Interface entre la chromosphère et la couronne solaire:

Modélisation avec une approche 16-moments multi-espèces

Nicolas Poirier
3rd yr PhD Student at IRAP in Toulouse, France

and Michael Lavarra, Alexis Rouillard, Pierre-Louis Blelly, Victor Réville, Rui Pinto, Andrea Verdini, Marco Velli, Eric Buchlin, Mikel Indurain

Work funded by the ERC SLOW_SOURCE project – DLV-819189

A peculiar composition of the solar atmosphere in heavy ions

Fractionation between low-FIP and high-FIP elements in the slow solar wind

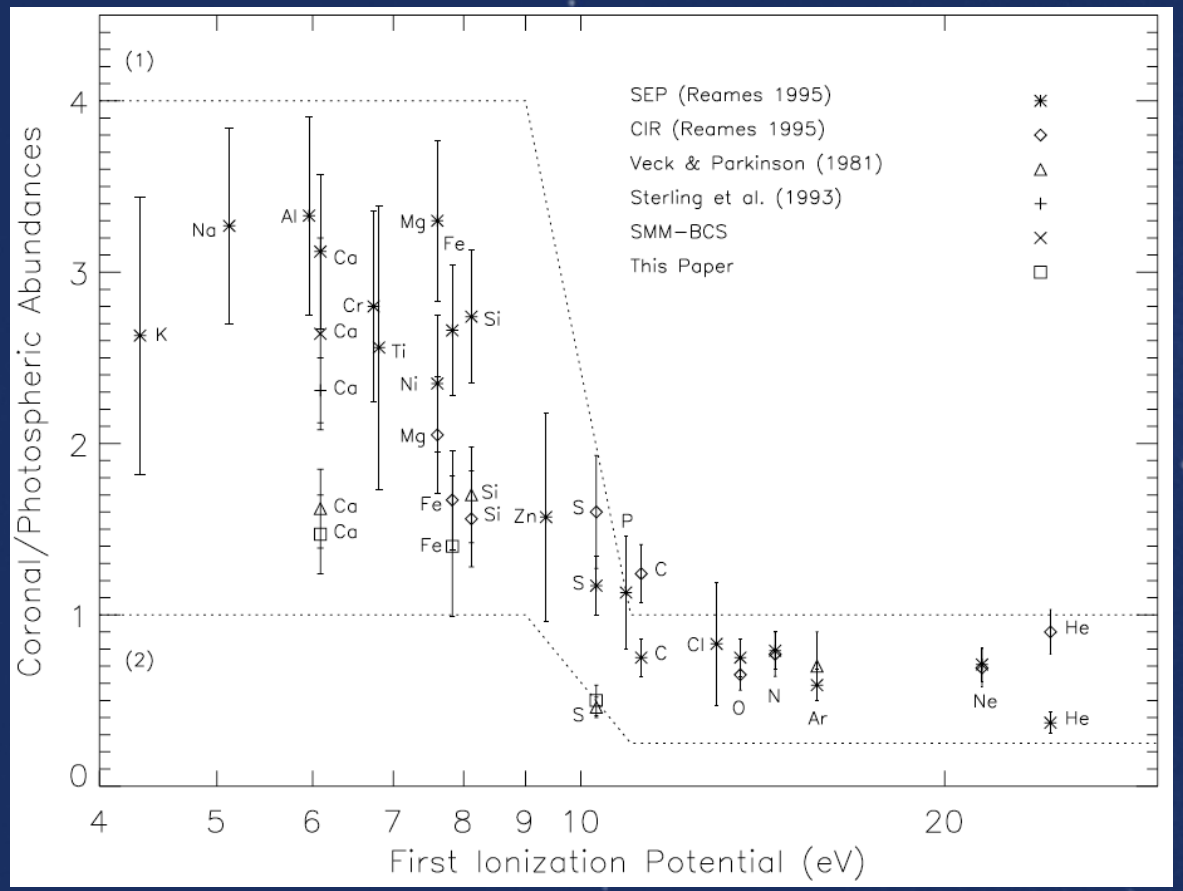


Figure 4 from *[Fludra & Schmelz 1999]*

2-D map of Si/S ratio on the solar disk

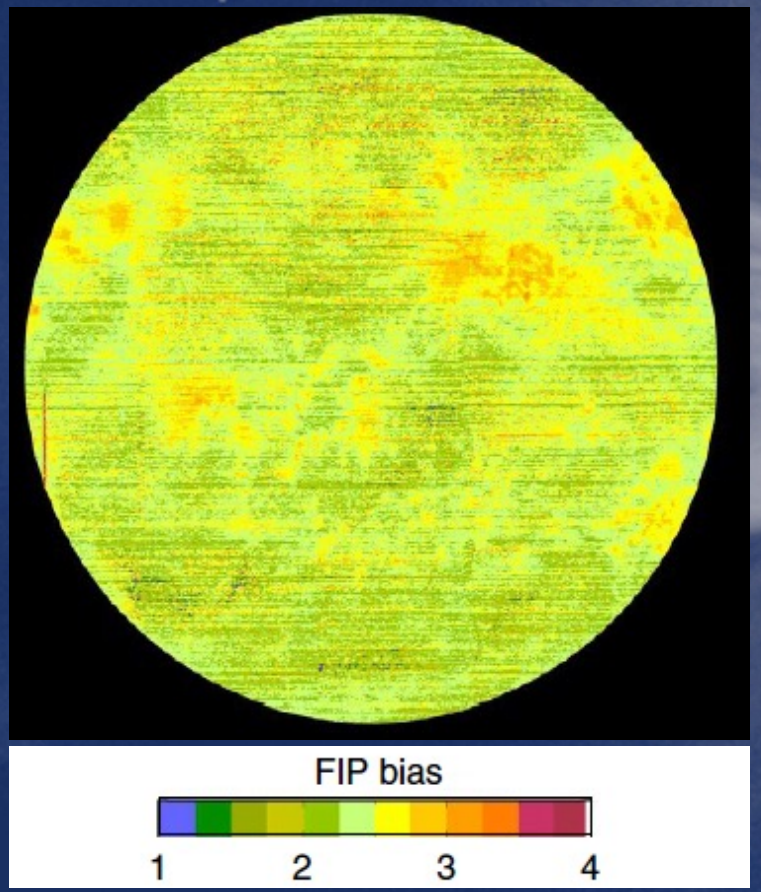


Figure 3 from *[Brooks et al. 2015]* (using Hinode/EIS full-disk observations)

Work funded by the ERC SLOW_SOURCE project – DLV-819189

On the mysteries about the FIP effect:

- What: A separation of heavy ions not by their mass but their FIP

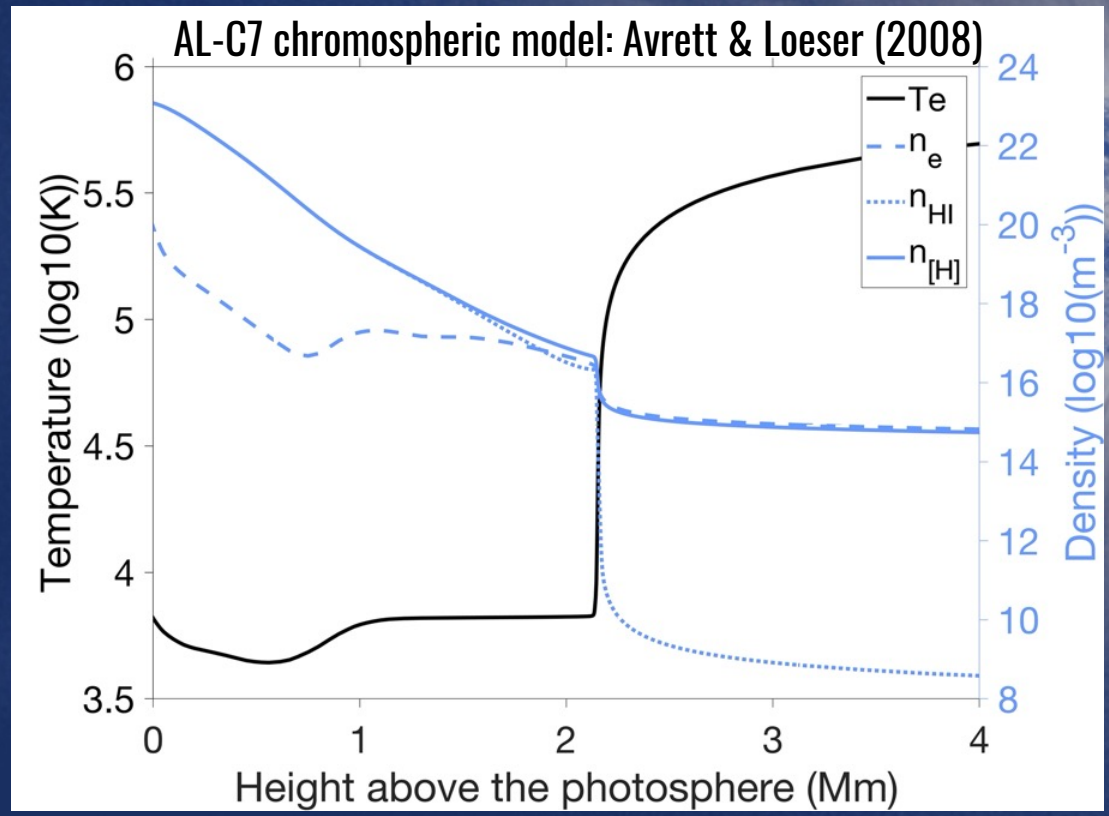
- Where: in the partially ionized chromosphere?

Photoionization of low-FIP first + many collisions

After then the composition becomes «frozen» in the corona

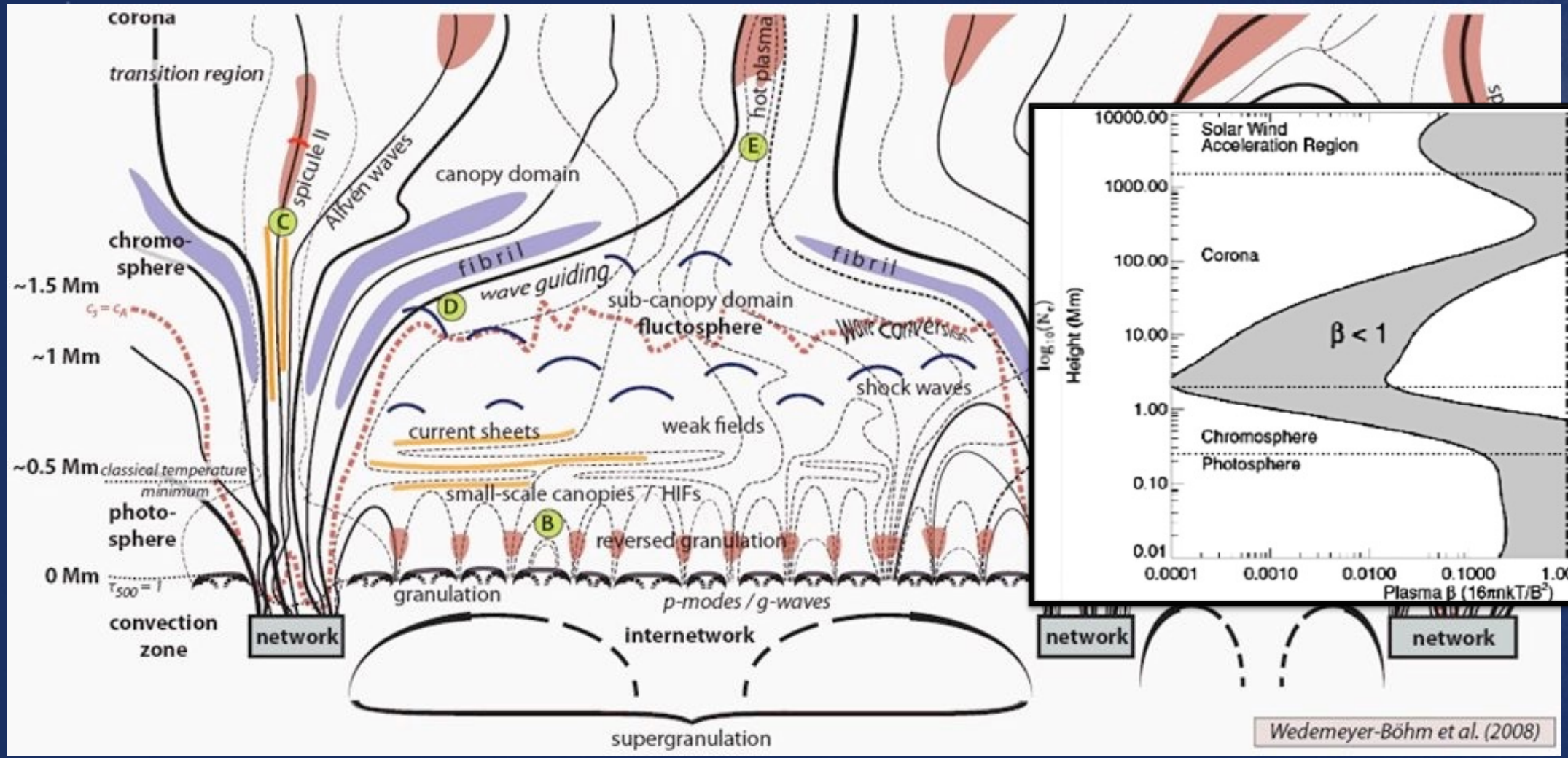
- How:

Coulomb collisions
Gravitational settling
Wave-particle interactions



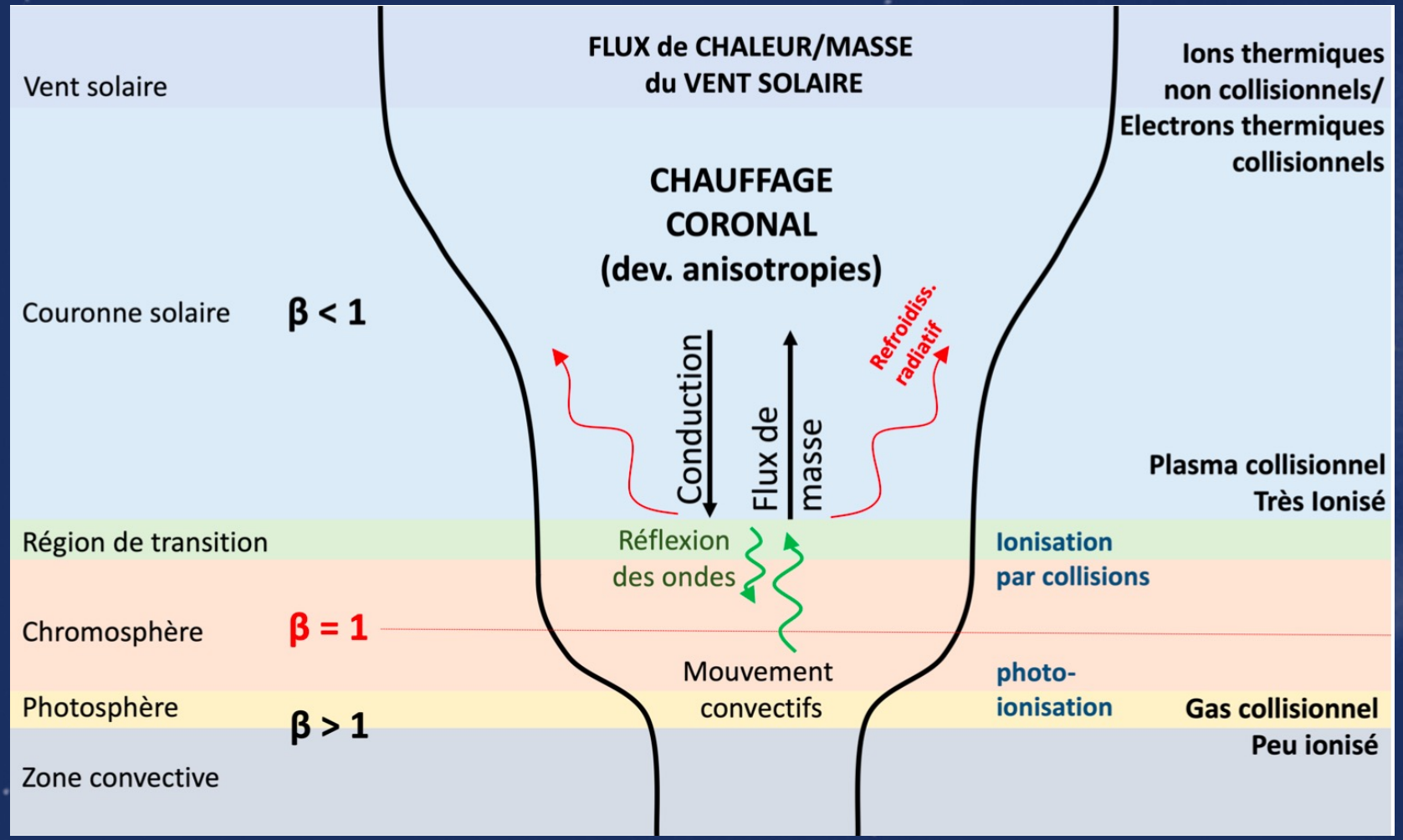
Work funded by the ERC SLOW_SOURCE project – DLV-819189

Interface chromosphere-corona:



Work funded by the ERC SLOW_SOURCE project – DLV-819189

Thermodynamics of the solar atmosphere:



HDR A. Rouillard (2021)

- ISAM:

Based on the IPIM ionospheric code (Blelly P.L. & Marchaudon A.)

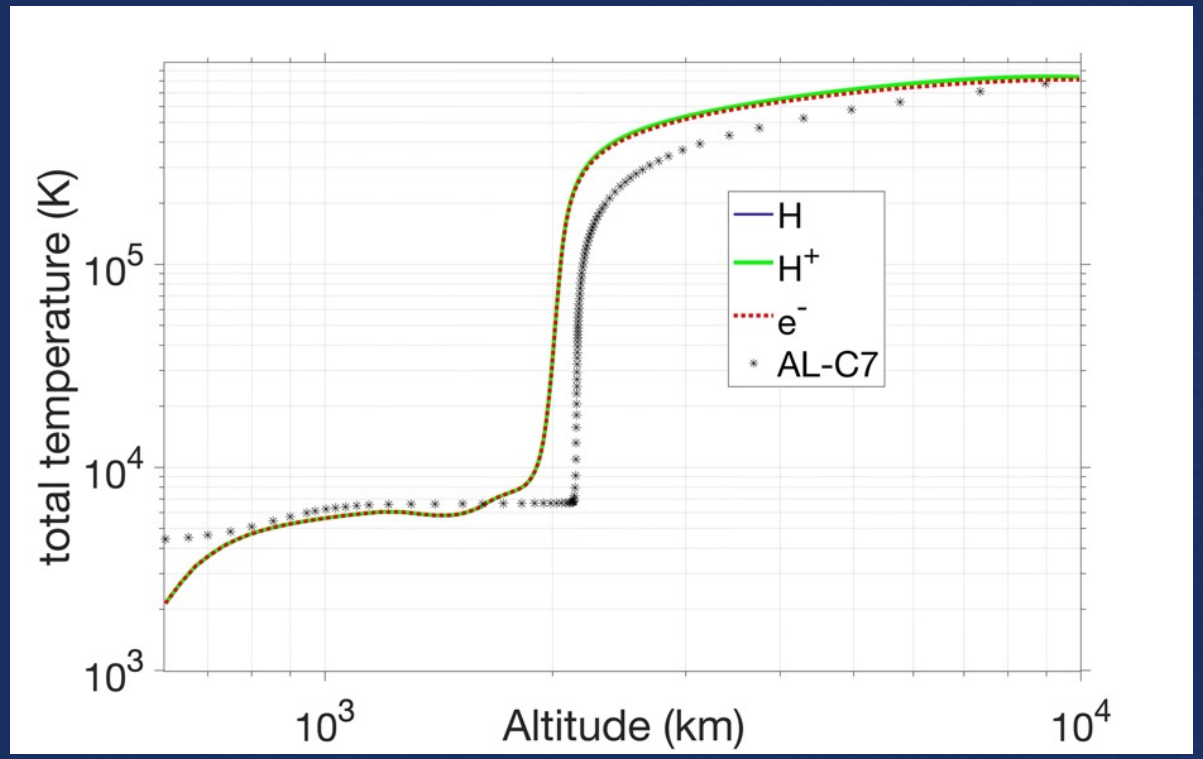
16-moment approach $(n, u, T_{\perp}, T_{\parallel}, Q_{\perp}, Q_{\parallel})$

Multi-specie
H + p + e^- + heavy particles

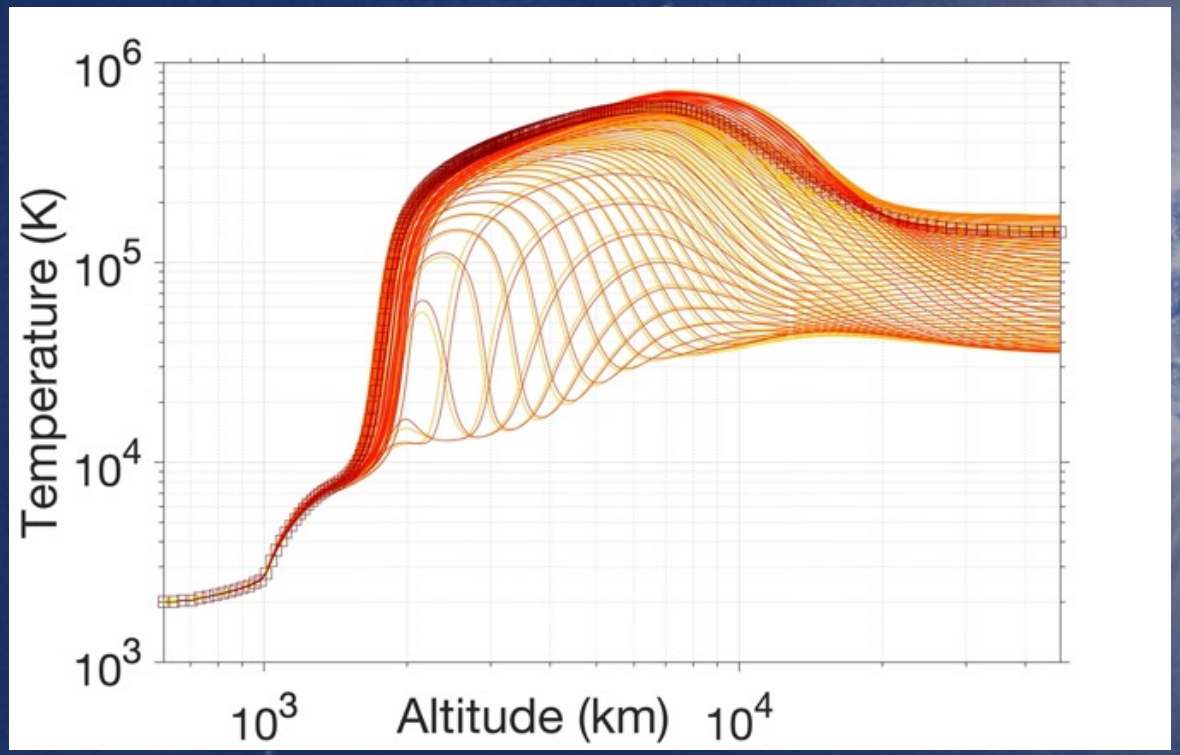
Work funded by the ERC SLOW_SOURCE project – DLV-819189

Quasi-static vs dynamic coronal loops:

thermodynamic equilibrium



Non-thermal equilibrium (TNE)



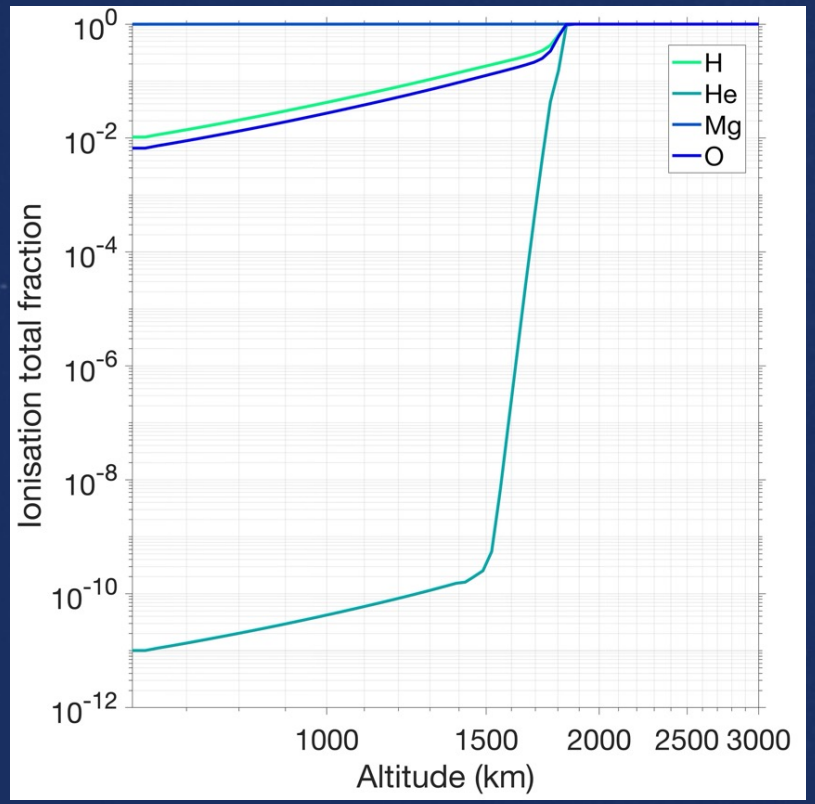
=> Effect on the composition of the solar atmosphere?

Work funded by the ERC SLOW_SOURCE project – DLV-819189

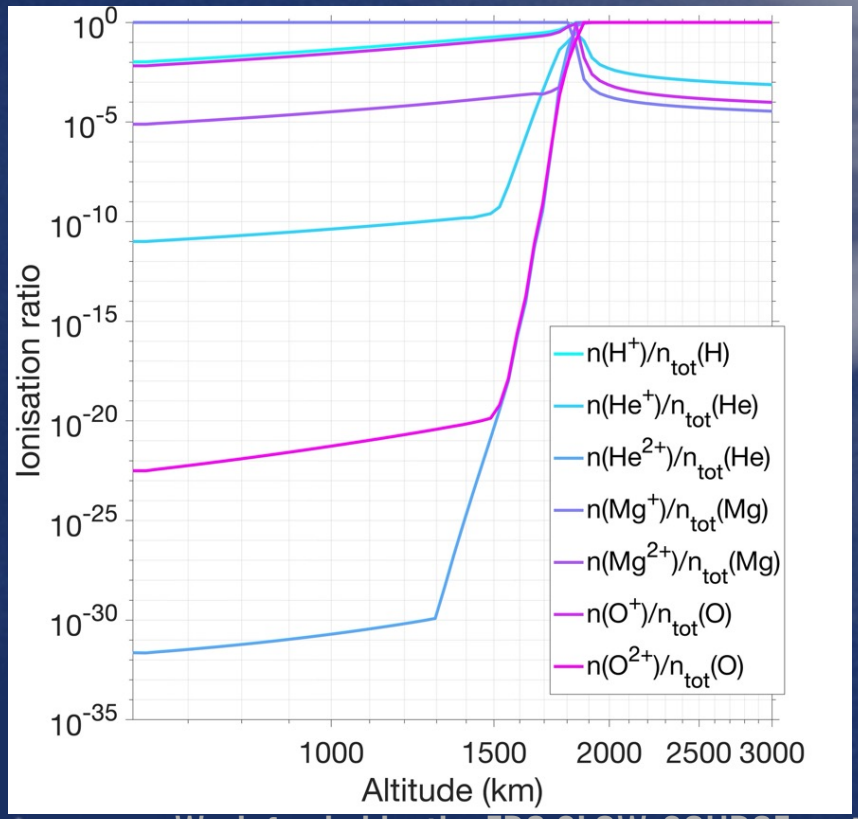
On the modeling of partial ionization:

- Ionization: photoionization, impact with e^-, auto-ionization, charge-exchange
- Recombination: radiative, dielectronic, charge-exchange $H^+ + O \rightarrow H + O^+$

Total ionization fraction



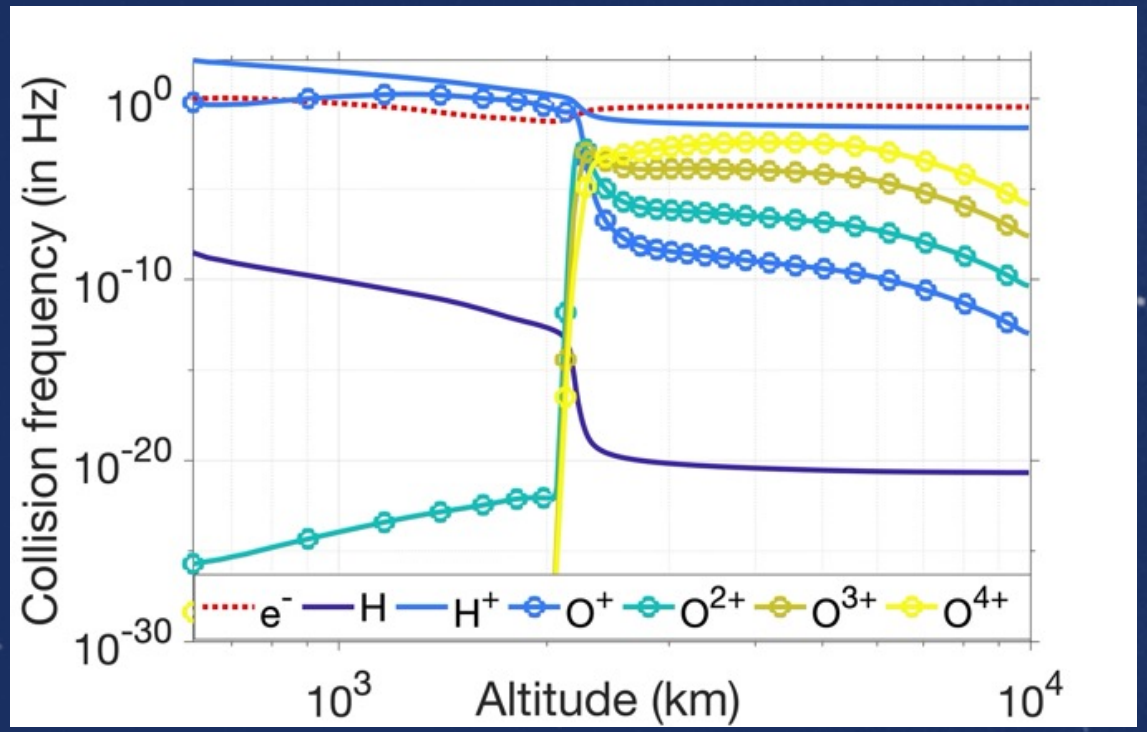
Partial ionization fractions

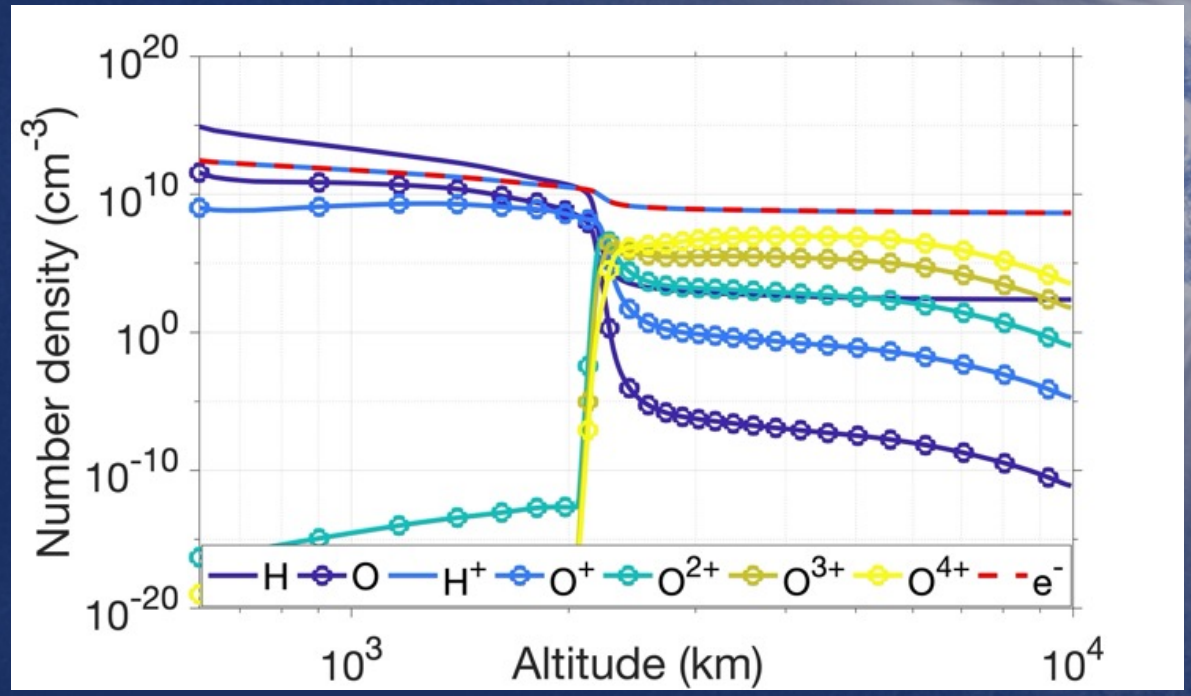


Work funded by the ERC SLOW_SOURCE project – DLV-819189

A comprehensive treatment of particle interactions:

- Ion-ion: long-range (Coulomb)
- Neutral-neutral: short-range (hard-sphere)
- Ion-neutral: mid-range (Resonant & non-Resonant)





=> Collisional coupling dependent on the local density & temperature

Work funded by the ERC SLOW_SOURCE project – DLV-819189

Key processes of the FIP effect:

Polarization
+ ponderomotive

$$\frac{\partial}{\partial t}u_s + u_s\nabla_{\parallel}u_s + \frac{\nabla_{\parallel}n_s k_b T_s^{\parallel}}{\rho_s} + \frac{k_b}{m_s}\left(T_s^{\parallel} - T_s^{\perp}\right)\frac{1}{A}\nabla_{\parallel}A + \frac{GM_{\odot}}{r^2}cos(\theta) - \frac{1}{m_s n_s}F_s = \frac{\delta u_s}{\partial t}$$

Pressure — Mirror — Gravity

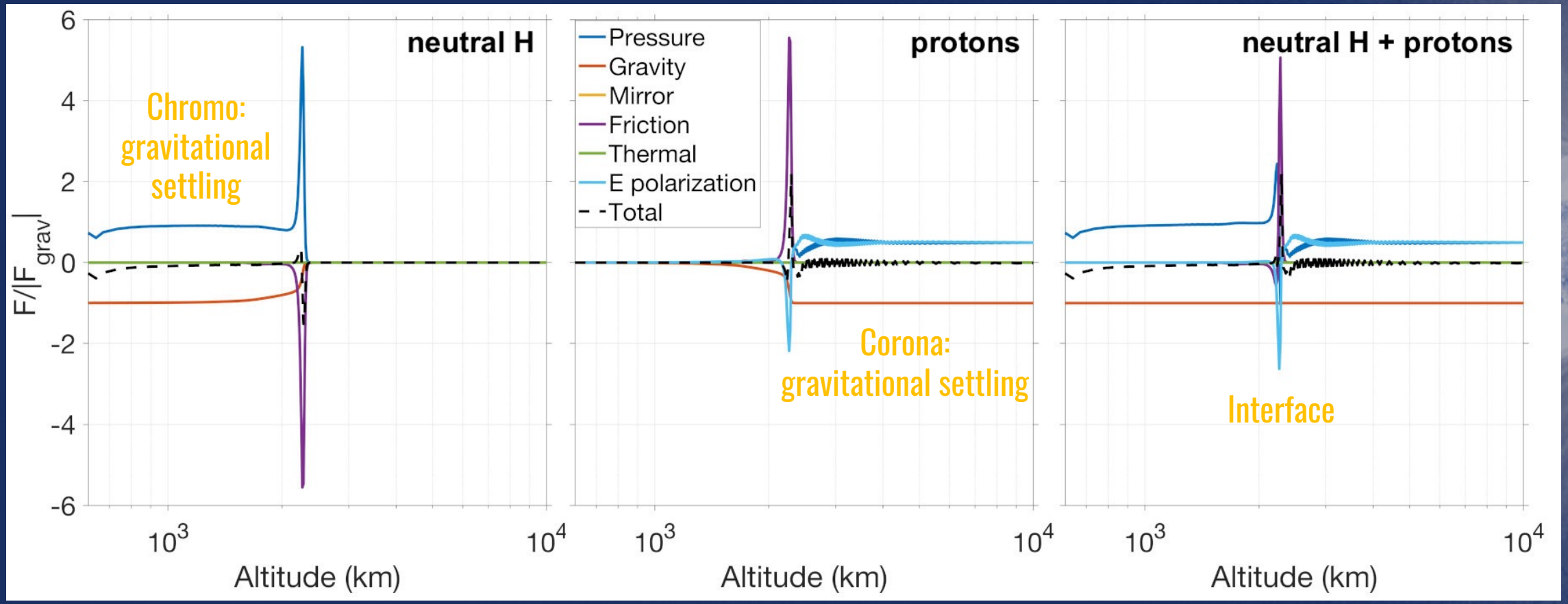
Diffusion effects

Lavarra et al. (2022)

$$\frac{\delta u_s}{\delta t} = \frac{1}{n_s m_s}\left[\underbrace{\sum_{t\neq s} n_s m_s \nu_{st}\left(u_t - u_s\right)}_{\text{Friction force}} + \underbrace{\sum_{t\neq s}\nu_{st}\frac{z_{st}\mu_{st}}{k_b T_{st}}\left(\frac{q_s^{\parallel} + 2q_s^{\perp}}{2} - \frac{q_t^{\parallel} + 2q_t^{\perp}}{2}\frac{n_s m_s}{n_t m_t}\right)}_{\text{Thermal force}}\right]$$

Work funded by the ERC SLOW_SOURCE project – DLV-819189

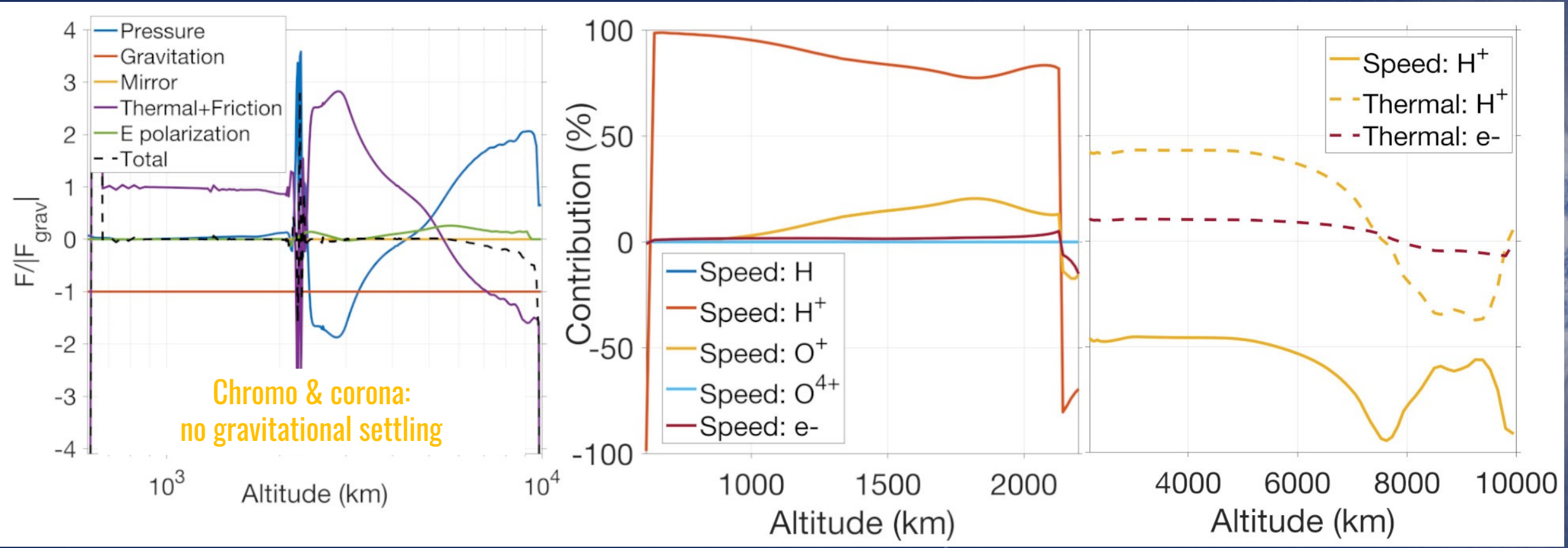
ISAM results: case of a pure H-p-e^- atmosphere:



Ambipolar flow in the transition region: up-streaming neutral H & down-streaming protons

Work funded by the ERC SLOW_SOURCE project – DLV-819189

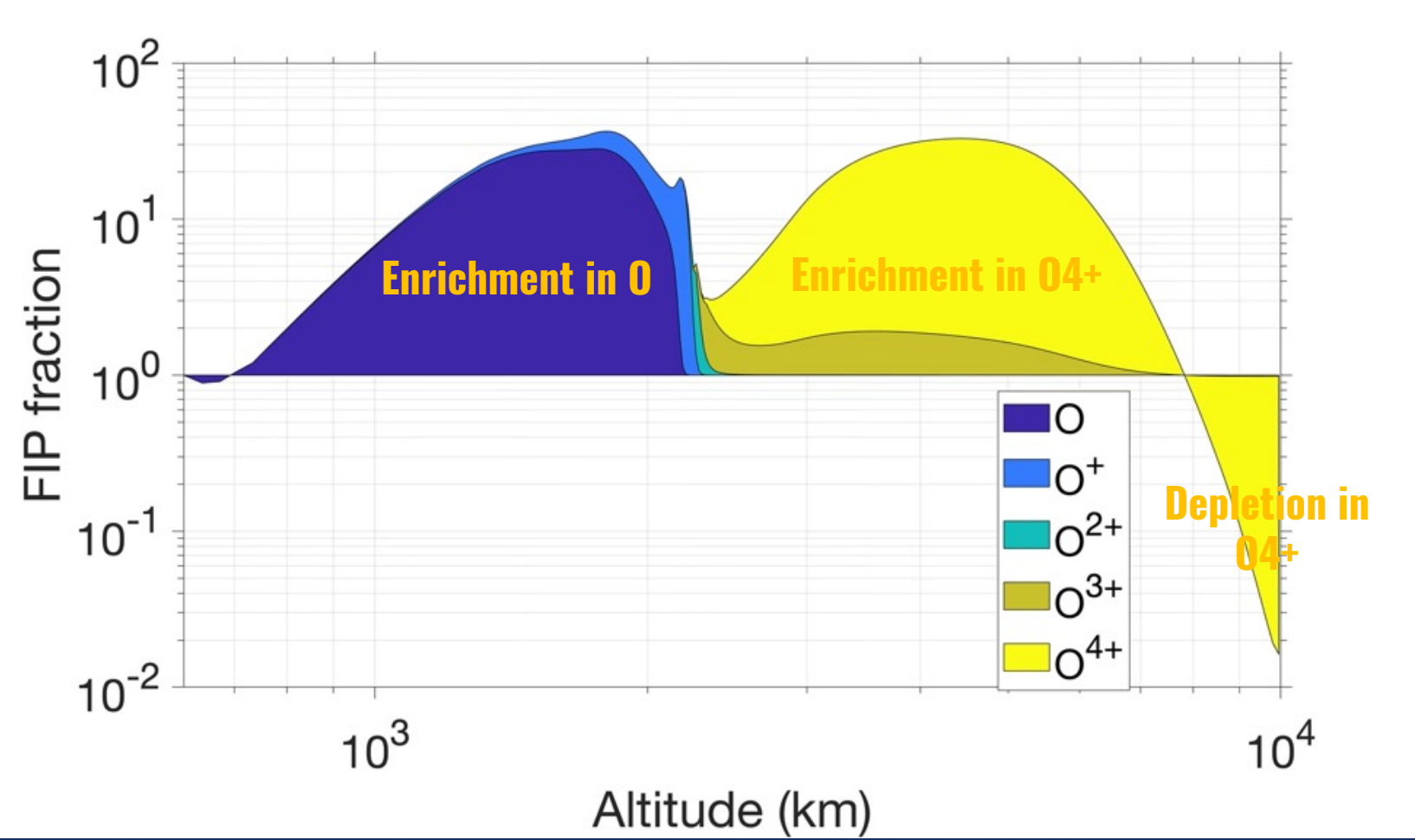
ISAM results: including Oxygen:



Oxygen strongly coupled with protons (Coulomb): both friction & thermal effects contribute

Work funded by the ERC SLOW_SOURCE project – DLV-819189

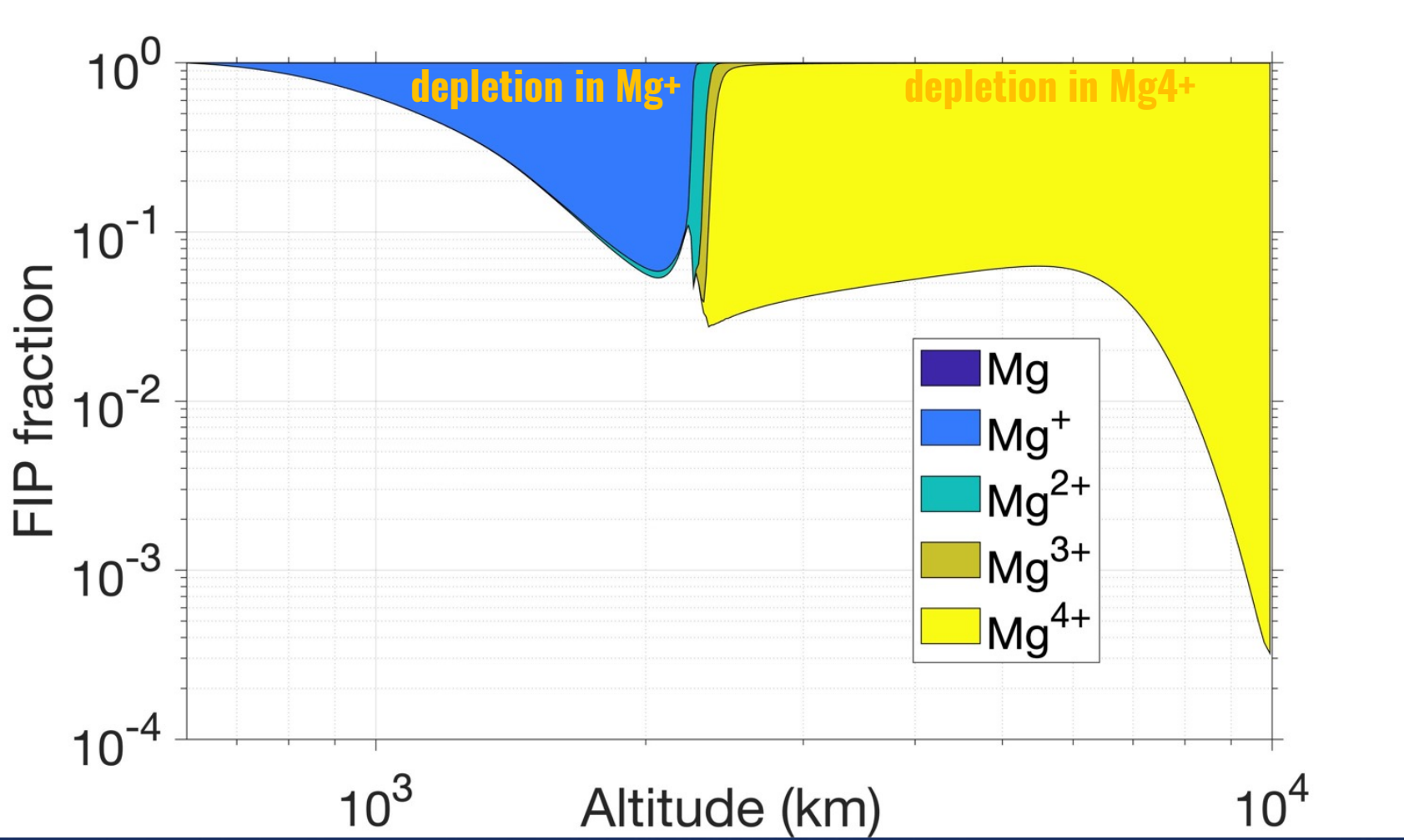
ISAM results: including Oxygen



Gravitational settling of Oxygen is prevented by collisions with the protons up to $\approx 7000\ km$

Work funded by the ERC SLOW_SOURCE project – DLV-819189

ISAM results: including Magnesium:



Magnesium is much heavier
&
Coulomb collisions alone can hardly balance the gravitational pull

Work funded by the ERC SLOW_SOURCE project – DLV-819189

Conclusion

A dynamic chromosphere
(waves + radiation + collisions + partial ioniz)

A quasi-static corona (+TNE)
(heating (Alfvén waves) + less collisions + fully ionized)

A complex interface
(very thin $\approx 100km$ + sharp gradients + unstable)

transfer of energy & heavy ions through the interface

- ISAM: a multi-specie model of the composition of solar atmosphere
- Results: Pure diffusive effects can separate heavy ions in the solar atmosphere
  => But tend to produce an inverse FIP (active stellar coronae)

Work funded by the ERC SLOW_SOURCE project – DLV-819189

Future perspectives

A dynamic chromosphere
(waves + radiation + collisions + partial ioniz)

A quasi-static corona (+TNE)
(heating (Alfvén waves) + less collisions + fully ionized)

A complex interface

OK THANKS TO: 16-moment (heat flux solved explicitely) & LCPFCT to handle sharp gradients

- Further investigation of the FIP effect:

wave-particle interactions & chromospheric mixing & influence from TNE? & more heavy ions

=> On the enigmatic origin of the slow solar wind

Work funded by the ERC SLOW_SOURCE project – DLV-819189