Connecting Solar-Heliosphere Structures Across the PUNCH Field of View: Heavy Ion Diagnostics

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Rivera+2022

Ideas developed through conversations with Enrico Landi, Sue Lepri, John Raymond, Martin Laming

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

General properties of heavy ions

Compositional makeup of solar wind plasma

- Can tell you what part of the Sun it came from
- How it evolved in through the low and middle corona

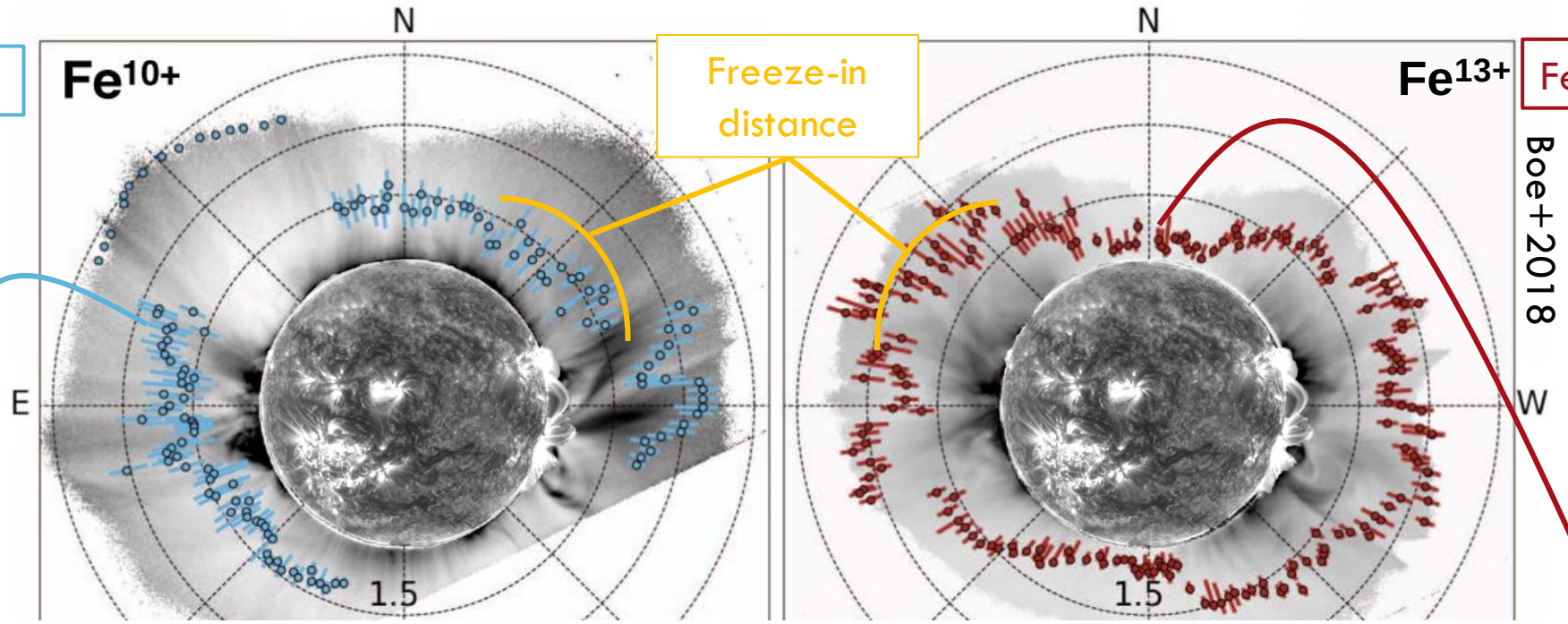
Preserve coronal properties – plasma intercepted by spacecraft within the PUNCH field of view can be:

- linked to properties and processes at the Sun
- used to map structures measured at spacecraft alignments

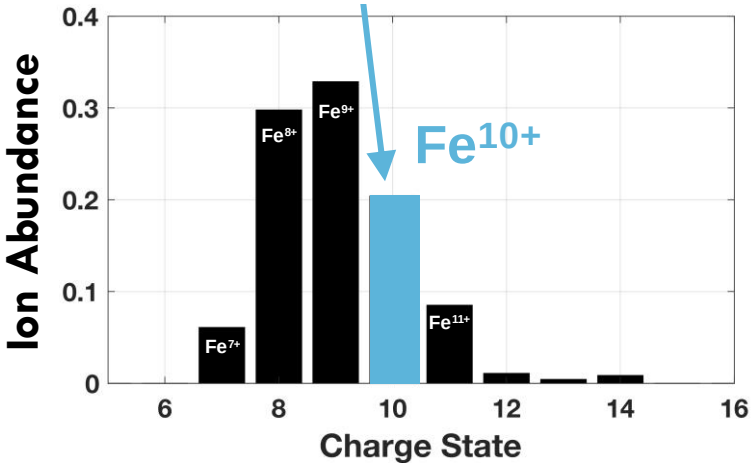
Conditions of solar wind outflow: Ion abundance

Fe XI 789.2 nm

Fe XIV 530.3 nm

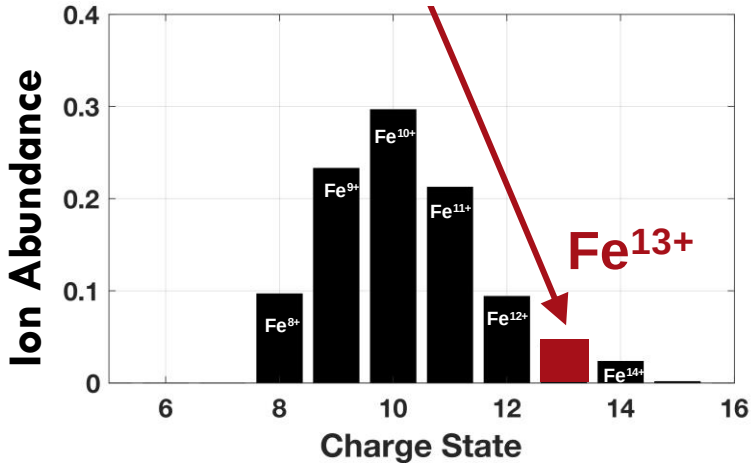


Streamer belt wind

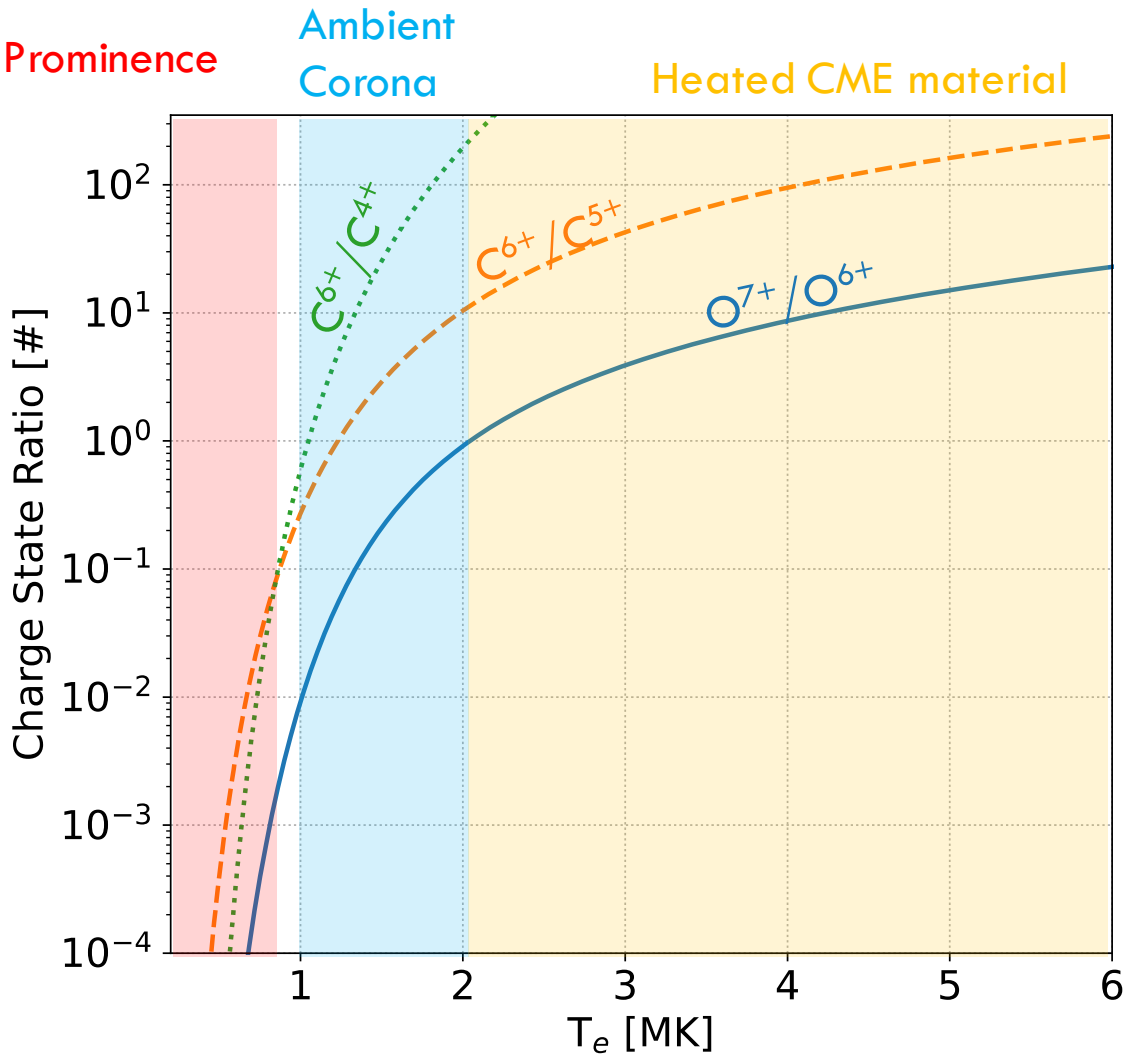


- **Freeze-in is unique** for individual ions (Landi+2012, Rivera+2019)
- Relative abundances **fixed** beyond freeze-in altitude – same as in-situ
- Plasma **across PUNCH FOV** remains imprinted coronal **thermal structure**
- NEI effects, non-thermal electrons – reflected in charge states

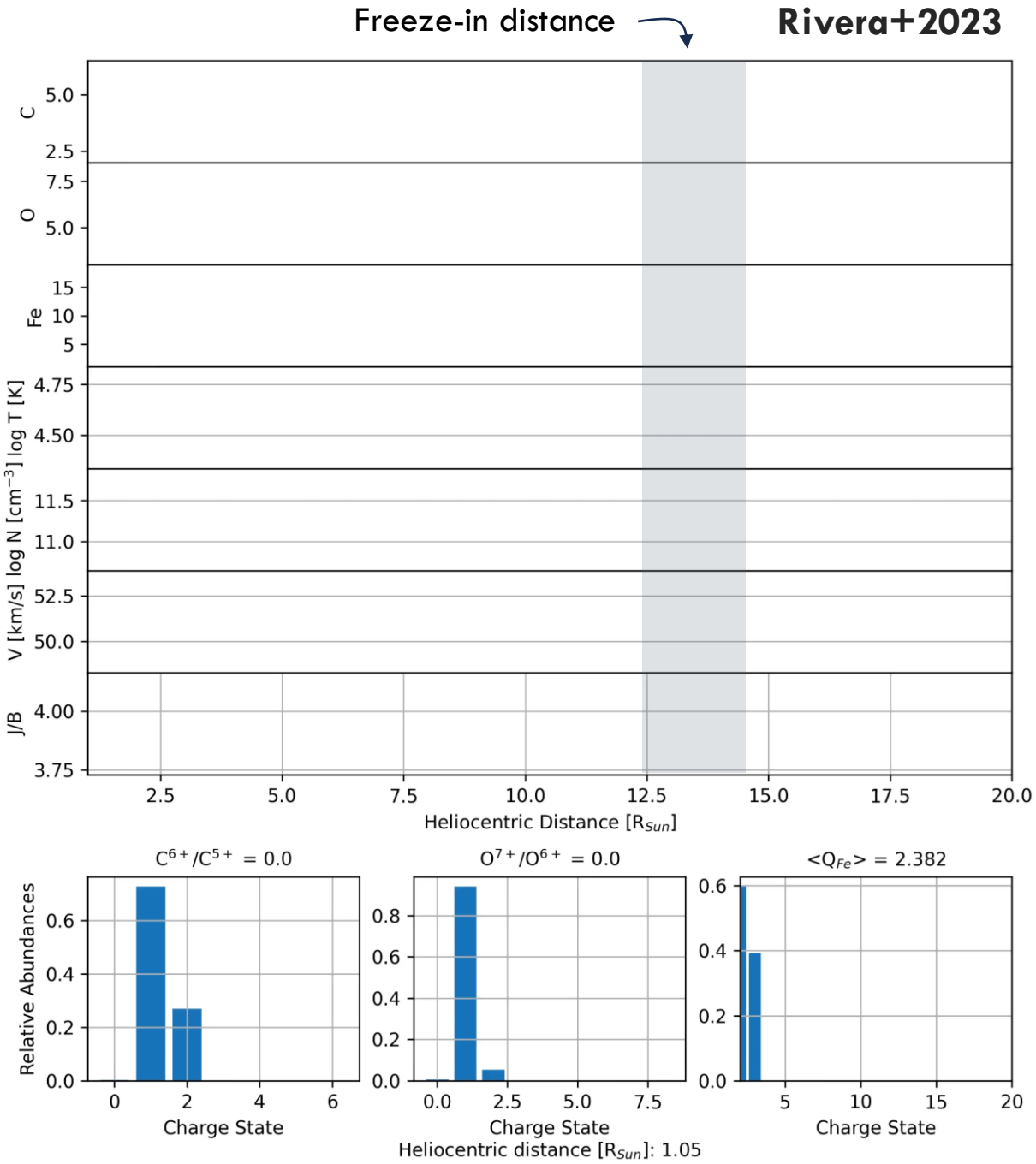
Coronal hole wind



Non-equilibrium ionization modeling



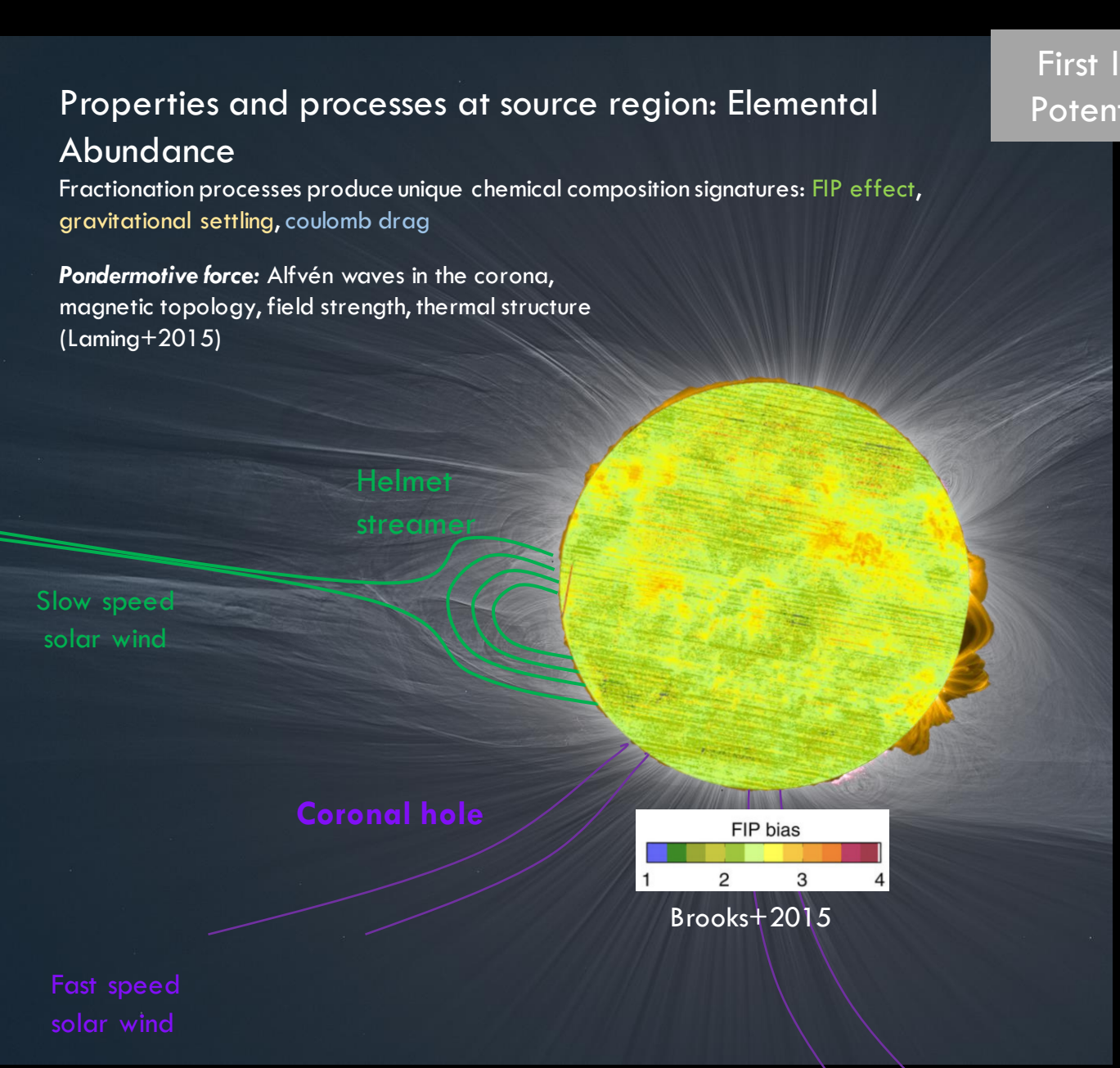
Ions measured in the heliosphere are a product of the ionization and recombination experienced below freeze-in



Properties and processes at source region: Elemental Abundance

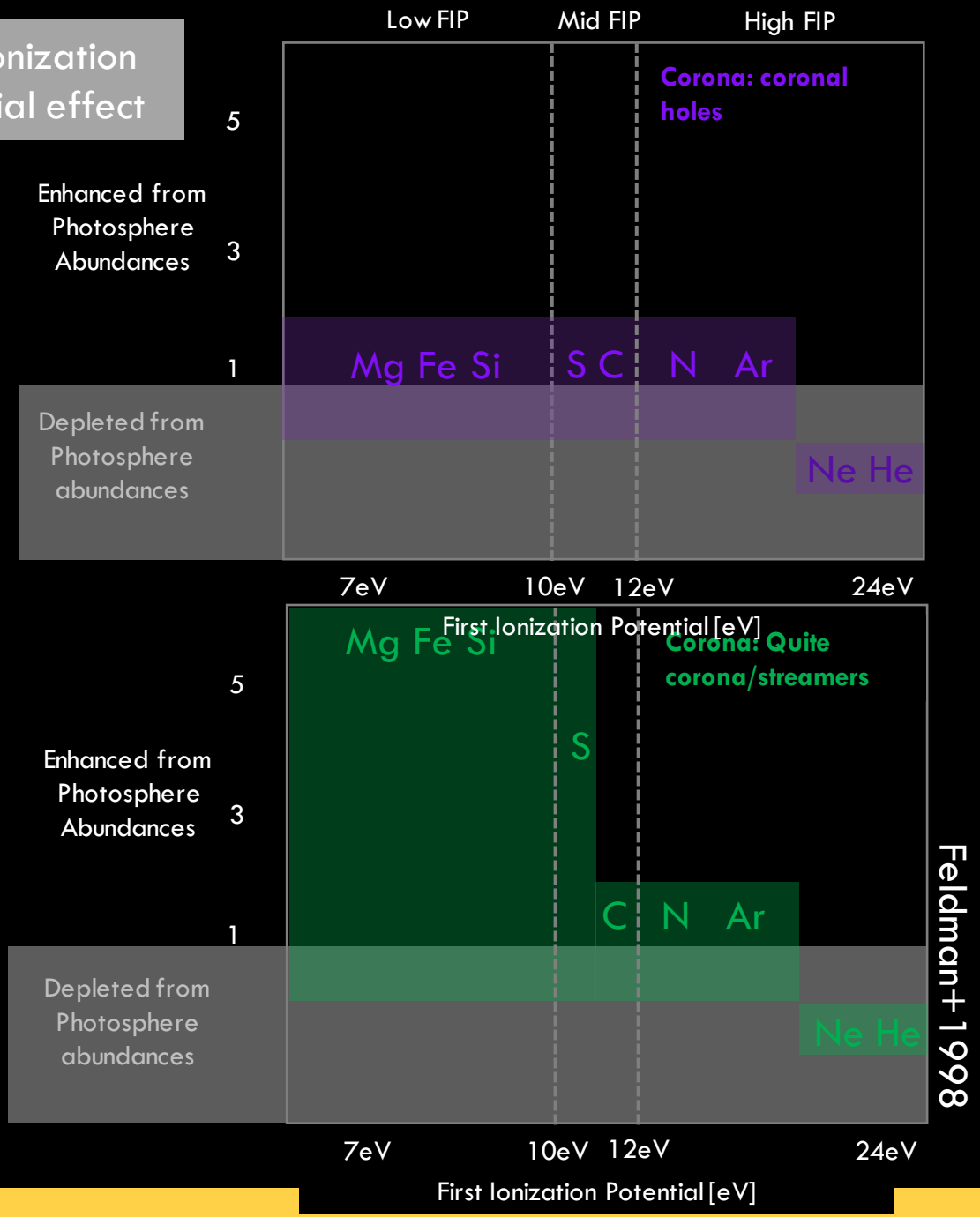
Fractionation processes produce unique chemical composition signatures: FIP effect, gravitational settling, coulomb drag

Pondermotive force: Alfvén waves in the corona, magnetic topology, field strength, thermal structure (Laming+2015)



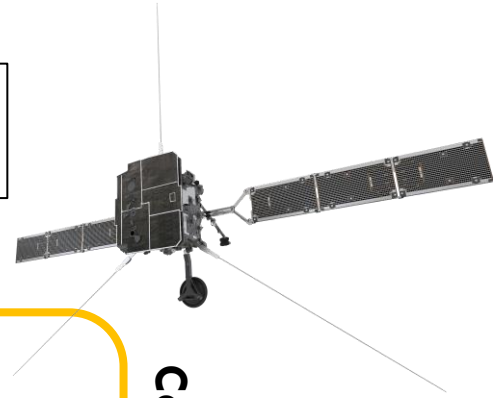
Brooks+2015

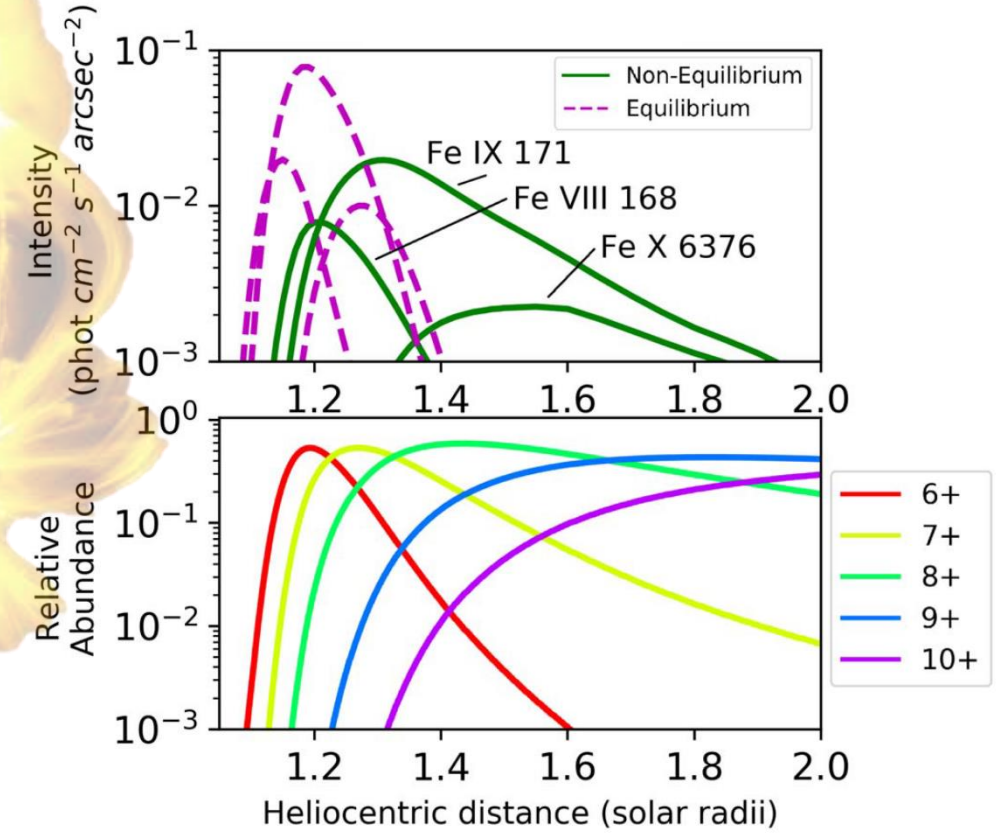
First Ionization Potential effect



Coronal – Heliospheric connection

[matched up with] emission ↔ derive outflow thermodynamics ↔ [matched up with] ion composition





Rivera+2019a, b

$I_{obs} = I_{coll} + I_{rad}$

Collisional

$$I_{\rm coll} = \frac{1}{4\pi}\int_{-\infty}^{\infty} G(T, n_e)\,\varphi(T)\,dT$$

$$G(T, n_e) = \frac{n_j(\mathrm{X}^{+q})}{n(\mathrm{X}^{+q})}\frac{n(\mathrm{X}^{+q})}{n(\mathrm{X})}\frac{n(\mathrm{X})}{n(\mathrm{H})}\frac{n(\mathrm{H})}{n_e}\frac{A_{ji}}{n_e}$$

Ion abundance | Elemental abundance

Radiative

$$I_{\rm rad} = \frac{BA_{ij}}{4\pi A_{\rm tot}}\int_{-\infty}^{\infty} W(r)N_{\rm abs}p(\varphi)F_{\rm inc}D(v)\,dr$$

$$N_{\rm abs} = \frac{n(\mathrm{X}^{+q})}{n(\mathrm{X})}\frac{n(\mathrm{X})}{n(\mathrm{H})}\frac{n(\mathrm{H})}{n_e}n_e$$

Connection to PUNCH science

Linking source region characteristics to heliospheric structures observed continuously by PUNCH

Heavy ions ideal for mapping throughout the sun-heliosphere system

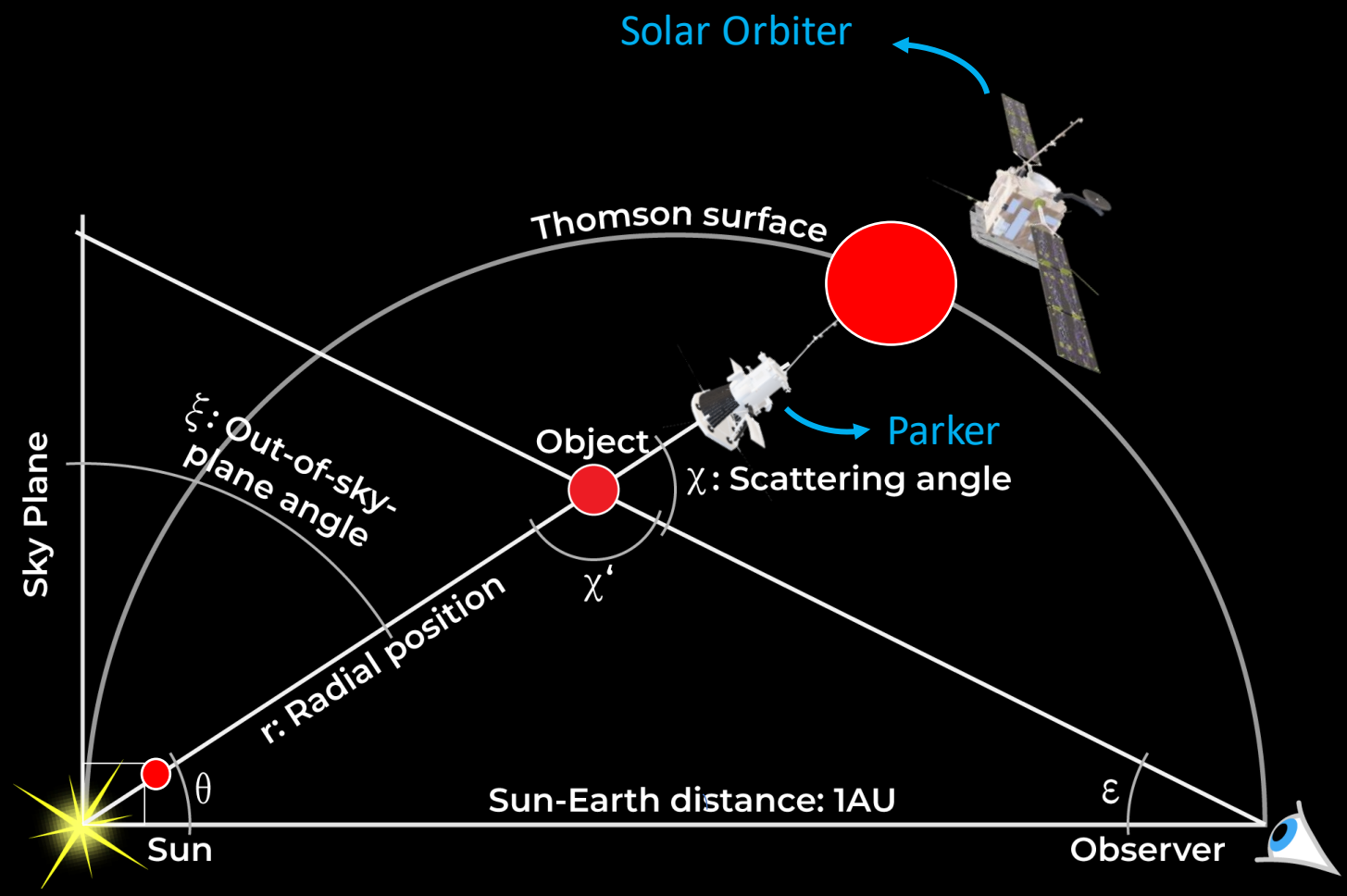
corona to heliosphere

heliosphere to heliosphere

PUNCH provides critical insight to the large-scale morphology, flow, detailed sub-structure of solar wind from Sun to spacecraft and between them –

- *Coronal context to PUNCH observations*
- *Enhancing conjunction studies*

Science Objectives: 1A (solar wind flow), 1C (Alfvén surface), 2A (CME evolution)



Adapted from PUNCH website: https://punch.space.swri.edu/

Connection to PUNCH science

PUNCH can strengthen the connection between particle observations and their remote sensing counterparts

Unifying different remote and in-situ observations of solar plasma

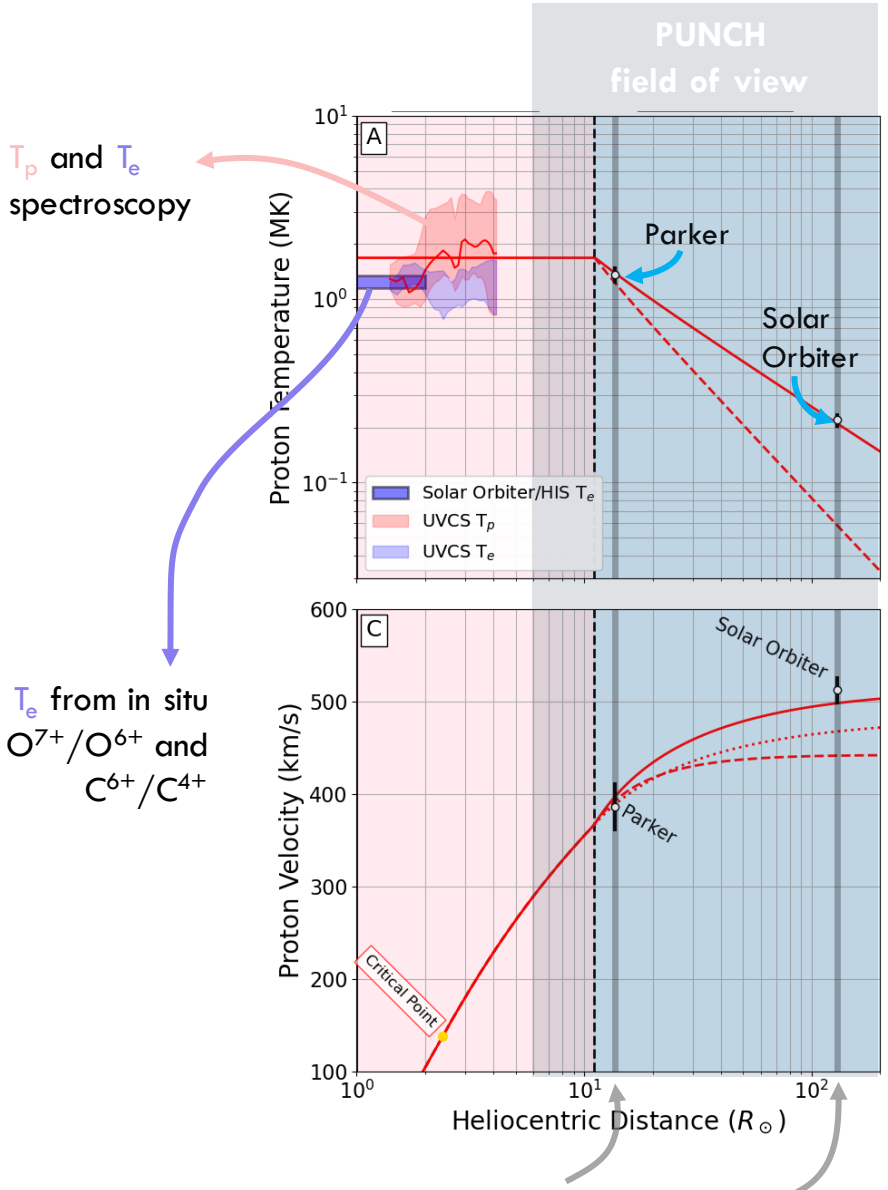
Elemental: Closed field dynamics are exhibited by the elemental makeup of plasma

Ions: Outflow dynamics as reflected in charge states

More complete picture of the full spatiotemporal plasma evolution

coronal dynamics,
solar wind formation,
super-sonic expansion,
sub-Alfvénic character in connection fully developed solar wind structures

Science Objectives: 1A (solar wind flow), 1C (Alfvén surface), 2A (CME evolution)



Fe/O ratio – source region in connection to PFSS field line tracing

Helium composition – connecting stream between spacecraft

(Rivera, Badman, +2024, *in review*)

Heavy Ion Composition

Detection

Sun (photons)
Spectroscopy

Heliosphere (particles)
Ion resolving particle detectors

Quantity

Elemental Abundance (e.g., Fe)

Ion Abundance (e.g., Fe^{12+} or Fe XIII)

Ion Temperature/Speed

Diagnostic

Properties and processes at source region

Conditions of solar wind outflow

Non-thermal process i.e., wave-particle interactions, turbulence

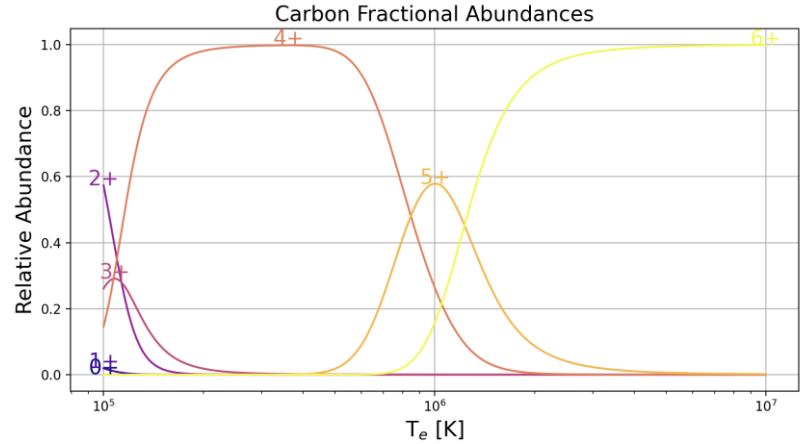
Open Questions

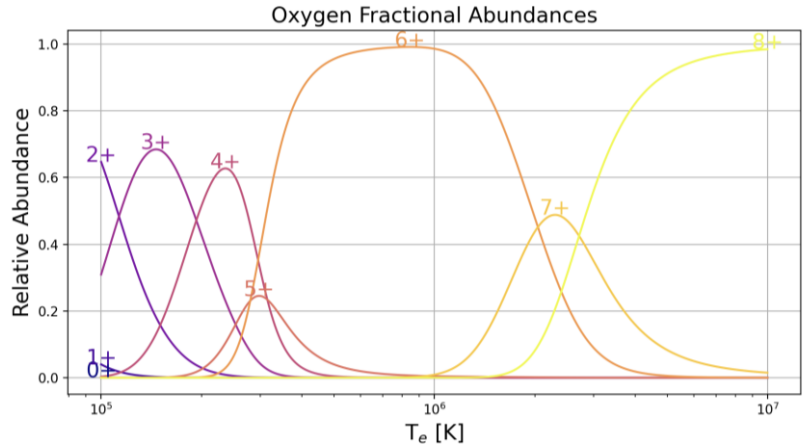
1) What drives the **compositional variation across coronal structures** and their associated solar wind streams?

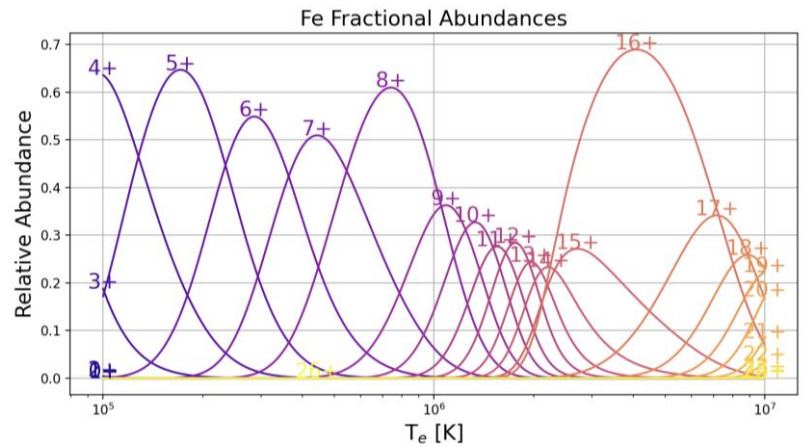
3) What are the specific **drivers of solar wind release**? What are the conditions of solar wind outflow?

4) What is the contribution and **interplay of reconnection, waves, and/or turbulence** driving the extended acceleration and heating of solar wind and transient plasma?

2) What are the **relative contributions** of active regions, quiet Sun, and coronal holes to the solar wind?


Carbon Fractional Abundances
Relative Abundance
T_e [K]
0+
1+
2+
3+
4+
5+
6+


Oxygen Fractional Abundances
Relative Abundance
T_e [K]
0+
1+
2+
3+
4+
5+
6+
7+
8+


Fe Fractional Abundances
Relative Abundance
T_e [K]
3+
4+
5+
6+
7+
8+
9+
10+
15+
16+
17+