A new method for measuring relative abundances in the solar corona

SDO Science Workshop 2018

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The FIP effect

« FIP bias » : $f_X = \frac{Ab_X^{corona}}{Ab_X^{photosphere}}$

- ★ FIP : First Ionization Potential
- ★ Ab_X^{region} : elemental abundance relative to hydrogen in a given region of the solar atmosphere

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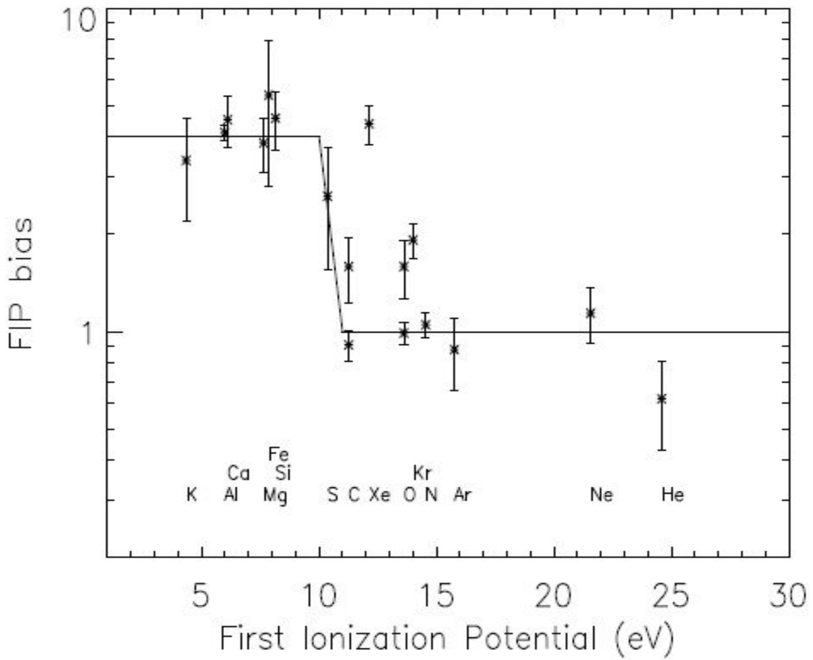

FIP bias as a function of FIP in the slow Solar Wind, von Steiger et al. (1997).

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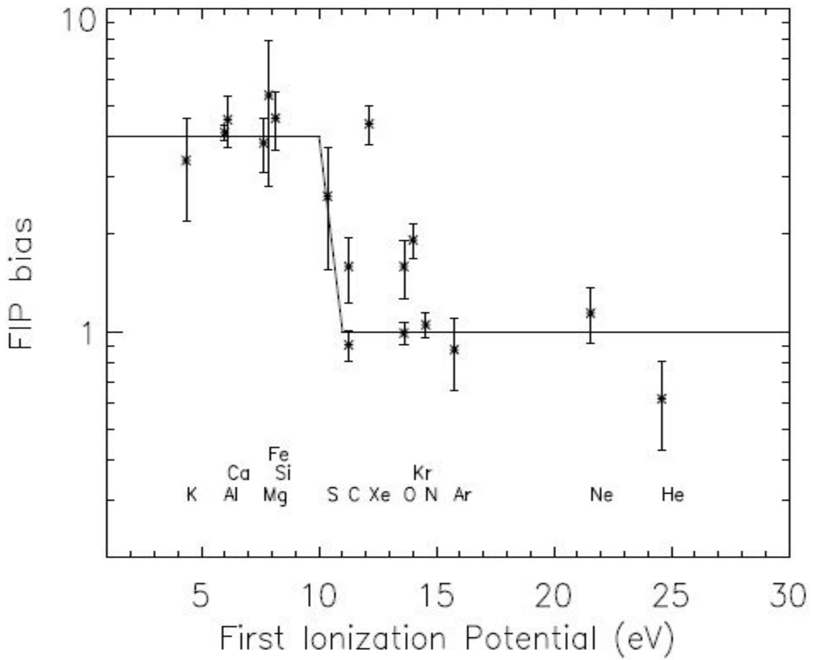

FIP bias as a function of FIP in the slow Solar Wind, von Steiger et al. (1997).

« FIP bias » frozen in the corona → **The FIP effect can allow us to trace back the source of heliospheric plasma**

Measuring relative abundances

In the coronal approximation, the radiance of the transition line from level i to j of ion X^{+m} is :

$$I_{X^{+m},\, i\rightarrow j} = Ab_X^{corona} \int C_{X^{+m},\, i\rightarrow j}(n_e, T)\, DEM\, dT$$

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Differential Emission Measure

Simplified notation :

$$I_{X,\, ij} = f_X^{bias} A_X^{\mathrm{ph}} \langle C_{X,\, ij}, \mathrm{DEM} \rangle$$

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$$\frac{f_{X_{\mathrm{LF}}}^{bias}}{f_{X_{\mathrm{HF}}}^{bias}} = \frac{I_{\mathrm{LF}}}{I_{\mathrm{HF}}} \left(\frac{A_{X_{\mathrm{LF}}}^{\mathrm{ph}}}{A_{X_{\mathrm{HF}}}^{\mathrm{ph}}} \frac{\langle C_{\mathrm{LF}}, \ \mathrm{DEM} \rangle}{\langle C_{\mathrm{HF}}, \ \mathrm{DEM} \rangle} \right)^{-1}$$

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Two Line Ratio

- ✔ Fast and simple
- ✔ Easy to automate
- ✖ Inaccurate unless contribution functions match perfectly

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Following DEM inversion

- ✖ Inverse problem difficult to constrain
- ✖ Complicated to automate
- ✔ More accurate

The game plan

What we have

Spectroscopic observations

What we want to do

★ Create accurate FIP bias maps systematically and semi-automatically

The game plan

What we have

Spectroscopic observations

How

A new FIP bias measuring method with:

- ★ No DEM Inversion
- ★ Optimized linear combinations of spectral lines

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The game plan

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How

A new FIP bias measuring method with:

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What we want to do

- ★ Create accurate FIP bias maps systematically and semi-automatically
- ★ Re-analyze past observations
- ★ Design observations : which lines should we use ?

The Linear Combination Ratio (LCR) method

Spectral lines of **low FIP** elements

$$\mathscr{I}_{\rm LF} \equiv \sum_{i\in(\rm LF)} \alpha_i \, \frac{I_i}{A_i^{\rm ph}}$$

$$\mathscr{C}_{\rm LF}(T) \equiv \sum_{i\in(\rm LF)} \alpha_i \, C_i(T)$$

Spectral lines of **high FIP** elements

$$\mathscr{I}_{\rm HF} \equiv \sum_{i\in(\rm HF)} \beta_i \, \frac{I_i}{A_i^{\rm ph}}$$

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The r**elative FIP bias** is

$$\frac{f_{\mathrm{LF}}^{bias}}{f_{\mathrm{HF}}^{bias}} = \frac{\mathscr{I}_{\mathrm{LF}}}{\mathscr{I}_{\mathrm{HF}}} \left(\frac{\langle \mathscr{C}_{\mathrm{LF}}, \mathrm{DEM} \rangle}{\langle \mathscr{C}_{\mathrm{HF}}, \mathrm{DEM} \rangle} \right)^{-1}$$

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The **relative FIP bias** is $\frac{f_{\mathrm{LF}}^{bias}}{f_{\mathrm{HF}}^{bias}} = \frac{\mathscr{I}_{\mathrm{LF}}}{\mathscr{I}_{\mathrm{HF}}} \left(\frac{\langle \mathscr{C}_{\mathrm{LF}}, \mathrm{DEM} \rangle}{\langle \mathscr{C}_{\mathrm{HF}}, \mathrm{DEM} \rangle} \right)^{-1}$ **≈1**

We **minimize** $\phi(\alpha, \beta) = \sqrt{\sum_{j \in (\mathrm{DEM}_j)_j} \left| \frac{\langle \mathscr{C}_{\mathrm{LF}}, \mathrm{DEM}_j \rangle}{\langle \mathscr{C}_{\mathrm{HF}}, \mathrm{DEM}_j \rangle} - 1 \right|^2}$ for a set of reference DEMs

Tests on uniform FIP bias maps

AIA observations

↓ Cheung+2015

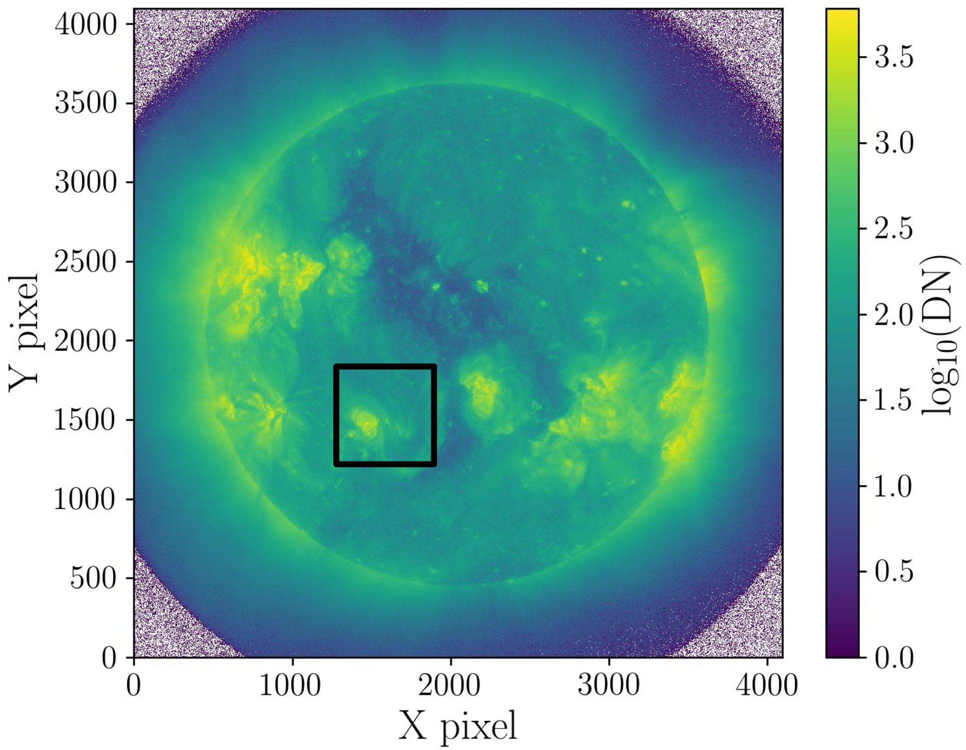
DEM cube

↓ CHIANTI

Synthetic intensities

↓ 2LR vs LCR

FIP bias maps



211 Å band, AIA/SDO
June 3rd 2012

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Synthetic intensities

- ★ Different temperatures
- ★ Different densities
- ★ **Uniform abundances**

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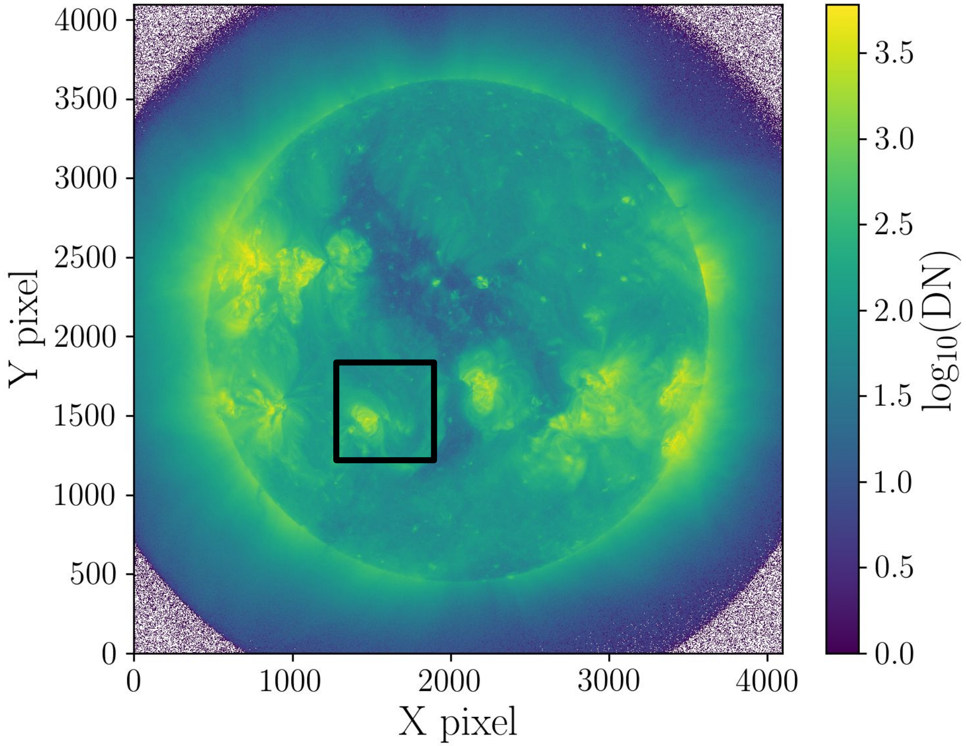

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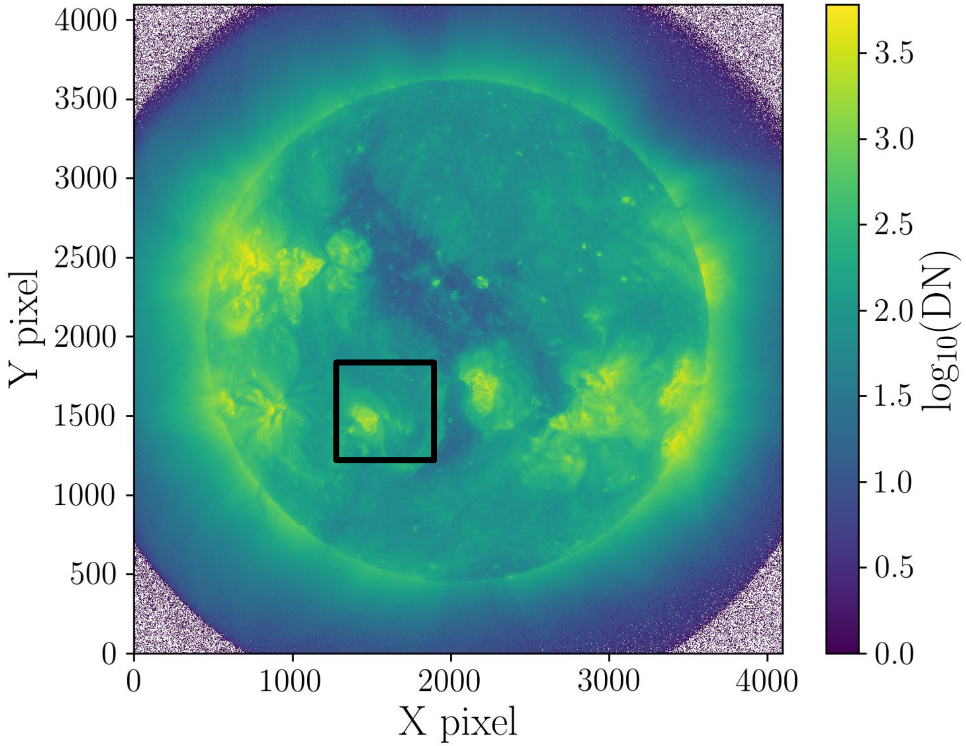
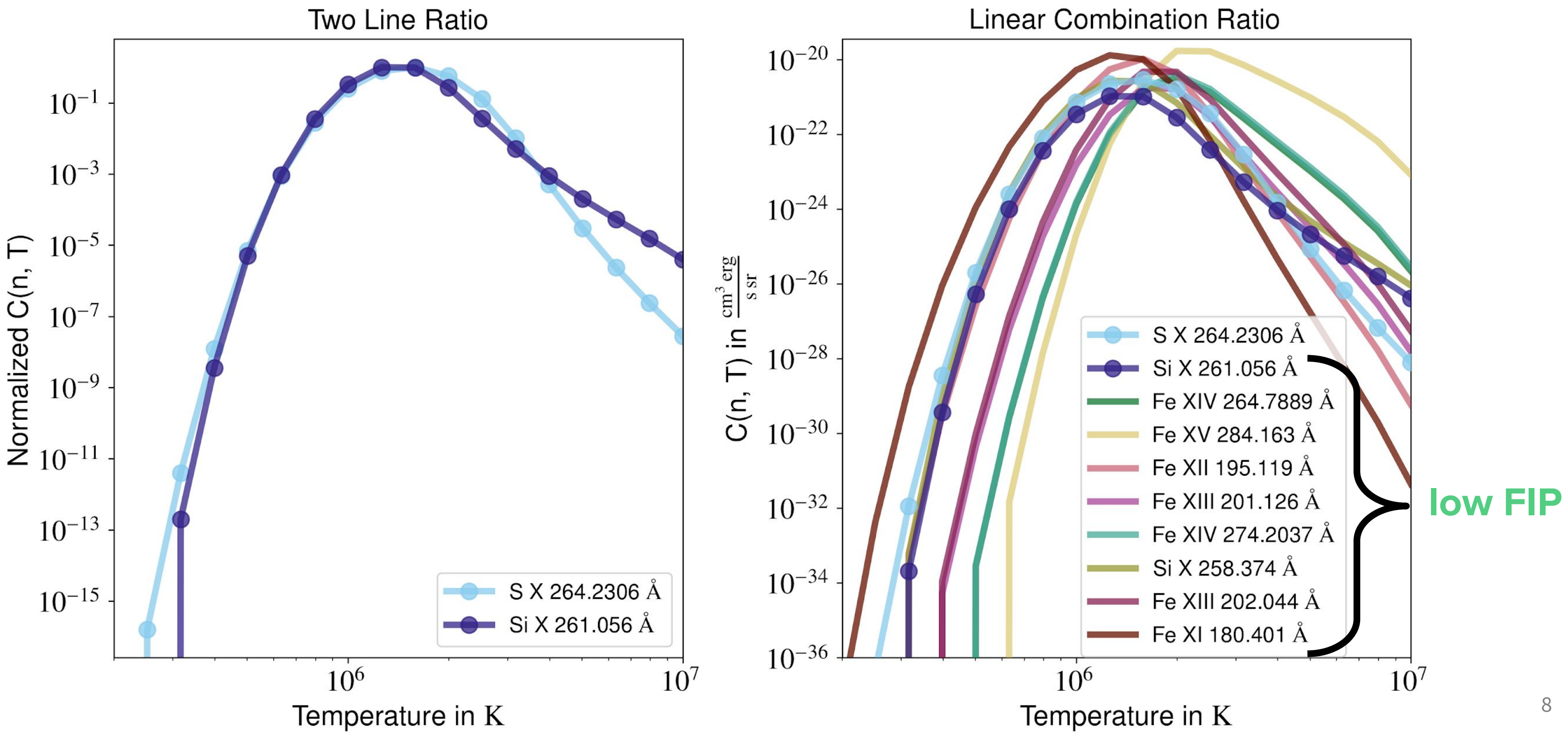


211 Å band, AIA/SDO
June 3rd 2012

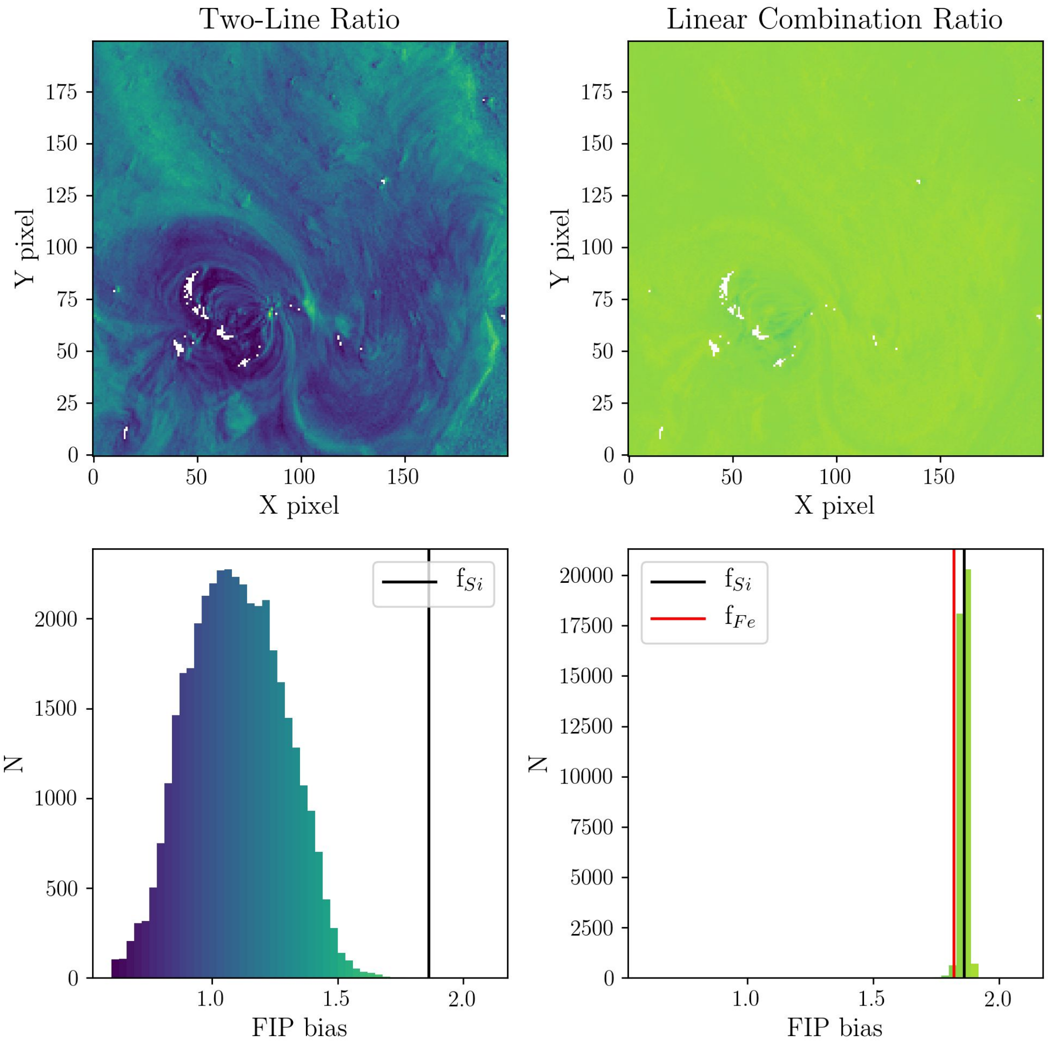
Contribution functions of the spectral lines that we use



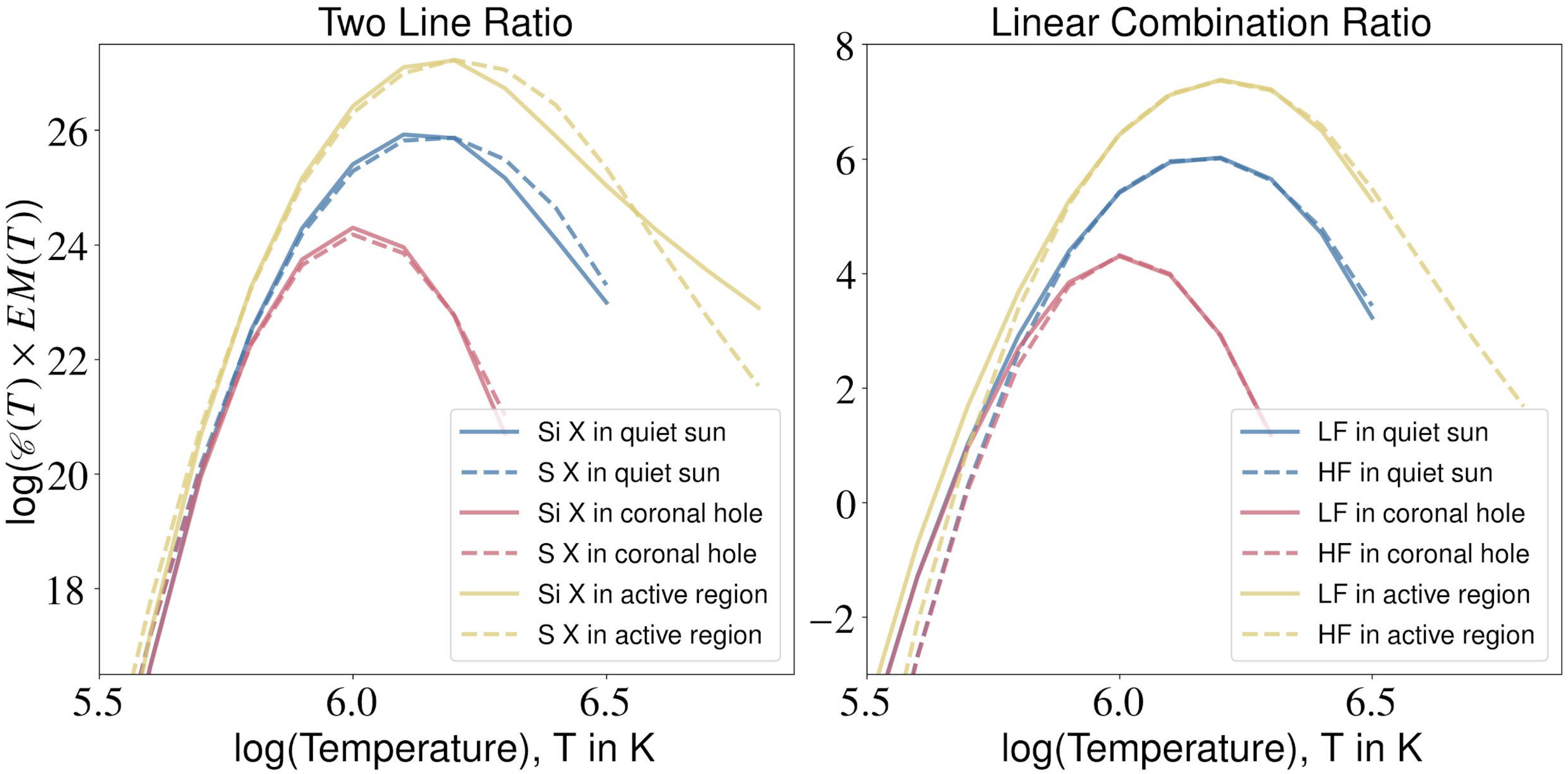
Tests on uniform FIP bias maps

Maps for relative FIP bias (ground truth: uniform, ≈ 1.8)

Histograms of values in maps



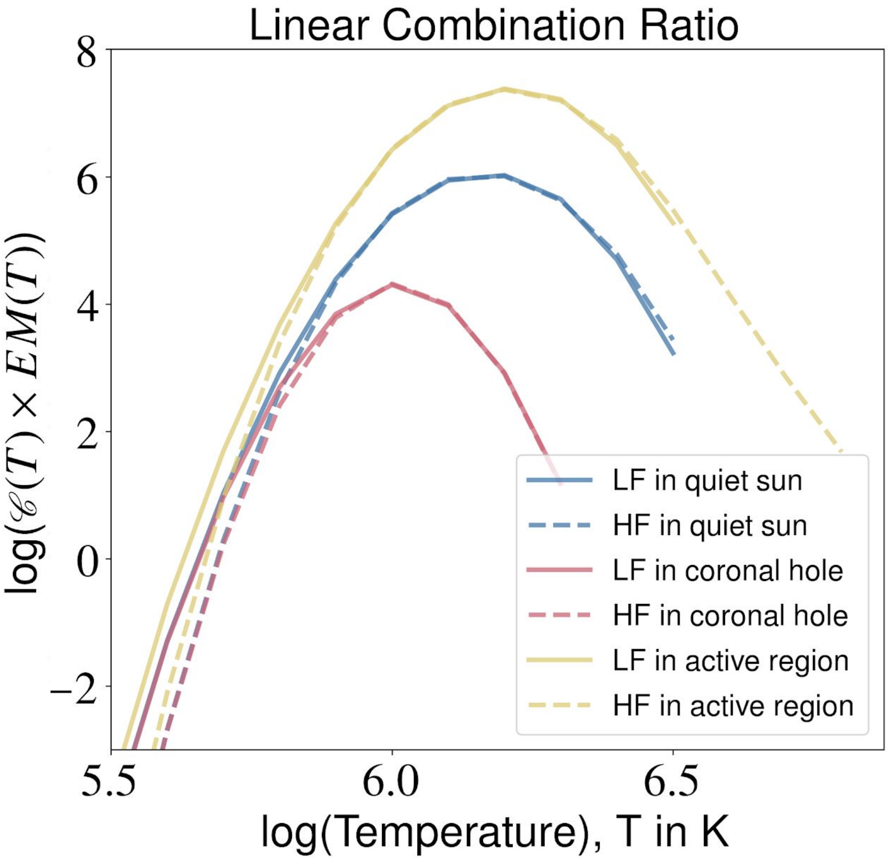
Sources of error - remaining non uniformity



Sources of error

Specific to the **LCR method** :

- ★ Minimized cost function is not equal to zero.
- ★ The DEMs in the map are different from the ones we used for the optimization.
- ★ Mixing of elements with different FIP biases



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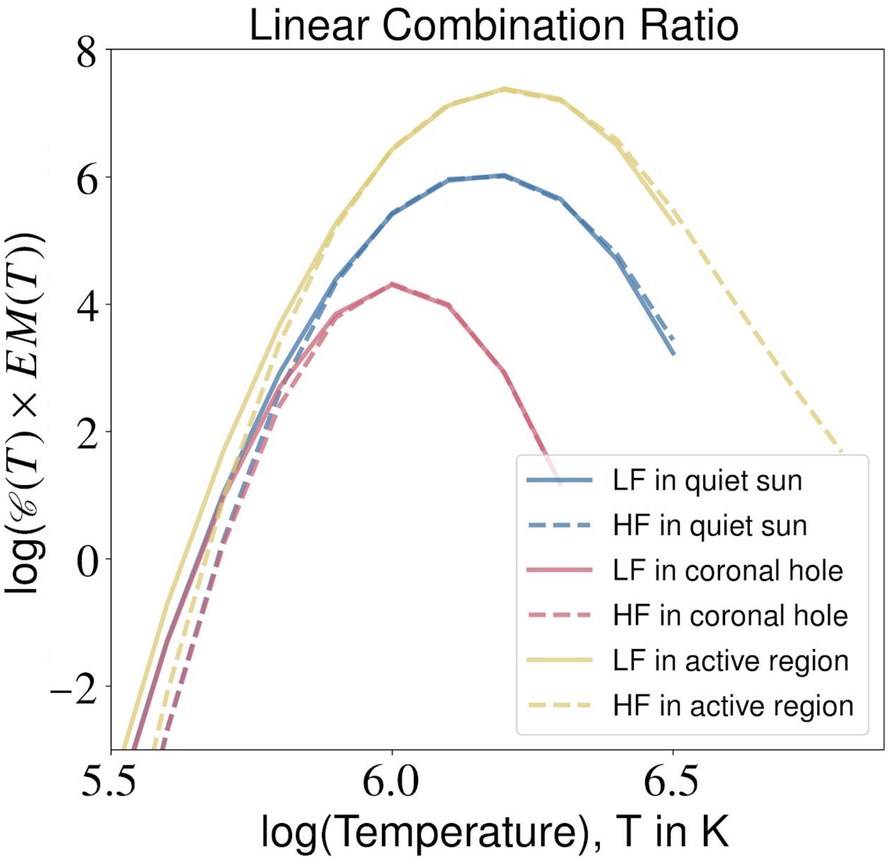
Other sources of error :

★ Radiometry

★ Atomic physics

★ Radiative transfer



In practice : Hinode/EIS

Application of the LCR method to spectroscopic observations of a sigmoidal anemone-like Active Region inside an equatorial Coronal Hole, previously studied in Baker et al. (2013).

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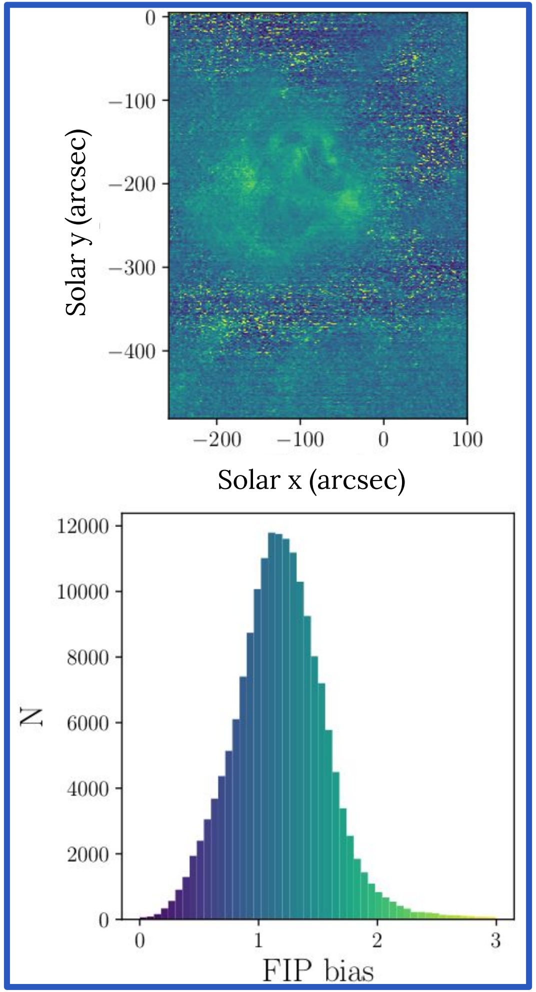
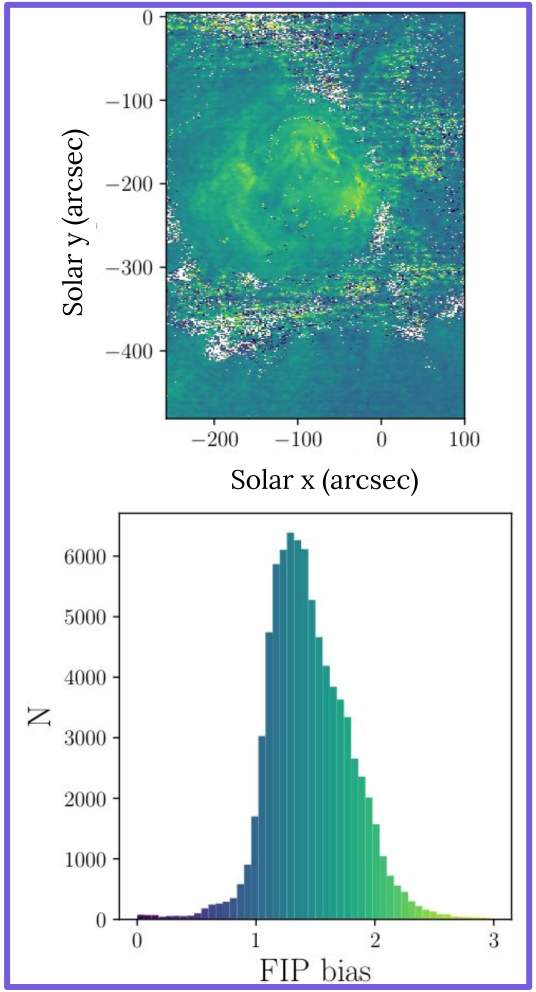
Following DEM inversion

$$\frac{f_{\mathrm{Si}}}{f_{\mathrm{S}}}$$

Linear combinations

$$\frac{f_{\mathrm{Si\ \&\ Fe}}}{f_{\mathrm{S}}}$$





Data courtesy of D. Baker

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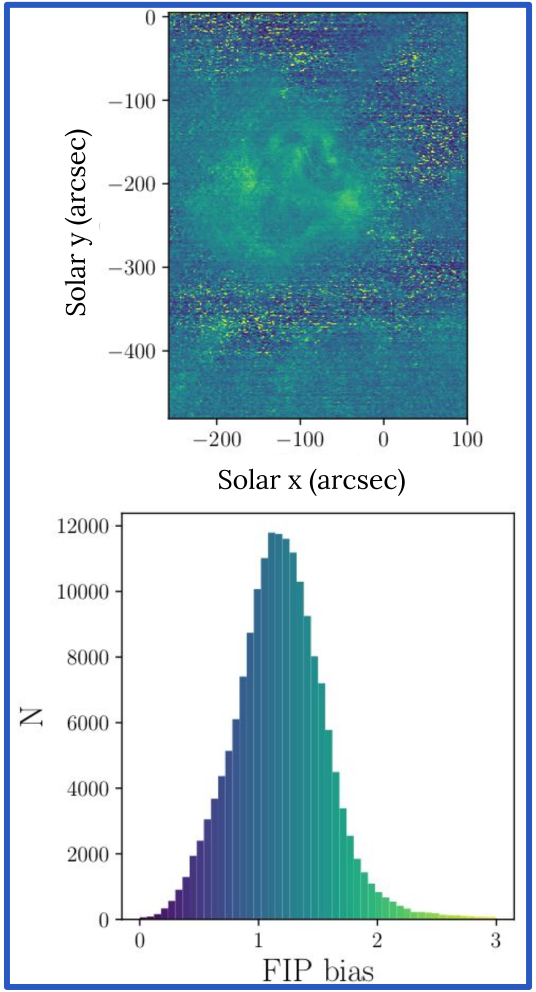

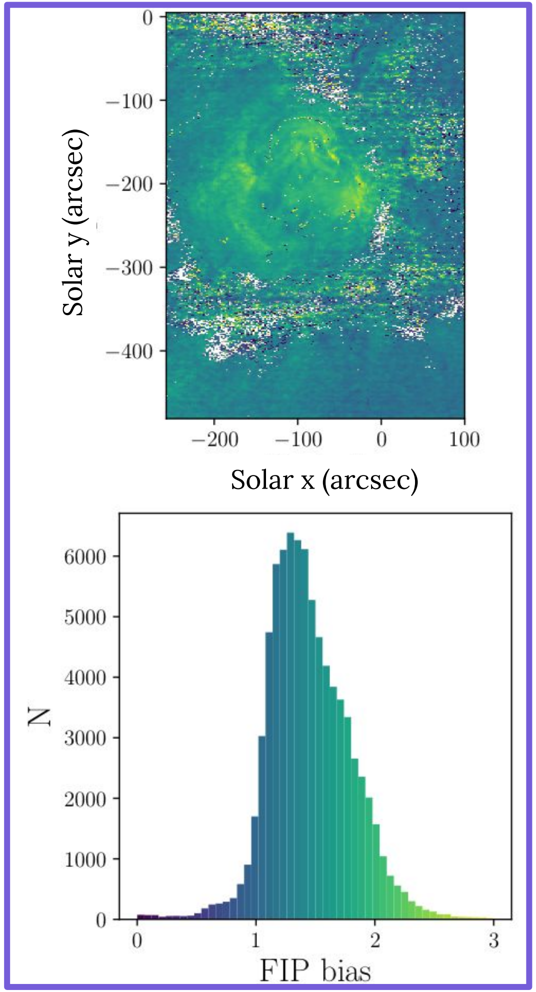

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★ Similar structures with enhanced or depleted relative FIP bias in both maps.

Conclusions

- ★ The tests show that **the LCR method performs well,** and **does not require prior DEM inversion**.
- ★ The LCR method could be useful to **re-analyze past observations** that were not intended for abundance measurements.
- ★ It could help us **prepare future observations**.

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Future work

- ★ Assessment of **linear combinations of lines** for the UV spectrometer **SPICE** on board Solar Orbiter to help connect remote and in-situ measurements from SWA/HIS.
- ★ Could become a SPICE **level 3 data product**.

Thank you for listening