# Simulating the FIP effect in coronal loops using a multi-species kinetic-fluid model

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



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# Motivations

The slow solar wind usually shows anomalies between photospheric and coronal abundances, but only for specific elements.
One mechanism, as stated in past studies (see e.g. *[Culhane et al. 2014]*), suggests that material is exchanged between closed coronal loops and their adjacent open flux tubes (via interchange reconnection for instance). Confined plasma can escape along these open flux tubes to form part of the slow solar wind.

Studying the composition of coronal loops may therefore shed new light on the origin of the slow solar wind.

# The method in a nuthshell

We investigate both the composition and heating of coronal loops using a 1-D multi-species kinetic-fluid model called ISAM.


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# What is the FIP effect?

- It is well-known that the solar atmosphere has a changing composition with altitude *(see e.g. [Feldman & Widing 2003])*.

- Neutral hydrogen (H) ionizes in the chromosphere together with minor ions, the elements with low FIP (e.g. Fe, Mg) ionize deep in the chromosphere while high FIP elements (e.g. He) ionize mostly near the transition region.

- There is an over abundance of low-FIP elements (relative to known photospheric abundances) in particular along (closed) coronal loops observed remotely and in the slow solar wind measured in situ.

These abundance anomalies, the so-called **FIP effect**, have been detected for many decades but their physical origin(s) are still debated


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# A peculiar composition of the solar atmosphere in heavy ions

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

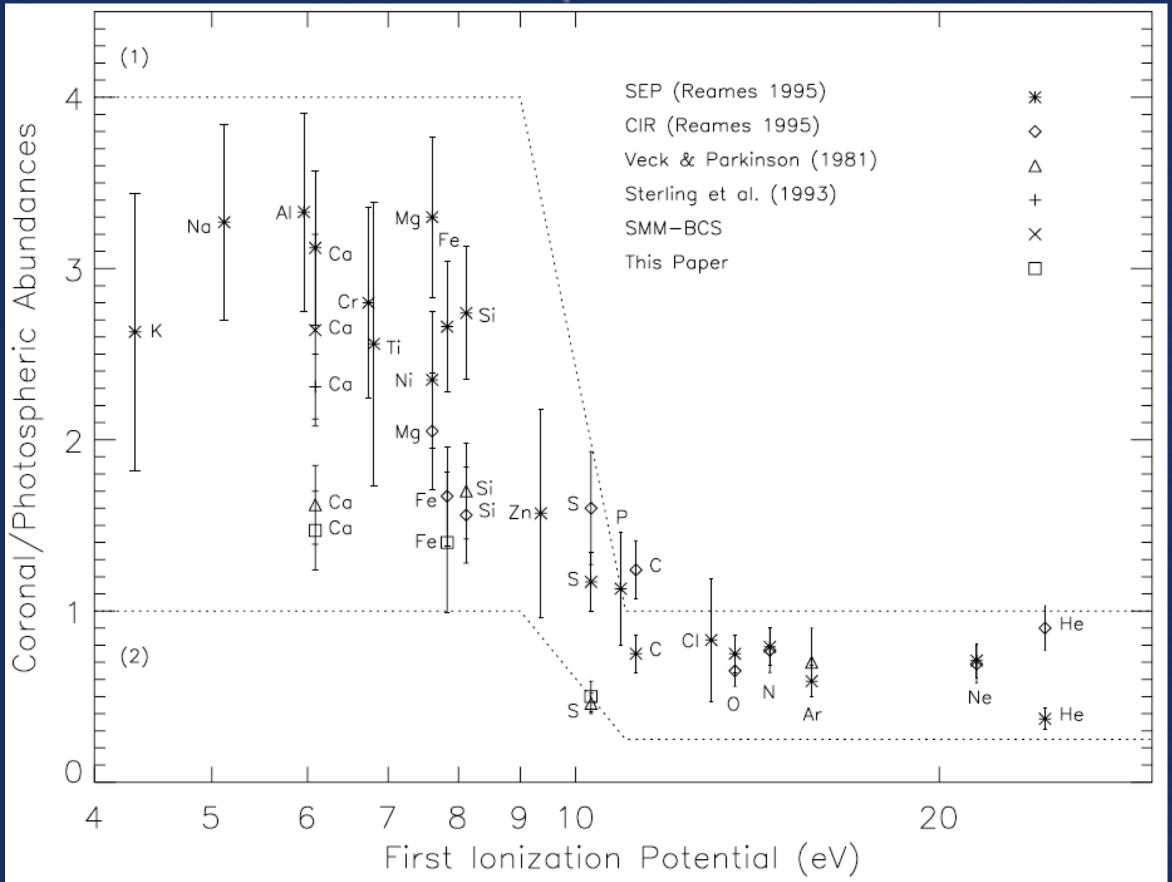


Figure 4 from *[Fludra & Schmelz 1999]*

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

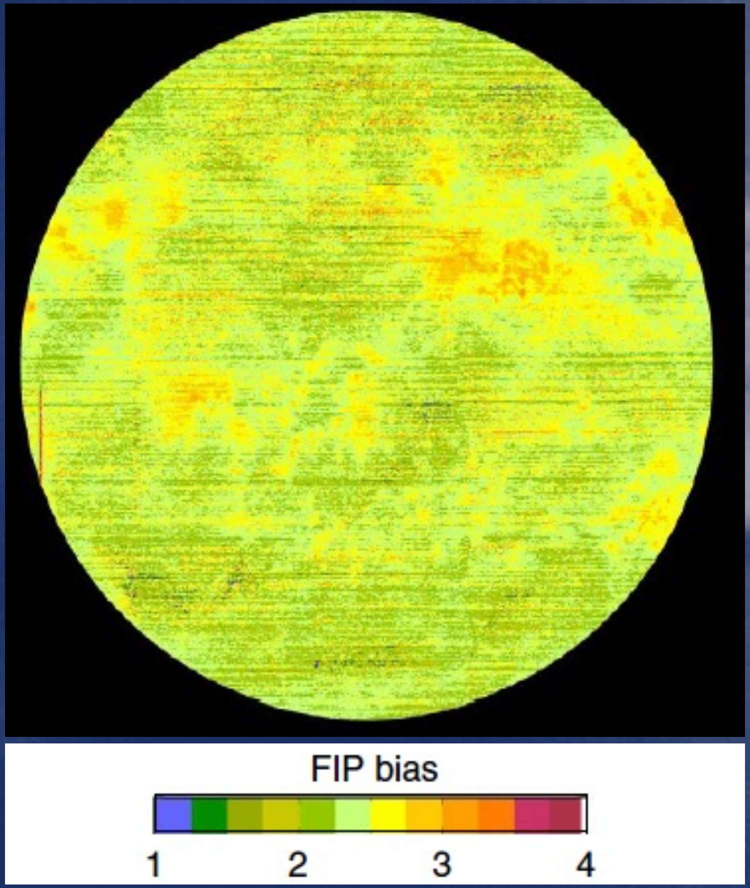


Figure 3 from *[Brooks et al. 2015]* (using Hinode/EIS full-disk observations)


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# On the mysteries of the FIP effect:

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

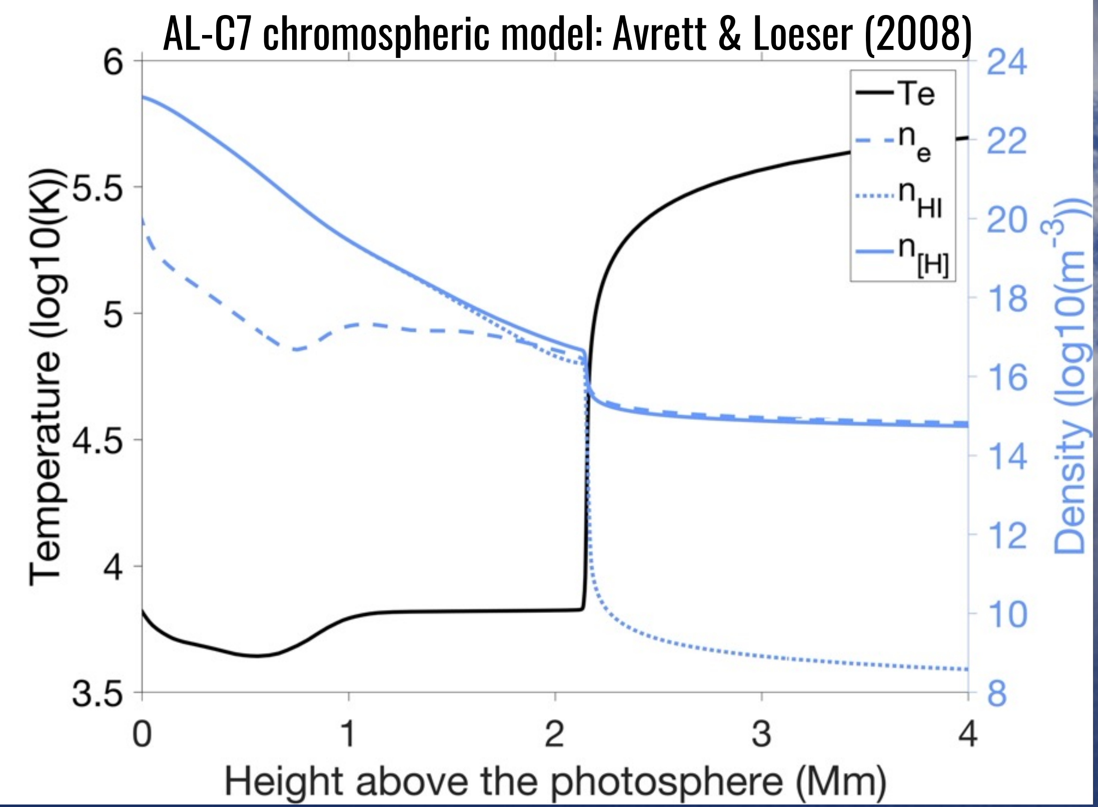
- Where: in the partially ionized chromosphere?

Photoionization of low-FIP first + many collisions

After then the composition becomes «frozen» in the corona

- How:

Coulomb collisions
Gravitational settling
Wave-particle interactions





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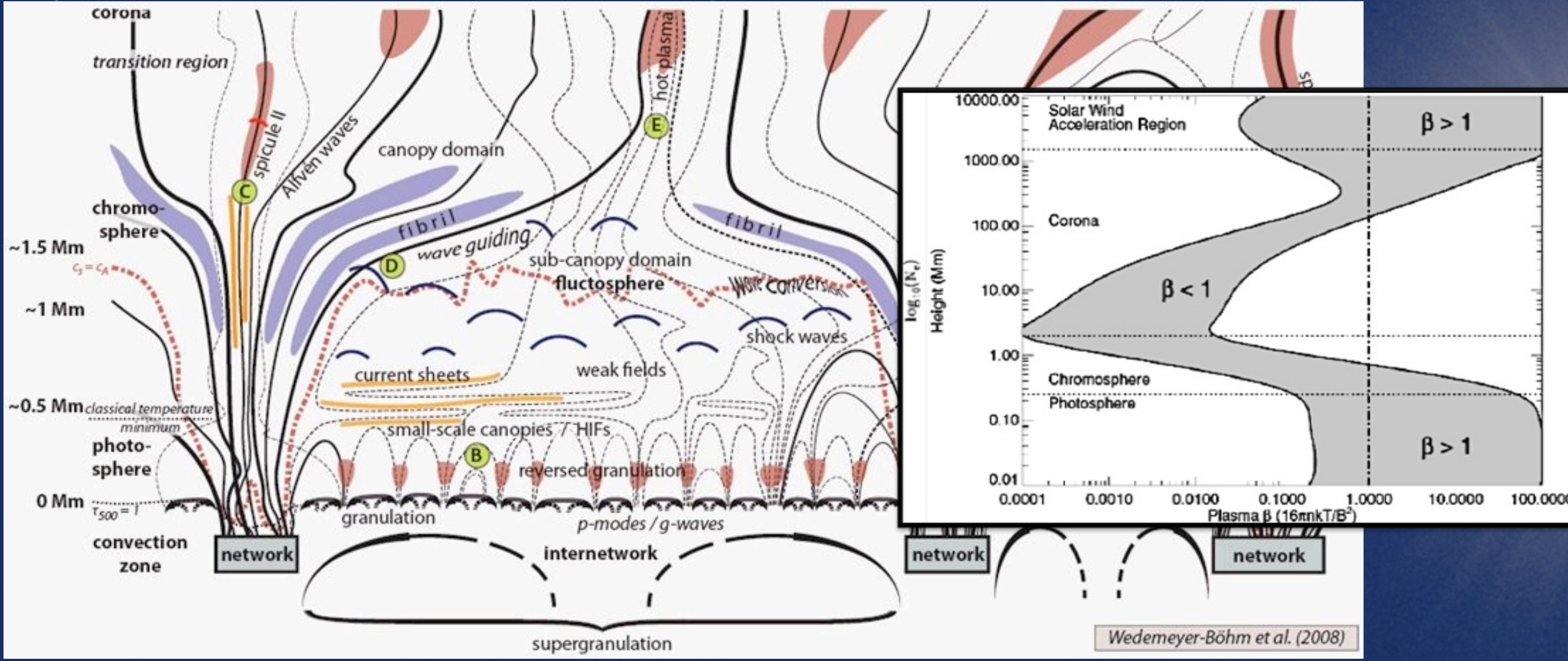
# A persisting mystery due to a complex chromosphere-corona interface:



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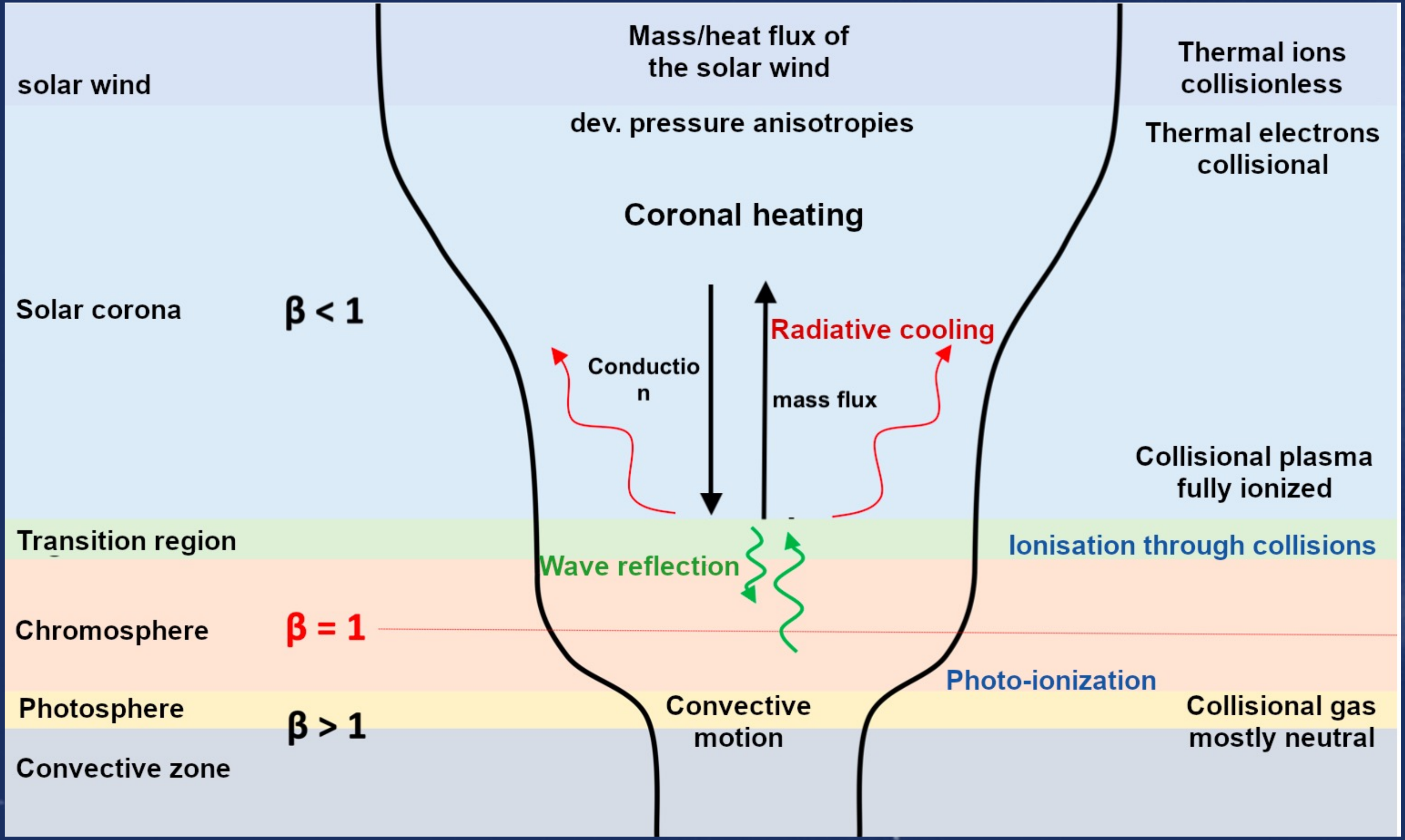
# Summary of our modeling approach: the Irap Solar Atmosphere Model (ISAM)




HDR A. Rouillard (2021)

Based on the IPIM ionospheric code *([Blelly & Schunk 1993],[Marchaudon & Blelly 2015])*

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

Gyrotropic approx along a given 3-D magnetic field line

Multi-specie

H + p + $e^-$ + heavy particles

Collisions & ioniz/recomb



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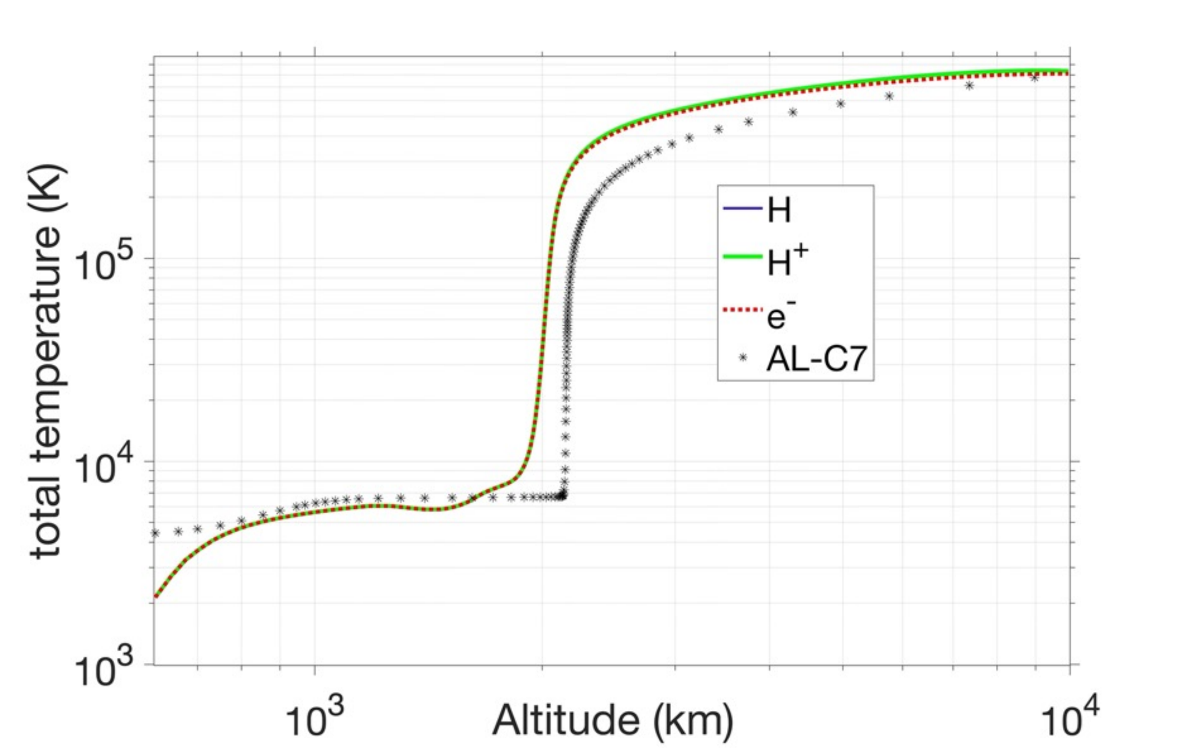
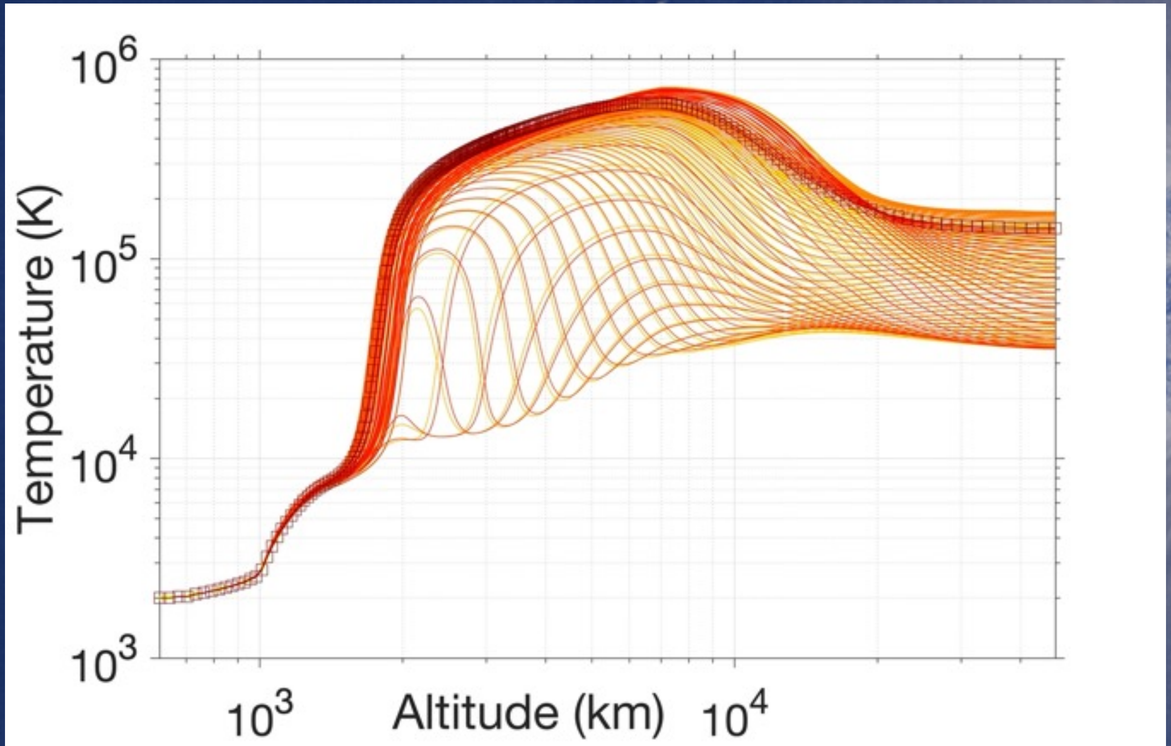
# Quasi-static vs dynamic coronal loops in ISAM:

## Thermal equilibrium




## Thermal non-equilibrium (TNE)




[Poirier et al. 2022, in prep]

=> Does TNE affects the transfer of heavy ions through the transition?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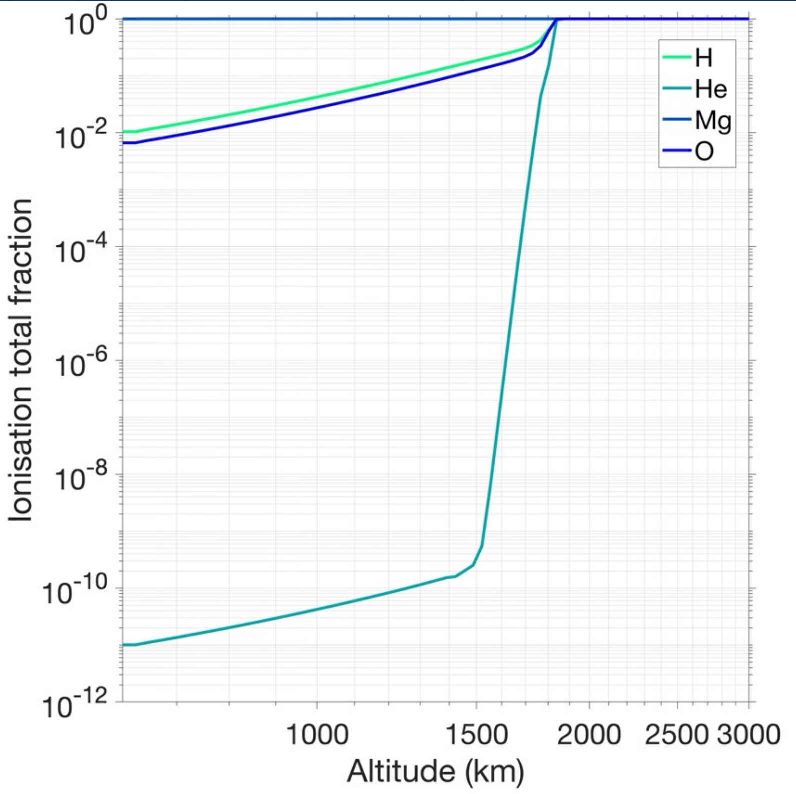
# On the modeling of partial ionization:

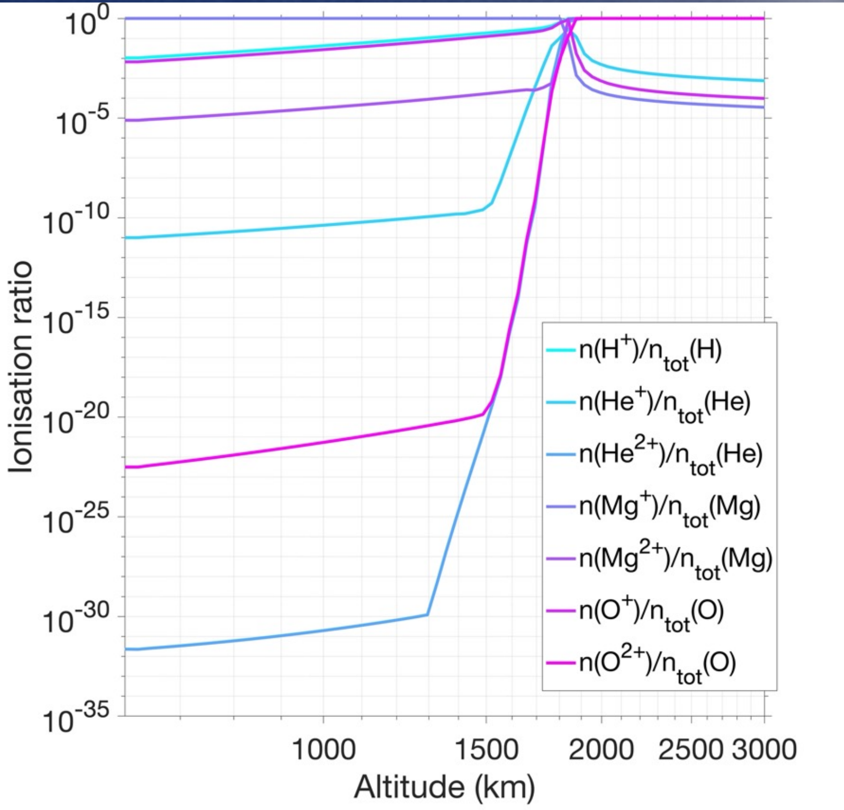
- Ionization: photoionization, impact with $e^-$, auto-ionization, charge-exchange
- Recombination: radiative, dielectronic, charge-exchange $H^+ + O \rightarrow H + O^+$

Total ionization fraction




[Poirier et al. 2022, in prep]

Partial ionization fractions



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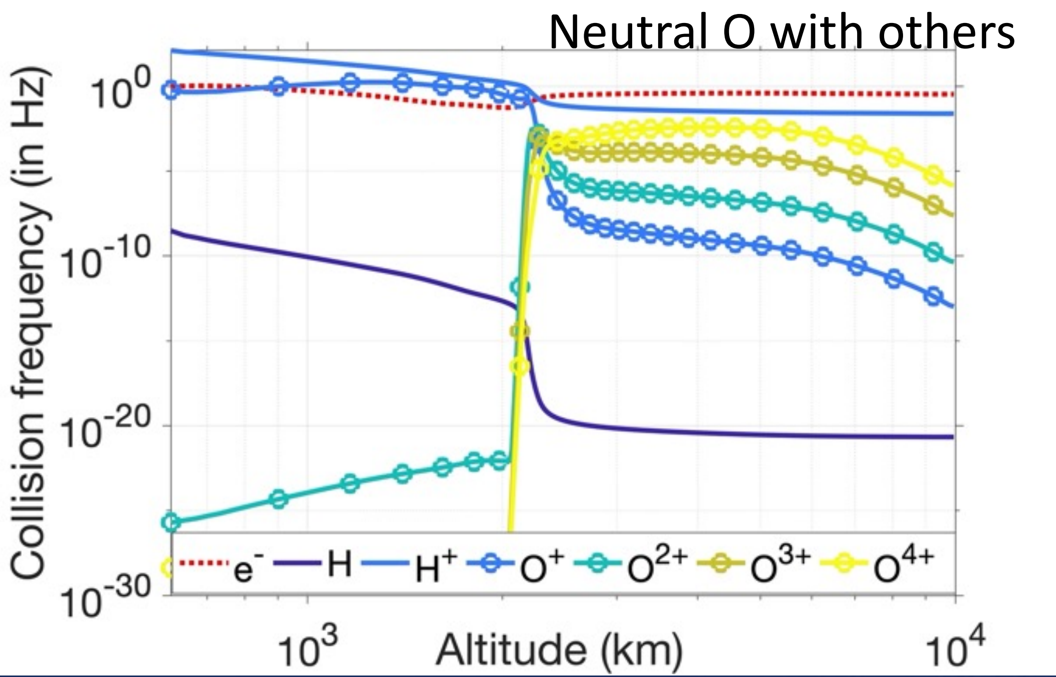
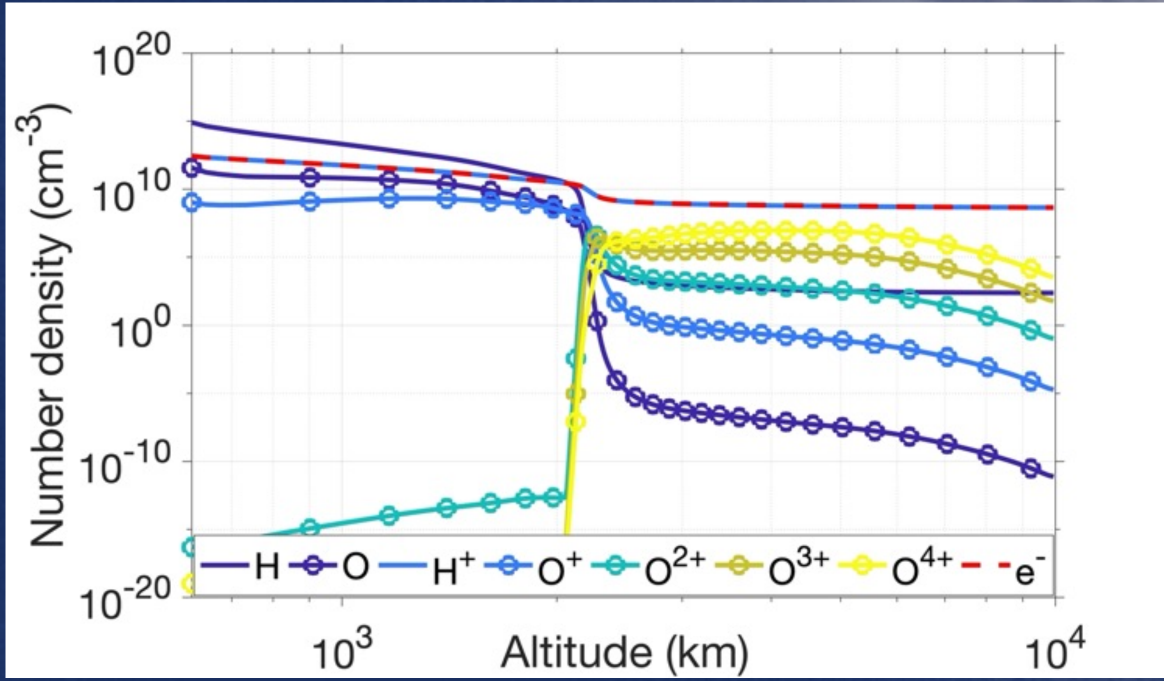
# A comprehensive treatment of particle interactions:

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




[Poirier et al. 2022, in prep]

=> Collisional coupling dependent on the local density & temperature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# 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)

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


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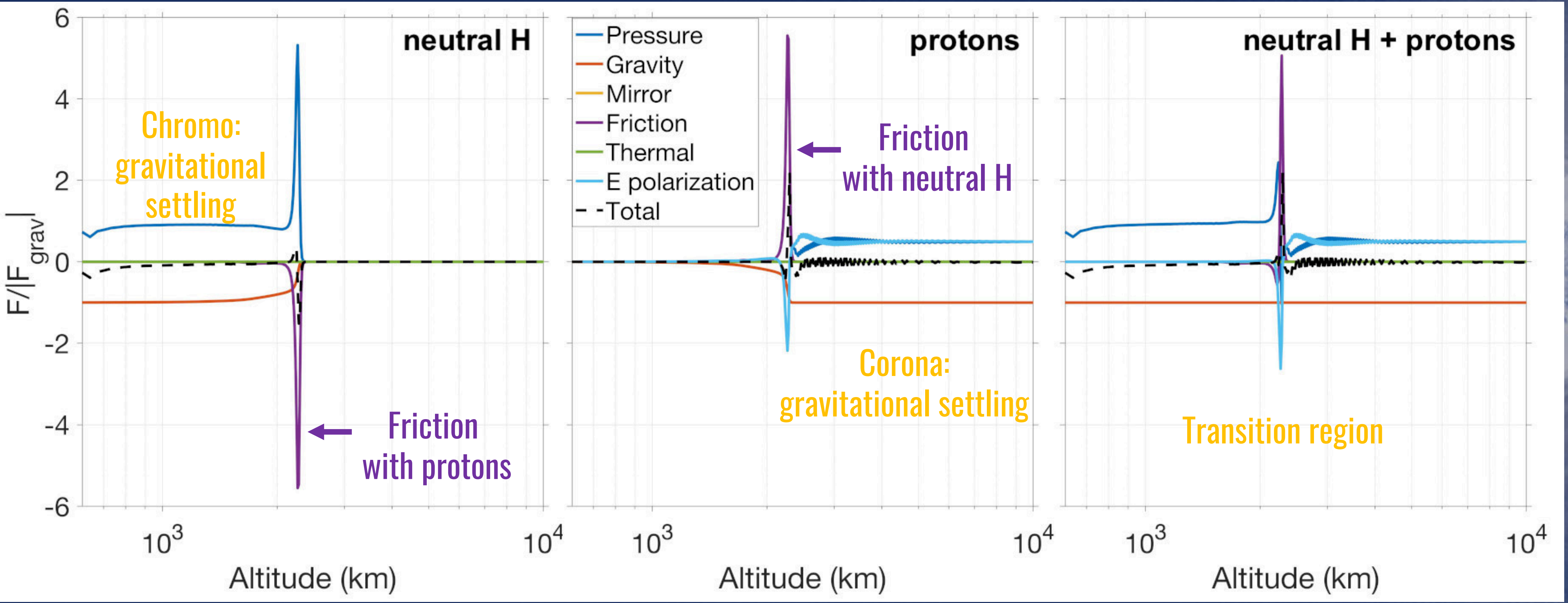
# ISAM results: case of a pure H-p-$e^-$ atmosphere:




[Poirier et al. 2022, in prep]

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



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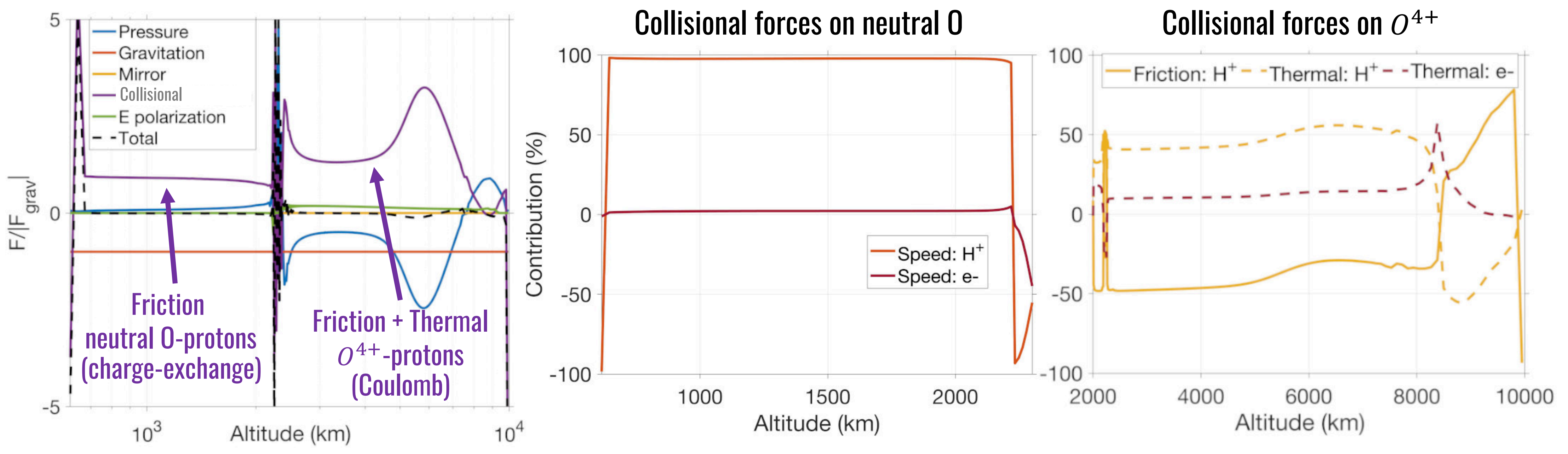
# ISAM results: including Oxygen (O):




*[Poirier et al. 2022, in prep]*

Oxygen strongly coupled with protons through charge-exchange & Coulomb

Stratification of Oxygen is partially prevented thanks to both thermal & friction effects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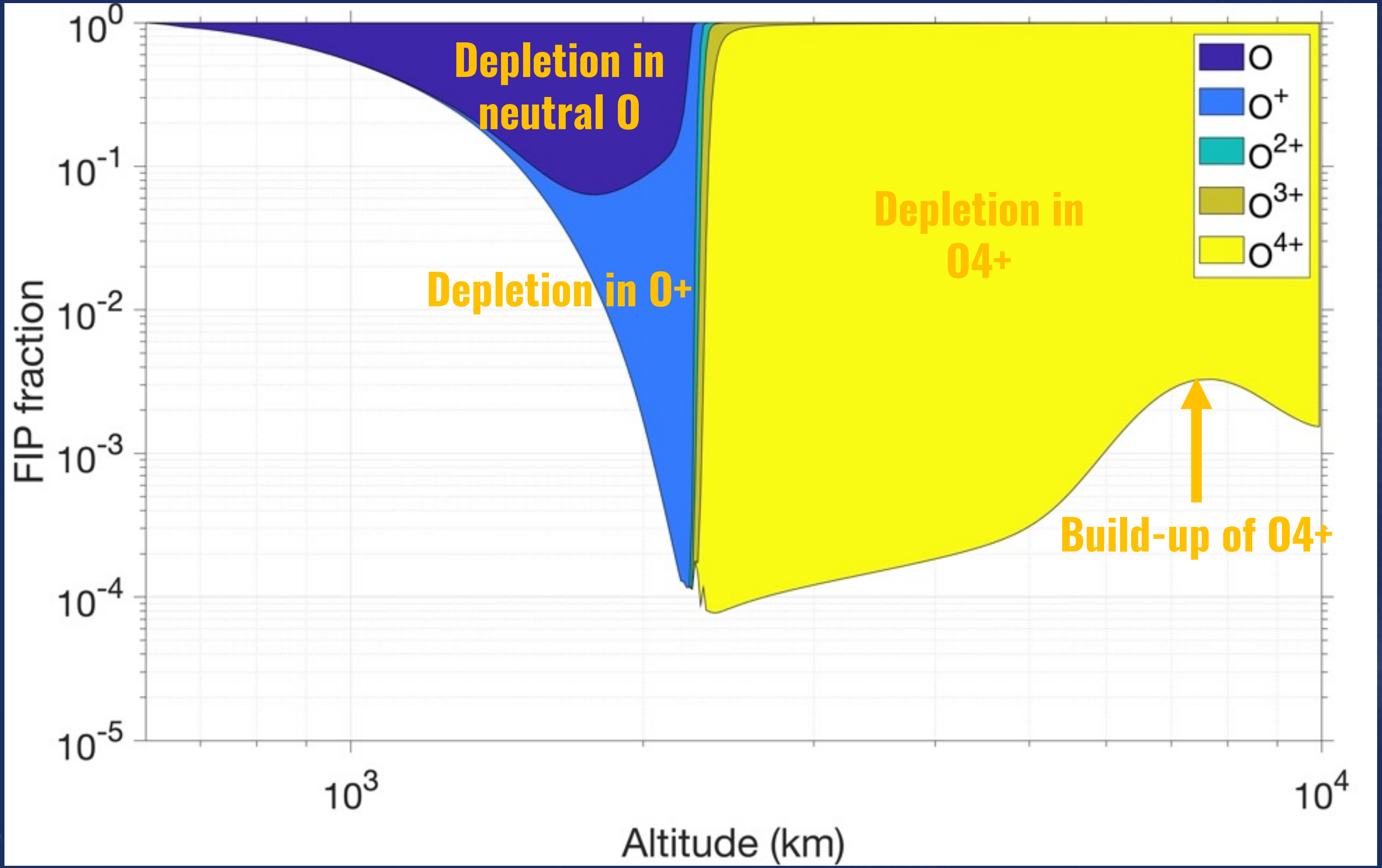
# ISAM results: including Oxygen (O)




*[Poirier et al. 2022, in prep]*

$$\text{FIP fraction(alt)} = \frac{n_{[O]}/n_{[H]}\big|_{alt}}{n_{[O]}/n_{[H]}\big|_{photosphere}}$$

**If no collisions with protons:**

FIP fraction $\approx 8\times10^{-52}$ at alt=2300 km

**If collisions with protons:**

FIP fraction $\approx 10^{-4}$ at alt=2300 km

**The collisional coupling with protons weakens at alt $\approx$ 7300 km**



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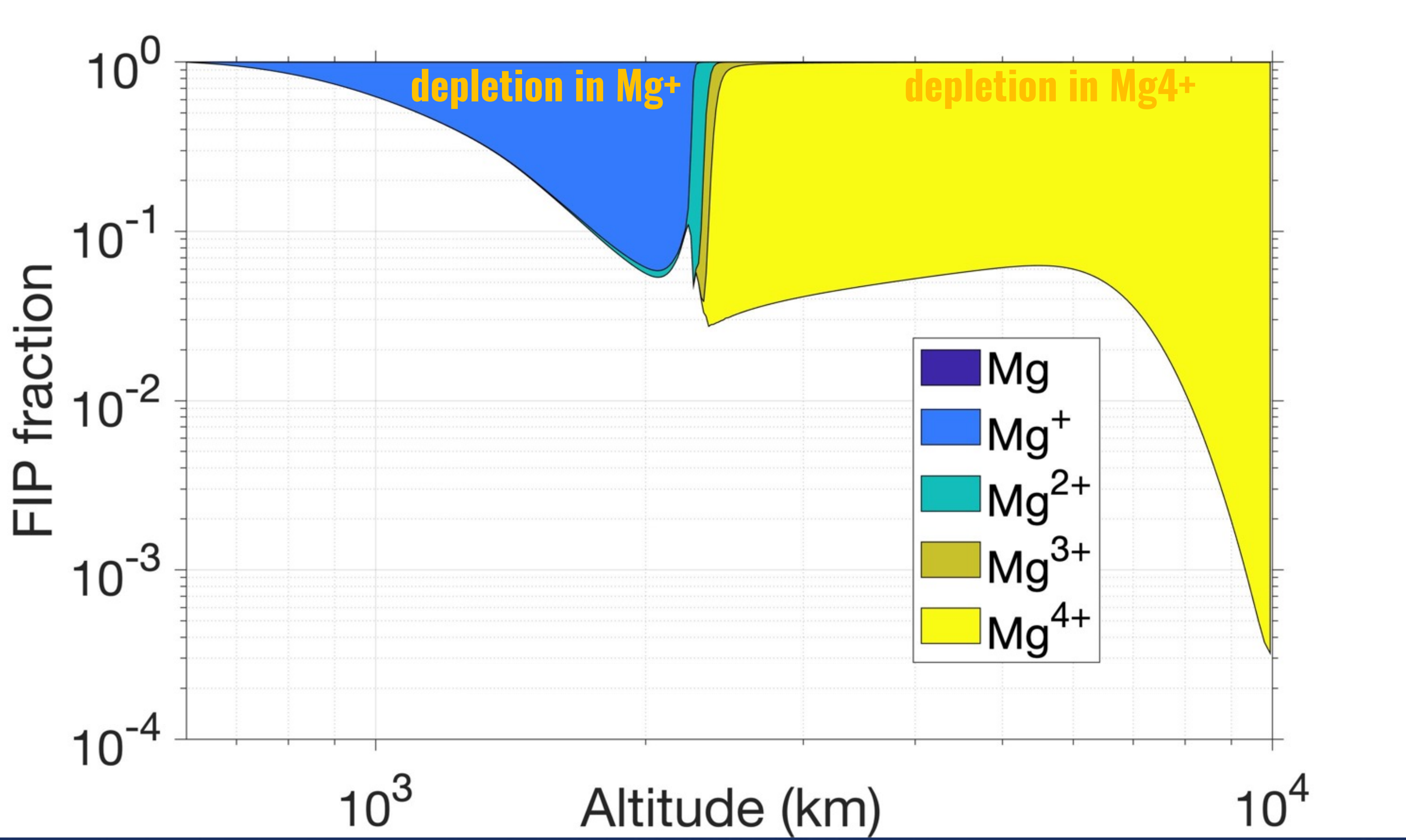
# ISAM results: including Magnesium (Mg):




[Poirier et al. 2022, in prep]

Mg is much heavier than O (16->24 uma), still it remains less depleted than O

In the chromosphere, Mg is fully ionized ⇒ stronger collisional coupling with protons (Coulomb)

But a partial stratification of Mg still occurs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# Conclusion

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

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

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

We studied the transfer of energy & heavy ions through the interface

- ISAM: a multi-specie model of the composition of the solar atmosphere
- Results: Pure diffusive effects can separate heavy ions in the solar atmosphere
  => But tend to produce an inverse FIP (not observed at the Sun but in active stellar coronae)


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# Future perspectives & improvements

Green color = already integrated in ISAM
Orange color = can be improved
Red color = being tested in ISAM

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: a 16-moment approach (heat flux solved explicitely) & LCPFCT to handle sharp gradients

- Further investigation of the FIP effect with ISAM:

wave-particle interactions & chromospheric mixing & influence from TNE & more heavy ions (high-FIP: e.g. Helium)

Thanks for your interest! Feel free to contact me by email: npoirier@irap.omp.eu


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