Exo-Atmospheres
Ecole de Physique des Houches

Exhaust and evaporation

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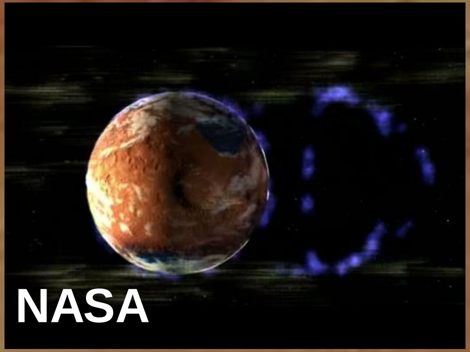
Outlines

Our Sun

Cremonese et al. (1997)

Signatures of a present escape



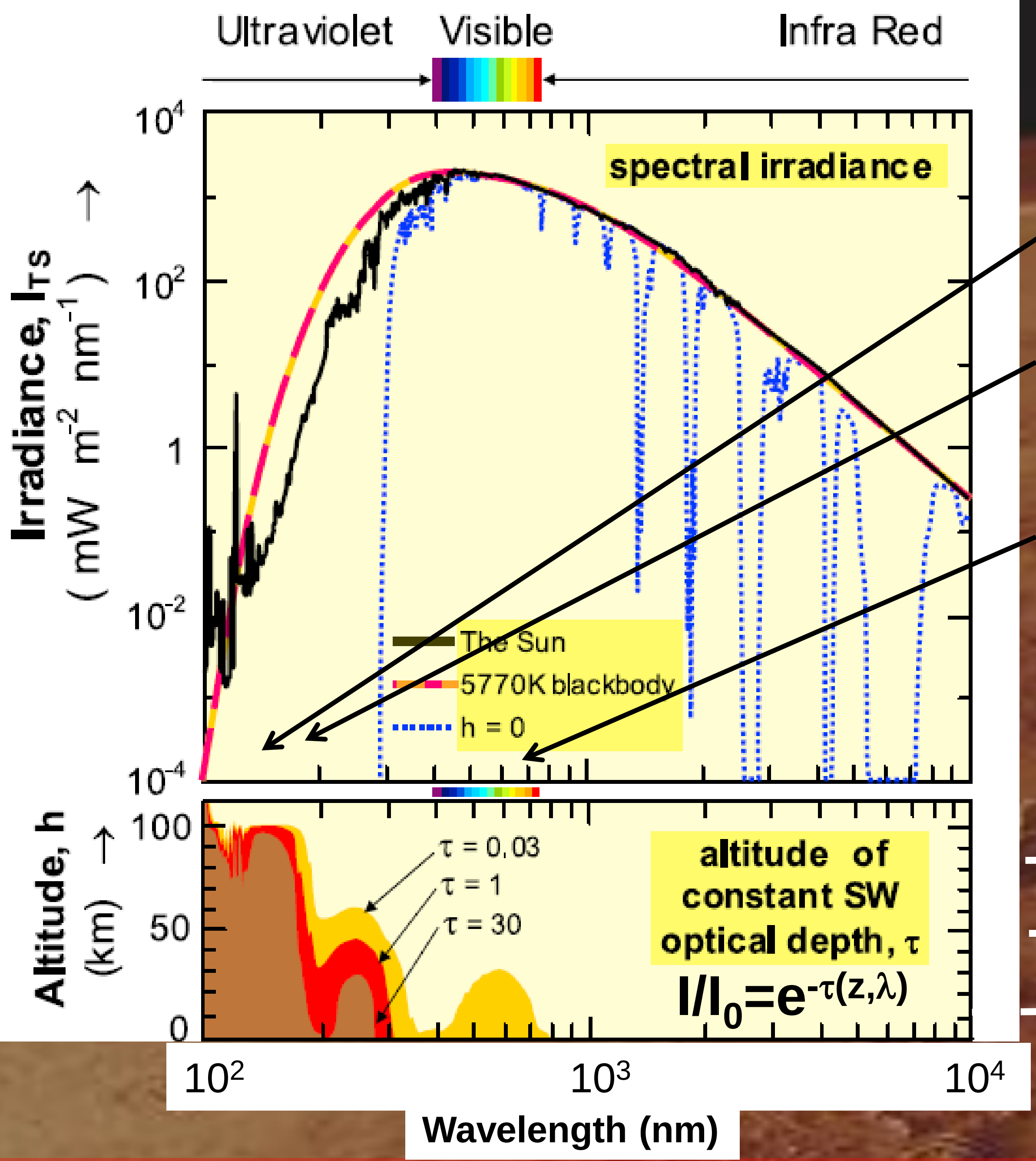
What possible past escape?

And what about extra-solar system?

Our Sun

A source of
photons
and
particles

EIT/SOHO



Ionization

Photo-chemistry
Airgow

Heat the atmosphere

Exosphere ↑

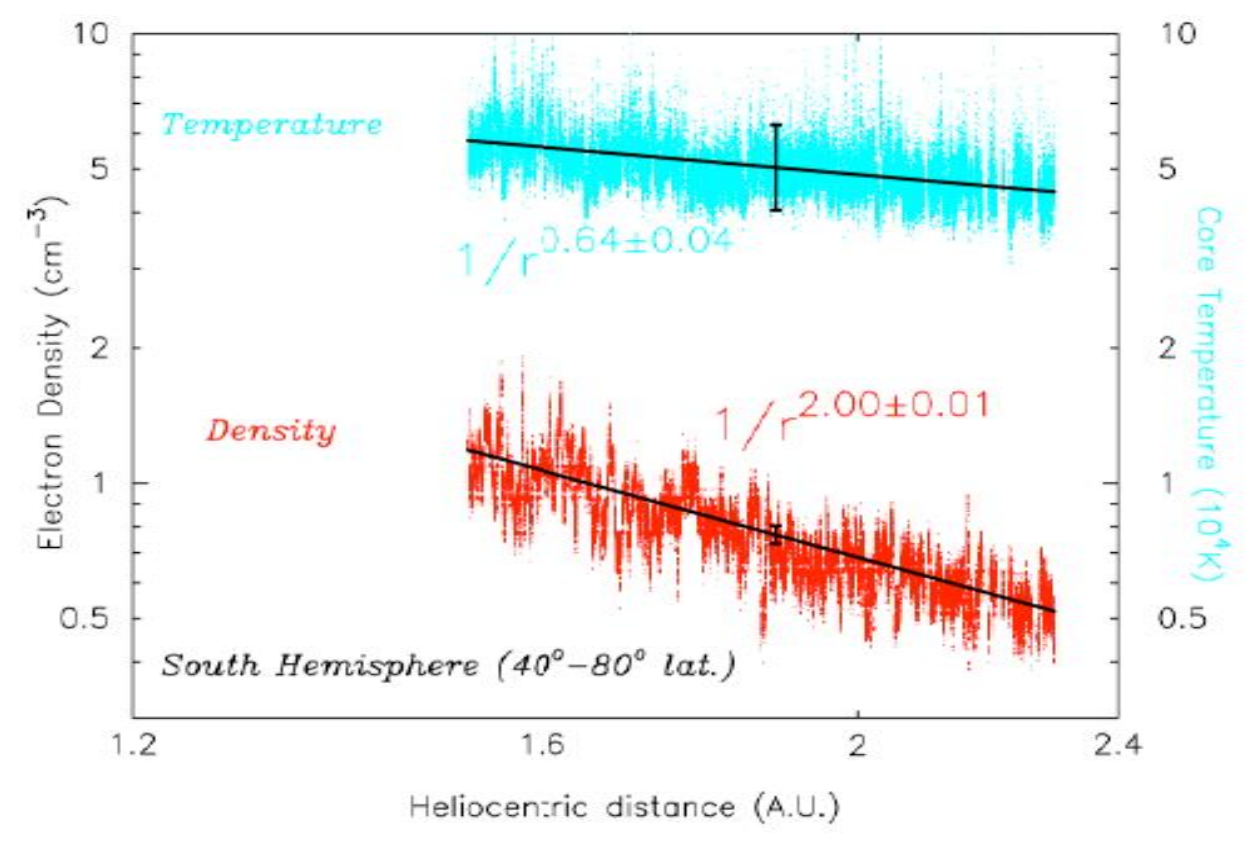
Thermosphere/Ionosphere

Mesosphere

Stratosphere

Troposphere

The Solar Wind: a supersonic coronal magnetized flow of e^-, p, He^{++} and minor heavy ions



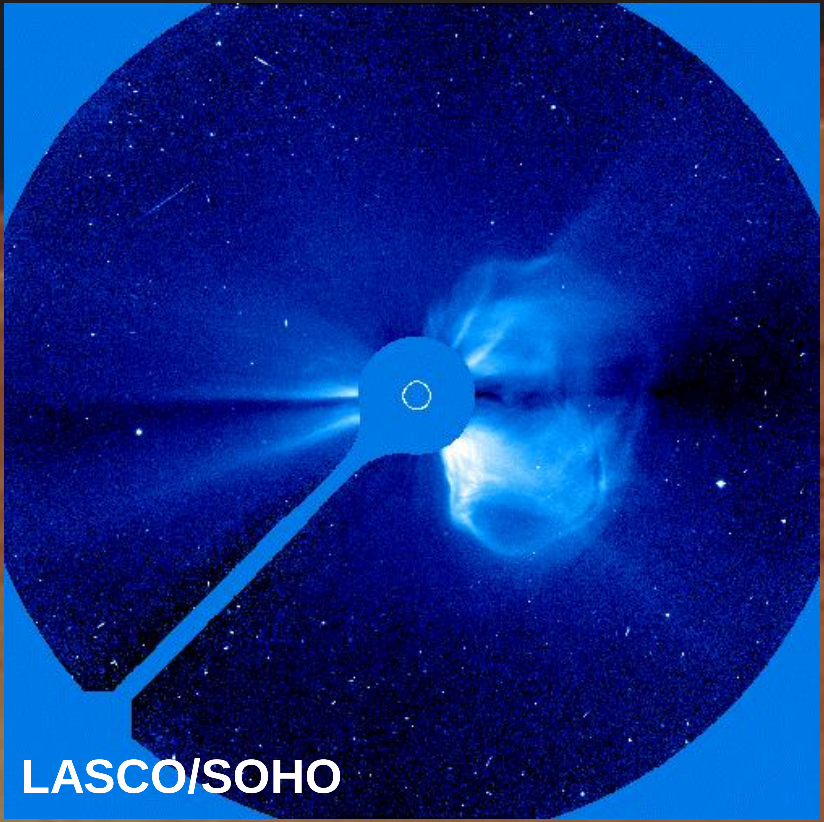
Issautier et al. (1998)

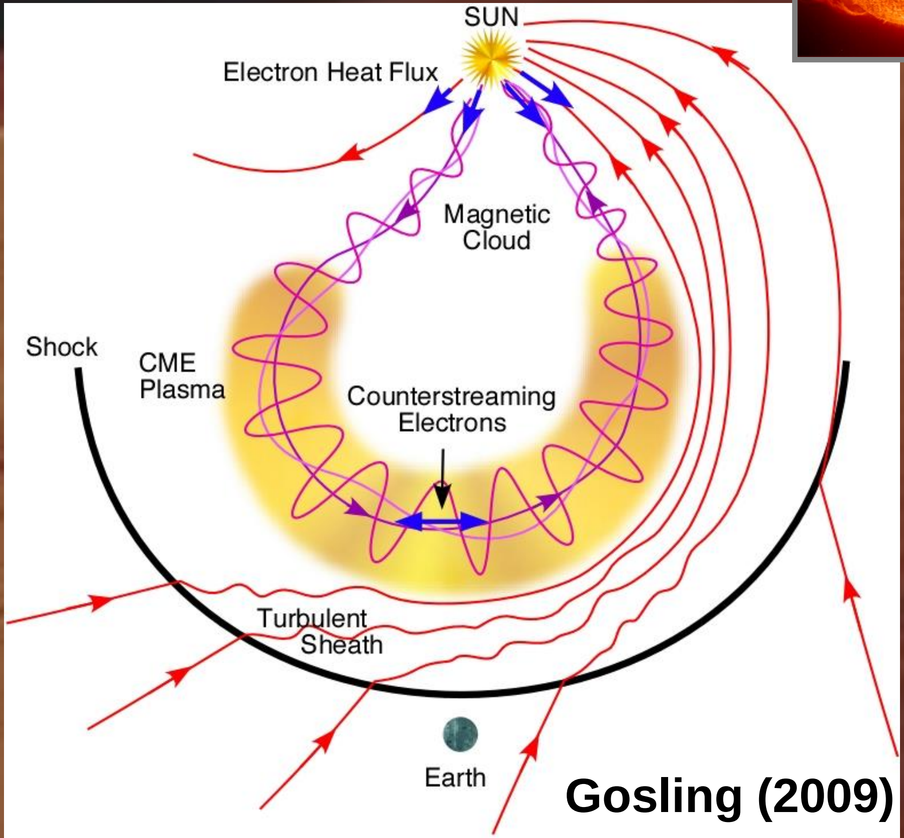
$$n(r_{hel}) = n_{1AU} \times (1/r_{hel})^2$$

with

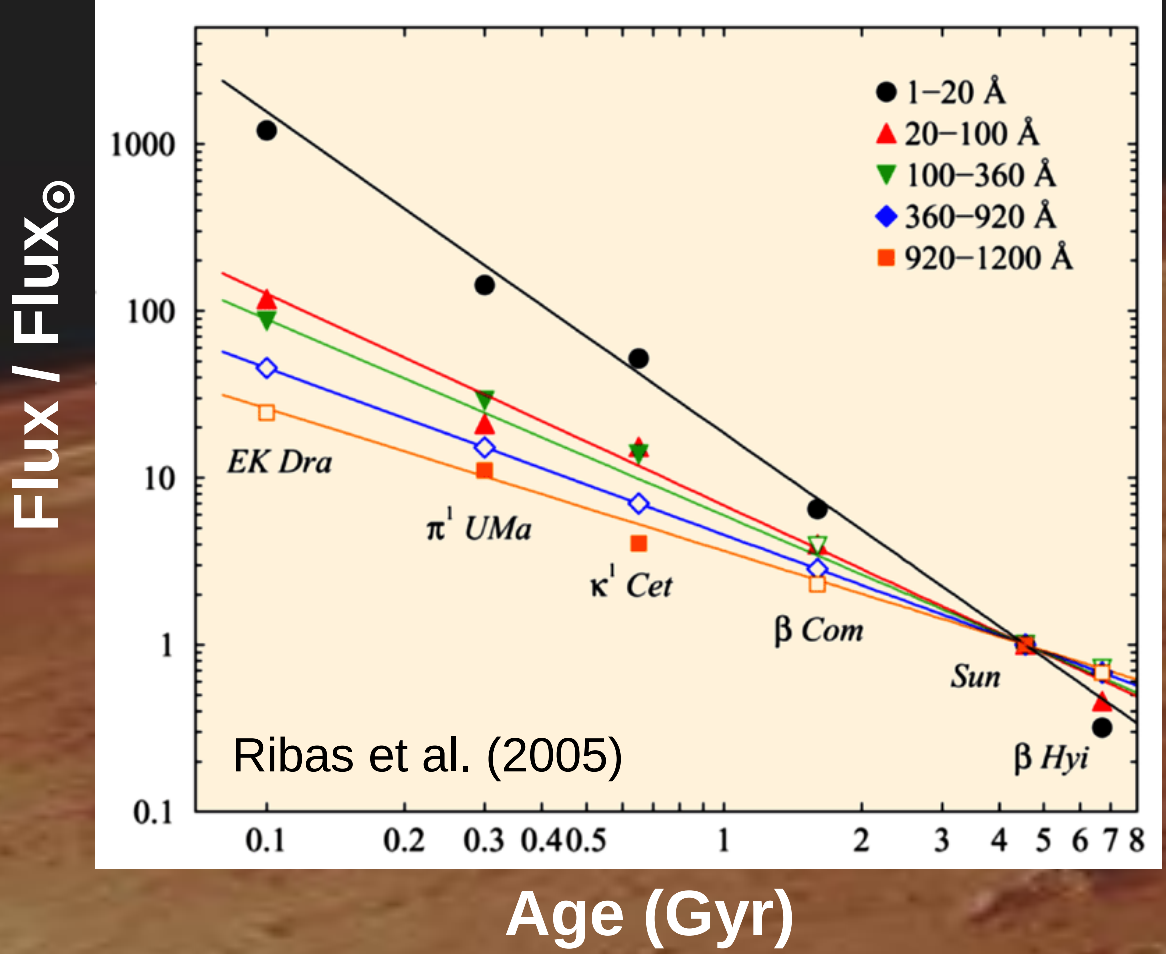
$$n_{1AU} = 8.7\ \mathrm{cm}^{-3}$$
$$V_{1AU} = 468\ \mathrm{km/s}$$
$$T_{1AU} = 1.2 \times 10^5\ \mathrm{K}$$

Coronal Mass Ejections





Increase of density, of B_{IMF}, He^{++} abundance
V_{CME} between 300 and 2000 km/s
Rotation of B_{IMF} orientation

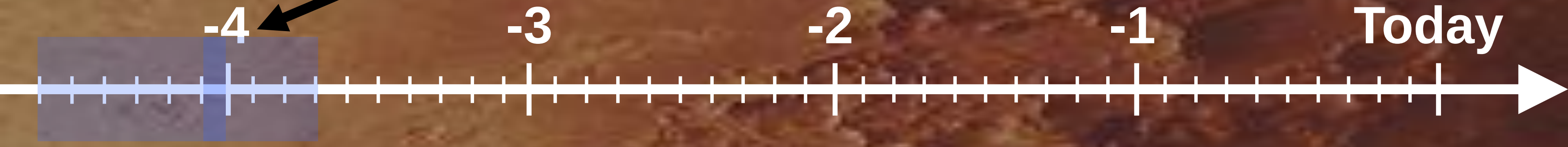


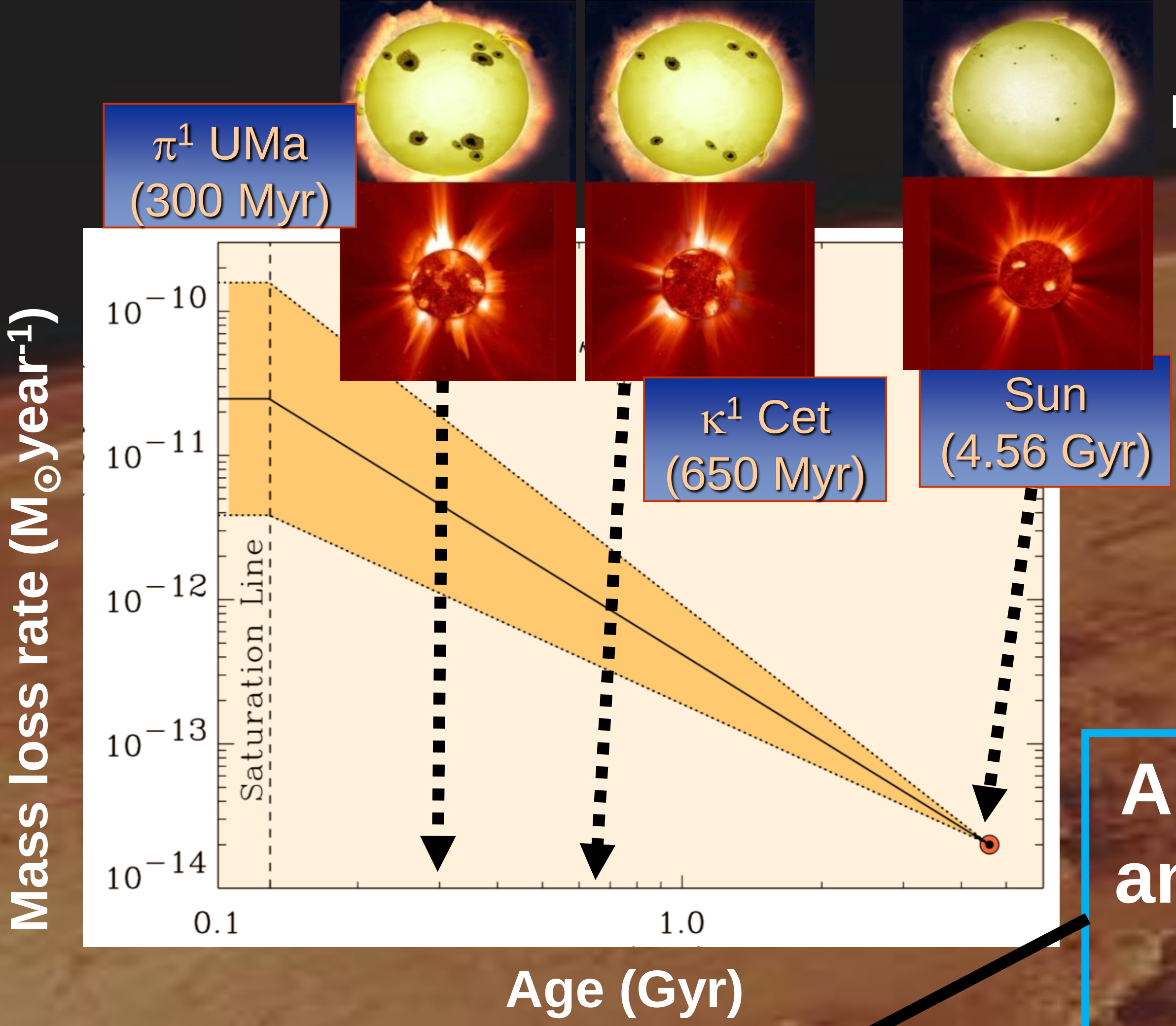
Ribas et al. (2005)

Young SUN: 30% less radiating than today

BUT

EUV/UV flux ~ 30 times higher

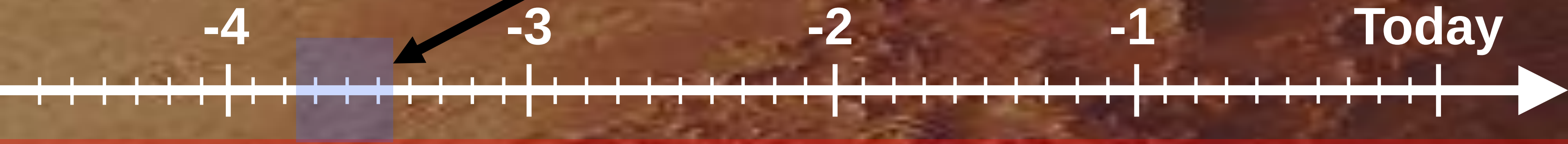




Ribas et al. (2005)

**Young Sun:
A much larger
loss rate and a
more active Sun**

A denser (up to 10 ×) and faster solar wind (up to 2 ×) 3.5 Gyr ago



What signatures of atmospheric escape?

Is there today an atmospheric loss into space?

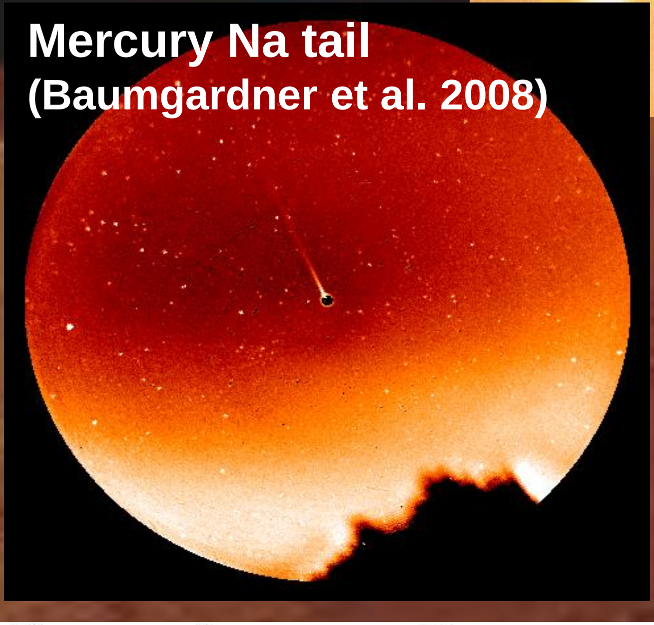
The Earth: in 3 billions years 2% of the present-day atmospheric oxygen would be lost.

Mars: few % of Mars atmosphere would be lost in 3 billions years, but may be enough to be a major driver of Mars' present atmosphere.

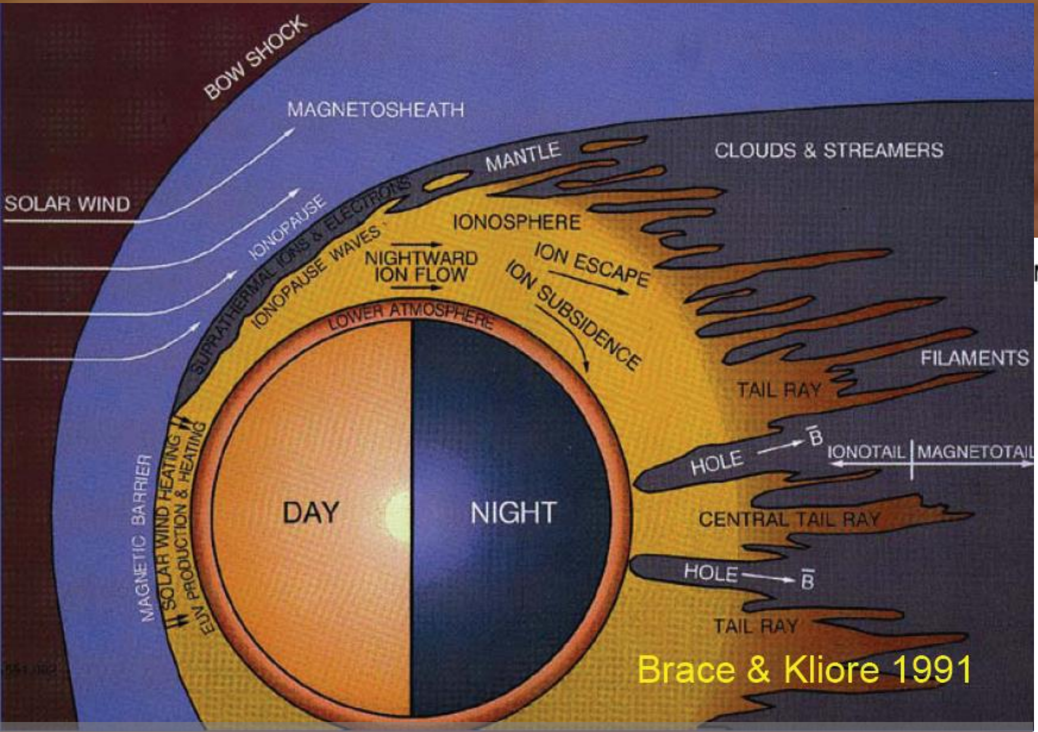
Venus: negligible, essentially light species (H and He).

Several atmospheric pathways

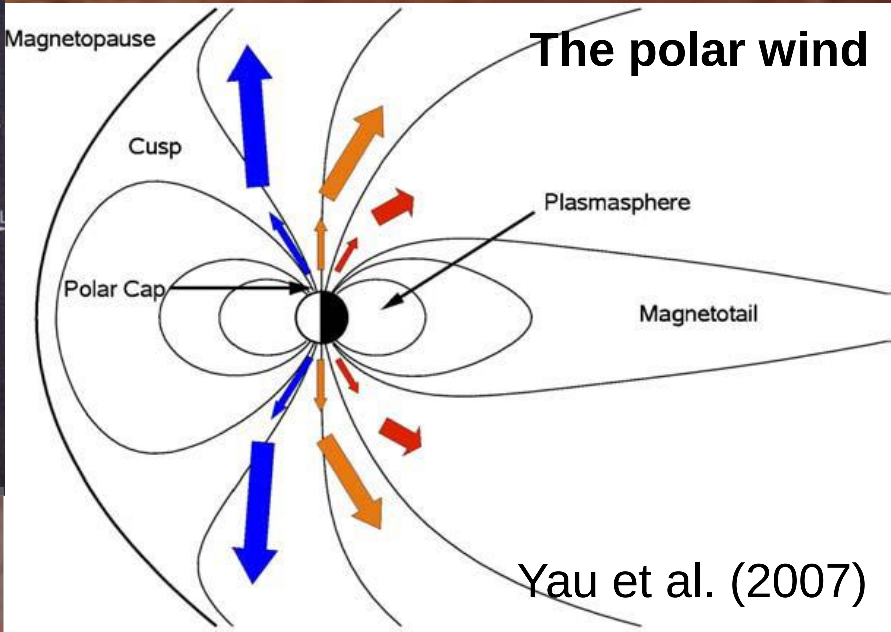
- **Ion escape: solar wind erosion & ionospheric outflow**
- **Thermal & non-thermal neutral escapes**



Mercury Na tail (Baumgardner et al. 2008)



Venus interaction with the Solar wind (Brace and Kliore 1991)



The polar wind

Yau et al. (2007)

Thermal escape flux: density profile

For a species of mass m, velocity u and density n

$m \times du/dt = -\nabla p + F$ with $F = -n \times m \times g \times e_r$

and Perfect gas $p = n \times k_B \times T$

with T atmospheric temperature and k_B Boltzmann Constant

If $g = cte$

$n(r) = n(r_0) \exp[-(r-r_0)/H]$ <u>Barometric law</u>

with $H = k_B T/mg$ scale height

If $g = G M / r^2 \times e_r$

$n(r) = n(r_0) \exp(\lambda(r) - \lambda(r_0))$ with r_0 reference altitude

$\lambda(r) = GMm/(k_B T r) = (V_{es}/V_{th})^2$ escape parameter

$V_{es} = (2 G M / r)^{1/2}$ escape velocity at r

$V_{th} = (2 k_B T / m)^{1/2}$ thermal velocity

$H = R^2 k_B T/(G M m)$ scale height

For $r \rightarrow \infty$, $n(r) \rightarrow ct$ ($\neq 0$) → An infinite extended atmosphere!

Thermal escape flux: notion of exobase

Neutral escape

At high altitude (low pressure), the pressure force doesn’t exert, because of rare collisions

→ hydrostatic law is no more true

Dimensionally, hydrostatic law $dp/dz \approx p/H \approx \rho g$

Effective if the medium is collisional over typical scale H,

→ the mean free path l_{mfp} :

$l_{mfp}(z) = 1/\sqrt{2}\, n(z)\, \sigma$ (σ : collision cross-section) << H

The altitude r_{ex} where $l(r_{ex}) \approx H$ is named the exobase.

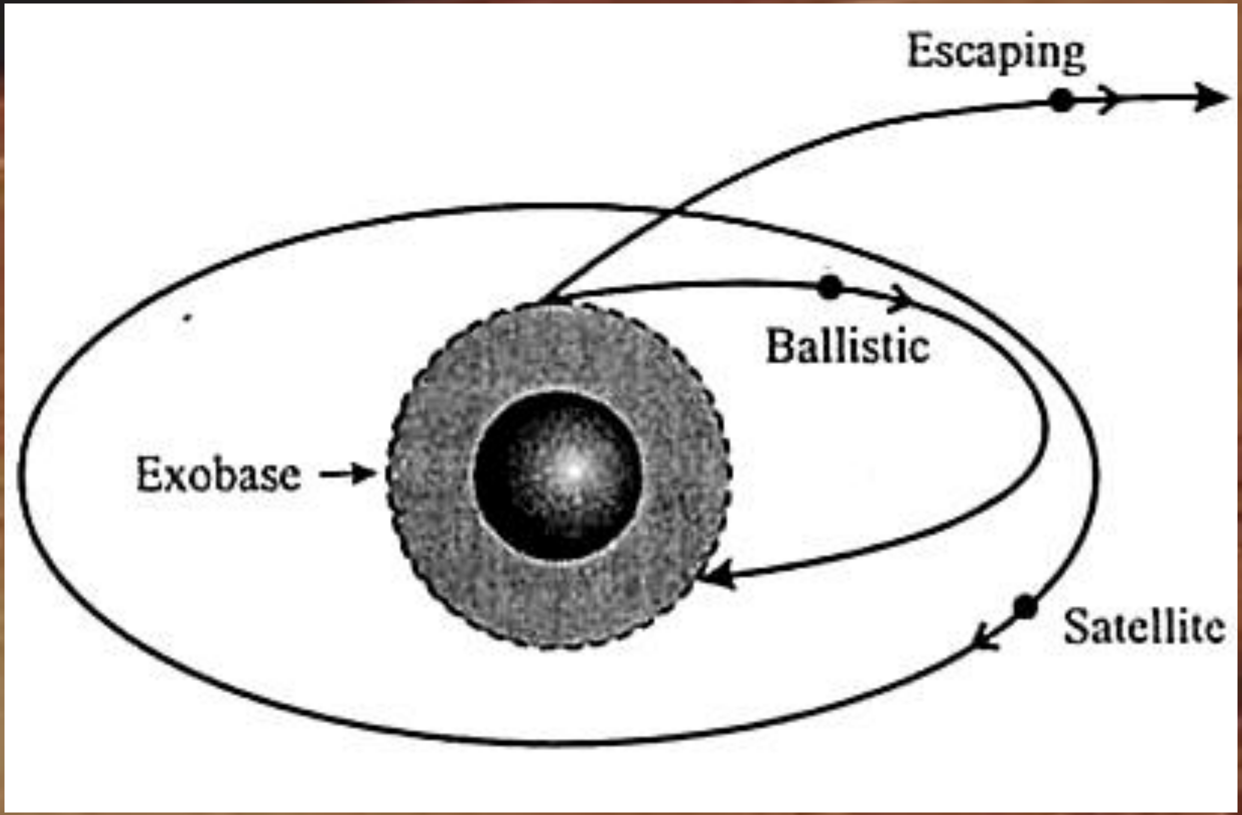
(altitude at which a particle has the probability to escape equal to 1/e)

≈500 km on Earth, ≈250 km on Mars, ≈1500 km on Titan.

Typically $n_{ex} = 10^7\text{-}10^8$ cm^{-3} ; $P_{ex} \sim 10^{-7}$ Pa

Thermal escape flux
Exospheric populations

Neutral escape



3 types of populations above the exobase level :

Ballistic trajectories

Satellite trajectories

Escaping trajectories

Theory elaborated by Chamberlain (1963)

Thermal escape flux
Chamberlain's kinetic theory

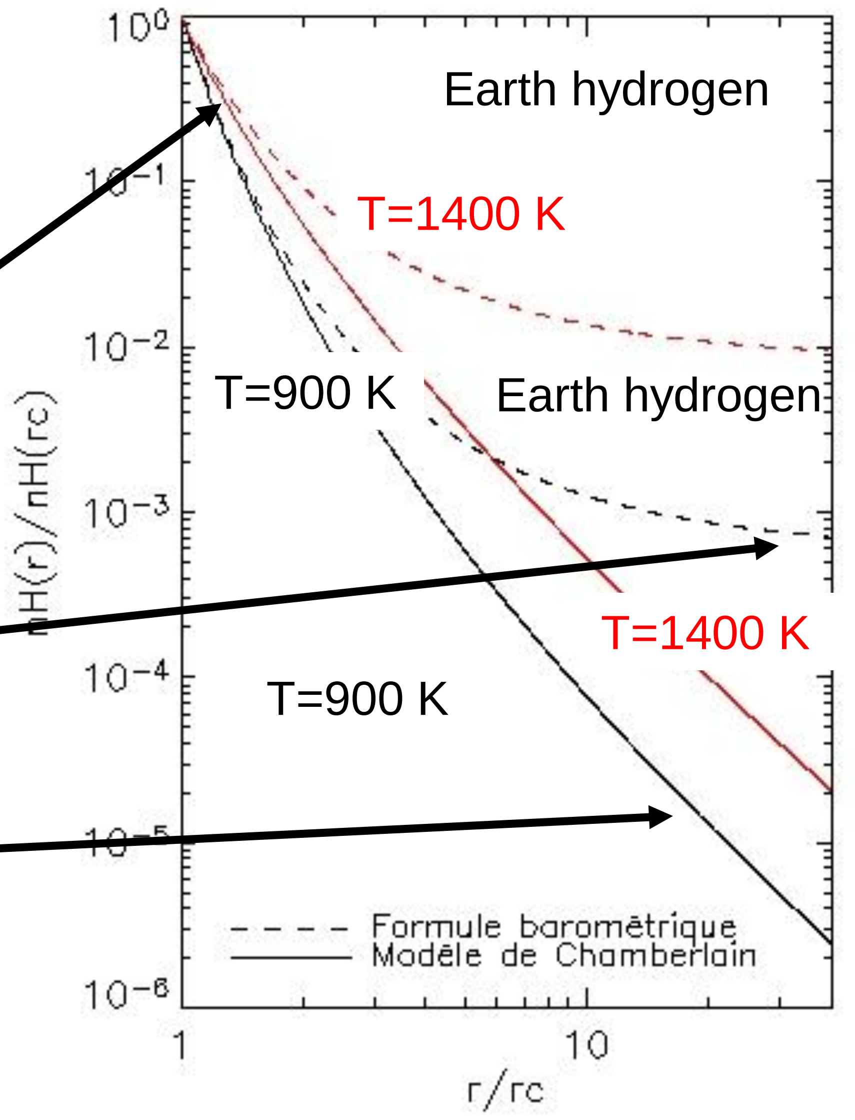
Neutral escape

Use of Liouville's equation (Boltzmann's equation without collisions), applied to the 6-D phase space density $f(q_i,p_i)$.

→ At low altitude, the ballistic particles dominate: both models provide similar results.

→ At high altitude, the Chamberlain model allows the description of the decreasing density whereas the barometric law is not anymore valid.

→ The altitude decrease of the density depends on the temperature



Thermal escape flux

Escape flux F_{esc} at the exobase (r_{ex}, n_{ex}, T_{ex})
= upward flux of particles with $V>V_{esc}$

$$\mathbf{F_{esc} = n_{ex} \times V_{eff}}$$

Where V_{eff} is the effusion velocity

$$\mathbf{V_{eff} \approx V_{th} e^{-\lambda_{ex}}}$$

The escape parameter

and $\lambda_{ex} = (\frac{V_{esc}}{V_{th}})^2$

$\lambda_{ex} >> 1$: $V_{eff} << V_{th}$

Jeans escape : slow depletion of the velocity distribution

$\lambda_{ex} \approx 1$: $V_{eff} \approx V_{th}$

Hydrodynamic escape : global escape of the atmosphere

Requires very high thermospheric temperature

→ very high level of solar UV flux

(only for primitive solar conditions or small gravity fields)

Thermal escape flux

Slow escape of H :

≈ 10^7 cm^{-2} s^{-1} on Earth

≈ 10^8 cm^{-2} s^{-1} on Mars

From Shizgal and Arkos (1996)

Planet	R_{ex} (km)	T_{ex} (K)	λ_{ex} (H)	V_{eff} (H) (cm/s)
Earth	500	1000	7.1	800
Mars	250	300	4.6	340

For atomic deuterium D :

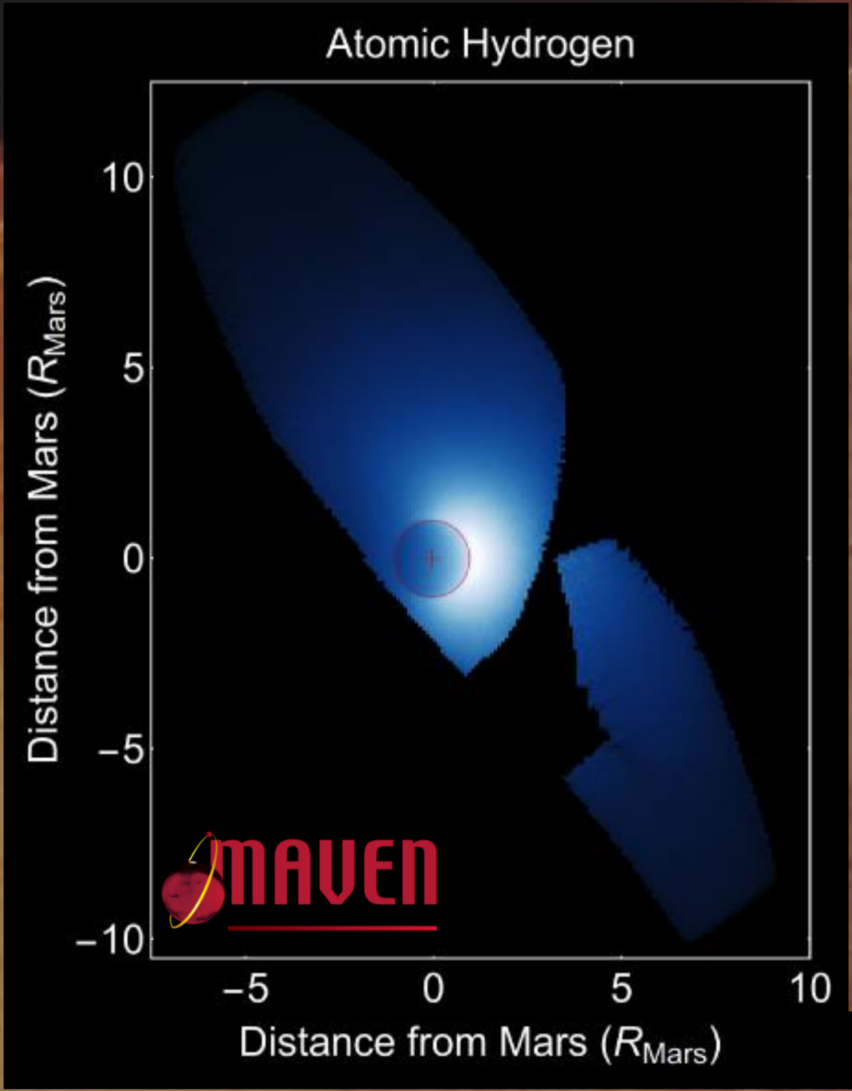
Earth : $\lambda_{ex} = 14.2$ V_{eff} (D) ≈ V_{eff} (H)/1000 ≈ 1 cm/s

Mars : $\lambda_{ex} = 9.2$ V_{eff} (D) ≈ V_{eff} (H)/100 ≈ 3 cm/s

At present, only H significantly escapes by thermal escape

But H can collisionnally drag heavy species for primitive solar conditions (Hunten et al. 1987)

Thermal escape flux at Mars



An extended corona of H atoms surrounding Mars;

Current rate: 1.6 – 11 × 10^{26} H/s

Highly dependent on the exobase conditions

Highly dependent on the low atmospheric conditions (amount of water), in particular during dust storms (Chaffin et al. 2017)

Chaffin et al. (2015)

An asymptotic case of thermal escape

Neutral escape

- **Assuming a progressive increase of solar EUV flux from present conditions (1 EUV) to 10 times the present EUV flux (~4 Gyr ago) :**
  - **High atmosphere temperature increases,**
  - **Exobase progressively climbs up,**
  - **At a certain point, there is no more static solution, $z_{ex} \rightarrow \infty$,**
  - **There is no more way to convert solar EUV energy in thermal energy : the excess thermal energy is directly converted to kinetic energy and hydrodynamic escape occurs.**

→ Jeans escape: when only a very small fraction of atoms escape from the energetic wing of the Maxwellian.

→ Hydrodynamic escape: a rapid depletion of the full Maxwellian, which cannot be re-populated on short enough time-scales.

Loss of heavy species by hydrodynamic escape

Neutral escape

- An heavy constituent [2] (mass m_2, mixing ratio X_2) can be dragged off along by a light escaping constituent [1], (m_1, X_1) according to :

$$F_2 = X_2/X_1\ F_1\ (m_c\text{-}m_2)/(m_c\text{-}m_1)$$ (Hunten et al, 1987)

where F_i are the fluxes,

$m_c=m_1+(kTF_1/bgX_1)$ “crossover mass” (b = product of density by diffusion coefficient of [2] in [1]).

- If $m_2 < m_c$, [2] can escape with [1] ($F_2 \alpha\ m_c - m_2$)
- Assuming that all the EUV flux is consumed in escape, the crossover mass is 1.5 amu for Earth, 5 amu for Mars for present solar conditions.

⇒Not an efficient mechanism to deplete atmosphere from their heavy component during the last 3 to 4 Gyr

Non-thermal escape: Photo-chemical

Neutral escape

Dissociative recombination : $AB^+ + e \rightarrow AB^* \rightarrow A^* + B + \Delta E$

Mars and Venus

$N_2^+ + e \rightarrow N + N$ ΔE =1.06, 2.44 et 3.44 eV

$O_2^+ + e \rightarrow O + O$ ΔE = 0.8 à 6.99 eV

$CO^+ + e \rightarrow C + O$ ΔE = 0.94, 1.64 et 2.90 eV

$CO_2^+ + e \rightarrow CO + O$ ΔE = 8.3 eV

- Efficient at Mars:

  $E_{esc}(^{16}O) = 2eV$ $E_{esc}(^{14}N) = 1.7eV$ eV $E_{esc}(^{12}C) = 1.6eV$

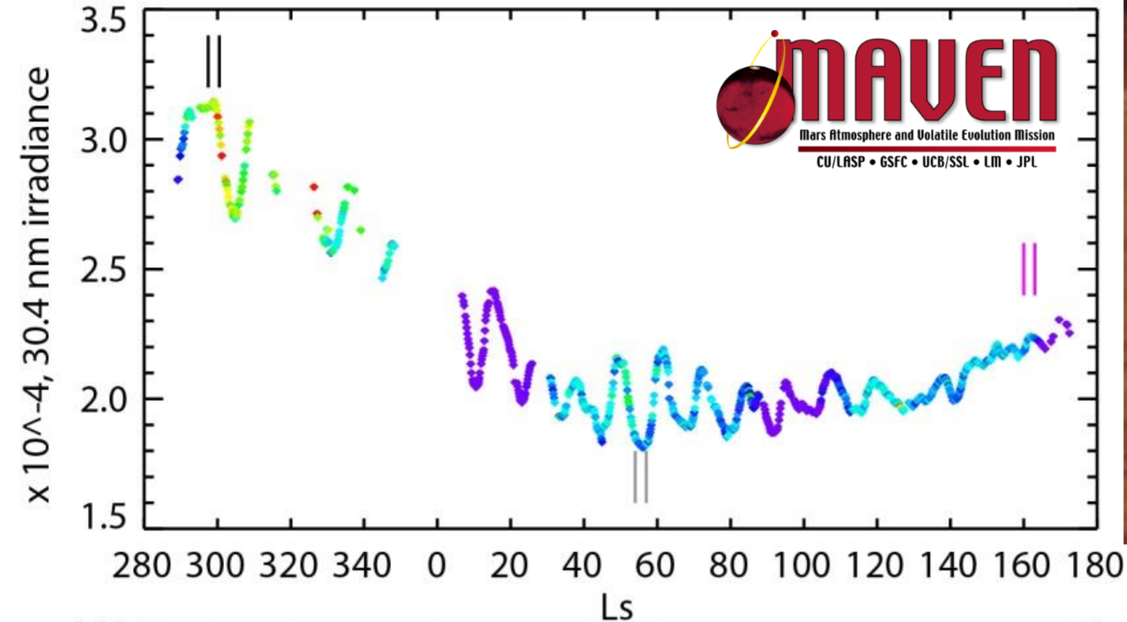
- Not efficient at Earth:

  $E_{esc}(^{16}O) = 9.6eV$ $E_{esc}(^{14}N) = 8.7eV$ $E_{esc}(^{12}C) = 7.5eV$

- Nor at Venus…

Non-thermal escape: Photo-chemical

Neutral escape



Derived dissociative recombination escape flux; it varies through mission due to changing orbital geometry, EUV flux, compositional variations

Lillis et al. (2017)

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

with ~74 % of O* having sufficient kinetic energy to escape

Dissociative recombination and loss rates derived orbit-by-orbit from MAVEN measurements of ionospheric ions, electrons, e^- temperatures; best estimates of cross sections

- Current escape rate: 5×10^{25} O/s

Non-thermal escape: Ion picked up loss

Ion escape

Main processes of ionization:

- Photo-ionization

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

- Ionization by electronic impact

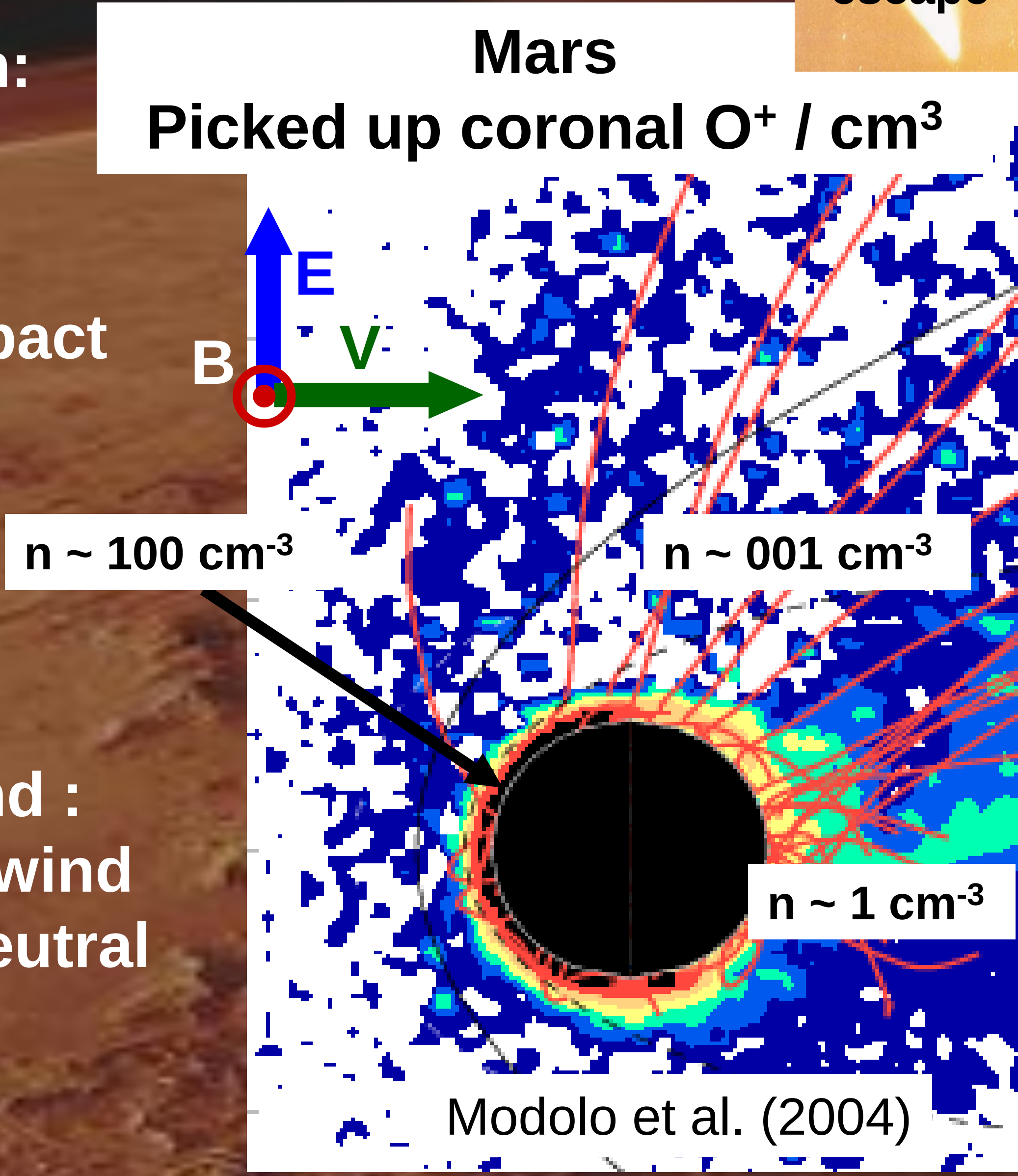
  $X + e^- \rightarrow X^+ + 2e^-$

- Charge exchange

  $M^+ + X \rightarrow M + X^+$

Production of picked up ion accelerated by the Solar Wind :

- ➢ Mass loading of the solar wind
- ➢ Production of energetic neutral
  - $\Rightarrow$Sputtering
- ➢Atmospheric loss

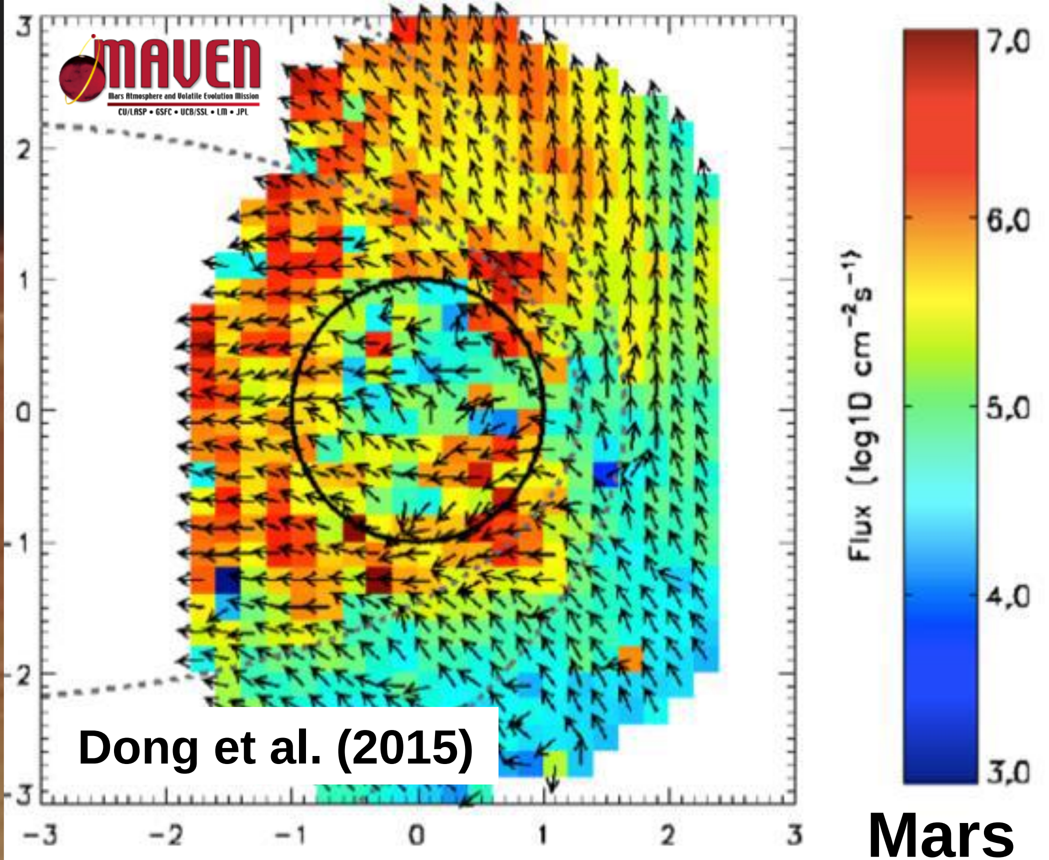


Mars

Picked up coronal O^+ / cm^3

Modolo et al. (2004)

Non-thermal escape: Ionospheric loss



Dong et al. (2015)

- At Mars, the solar wind is observed deep in the atmosphere (Lundin et al. 2004)
- In the tail, a large component is ionospheric plasma:

$CO_2^+/O^+ = 0.14$

$O_2^+/O^+ = 2.3$

(Inui et al. 2018; 2019)

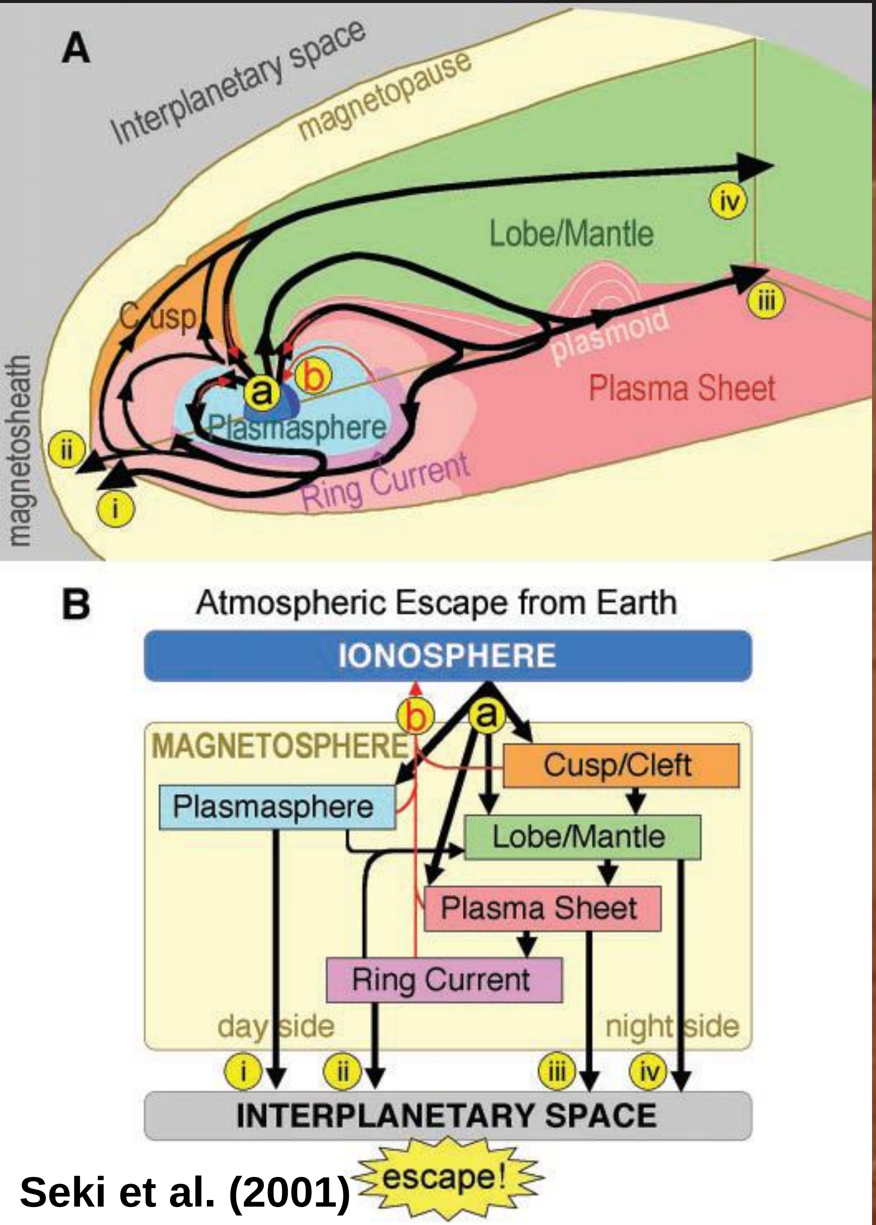
Ions are stripped away from the upper atmosphere by the Solar Wind

Mean Mars loss rate = 5×10^{24} O^+/s (Jakosky et al. 2018)

Mean Venus loss rate = 0.2 - 1×10^{25} O^+/s (Dubinin et al. 2011)

Non-thermal escape: Ionospheric loss at the Earth

Ion escape



Seki et al. (2001)

- Polar outflow of O^+ ions

= loss of 18% of the present atmospheric O over 3 Gyr

- Four escape routes observed with high-altitude spacecraft: Total oxygen loss rate ~ one order of magnitude smaller

⇒ A substantial return flux from the magnetosphere to the low-latitude ionosphere.

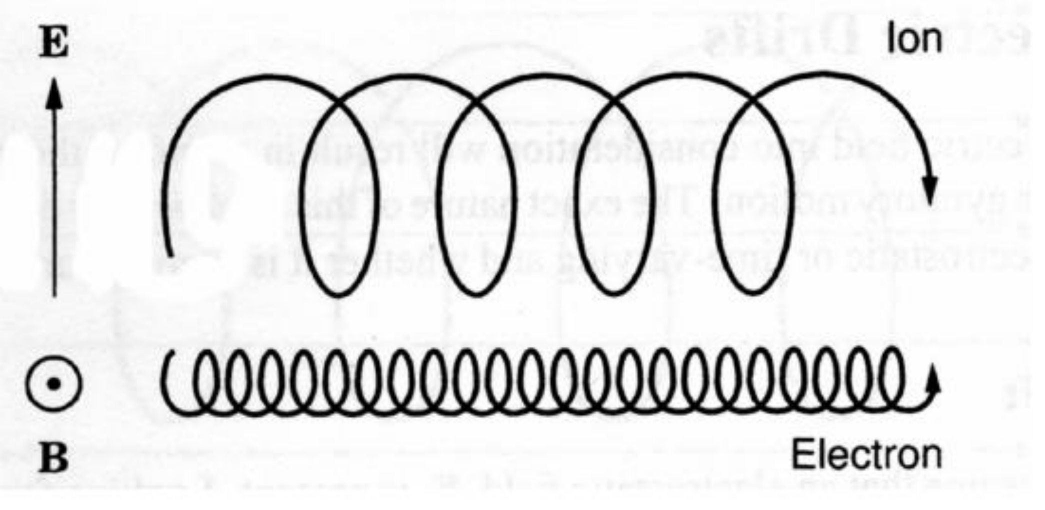
⇒ Net oxygen loss over 3 Gyr ~2% of the current atmospheric oxygen content.

Non-thermal escape:
Sputtering by planetary picked up ions

Lorentz Force: $F = \frac{q}{m}(V - V_{SW}) \times B_{SW}$

Gyroperiod: $\Omega = \frac{m}{qB_{SW}}$ ⇒ $\Omega = 1 - 10$ s

Gyroradius : $R = \frac{2\pi V}{\Omega}$ ⇒ $R(H^+) = 2\ R_M$ $R(O^+) \sim R_M$

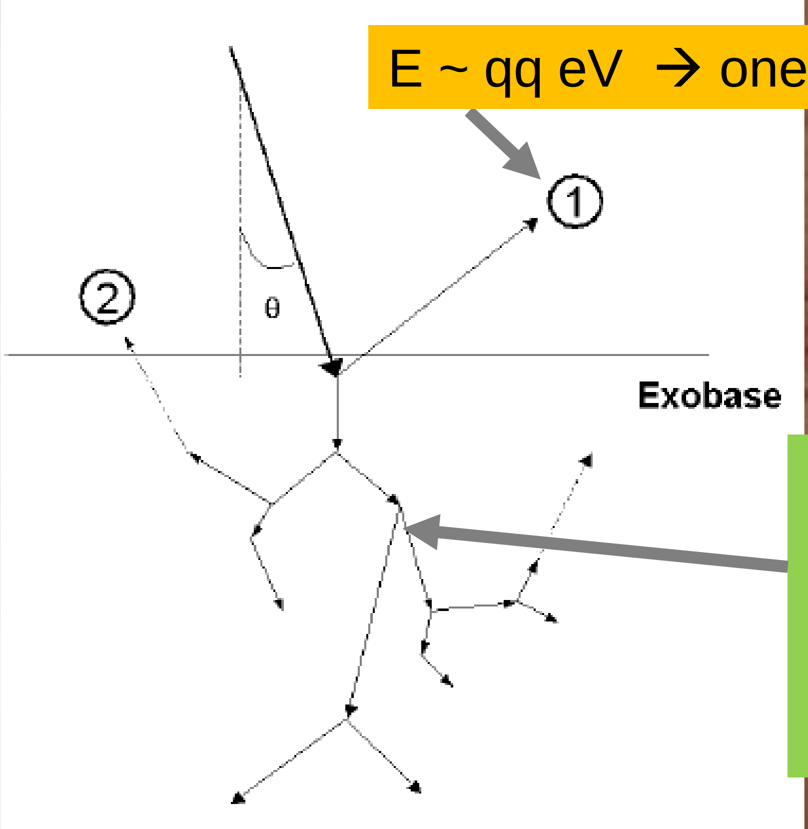


⇒ Some of the picked up ions reimpact and sputter the atmosphere

Non-thermal escape:
Sputtering by planetary picked up ions

Neutral escape

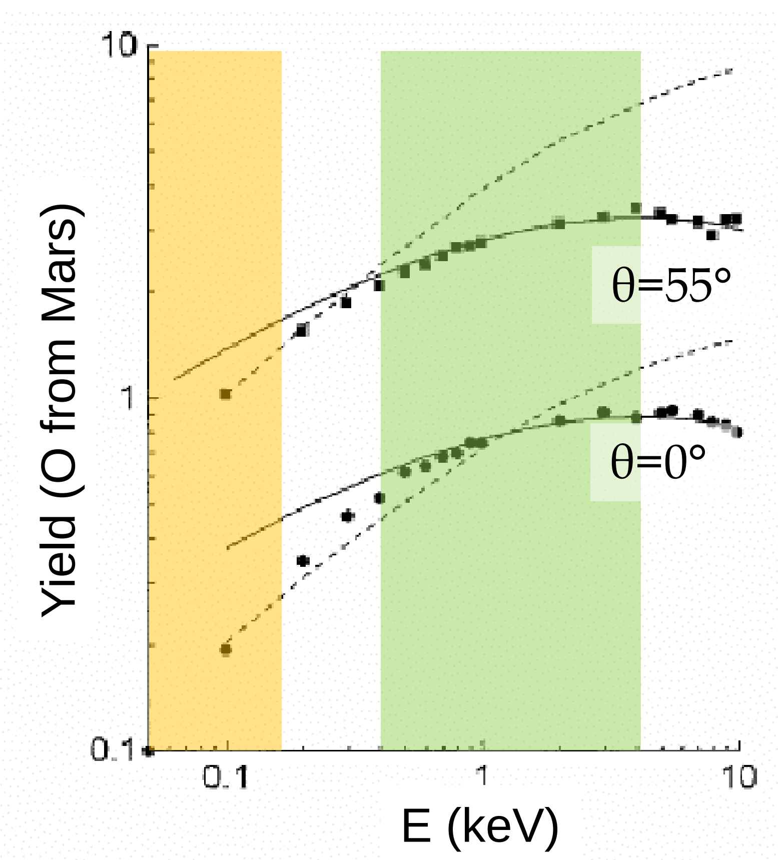
$Y(E,\theta) = \Phi_{ejecta}/\Phi_{incident}$ **Sputtering efficiency/Yield**



E ~ qq eV → one single collision Y < 0.1

E~ 1keV
→
collisionnal
cascade
Y > 1

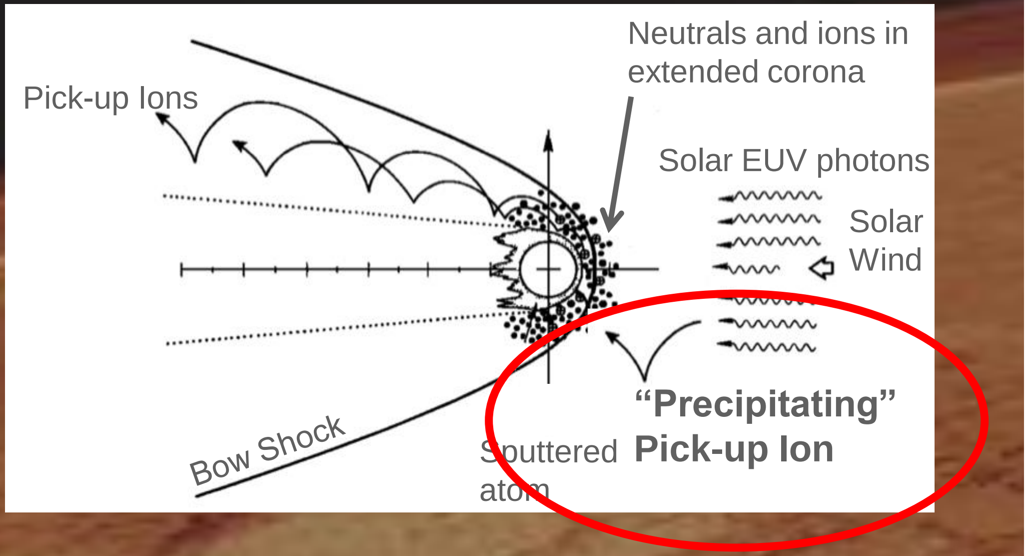
Johnson et al. (2000)

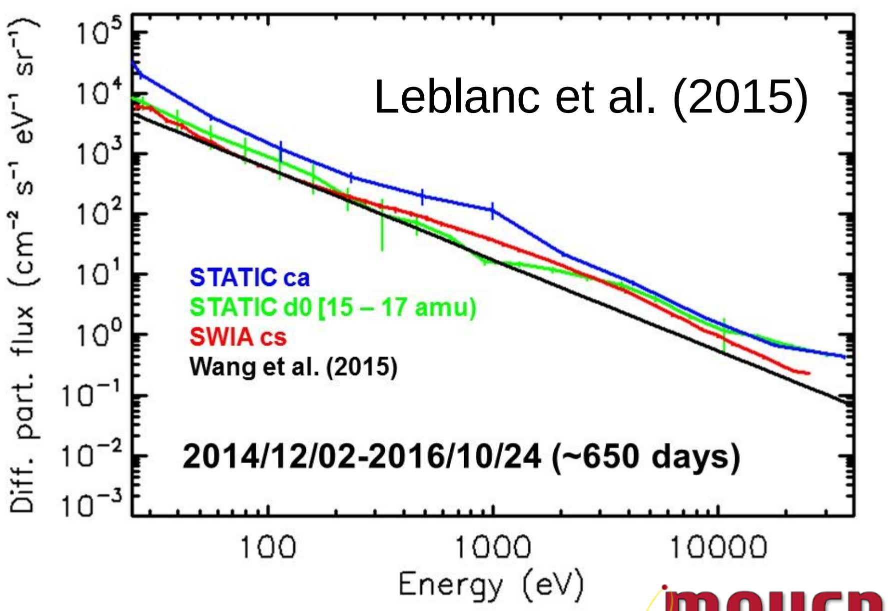


Efficiency increases with increasing grazing incidence

Non-thermal escape: Sputtering by planetary picked up ions / Mars

Neutral escape



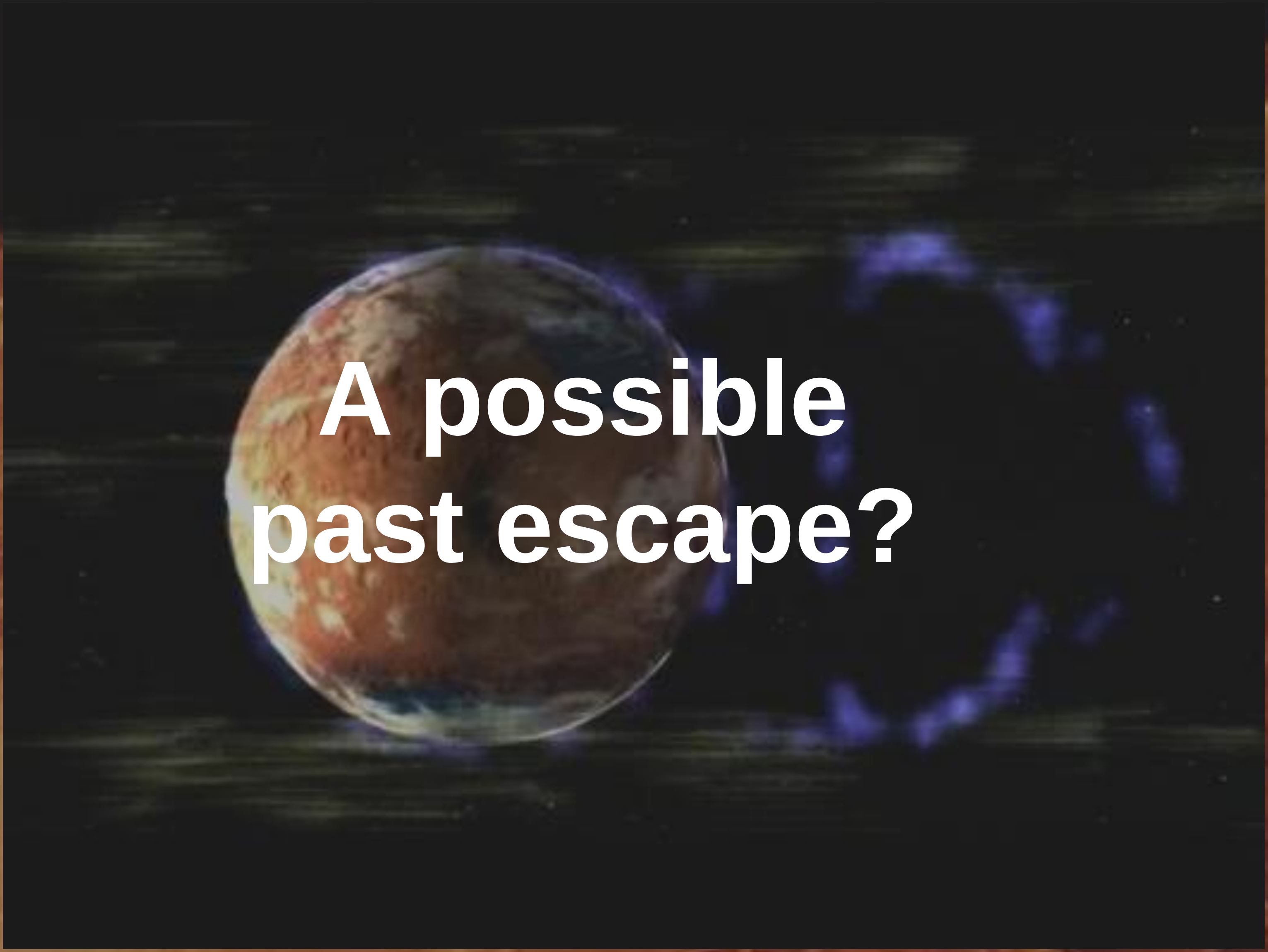


First measurement of the precipitating planetary picked-up ions

Sputtered escape atmospheric rate ~ ion escape rate :

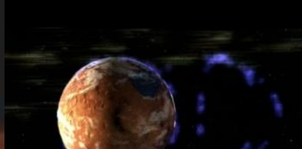
2.7×10^{23} O/s, 3.8×10^{22} CO/s, 2.3×10^{23} CO_2/s, 7.5×10^{22} C/s, 2.8×10^{23} N_2/s, 2.4×10^{23} N/s and 4.9×10^{22} Ar/s

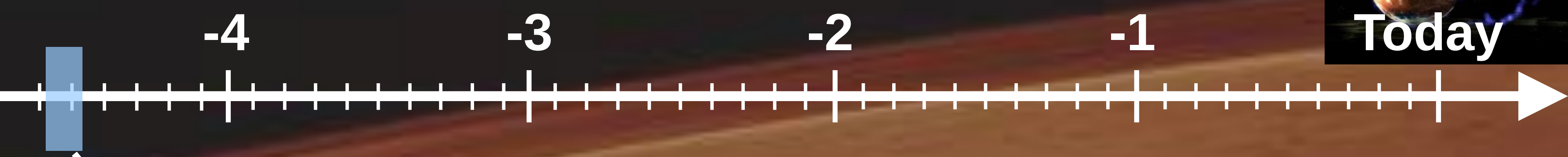
Leblanc et al. (2019)



A possible past escape?

When did the atmospheres form?





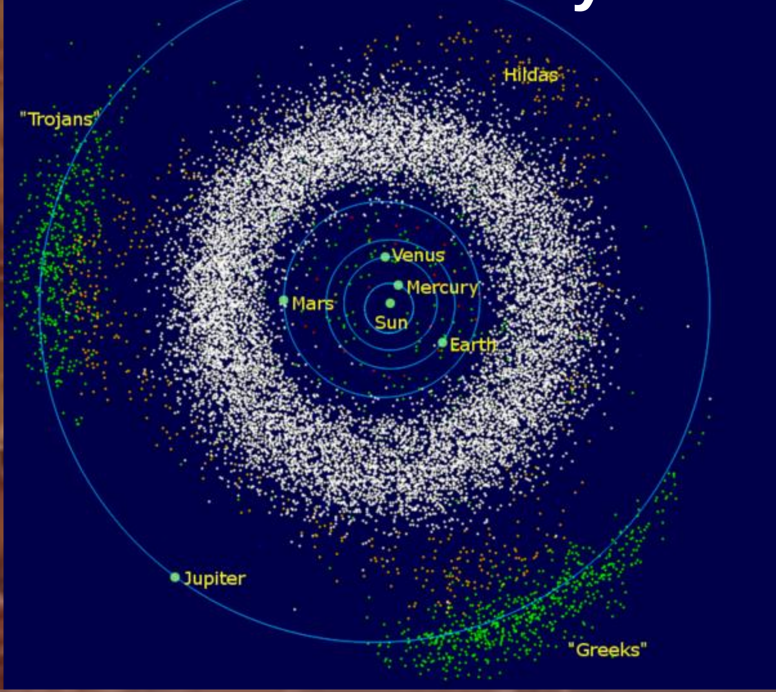
-4.5 billions years: planets and atmospheres are formed

Original disk well mixed over 10 AU

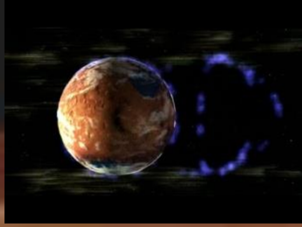
Increase of water content with distance to the Sun

First trace of life on Earth: -3.8 Gyr

Inner solar system



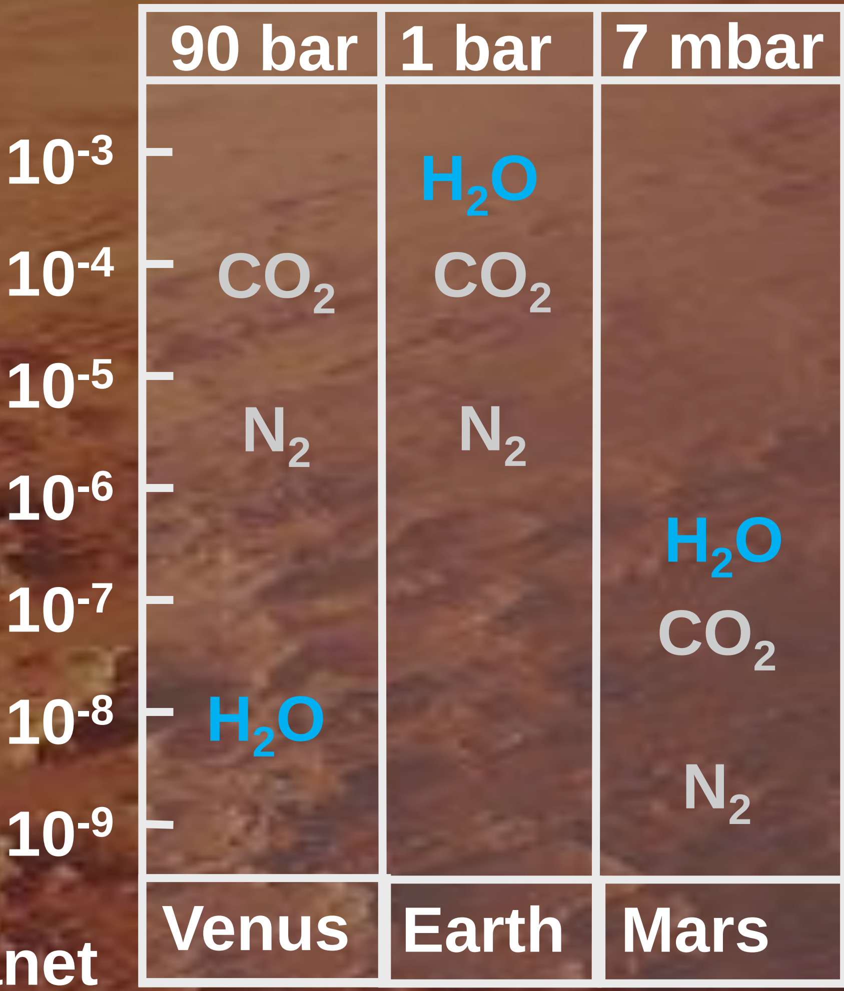
⇒ Same amount of water accreted by Mars, Earth and Venus



Therefore, why Mars, Venus and the Earth are so different today?

No more H_2O
on Mars and Venus

Mars CO_2 and N_2
depleted by a factor 3000
with respect to the Earth and
Venus (but difficult to
estimate…)

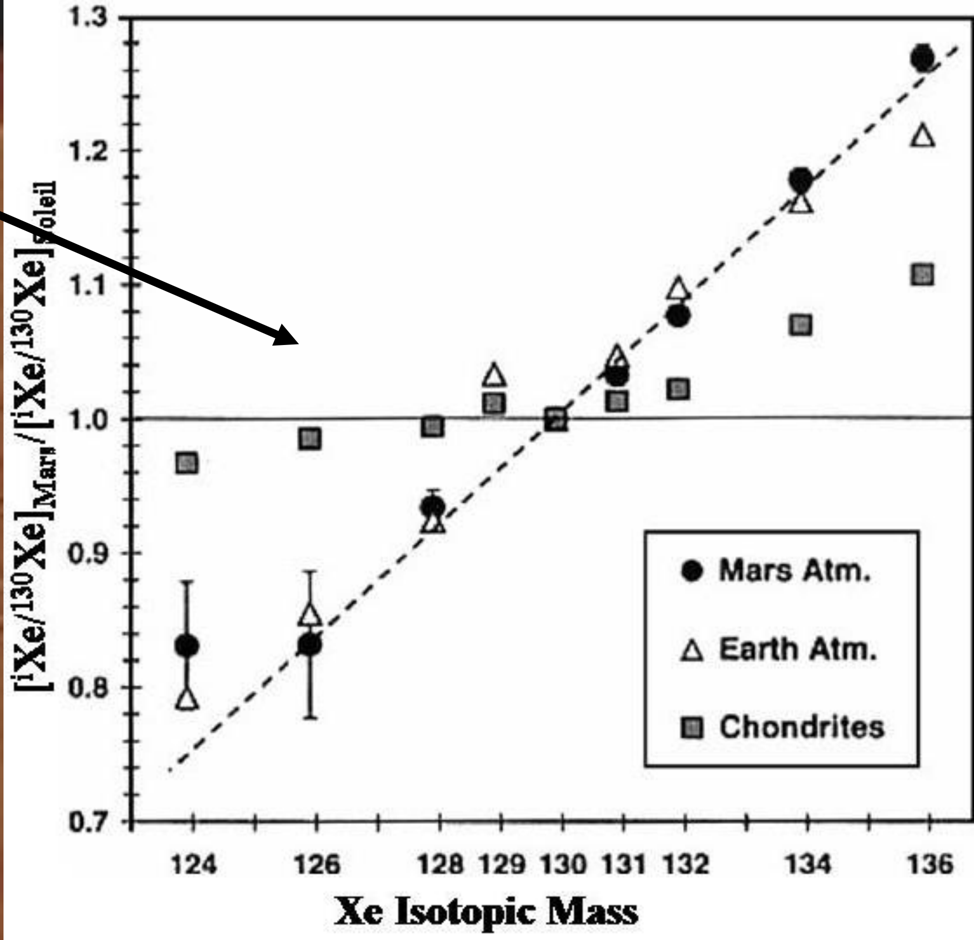


Mass fraction with respect to planet

Past atmospheric escapes at the Earth and Venus

The Earth:

Xenon is fractionated



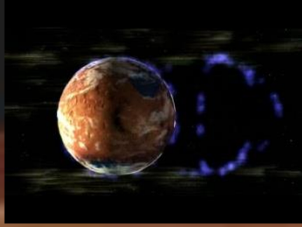
Venus:

D/H at Venus
=
100 D/H at Earth
(De Bergh et al. 1991)

⇒ hydrodynamic escape?

- Venus present content of water ~0.0014% Earth (Kasking and Pollack 1993) ⇒ Where is Venus oxygen (~2×10^{23} g of water disappeared)? oxydation of the soil or escape to space?

Mars isotopic evidence for an escape?

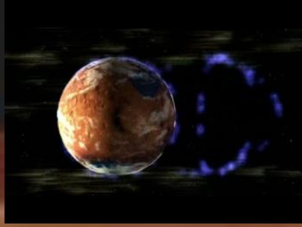


- Argon :
  - Mars : Escape of most ^{36}Ar before ^{40}Ar outgassing (≈ 1 Gyr)
  - Venus : More solar-like (high) ^{36}Ar + no outgassing > 300 Myr (low ^{40}Ar)
- D/H:
  - Mars : fractionation by escape.
  - Venus : supply of (deuterium enriched) cometary material after rapid ocean escape? No substantial further escape?

Isotopic ratio	Mars	Earth	Venus
δ^{13}C	46±4	-	22
^{14}N/^{15}N	173±9	272	273
δ^{18}O	48±5	-	22
^{36}Ar/^{38}Ar	4.2±0.1	5.3	5.4
^{40}Ar/^{36}Ar	1900±300	296	1.1
δD	4950±1080	-	150000

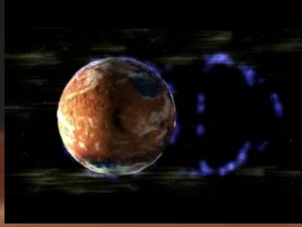
$\delta D = 1000\{[(D/H)_{sample} - (D/H)_{SMOW}]/ (D/H)_{SMOW}\}$ in ‰

SMOW: Standard Mean Ocean Water

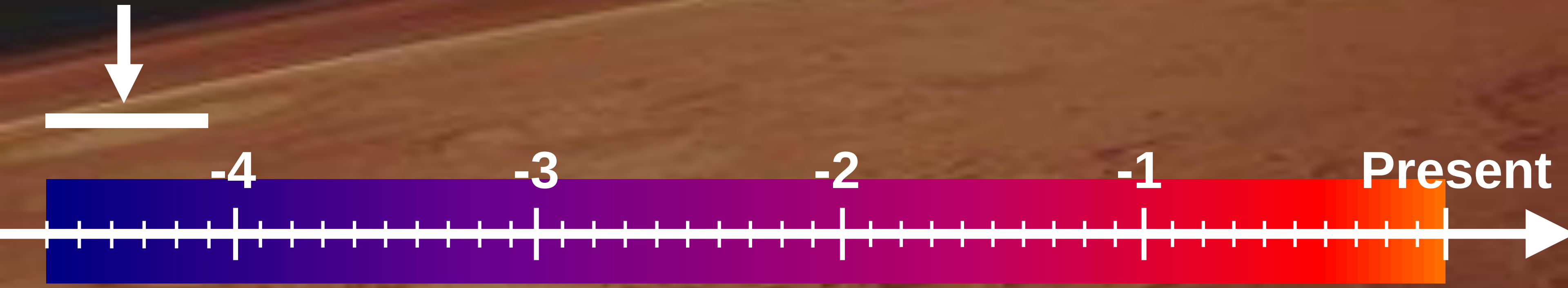


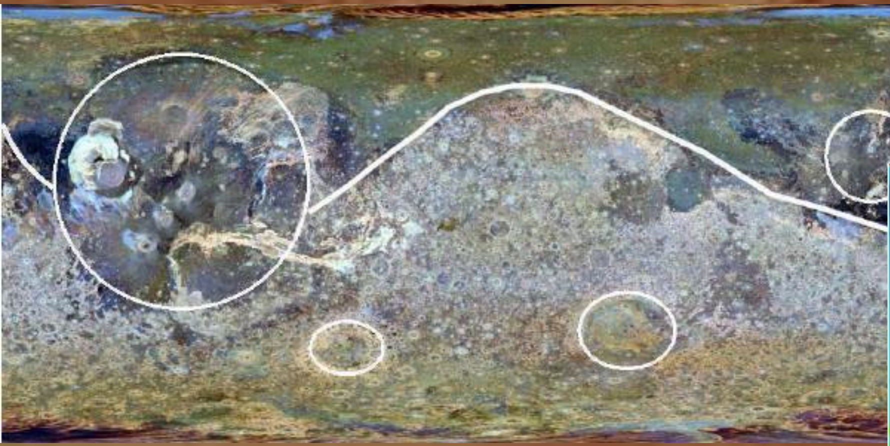
As an example, the possible role of atmospheric escape in Mars' evolution

What do we know on Mars?



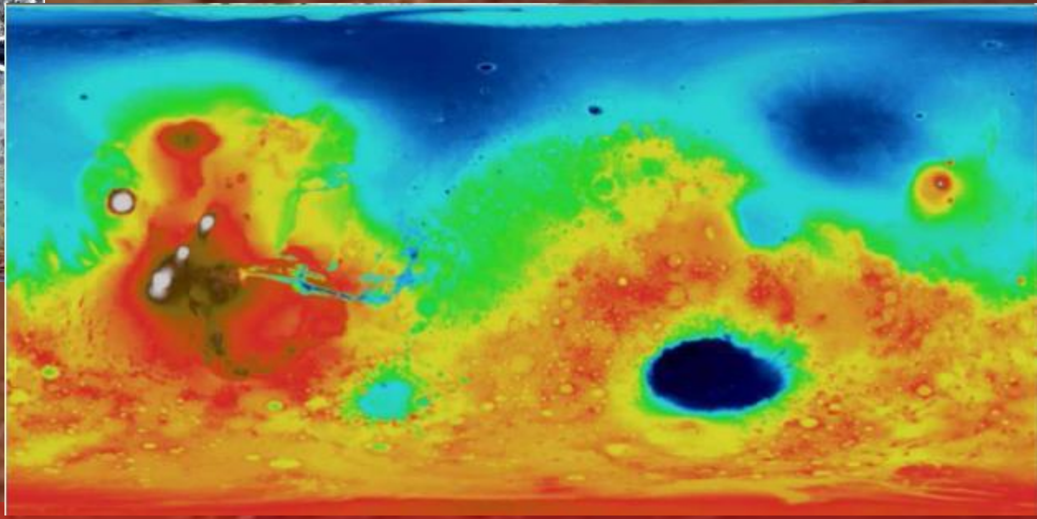
Volcanism & Giant impacts
(origin of the North/South dichotomy)



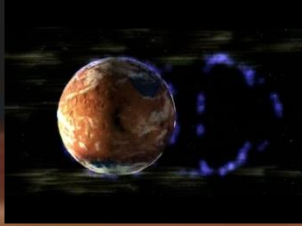


Surface rugosity
(Kreslavsky and Head 2000)

Surface altimetry
(MOLA/MGS)

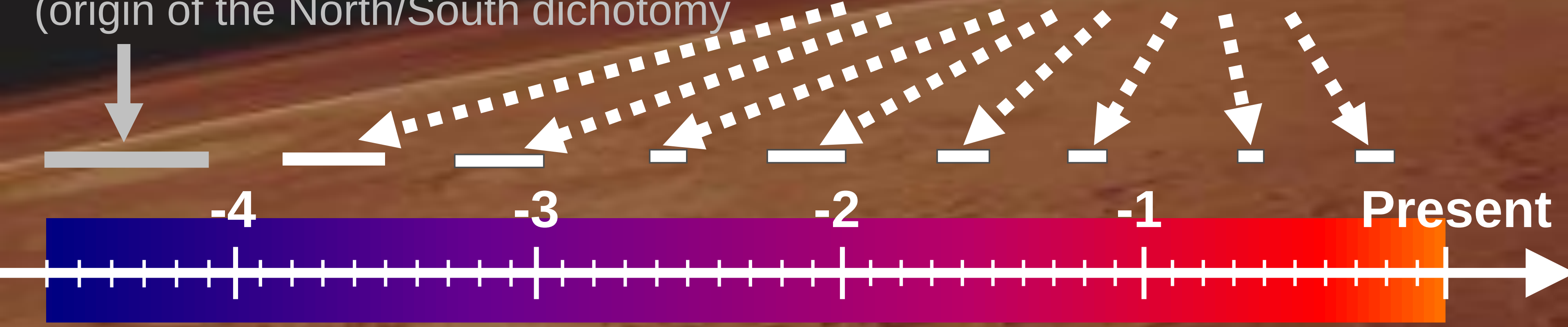


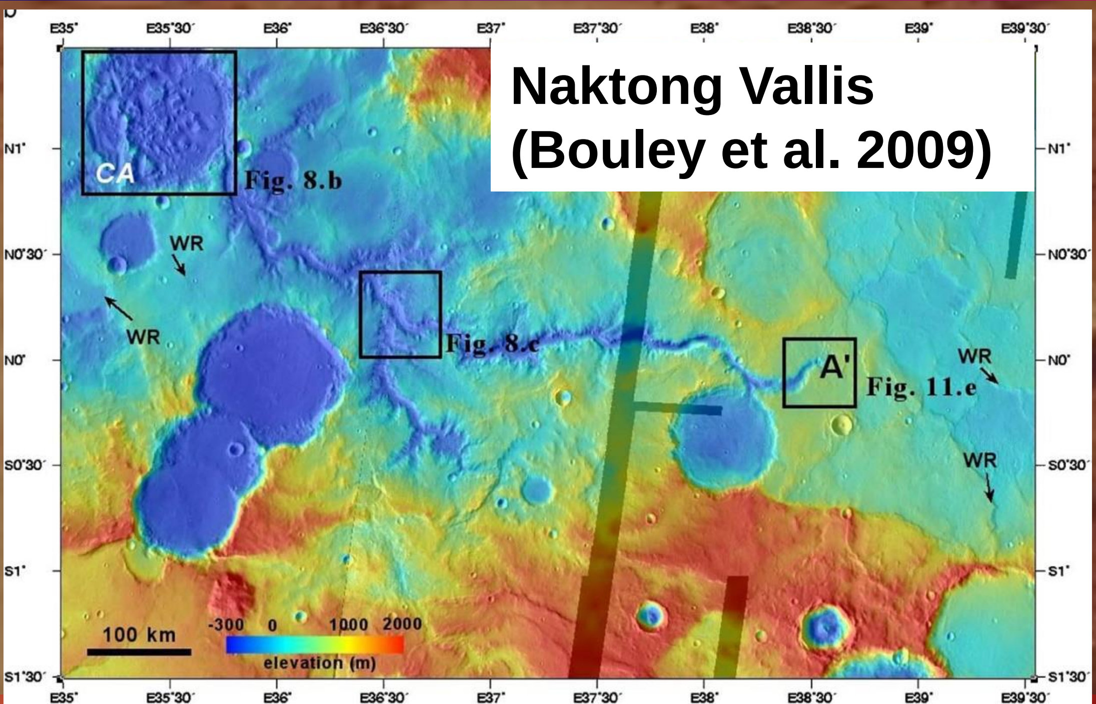
What do we know on Mars?



Volcanism & Giant impacts
(origin of the North/South dichotomy

Degassing episodes

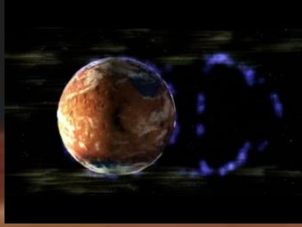


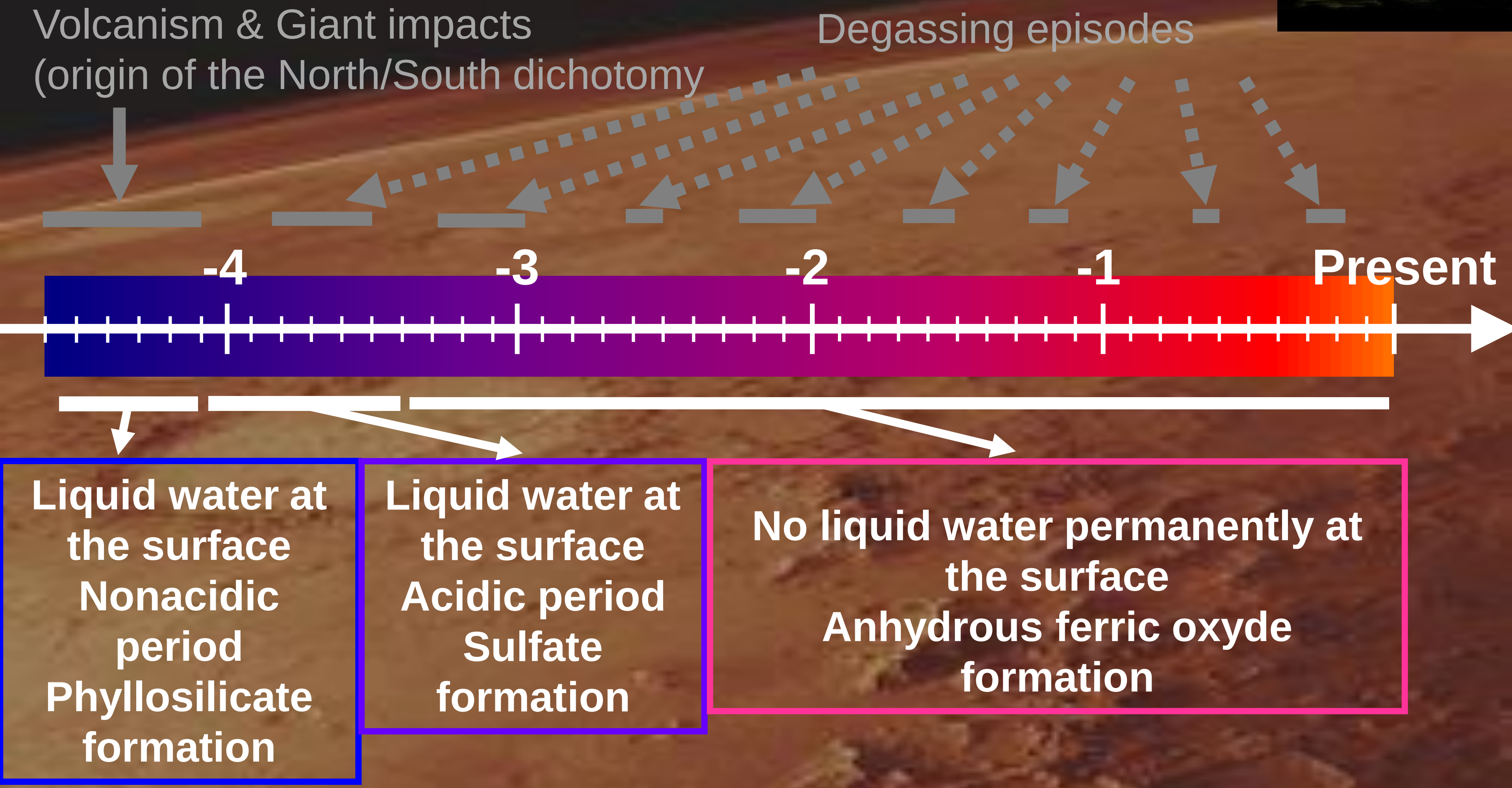


**Naktong Vallis
(Bouley et al. 2009)**

Beginning Hesperian, still fluvial activity (periodic few hundred mb atmosphere…)

What do we know on Mars?





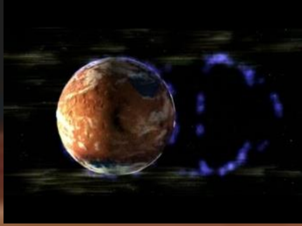
Liquid water at the surface
Nonacidic period
Phyllosilicate formation

Liquid water at the surface
Acidic period
Sulfate formation

No liquid water permanently at the surface
Anhydrous ferric oxyde formation

From Bibring et al. (2006)

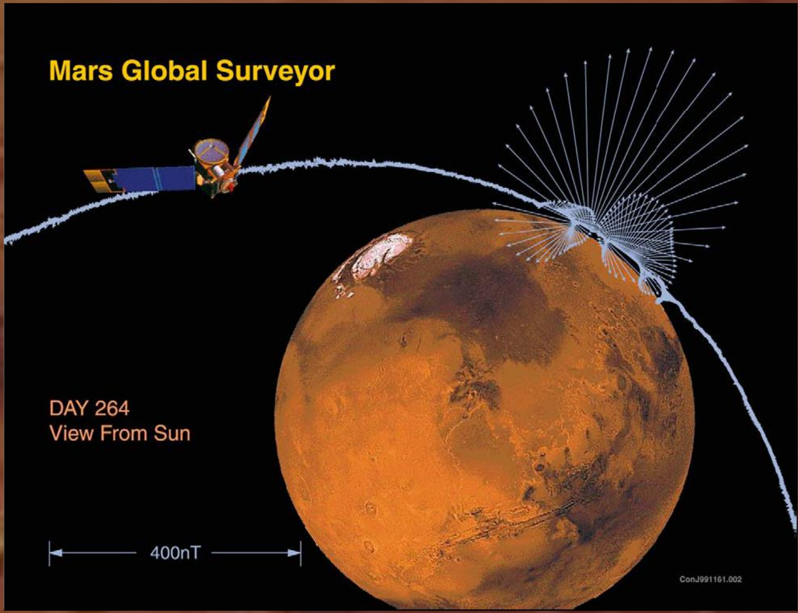
4.1 Gyr ago: a major change at Mars



Mars Global Surveyor (1999 - 2006):

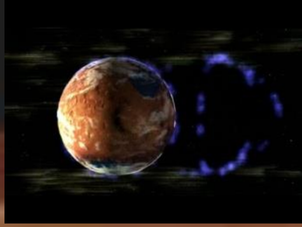
First mapping of Mars magnetic environment (Acuňa et al. (1999)

⇒ Discovery of a remanent magnetic field



Magnetic field(3 s) measured along MGS orbit (Connerney et al. 2004)

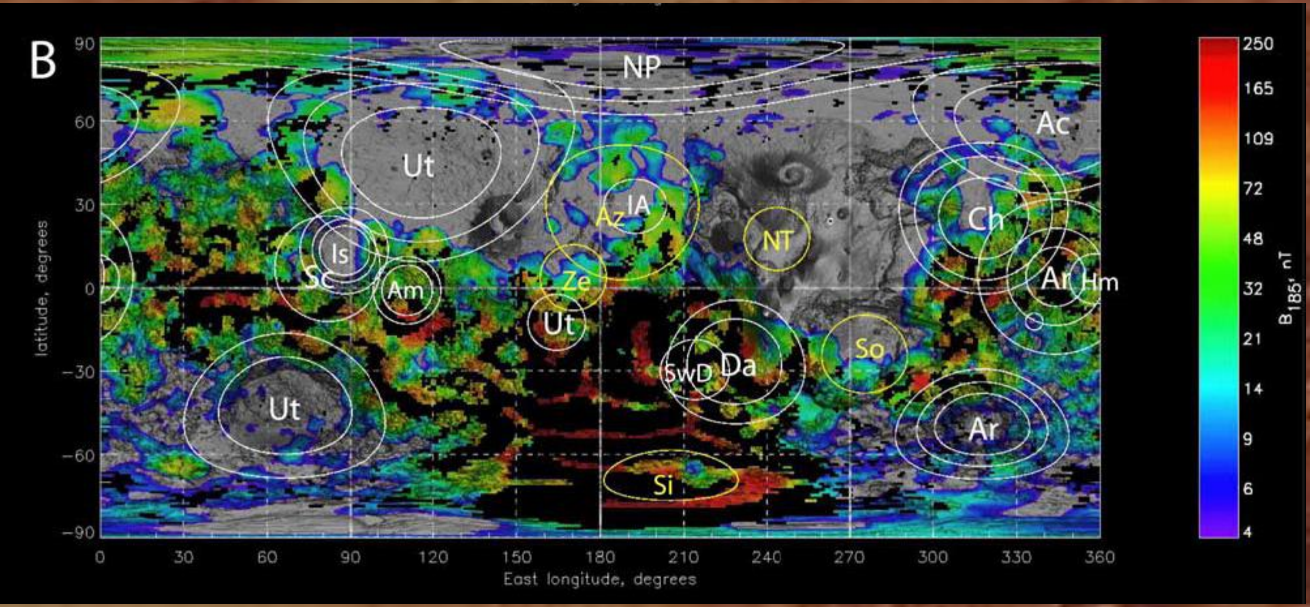
4.1 Gyr ago: a major change at Mars



Mars Global Surveyor (1999 - 2006):

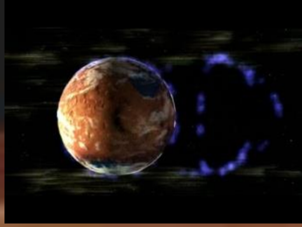
⇒ There was an active dynamo 4.11 – 4.13 Gyr ago

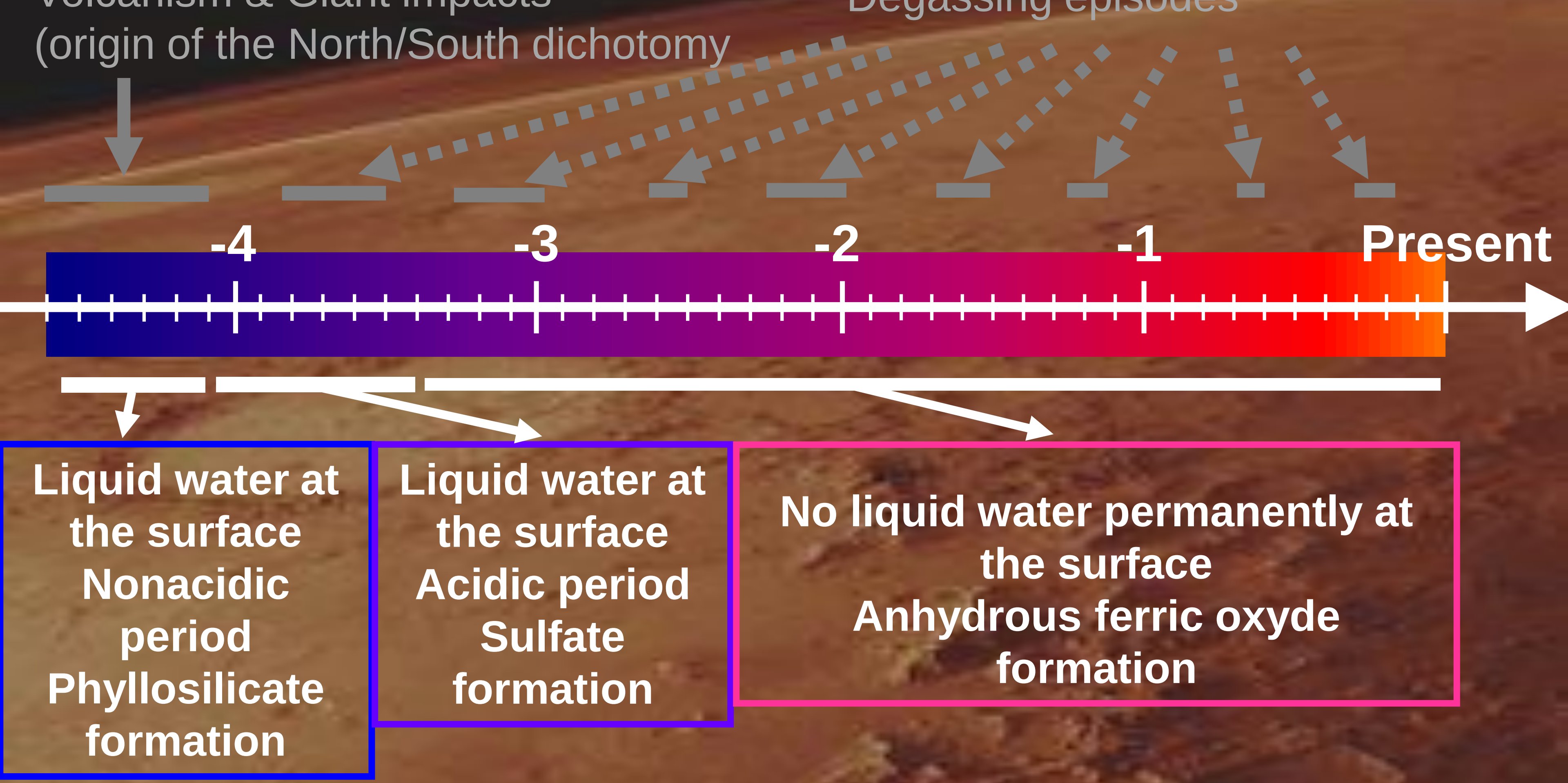
⇒ Correlated with the last large impacts (>1000 km)



Radial component of the B field deduced from electron measurements (Lillis et al. 2008)

Mars' atmospheric evolution





Volcanism & Giant impacts
(origin of the North/South dichotomy

Degassing episodes

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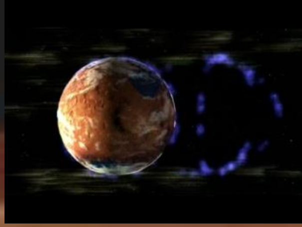

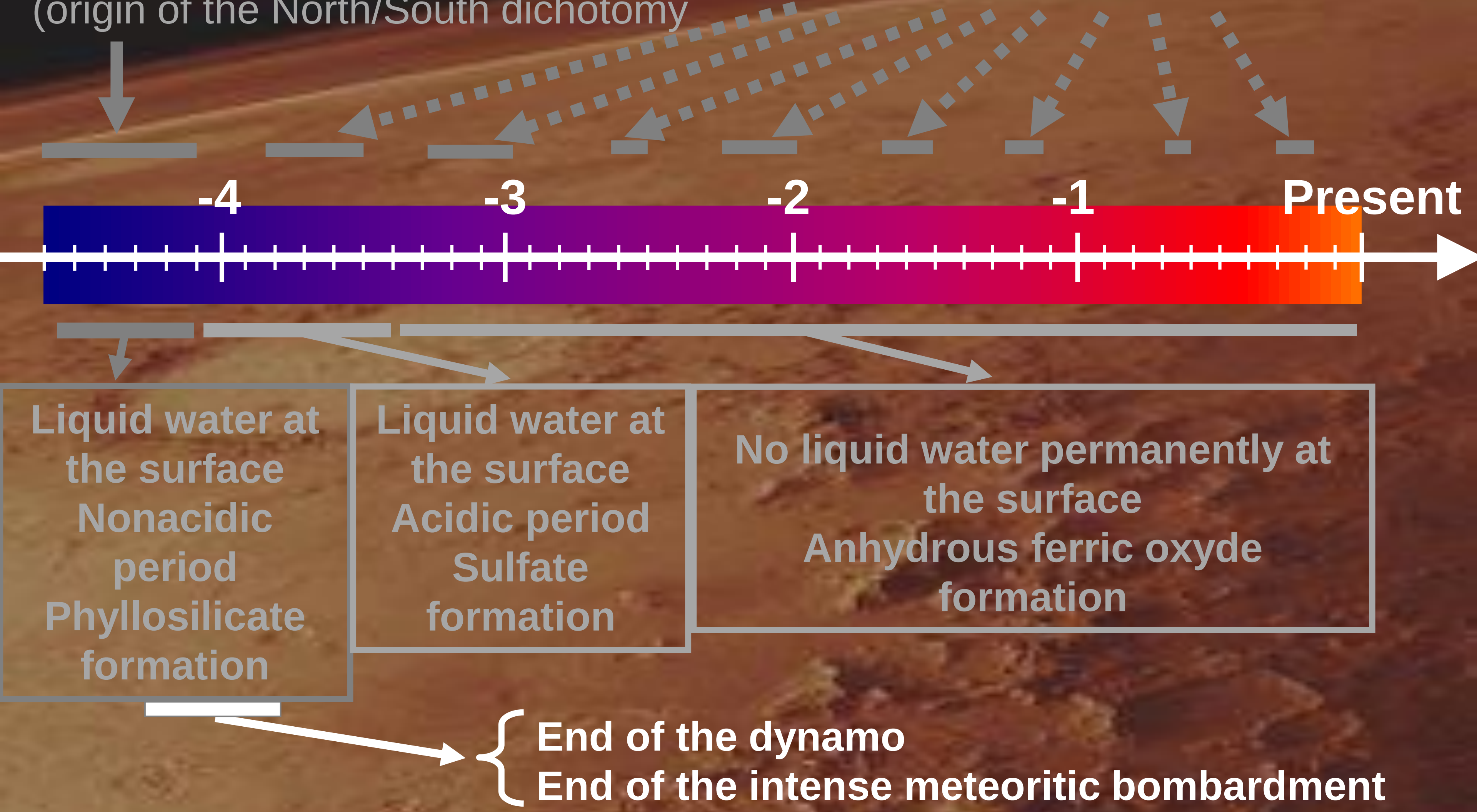

Volcanism & Giant impacts
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Degassing episodes?

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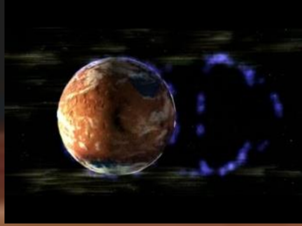
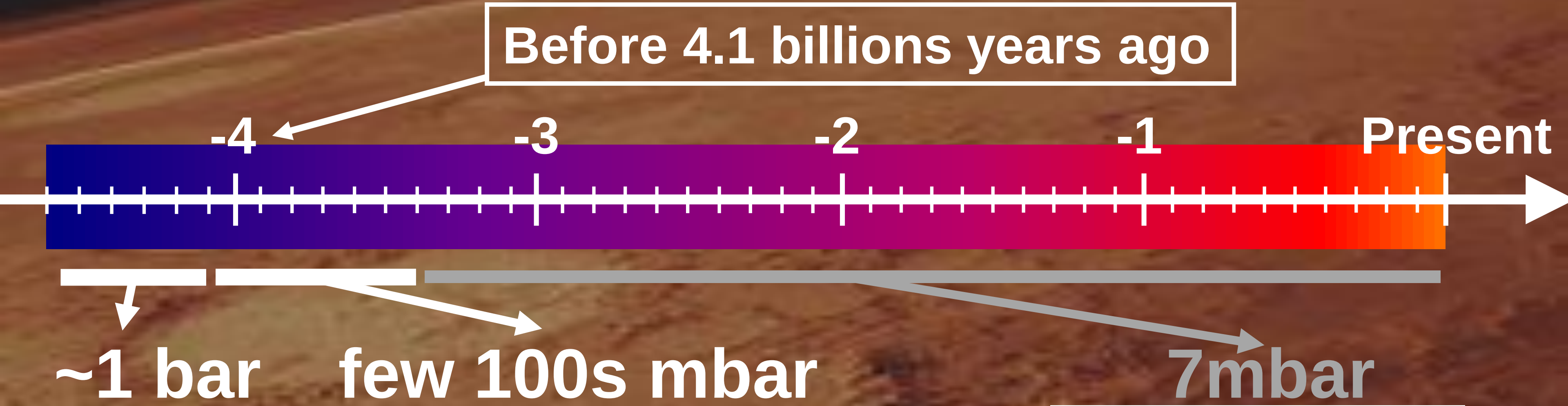
End of the dynamo
End of the intense meteoritic bombardment

Mars’ atmospheric evolution:

a possible scenario driven by atmospheric escape





Before 4.1 billions years ago

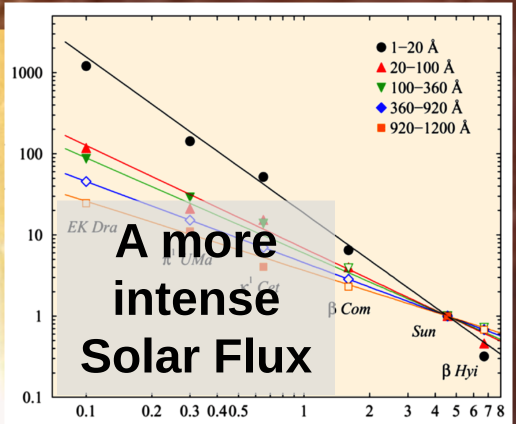
~1 bar

few 100s mbar

7mbar

Hydrodynamic escape

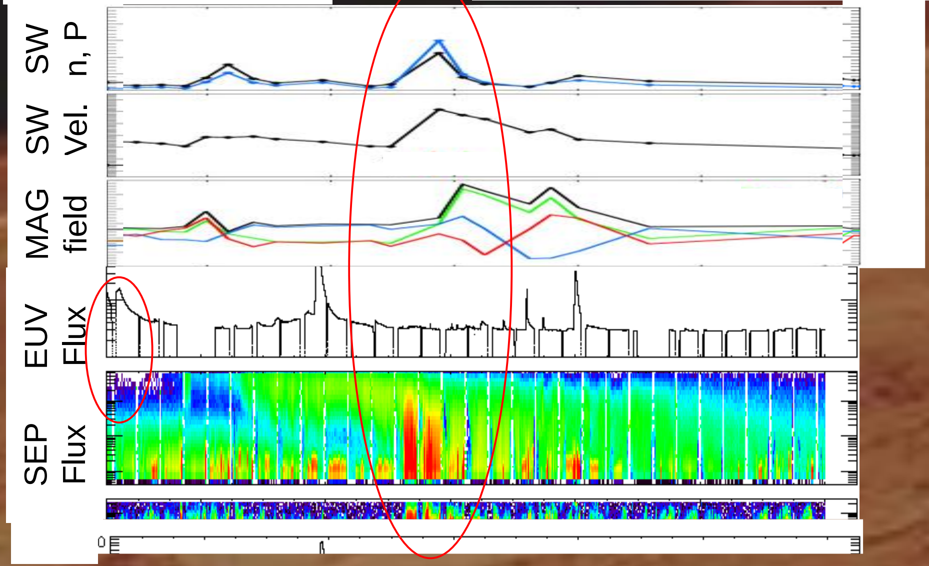
Cremonese et al. (1997)



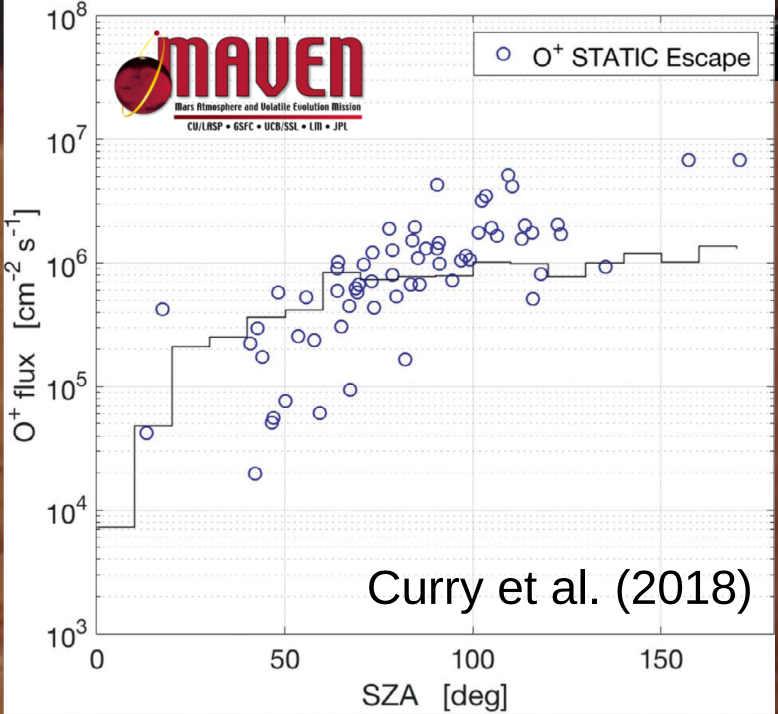
A more intense Solar Flux

Single event

Jakosky et al. (2015)



Date (March 2015)



Curry et al. (2018)

Left ⇒ **Escape enhanced by ~20 times during moderate solar event,**

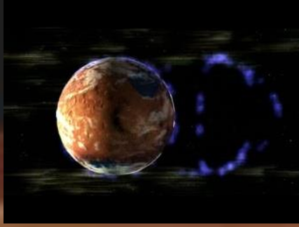
Right ⇒ **Escape enhanced up to a factor 10 during many solar events**

⇒ **Solar events are analog of primitive solar conditions**

Primitive solar conditions enhance efficiency of atmospheric escape

Mars' atmospheric evolution:

a possible scenario driven by atmospheric escape



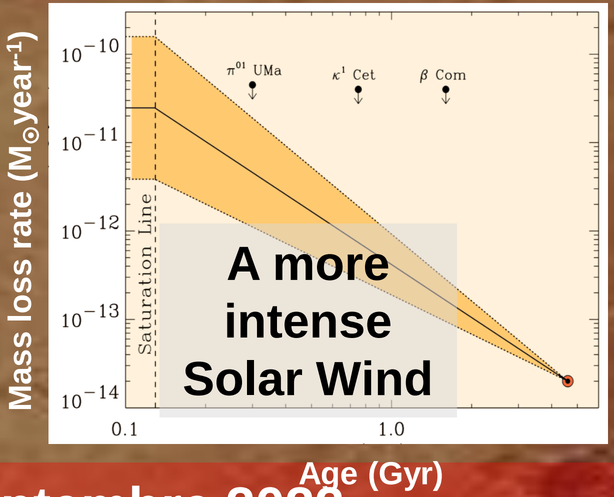
After 4.1 billions years ago

-4 -3 -2 -1 Present

~1 bar

few 100s mbar

7mbar



A more intense Solar Wind

Atmospheric escape during late Noachian by non-thermal processes?

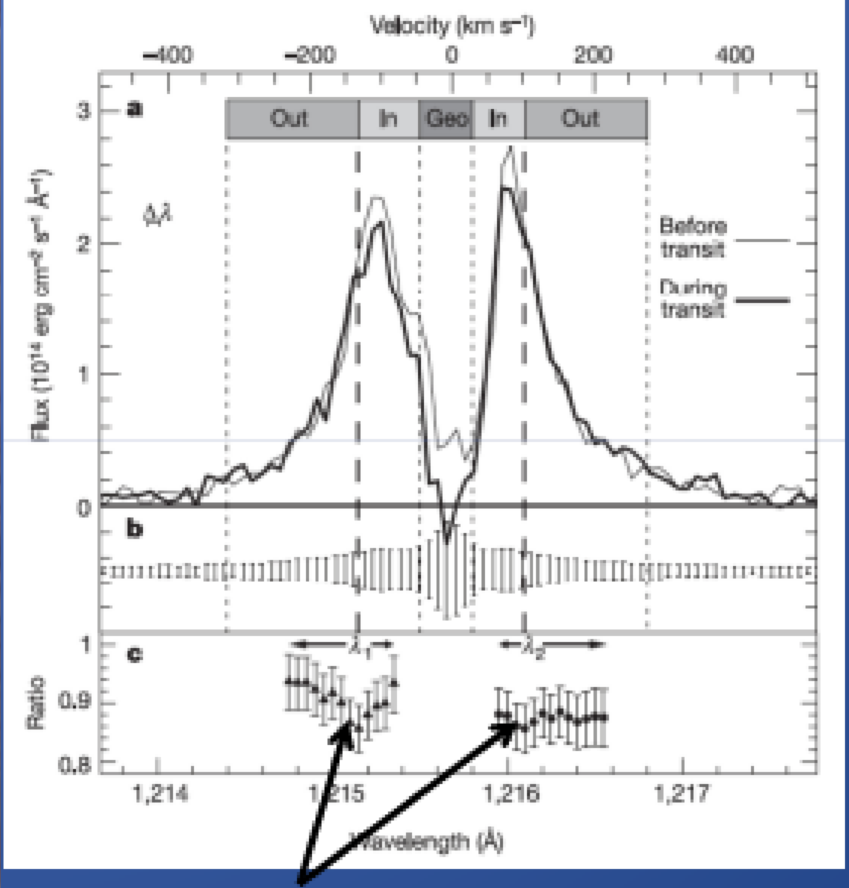
And what about exo-atmospheres?

Atmospheric escapes at extra-solar planets

- detection of an hydrogen atmospheric escape of HD209458b a gas giant planet (1.3 Jupiter Mass at 8.6 stellar radii) with an escaping rate > 10^{10} gs^{-1} (Vidal-Madjar et al. 2003)

- detection of oxygen O I and carbon C II at large distance from HD209458b with an velocity dispersion larger than 15 km/s (Vidal-Madjar et al. 2004)

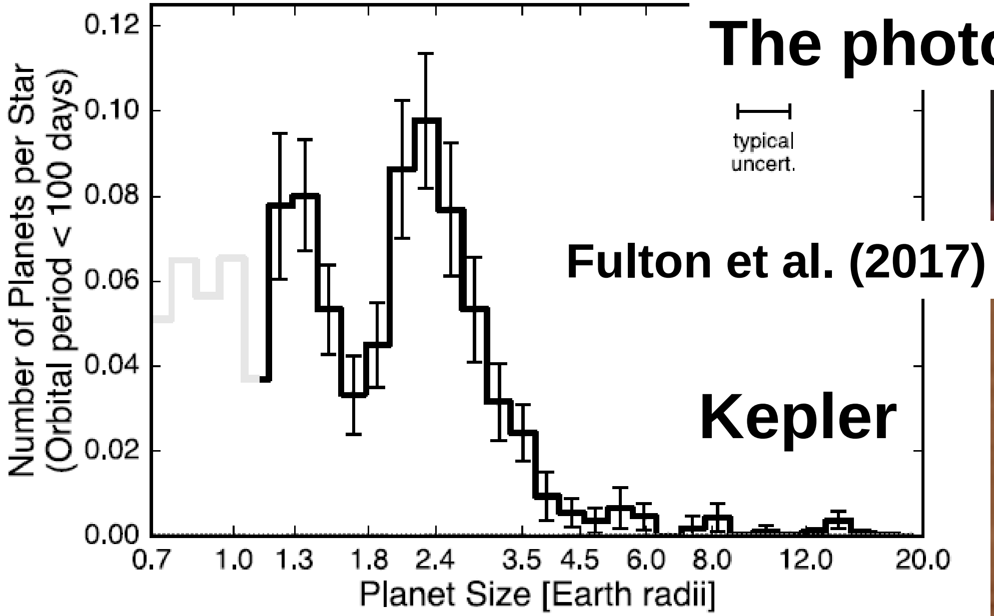
⇒ Hydrodynamic escape of H dragging O and C?



-130, 100 km s^{-1}

Vidal-Madjar et al. (2003)

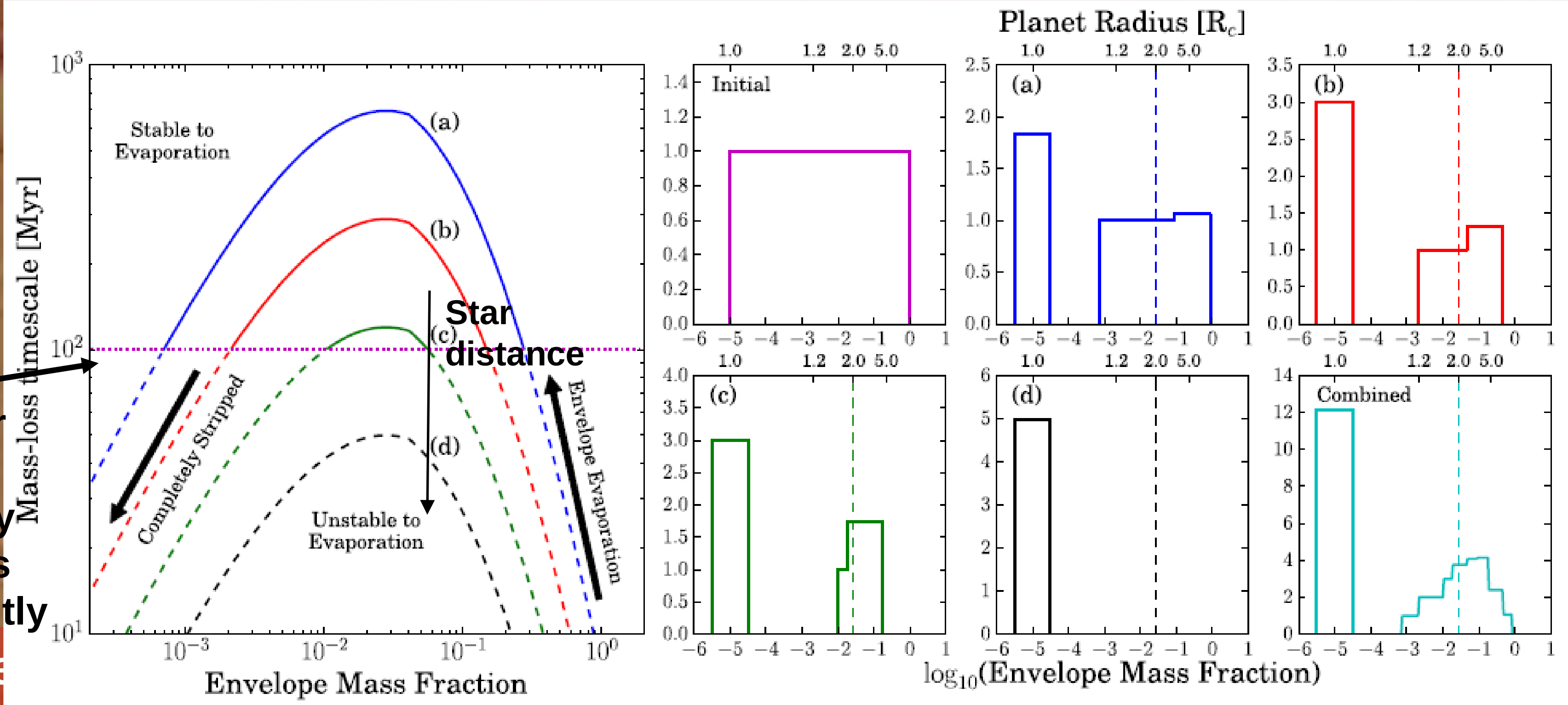
The photoevaporation valley



Fulton et al. (2017)

Kepler

Owen and Wu (2017):
« The mass loss timescale always peaks for a H/He envelope of a few percent in mass, where the atmosphere roughly doubles the planet's radius »



Star distance

Time after which the luminosity decreases significantly

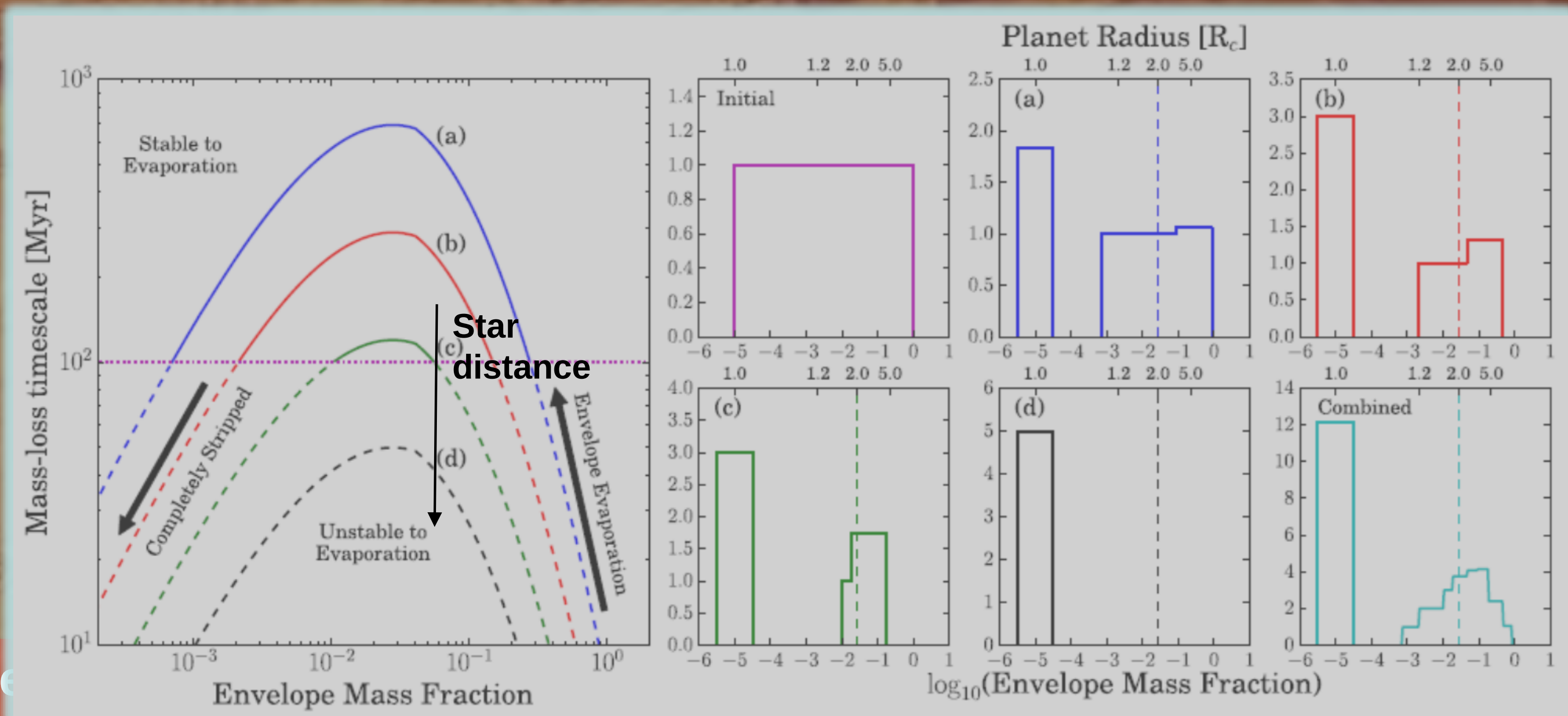
The photoevaporation valley

But very simple model of « evaporation »:

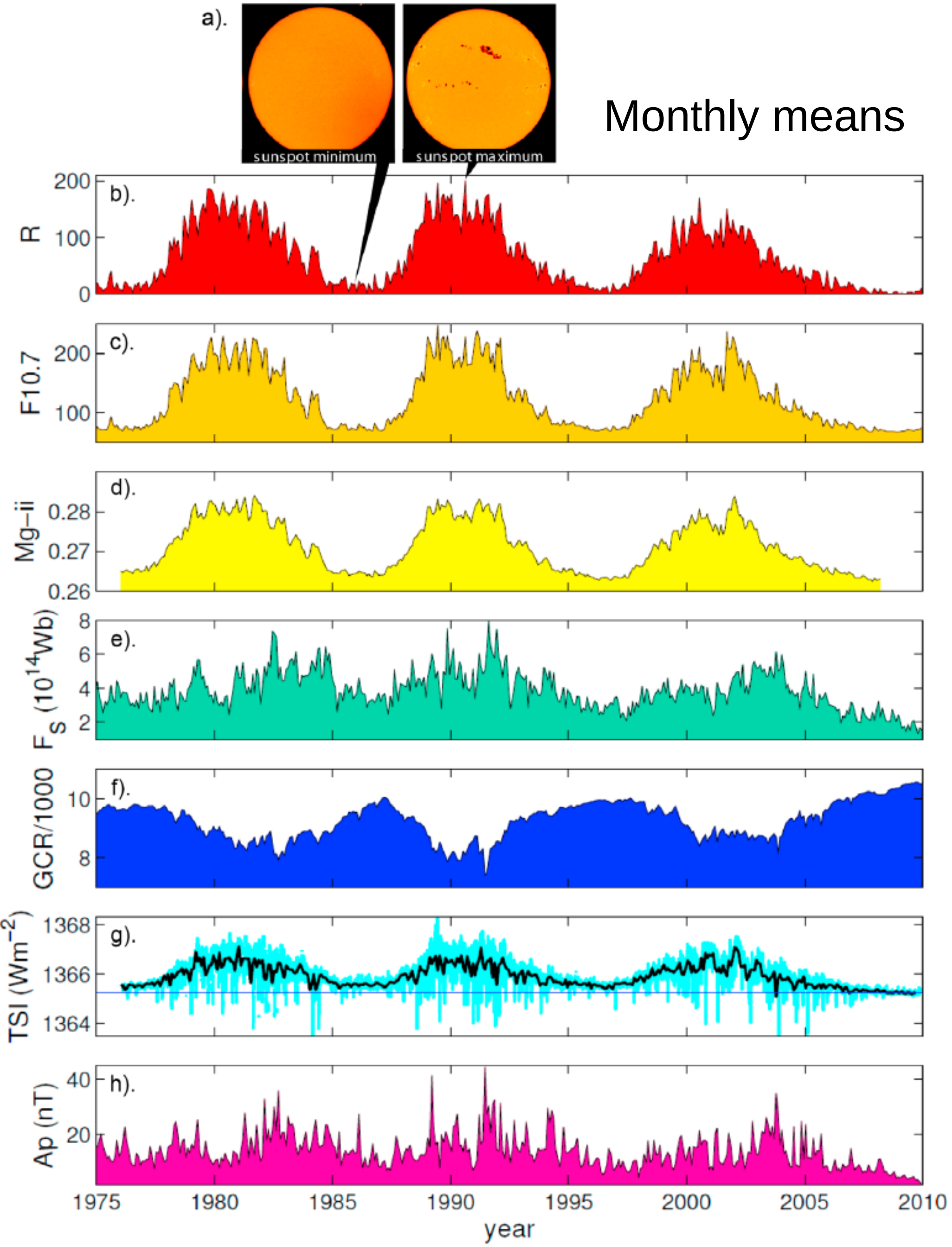
The loss rate is estimated from the EUV/UV luminosity and an « efficiency » of evaporation (no notion of Jeans or hydrodynamic regimes as an example…):

No non-thermal mechanisms

No Stellar wind stripping…



BACK-UP



From Gray et al. (2010)

Sunspot number

The 10.7 cm radio flux (W m^{-2} Hz^{-2})

The Mg-ii line (280 nm) core to wing ratio (correlated with 150-400 nm)

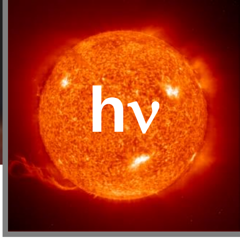
Open solar flux (radial component of the IMF)

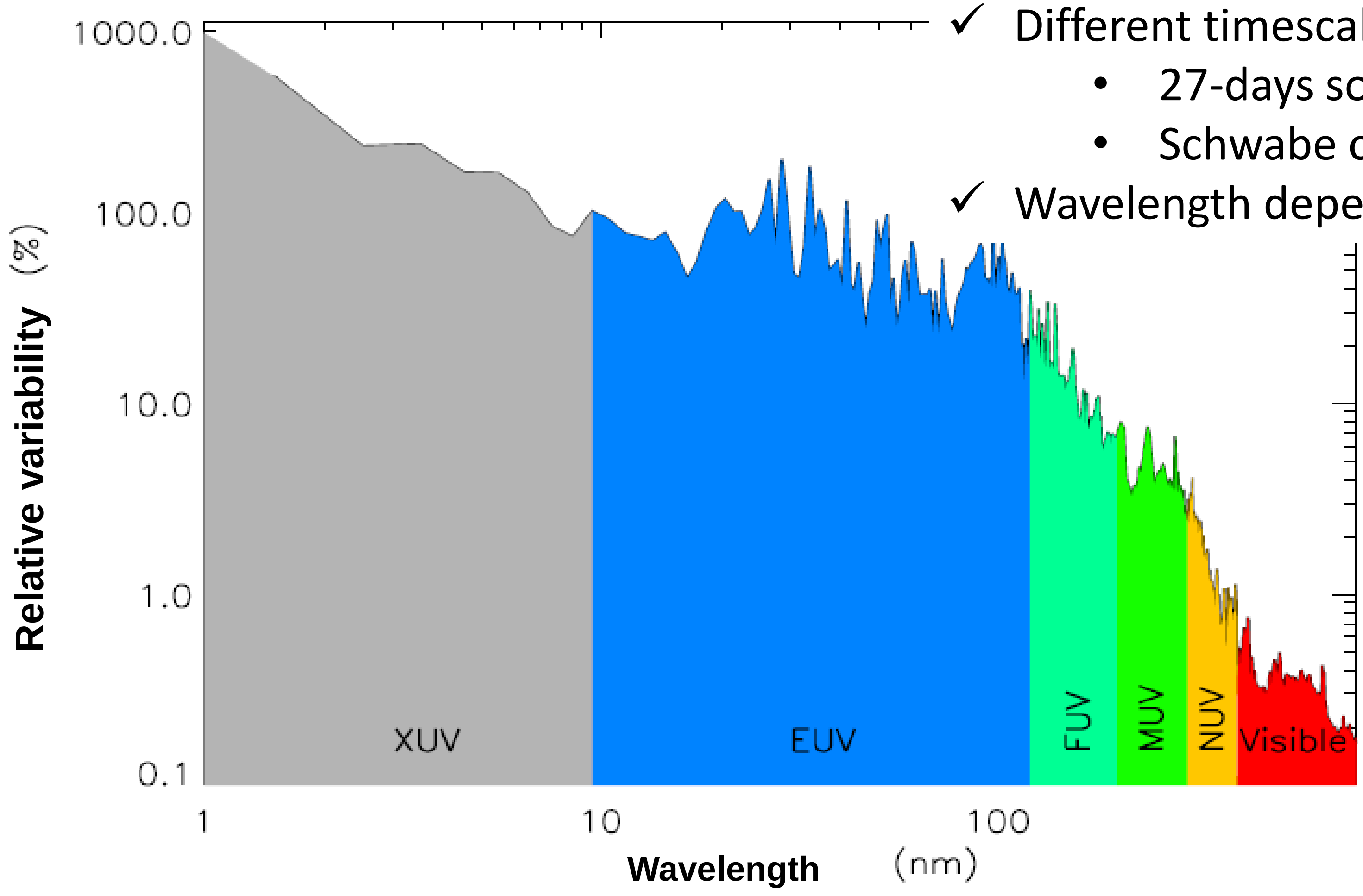
Nb of neutron counted / mn at McMurdo (Antartica)

Total Solar irradiance

Geomagnetic activity index

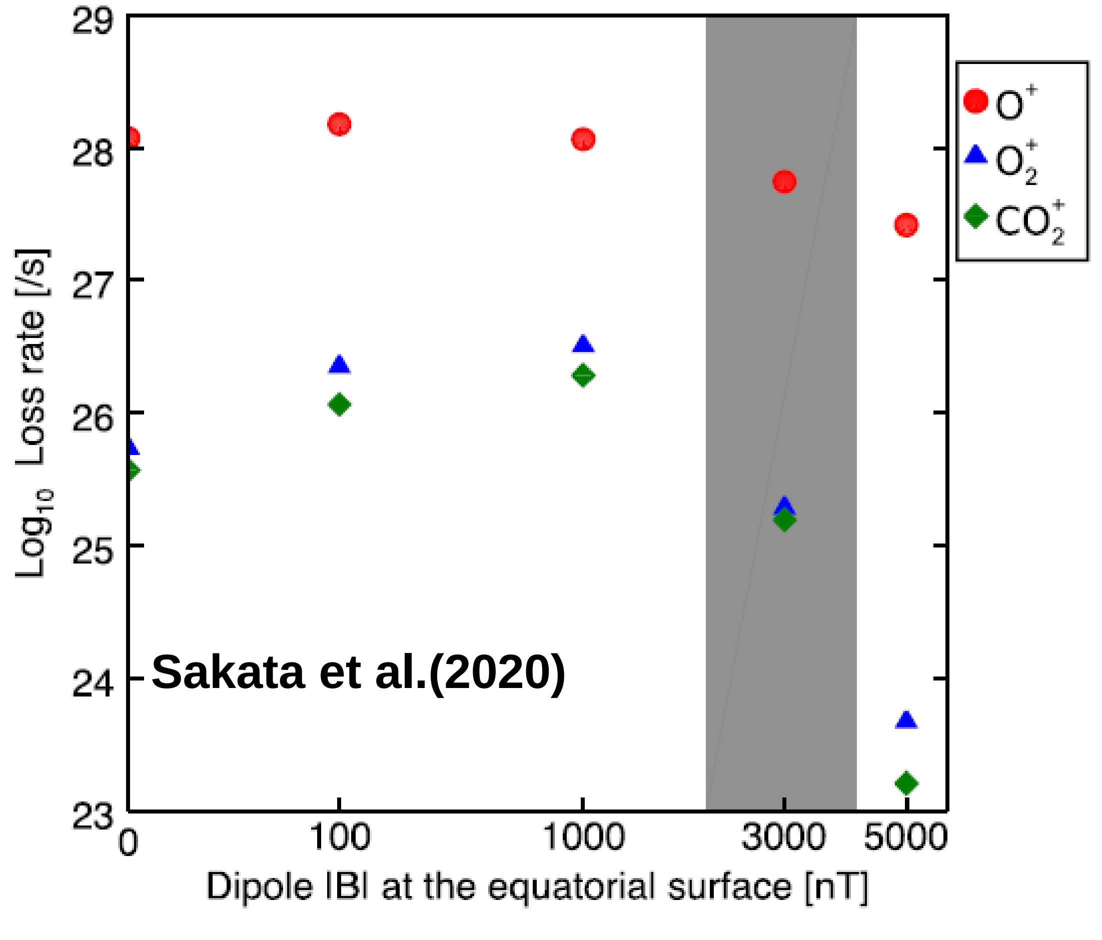
From Lilensten and Blelly (1999)





- ✓ Different timescales
  - 27-days solar rotation
  - Schwabe cycle (10-12 years)
- ✓ Wavelength dependent

Variation of the solar flux on a 11 years cycle (from TIMED and SORCE 2003 – 2010 data)



Sakata et al.(2020)

“The effects of a dipole field on ion loss depend on whether the dipolar magnetic pressure is strong enough to sustain the solar wind dynamic pressure. When the dipole field is existent but weak, it facilitates the cusp outflow and increases the loss rates of molecular ions (O2+ and CO2+) by a factor of 6 through the high-latitude magnetotail. When the dipole field is strong enough, the loss rates of molecular ions are decreased by 2 orders of magnitude”