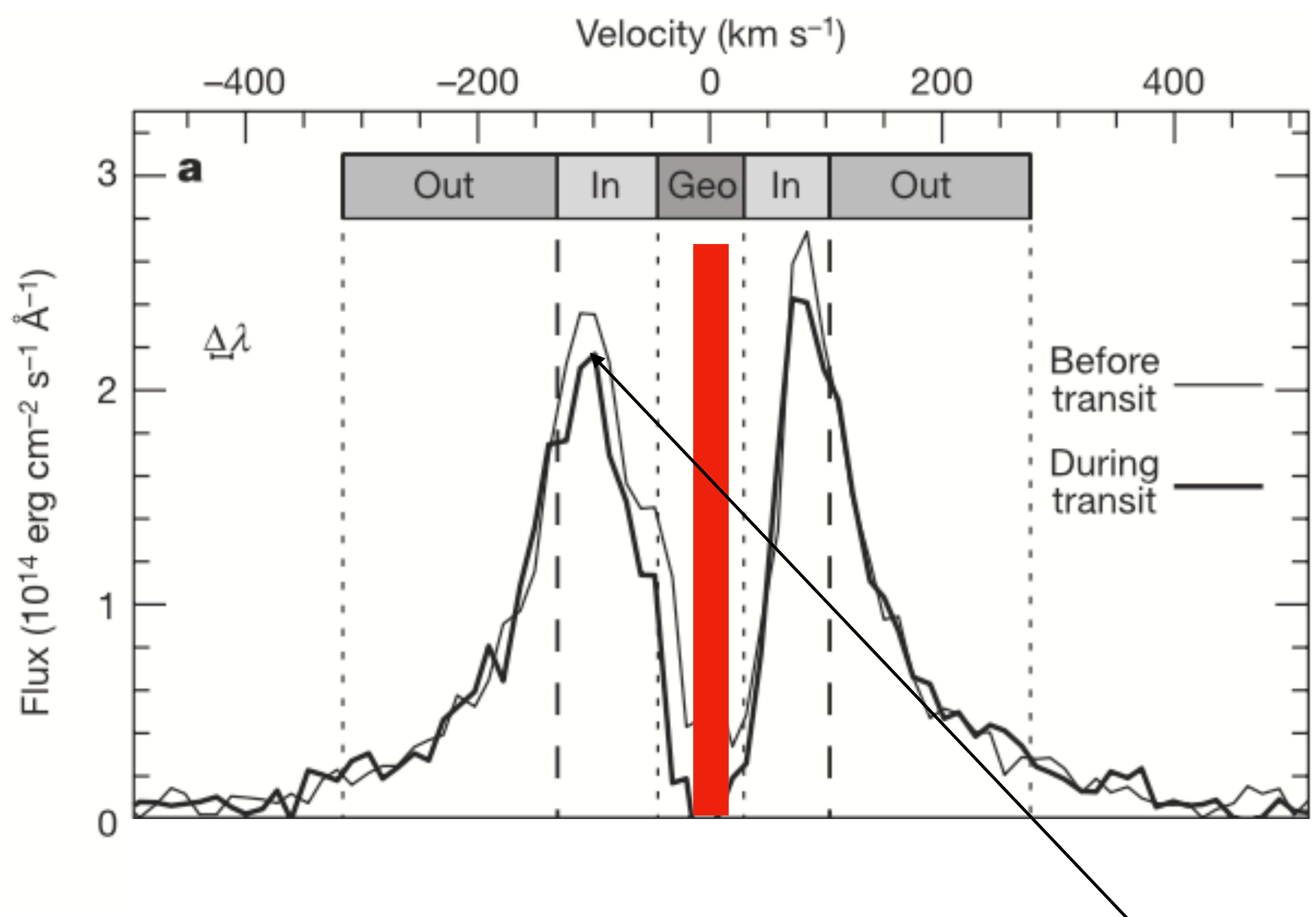
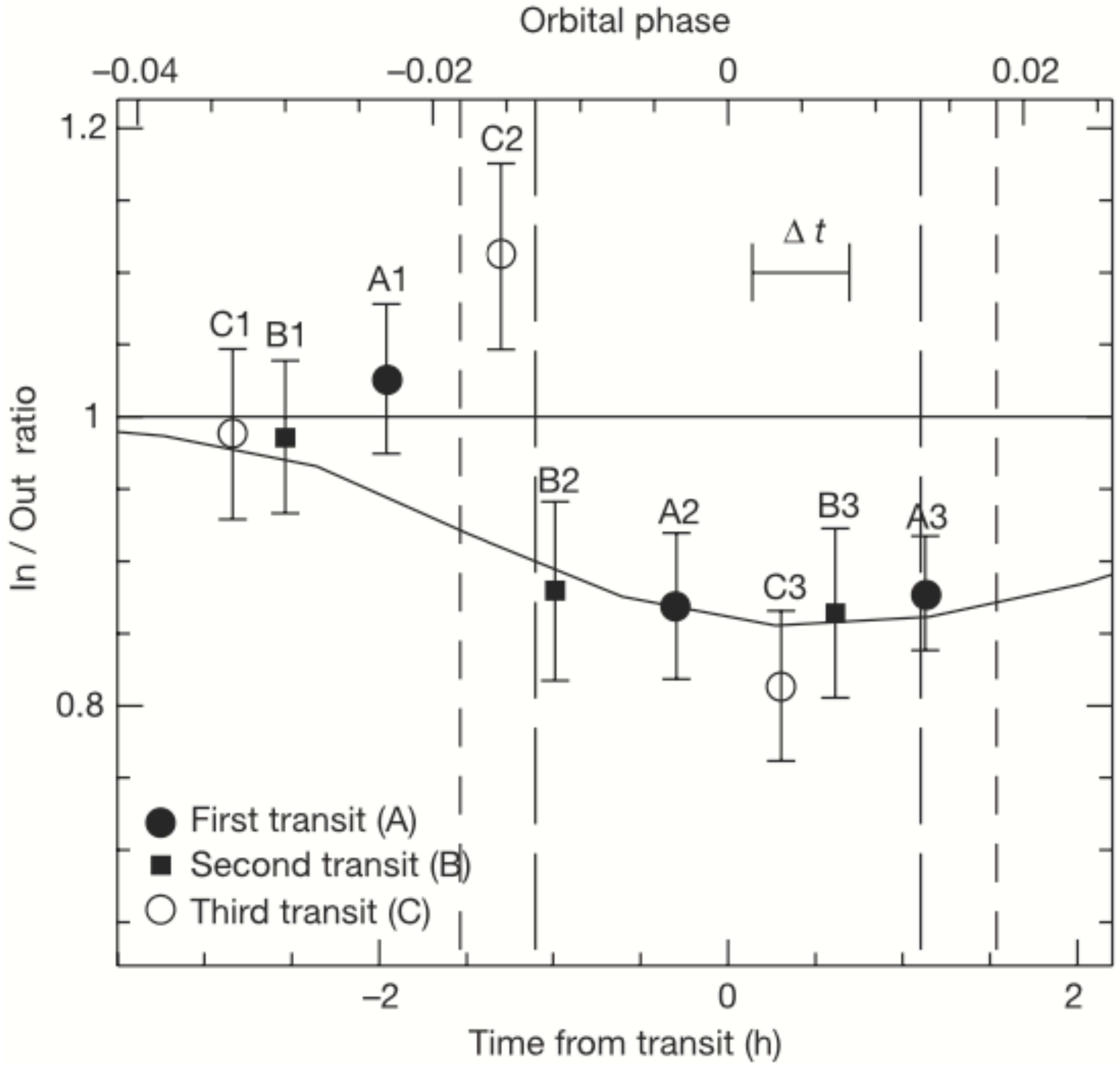


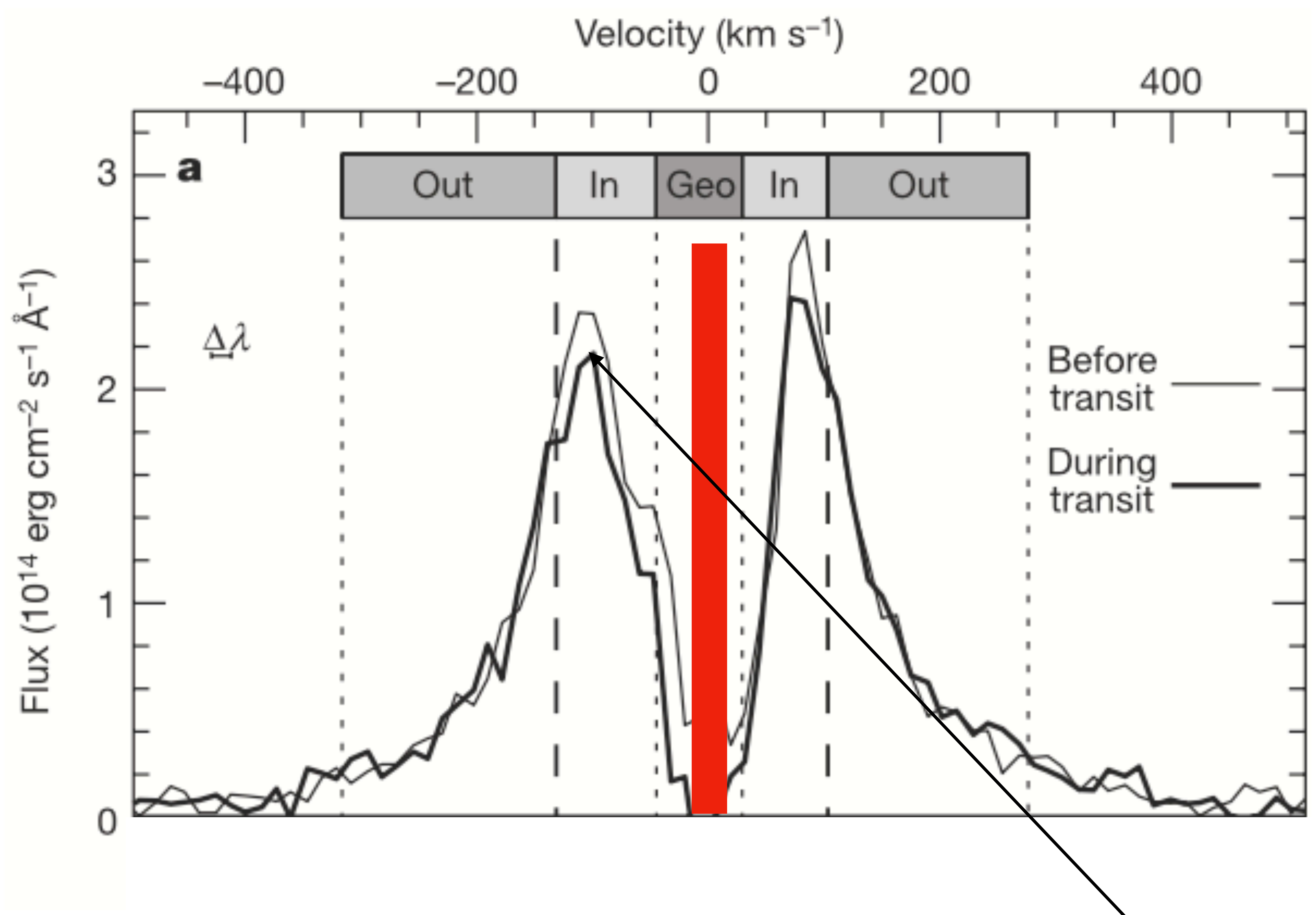


~15% Transit depth - Escape!

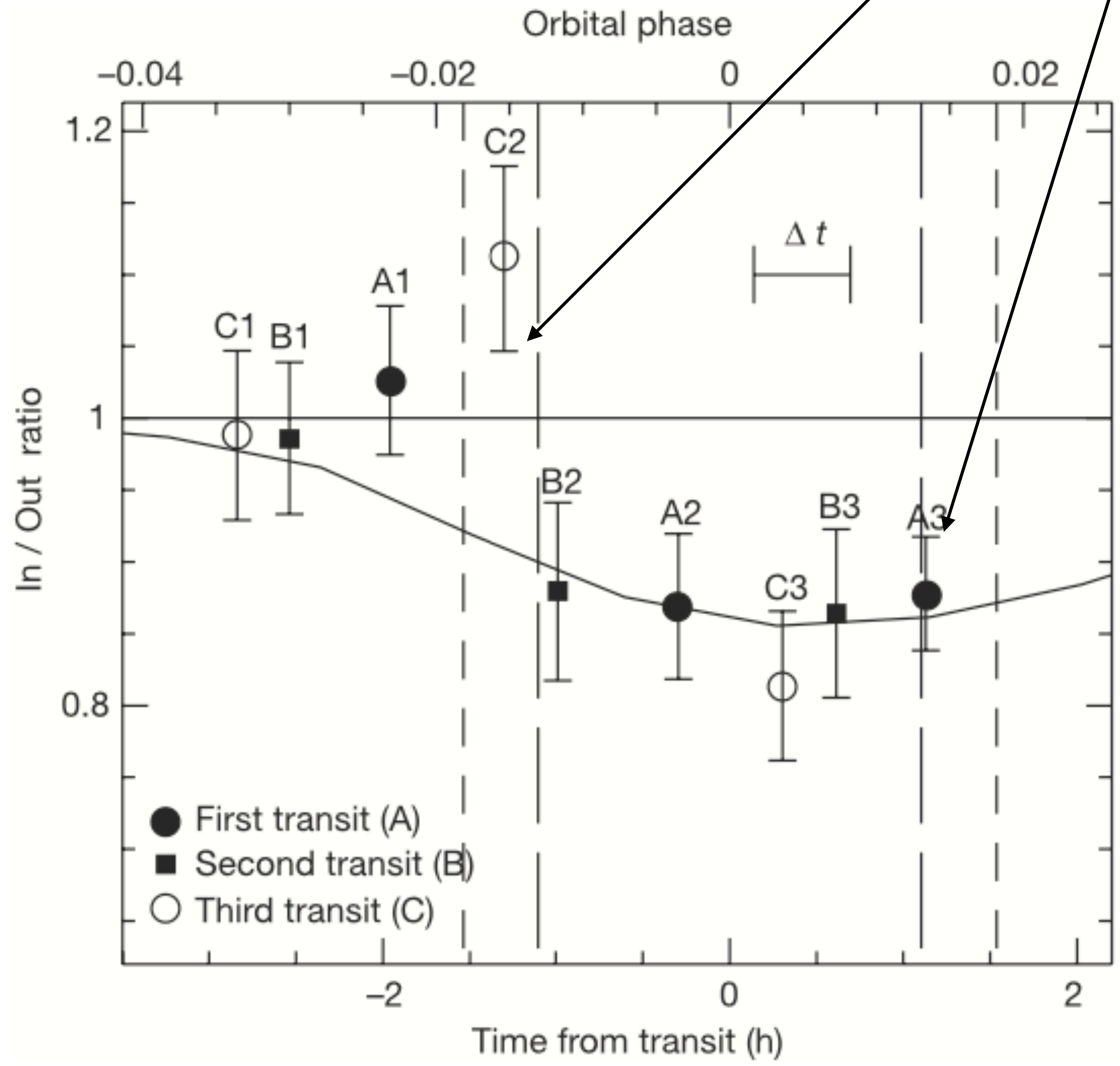
We see absorption at ~100 km/s

HD209458 b - Lyman-alpha

Typical velocity of outflows is ~10 km/s



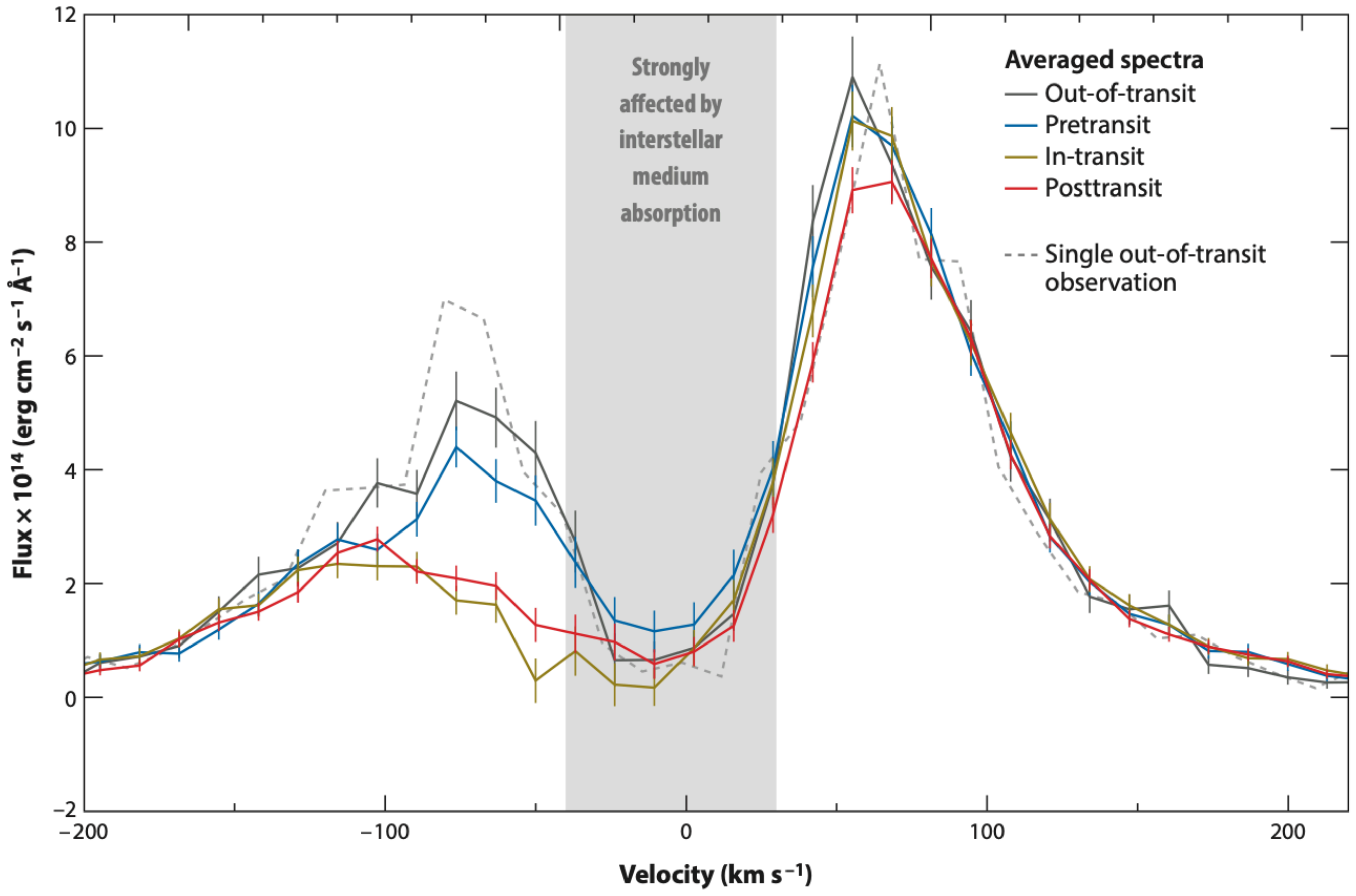
Evidence of a sharp ingress, and slow egress



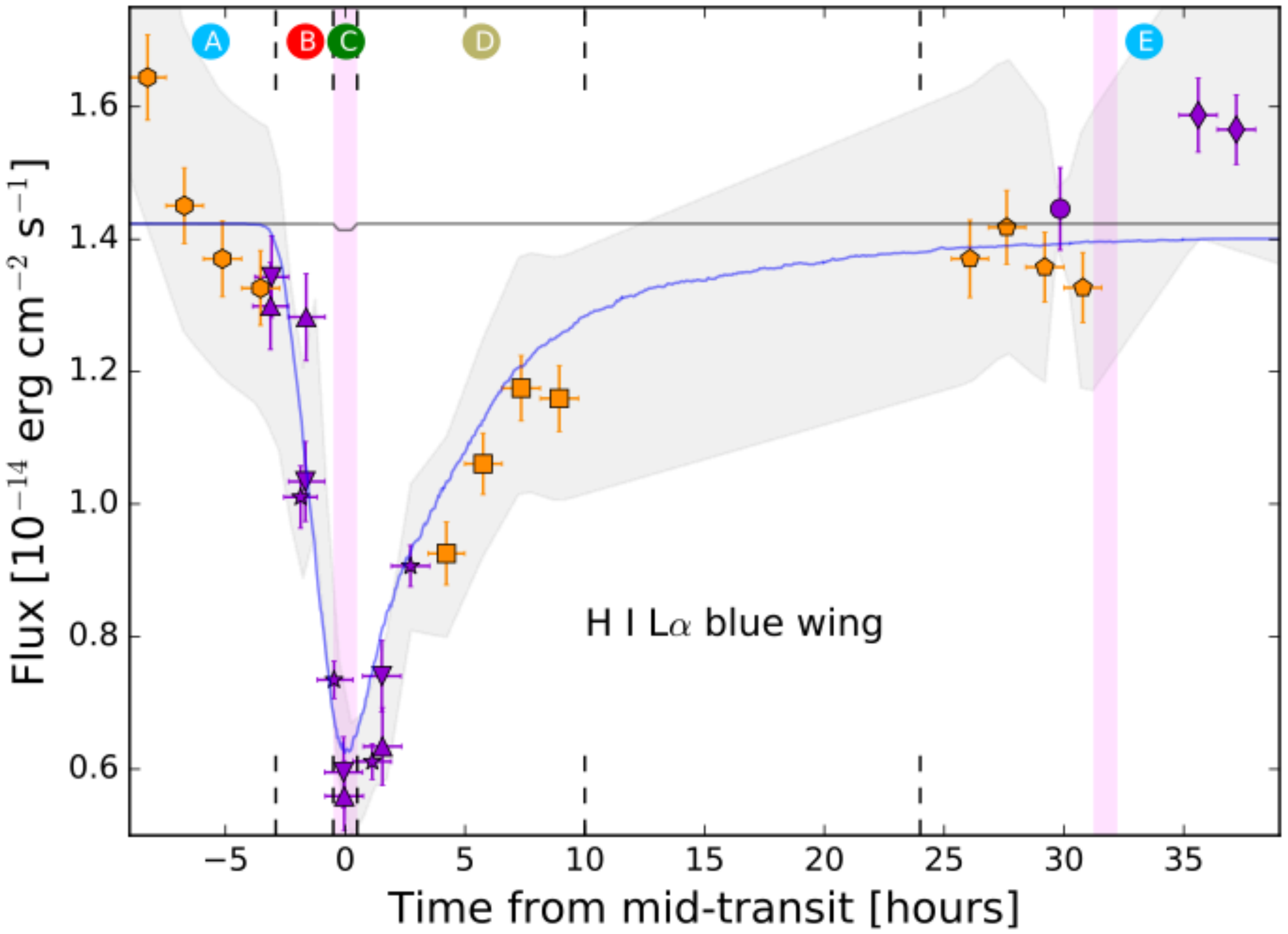
~15% Transit depth - Escape!

We see absorption at ~100 km/s

GJ436 b - Lyman-alpha



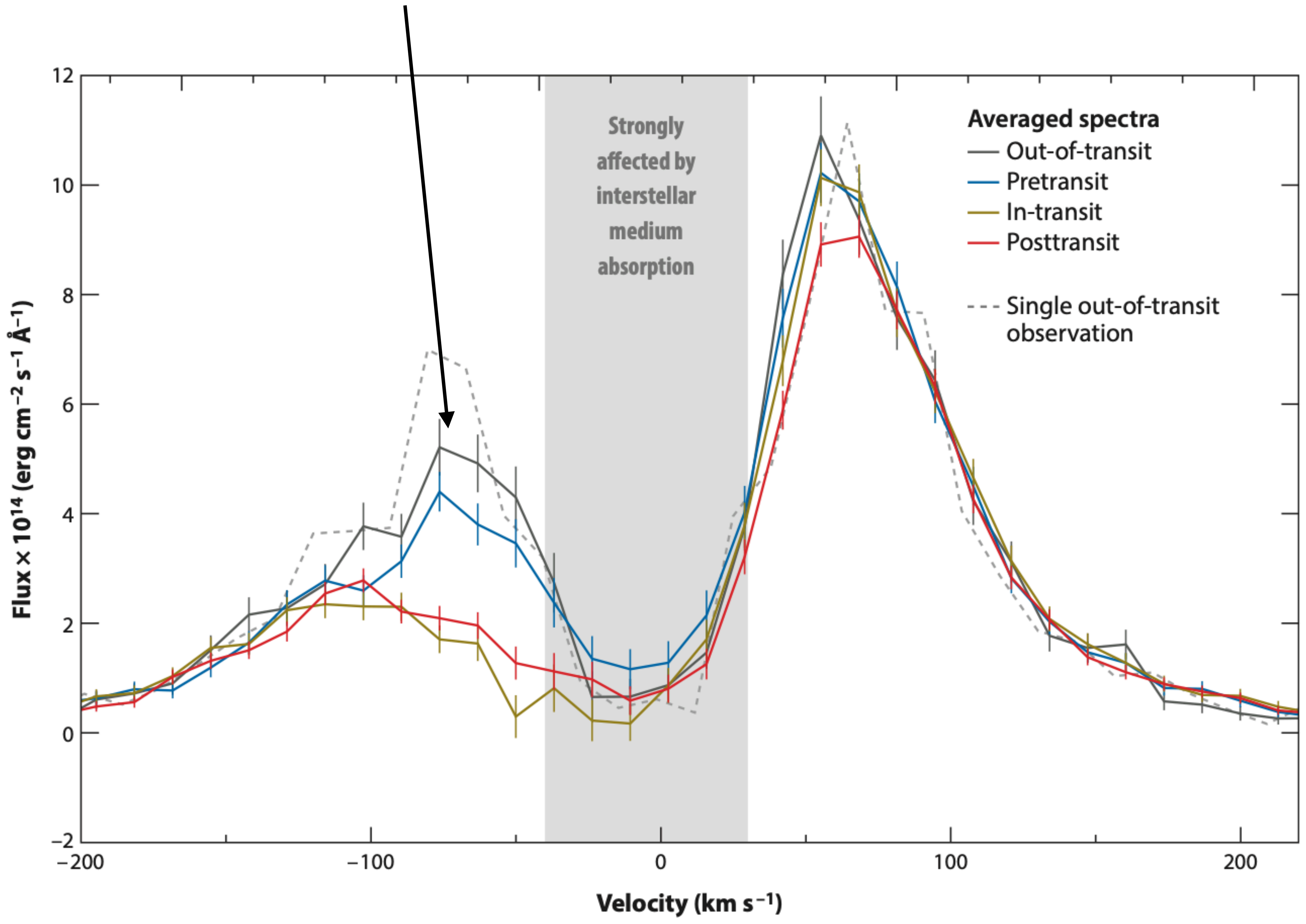
Ehrenreich et al. (2015)



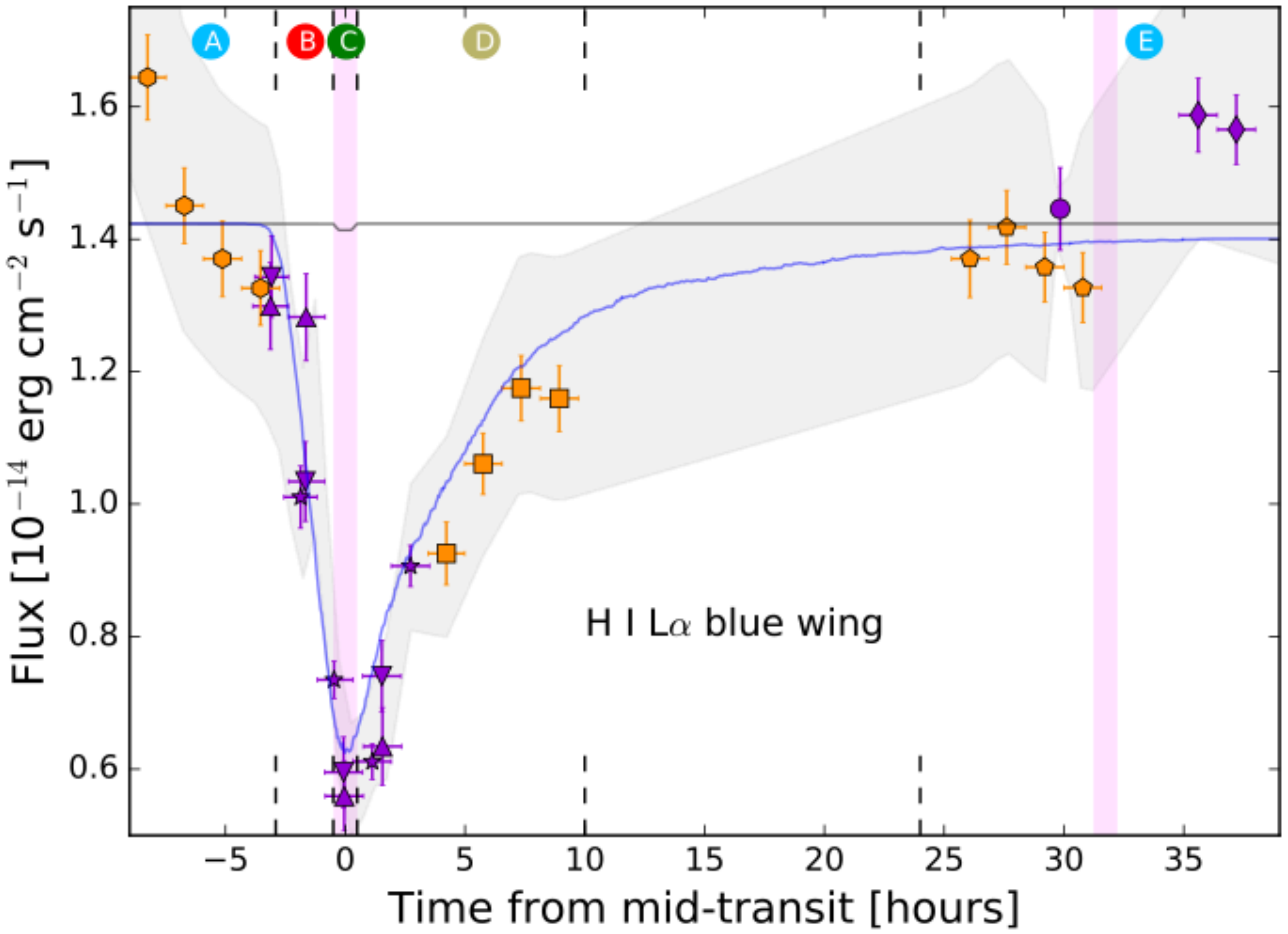
Lavie et al. (2017)

GJ436 b - Lyman-alpha

Stellar variability

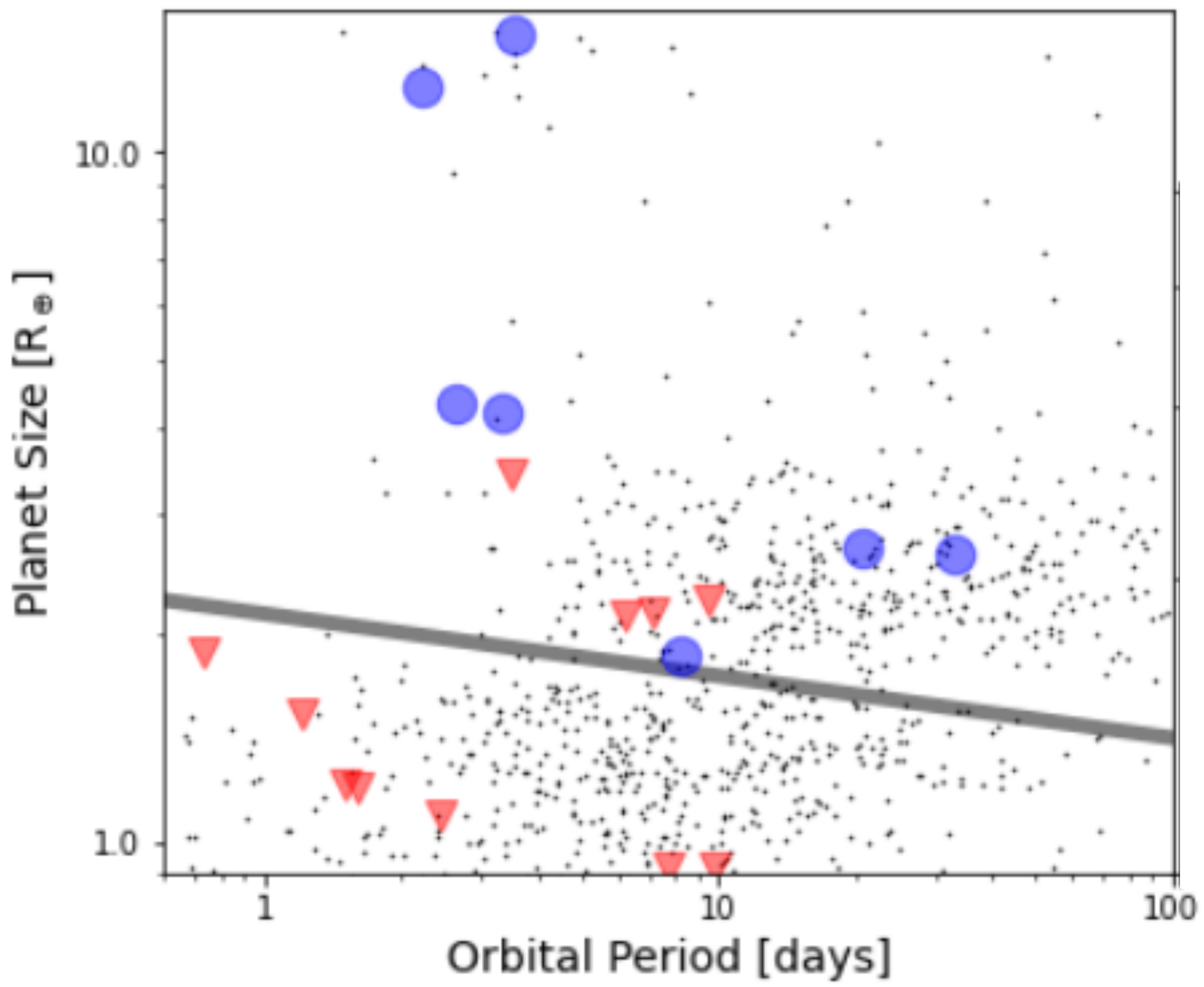


Ehrenreich et al. (2015)

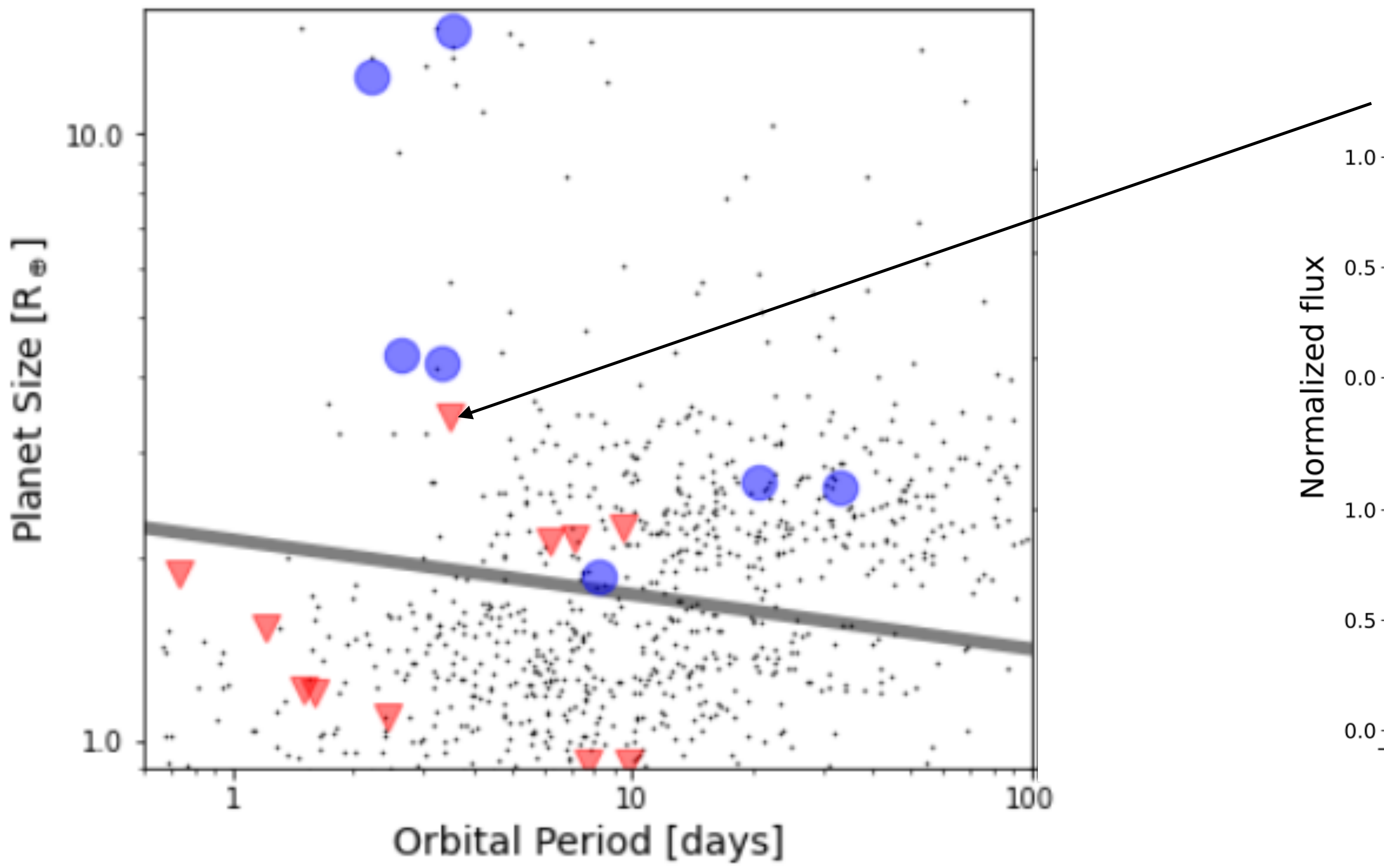


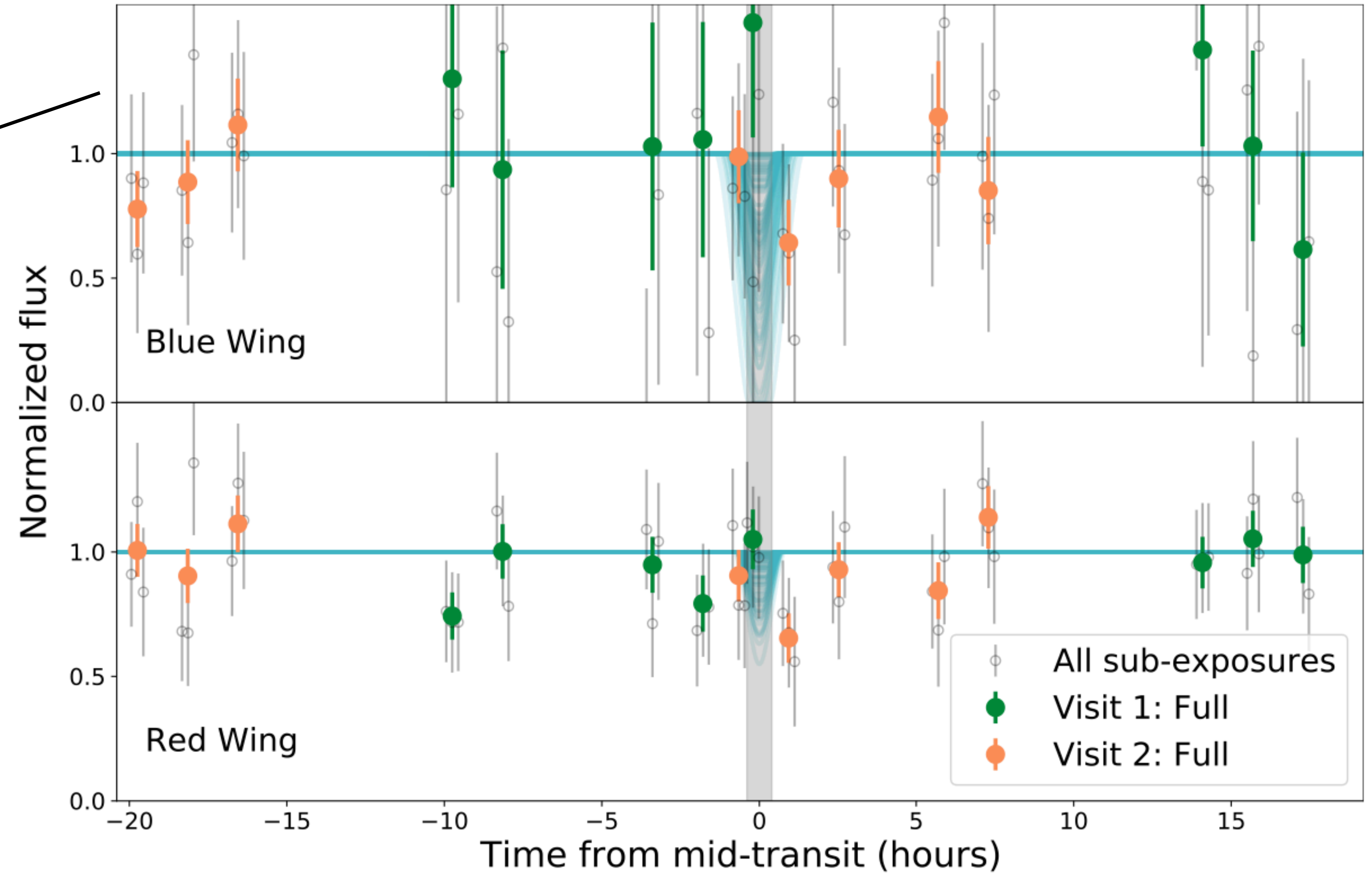
Lavie et al. (2017)

What have we learned?



What have we learned?



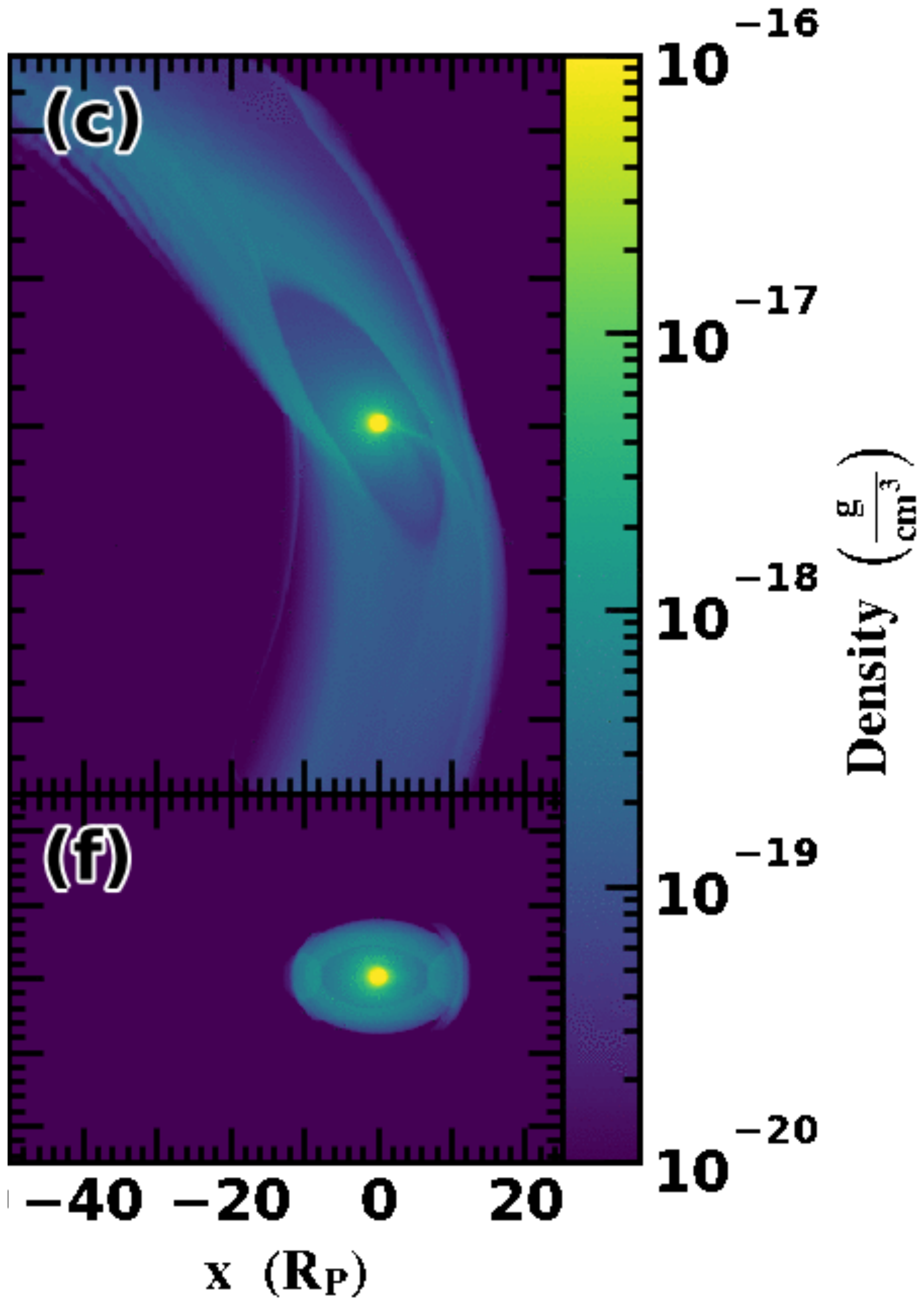


K2-25b Rockcliffe et al. (2021)

Lyman-alpha mysteries

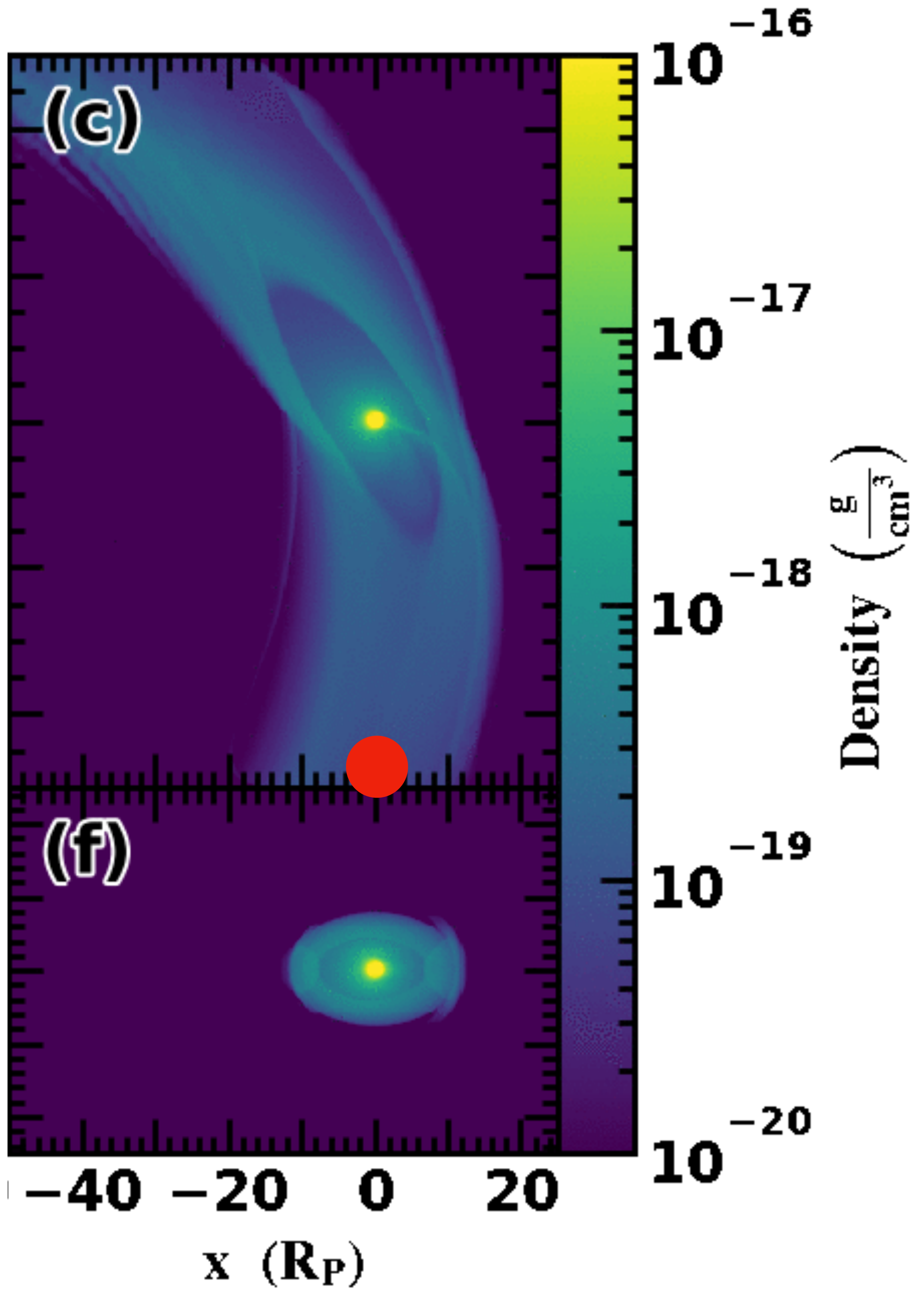
- Why is the absorption at such high-velocities and often blue-shifted?
- Why do we see some transits and not others?
- Why are the transits asymmetric?

Simulations



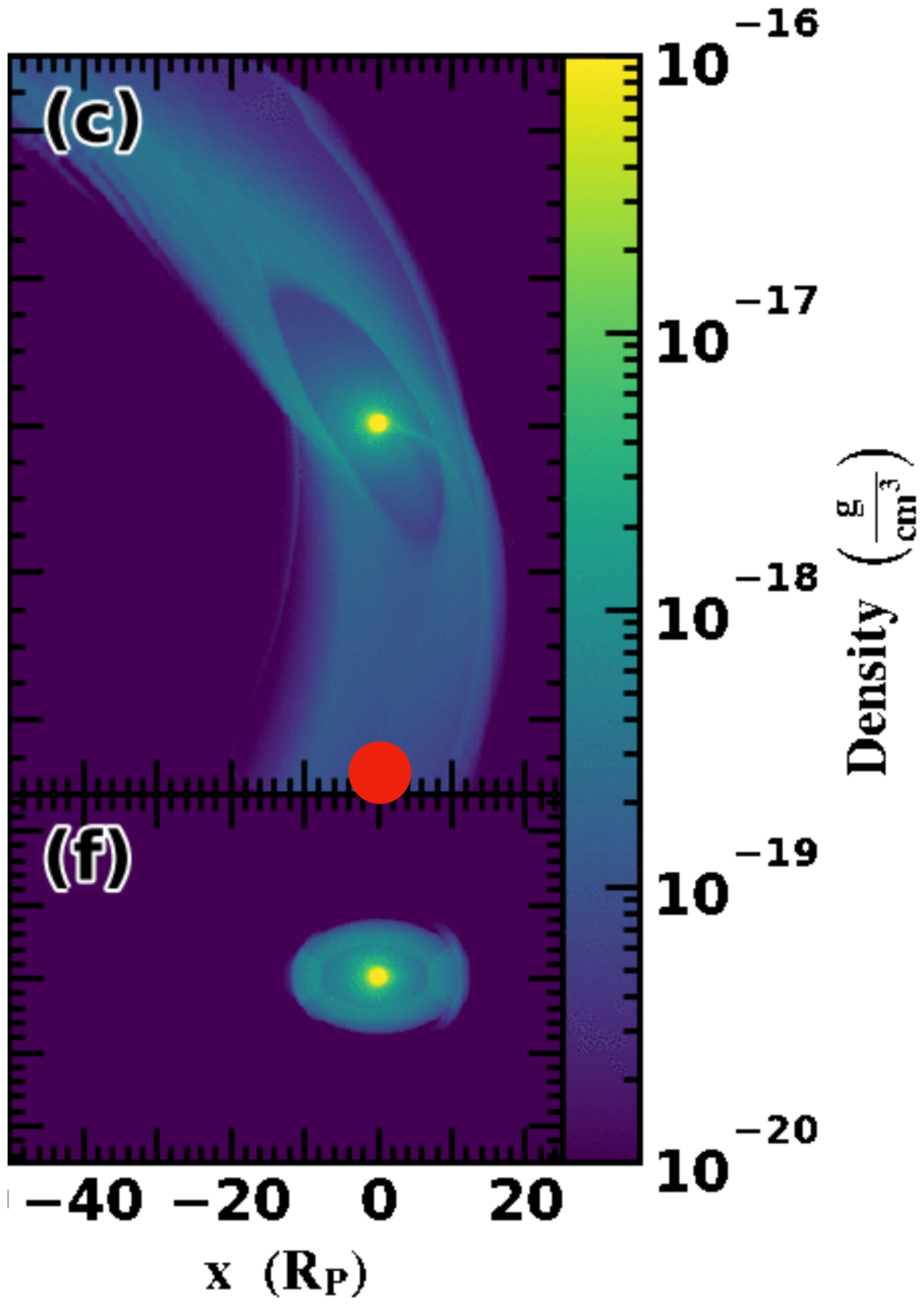
McCann et al. (2019)

Simulations



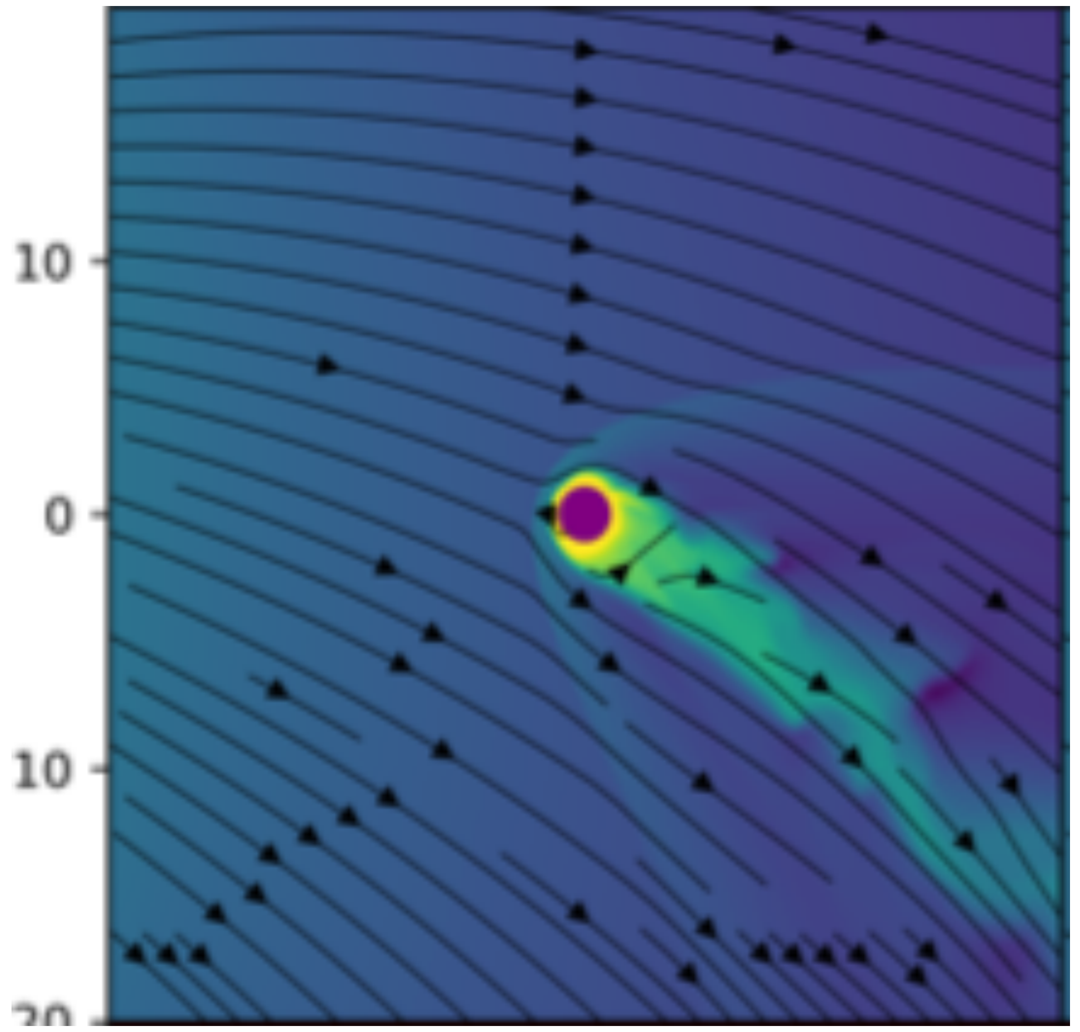
McCann et al. (2019)

Simulations

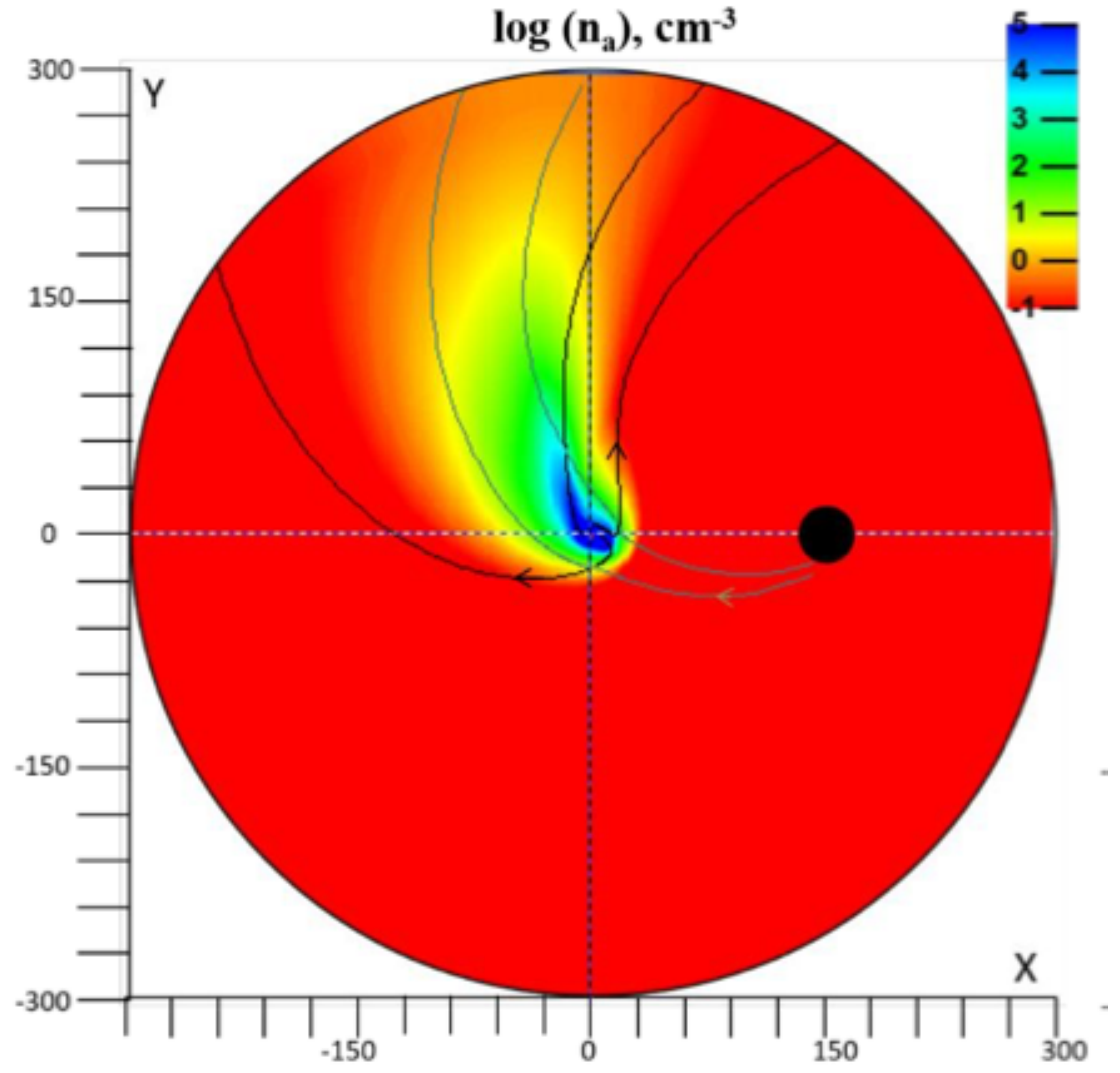


McCann et al. (2019)

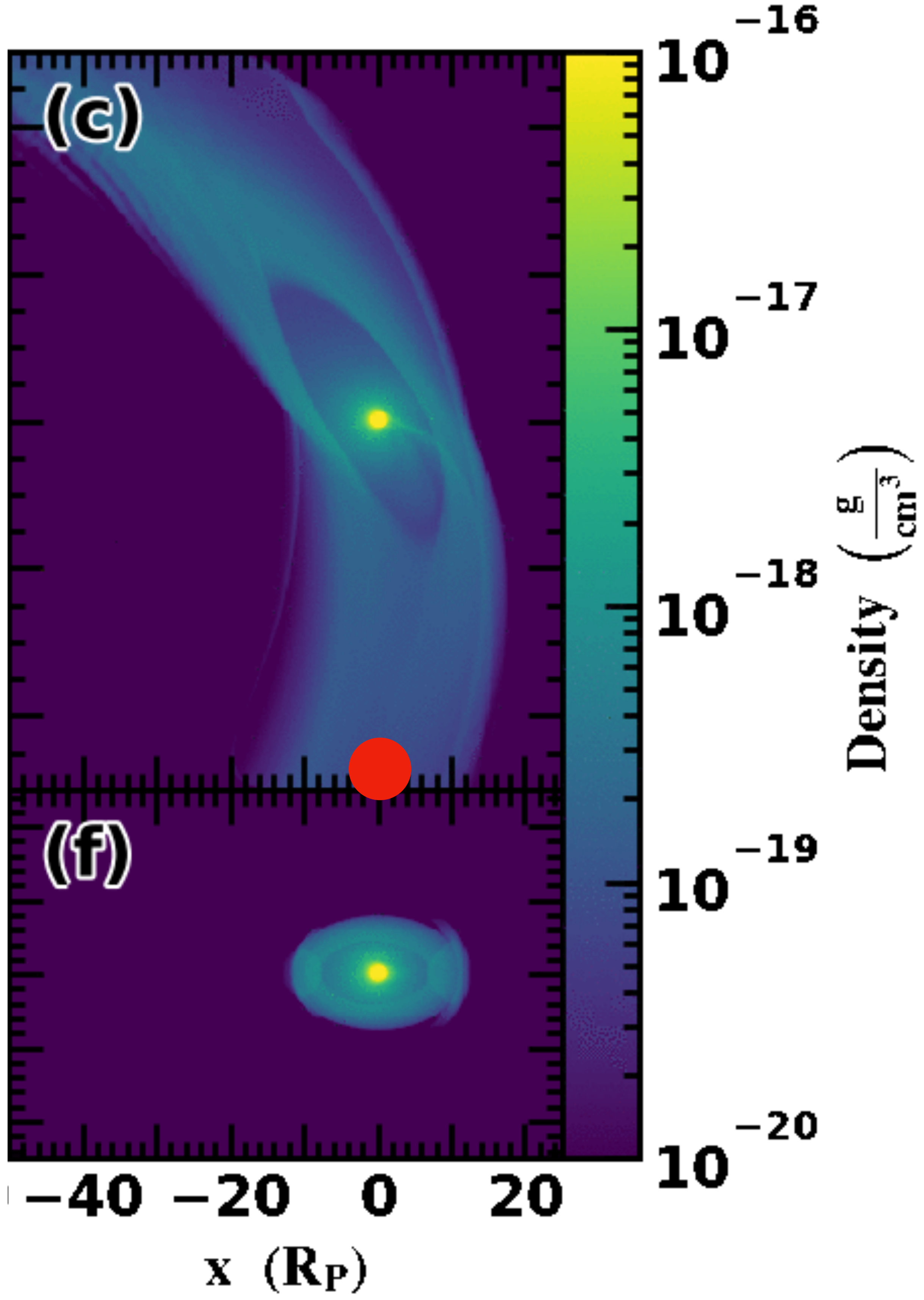
Simulations



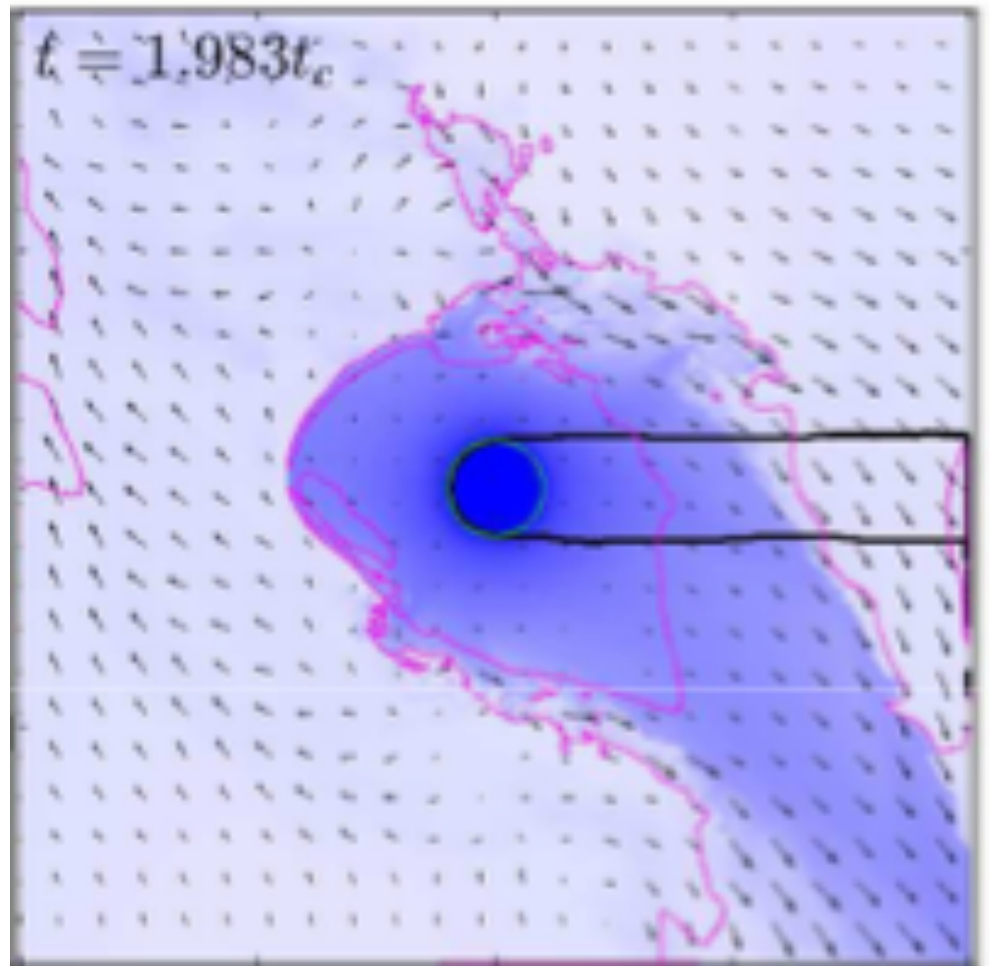
Hazra et al. (2022)



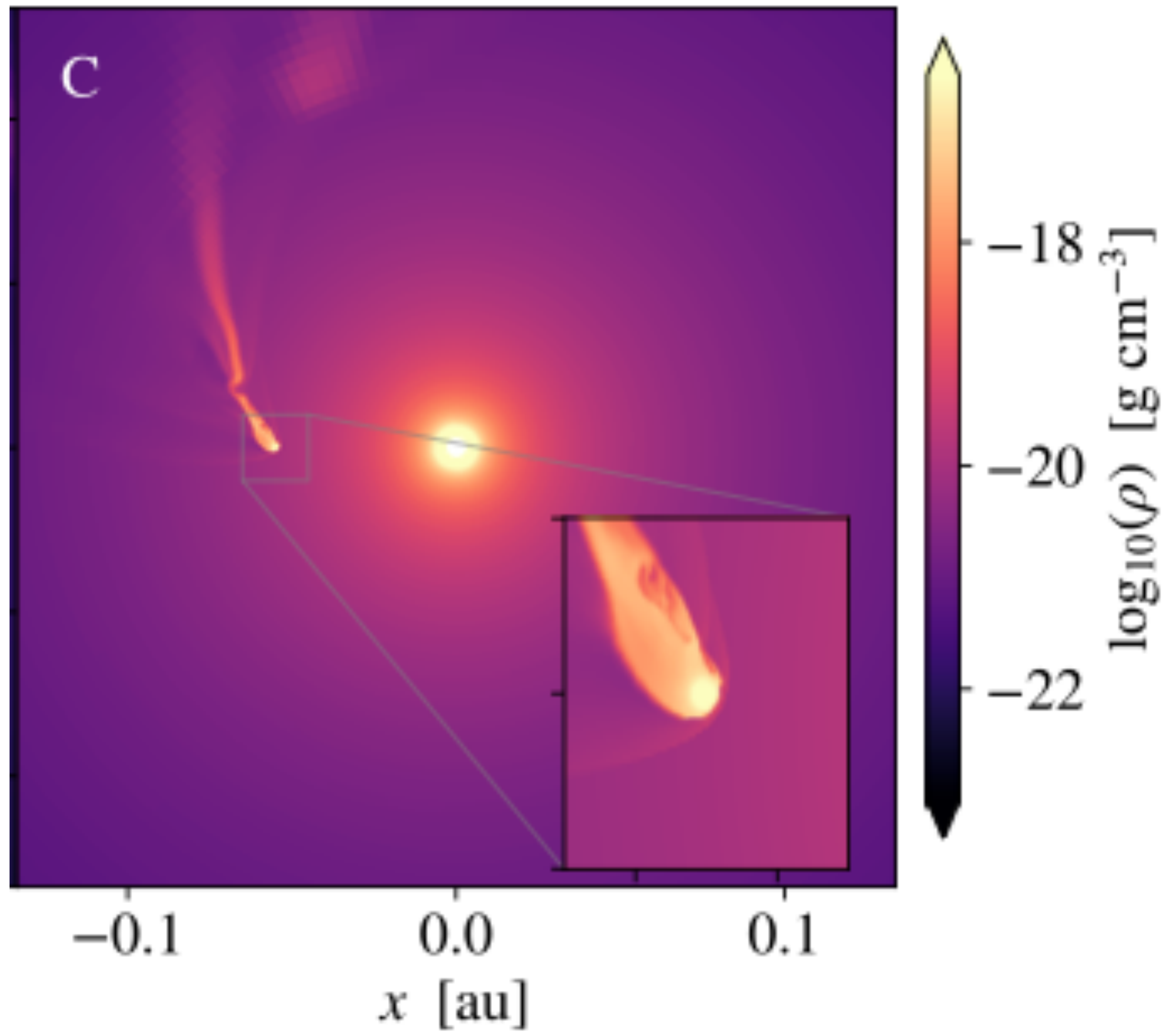
Khodachenko et al. (2019)



McCann et al. (2019)



Debrecht et al. (2022)

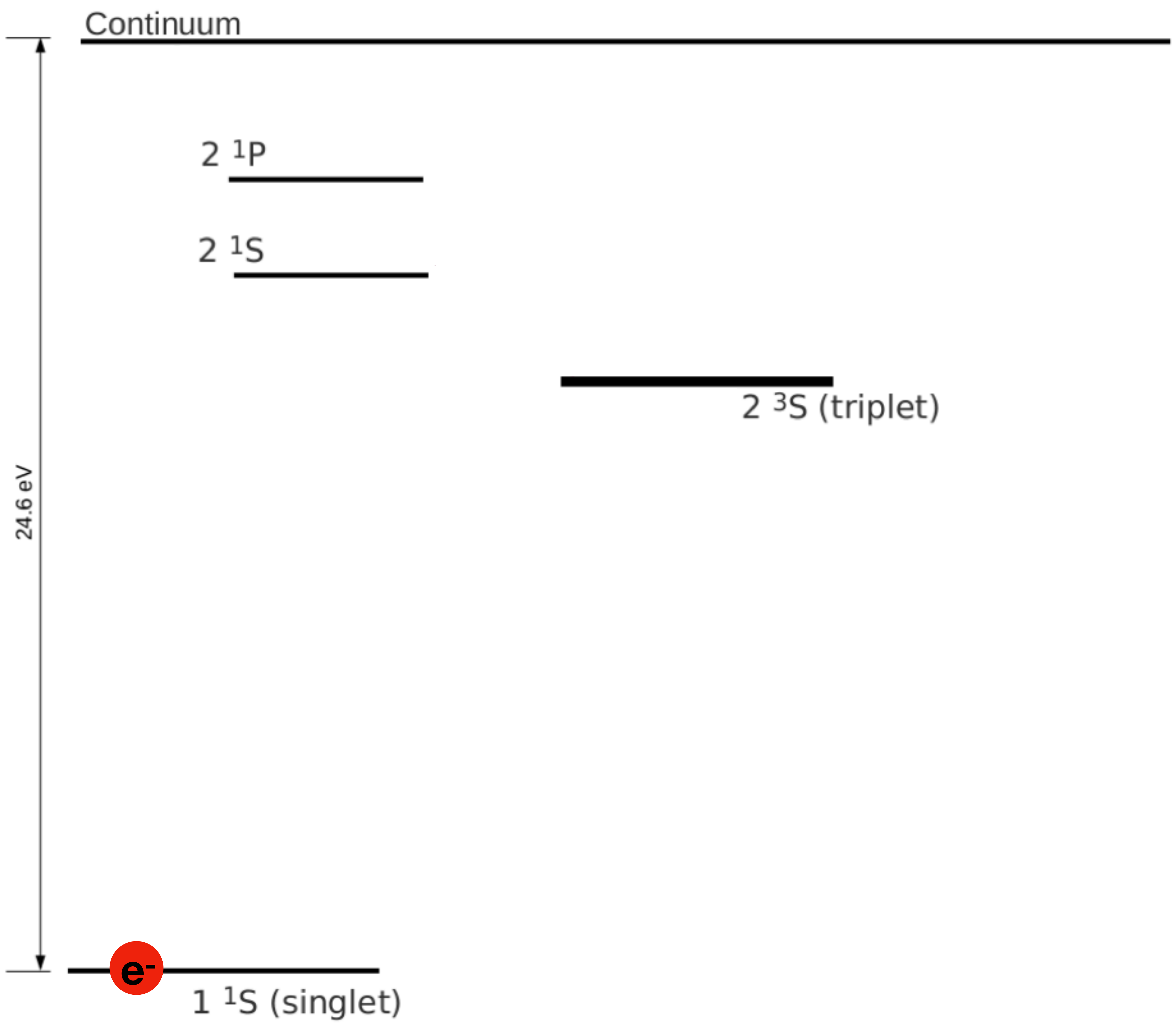


Macleod & Oklopčić (2022)

Metastable He 10830 Ang

- Originally indicated in numerical work by Seager & Sasselov (2000) and Turner et al. (2016).

- Understanding He 10830 Ang absorption for exoplanet escape comes from Oklopčić & Hirata (2018)



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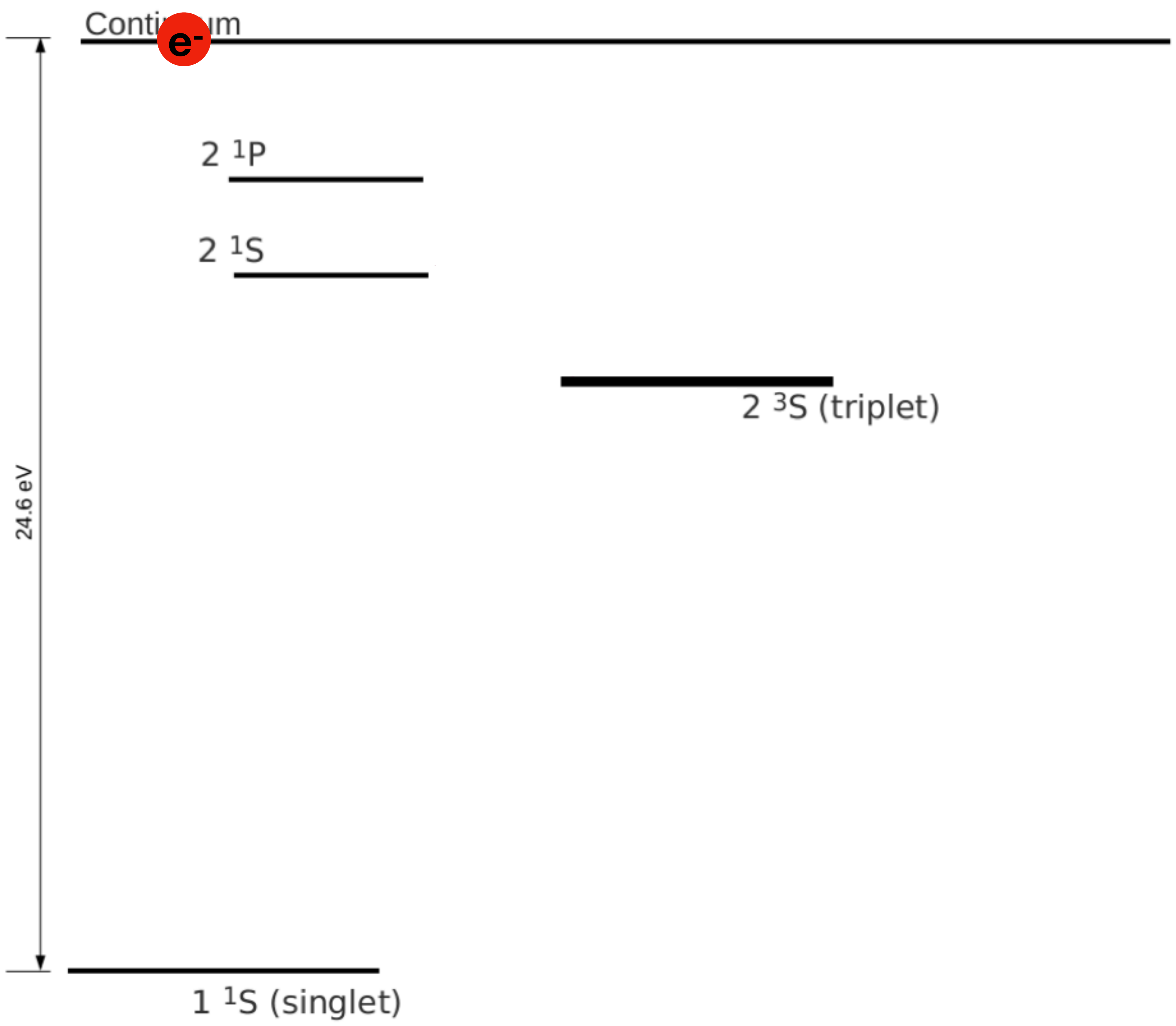

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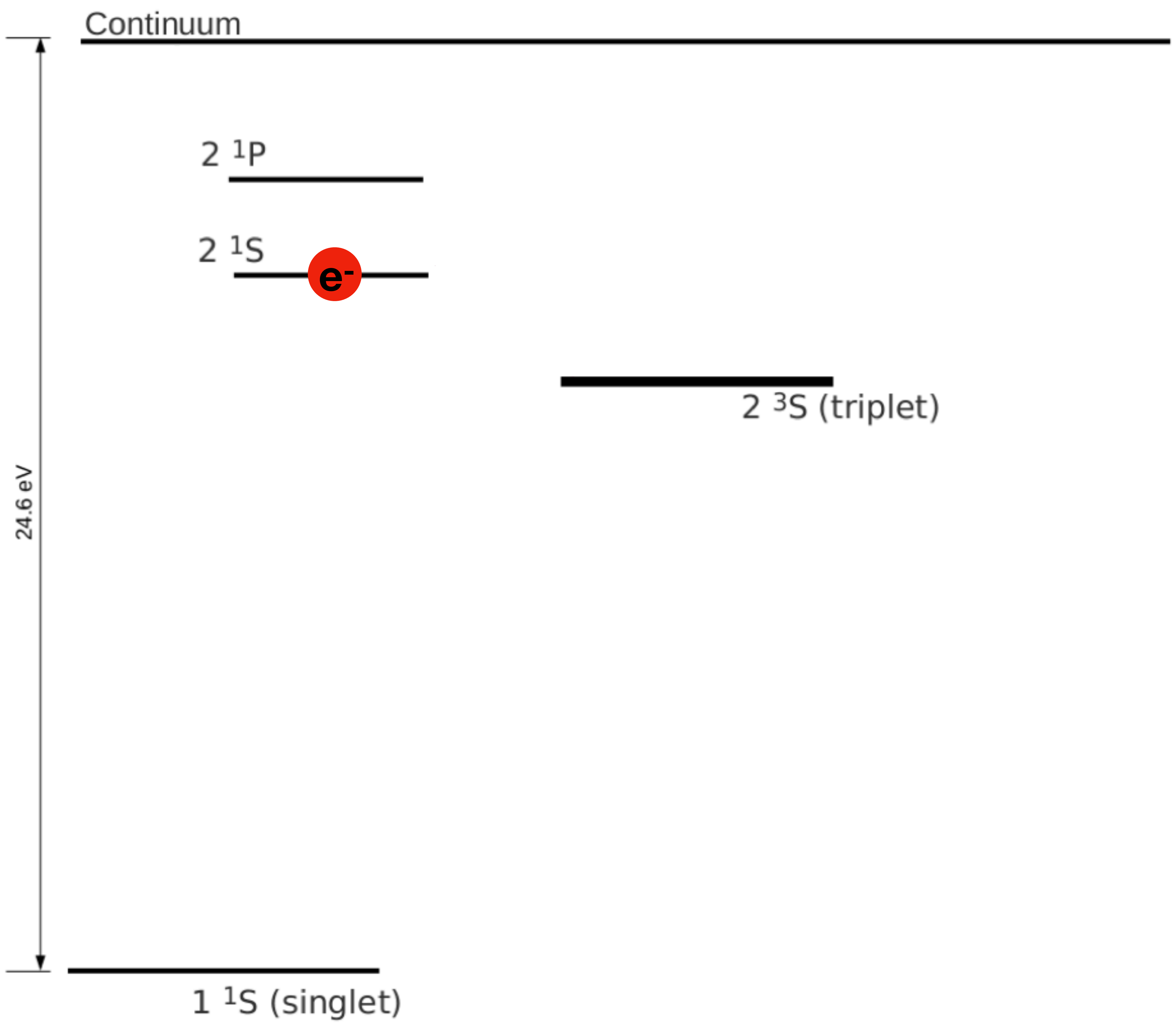

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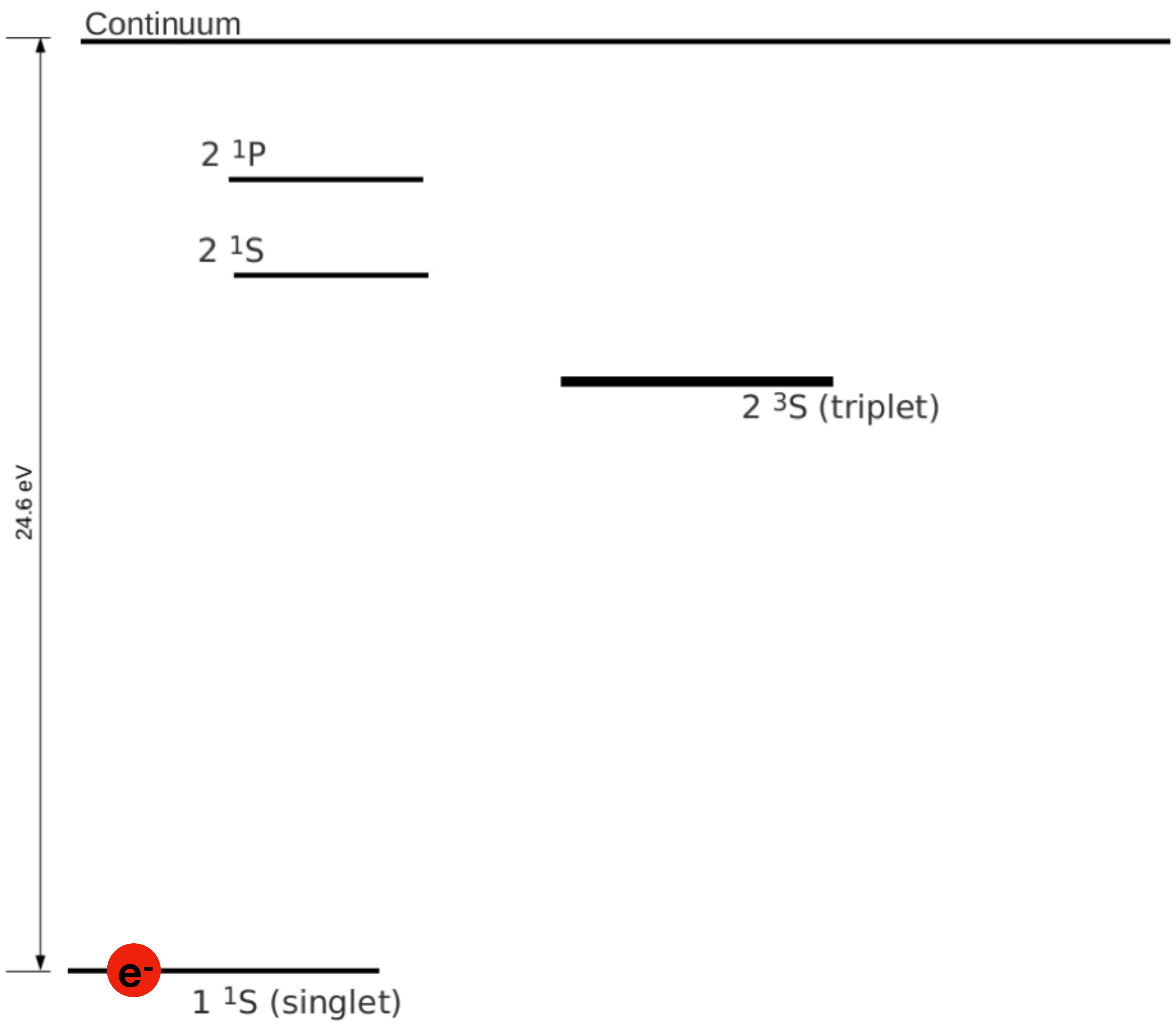

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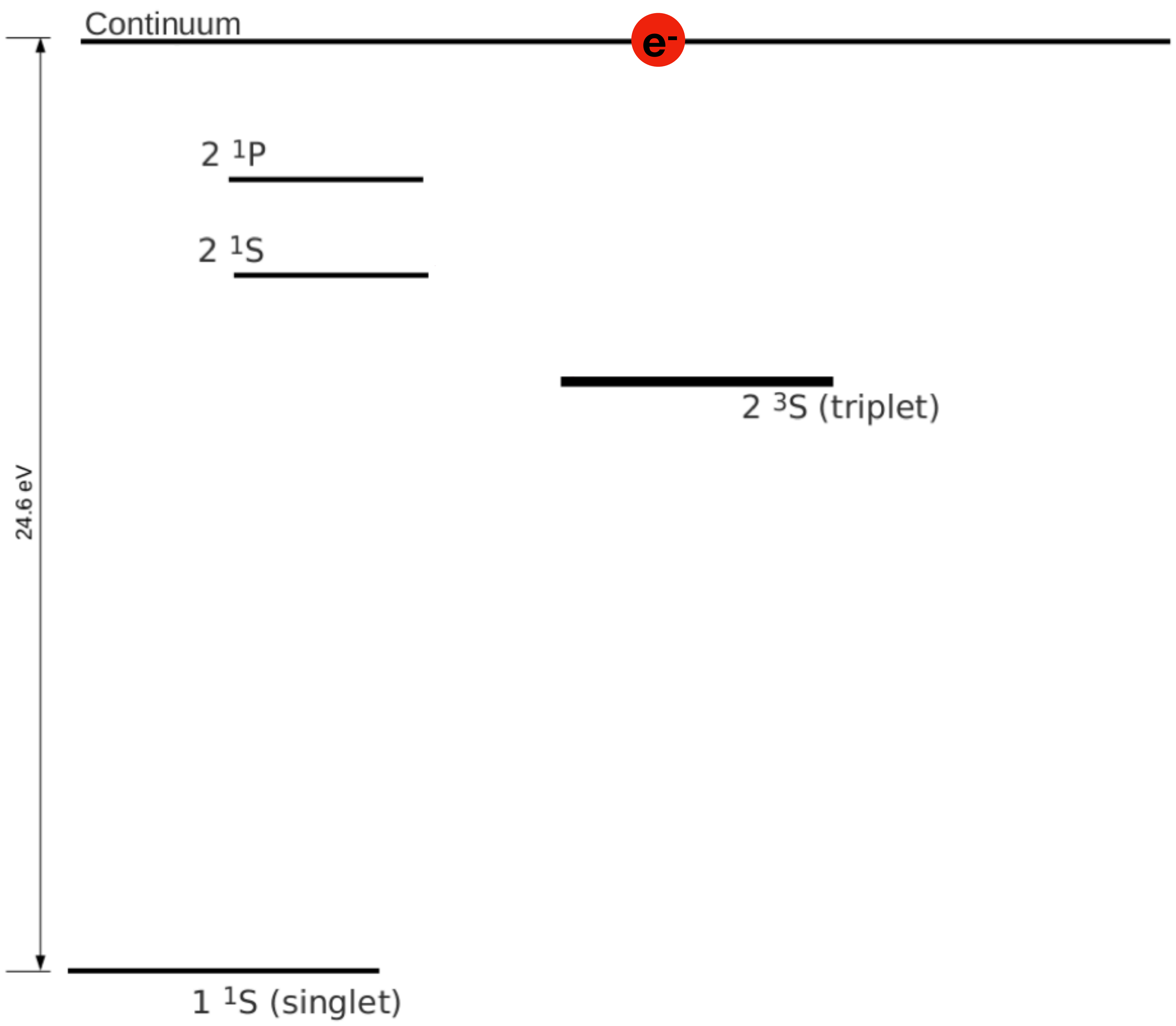

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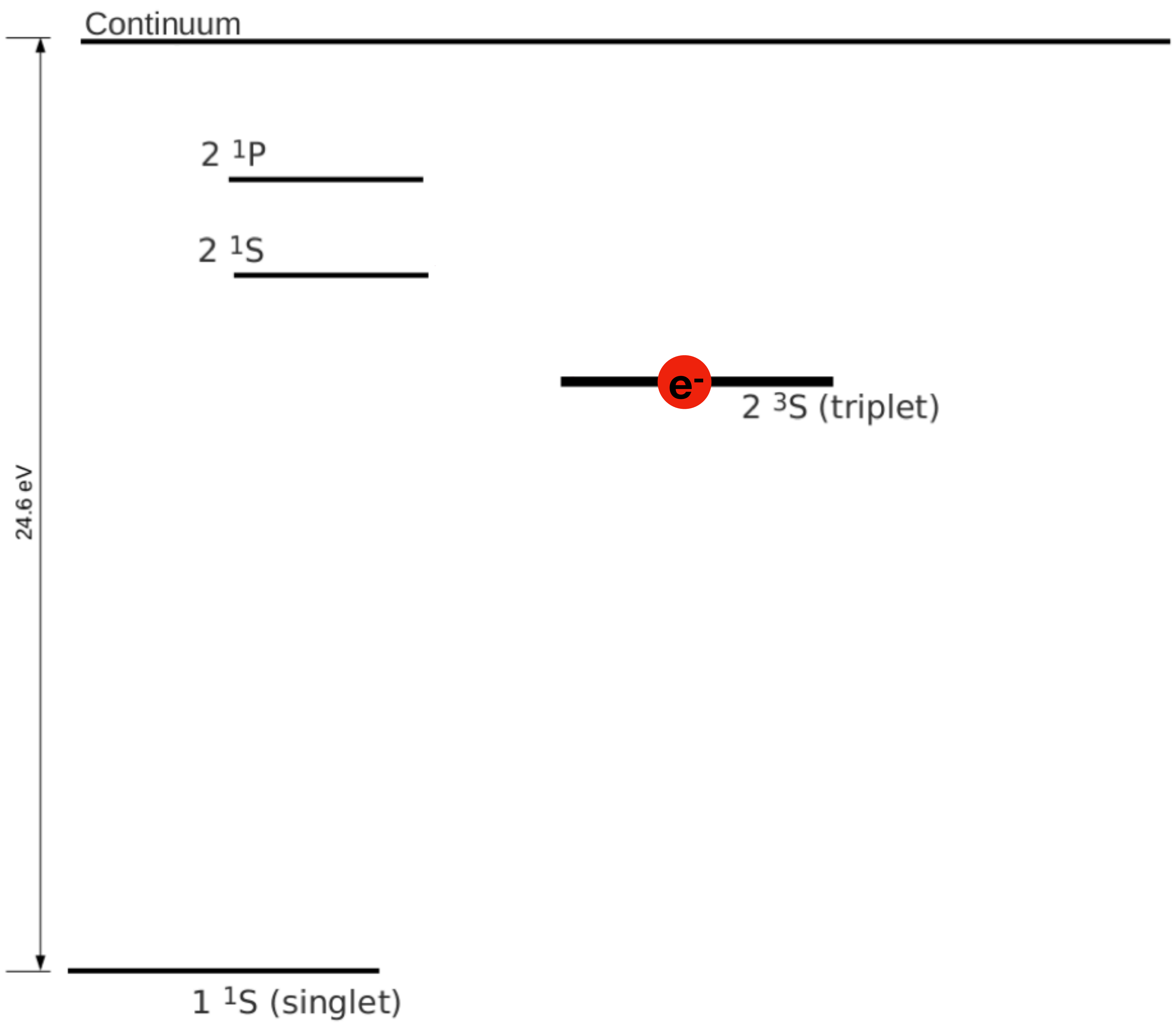

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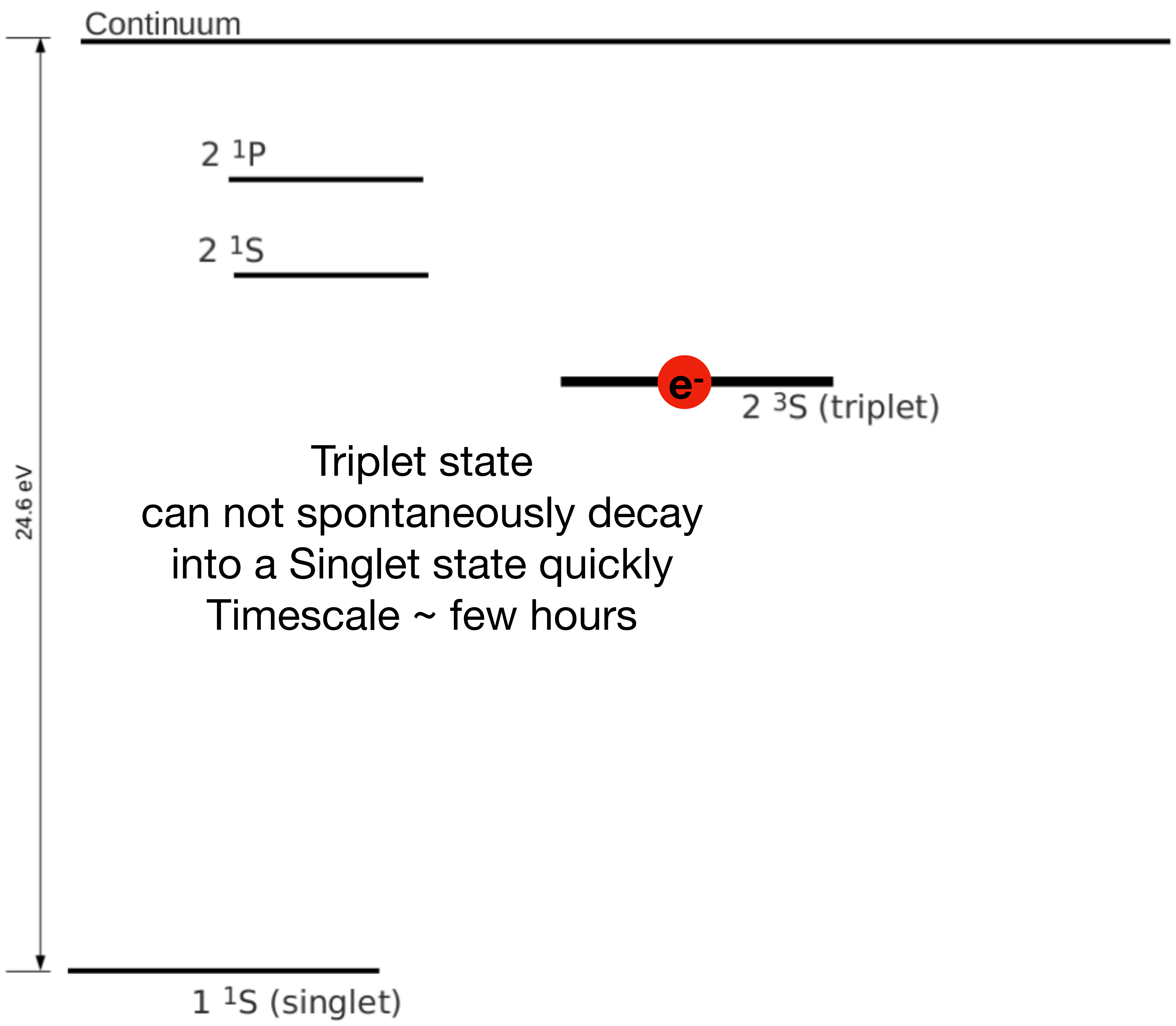

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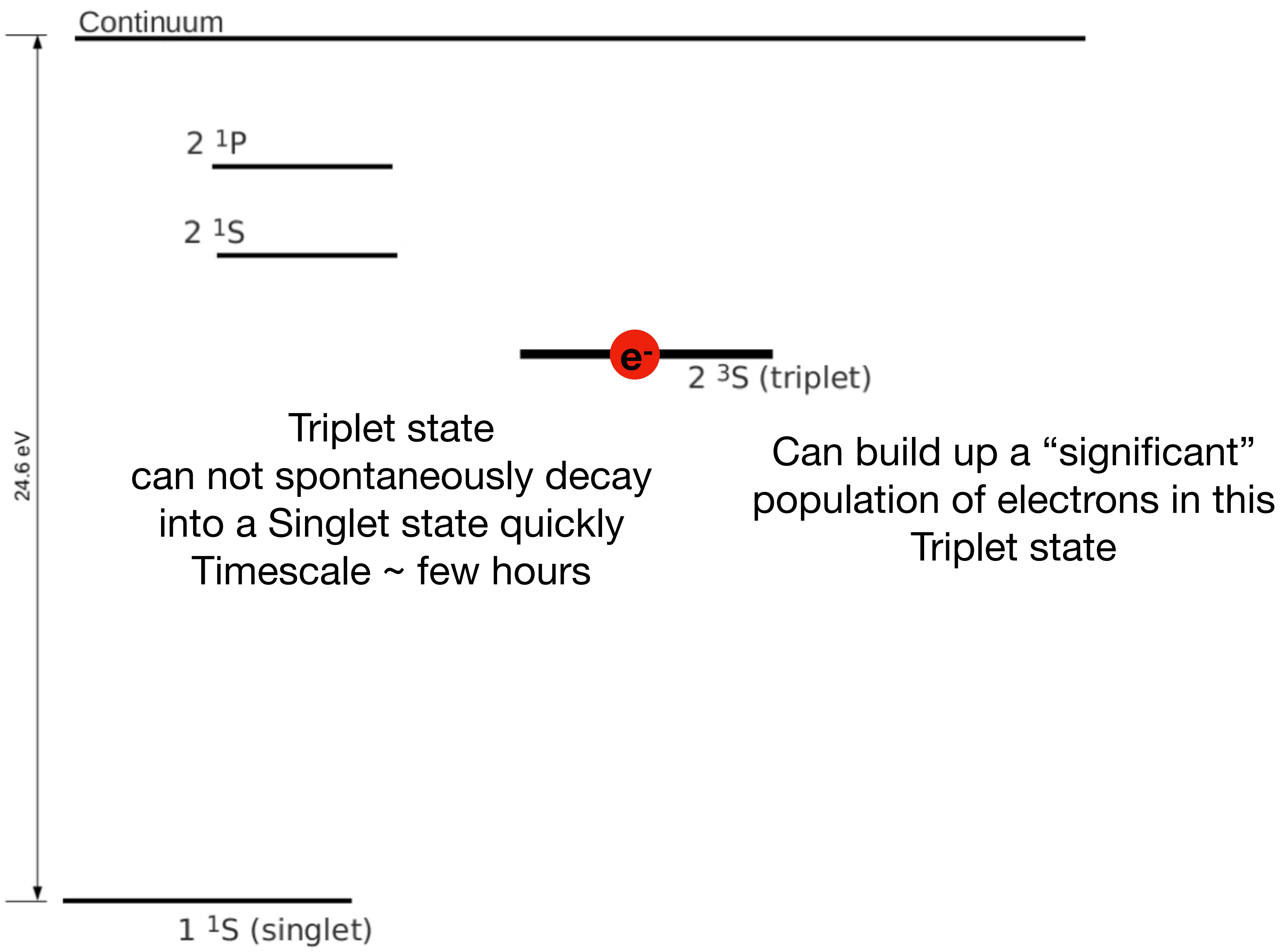

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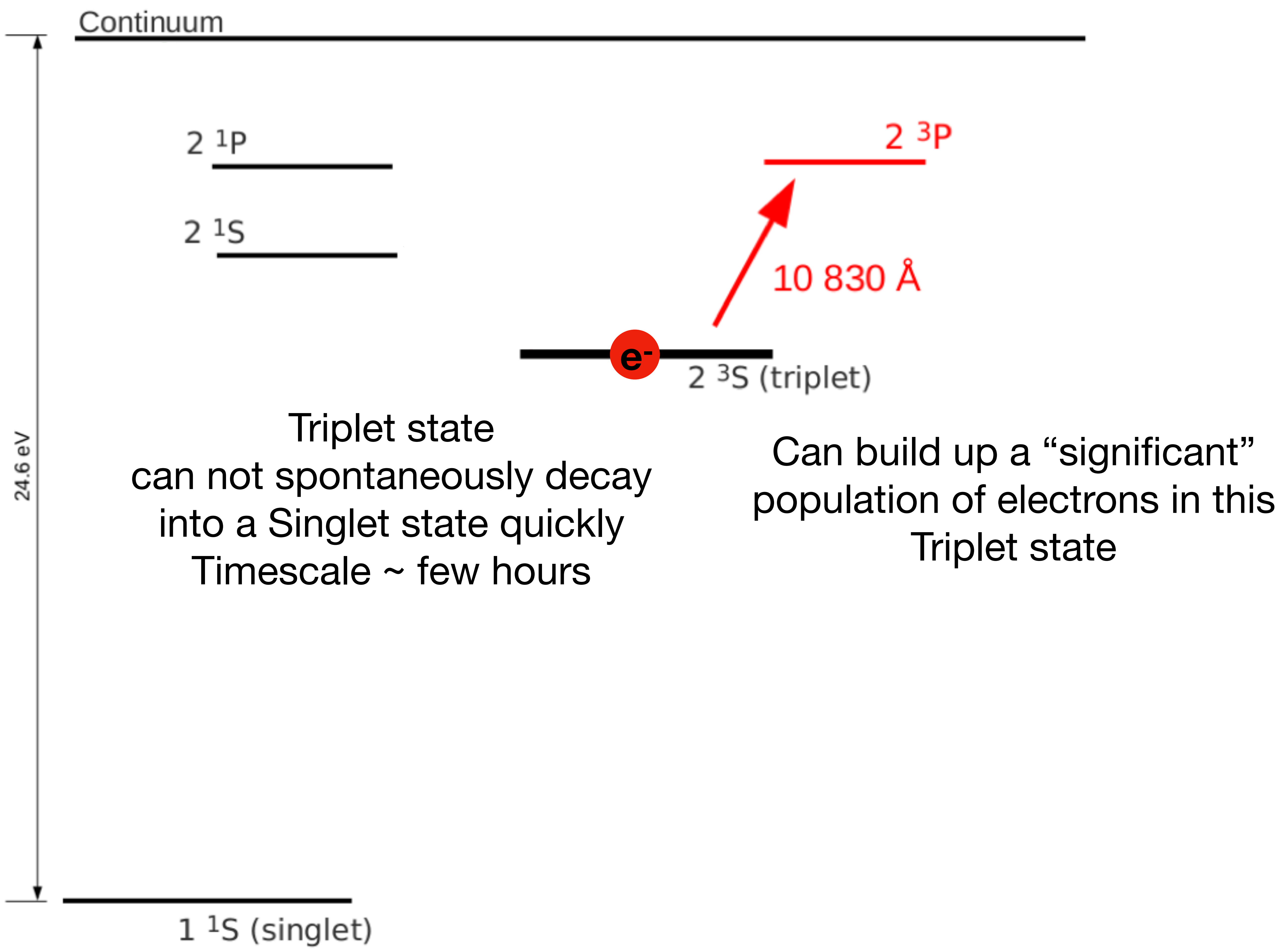
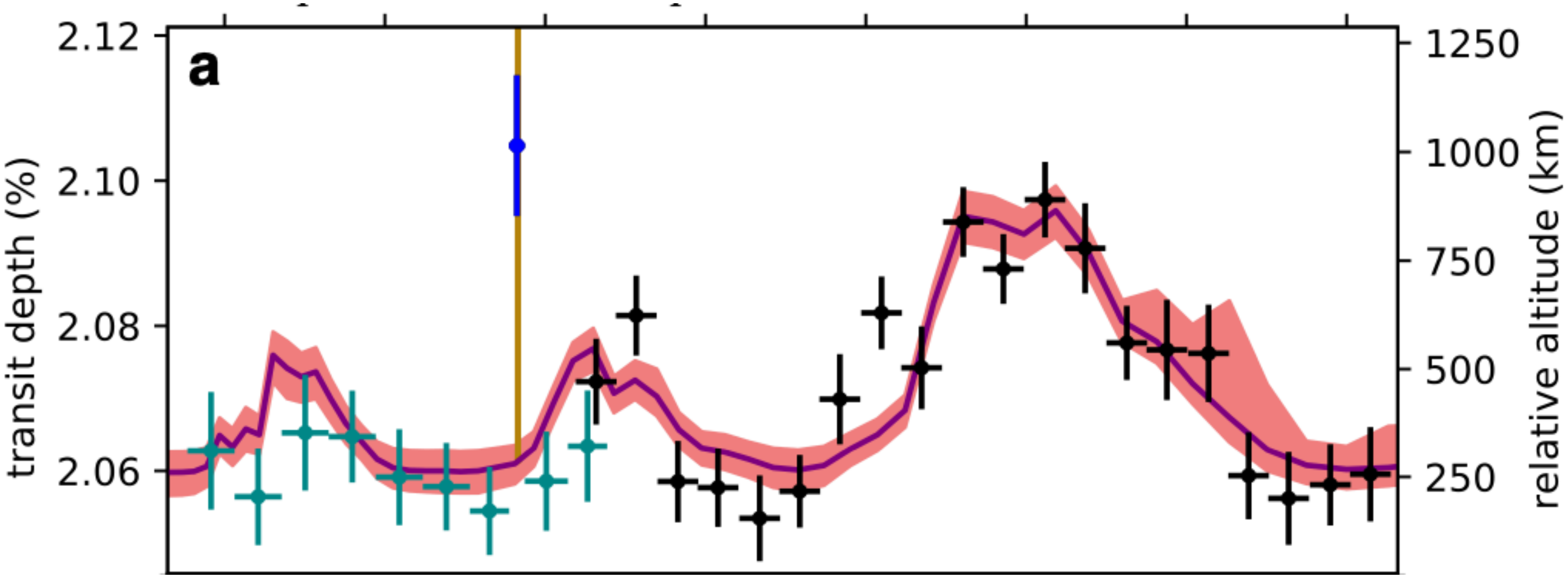
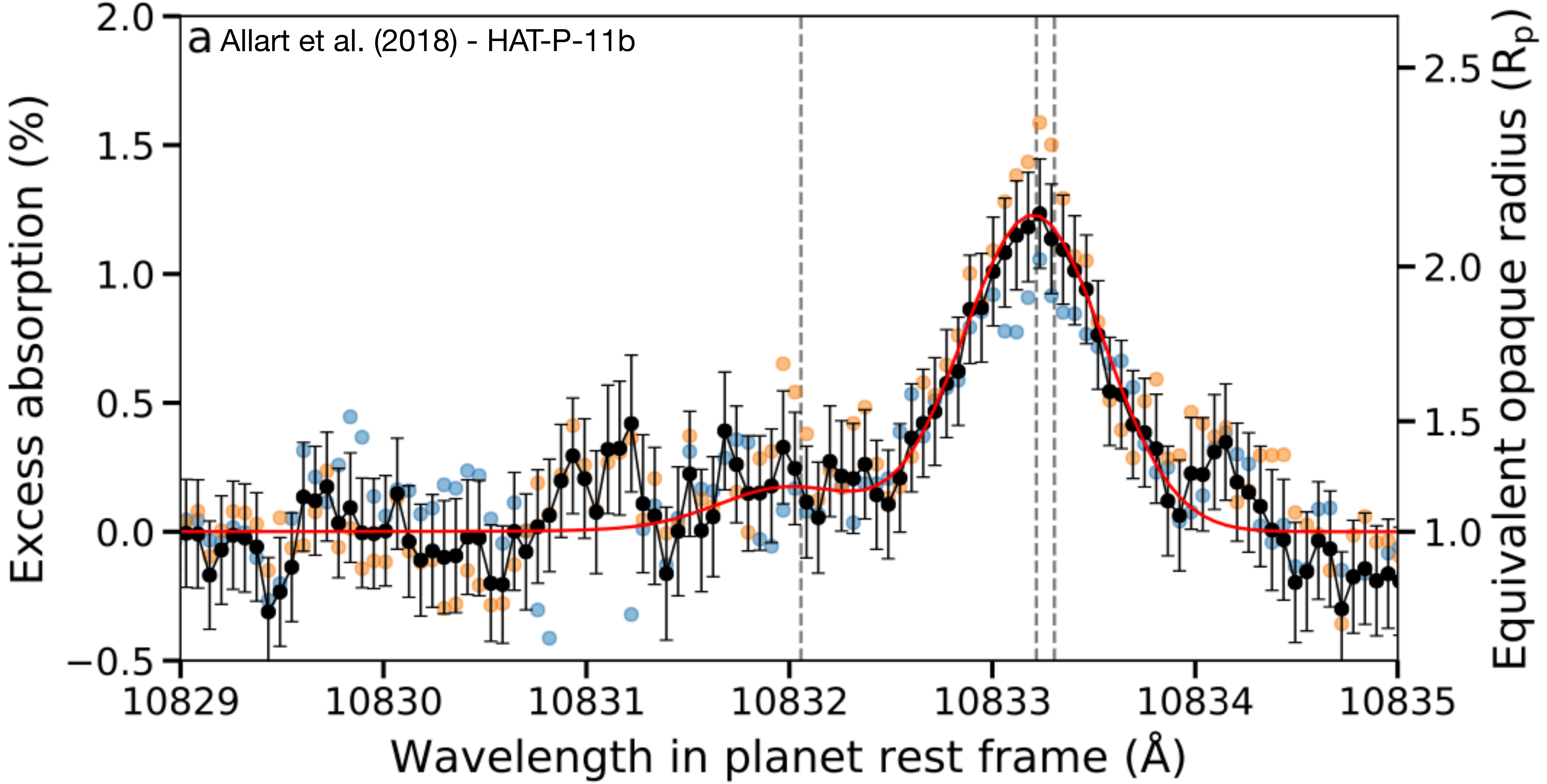


First detection with HST



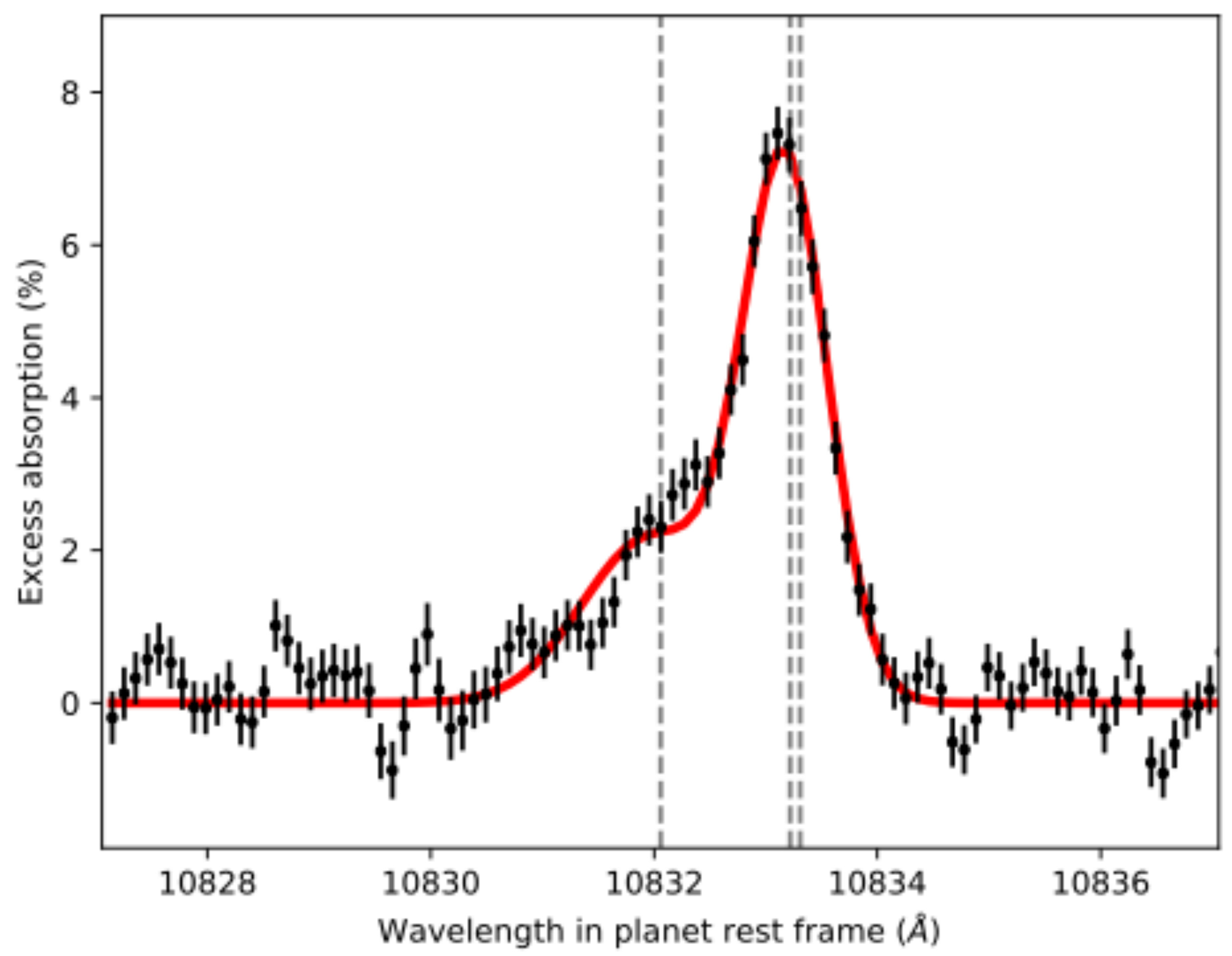
Spake et al. (2018) Wasp-107b

He can be done at high-resolution from the ground

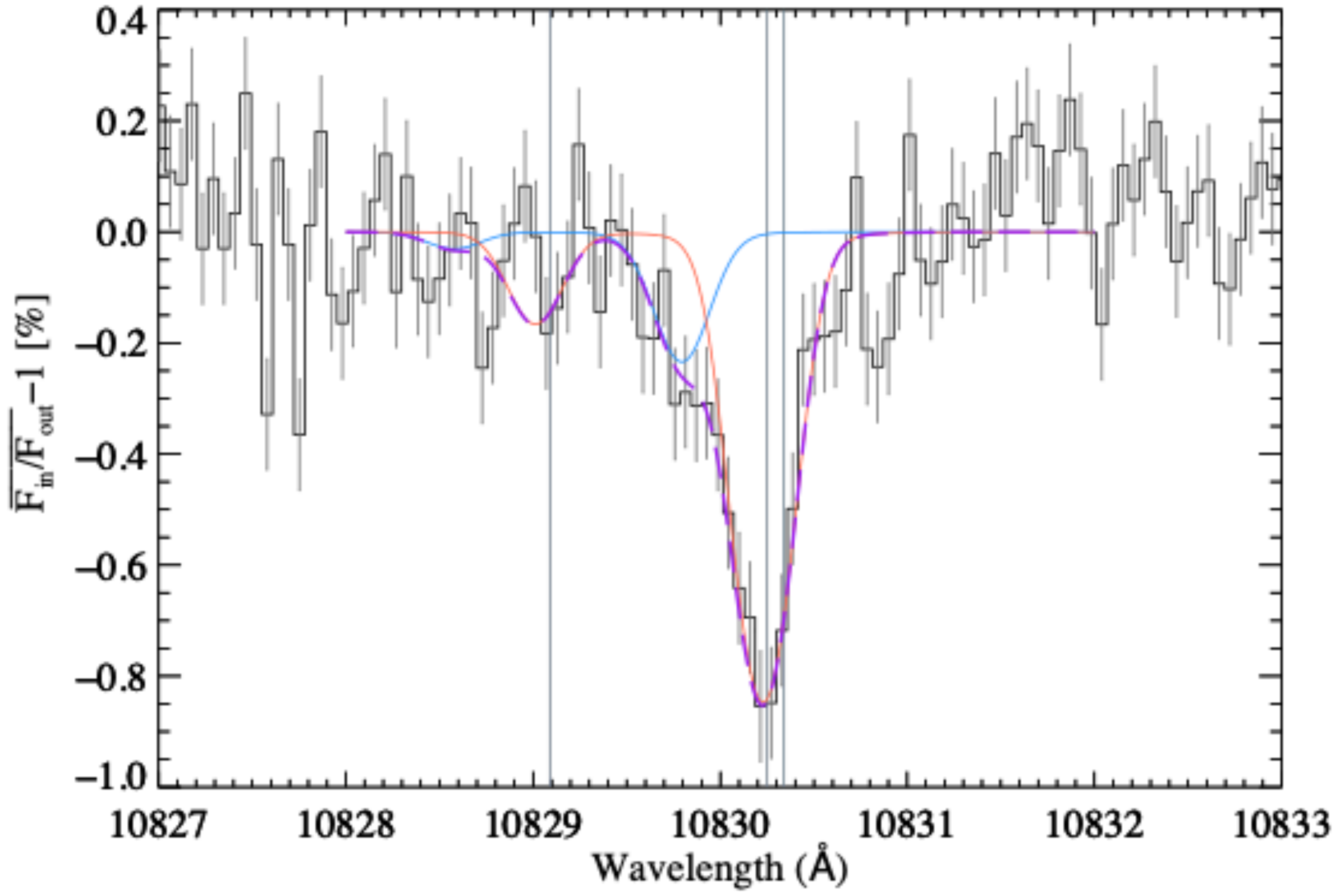


He has become incredibly successful in the last 5 years

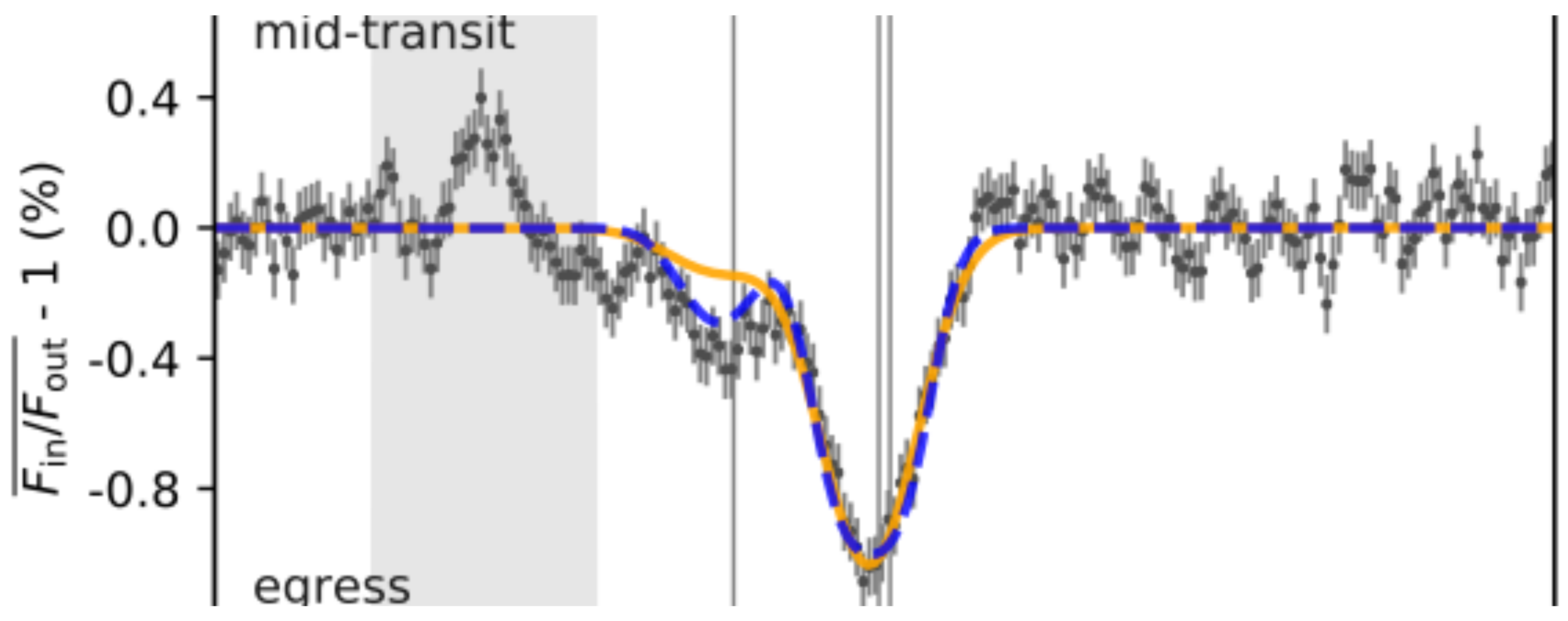
Wasp-107b - Kirk et al. 2020



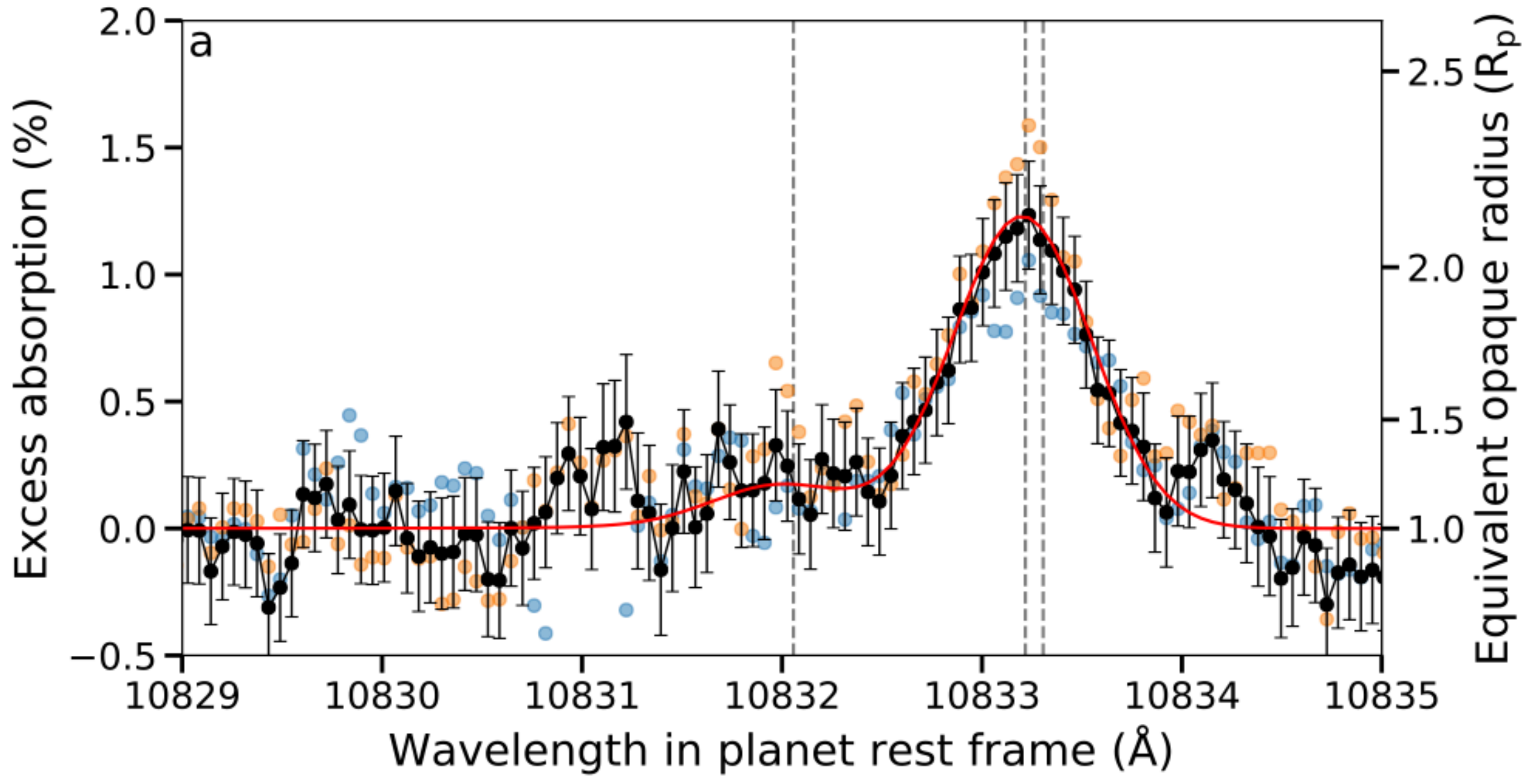
HD209458b - Alonso-Floriano 2019



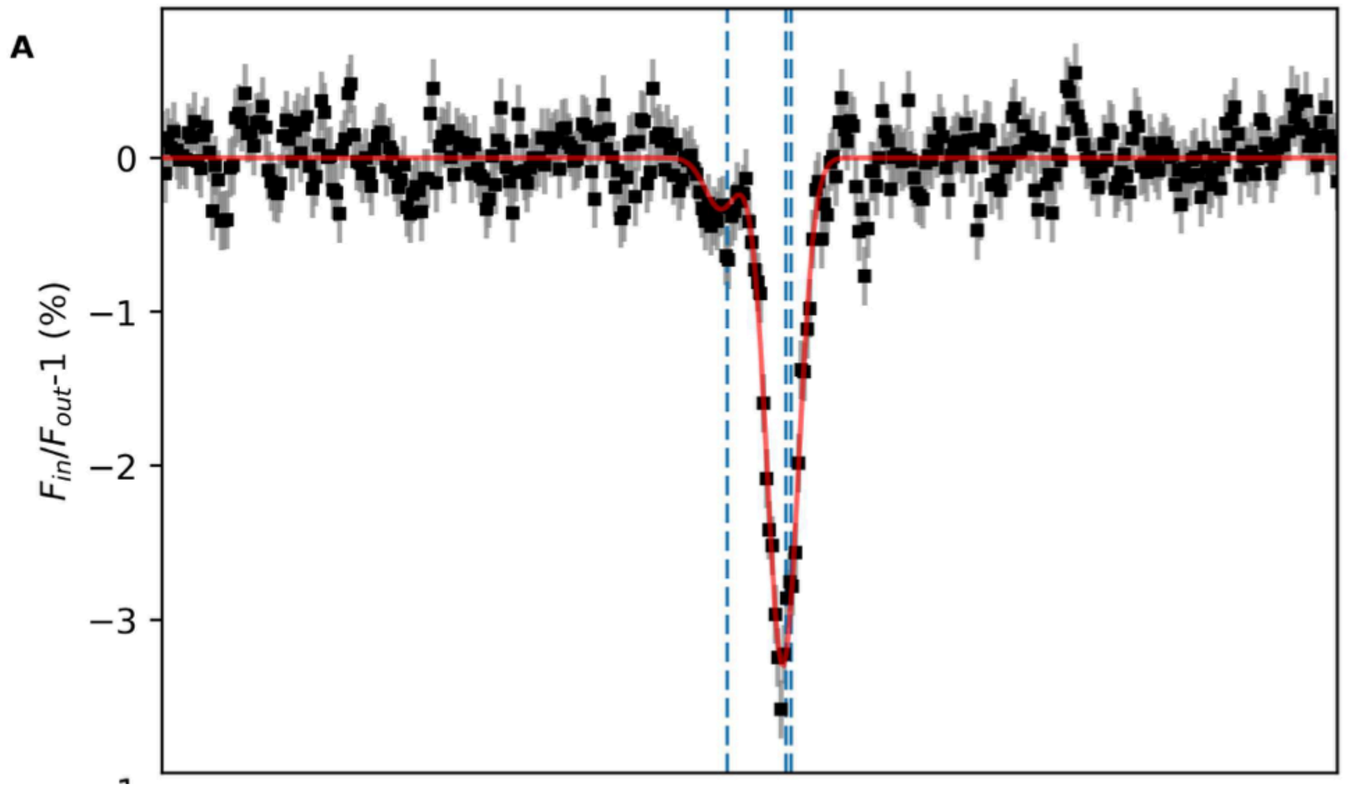
HD189733b - Salz et al. 2019



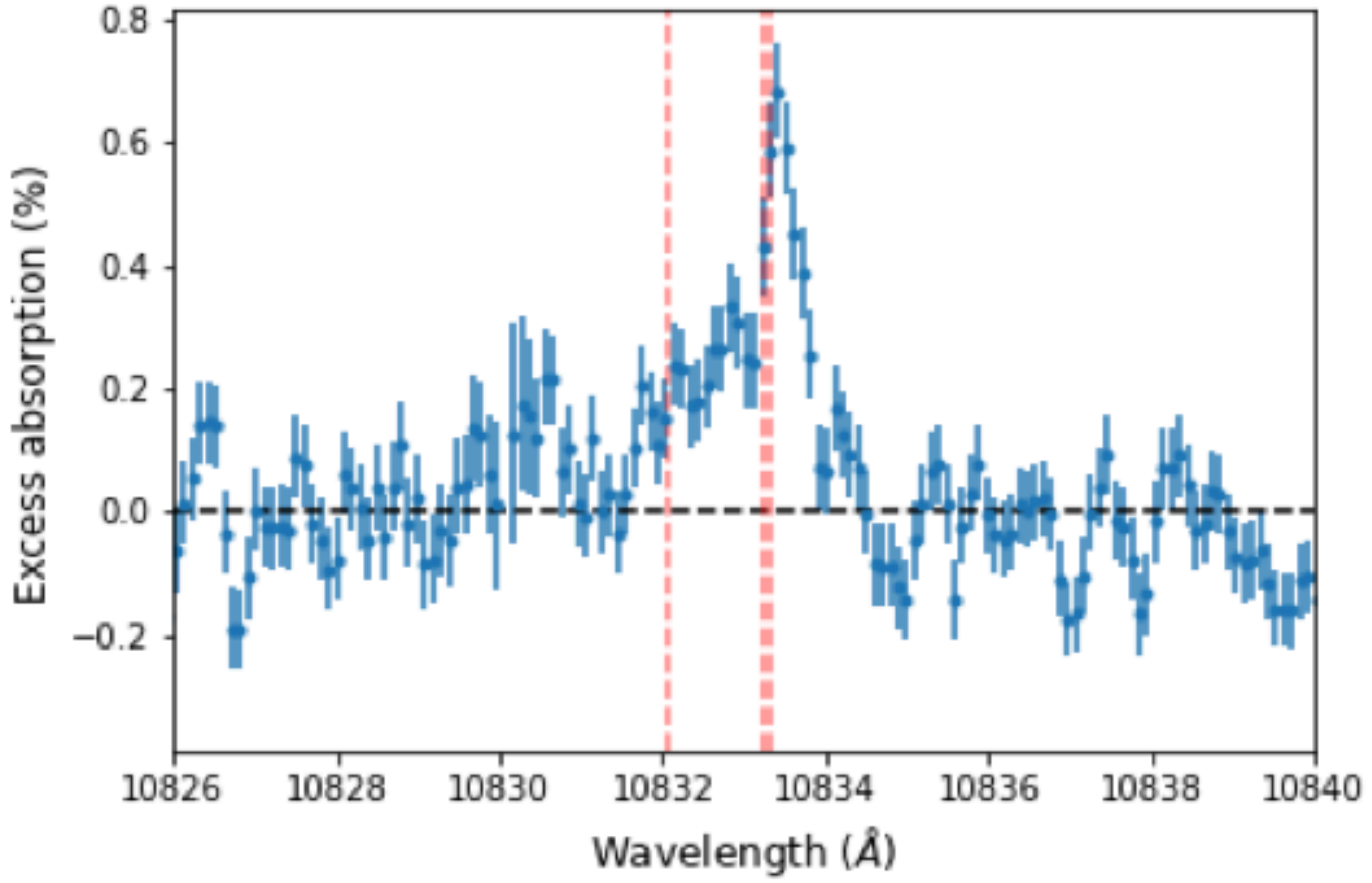
HAT-P-11b - Allart et al. 2018



Wasp-69b - Nortmann et al. 2019

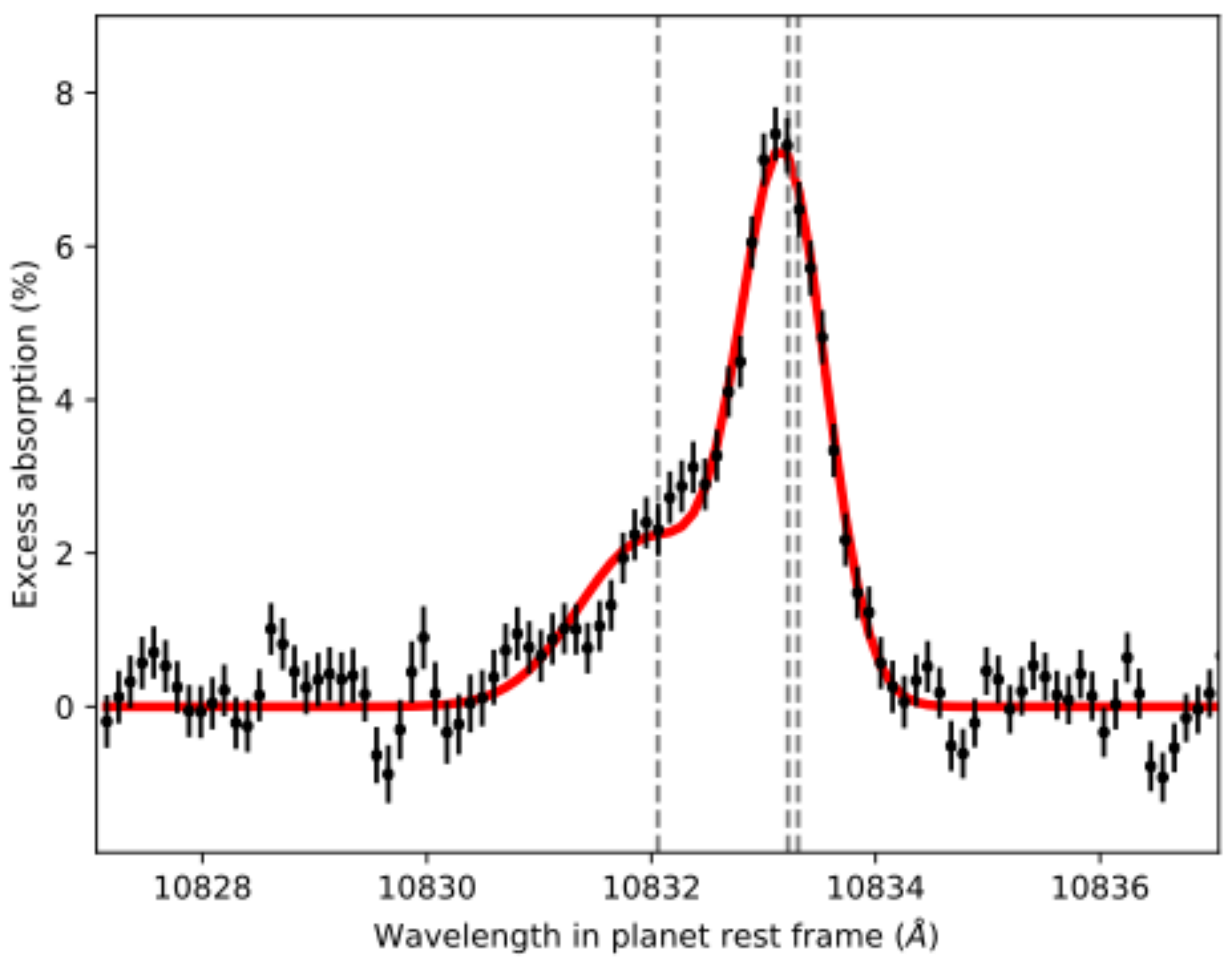


TOI- 560.01 - Zhang et al. 2022

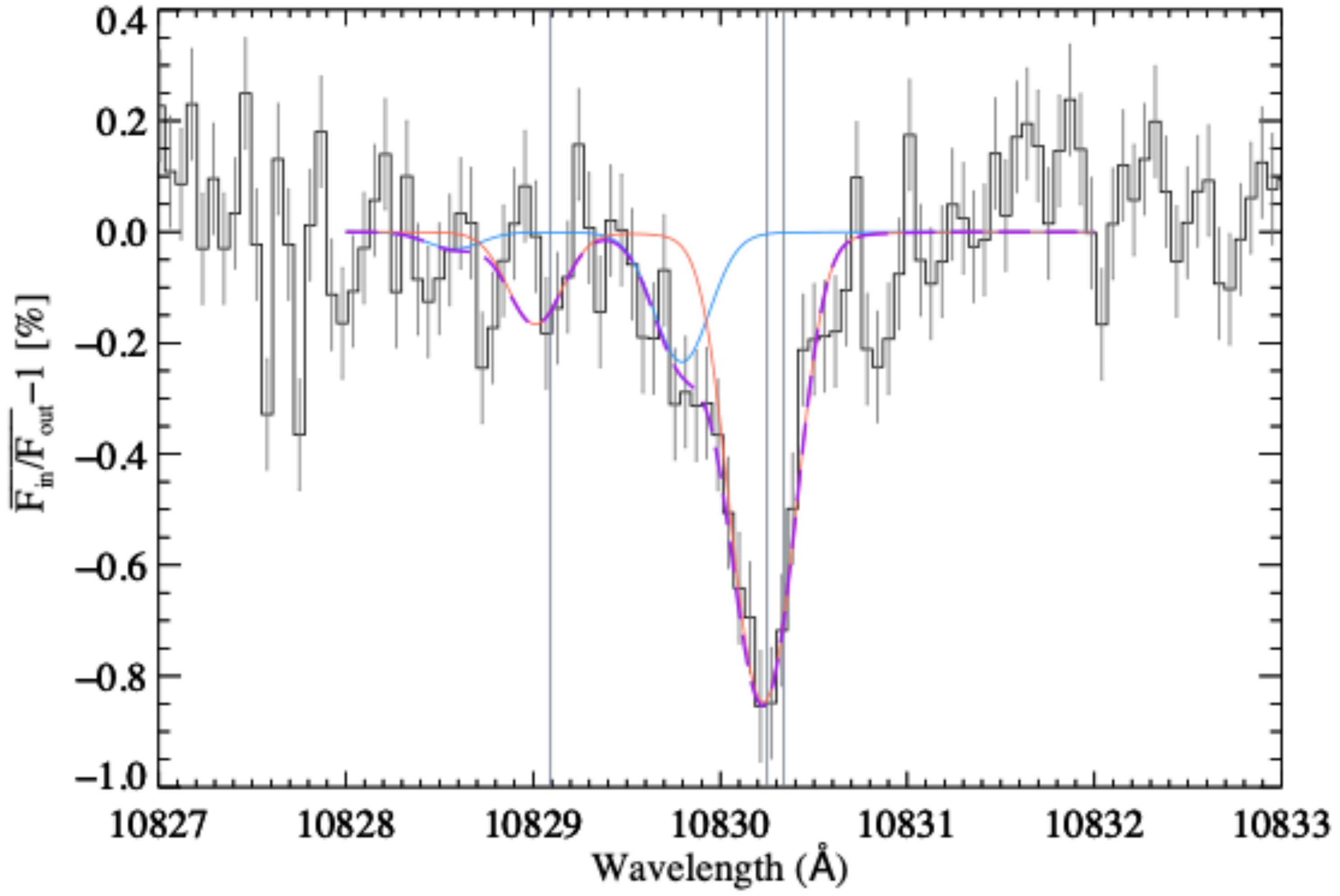


He has become incredibly successful in the last 5 years

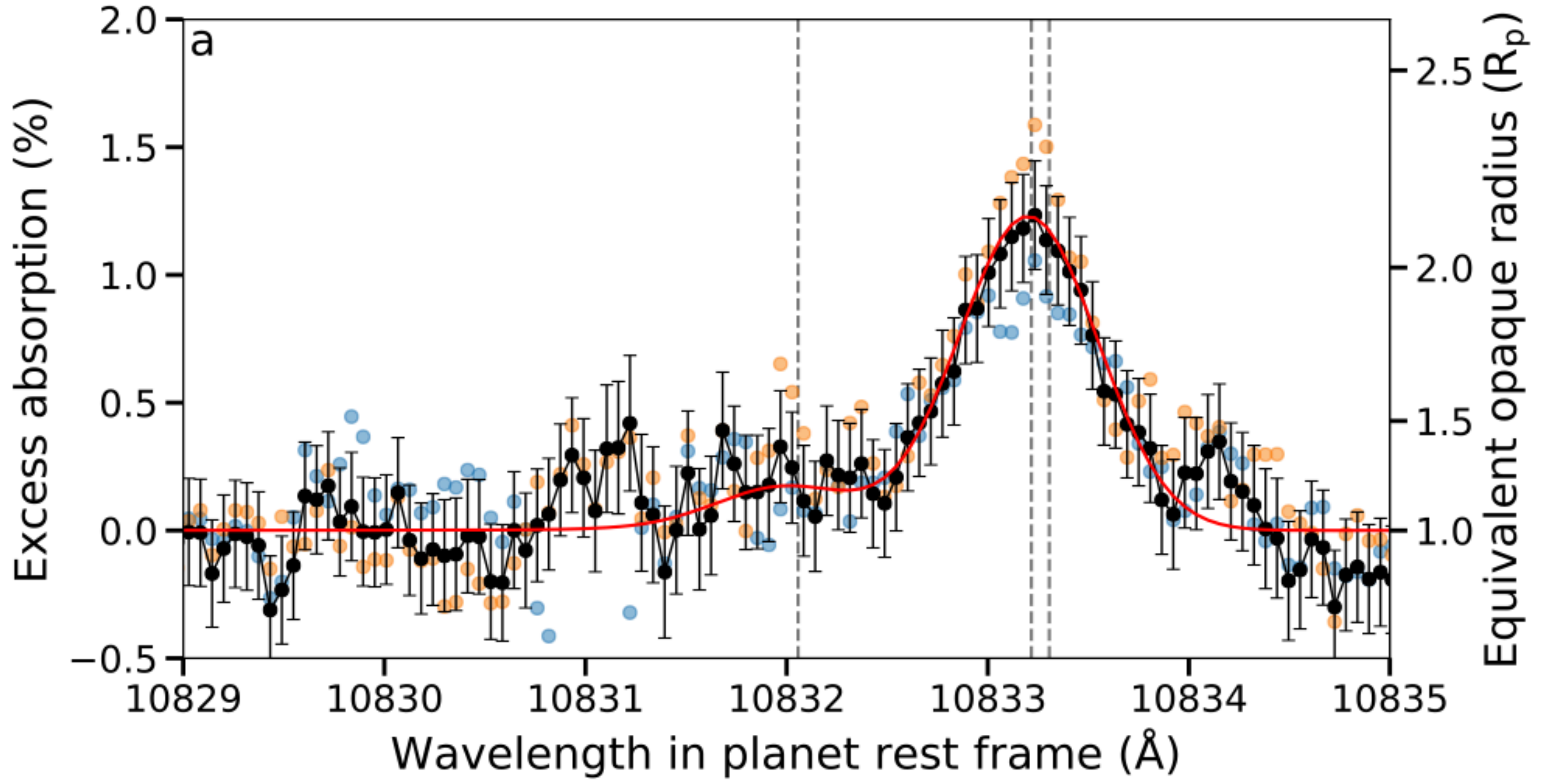
Wasp-107b - Kirk et al. 2020



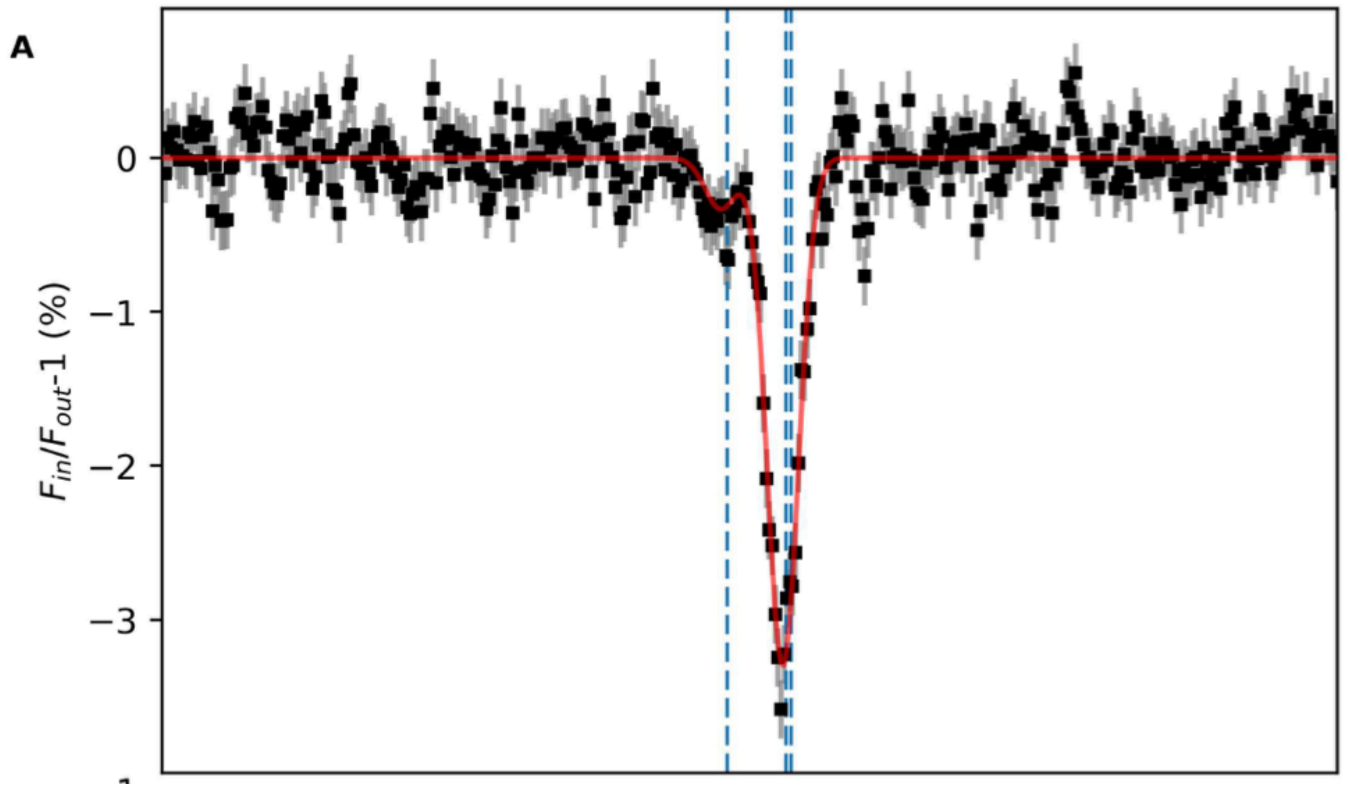
HD209458b - Alonso-Floriano 2019

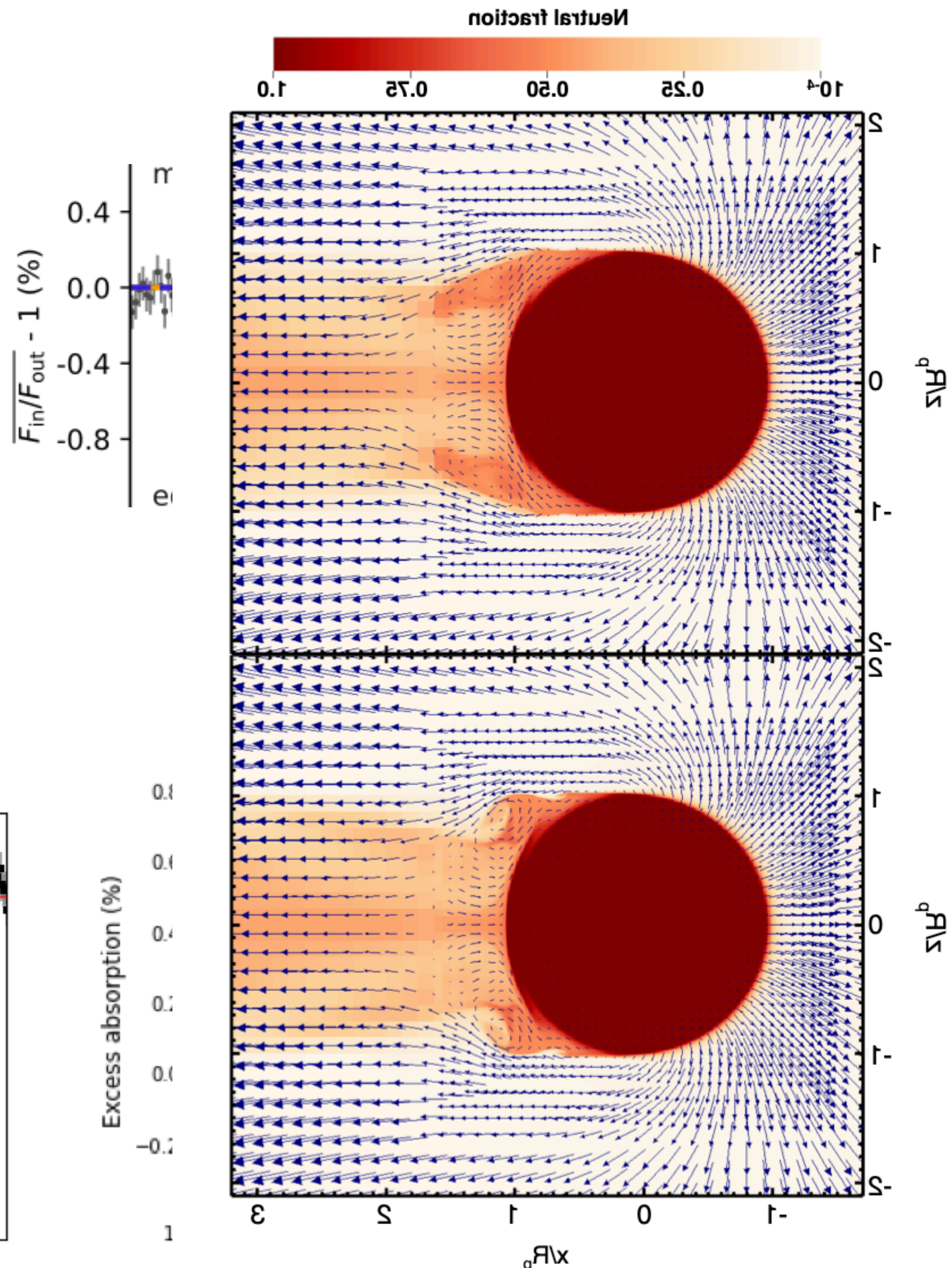


HAT-P-11b - Allart et al. 2018



Wasp-69b - Nortmann et al. 2019

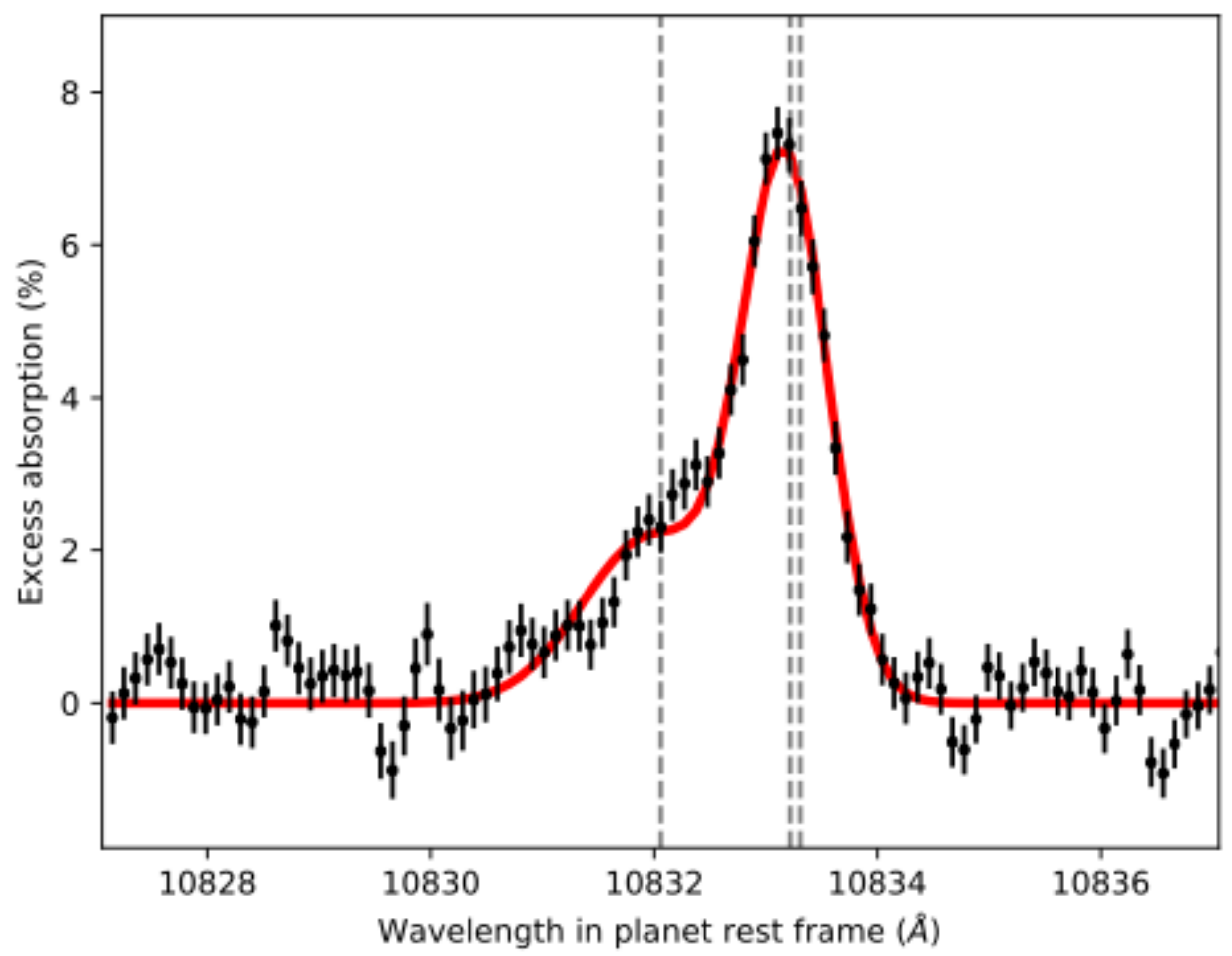




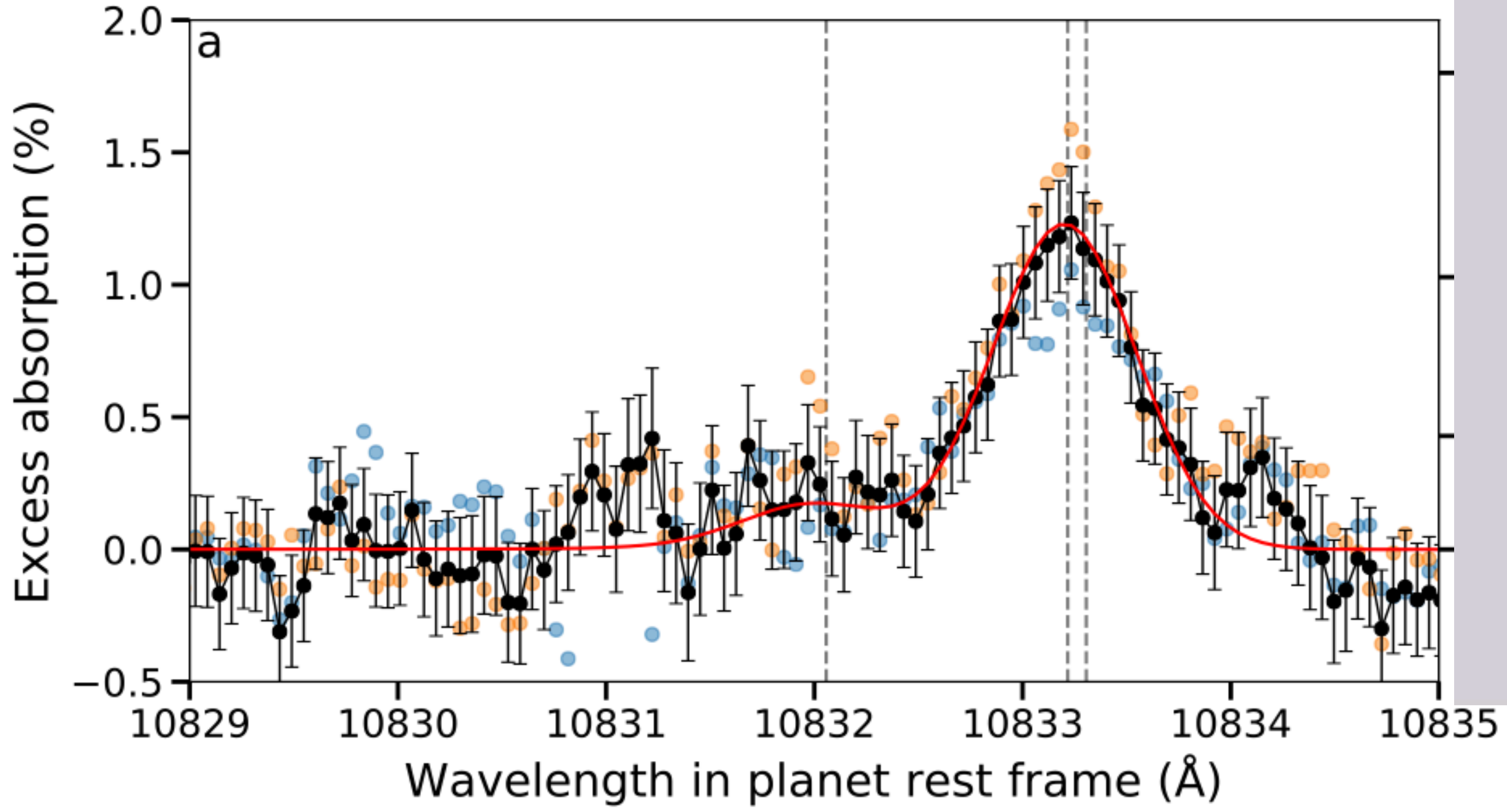
Tripathi et al. (2015)

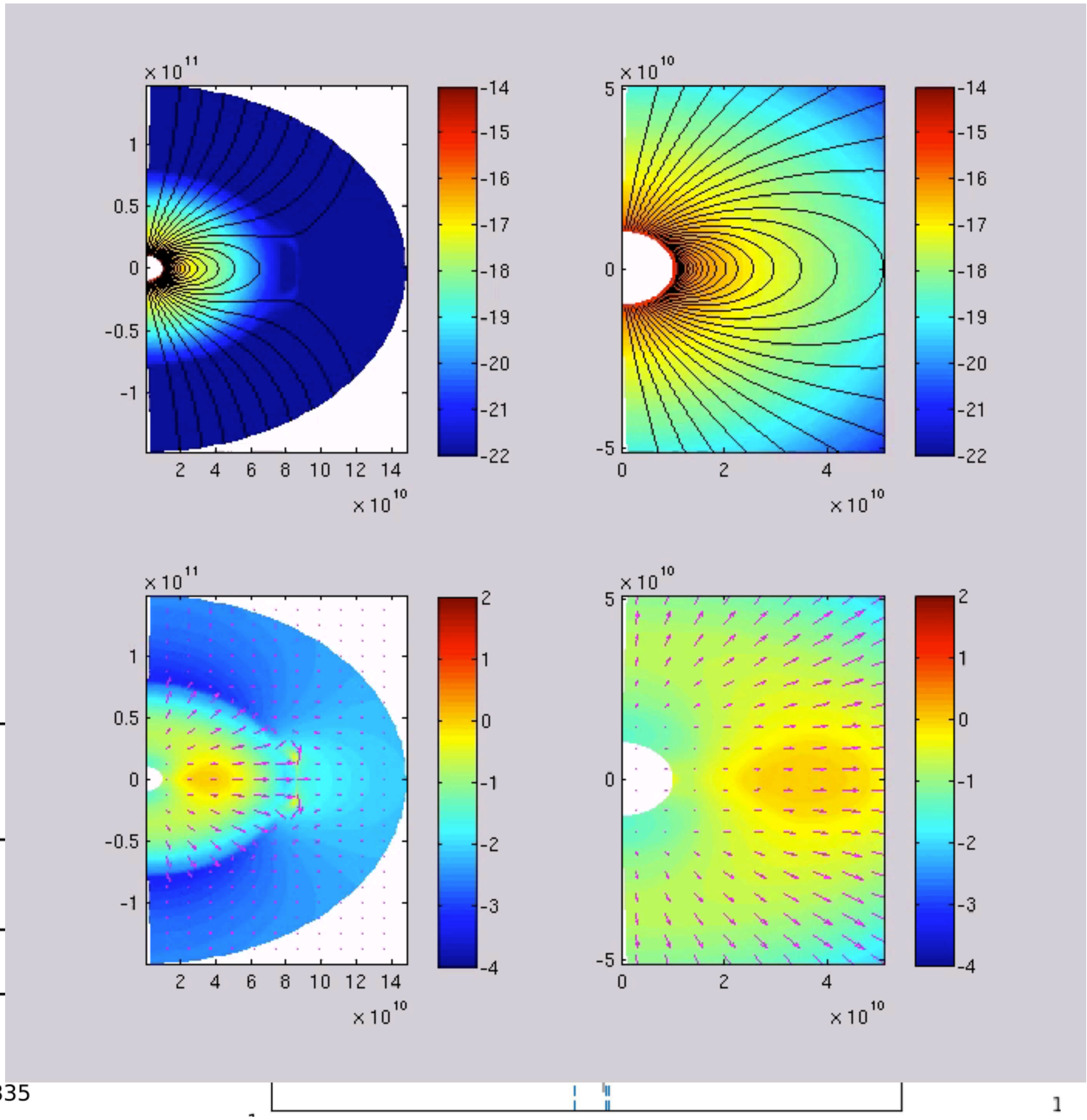
He has become incredibly successful in the last 5 years

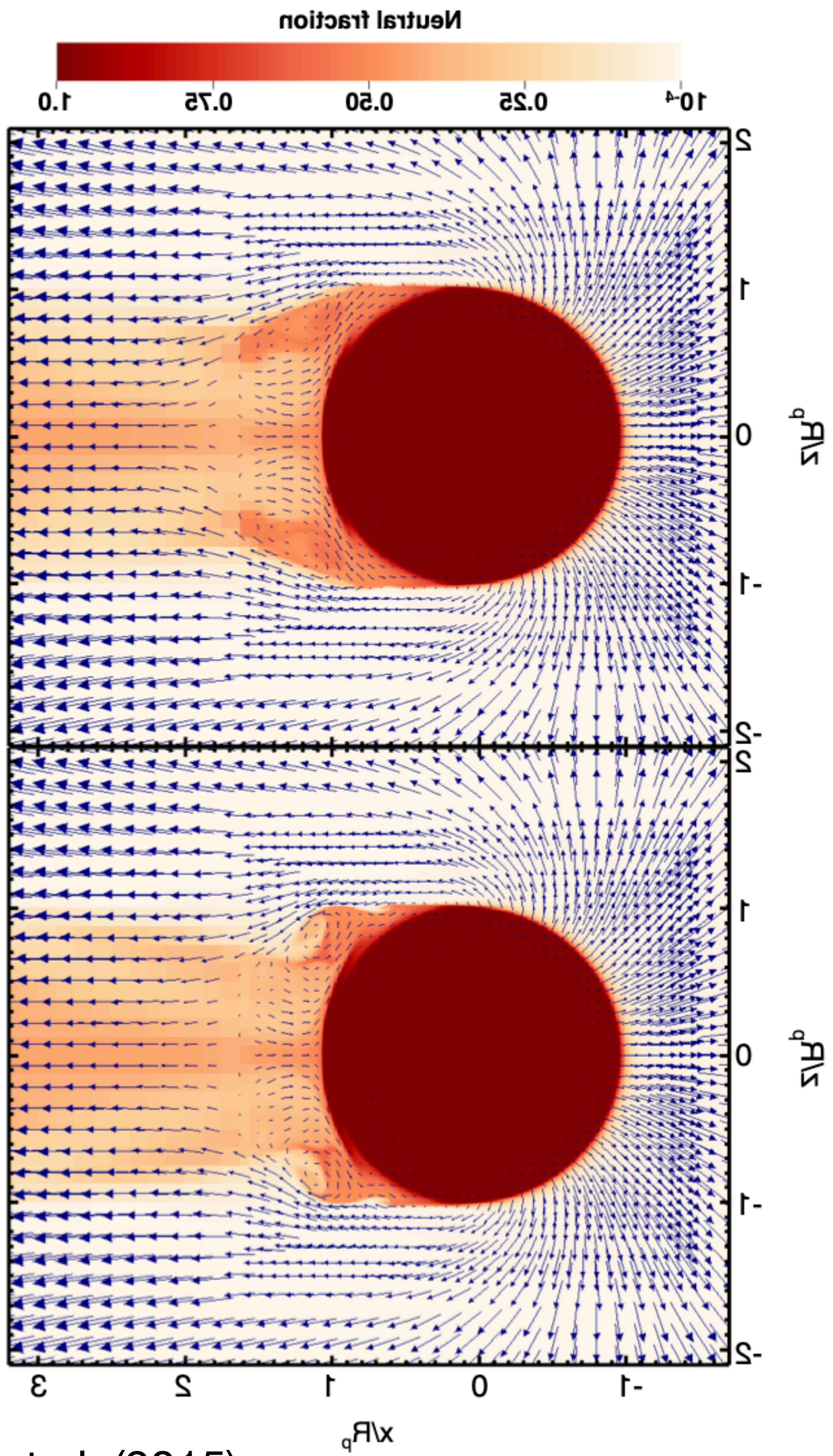
Wasp-107b - Kirk et al. 2020



HAT-P-11b - Allart et al. 2018



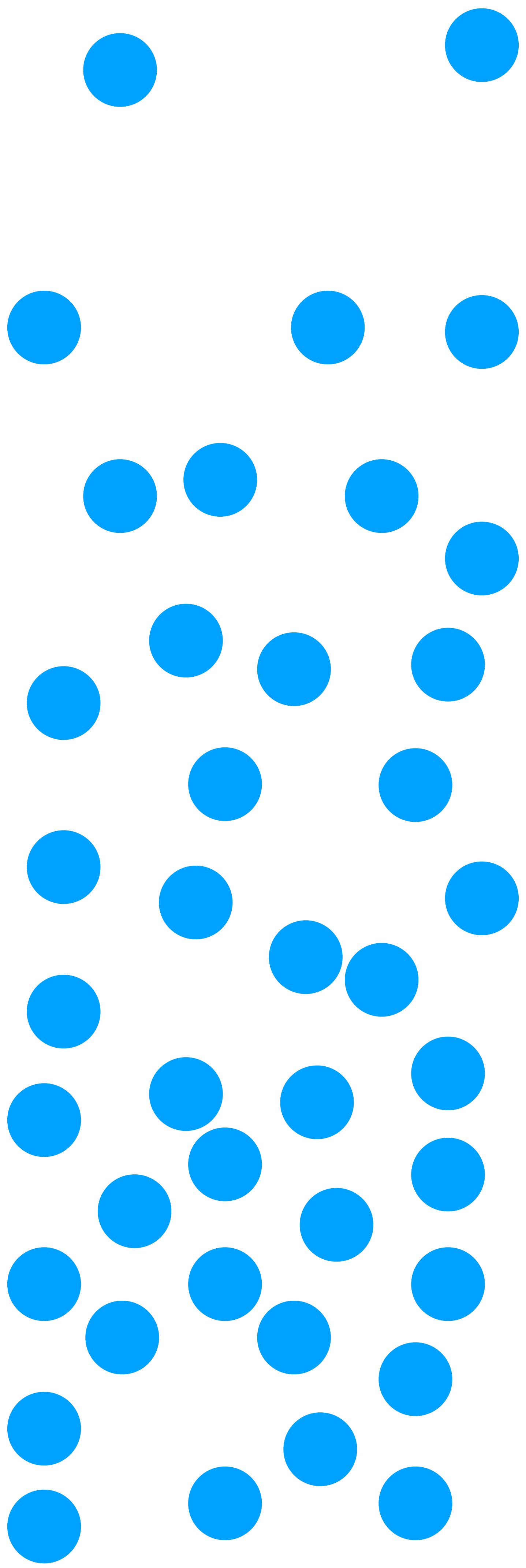




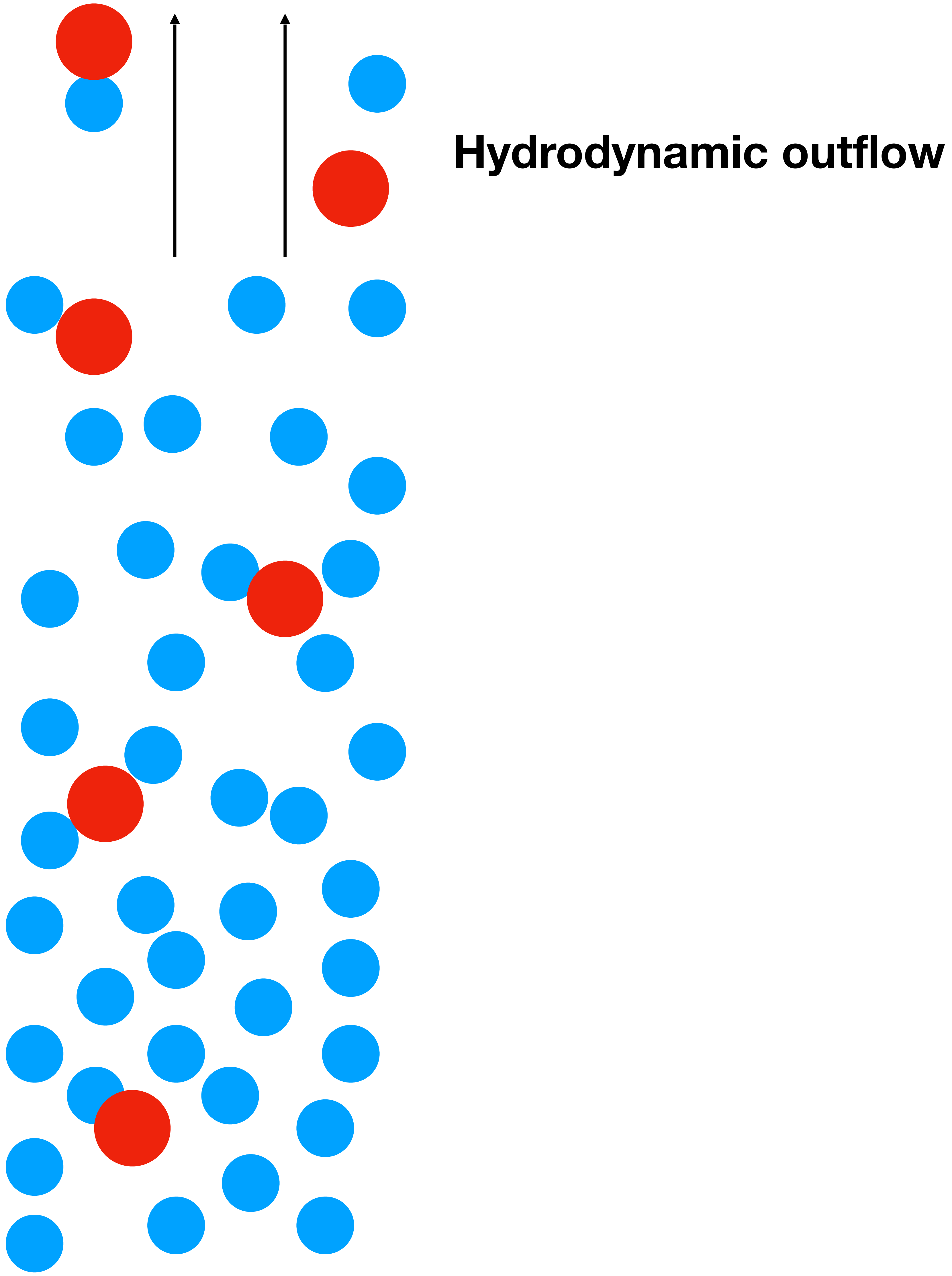
Tripathi et al. (2015)

Future…

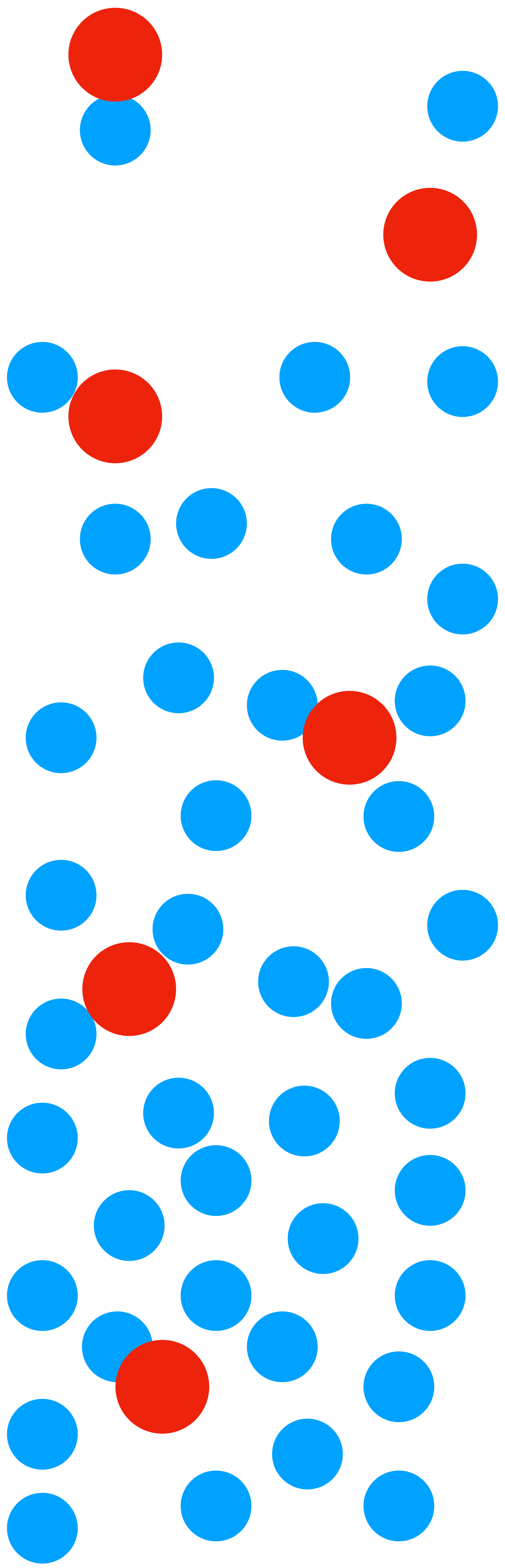
Heavy element fractionation



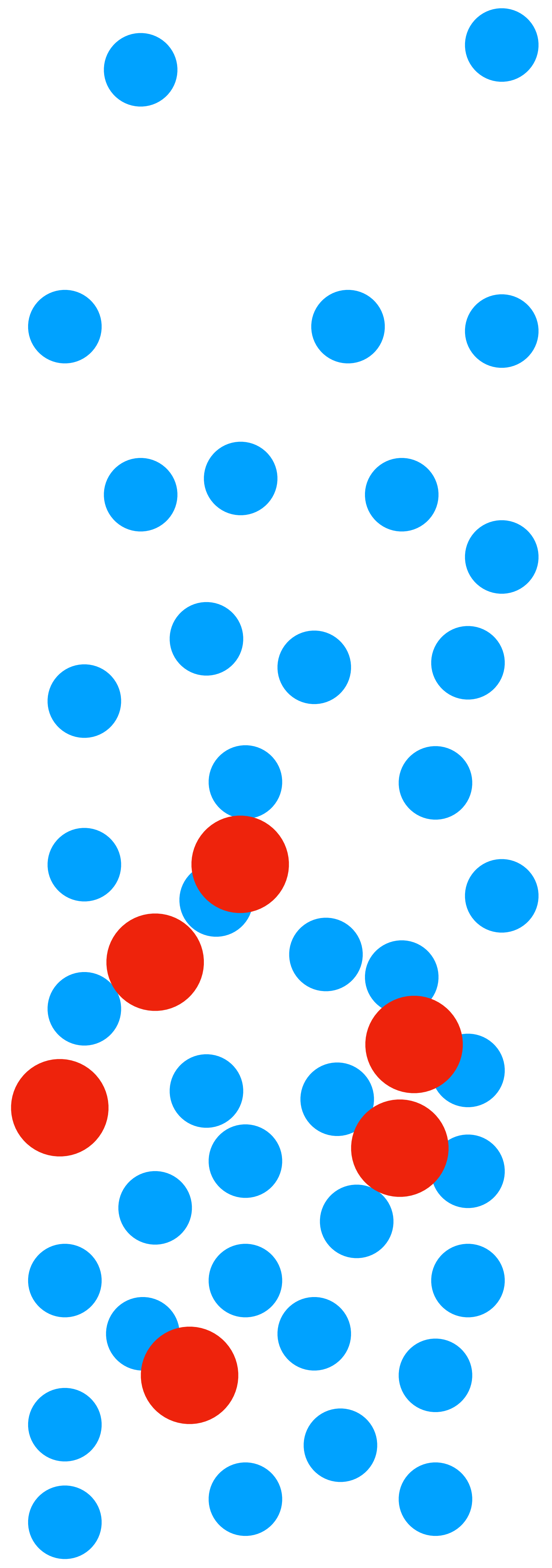
Heavy element fractionation



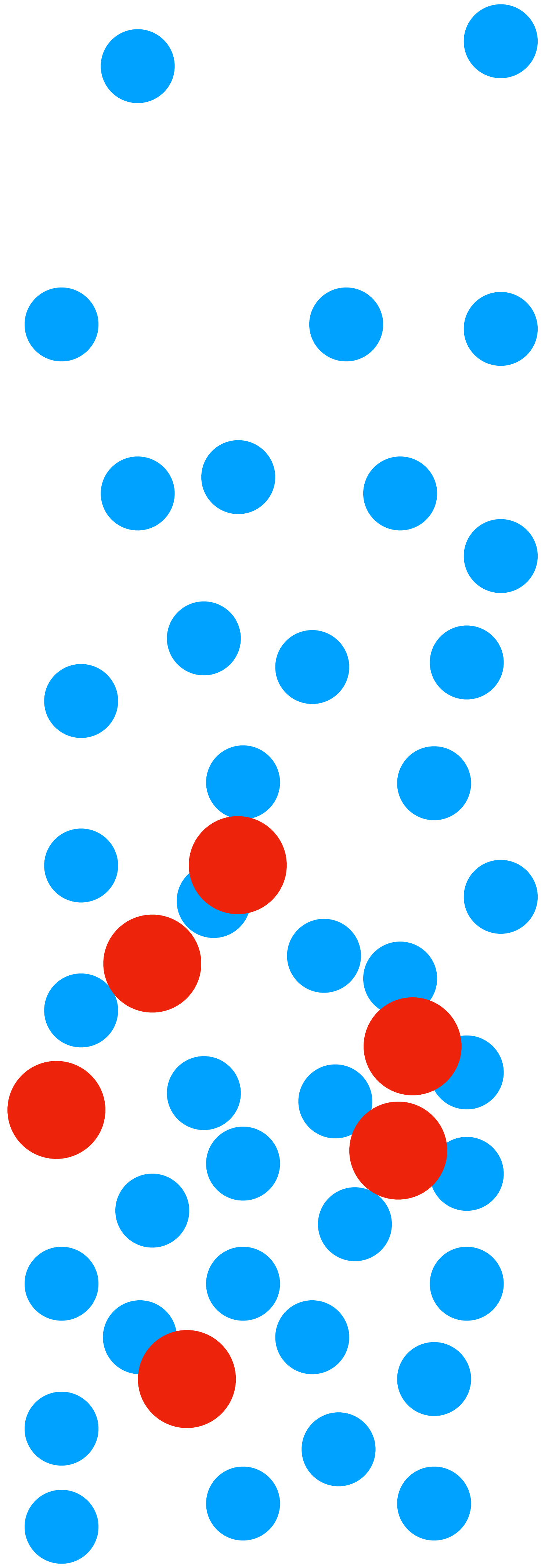
Heavy element fractionation



Heavy element fractionation

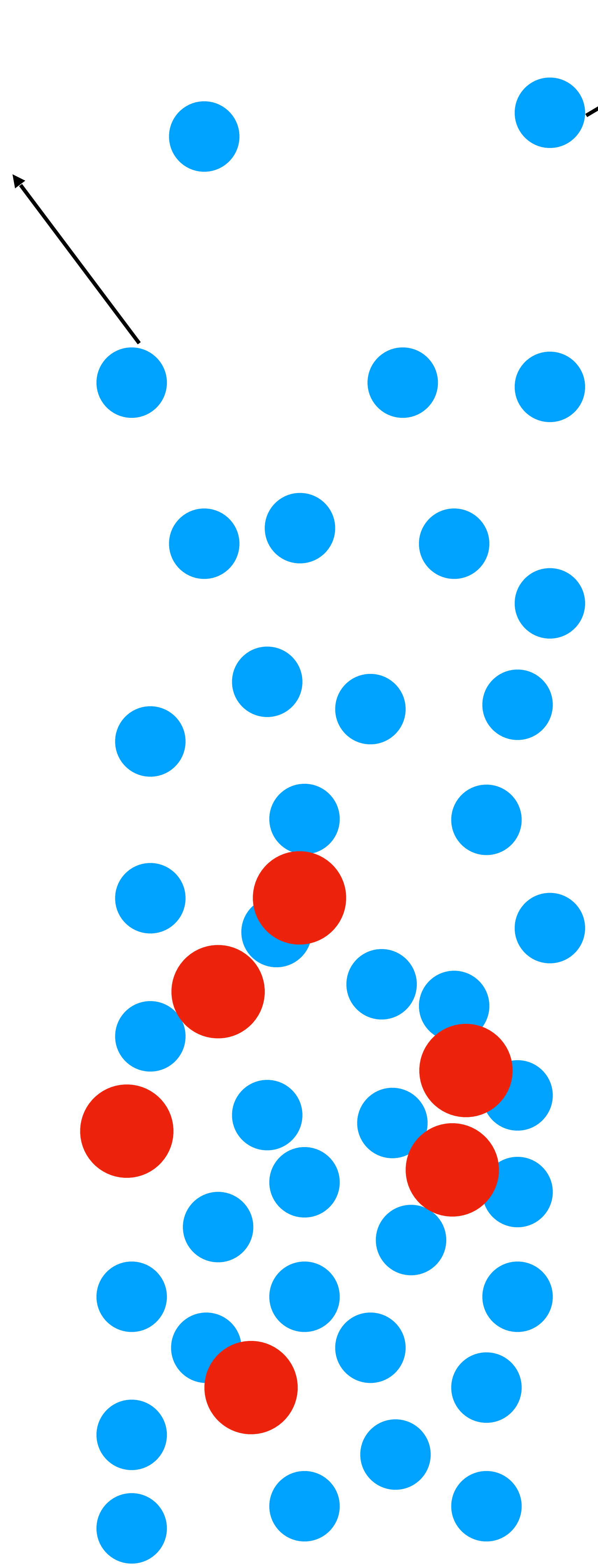


Heavy element fractionation



Heavy species to not make it to high altitudes and their escape is inefficient

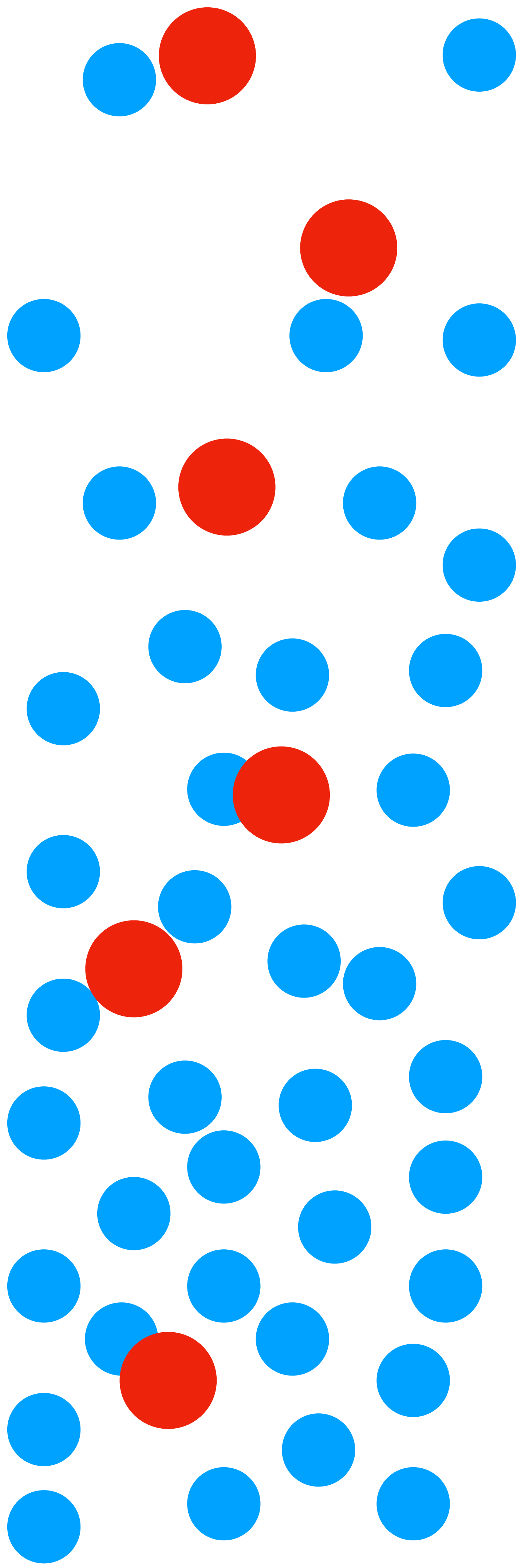
Heavy element fractionation



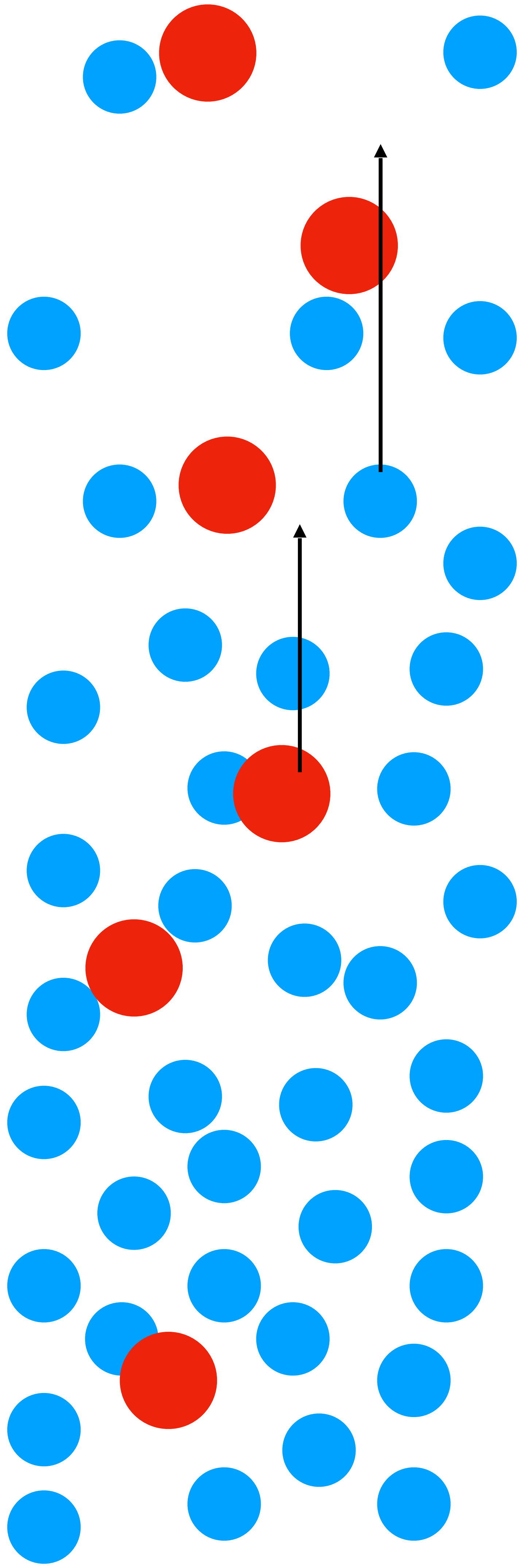
Light species can still escape

Heavy species to not make it to high altitudes and their escape is inefficient

Heavy element fractionation

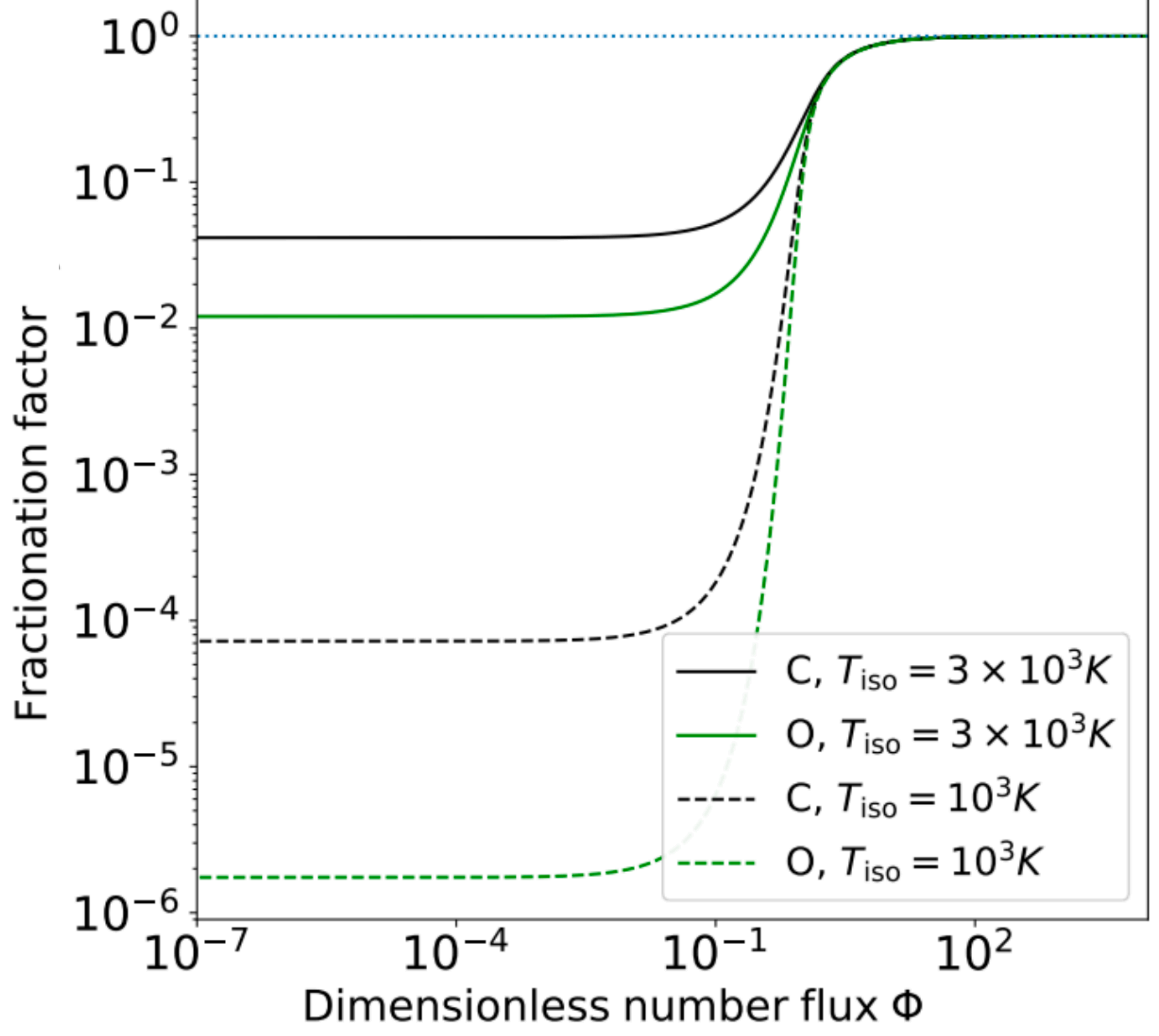


Heavy element fractionation



Fractionated escape

Fractionation factor: c.f. Zahnle & Kasting (1986)



What happens as the light species escape, leaving behind heavy elements?

New questions, new physics … a new code

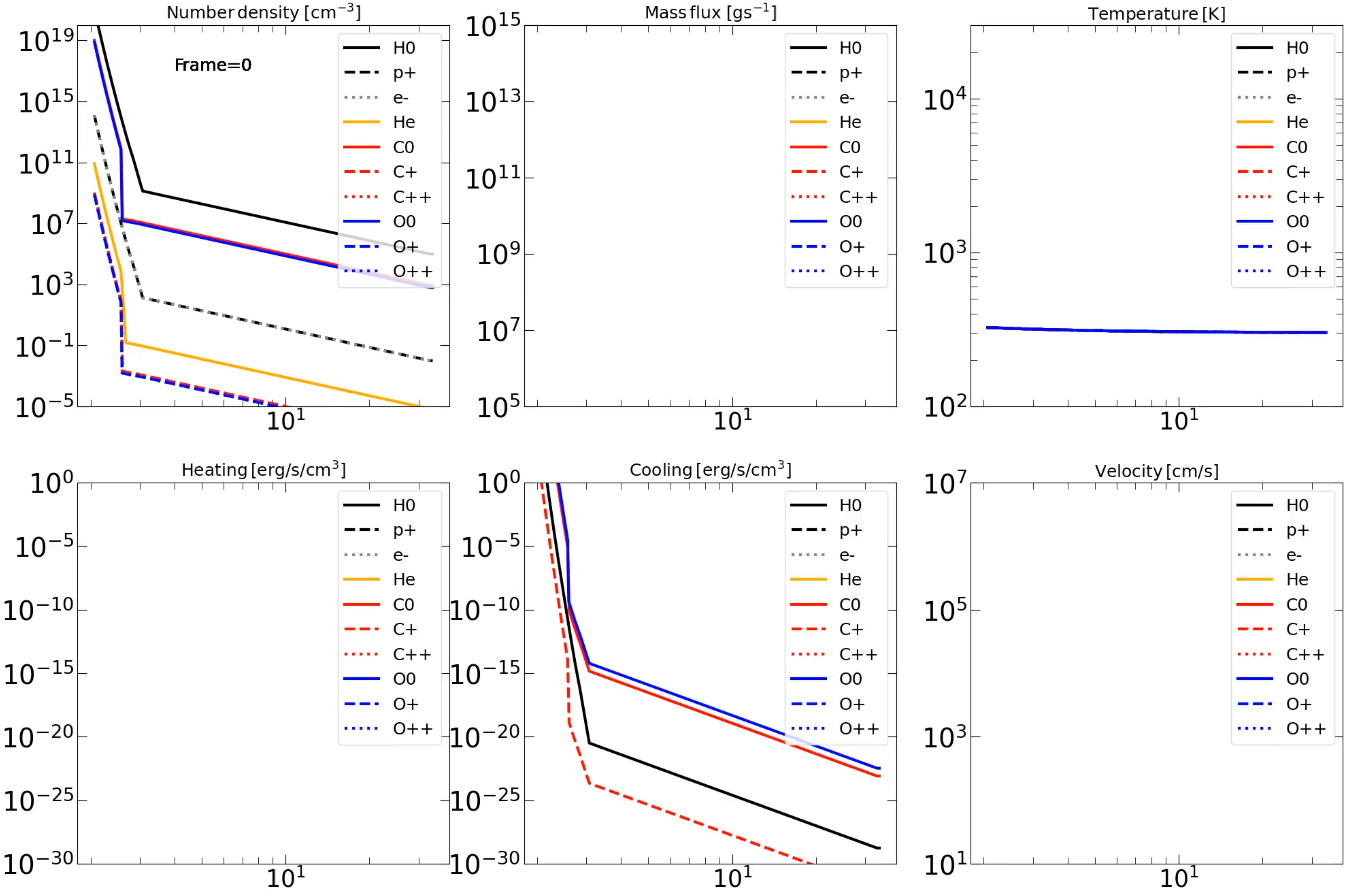
Matthäus Schulik

Aiolos

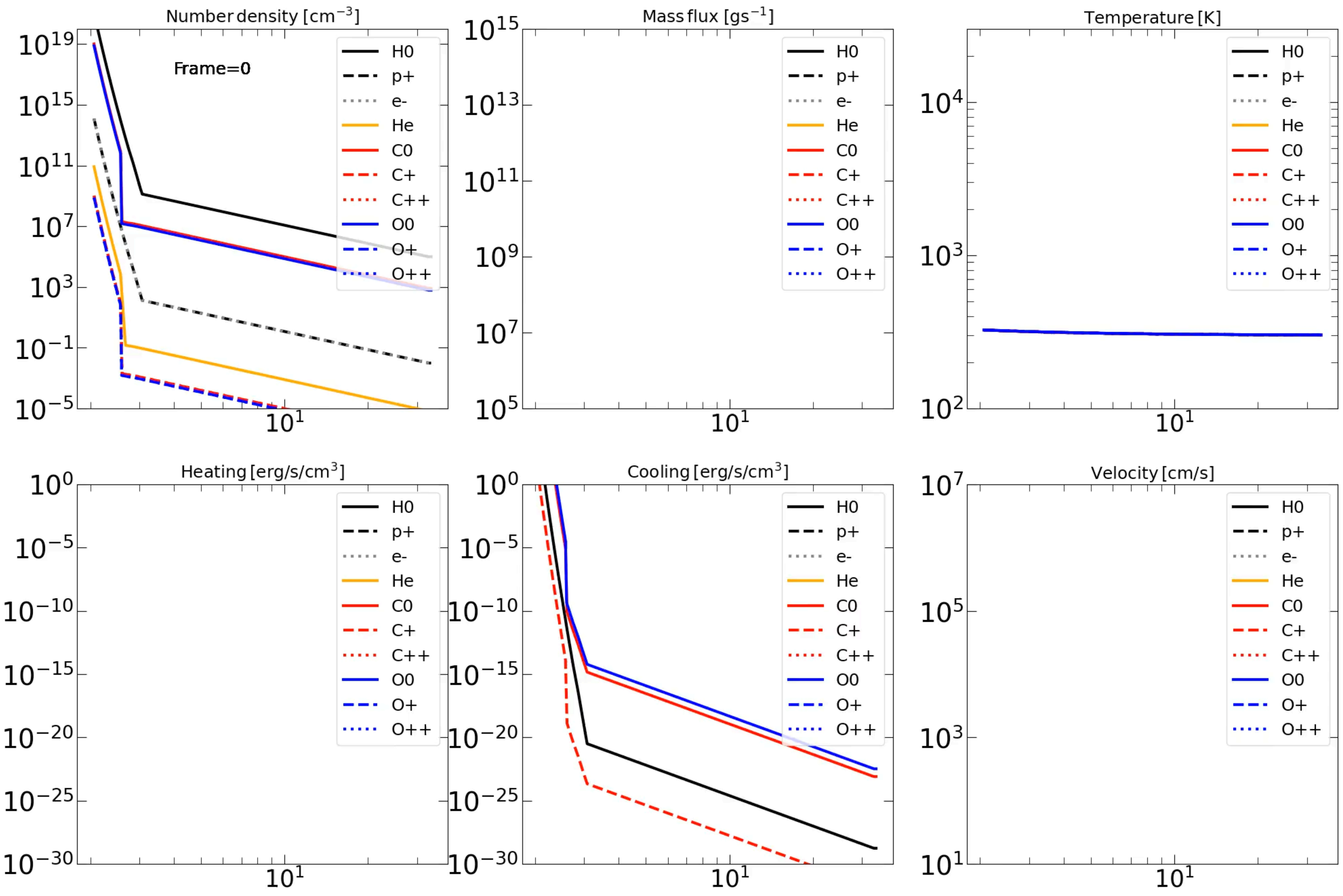
http://github.com/schulik/aiolos

- 1D well-balanced hydro scheme.
- Multi-species with drag
- Multi-band ionizing and non-ionizing radiative transfer.
- Chemistry

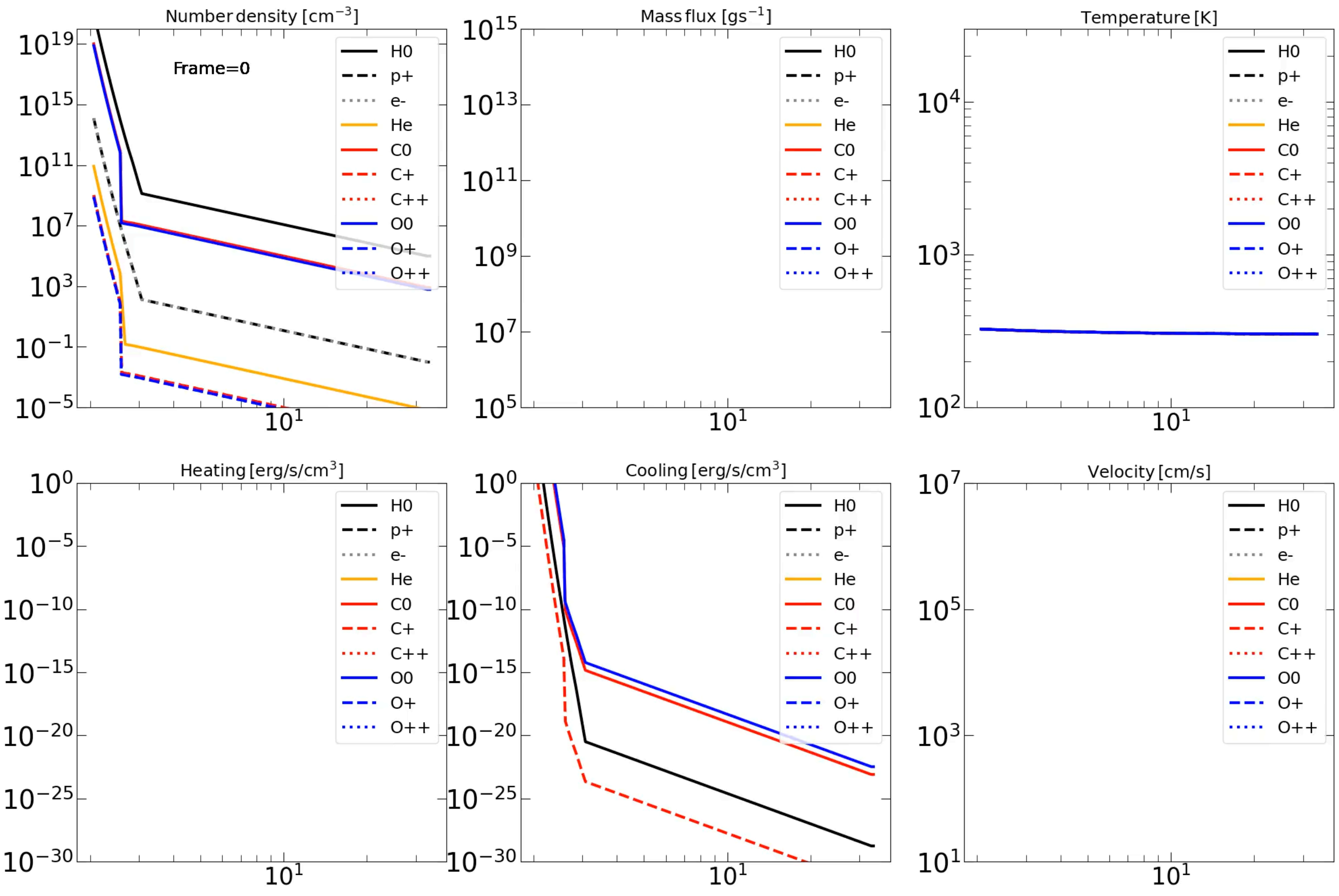
Models of fractionated escape



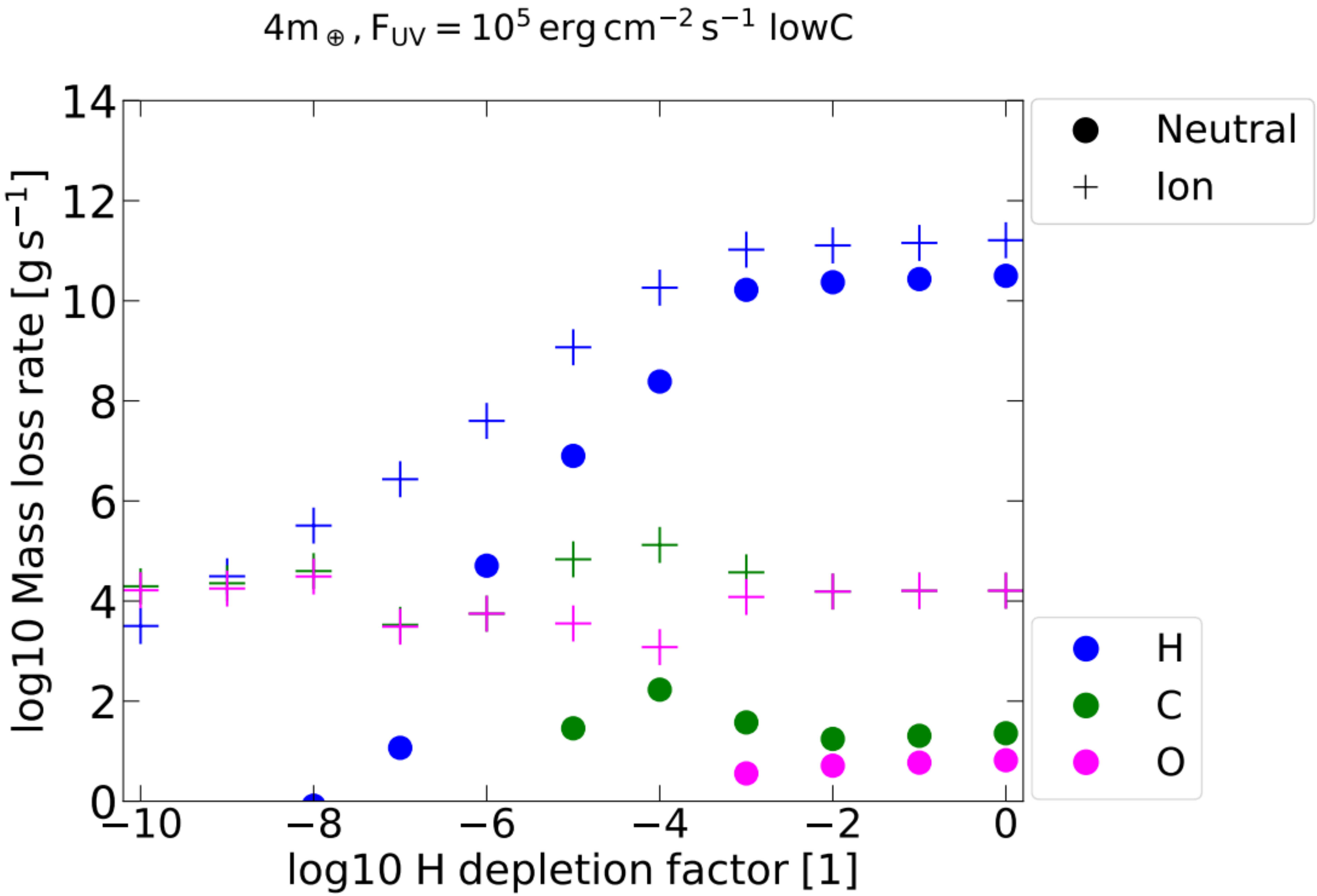
Models of fractionated escape



Models of fractionated escape



C/O variations from fractionated escape



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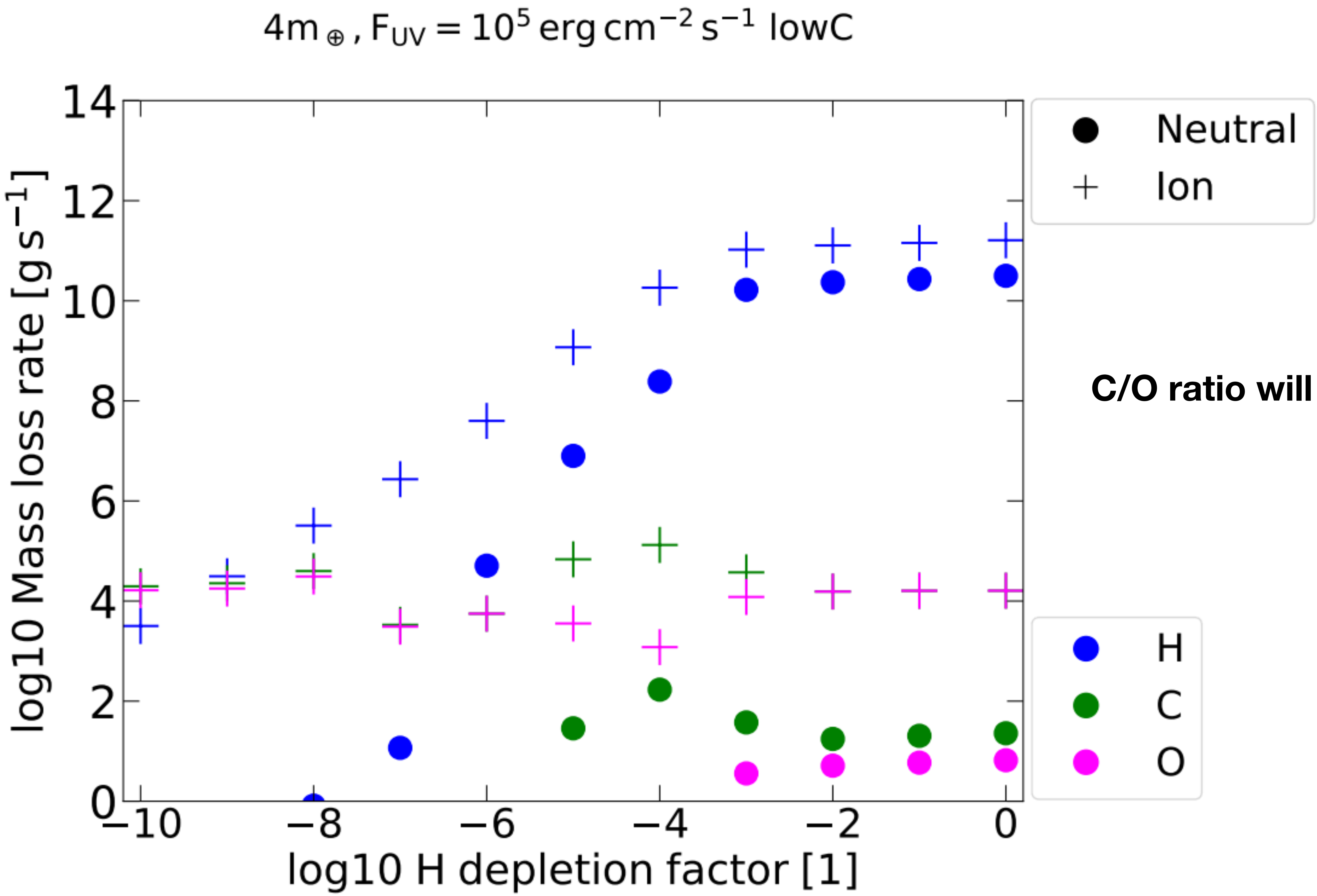
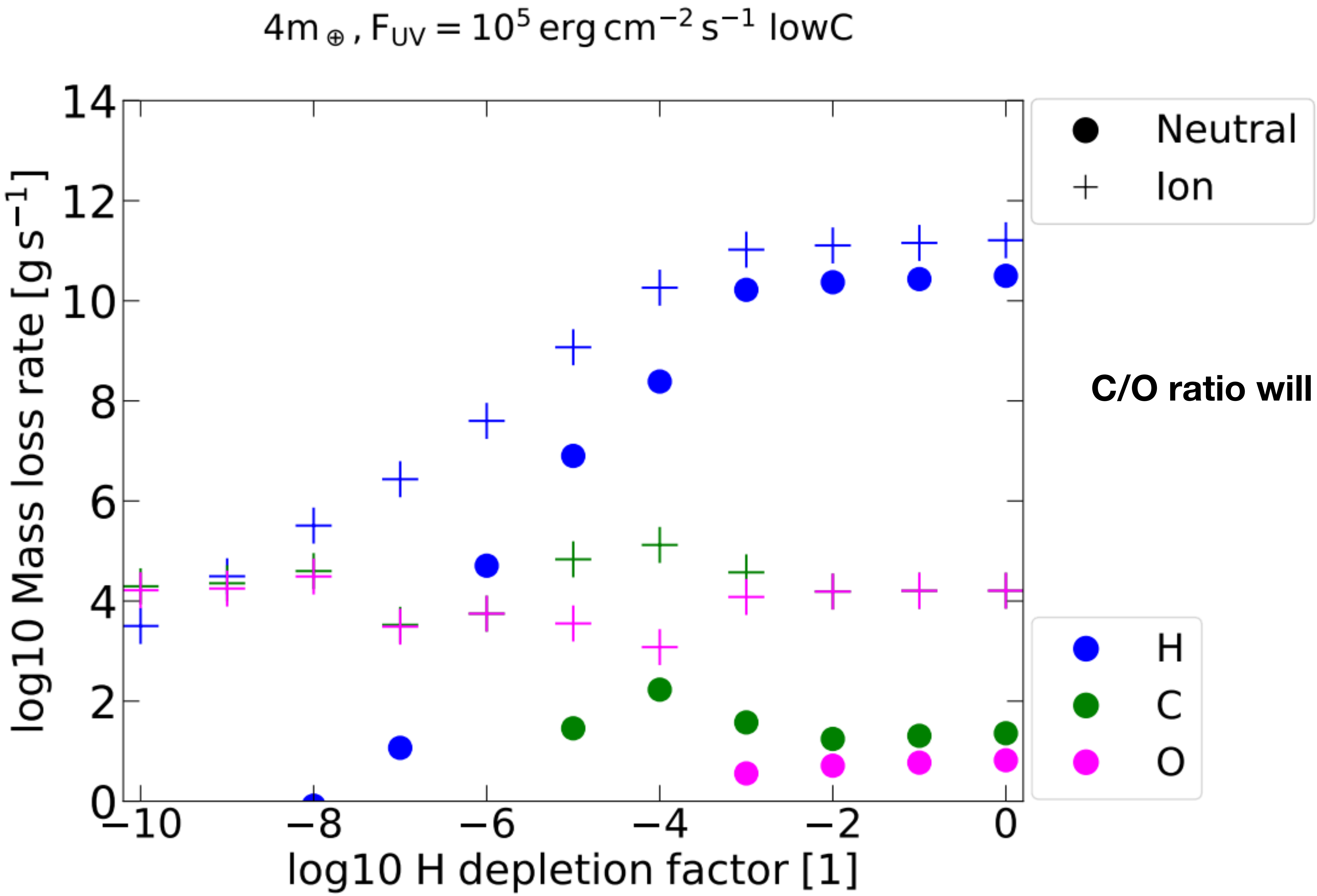


C/O ratio will result due to escape

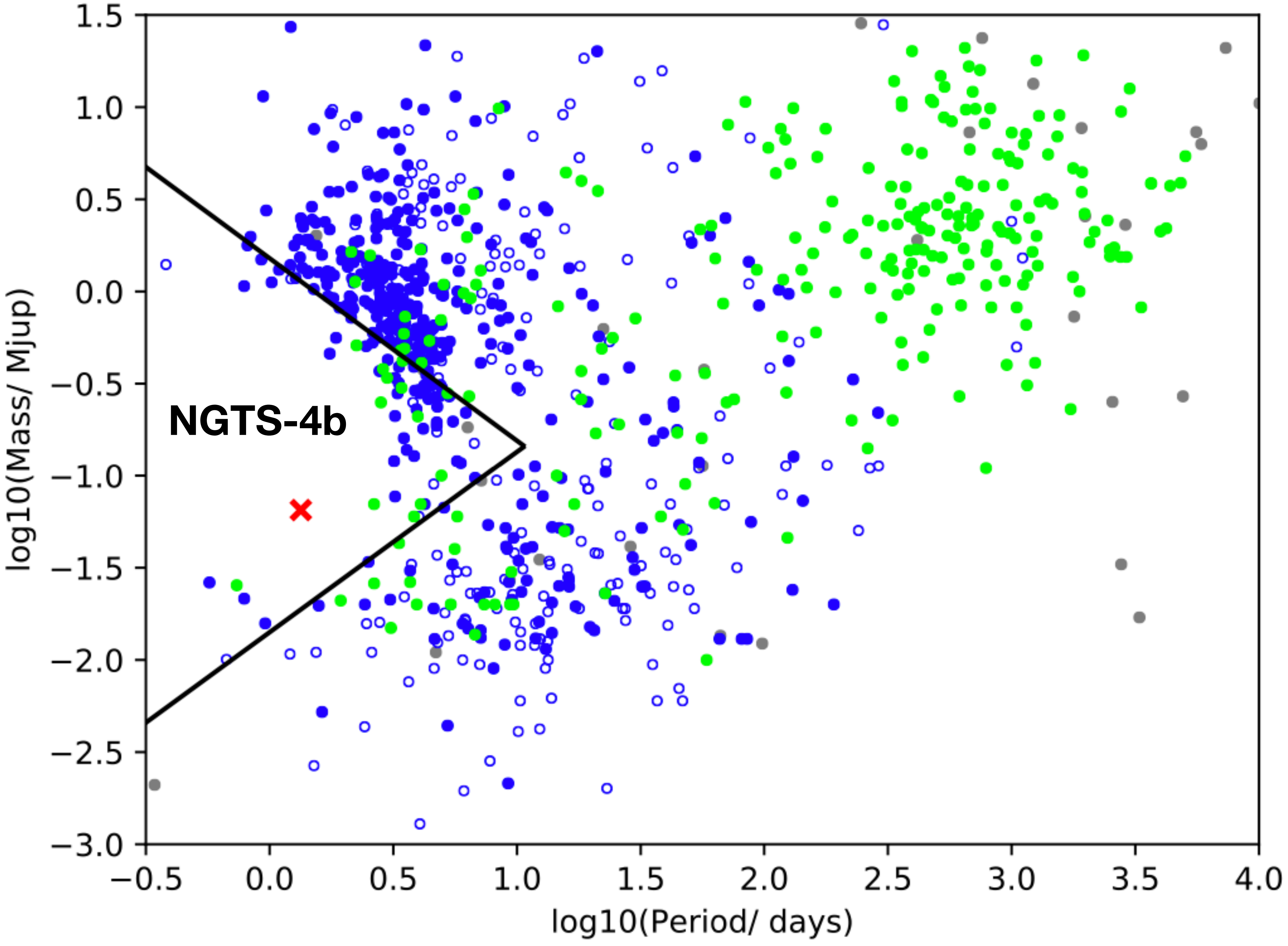
C/O variations from fractionated escape



As heavy elements build-up in the atmosphere hydrogen escape is suppressed

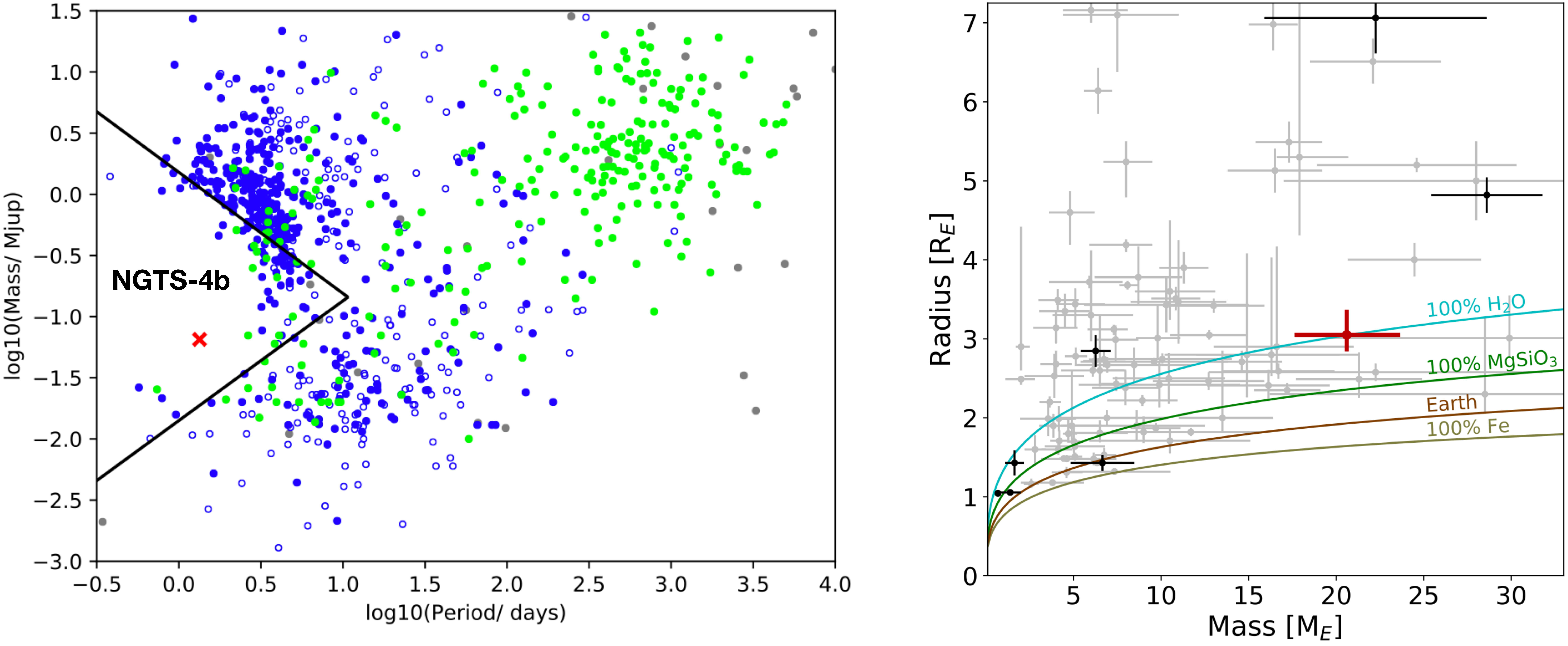
C/O ratio will result due to escape

One way to investigate this - desert dwellers



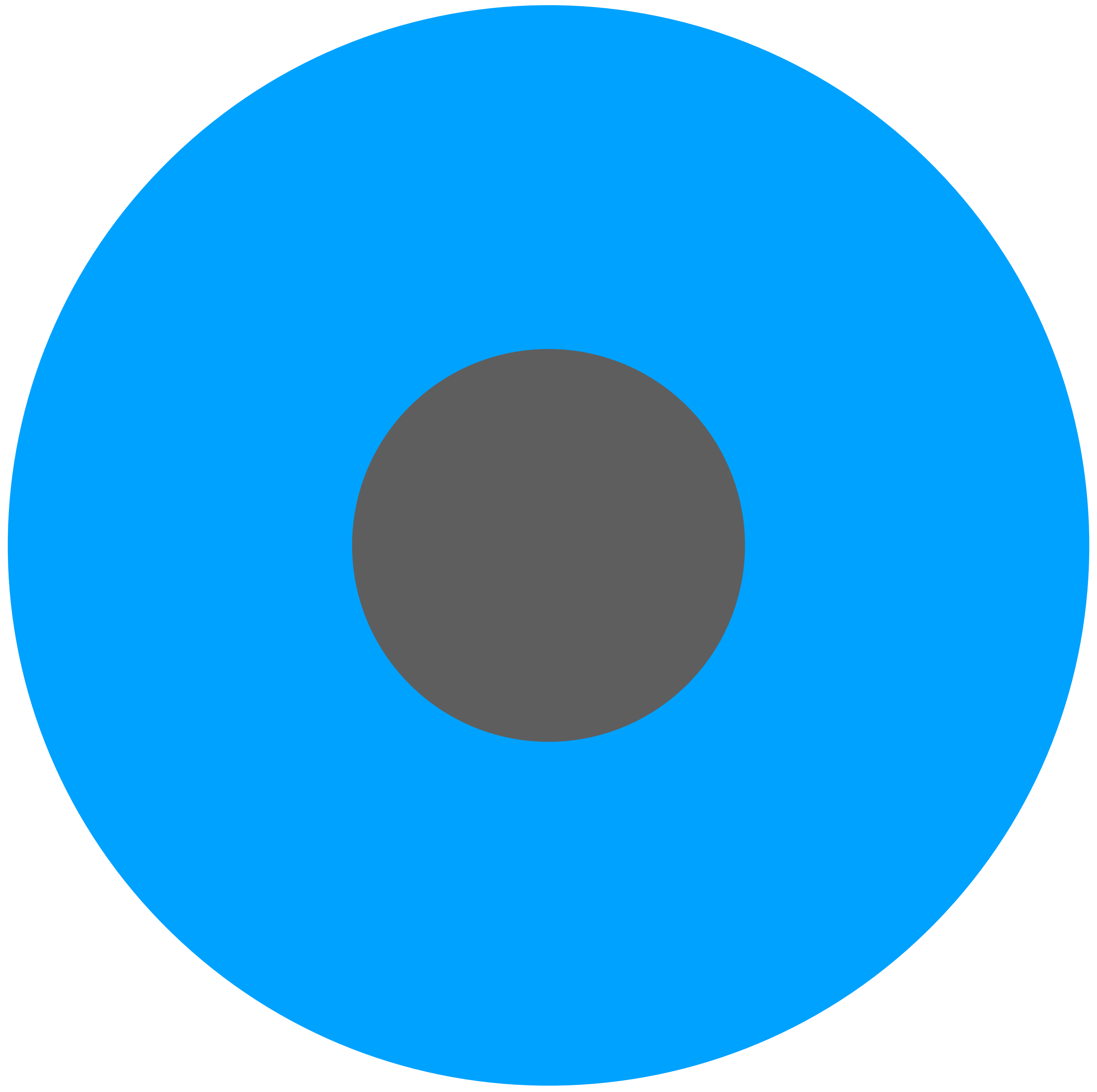
West et al. (2019)

One way to investigate this - desert dwellers

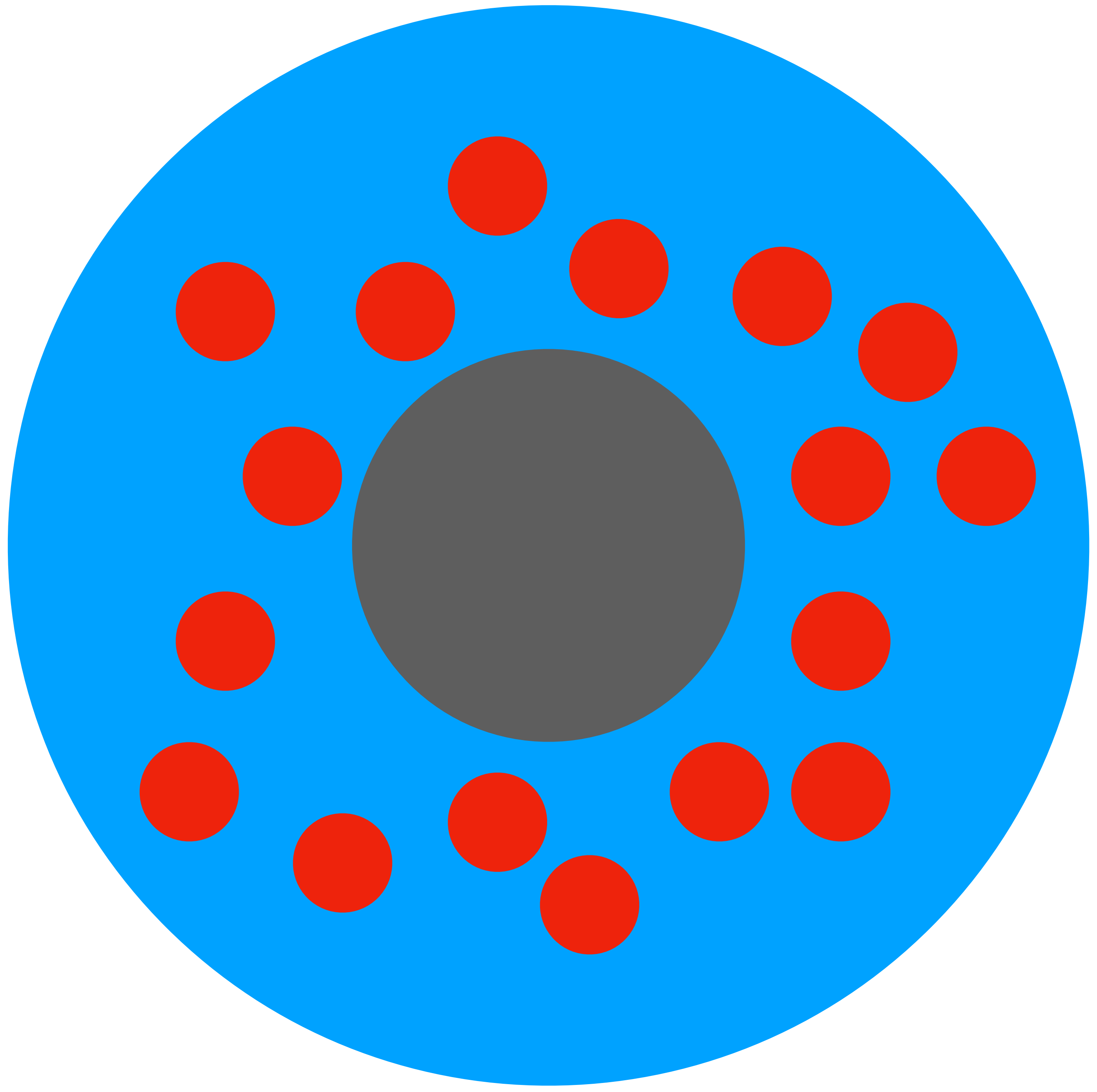


West et al. (2019)

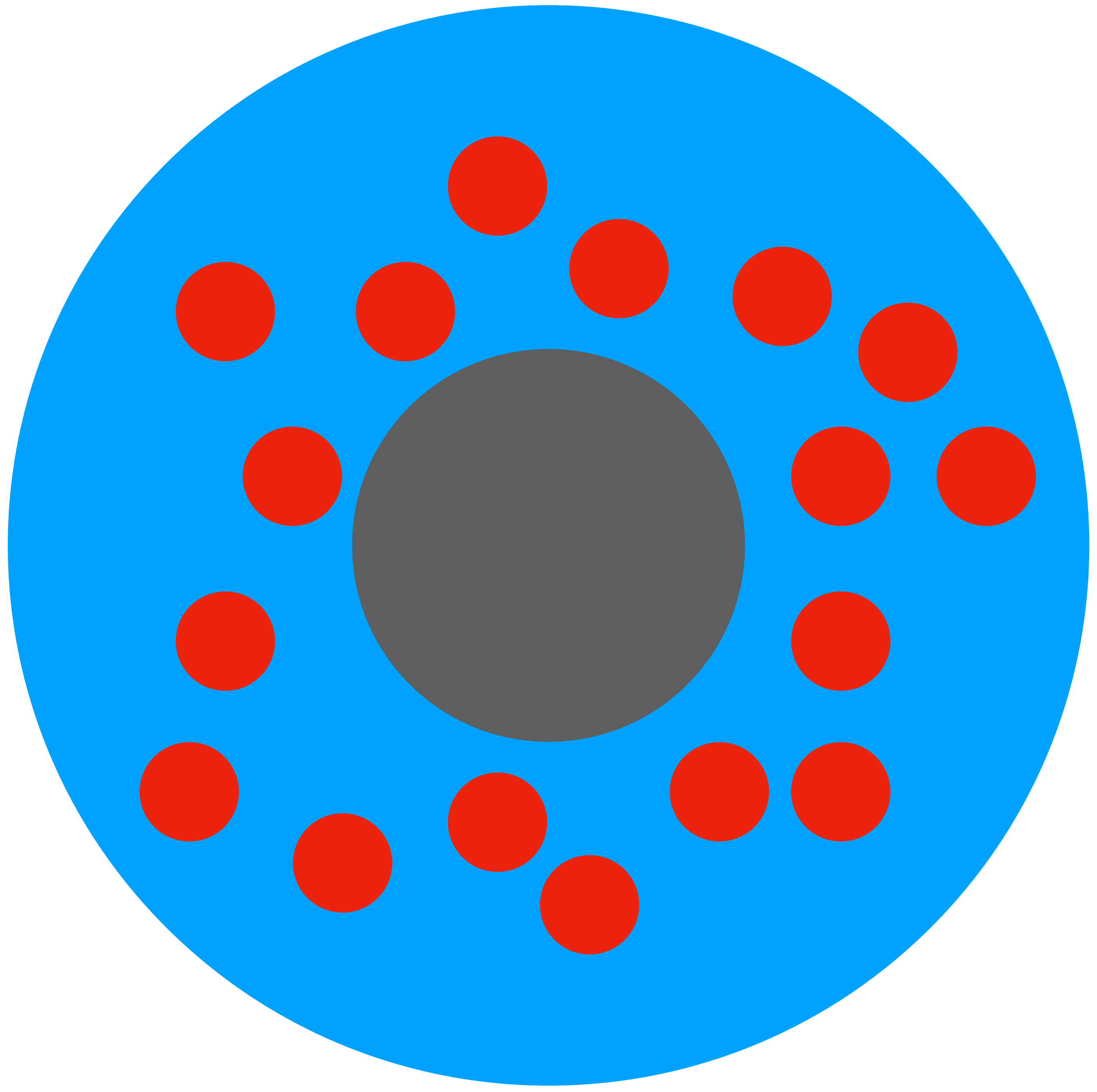
Schematic picture



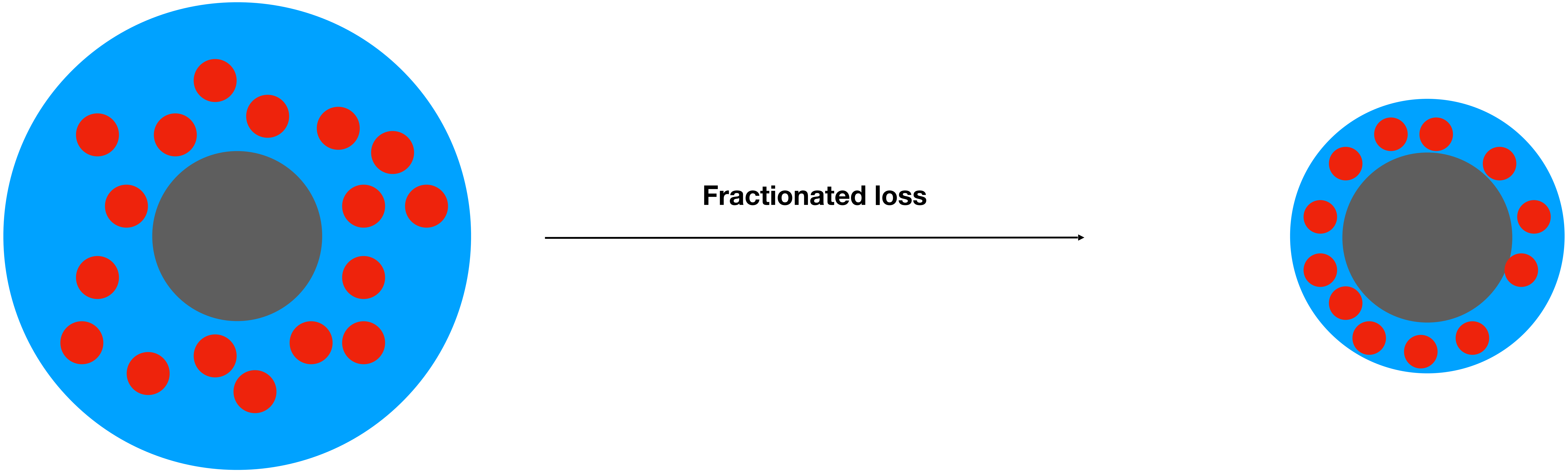
Schematic picture



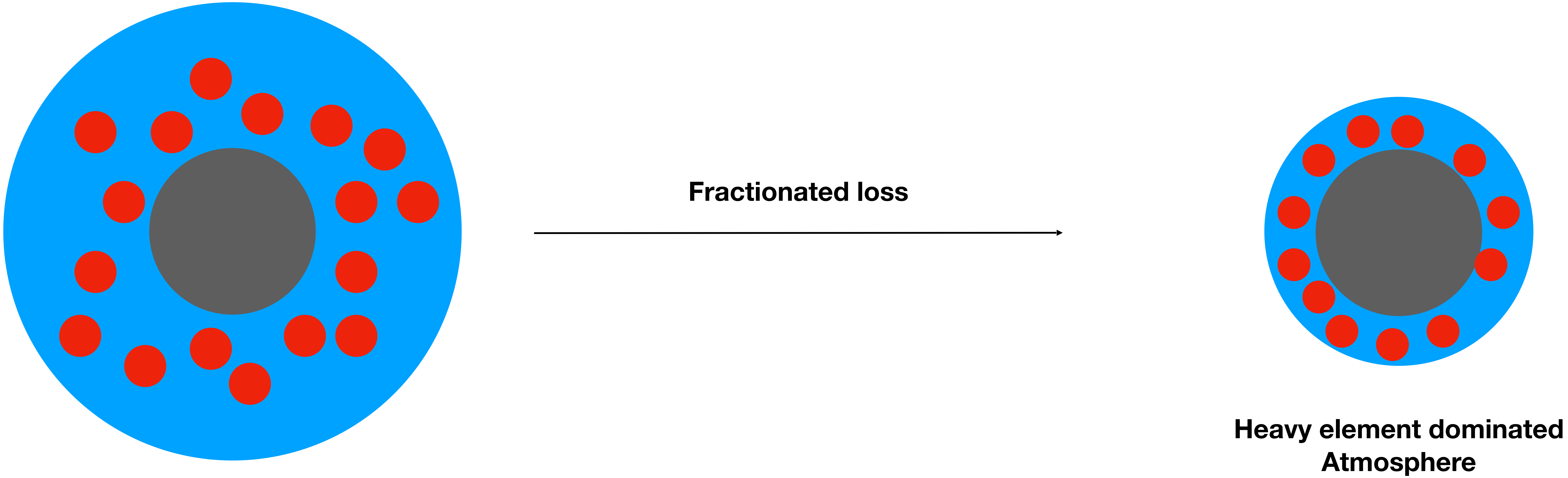
Schematic picture



Schematic picture



Schematic picture



Schematic picture

Heavy element dominated
Atmosphere

Perhaps with trapped Hydrogen?

Summary: atmospheric escape matters for exoplanet atmospheres

There's still lots to do!

Questions?