Planetary Atmospheres and Habitability

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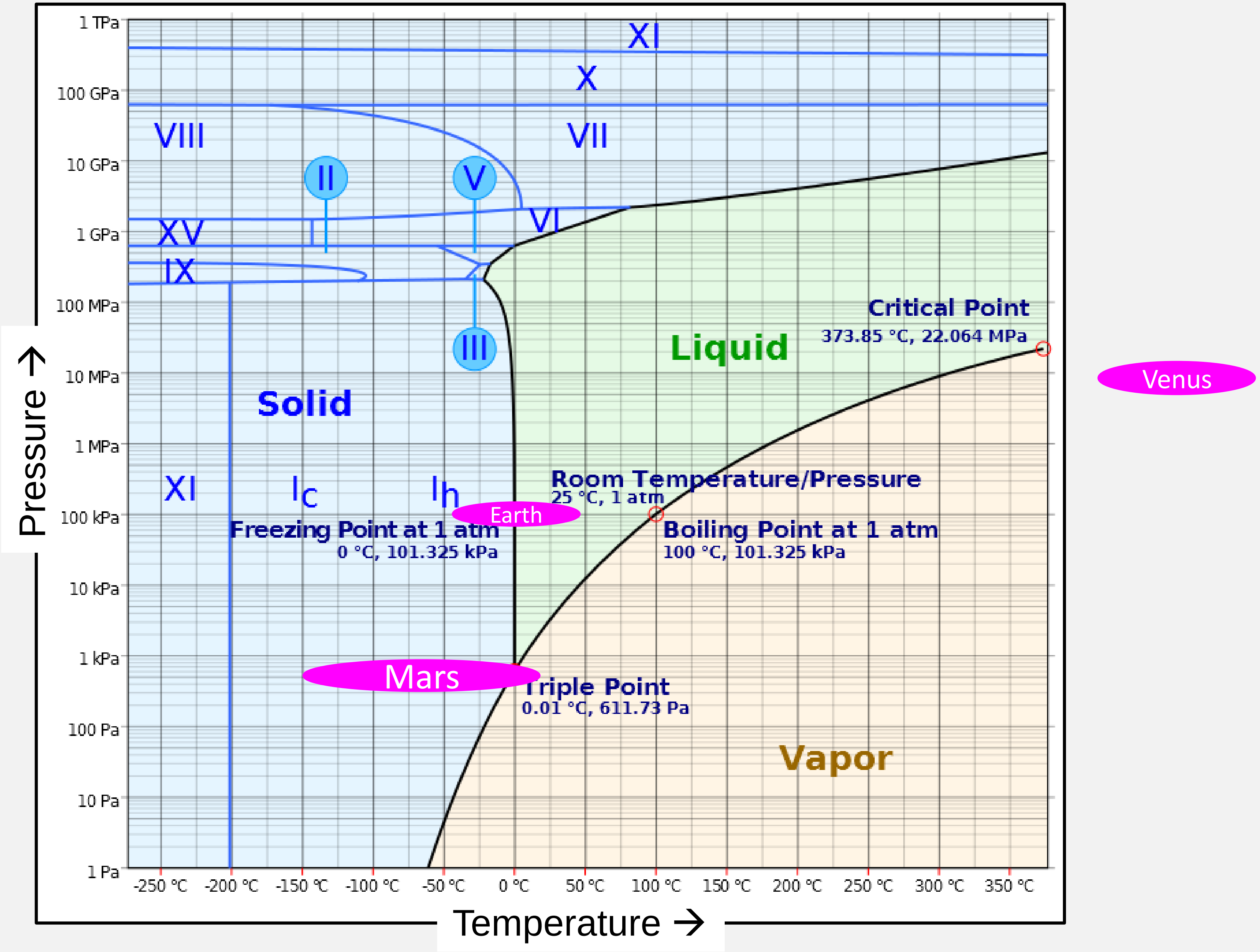
You are encouraged to be interactive

I. Atmospheres, Climate, and Habitability

The Contemporary climates of the terrestrial worlds are varied

	Venus	Earth	Mars
Surface Temperature	740 K	288 K	210 K
Surface Pressure	92 bars	1 bar	7 mbar
Composition	96% CO_2; 3.5% N_2	78% N_2; 21% O_2	95% CO_2; 2.7% N_2
H_2O content	20 ppm	10,000 ppm	210 ppm
Precipitation	None at surface	rain, frost, snow	frost
Circulation	1 cell / hemisphere, quiet at surface but very active aloft	3 cells / hemisphere, local and regional storms	1-2 cells / hemisphere or patchy circulation, global dust storms
Maximum surface winds	~3 m/s	> 100 m/s	~30 m/s
Seasonal Variation	None	Comparable northern and southern seasons	Southern summer more extreme

Climate influences (surface) habitability



II. Changing Climate

Question: What could you do to a planet to change its climate?

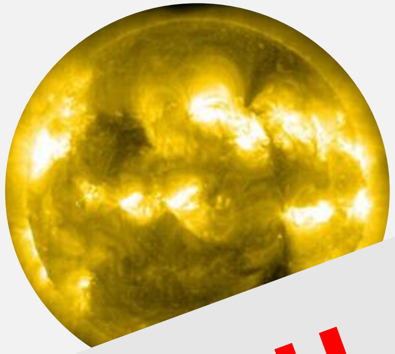
Come up with 4 (or more) fundamentally different answers
You have 6 minutes

Action	Climate response
• Remove magnetic field	T decreases
• Change distance to Sun	Affects solar flux, which changes temperature
• Add life	Changes composition of atmosphere and hilarity ensues
• Change size	Change gravity, change extent of atmosphere
• Change tilt of planet	Influence seasons, and temperature
• Add ice cover	Increase albedo, reduce temperature
• Increase GHGs in atmosphere	Increase temperature
• Have large impacts	Without Bruce Willis, we’re doomed
• Change oceans	Change atmos. circulation
• Change plate tectonics	Also change atmos. Circulation
• Change planetary rotation	changes weather, circulation
• Change surface pressure	
• Add more volcanism	
• Seed clouds!	
• Change eccentricity of orbit	
• Change the star	
• Add large moons	

Four Ways to Change $T_{Surface}$

$$\frac{S}{d^2}(1-A)\,\pi R_P^2 = \sigma T_{eff}^4\, 4\pi R_P^2 \qquad T_{surface}^4 = (\tau+1)\,T_{eff}^4$$

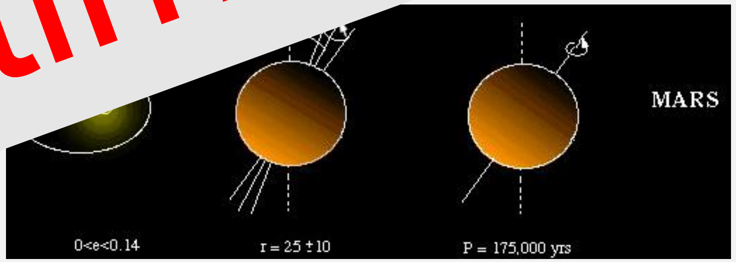
Solar Output



Planetary Albedo

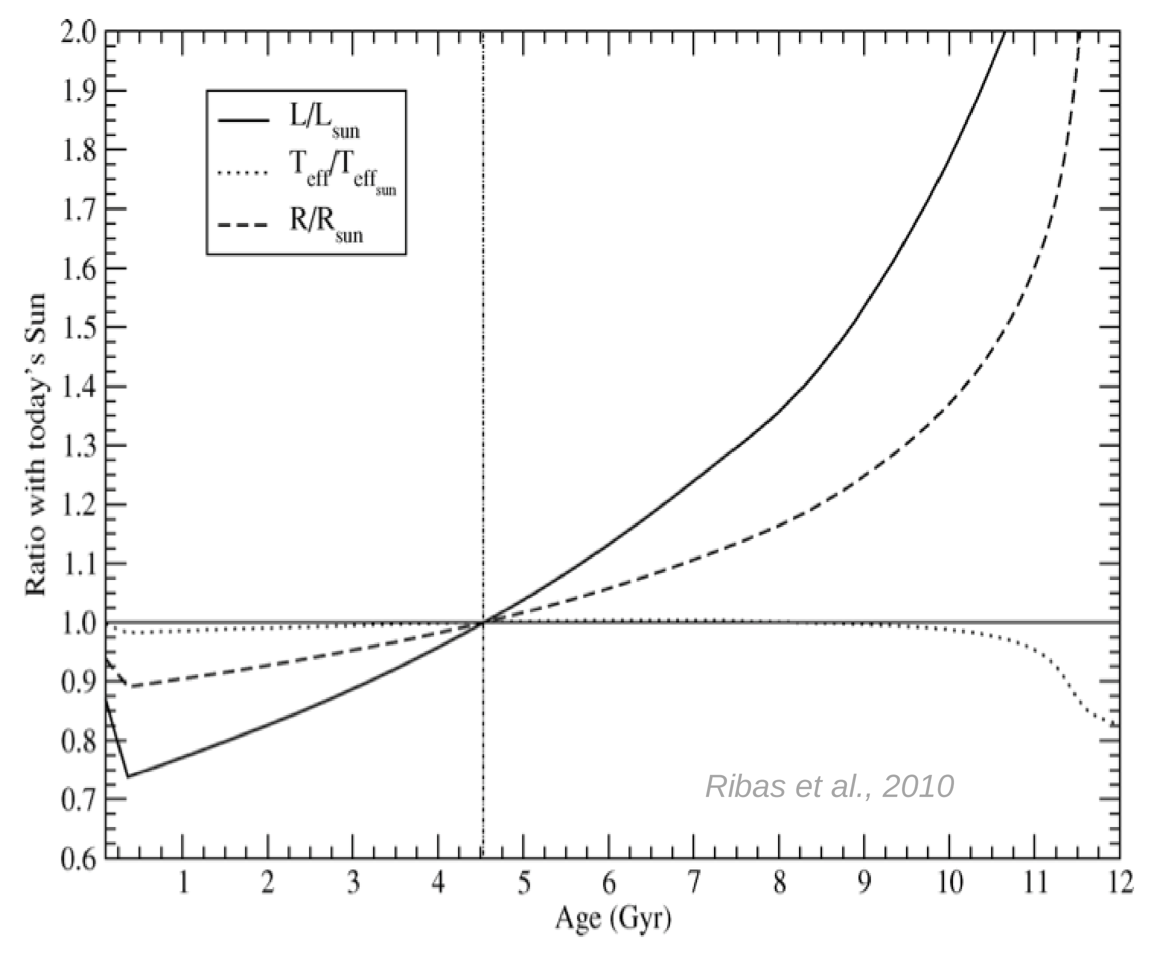
All change with time!

Greenhouse Gas Content



Planetary Orbital Elements

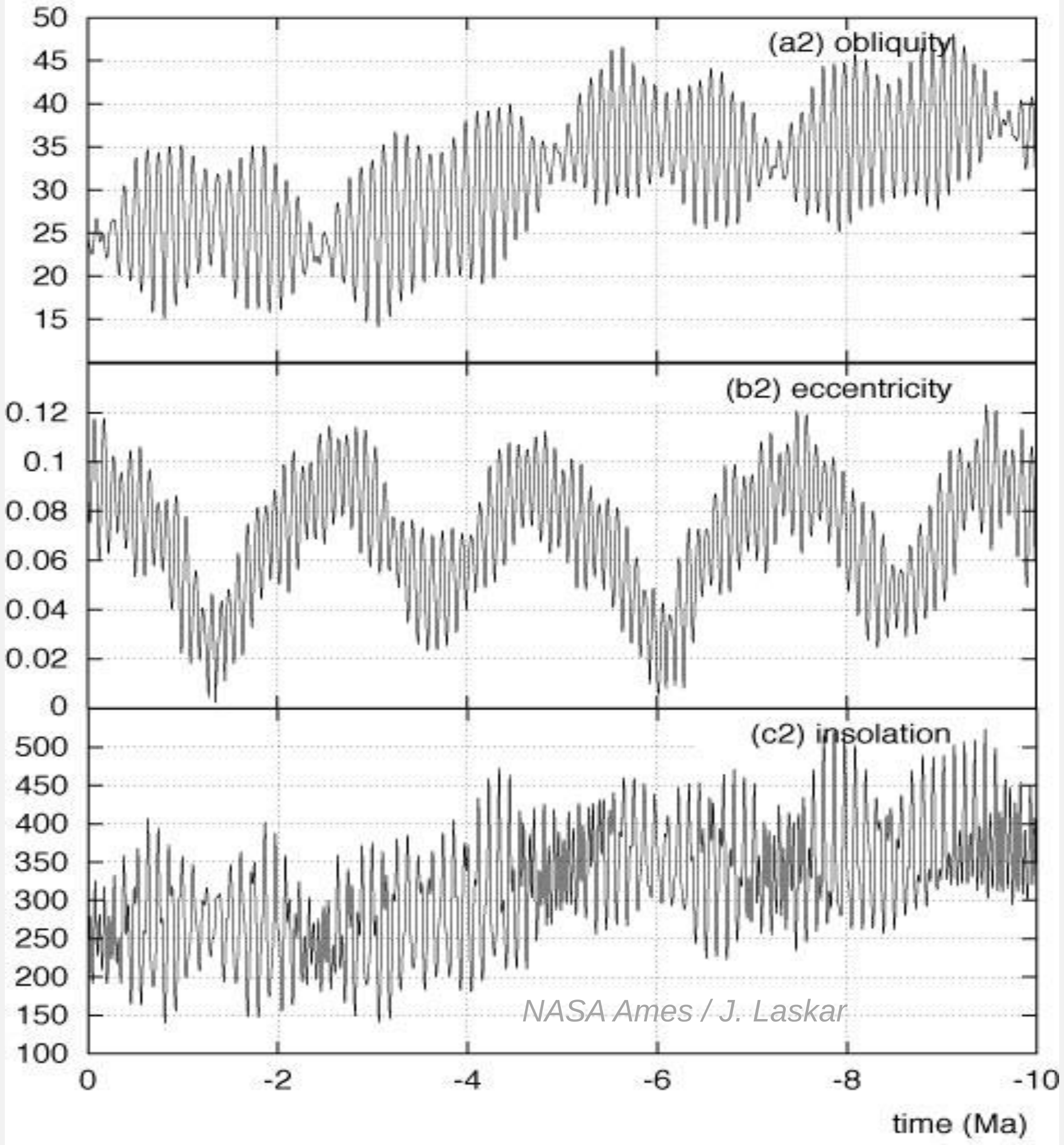
Solar Output



Total Luminosity

The Sun was 25-30% fainter long ago

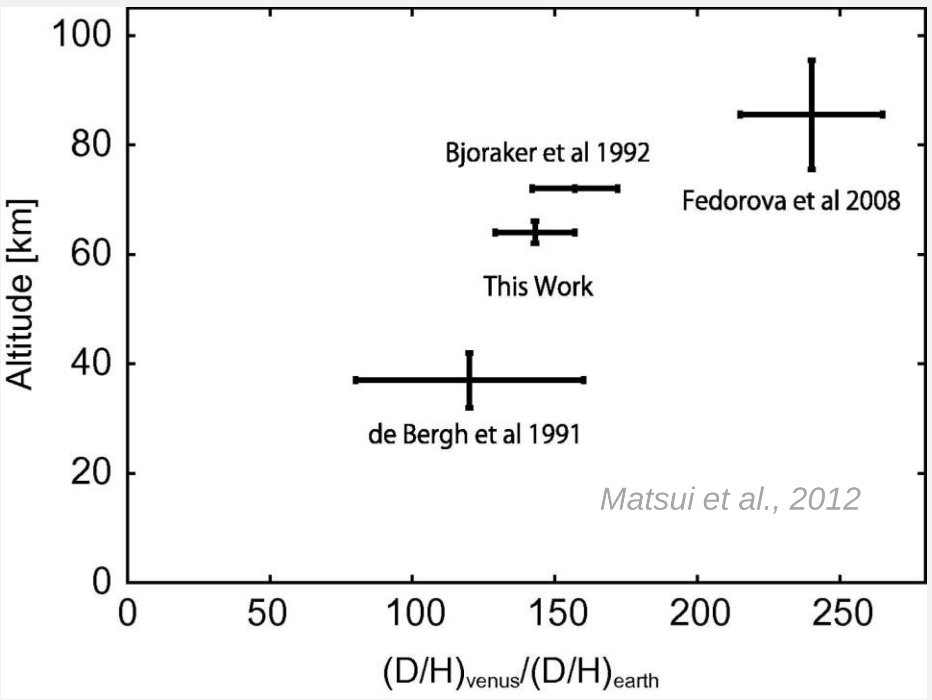
Planetary Orbital Elements



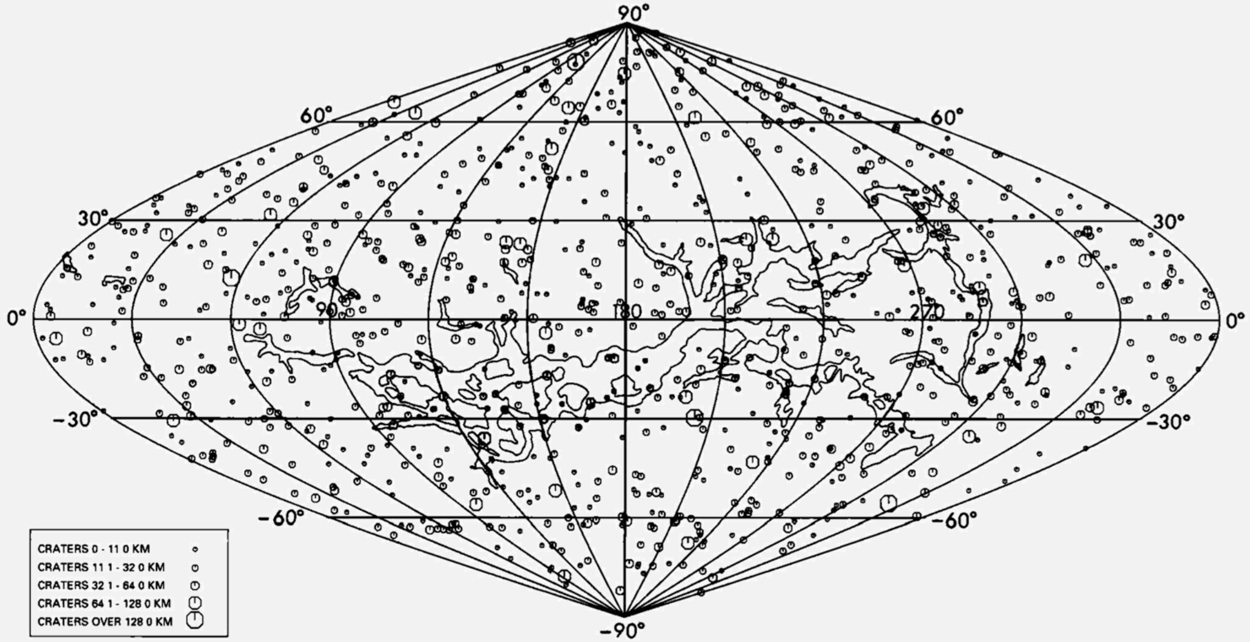
Mars tilt and eccentricity have led to periods of large and small polar caps (small and large atmosphere?)

Evidence for Climate Change

Venus



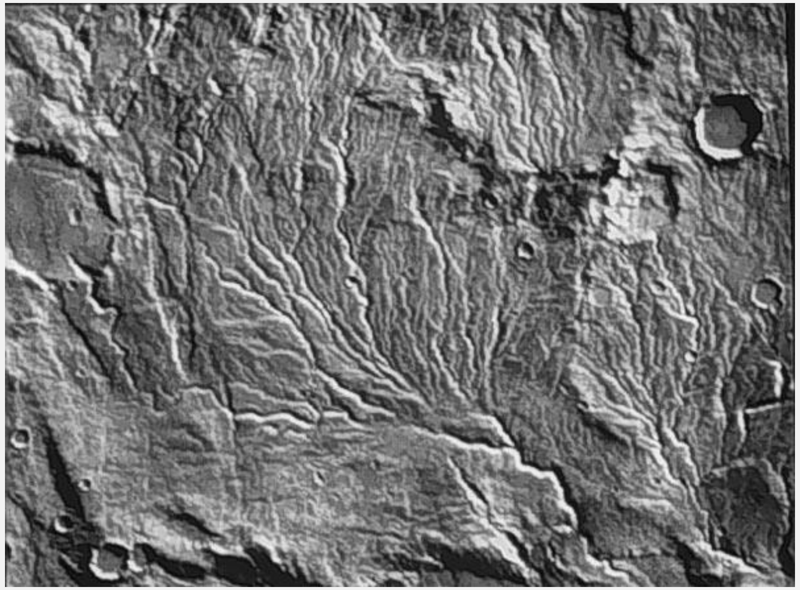
Matsui et al., 2012



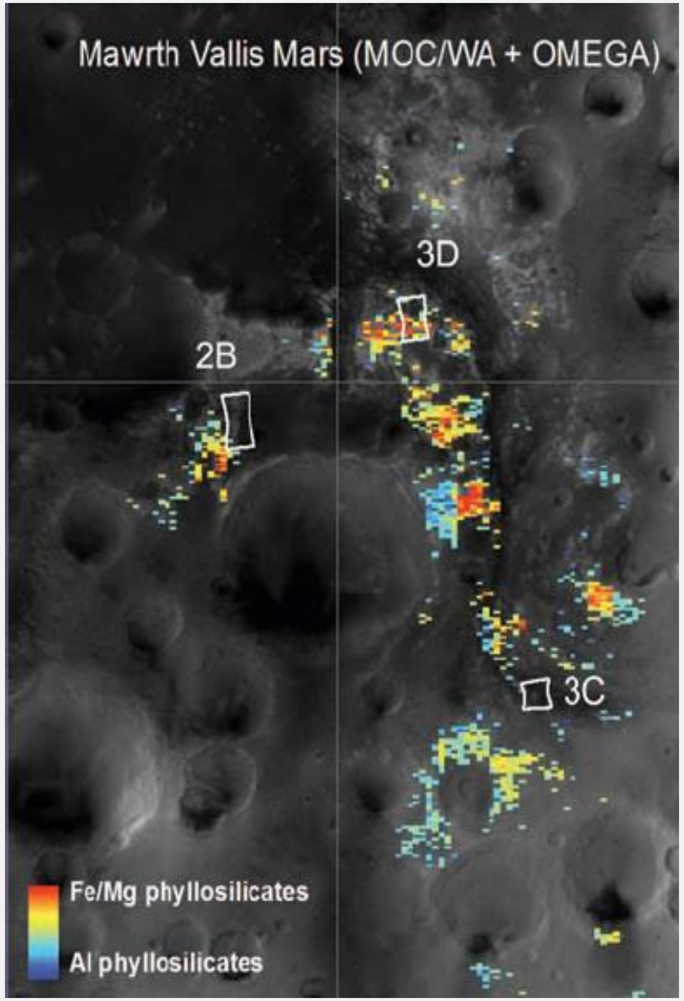
Strom et al., 1994

Evidence for Climate Change

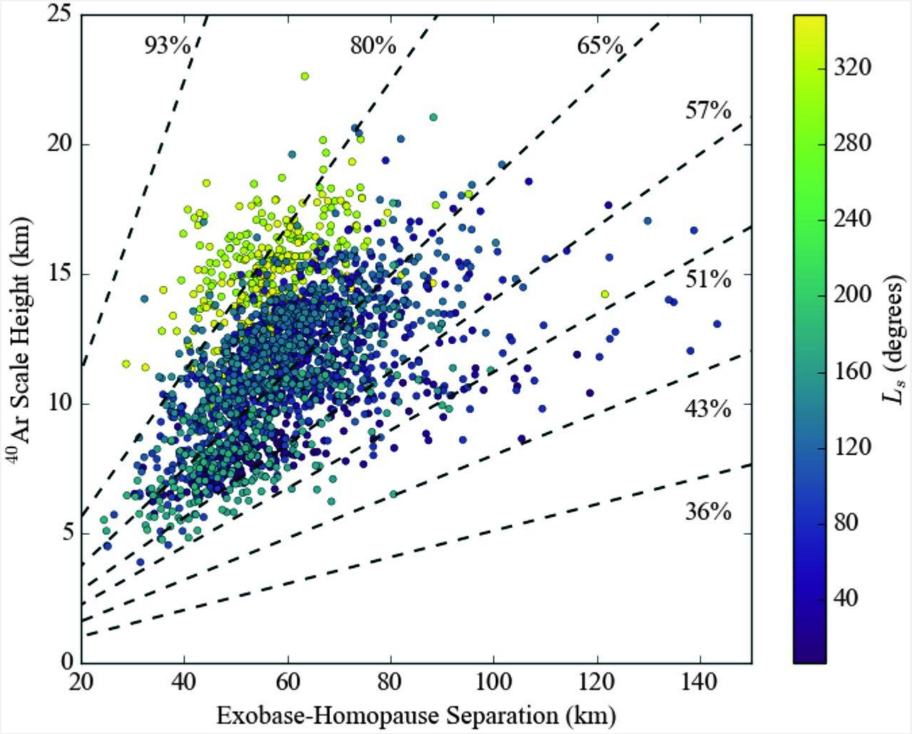
Mars



Geomorphology



Geochemistry



Isotopes

Jakosky et al., 2017

Evidence for Climate Change

Earth

100's-1000's yrs

Trees and Coral

Separation → growth rate → climate

Ice

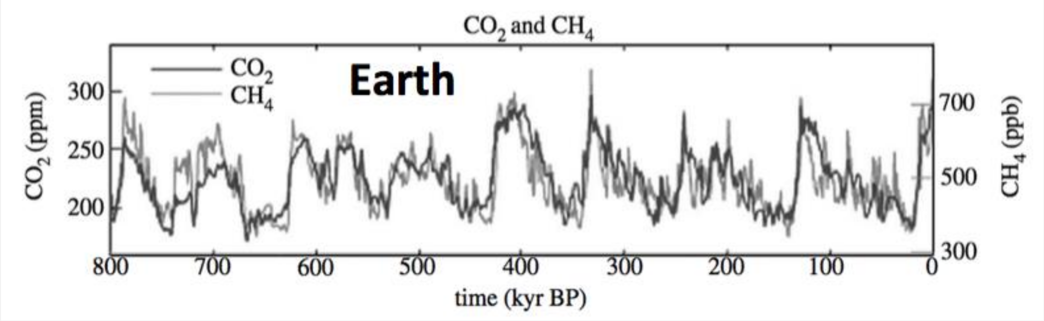
100,000's yrs

Bubbles → composition
Isotopes → temperatures
Pollen → conditions

Sediment

>1 million yrs

Fossils / pollen → conditions
Composition → temperature
Layering → climate shifts
Texture → environment



Diffusive equilibrium, isotope ratios, and atmospheric loss

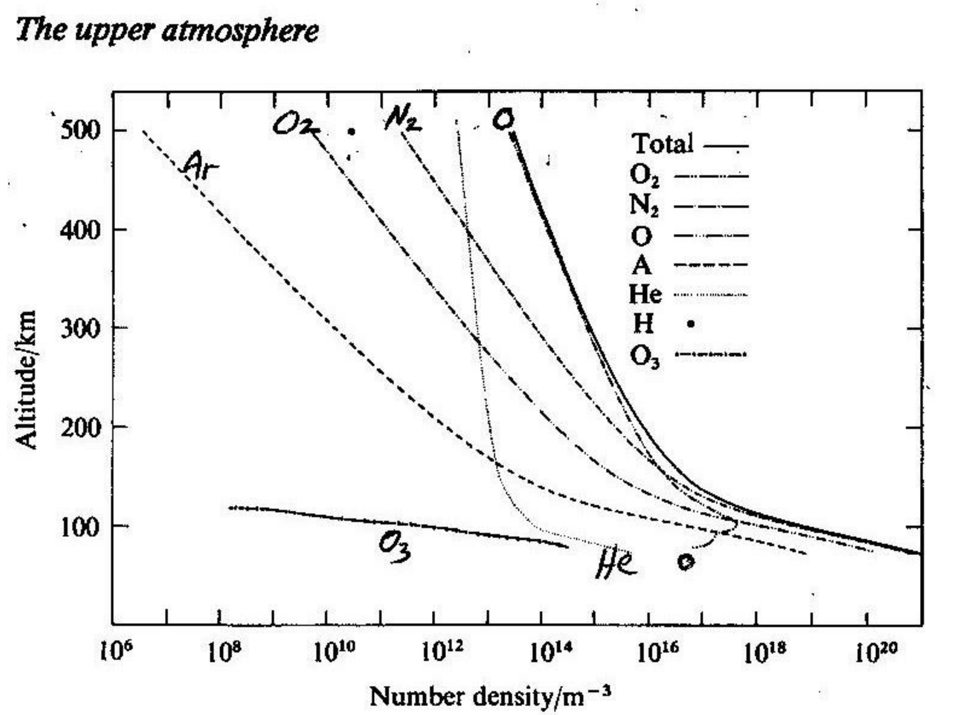


Fig. 5.2. Total number density and number densities of various constituents for mean atmospheres (from COSPAR, 1972).

Example:

Earth D/H ~1/1000
Venus D/H ~(8-120)/1000
Mars D/H ~(5-6)/1000

Table 1 Martian isotope ratios and atmospheric loss*

Isotope ratio	Measured value†	Amount lost to space (%)‡
D/H	5	~60–74
$^{38}Ar/^{36}Ar$	1.3	~50–90
$^{13}C/^{12}C$	1.05–1.07	~50–90
$^{15}N/^{14}N$	1.7	~90
$^{18}O/^{16}O$	1.025	~25–50

*Values taken from refs 57–59, 62, 77 and 78, and references therein.
†Value estimated, observed or derived for martian atmosphere relative to terrestrial.
‡Calculated assuming Rayleigh fractionation. D/H range includes uncertainty in escape processes. Other ranges are based on uncertain timing of outgassing relative to escape.

Question: Suppose Mars loses oxygen atoms at a rate of 10^{26} s^{-1}. How much atmosphere (in bars) would be lost in 4 Gy at this rate?

Helpful information:

- 1 bar = 10^5 Pascals
- R_M ~ 3400 km
- g_M ~ 3.8 m/s^2
- Atomic number of oxygen = 8
- 1 year ~ π x 10^7 s

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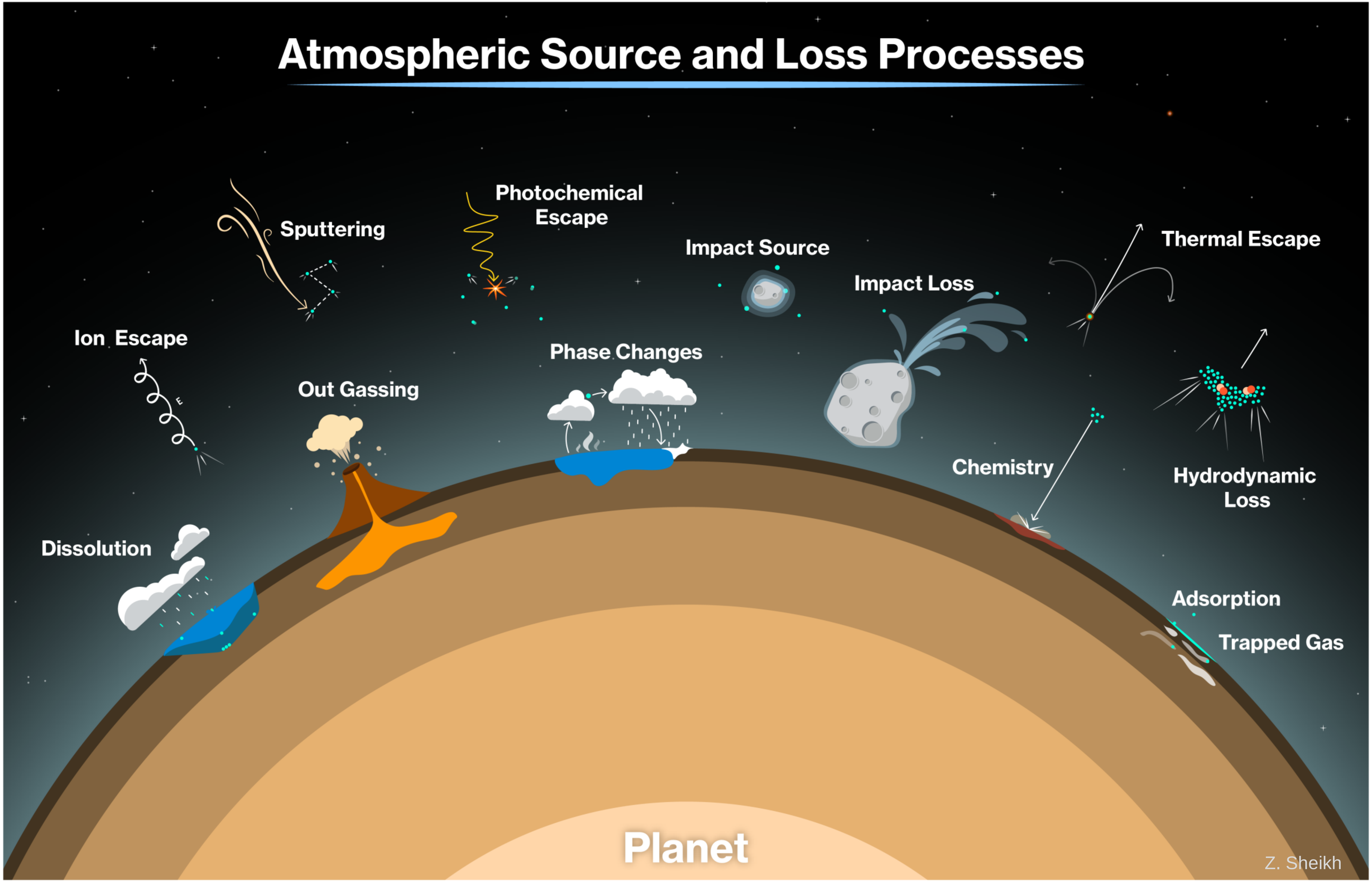
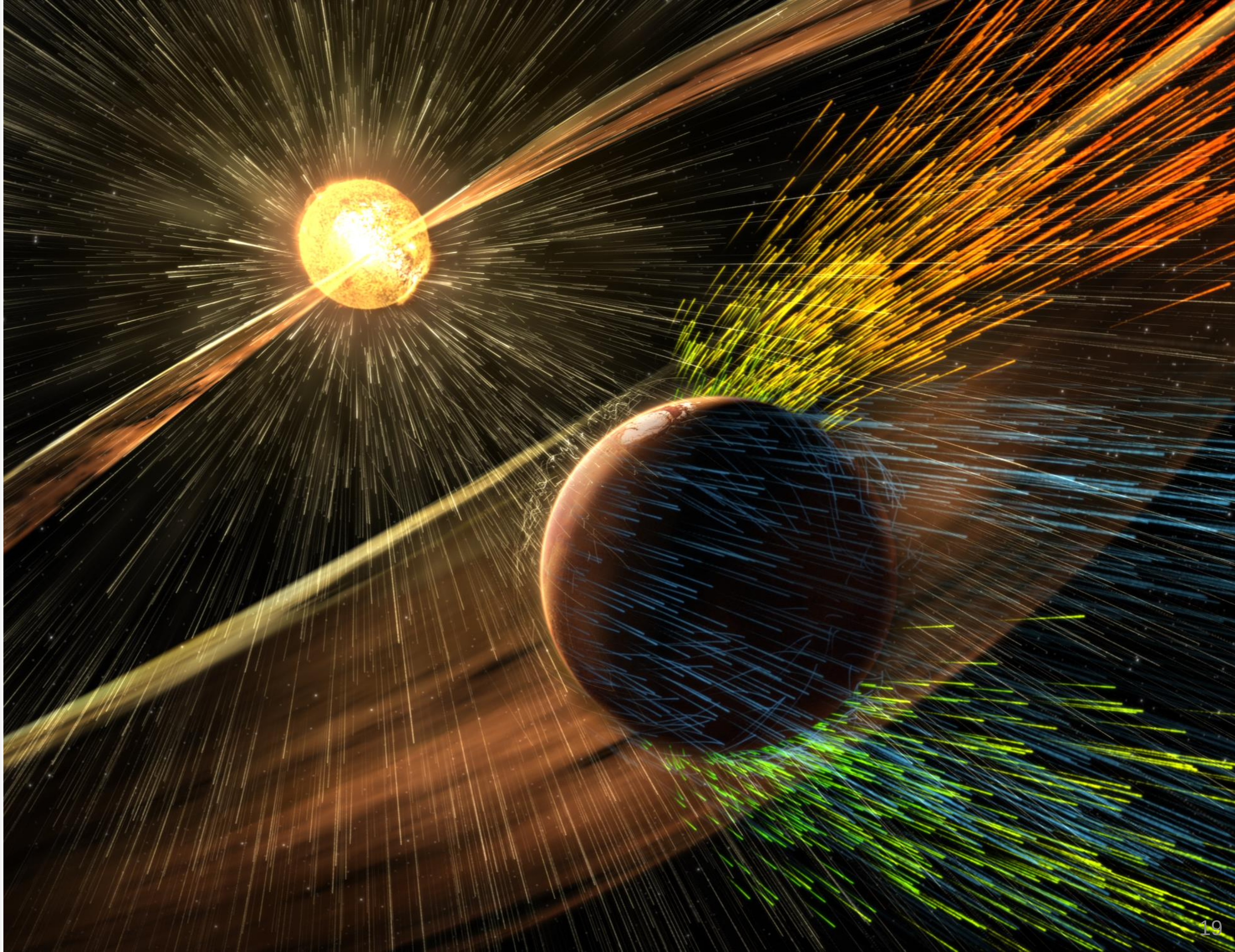
BREAK

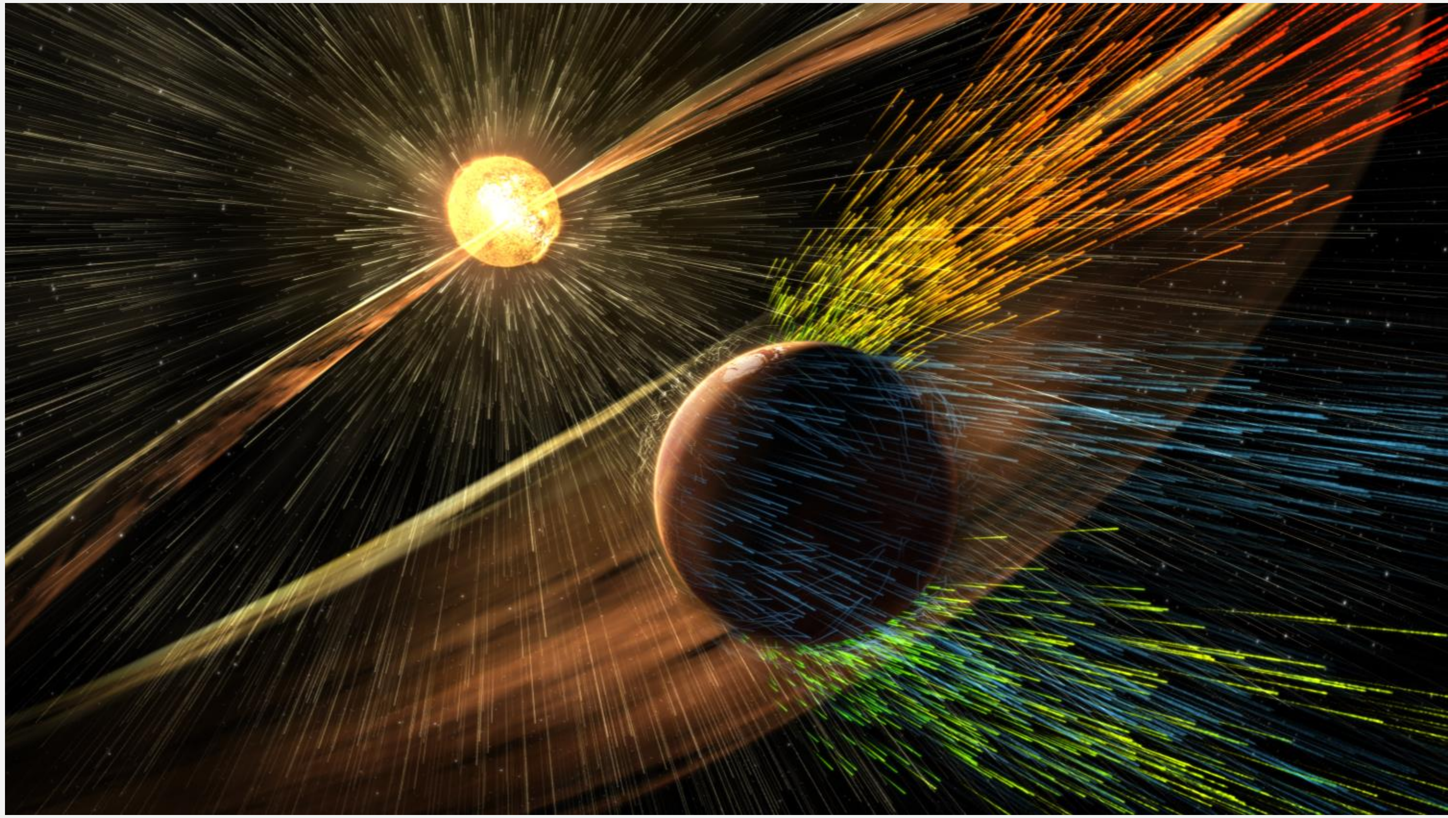

Atmospheric Source and Loss Processes
Sputtering
Photochemical Escape
Impact Source
Impact Loss
Thermal Escape
Ion Escape
Out Gassing
Phase Changes
Chemistry
Hydrodynamic Loss
Dissolution
Adsorption
Trapped Gas
Planet
Z. Sheikh

III. Atmospheric Escape (theory)



October 2015

→



Dave: “Can you make a graphic that looks something like this?”

NASA: “Yes.”

Requirements for Escape

1. Escape Energy

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$\text{Þ} \quad v = \sqrt{\frac{2GM}{r}}$$

	Venus	Earth	Mars
v_{esc}	10 km/s	11 km/s	5 km/s
$E(H^+)$	0.5 eV	0.6 eV	0.1 eV
E(O)	9 eV	10 eV	2 eV

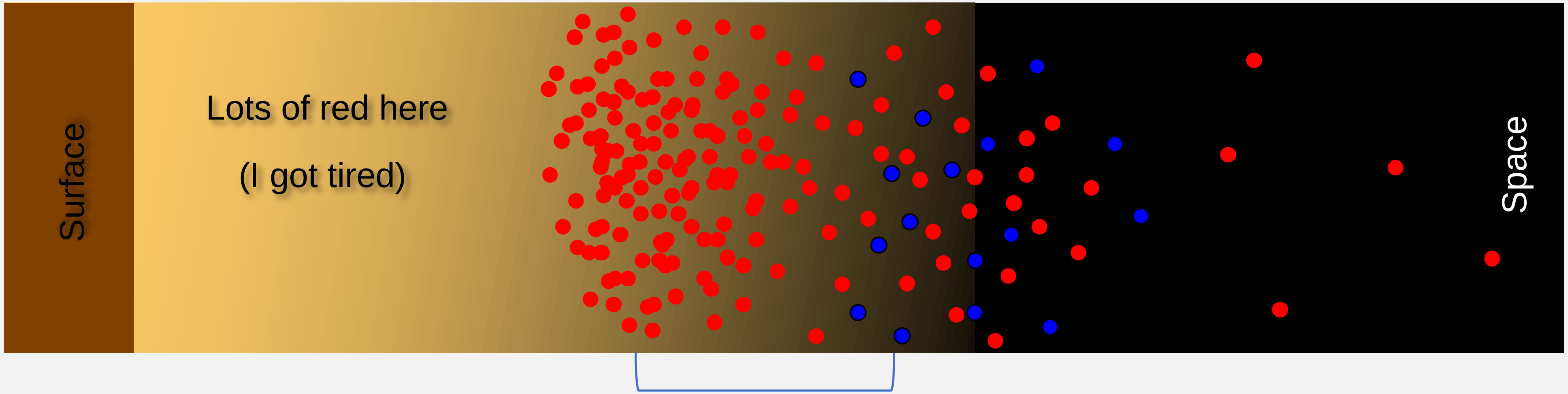
2. Directed Upward

3. No Collisions

Escape from exobase region

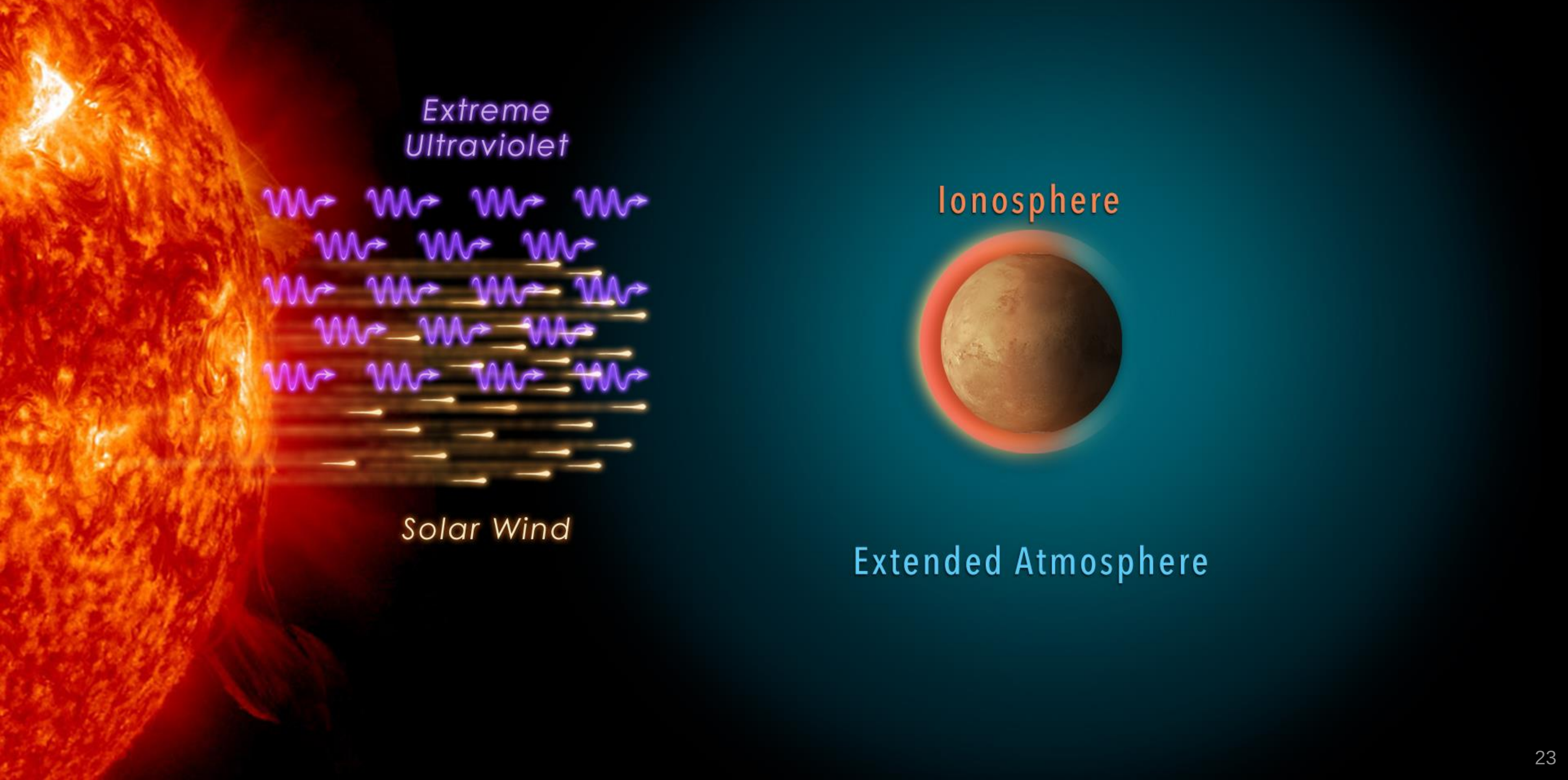
$$\frac{kT}{mg} = \frac{1}{ns}$$

Reservoirs for Escape

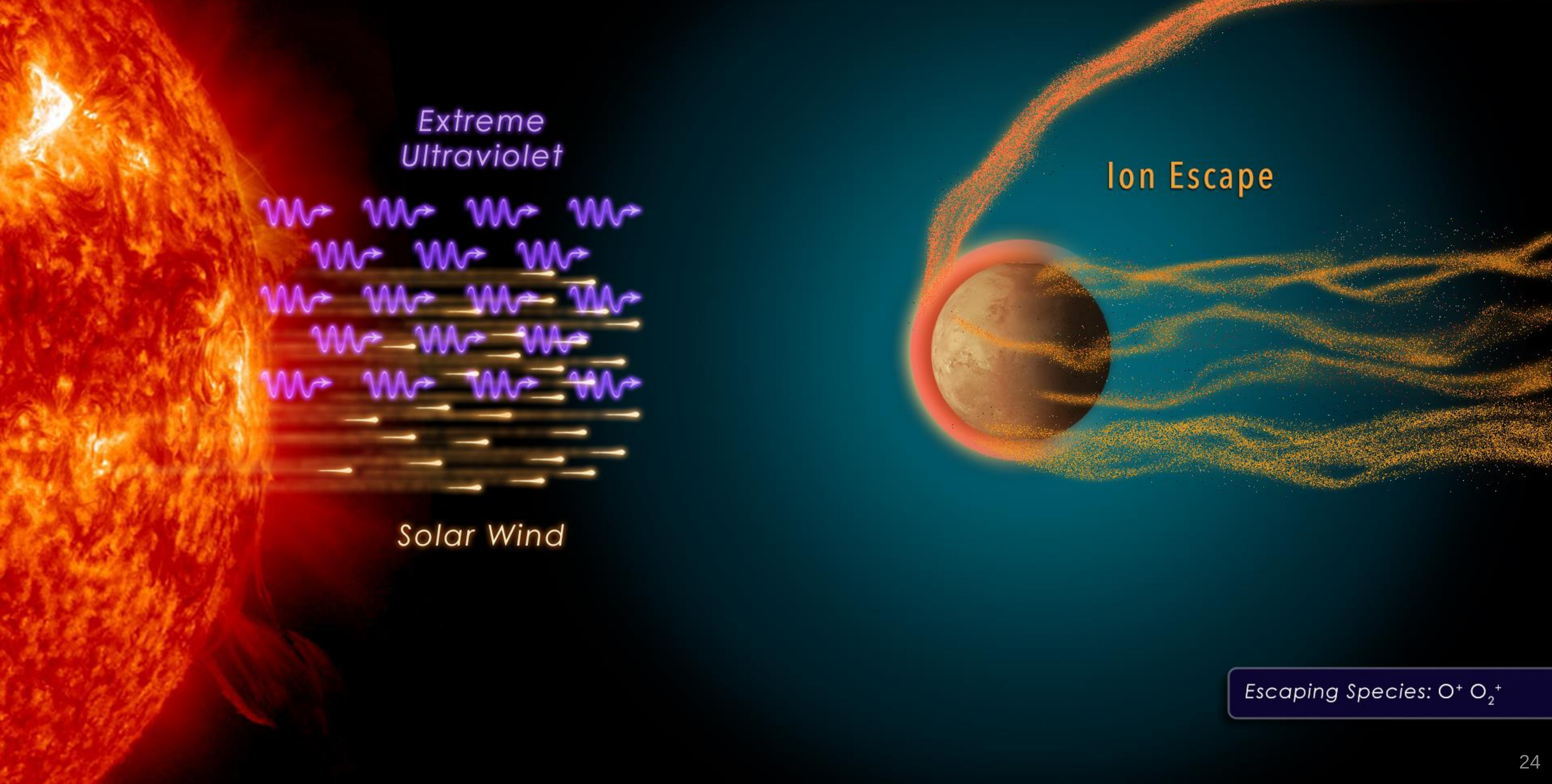


Thermosphere	Ionosphere	Exosphere
T(z) ⇧	Density << neutral density	"collisionless"
Diffusive equilibrium	Chapman peaks from incident energy	Ballistic trajectories
V: ~120-250 km CO_2, CO, O, N_2	V: ~120-300 km O_2^+, O^+, H^+	V: ~250-8,000 km H
E: ~85-500 km O_2, He, N_2	E: ~75-1000 km NO^+, O^+, H^+	E: ~500-10,000 km H, (He, CO_2, O)
M: ~80-200 km CO_2, N_2, CO	M: ~80-200 km O_2^+, O^+, H^+	M: ~200-30,000 km H, (O)

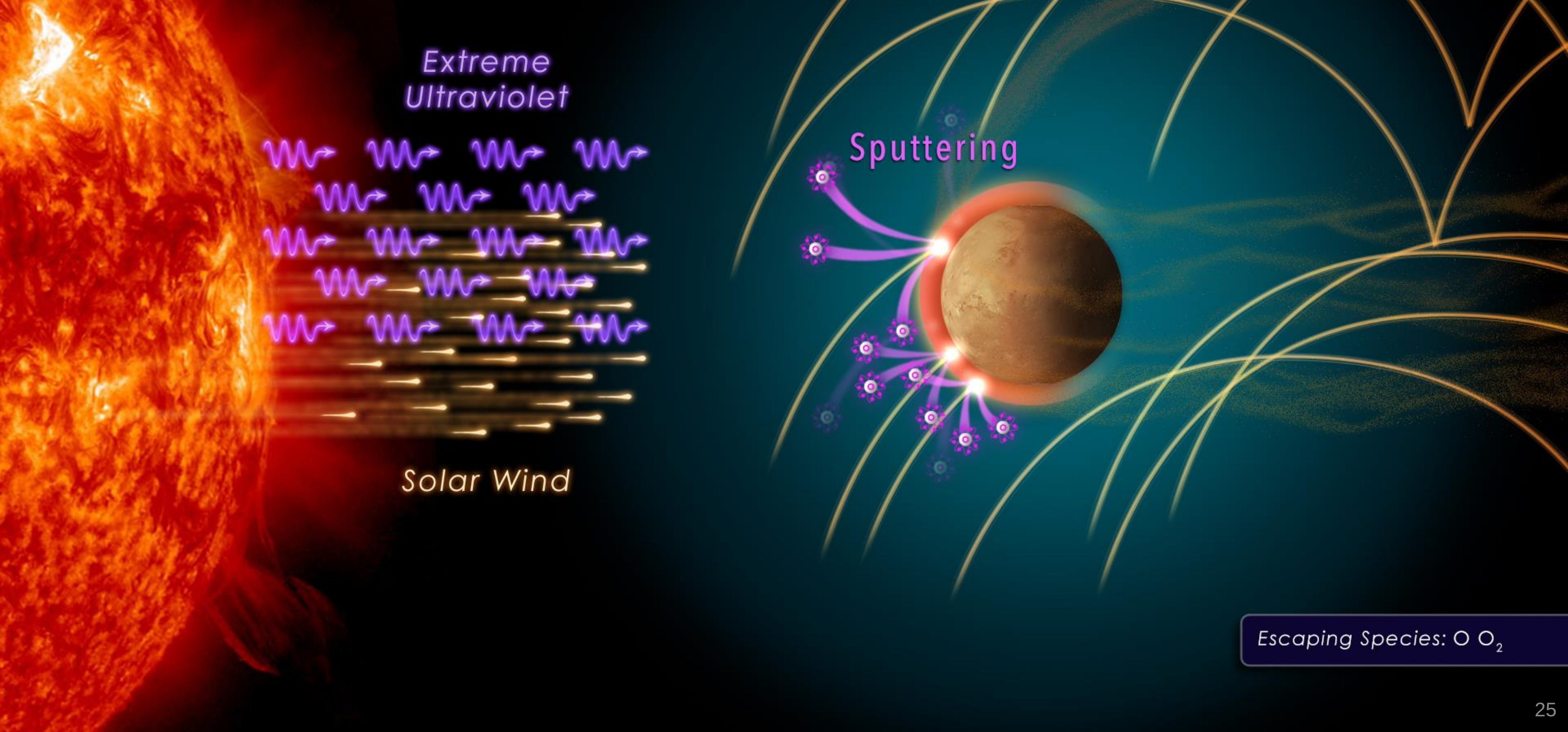
Our star drives atmospheric escape (actually *many* processes!)



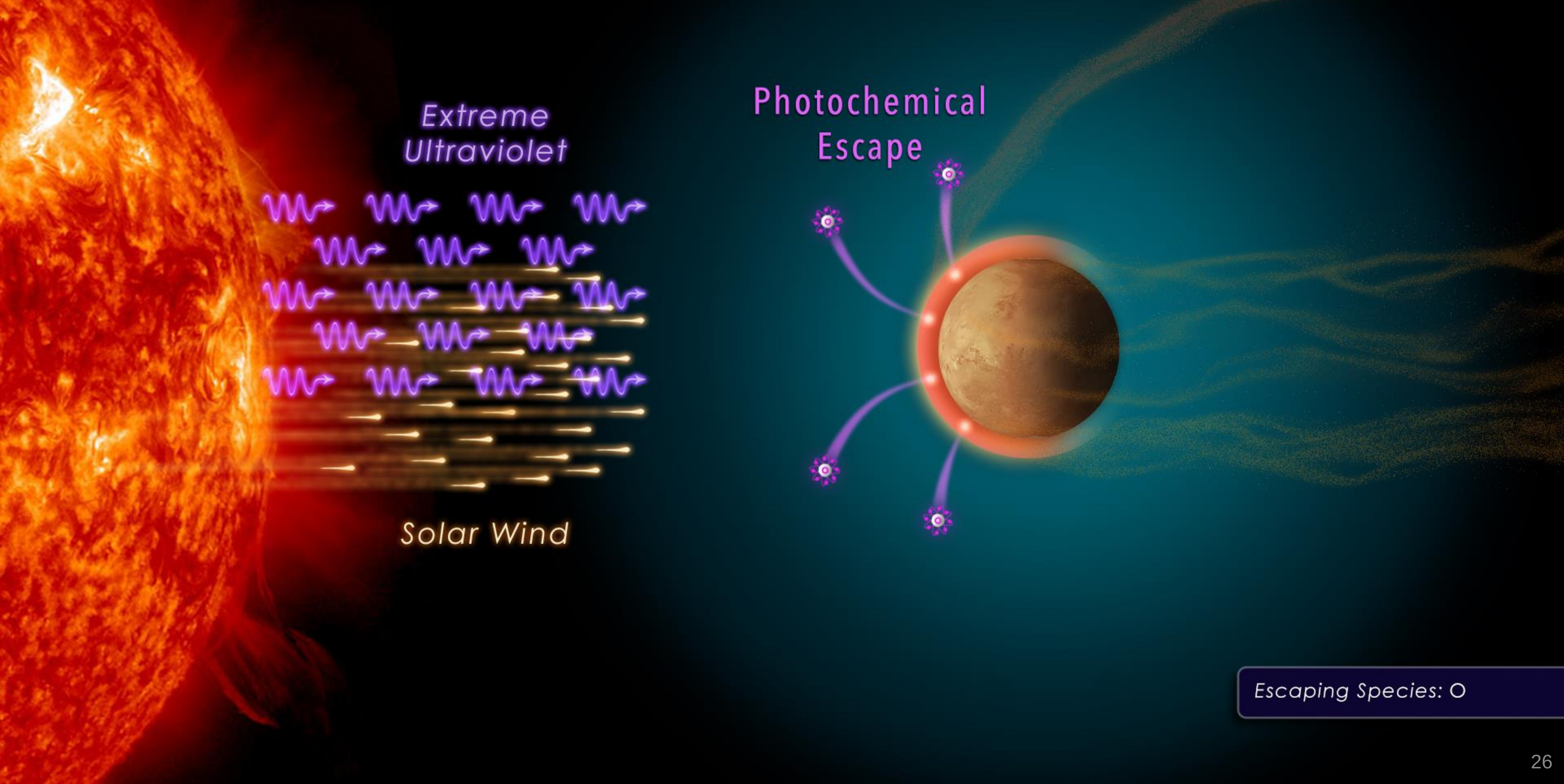
Ions escape via multiple mechanisms



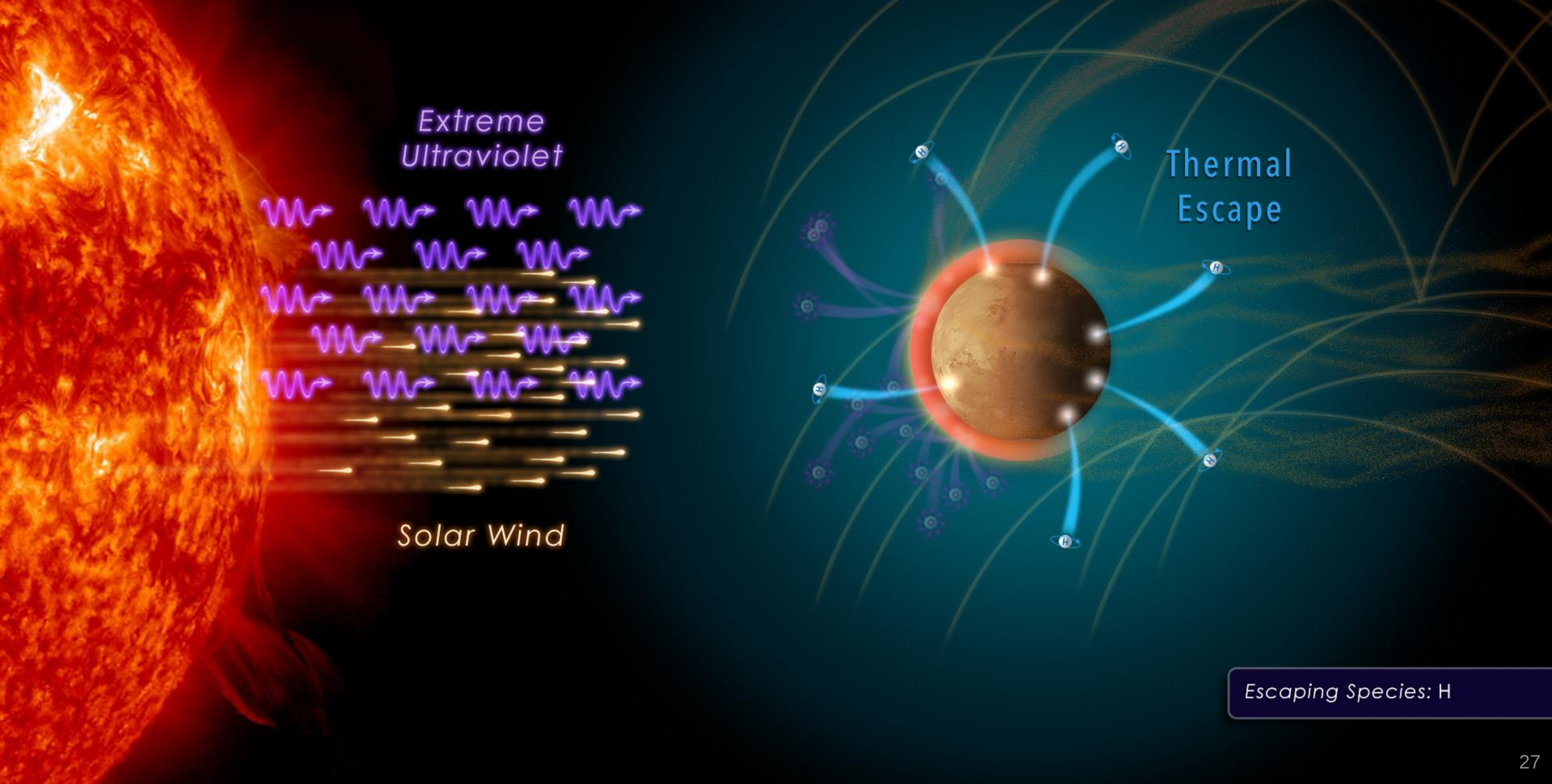
Some ions crash into Mars and splash stuff out



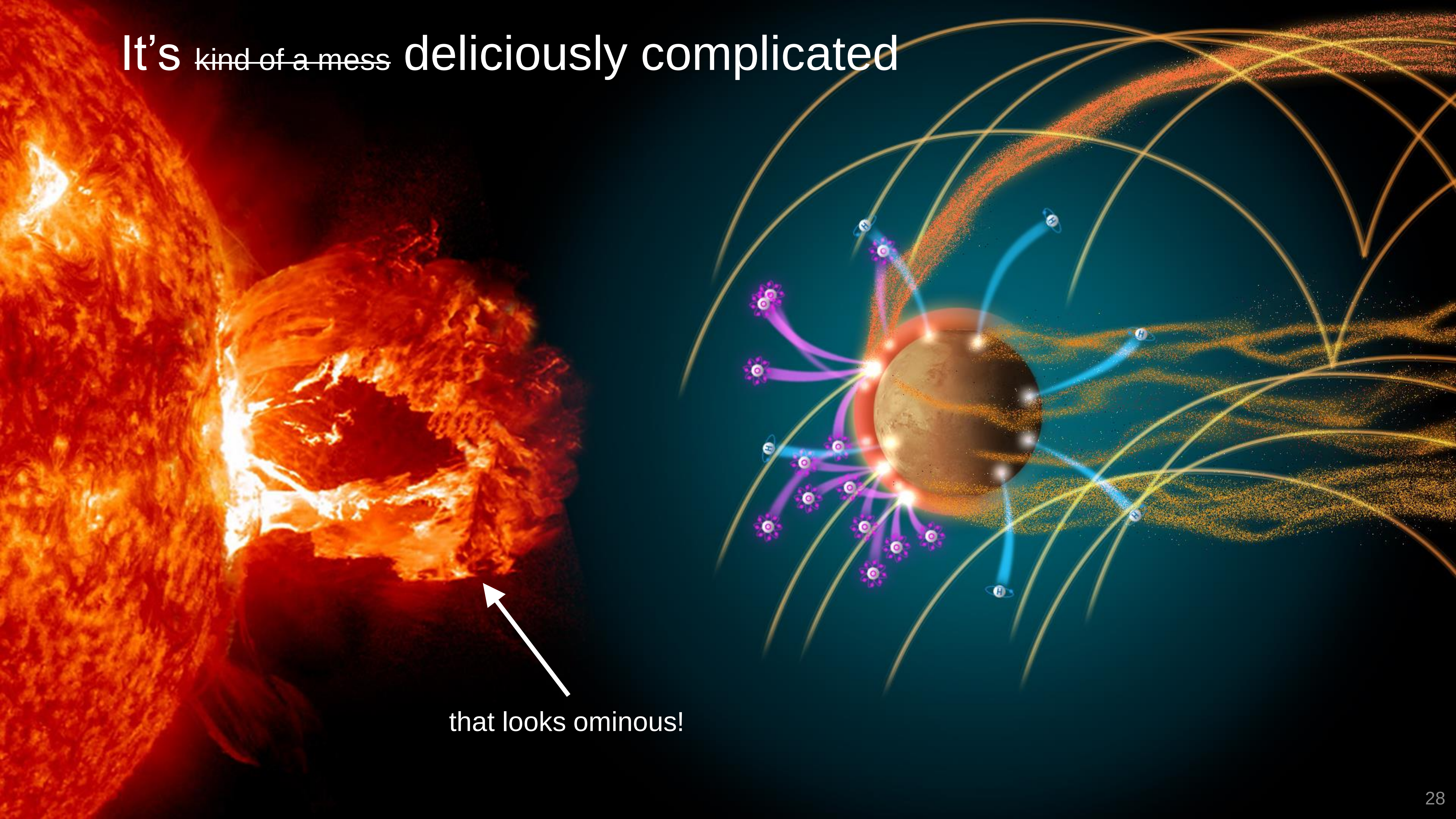
Photochemistry removes neutral oxygen



Hydrogen escapes thermally

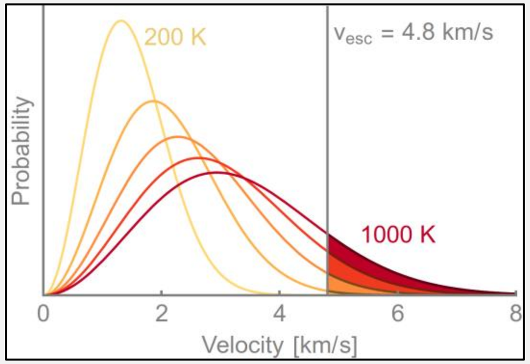


It’s ~~kind of a mess~~ deliciously complicated



Summary of Escape to Space

← a significant fraction of Dave's professional life currently resides here



Thermal Escape

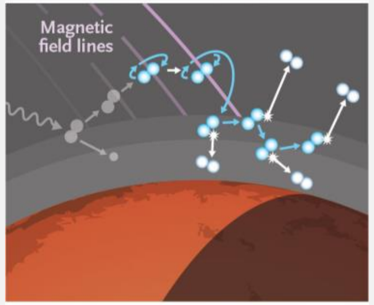
Some particles in a Boltzmann distribution have $v > v_{esc}$

Photochemical Escape

Photodissociation of molecules produces atoms with $v>v_{esc}$

$$O_2 + h\nu \rightarrow O_2^+ + e^-$$

$$O_2^+ + e^- \rightarrow O^* + O^*$$



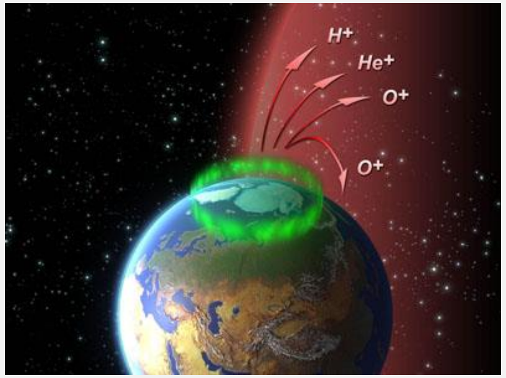
Sputtering

Particles crashing into the atmosphere splash others out

Ion Loss

← and especially here

Atmospheric ions accelerated in a planet's cusps, or get carried away by the solar wind



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$R_M \sim 3400$ km

$g_M \sim 3.8$ m/s^2

Atomic number of oxygen = 8

1 year ~ π x 10^7 s

$$\Delta P = \Delta \frac{F}{A} = \frac{\Delta F}{A} = \frac{\Delta m \, g_{Mars}}{A} = \frac{\Phi \, m_O \, \Delta t \, g_{Mars}}{4 \, \pi \, R_{Mars}^2} = \sim 100 \, mbar$$

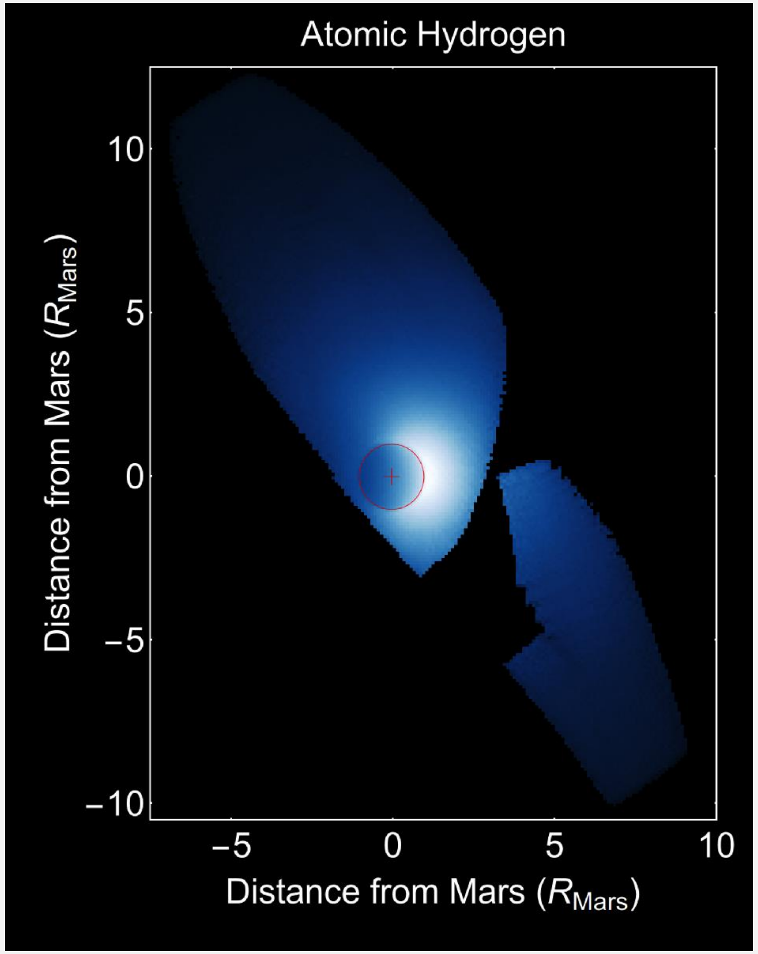
Is this enough to change climate?

Is it a lot?

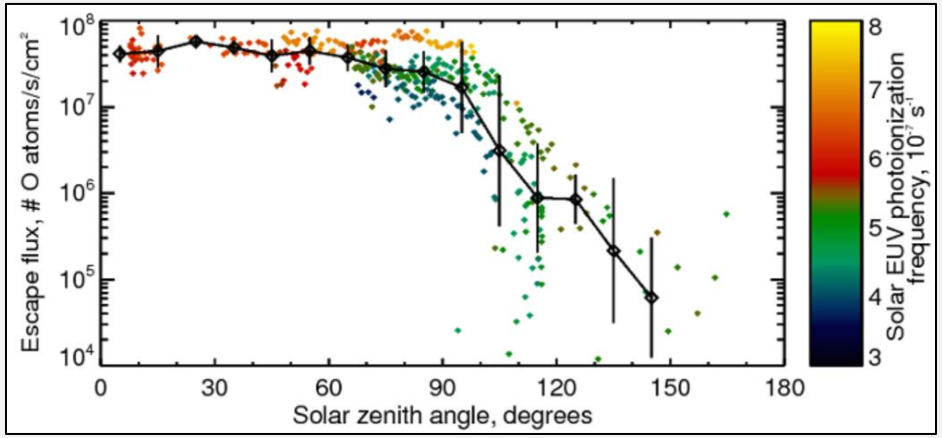
Is it a little?

IV. Atmospheric Escape (observed)

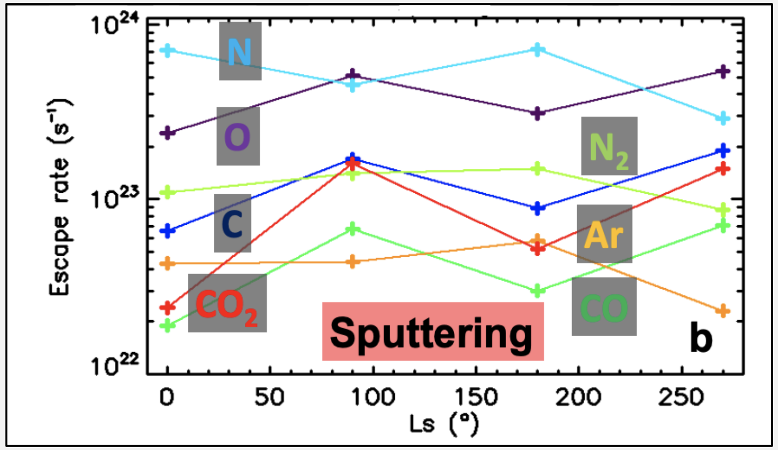
Atmospheric Escape from Mars



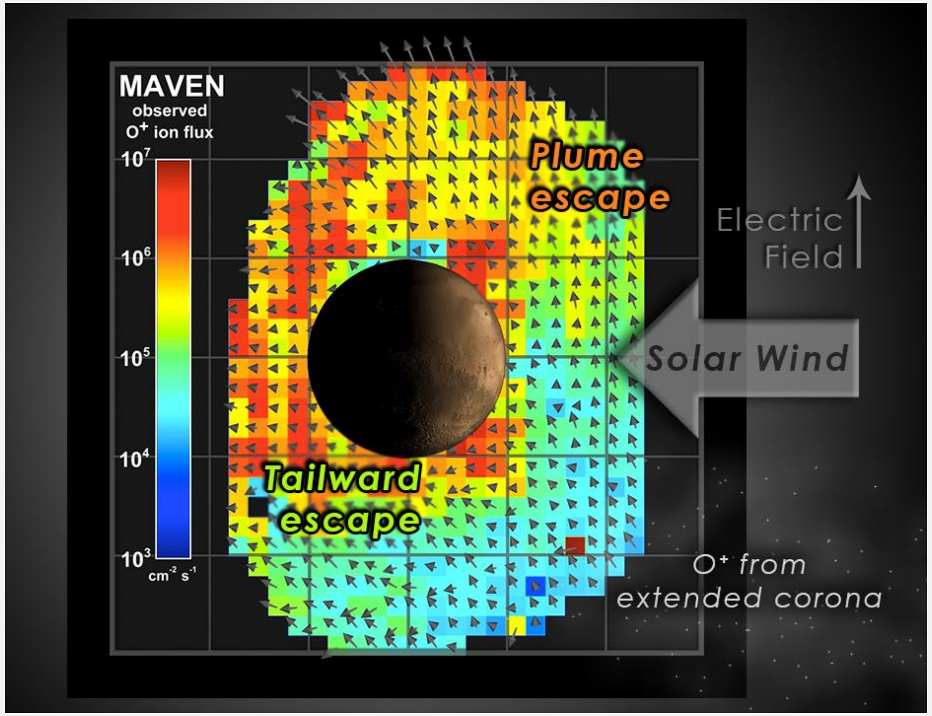
Thermal Escape (H) ~10^{26} s^{-1}



Photochemical Escape (O) ~1-5 × 10^{25} s^{-1}



Sputtering Escape (N,O,C,etc.) ~ 10^{23} s^{-1}



Ion Escape (O^+, O_2^+, CO_2^+) ~7 x 10^{24} s^{-1}

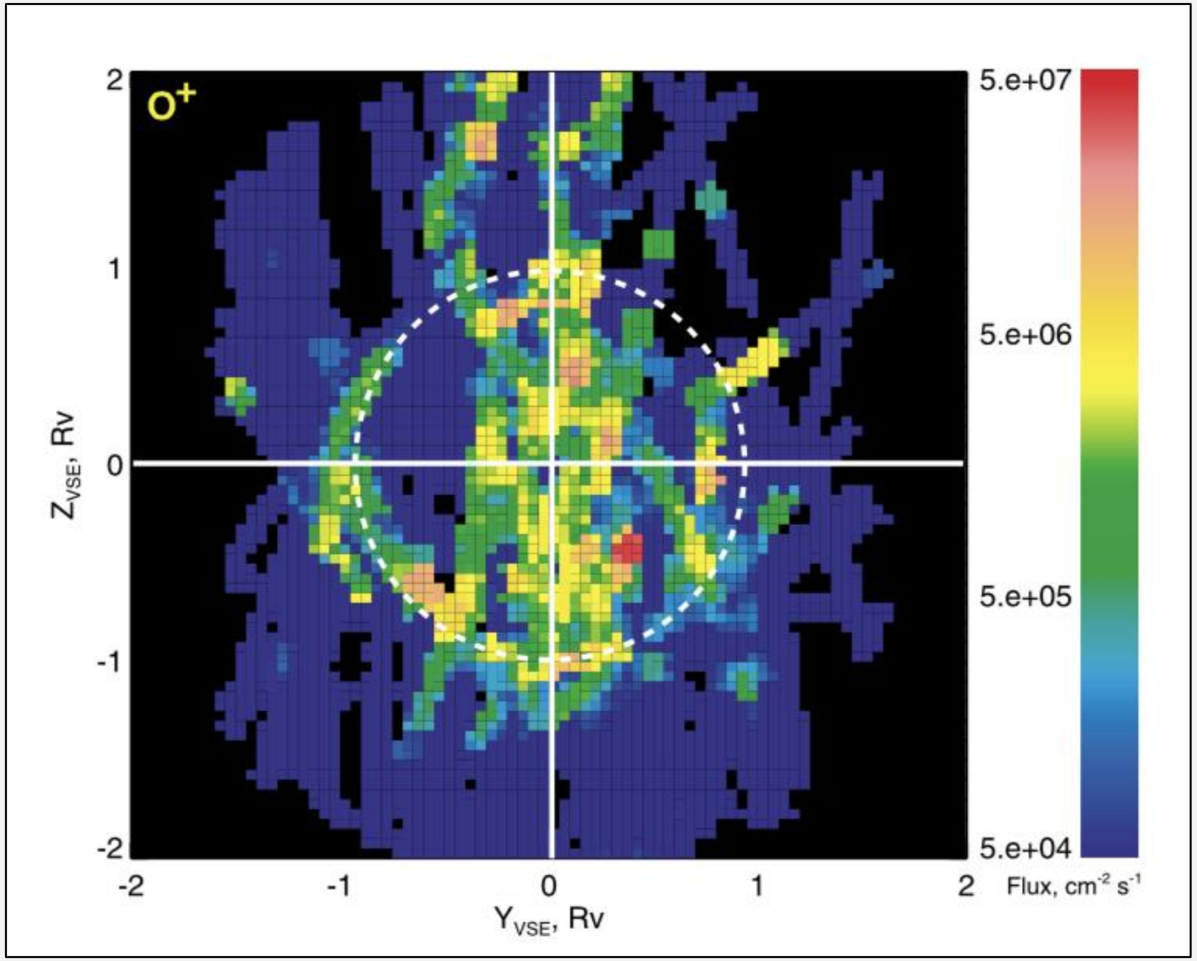
Atmospheric Escape from Venus

~~Thermal Escape (H)~~

~~Photochemical Escape (O)~~

Sputtering Escape (N,O,C,etc.) ~ ??? s^{-1}

Ion Escape (O^+, O_2^+, CO_2^+, H^+) ~5×10^{24} s^{-1}



Fedorov et al., 2011

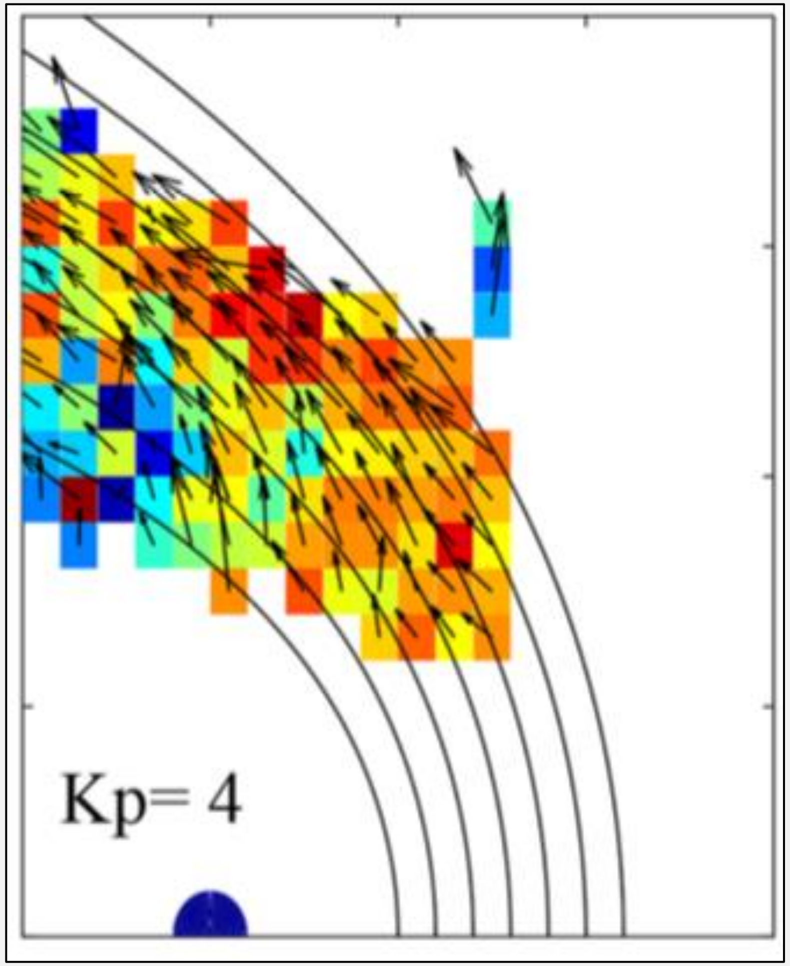
Atmospheric Escape from Earth

Thermal Escape (H) ~ 10^{26} s^{-1}

~~Photochemical Escape (N,O)~~

~~Sputtering Escape (N,O,C,etc.)~~

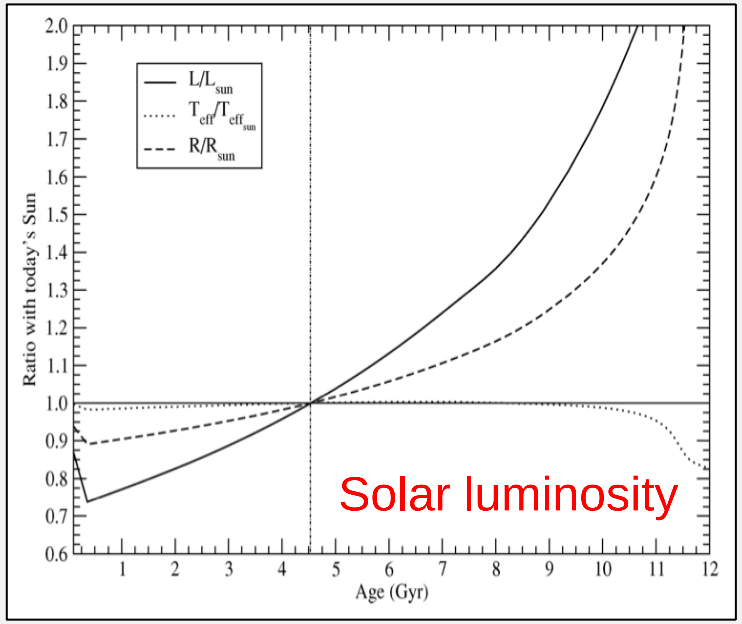
Ion Escape (O^+, H^+) ~10^{25} - 10^{26} s^{-1}



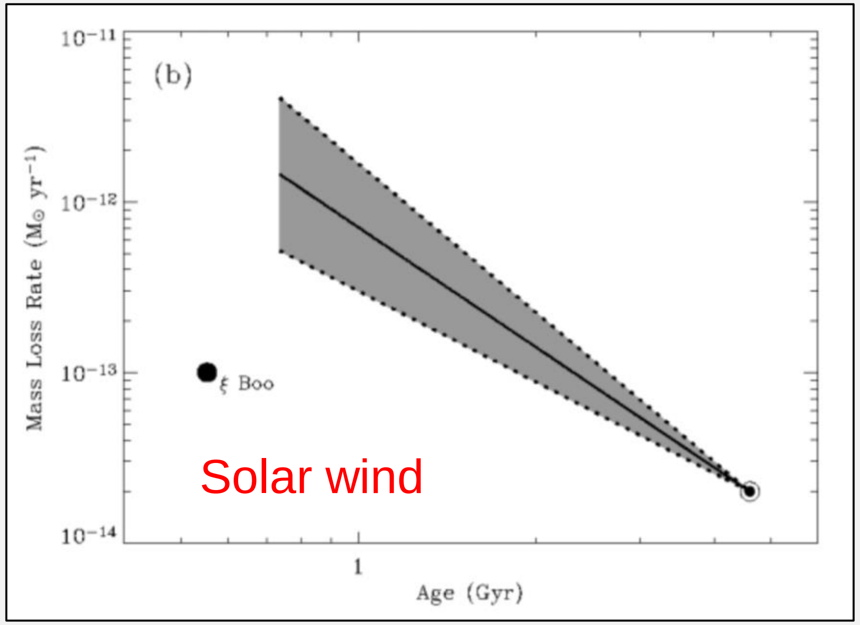
Slapak et al., 2017

V. Drivers of Atmospheric Escape

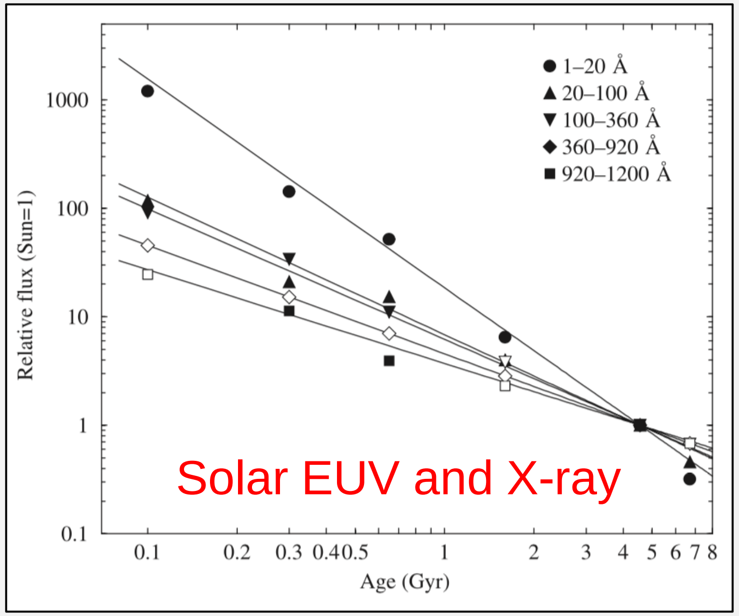
“External” drivers include photons, particles, and fields



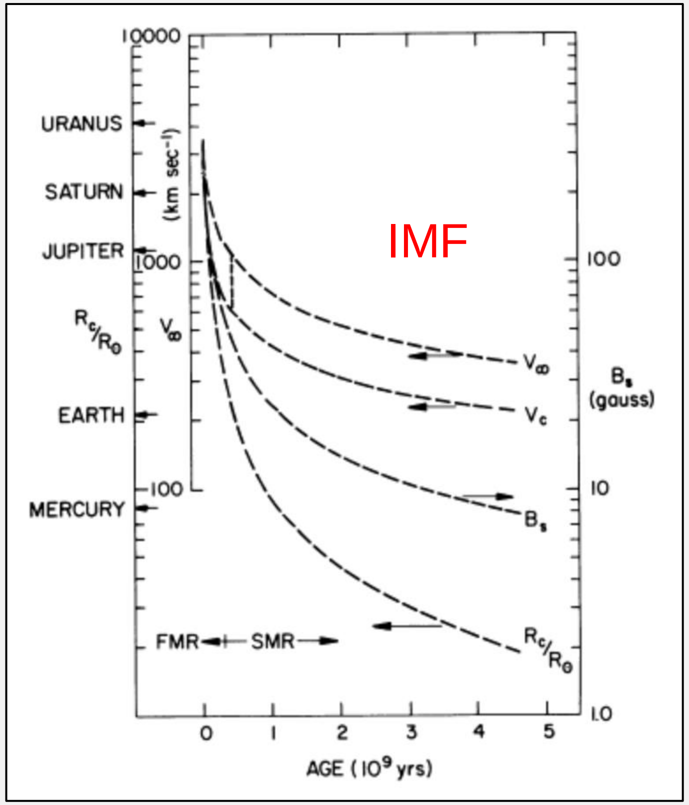
Ribas et al., 2010



Wood et al., 2005

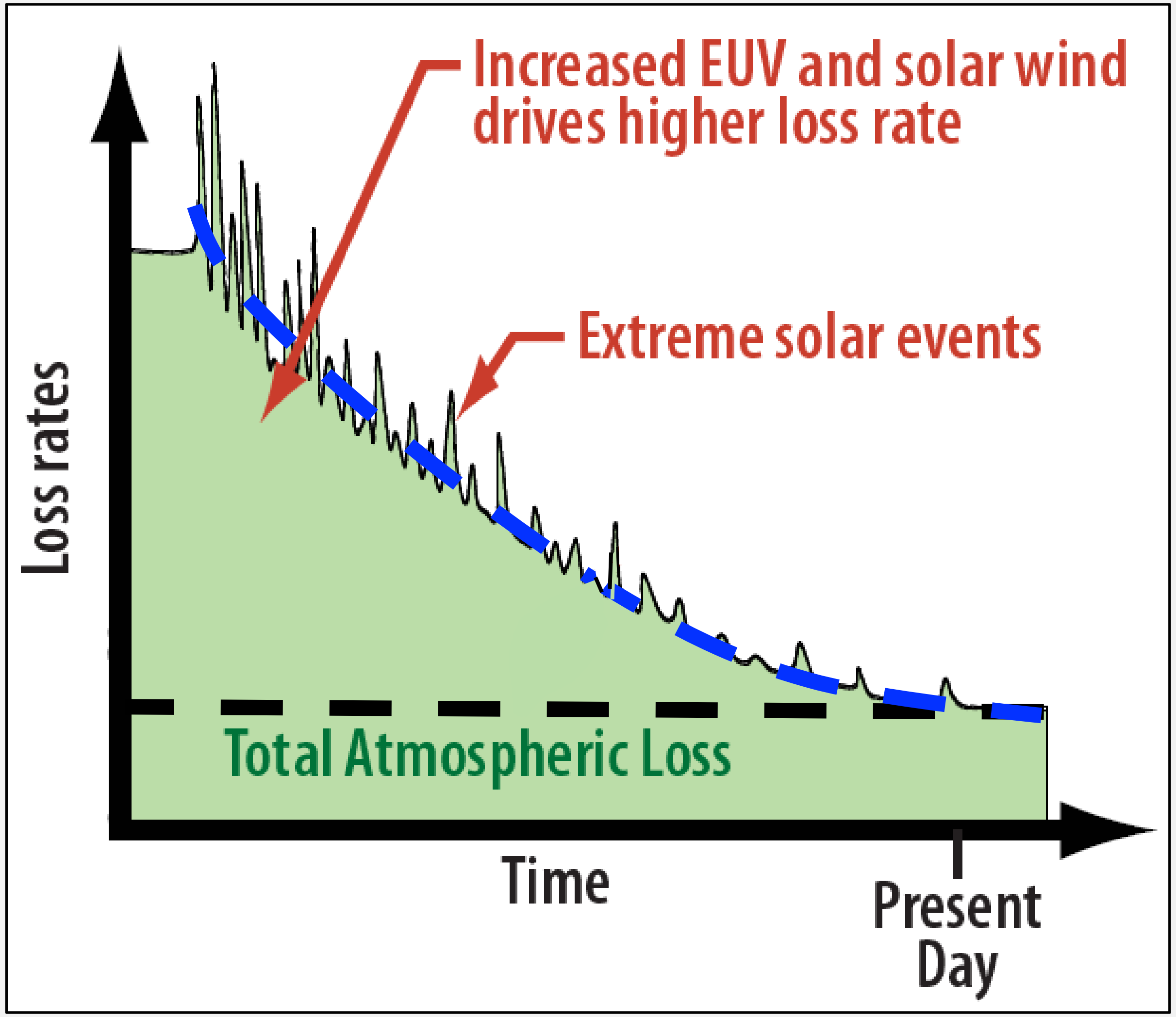


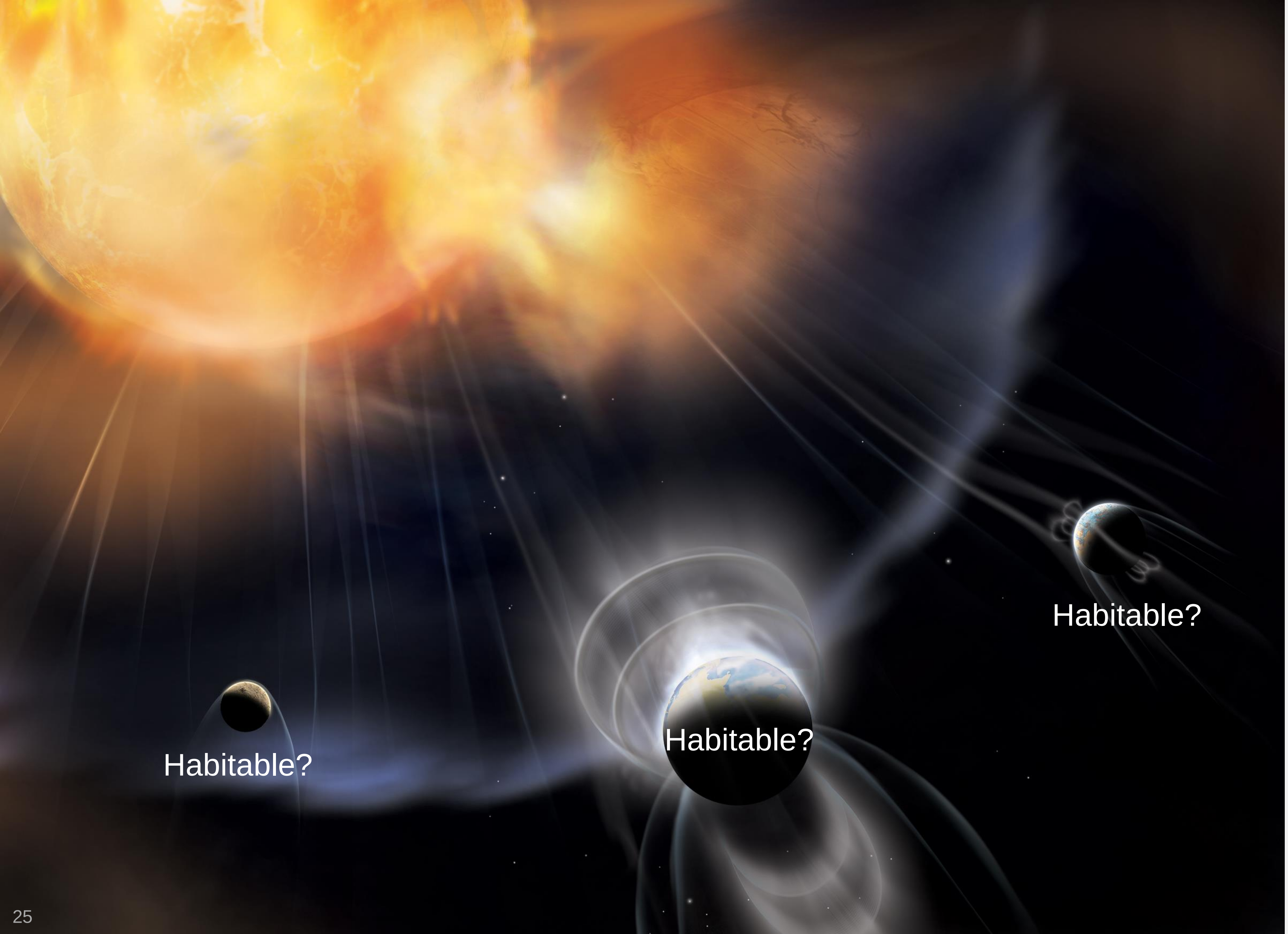
Ribas et al., 2005



Newkirk Jr., 1980

Escape rates should have been greater long ago





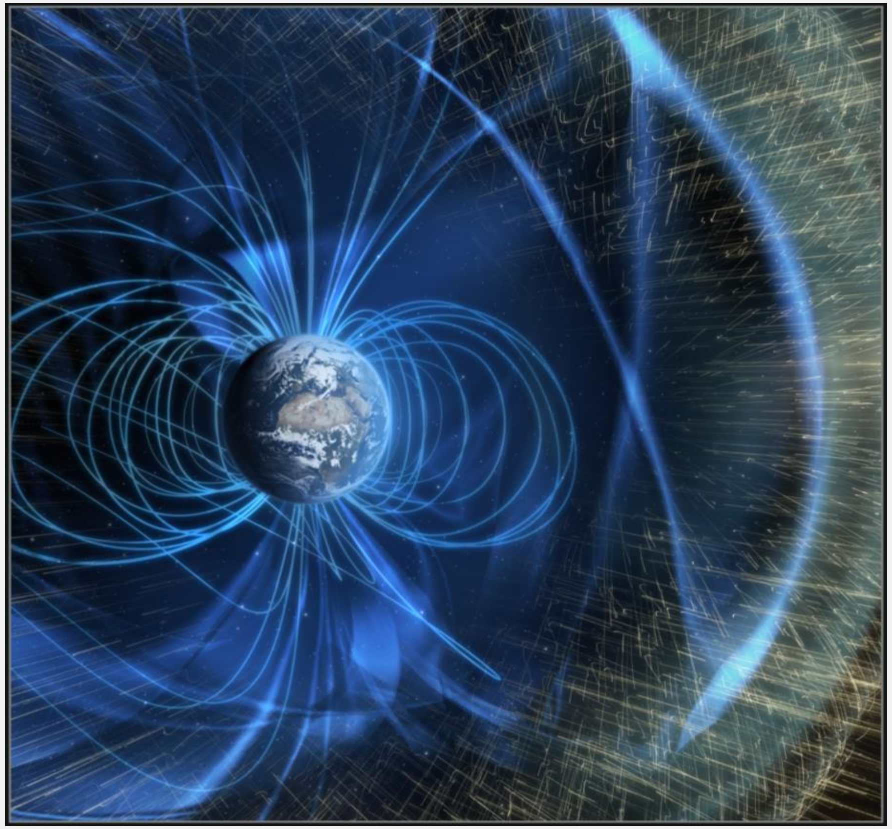
VI.

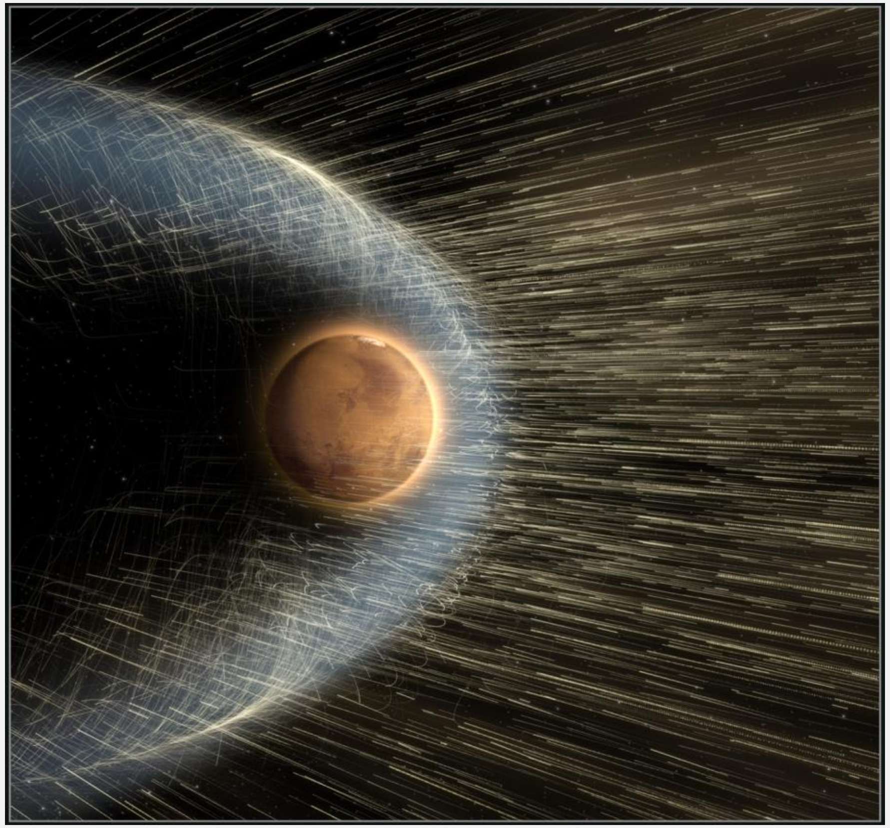
Do Habitable Worlds Require Magnetic Fields?

Question:
How should planetary magnetic fields influence atmospheric escape?

A. They shouldn't
B. The presence of a planetary magnetic field should decrease escape rates
C. The presence of a planetary magnetic field should increase escape rates
D. It depends

Magnetic fields should protect atmospheres





Simple physics: A magnetized planet deflects solar wind charged particles far from the atmosphere

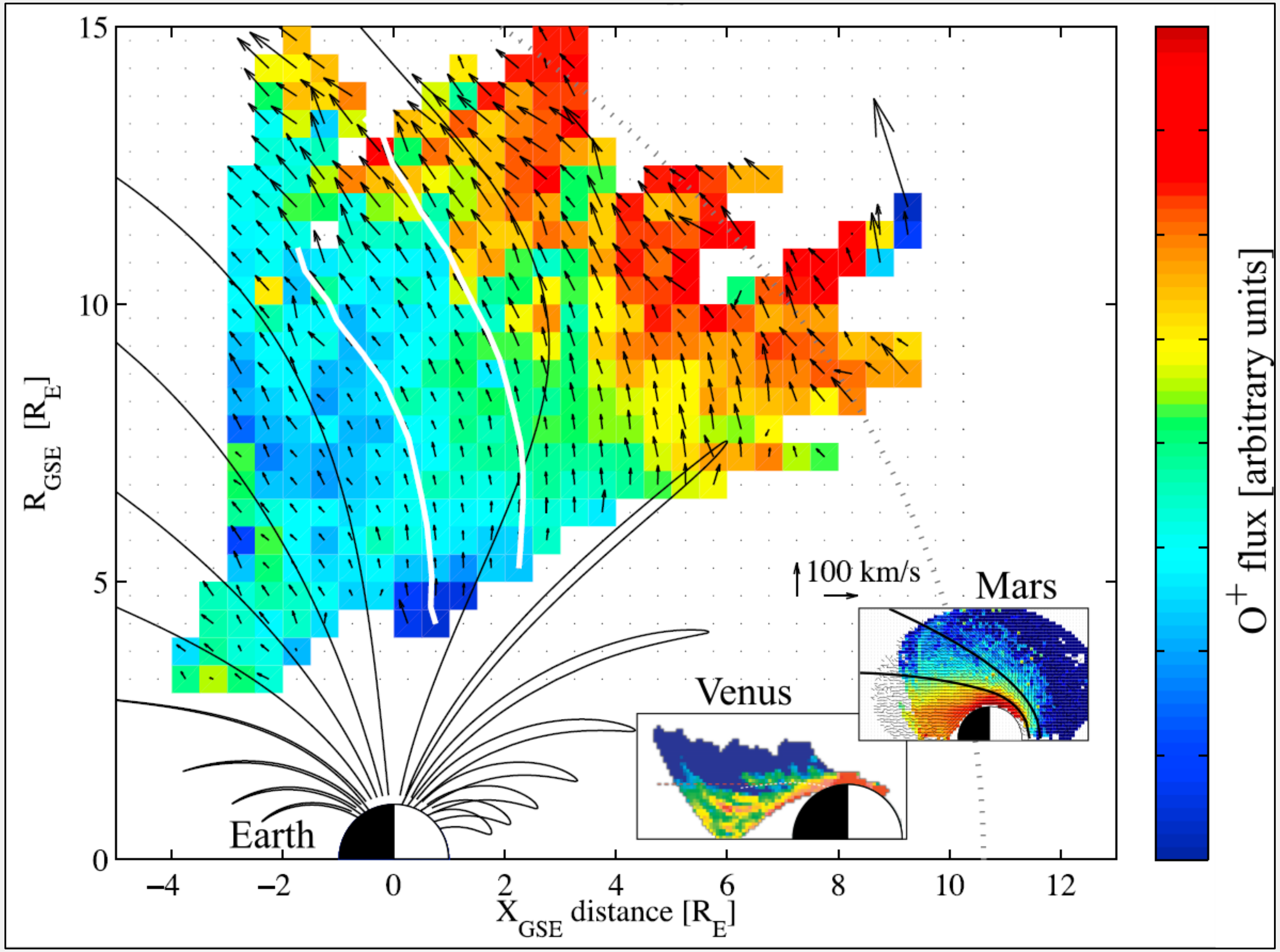
- Solar wind doesn't encounter atmosphere
- Less energy for top of atmosphere

→ Atmosphere can't escape efficiently

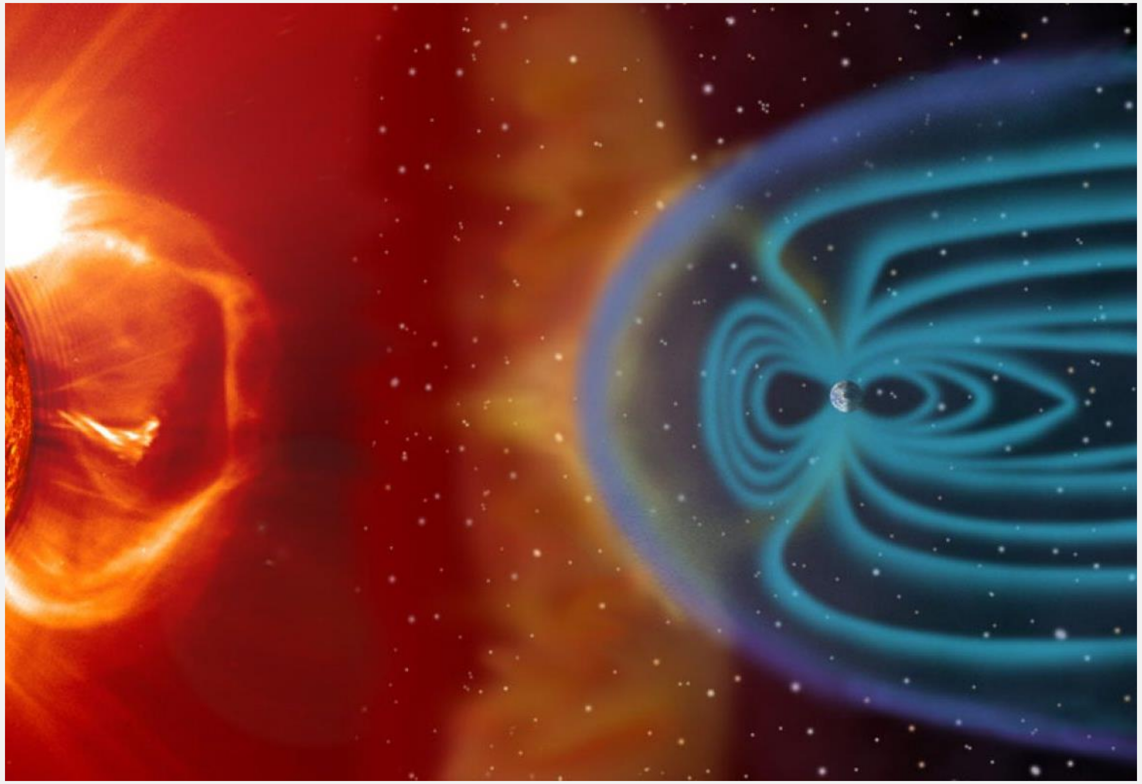
Ion Escape Rates at Terrestrial Planets

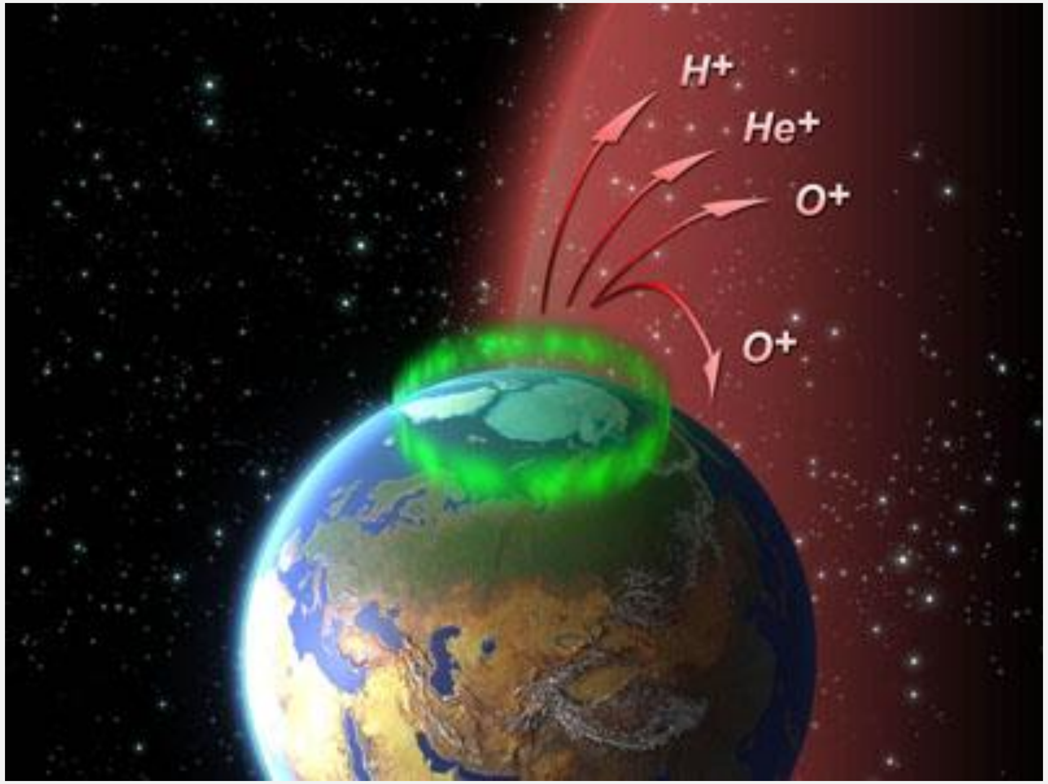
Loss rate of “heavy” ions:

~10^{25} s^{-1}, give or take



Magnetic fields should not protect atmospheres

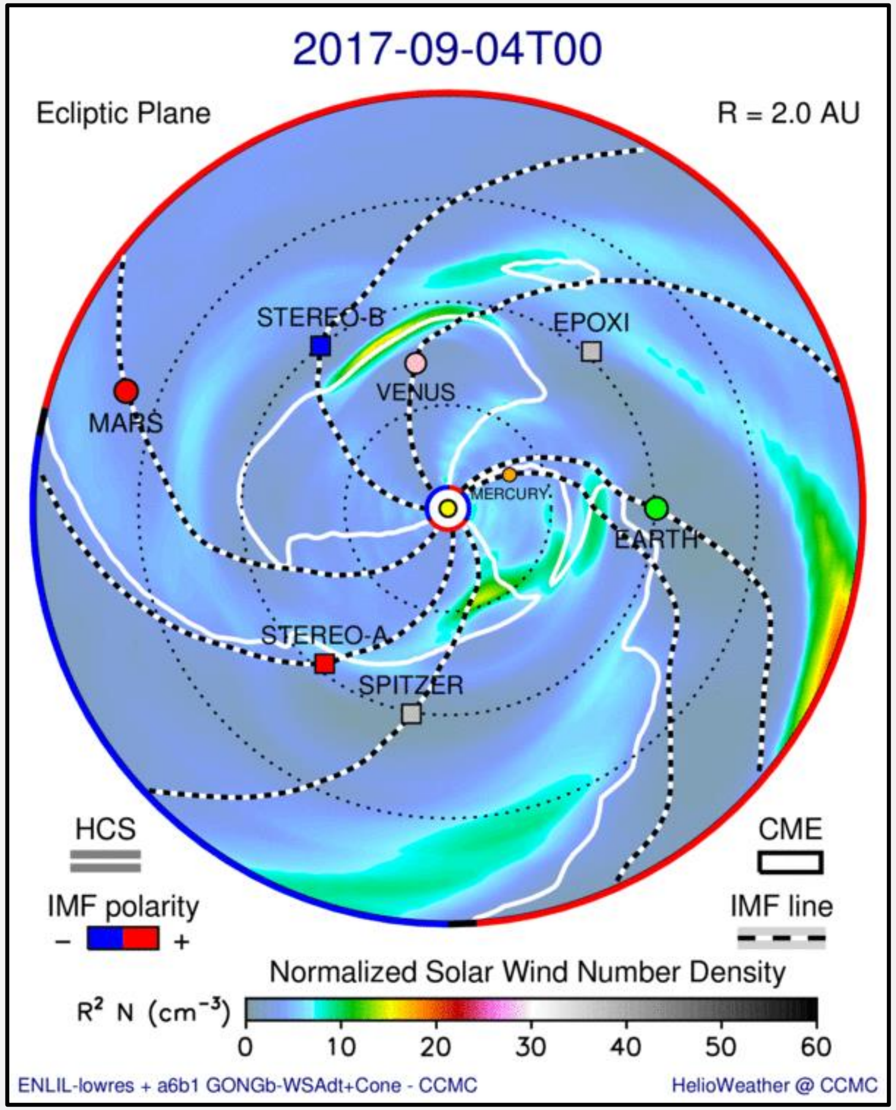




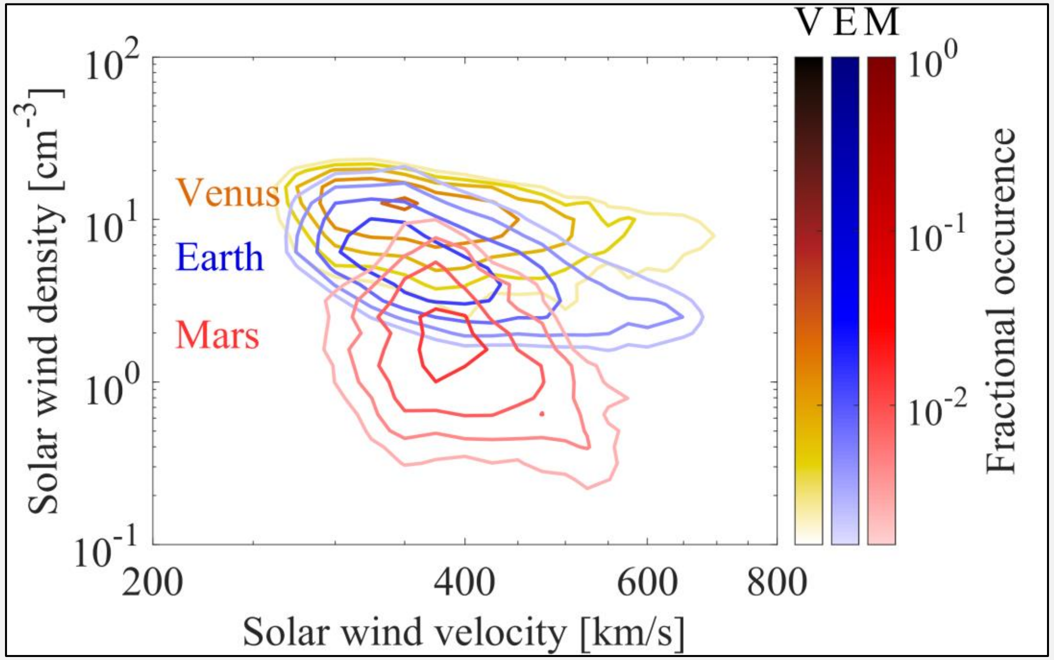
Simple physics: A magnetized planet captures more energy from the solar wind

- A magnetic field gives a larger cross-section
- Energy transferred to the atmosphere along magnetic field (e.g. aurora!)
- Escape is efficient, but non-global

Not all escape measurements are created equal



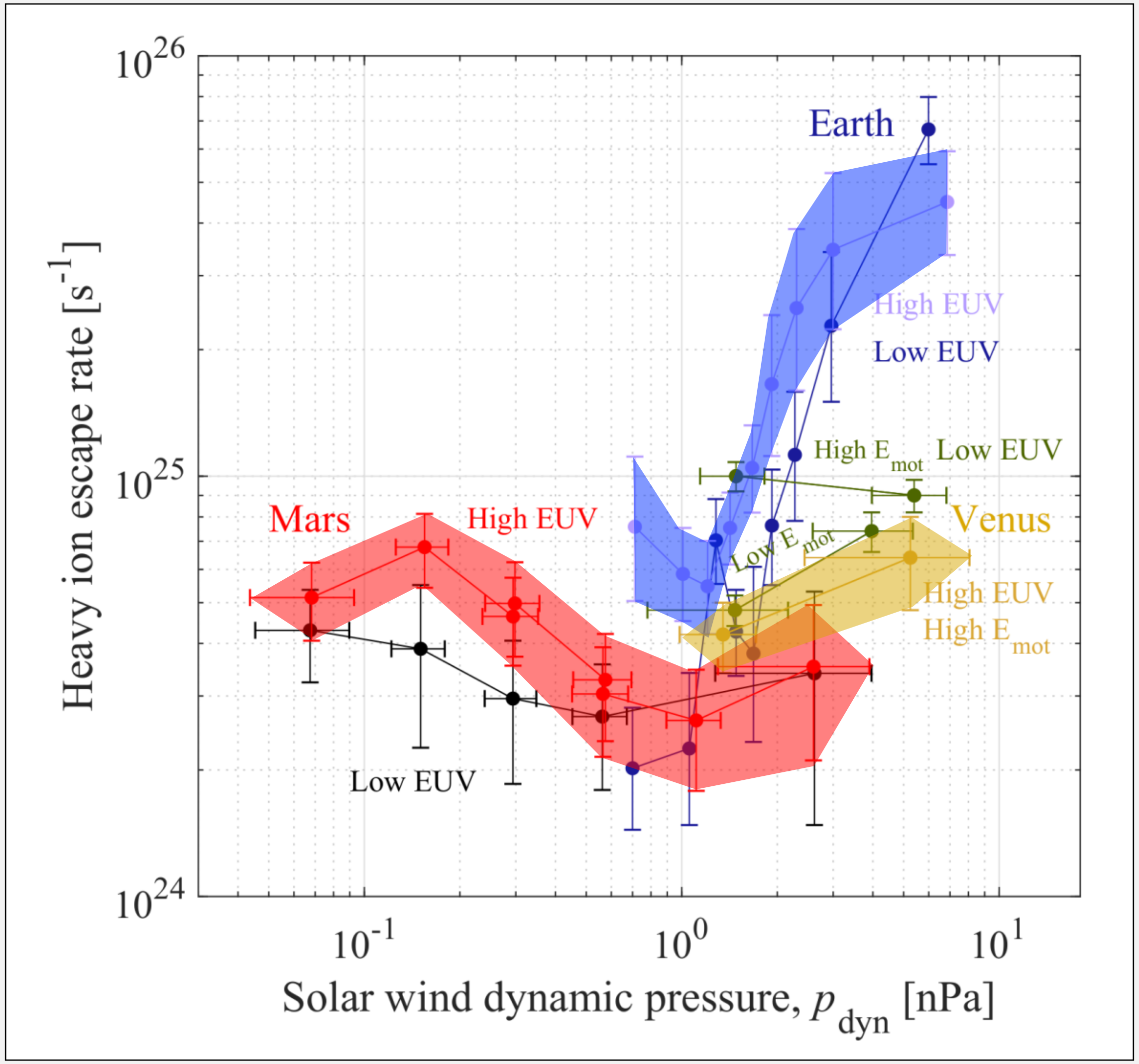
Courtesy L. Mays - GSFC



Courtesy R. Ramstad

Also, different escaping species reported by different instruments over different energy ranges by different investigators

Earth responds more strongly to the solar wind that Venus or Mars



Ramstad and Barabash, 2020

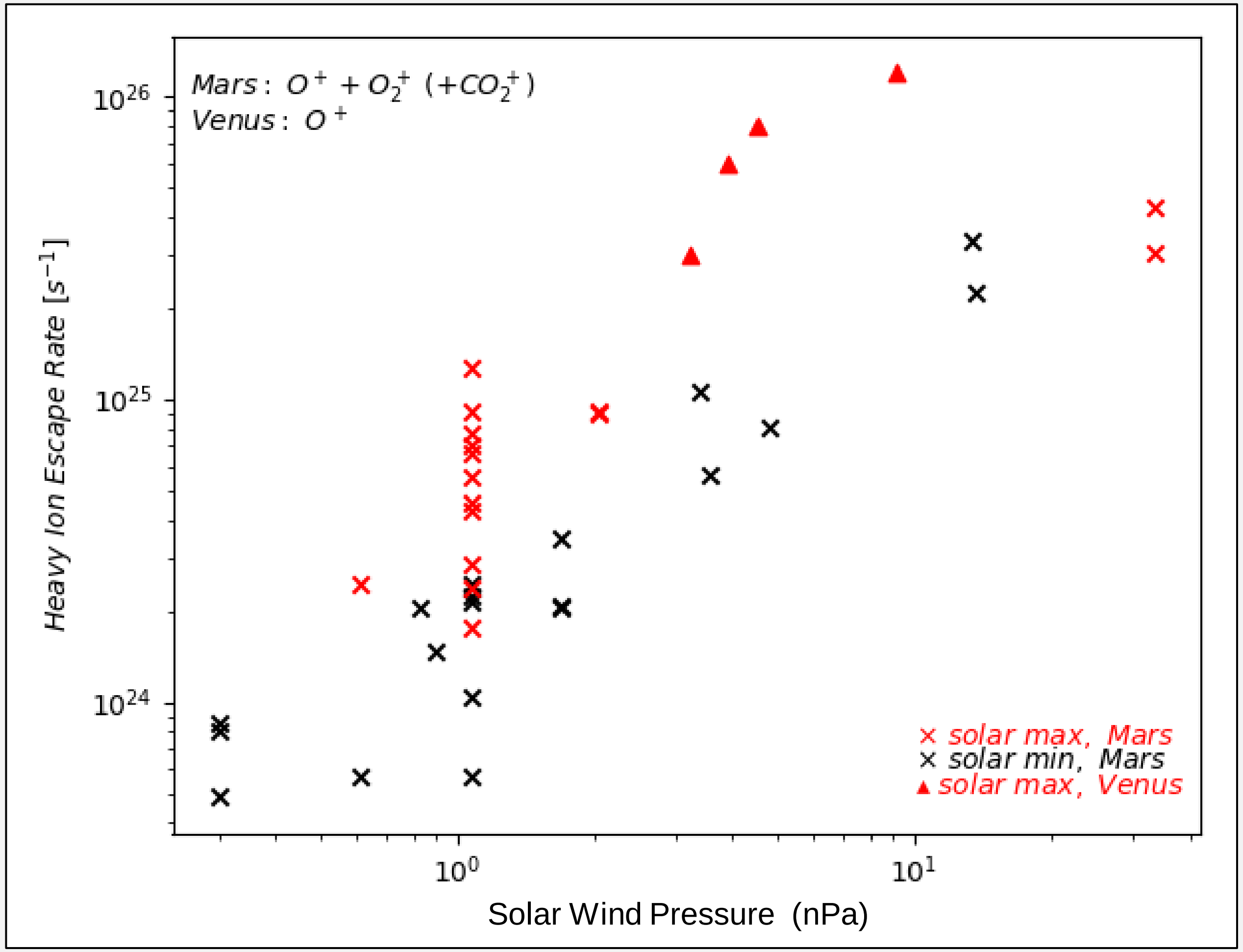
Mars – Negligible / inverse dependence

Venus – Weak positive dependence

Earth – Strong positive dependence

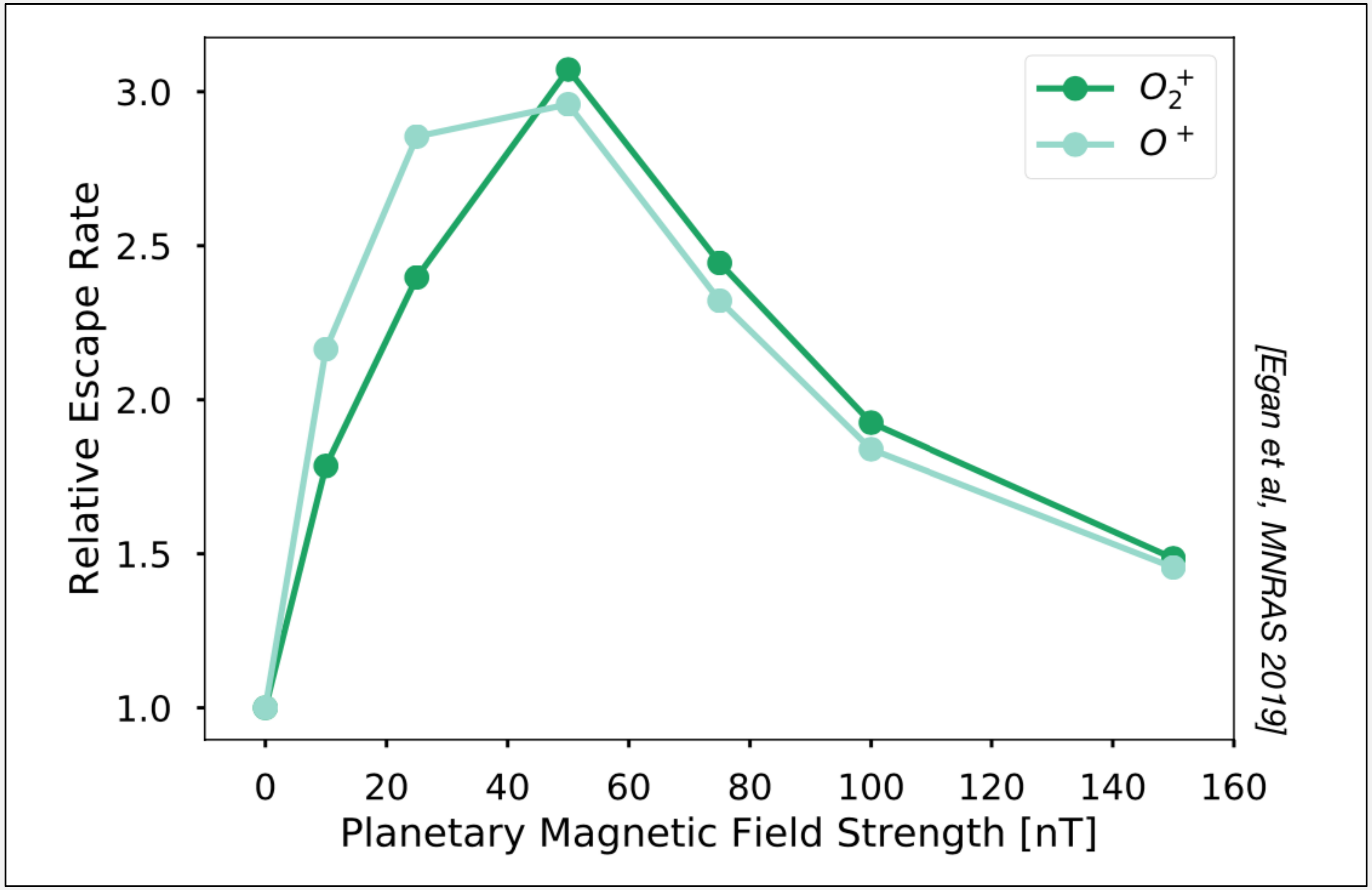
Masunaga et al., [2019]
Ramstad et al., [2018c; 2020]
Schillings et al., [2019]

There are lots of published studies of atmospheric escape based on simulations



Sun et al., 2021

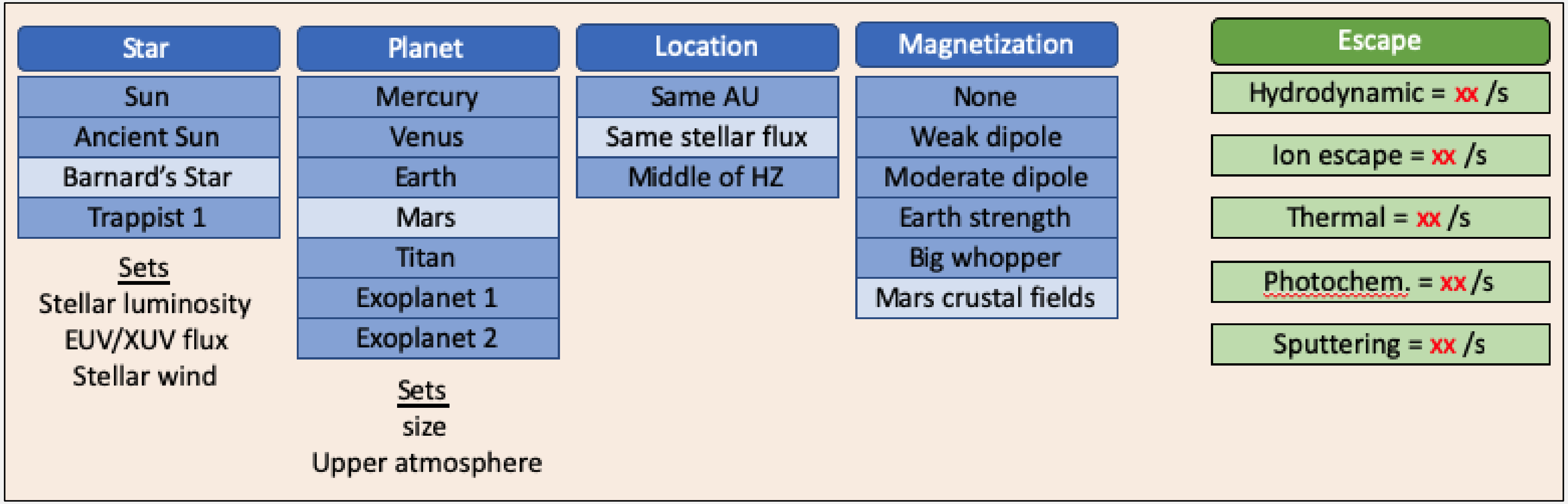
Magnetic field influence on escape is not so simple!



Egan et al., 2019

A community tool for assessing atmospheric loss

MACH will construct a framework that enables the evaluation of atmospheric loss from an arbitrary rocky planet given information about the planet and its host star



Question: Suppose we detect a planet double the size of Venus around a 5 billion year old M-type star. The IAU names it AmitCopeLikaGross. The planet has half the orbital distance of Venus and, to our surprise, has detectable radiation belts. How might AmitCopeLikaGross's climate and surface habitability be different from that of Venus?

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