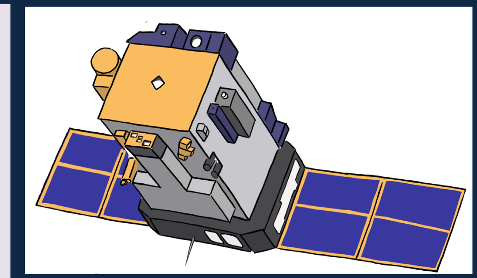


Estimating Ion Temperatures at the Polar Coronal Hole Boundary

Yingjie Zhu[1†], Judit Szente[1], Enrico Landi[1]

[1]Department of Climate and Space Sciences and Engineering, University of Michigan

[†]DKIST Ambassador, yjzhu@umich.edu

Introduction & Motivation

Alfvén waves and other MHD waves and turbulences might be one of the causes that heat the million-degree solar corona. Some of the wave heating models, like the ion-cyclotron model, predict that the ion temperatures (T_i) depend on the ion charge-to-mass ratios (Z/A). However, it's difficult to measure the ion temperature precisely from spectral line widths, since both the thermal motion and wave-induced nonthermal (NT) motion ξ broaden the lines.

Previous study suggested:

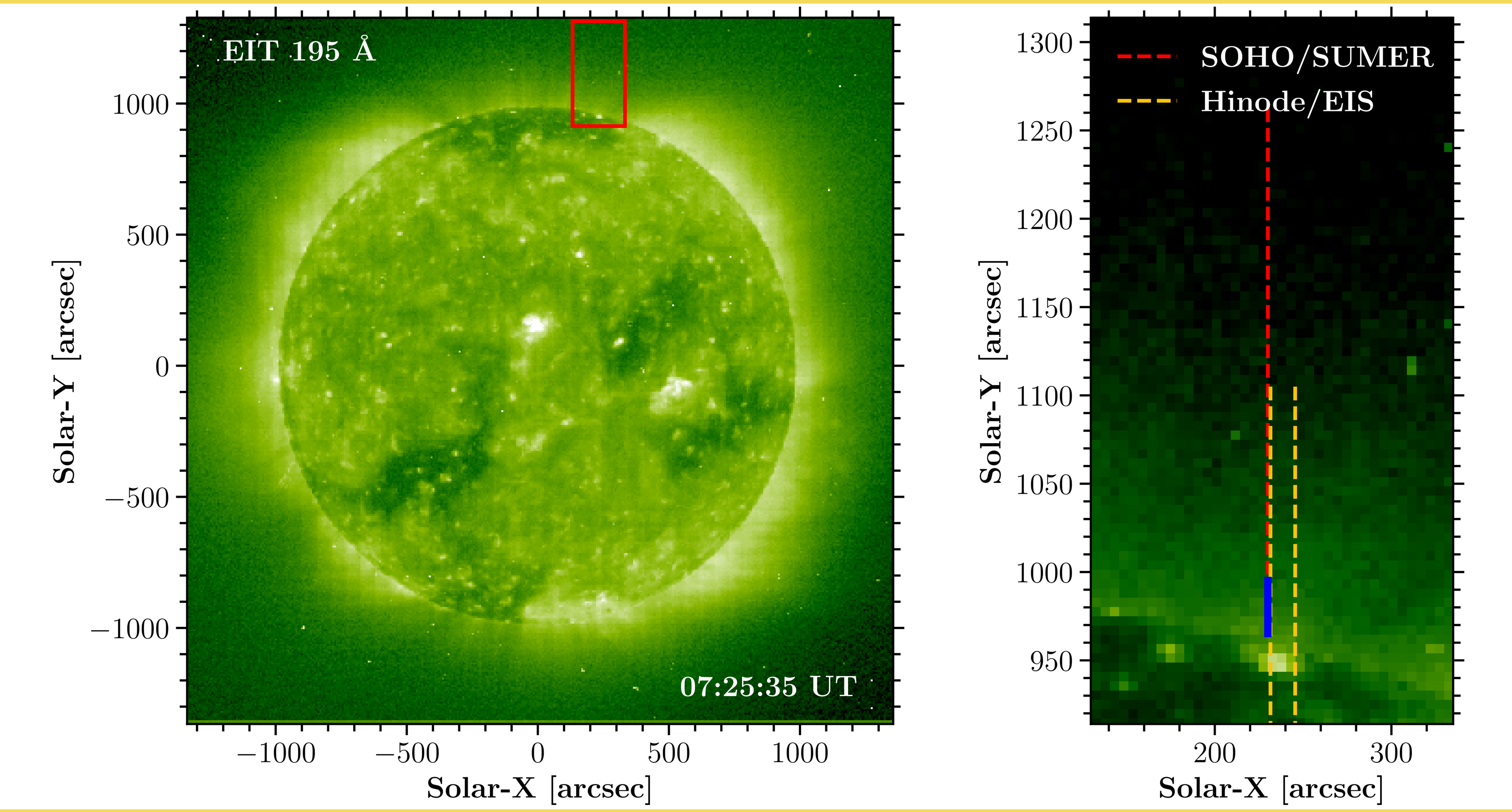
- T_i remains constant or decreases with Z/A (Tu et al. 1998).
- $T_i > T_e$ in the quiet Sun, with no correlation to Z/A (Landi 2007).
- $T_i > T_e$ in the coronal hole, decrease monotonically with Z/A (Dolla et al. 2008) or nonmonotonic depedence (Landi et al. 2009)

Scientific Questions:

- How does the T_i vary with Z/A in the polar coronal hole (especially low Z/A elements)?
- Does the T_i deviate from T_e in the polar coronal hole?

Methodology

Simultaneous Hinode/EIS and SOHO/SUMER observation of an off-limb polar coronal hole on 2007 November 16 at ~ 1.03 Rsun.



The positions of the SUMER and EIS slit on SOHO/EIT 195 context images of the coronal hole. Data along the slit marked by blue (right) are analyzed.

Data Reduction & Analysis (Tu et al. 1998)

- T_i and ξ are coupled in line widths $\Delta\lambda^2 = 4\ln 2\left(\frac{\lambda_0}{c}\right)^2\left(\frac{2k_BT_i}{m_i}+\xi^2\right)$
- Assuming a universal non-thermal width ξ for all lines
- Maximum NT velocity $\xi_{\max}$ from the narrowest line assuming zero thermal broadening --> Minimum T_i
- Assuming zero NT velocity for all lines --> Maximum T_i

Simulation

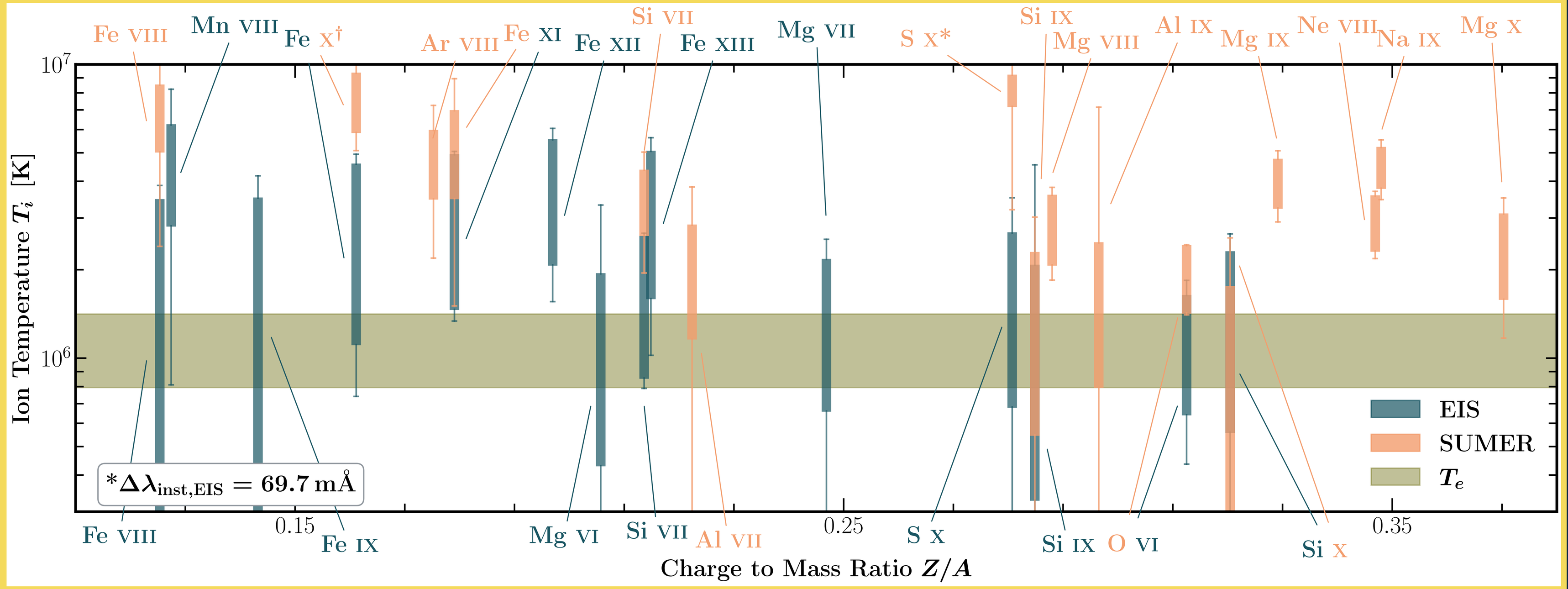
- Alfvén Wave Solar Wind Model - Realtime (AWSoM-R, Sokolov et al. 2021) simulation of the global corona. SPECTRUM (Szente et al. 2019), a post-processing module, for spectral line synthesis.

Takeaway:

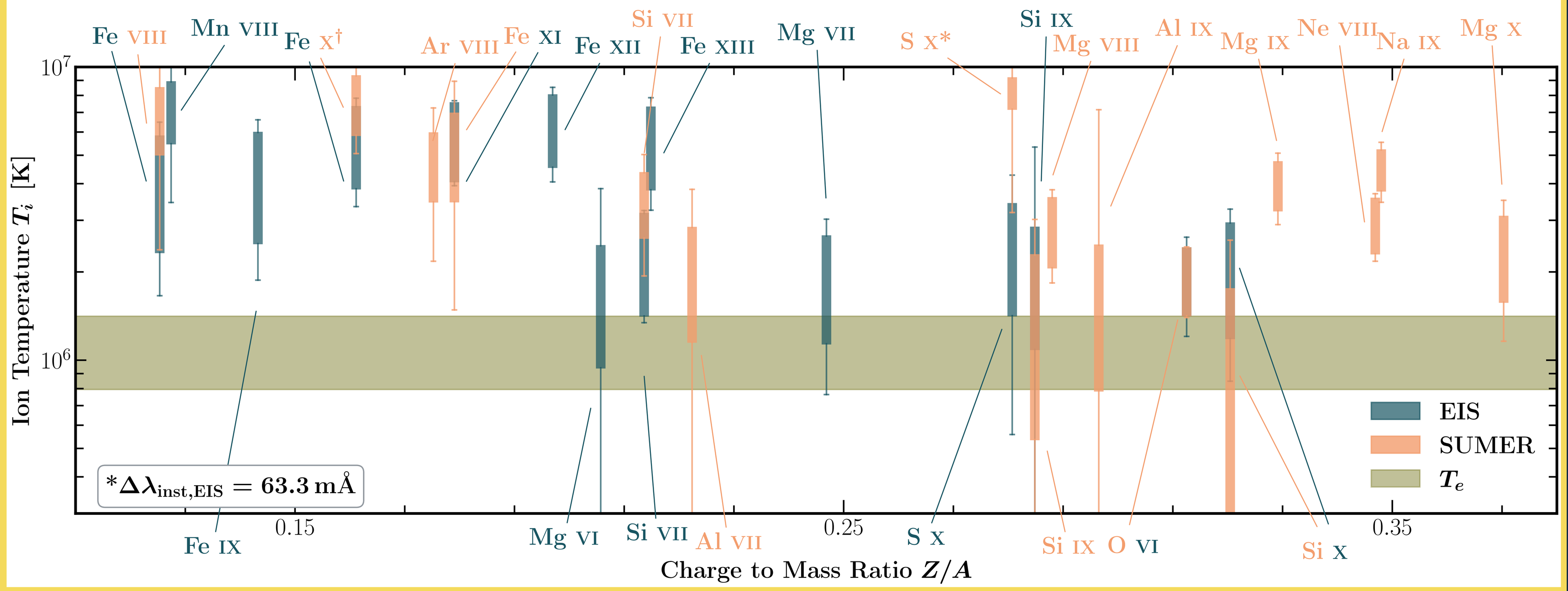
Ion temperatures are higher than the electron temperature at the polar coronal hole boundary ~ 1.03 Rsun.

Ion temperatures show U-shaped dependence on charge to mass ratio.

Results



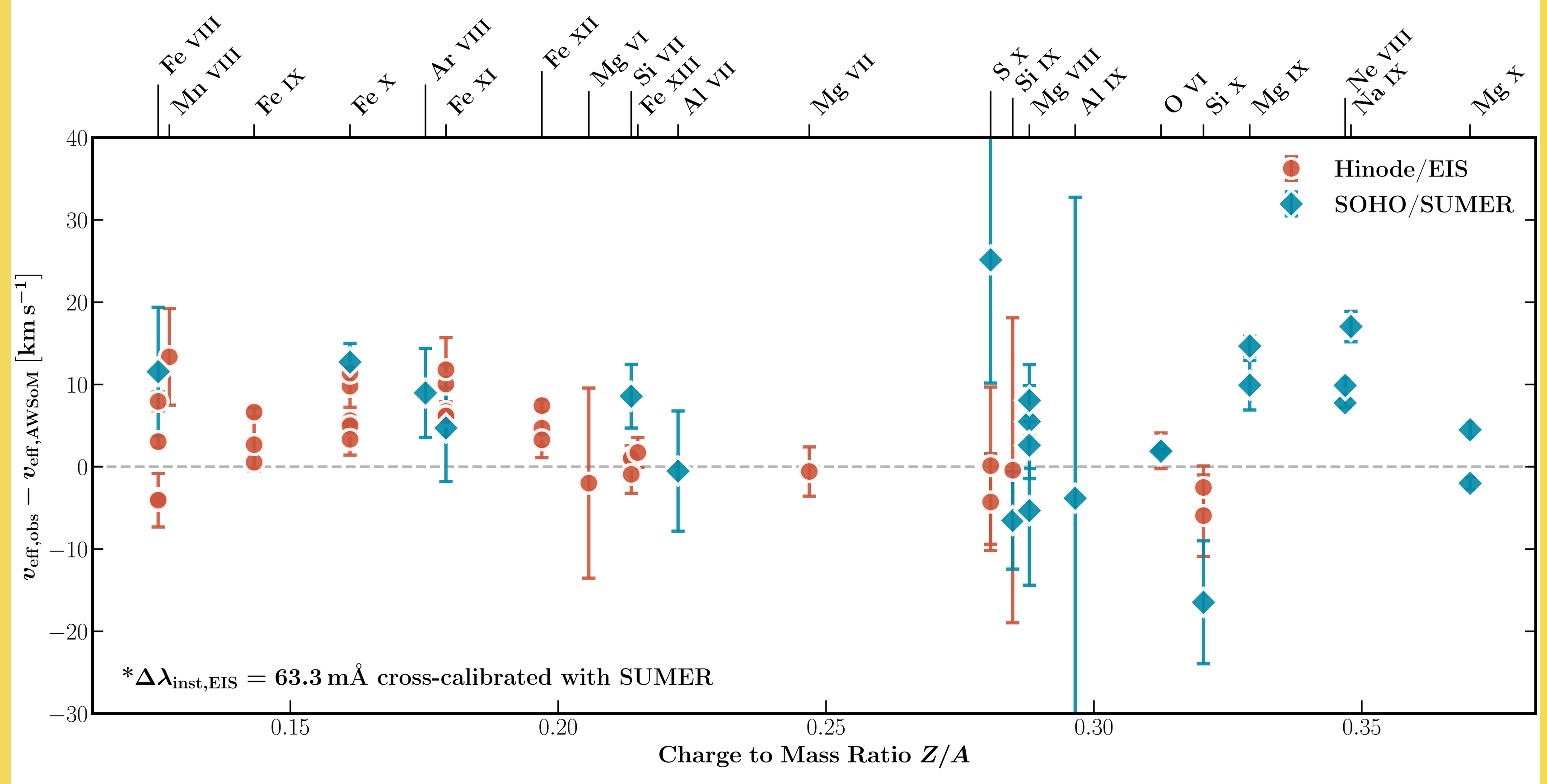
Estimated maximum and minimum ion temperature observed by EIS (blue box) and SUMER (orange box) with error bars vs Z/A at the coronal hole boundary. Electron temperature measured from line ratios is indicated by the horizontal shaded area. *: poor fitting. †: Fe X 1028 is self-blended.



Estimated maximum and minimum ion temperature using the cross-calibrated EIS instrumental width.

- Two EIS instrumental width $\Delta\lambda_{\rm inst,EIS} = 69.7\,$mÅ from EIS Software and $\Delta\lambda'_{\rm inst,EIS} = 63.3\,$mÅ cross-calibrated by O VI 184/1032&1037
- Most of $T_i > T_e$ $\log T_e \in [5.9, 6.15]$ $\log N_e \in [8, 8.5]$
- SUMER lines are usually broader than EIS lines of the same ion if $\Delta\lambda_{\rm inst,EIS} = 69.7\,$mÅ is used.
- T_i show a quasi U-shape dependence of Z/A in the coronal hole.
- Preferential heating of ions with $Z/A < 0.2$ and $0.33 < Z/A < 0.36$
- Fe XII and Fe XIII are much "hotter" than Mg VI, Si VII, and Al VII with similar Z/A, which might be affected by bulk motions along the LOS.

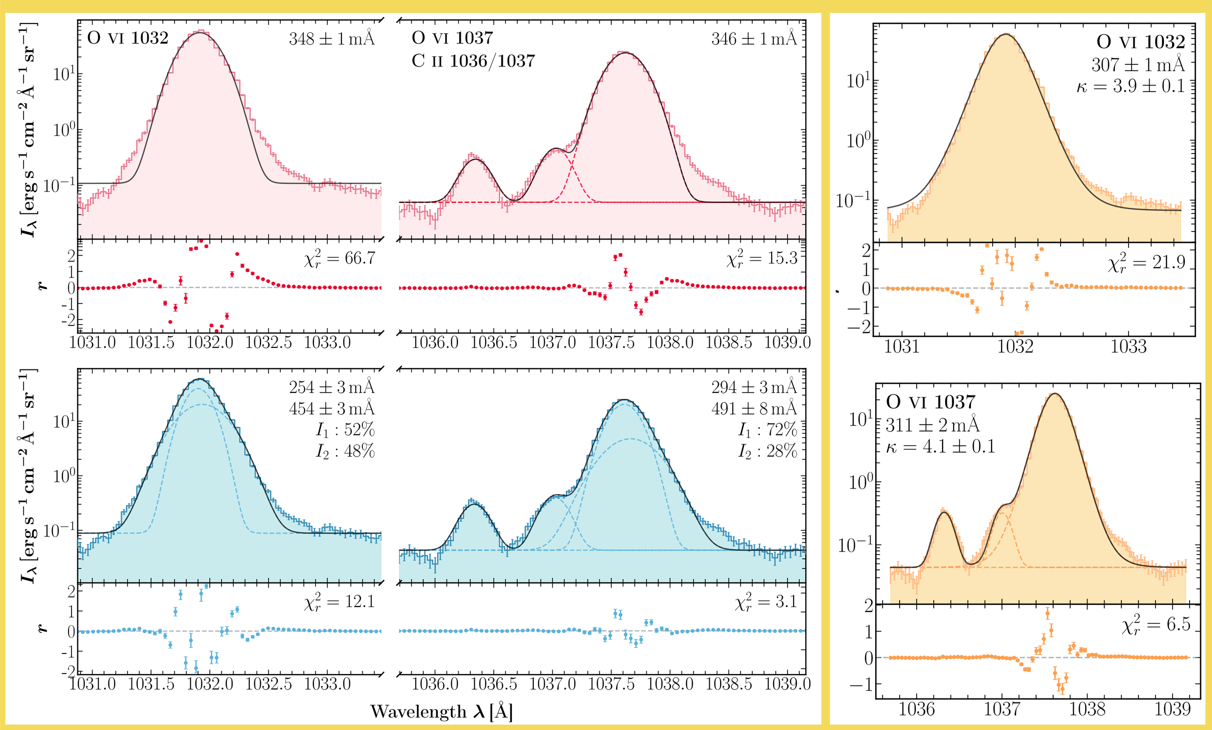
AWSoM-R Simulation



Comparison between observed effective velocity and AWSoM synthetic effective velocity.

- AWSoM-R synthetic lines are broadened by proton temperature and Alfvén turbulence.
- Observed line widths of ions with $Z/A < 0.2$ and $0.33 < Z/A < 0.36$ are larger than the synthetic widths by $10 - 20\,{\rm km\,s^{-1}}$

Non-Gaussian Profiles



(Left Top) Single-Gaussian fitting of O VI 1032/1037. (Left Bottom) Double Gaussian fitting of O VI 1032/1037. (Right) Kappa fitting of O VI 1032/1037.

- Non-Gaussian wings in the brightest SUMER lines (e.g., O VI, Ne VIII, Mg X)
- Fit with double-Gaussian or Kappa distribution.
- Including high-energy tails may increase $T_{i,\max}$ by 10-20%

Summary & Discussion

- Estimate Ion temperature (T_i) at the coronal hole boundary using two spectrographs EIS & SUMER
- No uniform T_i, $T_i > T_e$ in the coronal hole
- T_i shows a quasi U-shape dependence on charge to mass ratio (Z/A) at the coronal hole boundary
- Ions with $Z/A < 0.2$ and $0.33 < Z/A < 0.36$ are preferentially heated
- Use AWSoM-R to validate the diagnostic techniques.
- Non-Gaussian wings of SUMER lines indicate high-energy tails.

References: Landi, E. & Cranmer, S. R. 2009, ApJ, 691, 794; Landi, E. 2007, ApJ, 663, 1363; Tu, C.-Y., Marsch, E., Wilhelm, K., et al. 1998, ApJ, 503, 475; Szente, J., Landi, E., Manchester, W. B., et al. 2019, ApJS, 242, 1; Sokolov, I. V., Holst, B. v. d., Manchester, W. B., et al. 2021, ApJ, 908, 172; Dolla, L., & Solomon, J. 2008, A&A, 483, 271.