Hinode/EIS measurements of the preferential heating of minor ions in the low corona (to test the role of different wave-particle mechanisms)

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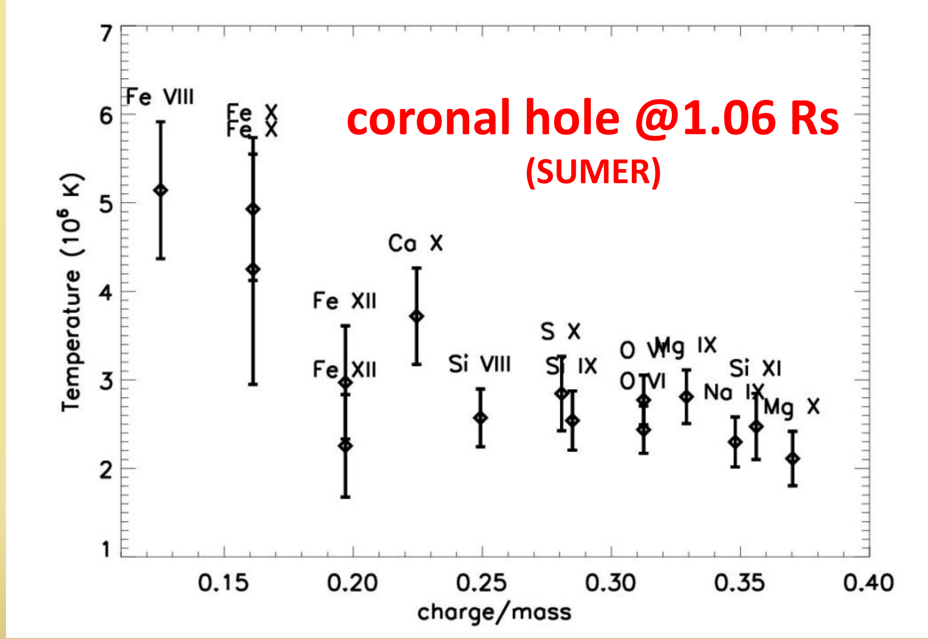
Context

- Heavy ions are found to be hotter than electrons and protons:
  - In the solar wind (+ anisotropy of temperature): Schwenn & Marsch 1991; …
  - In the high corona >2.5 Rs (+ anisotropy of temperature) with SoHO/UVCS: Li et al., 1998; Cranmer et al., 1999; …
  - In the lower corona between 1.06 and 1.2 Rs with SoHO/SUMER: Tu et al. 1998; Dolla & Solomon (2004, 2008, 2009); …

⇒ Preferential heating of ion species with the lowest charge-to-mass ratios (q/m) is possibly indicative of a wave-particle process



(Dolla & Solomon , 2009)

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Objectives

- Preferential heating is relevant for coronal heating and fast solar wind acceleration:
  - Which wave-particle process(es) is (are) at work?
  - Can the same mechanism also efficiently heat the protons?

- Providing new measurements:
  - to confirm the results of SUMER with another instrument to rule out particular line and instrumental effects
  - at even lower height in the corona (<1.06 Rs): where does the preferential heating starts?

Measuring the temperature of each ion species remotely

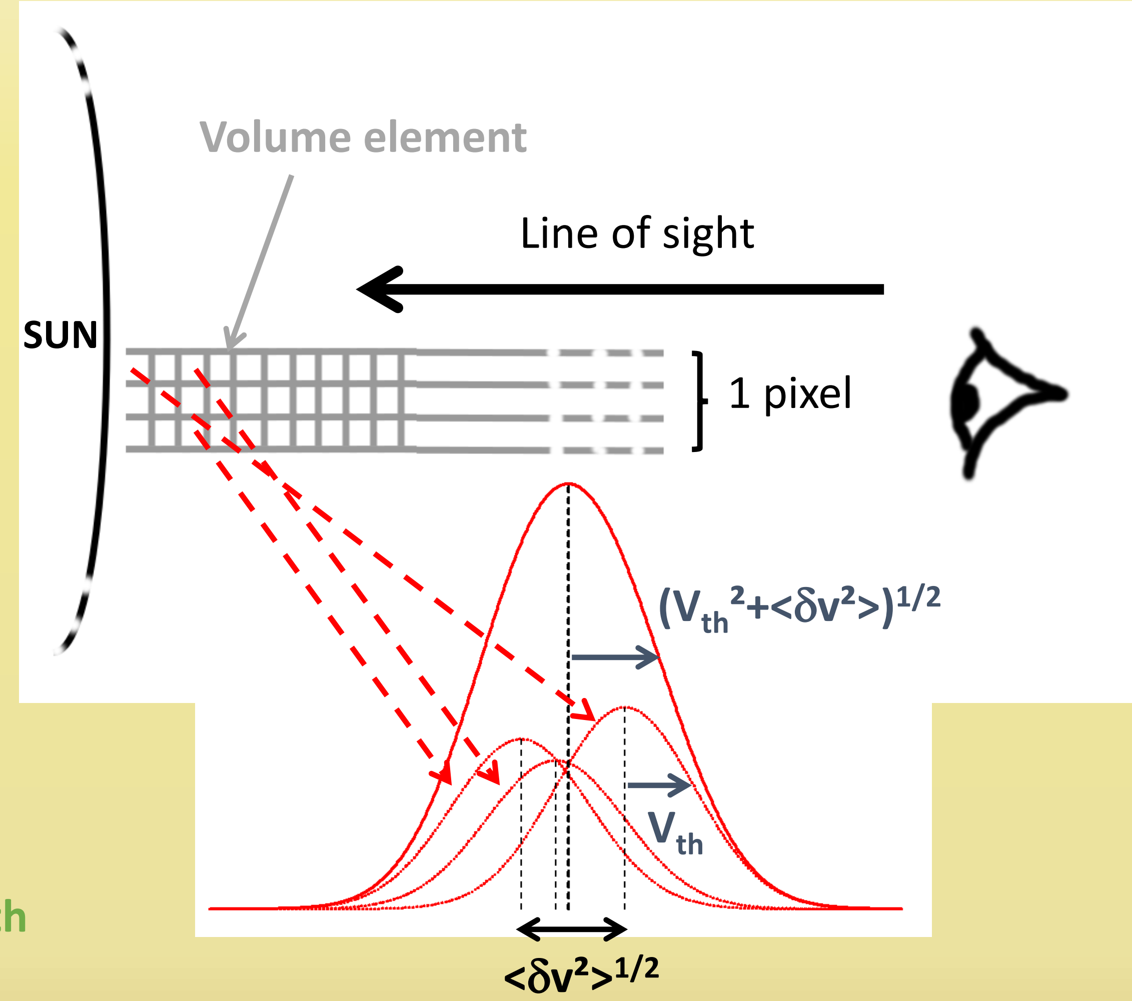
- Observed spectral line results from integration over:
  - the line of sight (LOS)
  - scales smaller than the resolution scale
  - exposure time

- For each volume element, the group velocity may be different due to MHD waves, turbulence, etc…

- $\xi \approx \langle \delta v^2 \rangle^{1/2}$

$$\sigma^2 = \frac{\lambda^2}{2c^2}\left(\frac{2kT}{M} + \xi^2\right) + \sigma_I^2.$$

Instrumental width



Disentangling thermal and non-thermal velocities in the spectral line width

- Not a trivial task because the 2 quantities are quadratically added in the same observable (and T_i may vary from ion to ion):
  - the result of the heating process: temperature
  - the possible energy source (waves): ξ

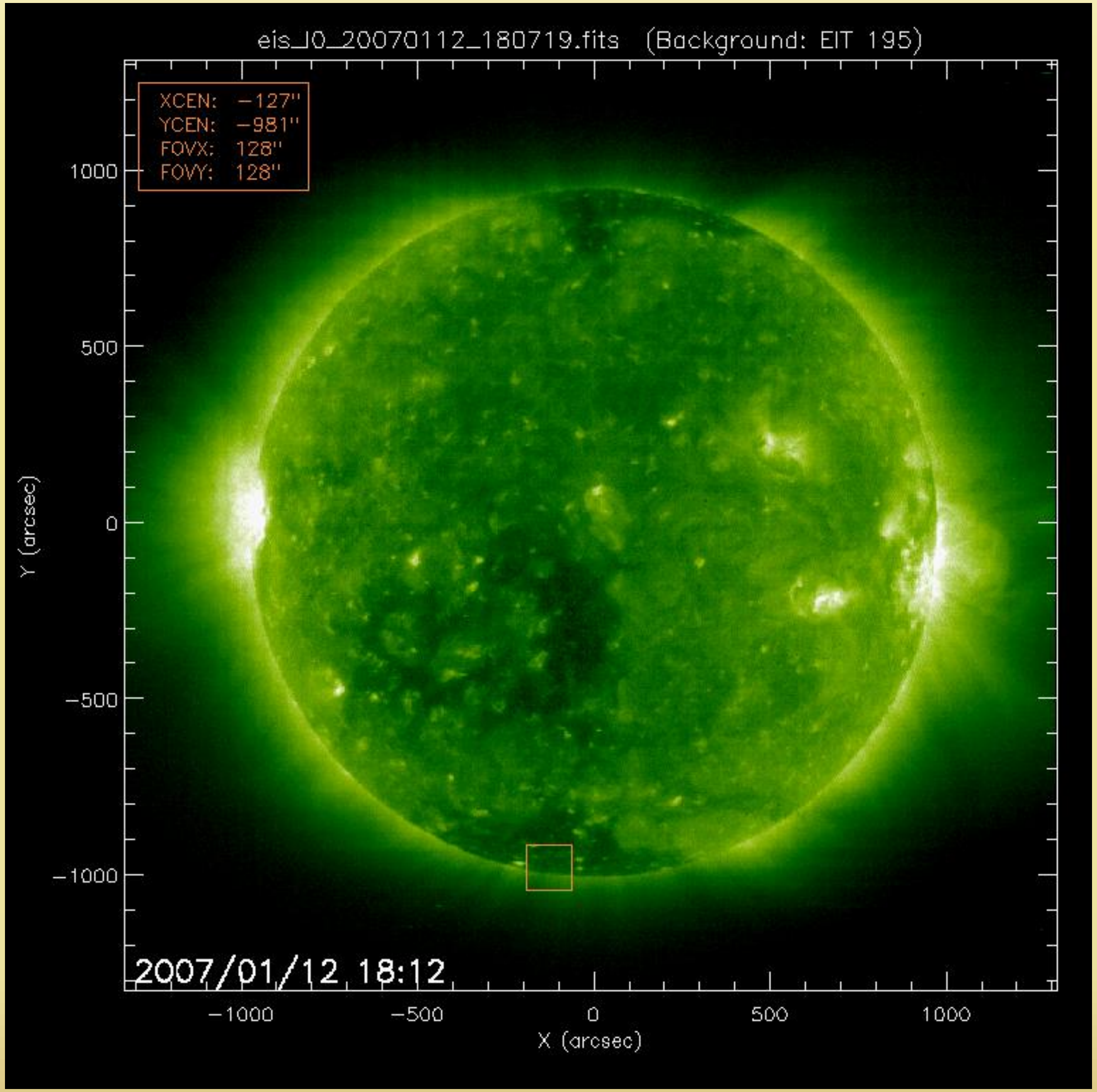
$$\sigma^2 = \frac{\lambda^2}{2c^2}\left(\frac{2kT_i}{M} + \xi^2\right)$$

- Various methods in the literature (see Dolla & Solomon, 2008)

- Method of Dolla & Solomon (2008) provides a lower boundary for the ion temperatures by constraining at the same time the non-thermal velocity and the ion temperatures, using the conservation of the Alfvén wave energy flux (assumed a low heights)

- **Important:**
  - **we do not assume T_i=$T_{max\ ionisation}$**
  - **We assume all ions "see" the same ξ**

Hinode/EIS observations in a coronal hole



- Above the South Pole on 2007-01-12
- Coronal hole
- Full EIS spectrum recorded ⇒ all possible lines
- Slit 1" (smaller instrumental profile)

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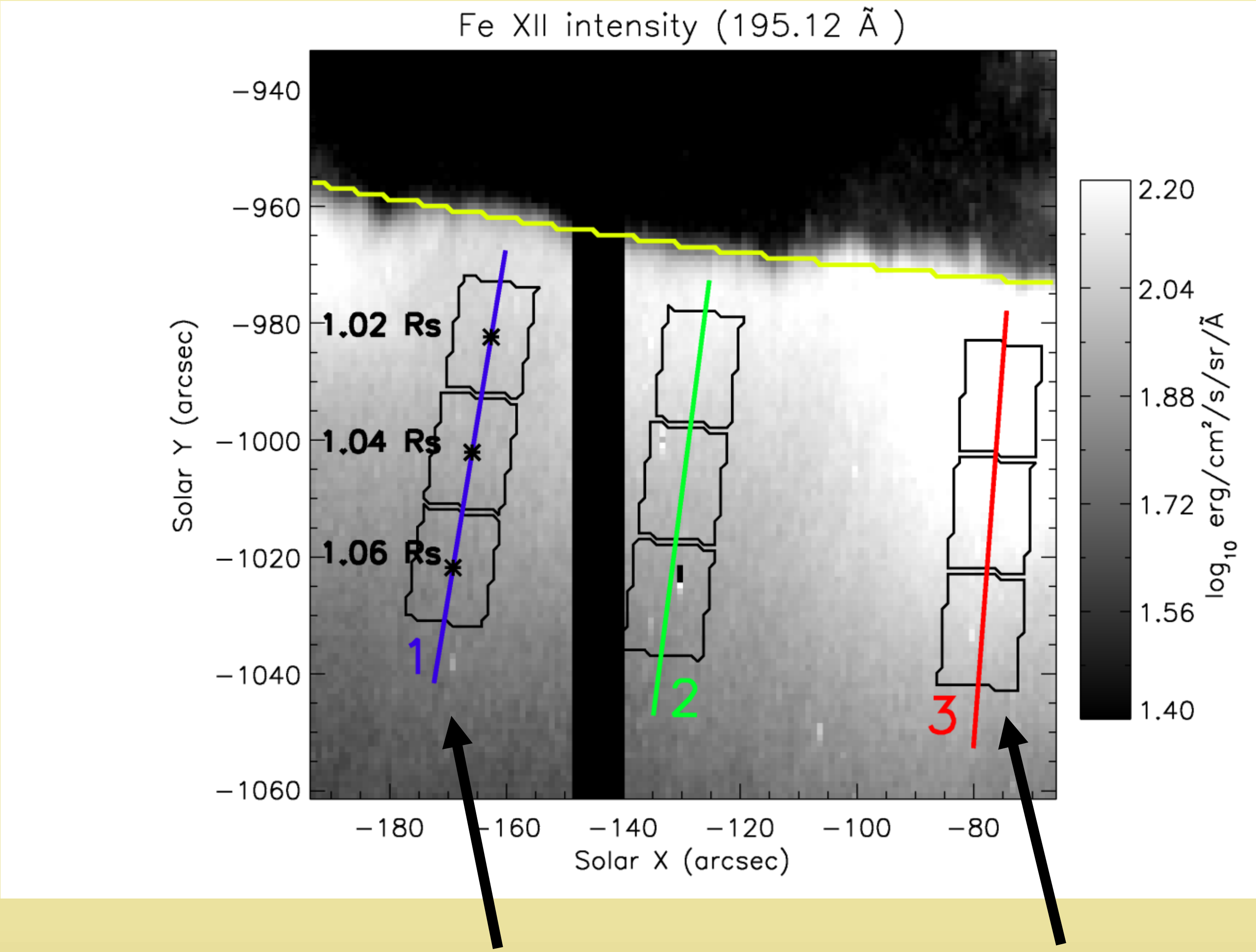
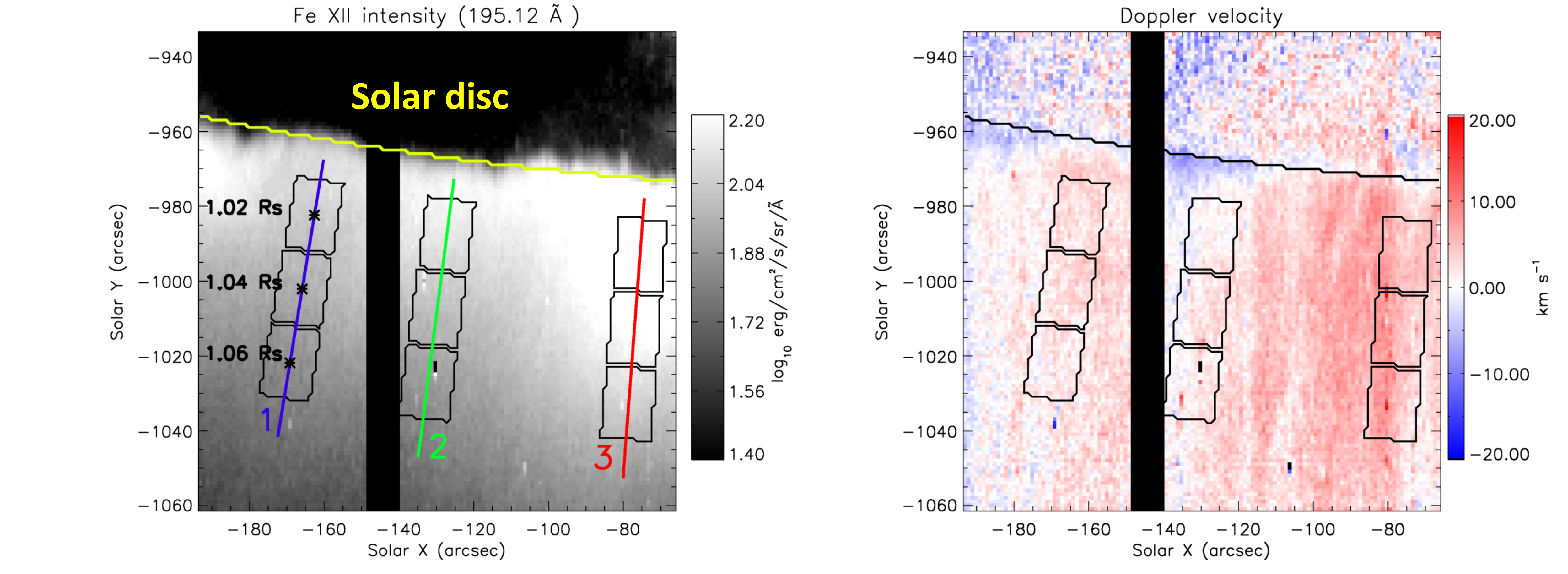
Large rebinning along 3 radial directions



- Above a coronal hole
- Large rebinning of EIS pixels to increase the SNR of the spectra and use as many lines as possible
- Bin centered at 1.02, 1.04 and 1.06 Rs (0.2 Rs bins)
  $\Rightarrow$ **Instrumental stray light is neglected**
- For plasma diagnostics, same width in PA, but smaller bins of 0.04 RS in height

Moderate Doppler velocities (flows in plumes?)



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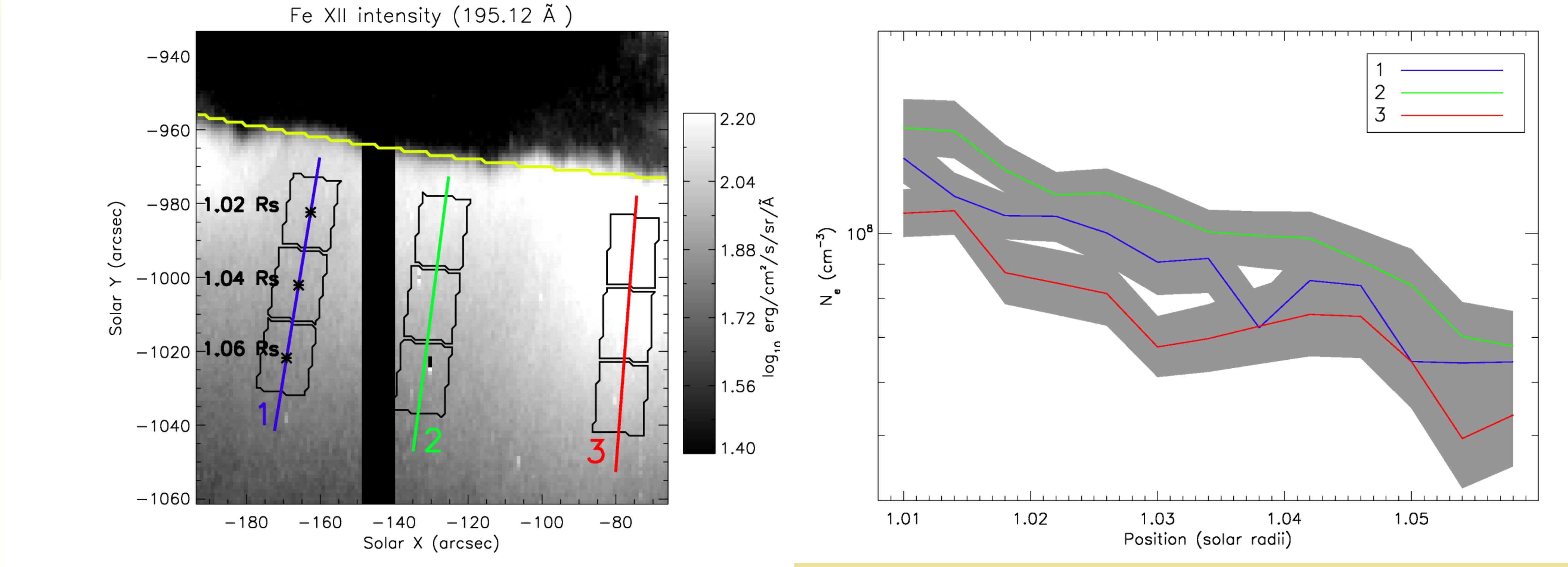
Density (Fe IX 189.94/188.49 ratio)



⇒ **values consistent with previous measurements in coronal holes**

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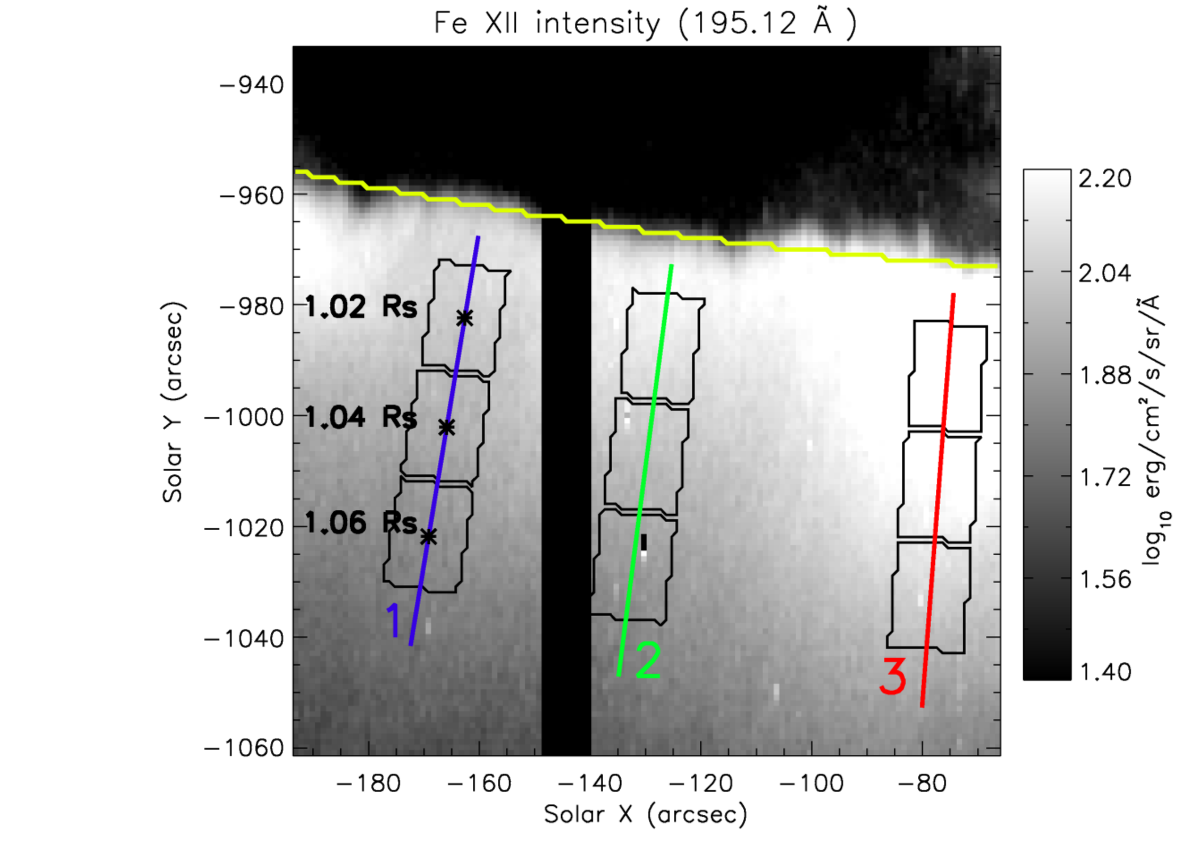
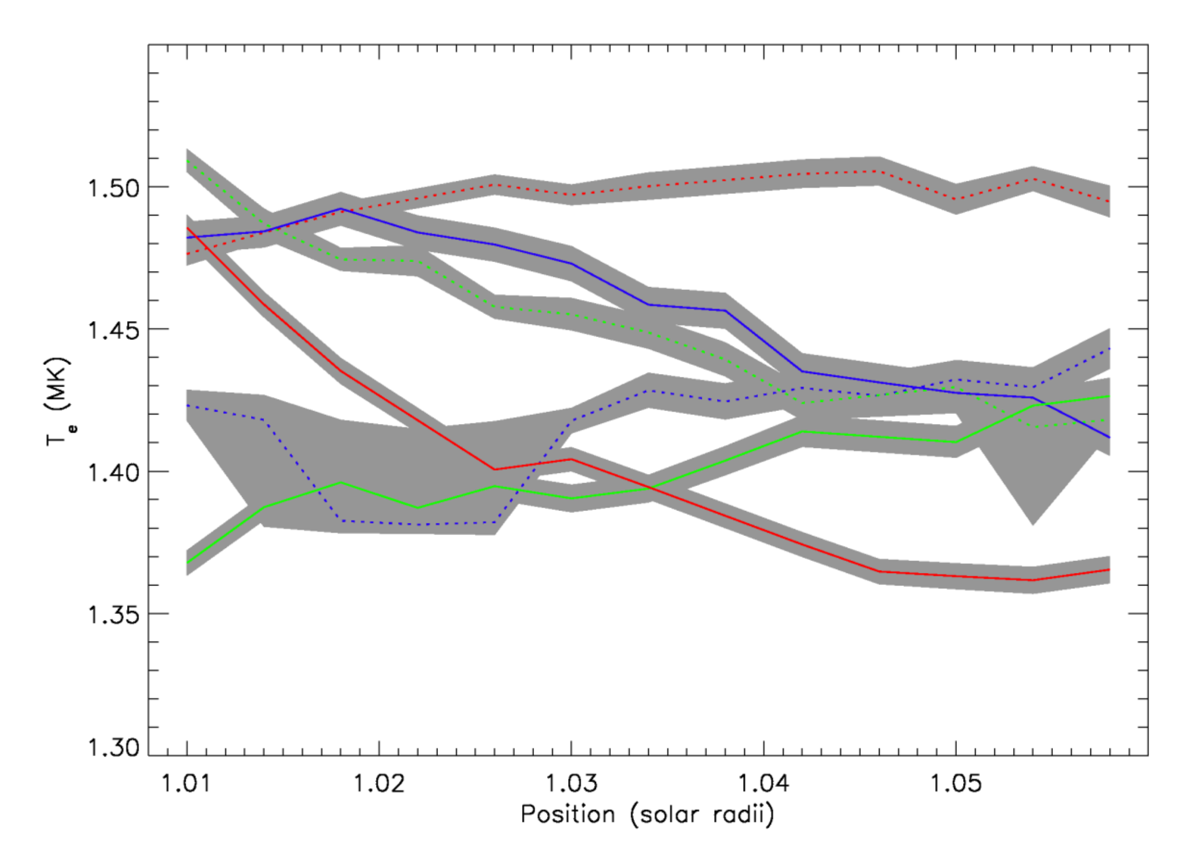
Electron temperature (Fe XI 188/Fe XII 195 blends, Fe XIII 202/Fe XII 195)





- **Consistent with constant T not varying with height: 1.45 MK**
- However, a bit hot for a CH (e.g. Landi, 2008); **or consequence of the new CHIANTI version?**

N.B: error bars correspond to photon statistics only, atomic physics uncertainties may add 20%

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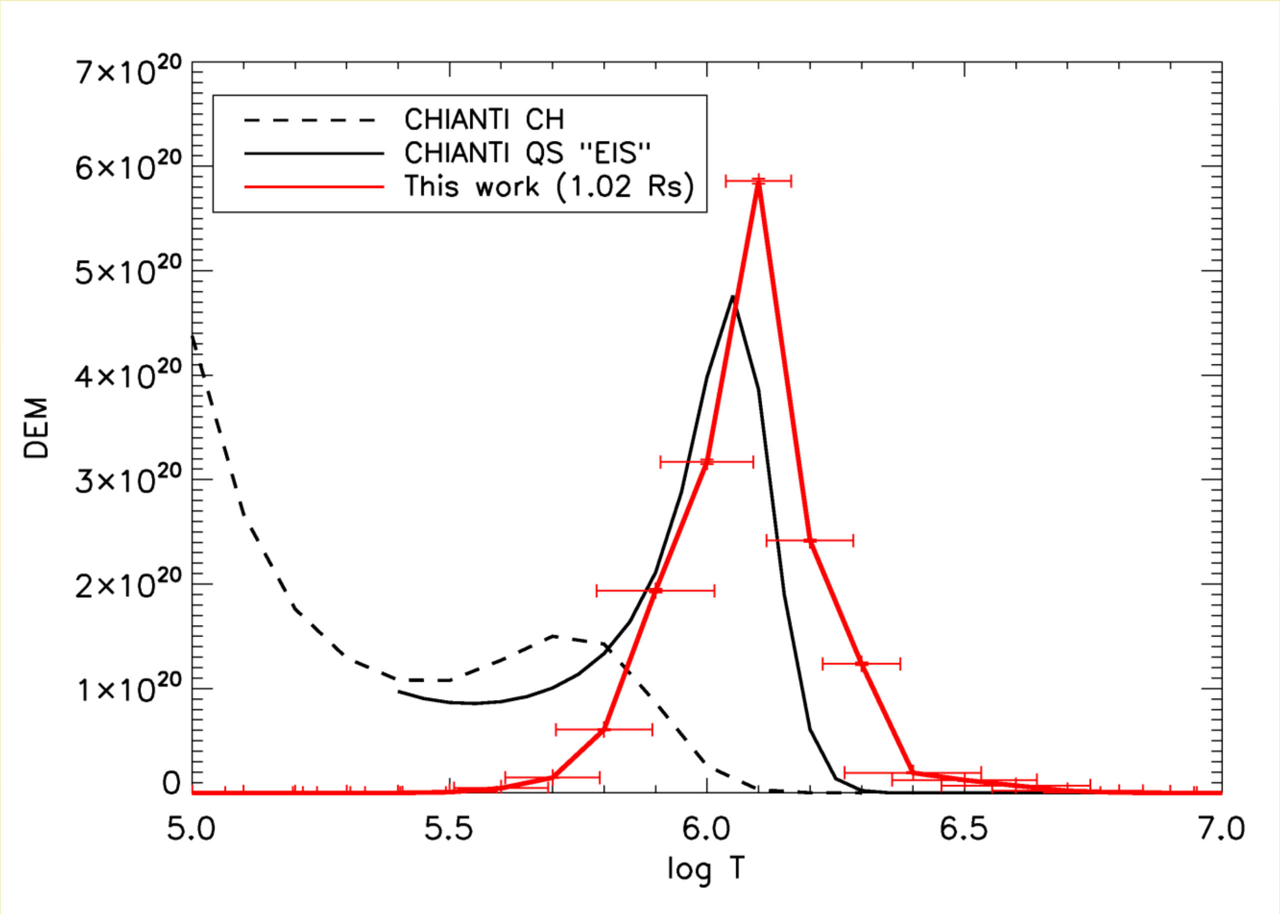
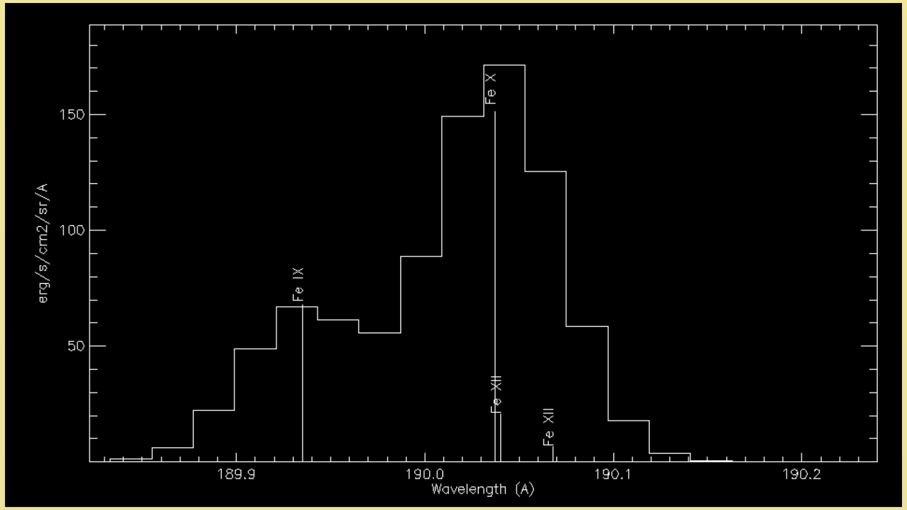
Differential Emission Measure



- Only with Iron lines to minimise abundance effects, from Fe VIII to Fe XV
- Method of Hannah & Kontar (2012)
- Photospheric abundances (Asplund, 2009)

- ⇒ used to analyse line blends and discard the lines <95% pure



(example of discarded lines)

⇒ Peak temperature consistent with temperature ratios

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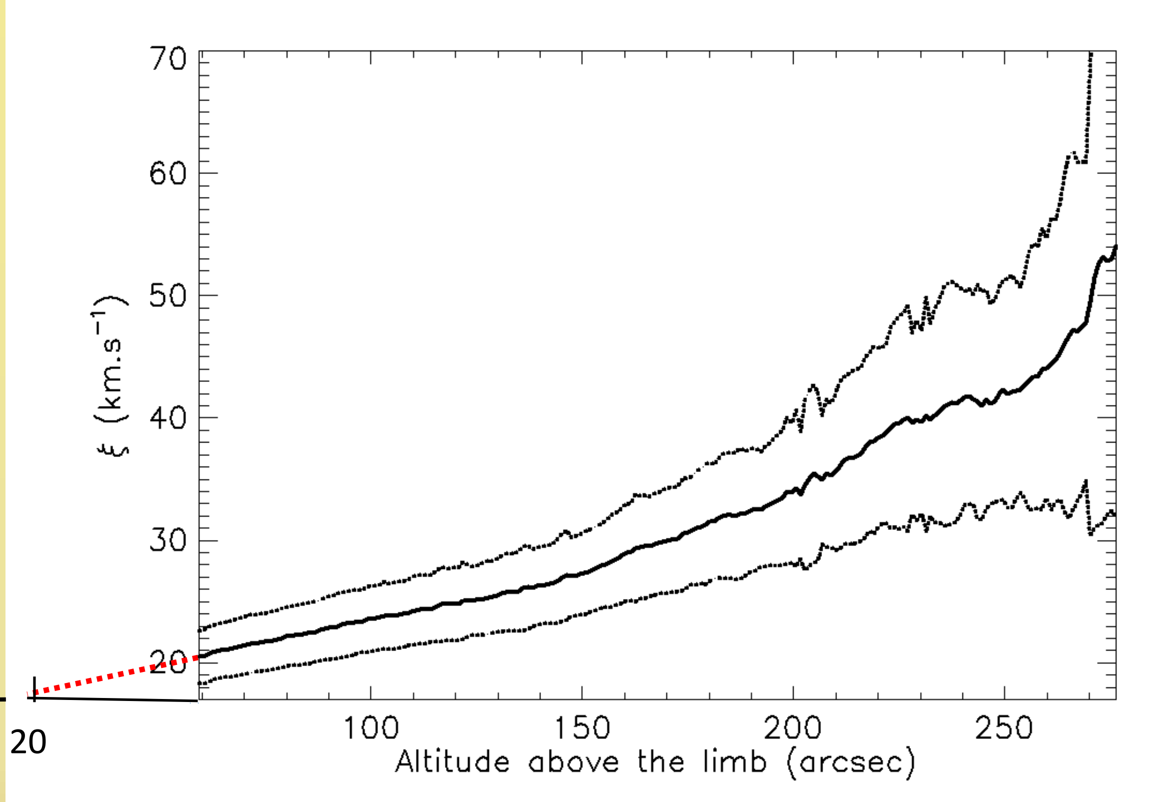
Value of the non-thermal velocity?

- Work in progress: for the moment, simply extrapolated from Dolla et al. (2009) results in a coronal hole

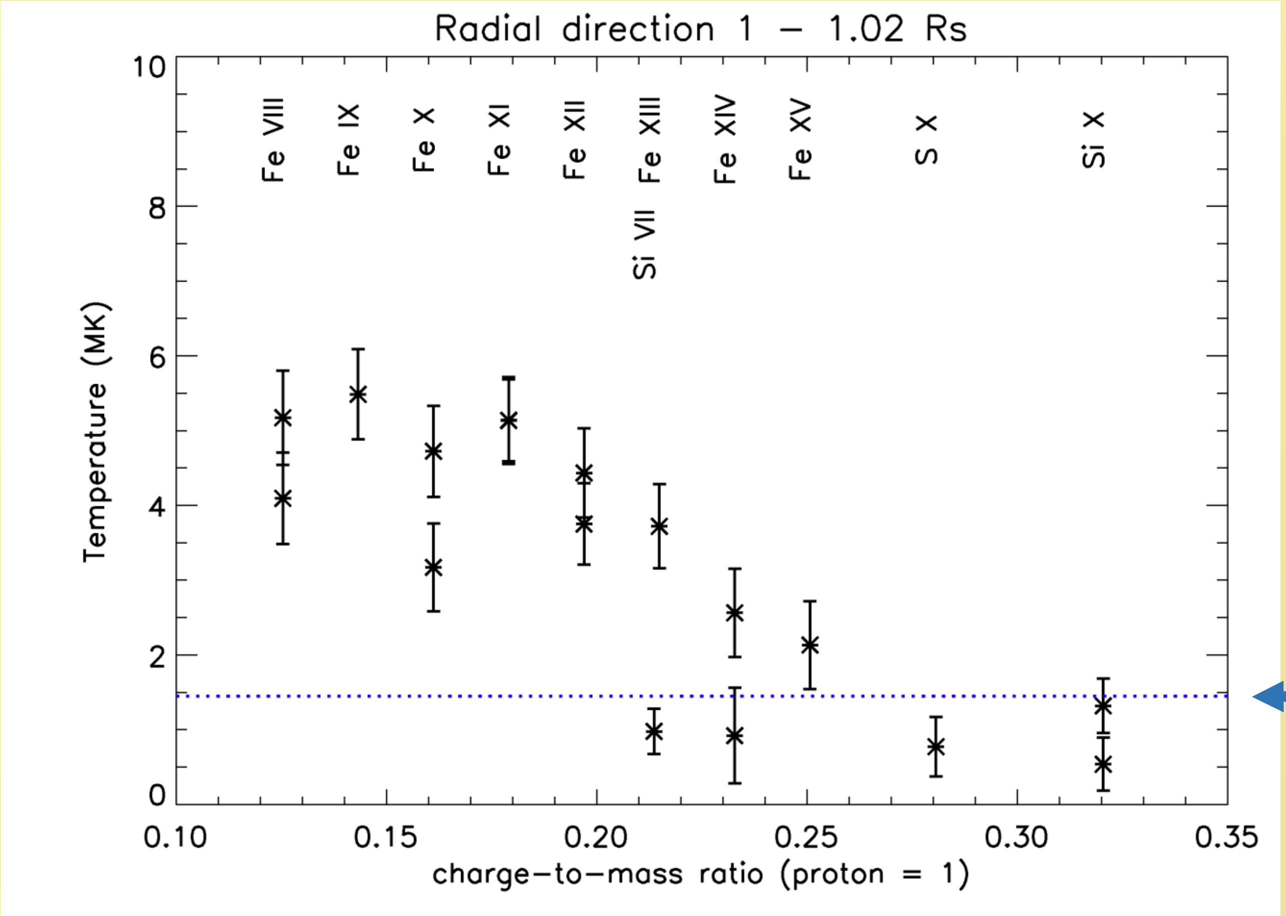
$\Rightarrow$ 15 $\pm$ 5 km/s at all heights in our

EIS data set (20 to 60” or 1.02-1.06 Rs)



15

Ions with low q/m are hotter than the others



- Confirms Dolla et al. (2004, 2008, 2009) which used SUMER spectra
- Consistent with Hahn & Savin (2013), with Hinode/EIS

Measured electron temperature

Also the temperature of the protons? (thermalisation through Coulomb collisions)

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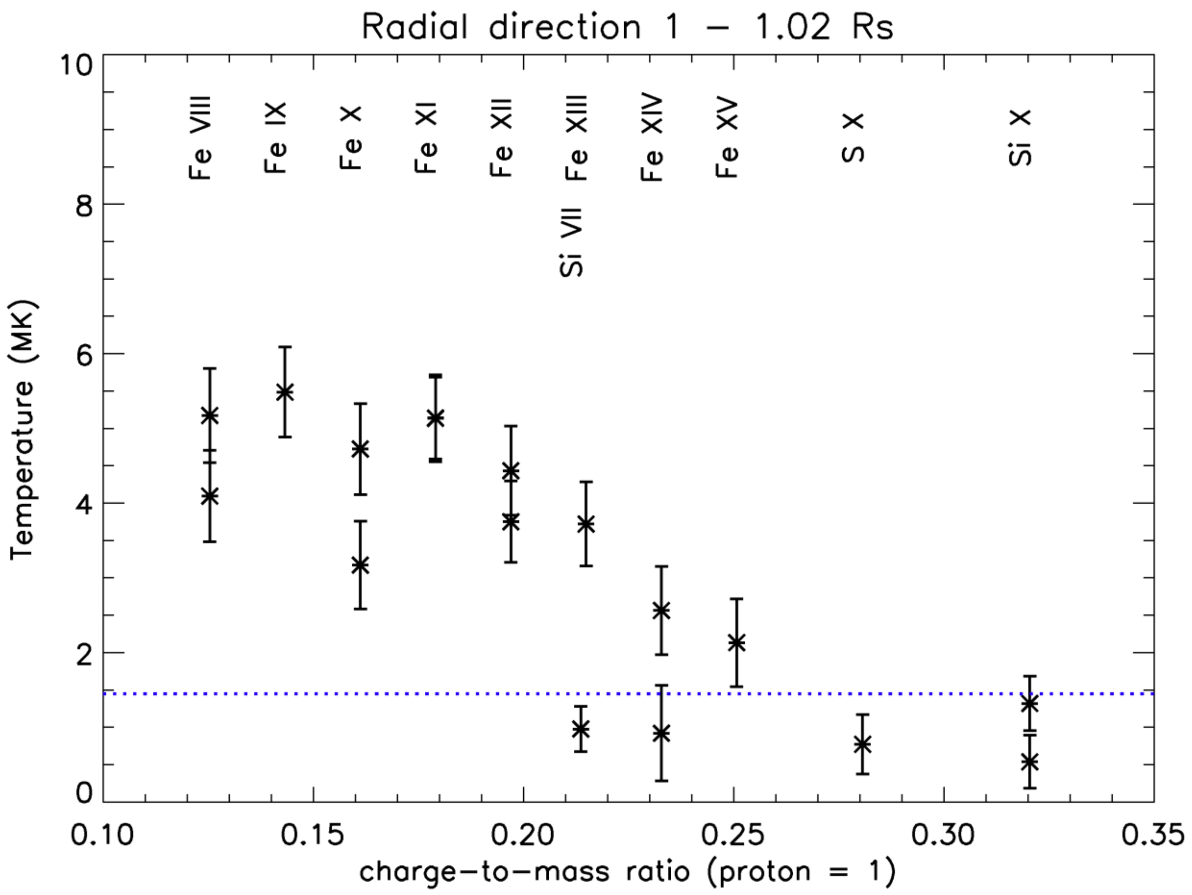
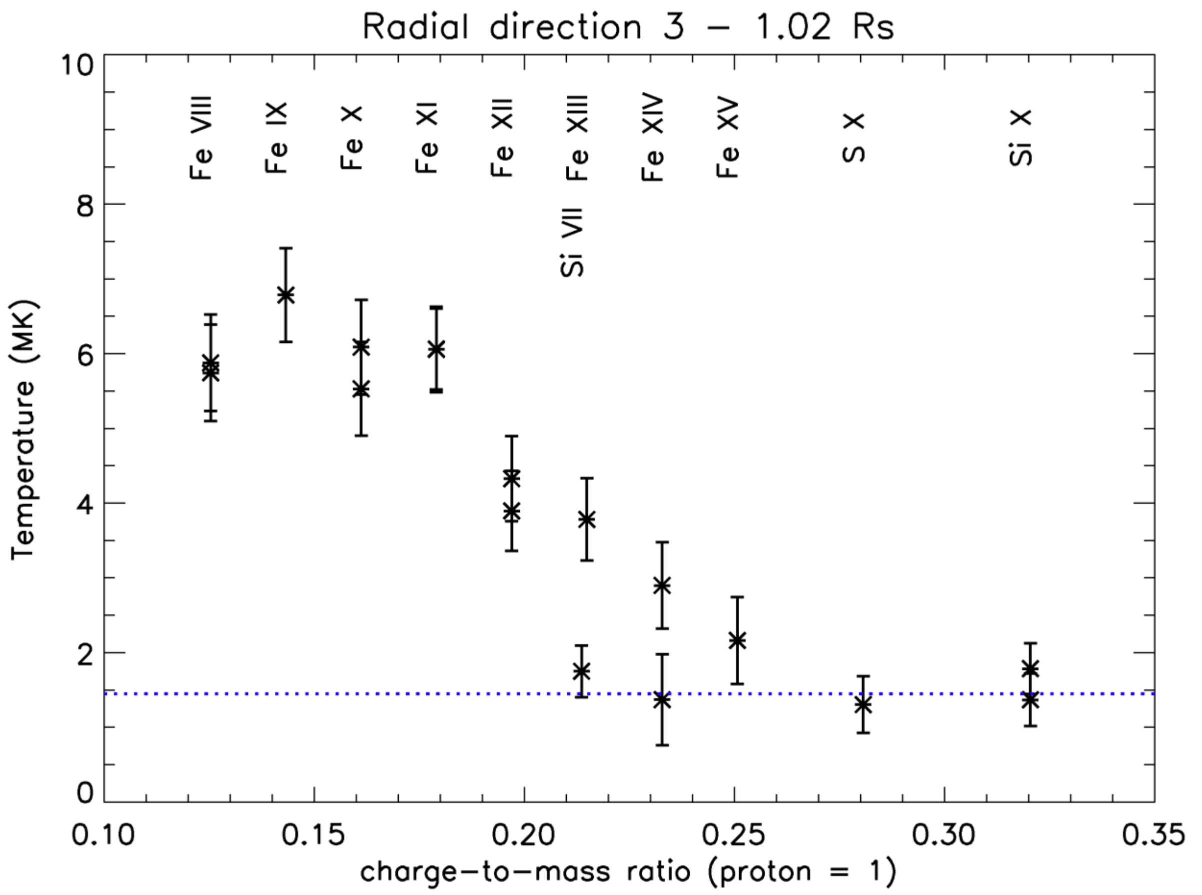
Radial variation (from 1.02 to 1.06 Rs)





(Animated GIFs)

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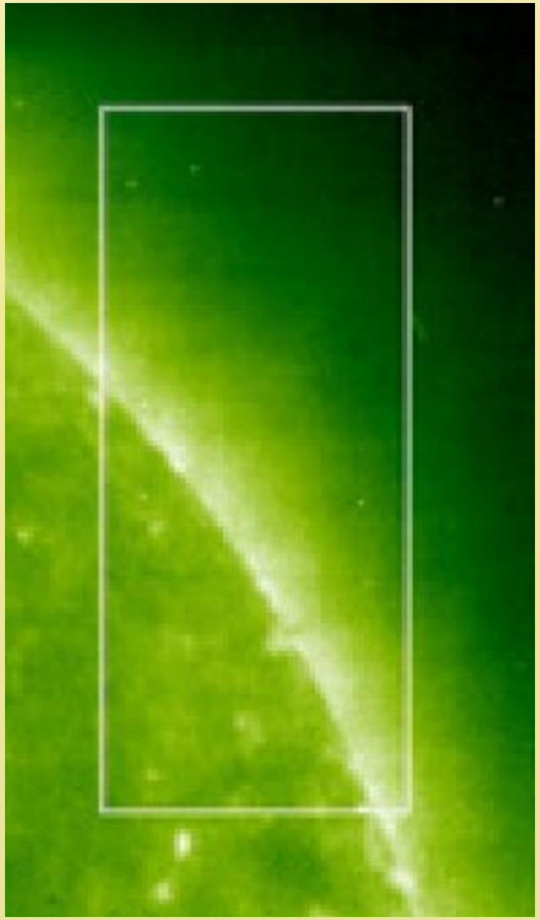
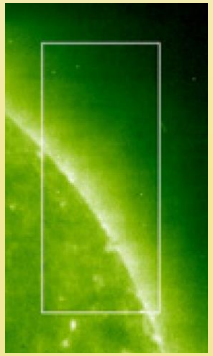
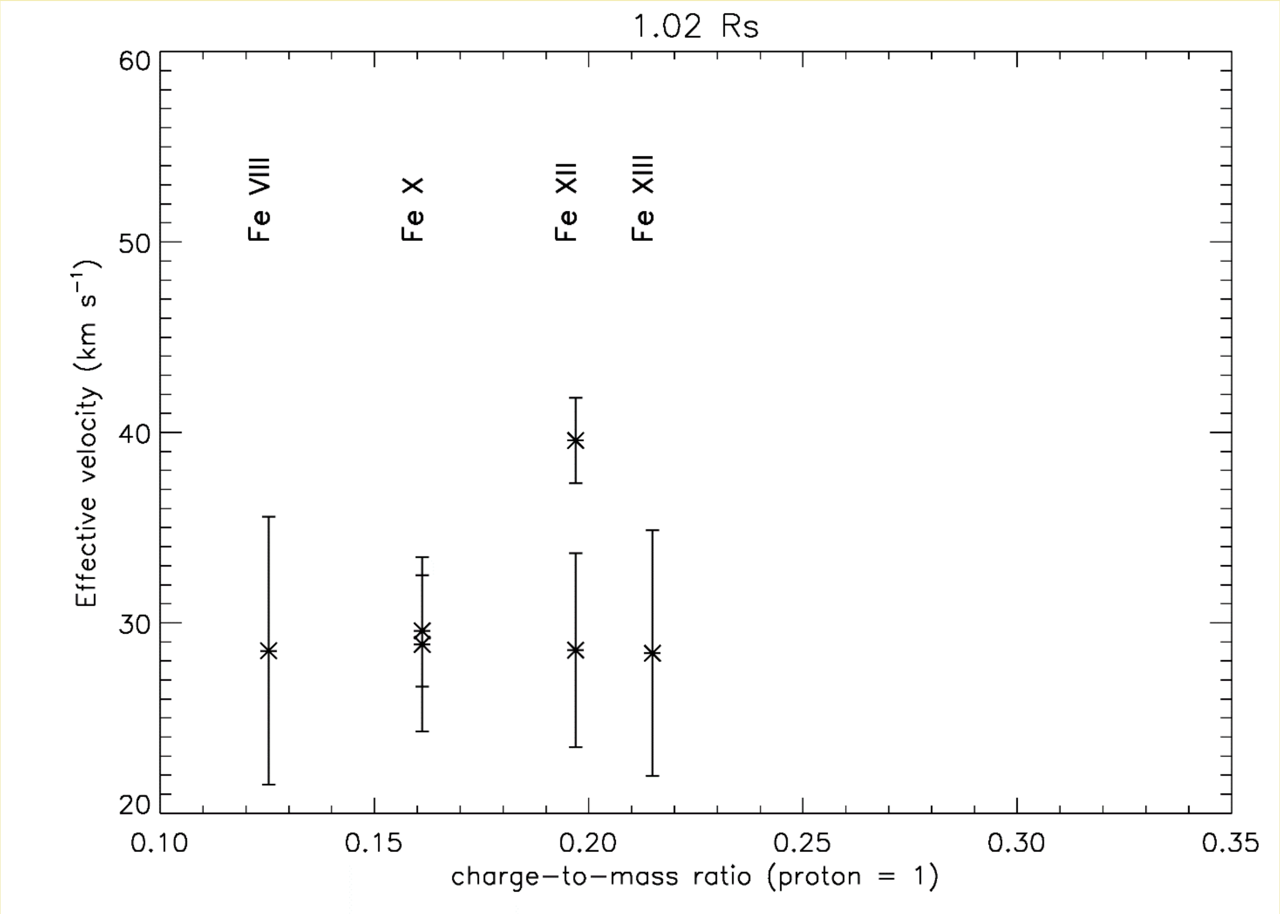
EIS observations above the Quiet Sun (data set 1)



- 21 October 2007 (Hahn & Savin, 2014)
- Average values of line widths for all pixels between 1.01 and 1.03 Rs

EIS observations above the Quiet Sun (data set 1)





- To avoid making an assumption about the non-thermal velocity, we reduce the data set to Iron lines only

⇒ no variation with mass: if the temperature is identical for all Fe ions, v_{eff}^2 will be a constant with q/m:

$$v_{eff}^2 = \frac{2kT}{M} + \xi^2$$

⇒ **No preferential heating!**

- Consistent with the results of Hahn & Savin (2014) on the same data set, but at odds with Dolla et al. (2004)

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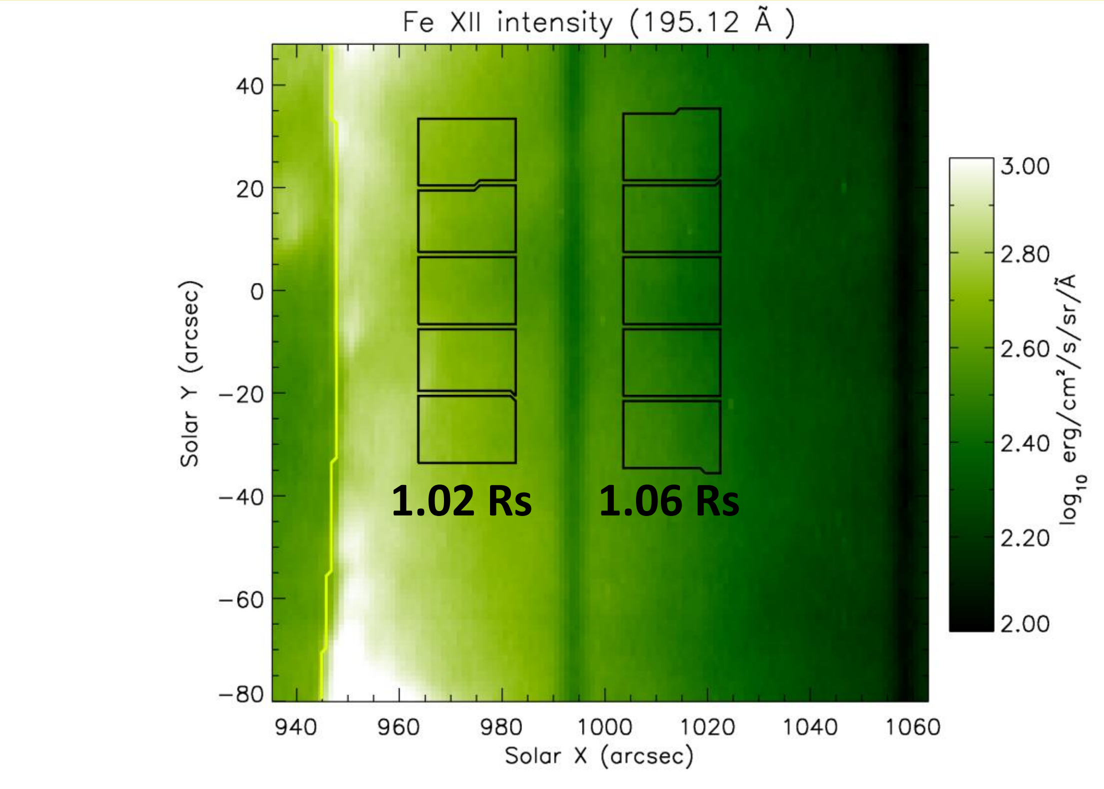
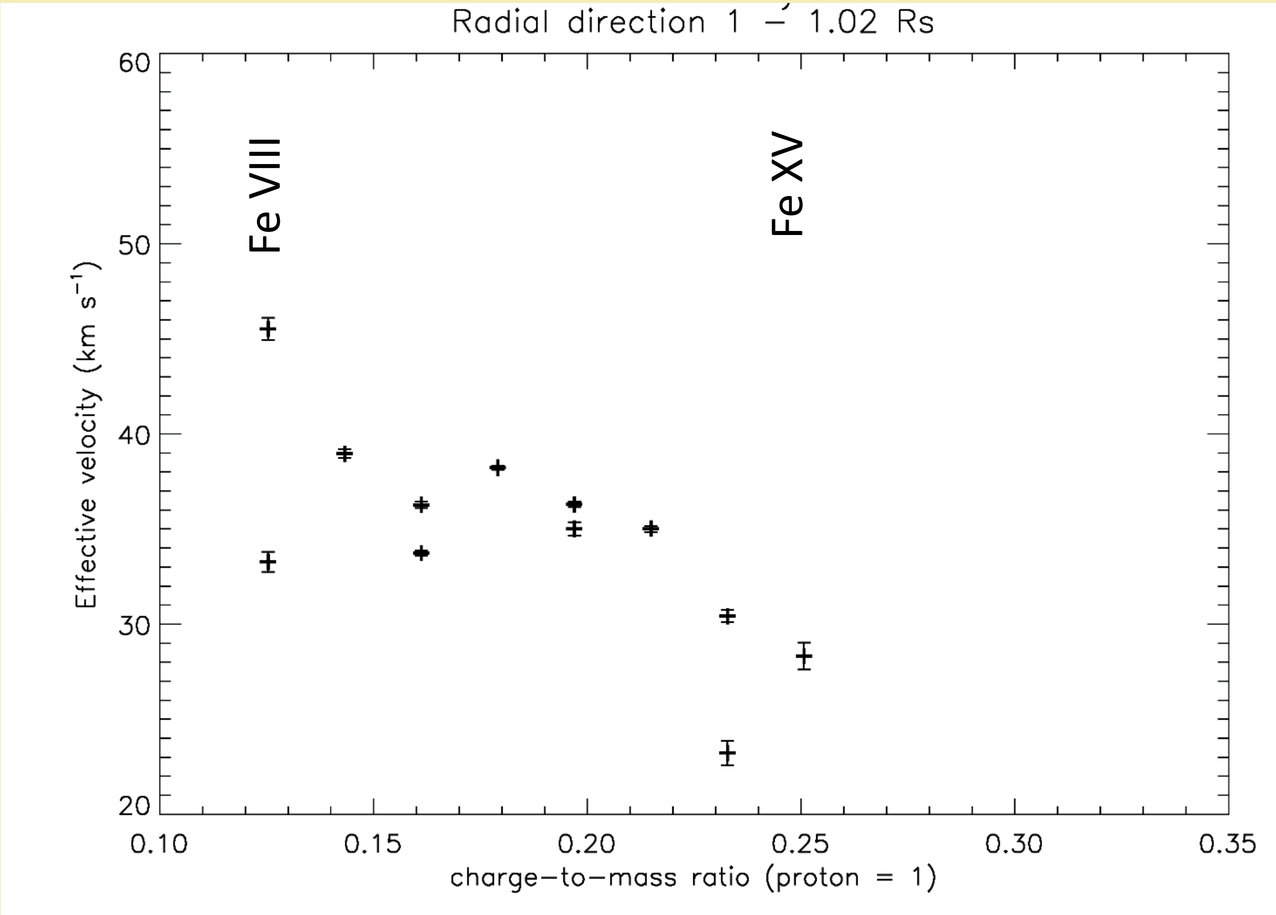
EIS observations above the Quiet Sun (data set 2)

- To verify if there are variations from one data set to another.
- 19 August 2007, above the West limb near the equator





⇒ **Preferential heating this time!**

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Can we explain the preferential heating with non-adiabatic acceleration by Kinetic Alfvén Waves?

- KAW: oblique Alfvén waves with short ion-scale wavelengths across the background magnetic field

- Can produce non-adiabatic acceleration of the ions: Voitenko & Goossens (2004)

- From the measured q/m value at which the temperature jumps, and the temperature of the heated ions, it is possibility to deduce:
  - the KAW magnetic amplitudes (≈ 2% of B_0)
  - the KAW cross-field wavelengths (≈ 8 proton inertial lengths)

$\Rightarrow$ very small wave scales, cannot be resolved

Conclusions

- Our study confirms the results of Dolla et al. 2004, 2008, 2009 obtained with SUMER

  $\Rightarrow$ One can rule out effects particular to one instrument or to one spectral line

  But still shows (too much) sensitivity to line blends

- Results:
  - Preferential heating occurs for ions with q/m<≈0.2, already close to the transition region (<1.02 Rs)
  - Preferential heating of low q/m also observed in the Quiet Sun
  - But seems to depend on time and location of observations
  - Width of some lines increases with height, and decrease for some others starting very low in the corona (below the usual turn-over point around 1.1–1.2 Rs)

  The new result compared to Dolla et al. is that this happens to lines with high q/m too… some artefact not taken into account?

- Applications:
  - to constrain theories of wave-particles interactions and their impact on the heating of the solar corona and acceleration of the solar wind;
  - to constrain the energy deposition rate necessary to reach observed temperatures

- **Analysis of coronal line widths is still an important topic. But it requires a spectrometer with very good spectral resolution and small instrumental width!**