# Non-Maxwellian Diagnostics of a Transient Coronal Loop


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# Outline

## I. The Non-Maxwellian κ-Distributions

Line intensity calculations
Selection bias and other problems
Ionization equilibrium for κ-distribution: Fe

## II. Imaging Observations of a Transient Loop

SDO/AIA multi-wavelength observations:
Evolution and DEM analysis

## III. Spectral Observations: Hinode/EIS (HOP 226)

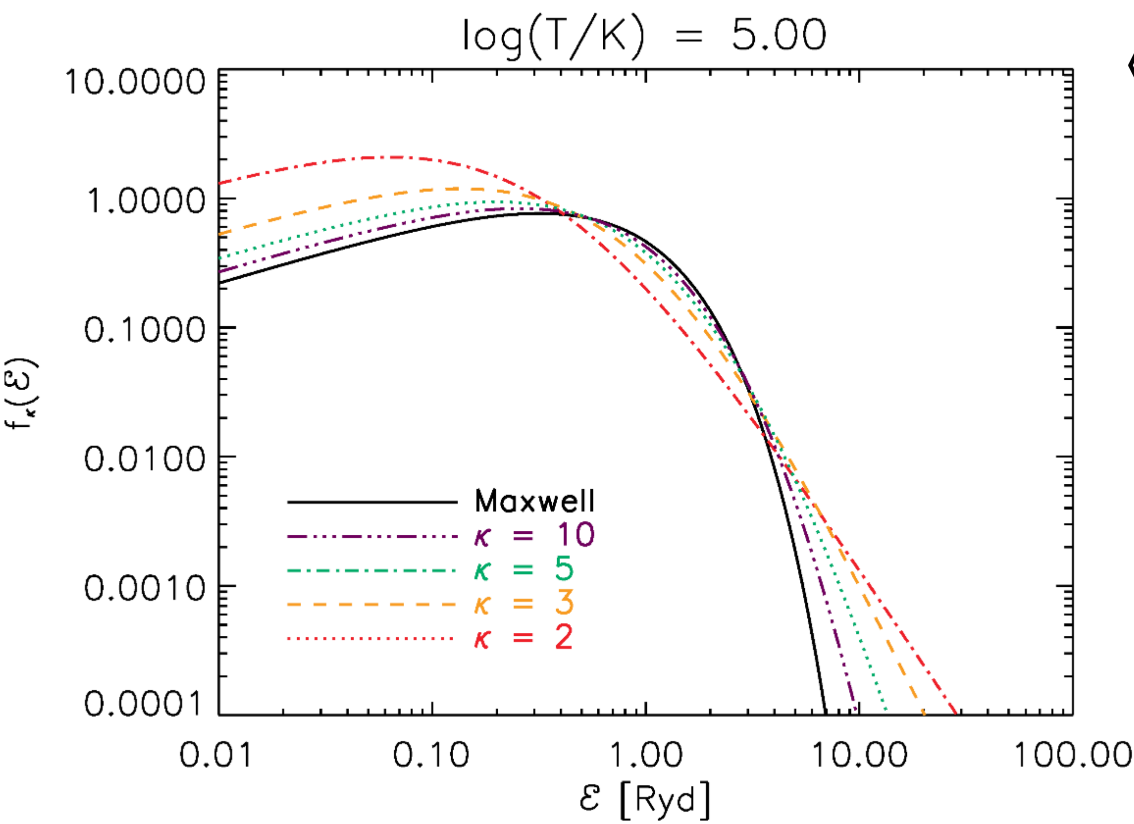
Loop and background
Calibration issues
Density diagnostics
Diagnostics of the non-Maxwellian κ-distributions
Influence of DEM on the diagnostics
Atomic data uncertainties and their effect on the diagnostics

***Dudík et al. (2014), ApJL, 780, L12, Dudík et al. (2014), A&A, 570, A124***
***Dzifčáková et al. (2015), ApJS, in press, Dudík et al. (2015) ApJ, submitted***

## IV. Summary

# I. The κ-distributions

$$f_\kappa(E)dE = A_\kappa \frac{2}{\sqrt{\pi}\left(k_\mathrm{B}T\right)^{3/2}} \frac{E^{1/2}}{\left(1+\frac{E}{(\kappa-3/2)\,k_\mathrm{B}T}\right)^{\kappa+1}} dE$$




$$\langle E \rangle_\kappa = \frac{3}{2} k_\mathrm{B} T_\kappa = \frac{3}{2} k_\mathrm{B} T$$

**κ differs from Mxw at all energies**

***Owocki & Scudder (1983)***
***Tsallis (1988, 2009)***
***Leubner (2004, 2005, 2008)***
***Livadiotis & McComas (2009, 2010)***

# Line Intensity Calculations

$$
\begin{aligned}
I_{ji} &= \int G_{ji}(T, n_\mathrm{e}, \kappa) A_X n_\mathrm{e}^2 \mathrm{d}l \\
&= \int G_{ji}(T, n_\mathrm{e}, \kappa) A_X \mathrm{DEM}(T) \mathrm{d}T \,,
\end{aligned}
$$

Excitation

Ionization

$$
G_{ji}(T, n_\mathrm{e}, \kappa) = \frac{hc}{\lambda_{ji}} \frac{A_{ji}}{n_\mathrm{e}} \frac{n_{X,i}^{+k}}{n_X^{+k}} \frac{n_X^{+k}}{n_X} \frac{n_\mathrm{H}}{n_\mathrm{e}} \,,
$$

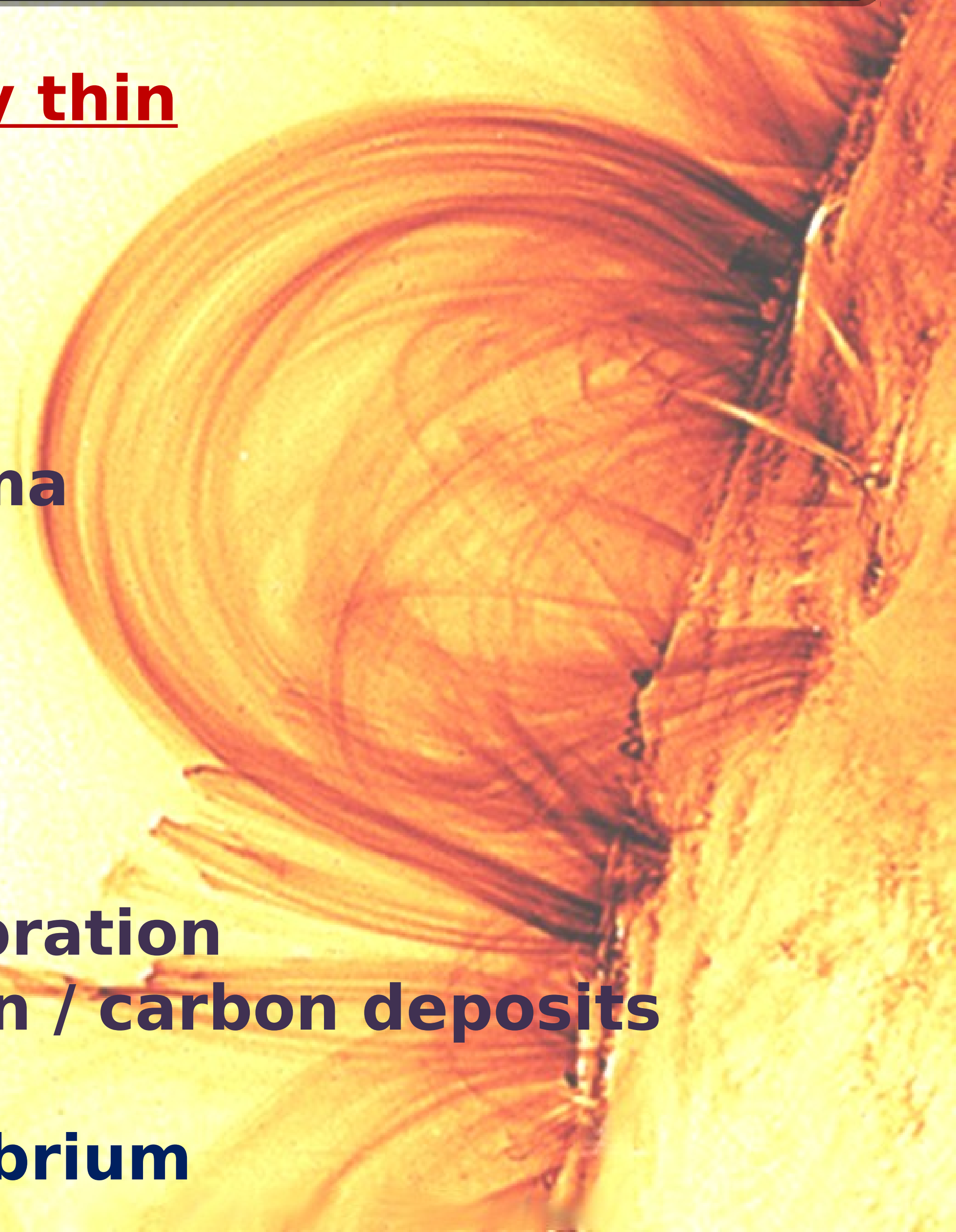
- **Ionization fractions:** ***Dzifčáková & Dudík (2013), ApJS 206, 6***
- **Excitation fractions: obtained from the original collision strengths Ω or using approximative method of *Dzifčáková et al. (2014)***
- **Best diagnostic options:**
  - **ratios of lines with widely different λ (sensitive to distribution)**
  - **X-ray lines with high excitation thresholds (sensitive to tails!)**

# Selection Bias and Other Problems

- **Solar corona is optically thin**
- $\varepsilon_{ij} = A_X \, G_{ij}(T, n_e, \kappa) \, n_H n_e$

**By definition, the signal is always biased**

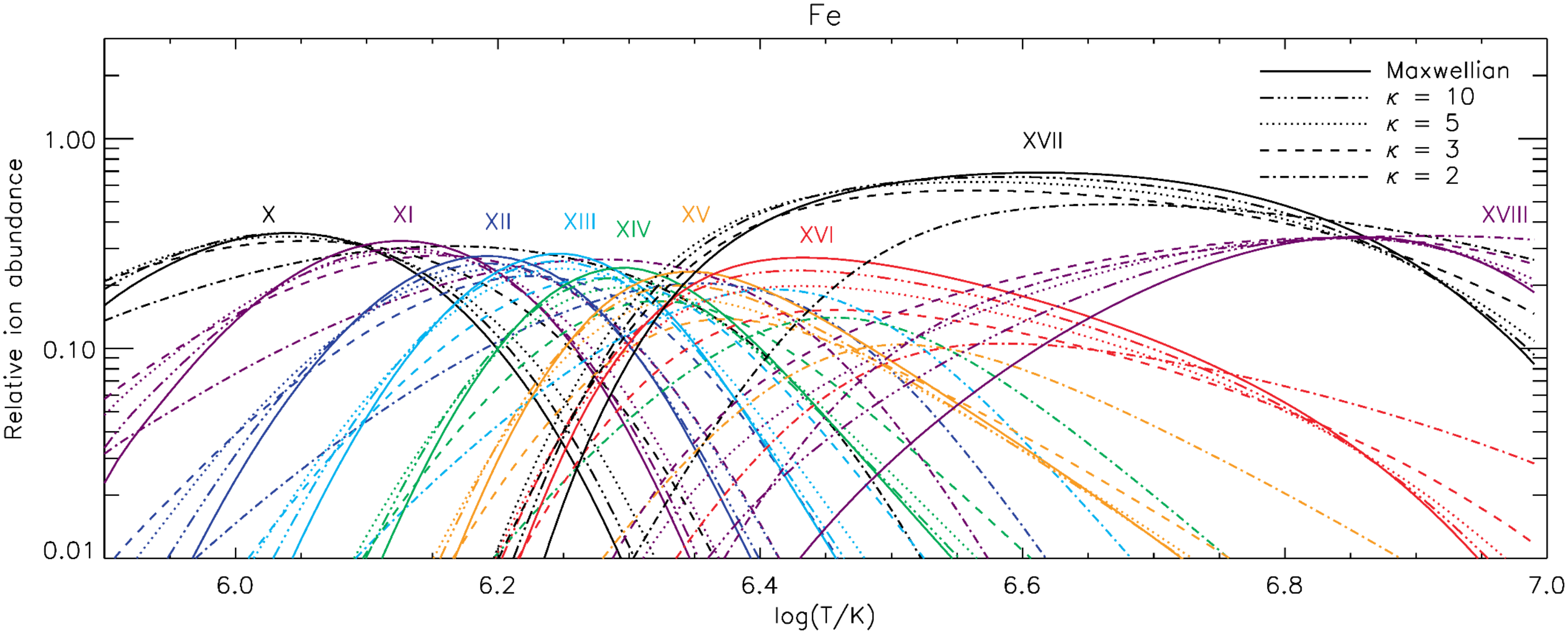
- **towards dense(r) plasma**



**Other problems:**

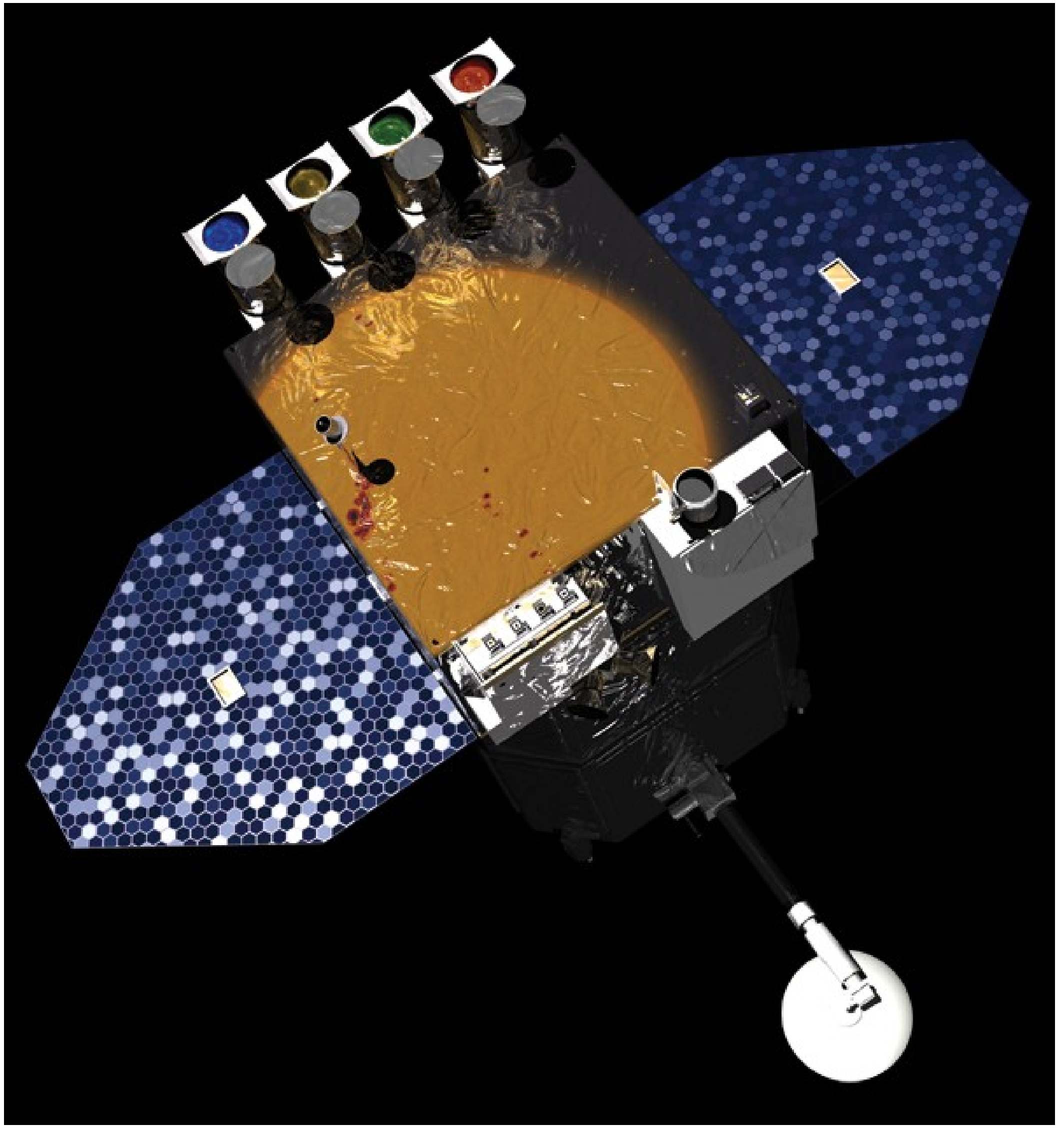
- **S/N**
- **photon statistics**
- **calibration / cross-calibration**
- **Instrument degradation / carbon deposits**
- **“Background”**
- **Ionization out of equilibrium**

# Ionization Equilibrium: Fe




***After Dzifčáková & Dudík (2013), ApJ Suppl. Ser. 206, 6***

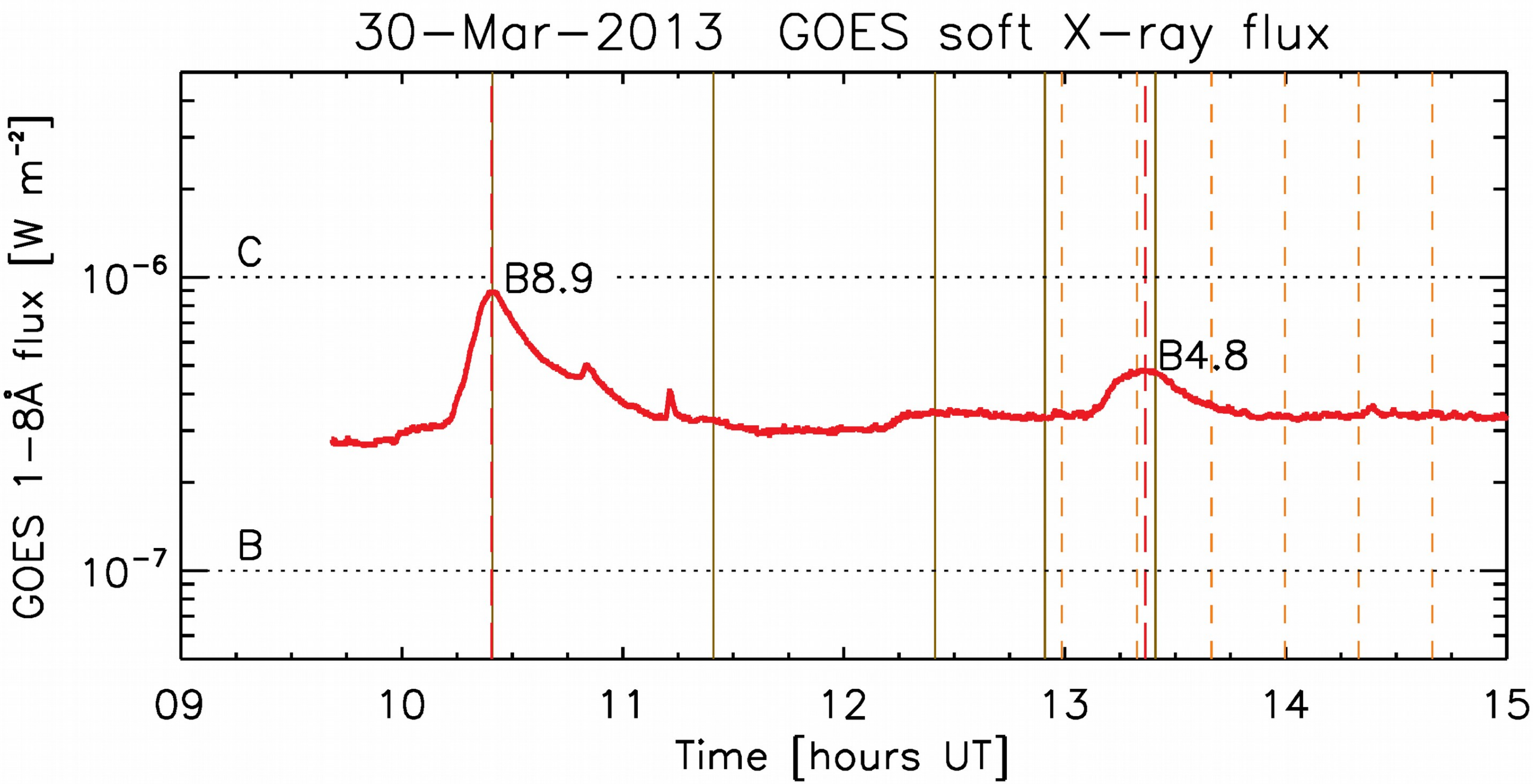
# II. Imaging Observations of a Transient loop



**Solar Dynamics Observatory:**
**NASA mission, launched 2010**

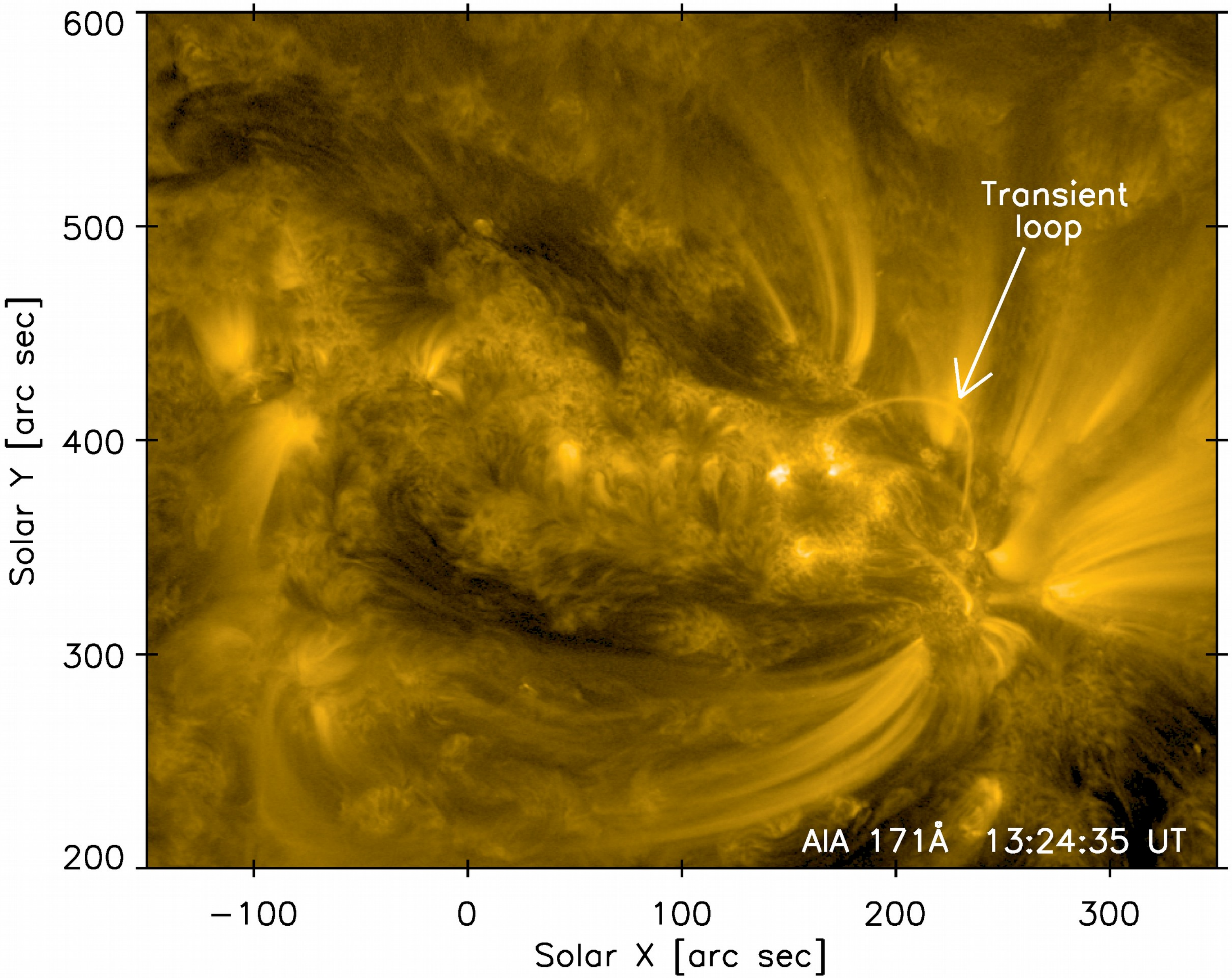
**Atmospheric Imaging Assembly (AIA):**
**– successor to SoHO/EIT and TRACE**
**– four identical EUV full-disc telescopes, state-of-the-art**
**– cadence of 12 seconds**
**– 0.6” px size, 1.5” resolution**
**– broad temperature coverage to study coronal and flare physics**

# Context – Flares and a Transient Loop




**B8.9 – maximum at 10:24 UT, NOAA AR 11 704**
**B4.8 – maximum at 13:21 UT, NOAA AR 11 708**

# SDO/AIA: Transient Loop



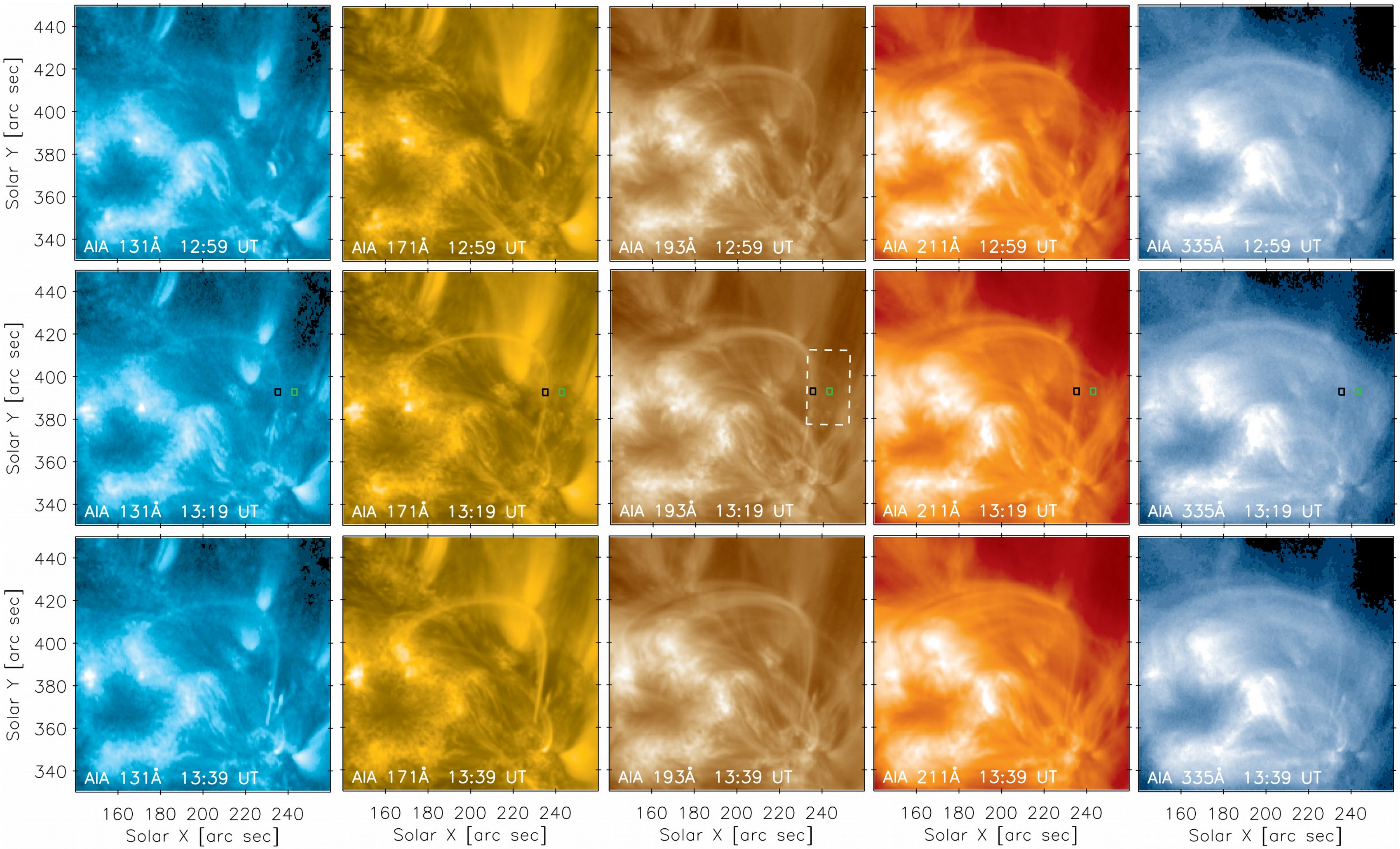
## Movie of the evolution of a transient coronal can be found at:

http://iopscience.iop.org/article/10.1088/0004-637X/807/2/123/meta;jsessionid=017AAC74038442C41CF6868F847EE736.c3.iopscience.cld.iop.org#apj515009s3

**Paper:**

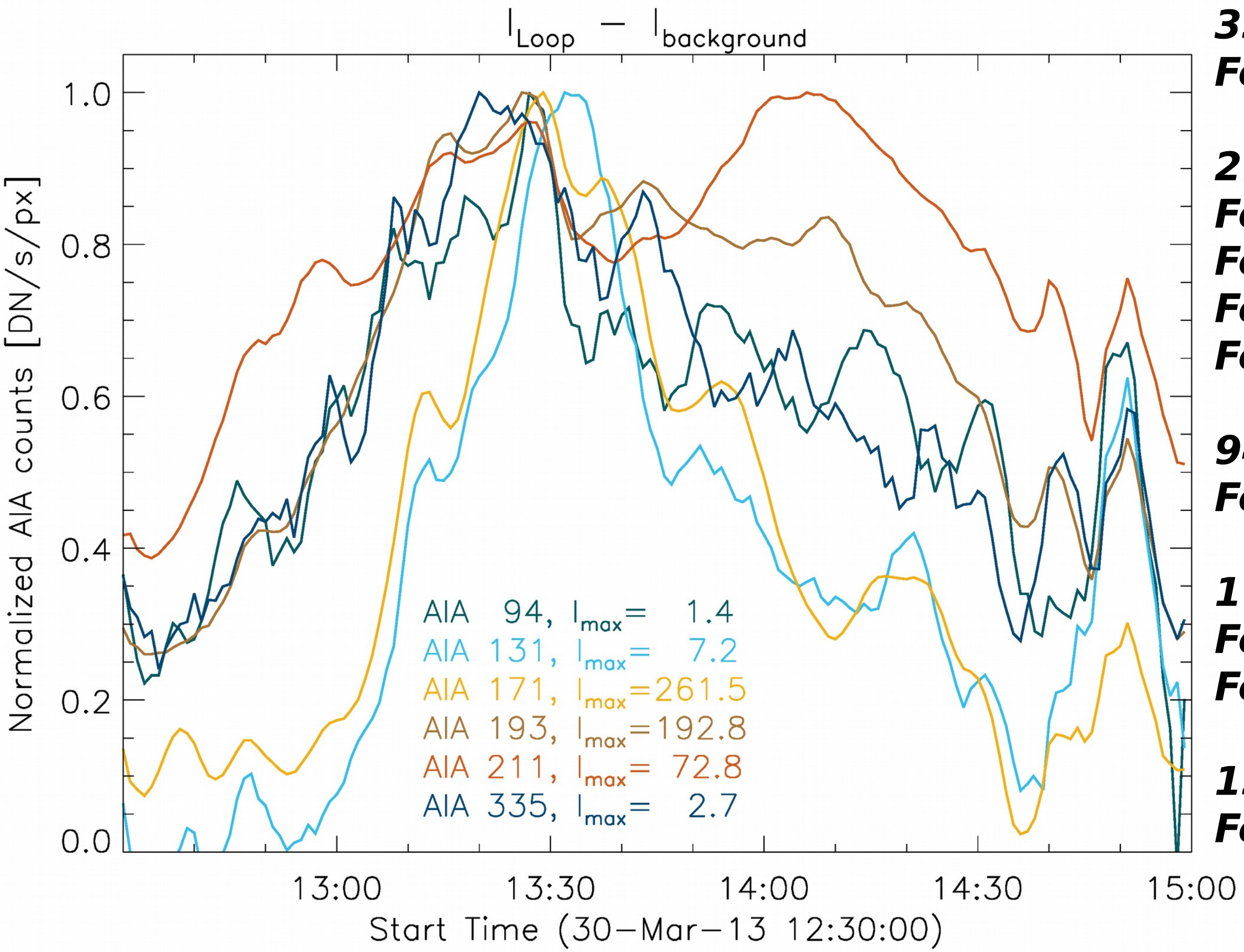
**Dudík J., *et al*.: 2015, The Astrophysical Journal 807, p. 123.**

# SDO/AIA: Transient Loop



# AIA Light curves

**Results for black square box from the previous slide:**




***335A 13:20 UT***
***Fe XVI log T= 6.45***

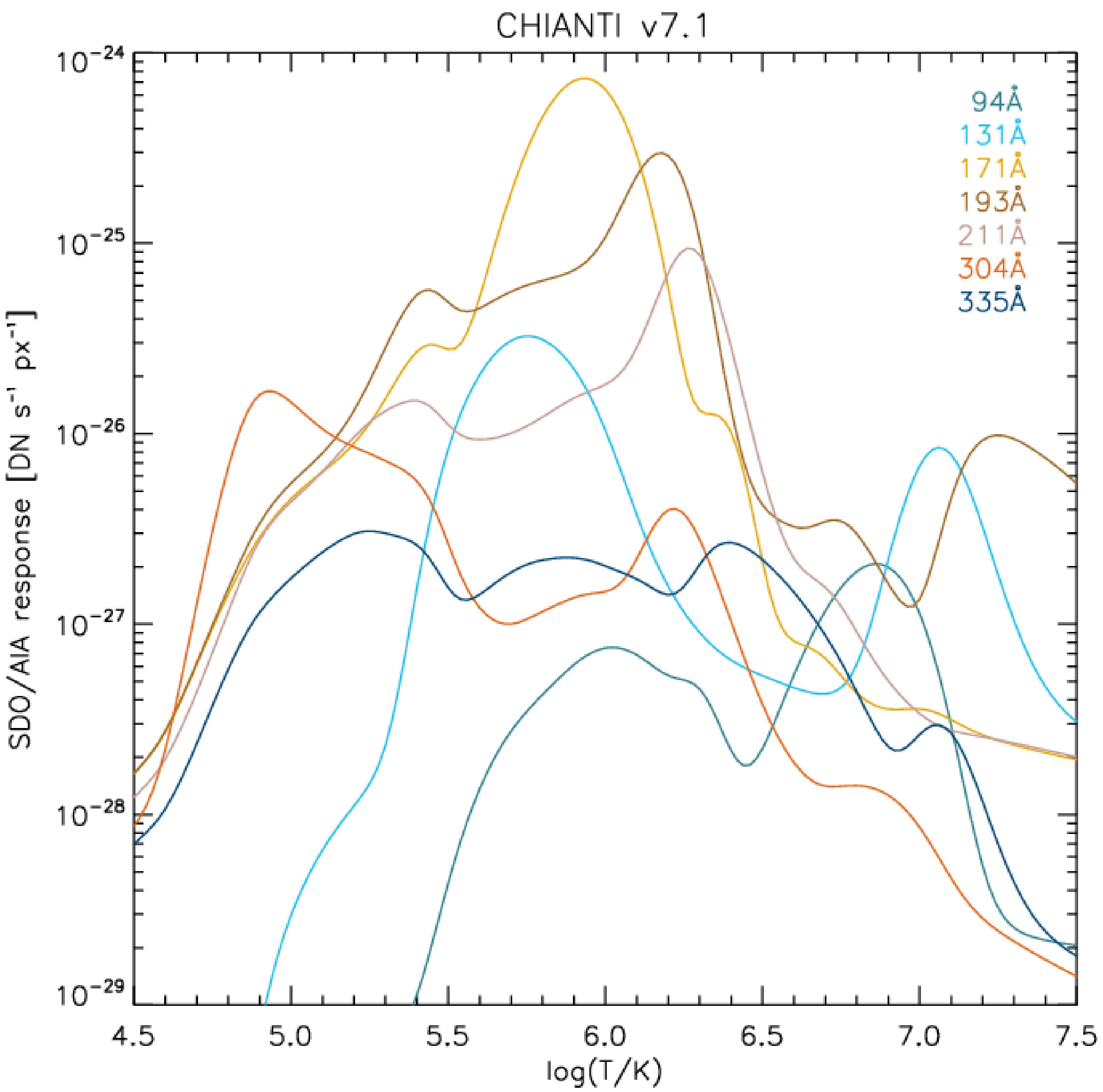
***211A , 193A 13:26 UT***
***Fe XIV log T=6.30***
***Fe XIII log T=6.25***
***Fe XII log T=6.20***
***Fe XI log T=6.15***

***94A 13:27 UT***
***Fe X log T=6.05***

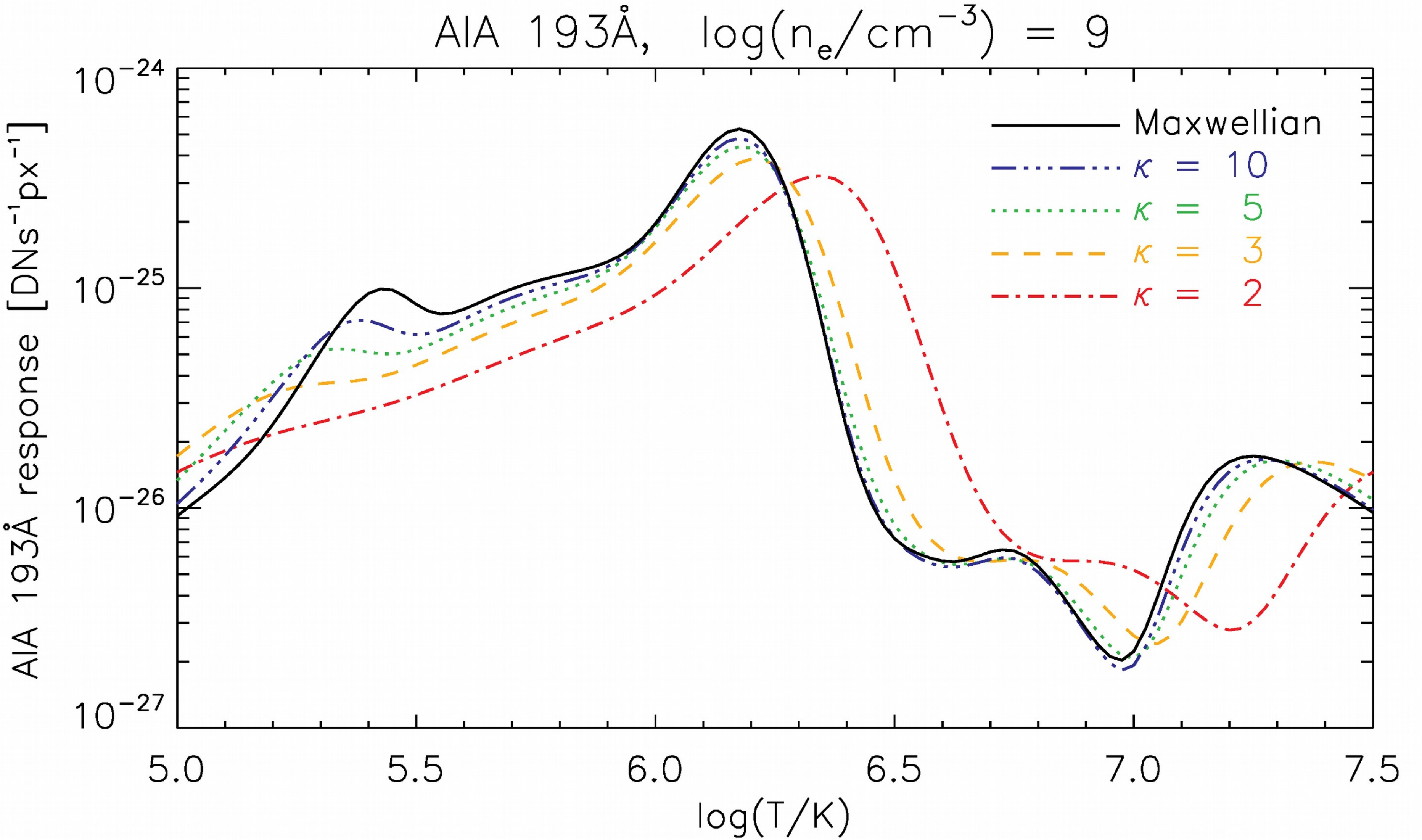
***171A 13:29 UT***
***Fe X log T=6.05***
***Fe IX log T=5.85***

***131A 13:32 UT***
***Fe VIII log T=5.60***

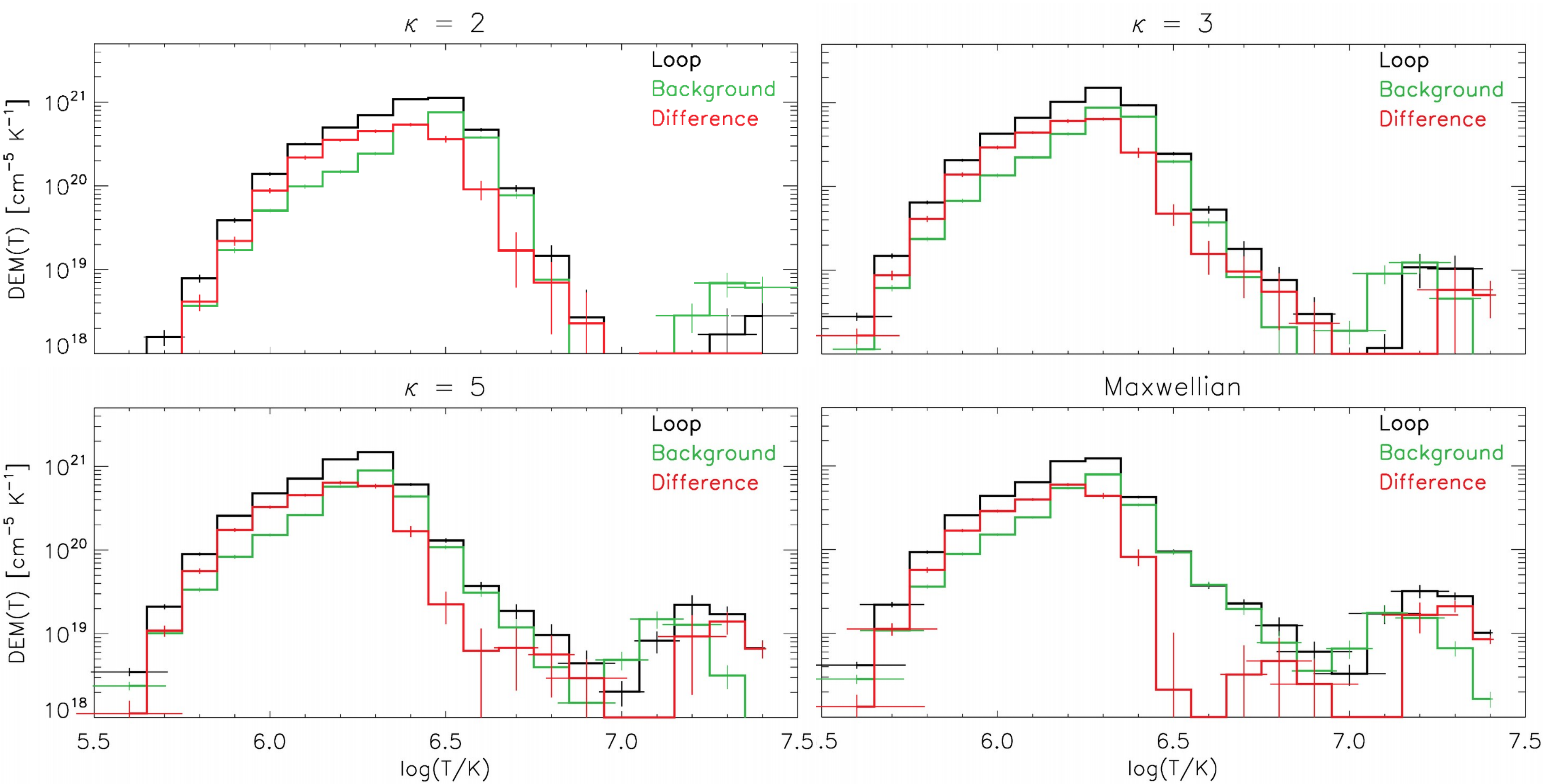
# AIA Temperature Responses - MXW



# AIA Responses for κ-distributions



# Regularized AIA DEMs

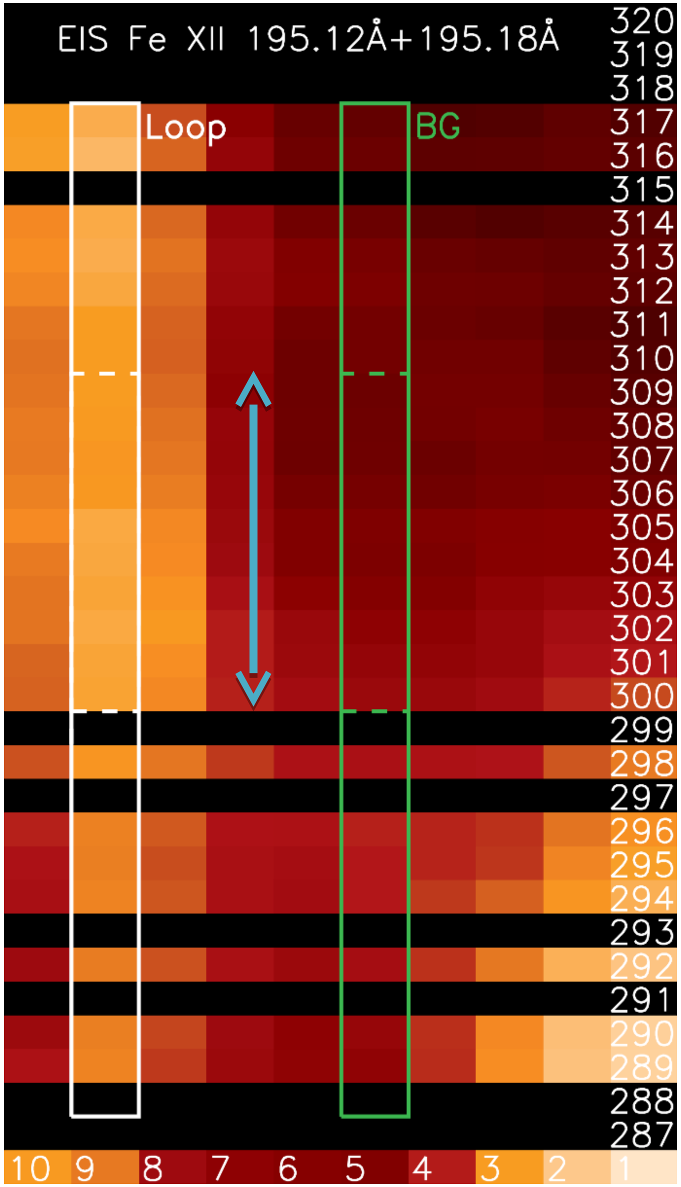



- **Multithermality is kept for all *κ*** (c.f., ***Mackoviak et al. 2014, A&A 564, A130***)
- **DEMs for low *κ* shifted towards hi**

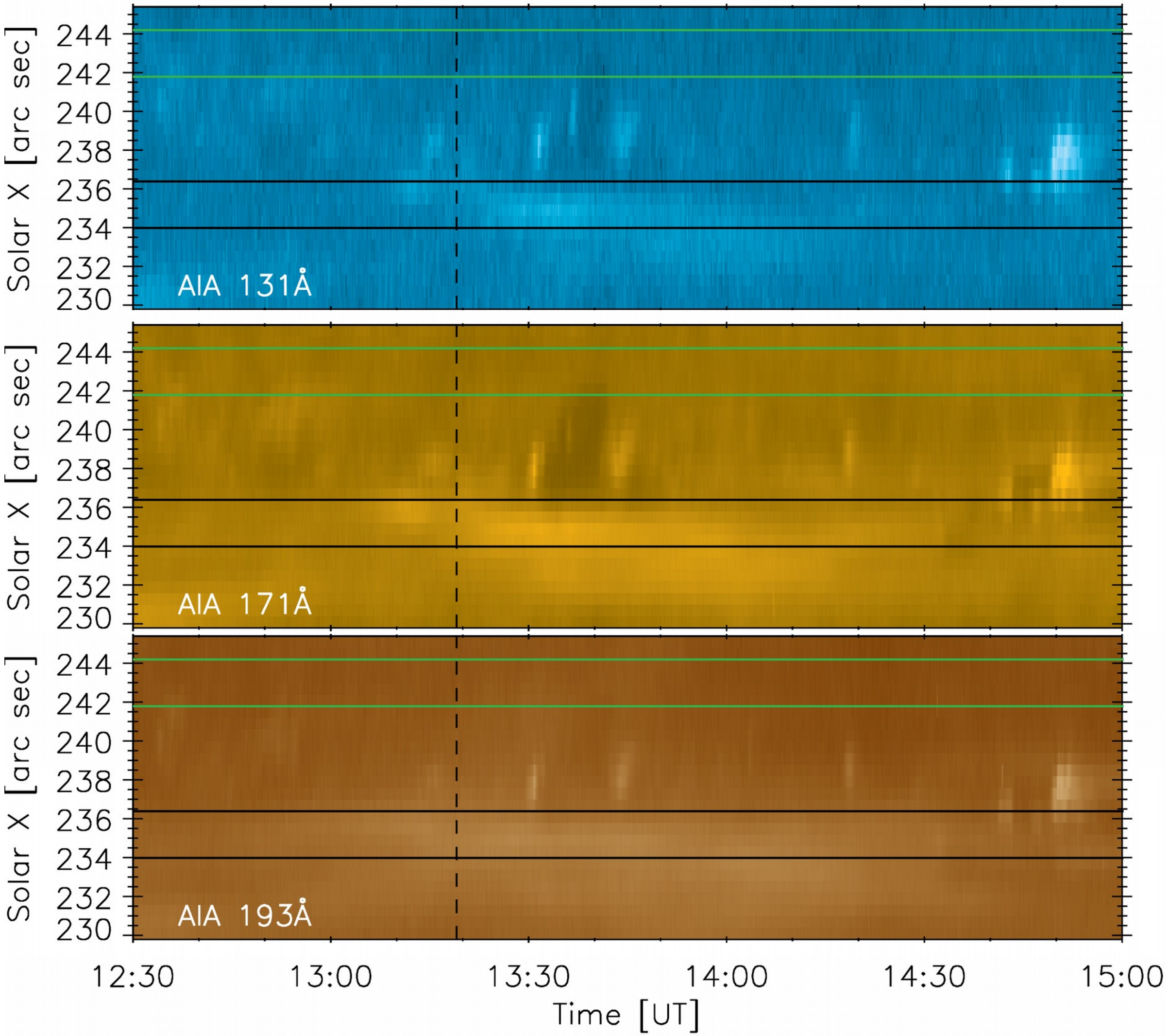
$$I_{ji} = \int G_{ji}(T, n_e, \kappa) A_X n_e^2 \mathrm{d}l$$

$$= \int G_{ji}(T, n_e, \kappa) A_X \mathrm{DEM}(T) \mathrm{d}T\,,$$

# III. Spectral Observations: EIS HOP 226

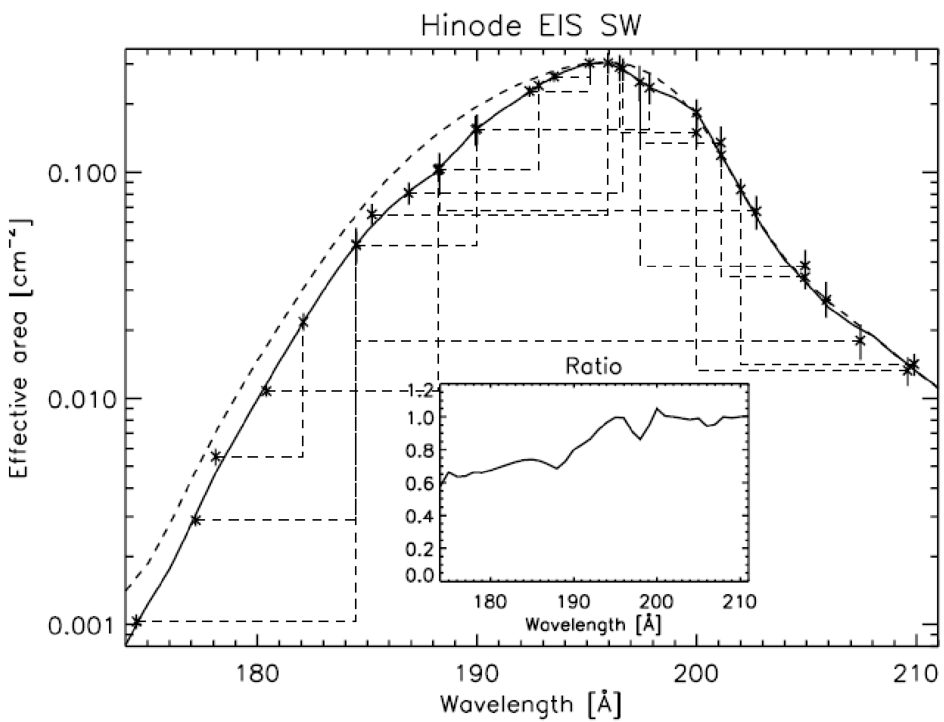


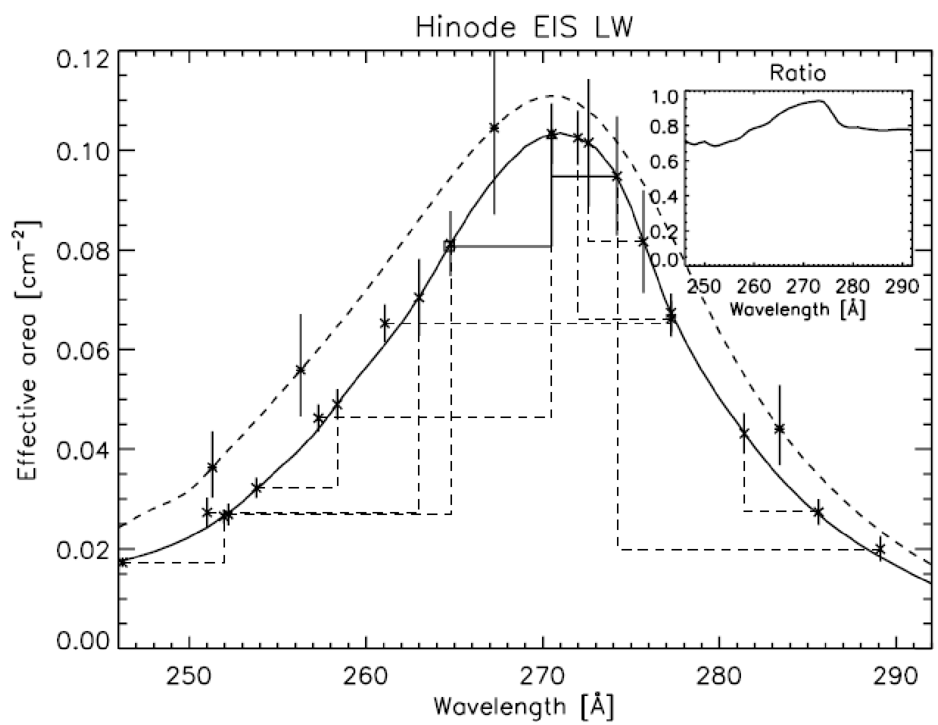

## Loop and its background



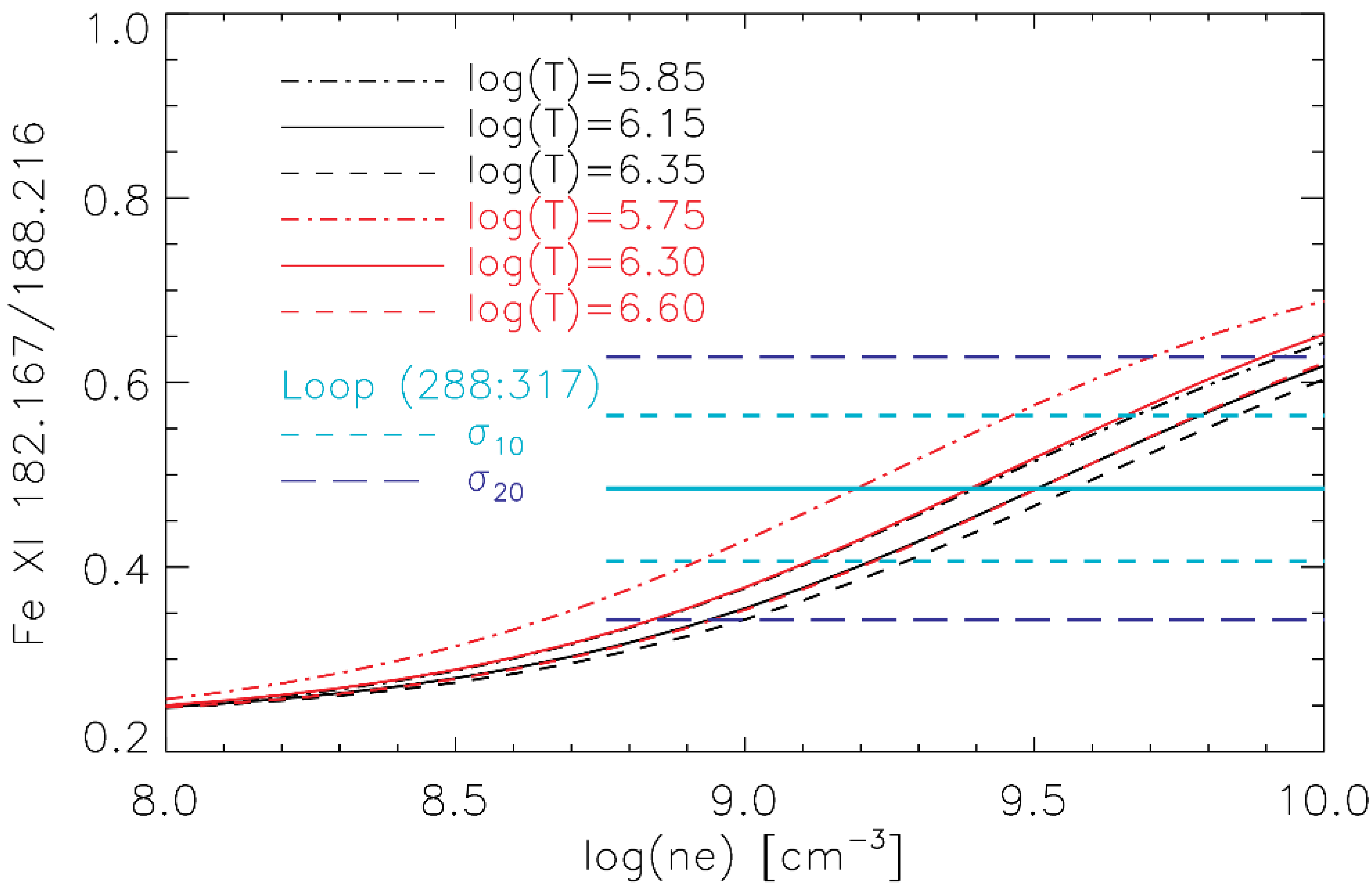
# Calibration Issues - Line Intensities

| Ion | $\lambda$ [Å] | selfblending transitions [Å] | Loop (288:317) | | | Loop (300:309) | | |
|---|---|---|---|---|---|---|---|---|
| | | | $I$ | $\sigma_{10\%}(I)$ | $\sigma_{20\%}(I)$ | $I$ | $\sigma_{10\%}(I)$ | $\sigma_{20\%}(I)$ |
| Fe XI | 182.167 | – | 795 | 99 | 169 | 934 | 117 | 199 |
| Fe XI | 188.216 | – | 1638 | 172 | 332 | 1947 | 204 | 394 |
| Fe XI | 257.554 | 257.538, 257.547, 257.558 | 398 | 45 | 82 | 414 | 47 | 86 |
| Fe XI | 257.772 | 257.725 | 178 | 23 | 38 | 234 | 30 | 50 |
| Fe XII | 186.887 | 186.854, (186.931) | 1406 | 145 | 283 | 1498 | 154 | 302 |
| Fe XII | 195.119 | 195.179, (195.078), (195.221) | 2256 | 228 | 453 | 2506 | 254 | 503 |
| Fe XIII | 196.525 | – | 261 | 27 | 53 | 223 | 23 | 45 |
| Fe XIII | 202.044 | – | 1346 | 153 | 279 | 1779 | 202 | 368 |
| Fe XIII | 203.826 | 203.772, 203.795, 203.835 | 2591 | 270 | 524 | 2532 | 264 | 512 |

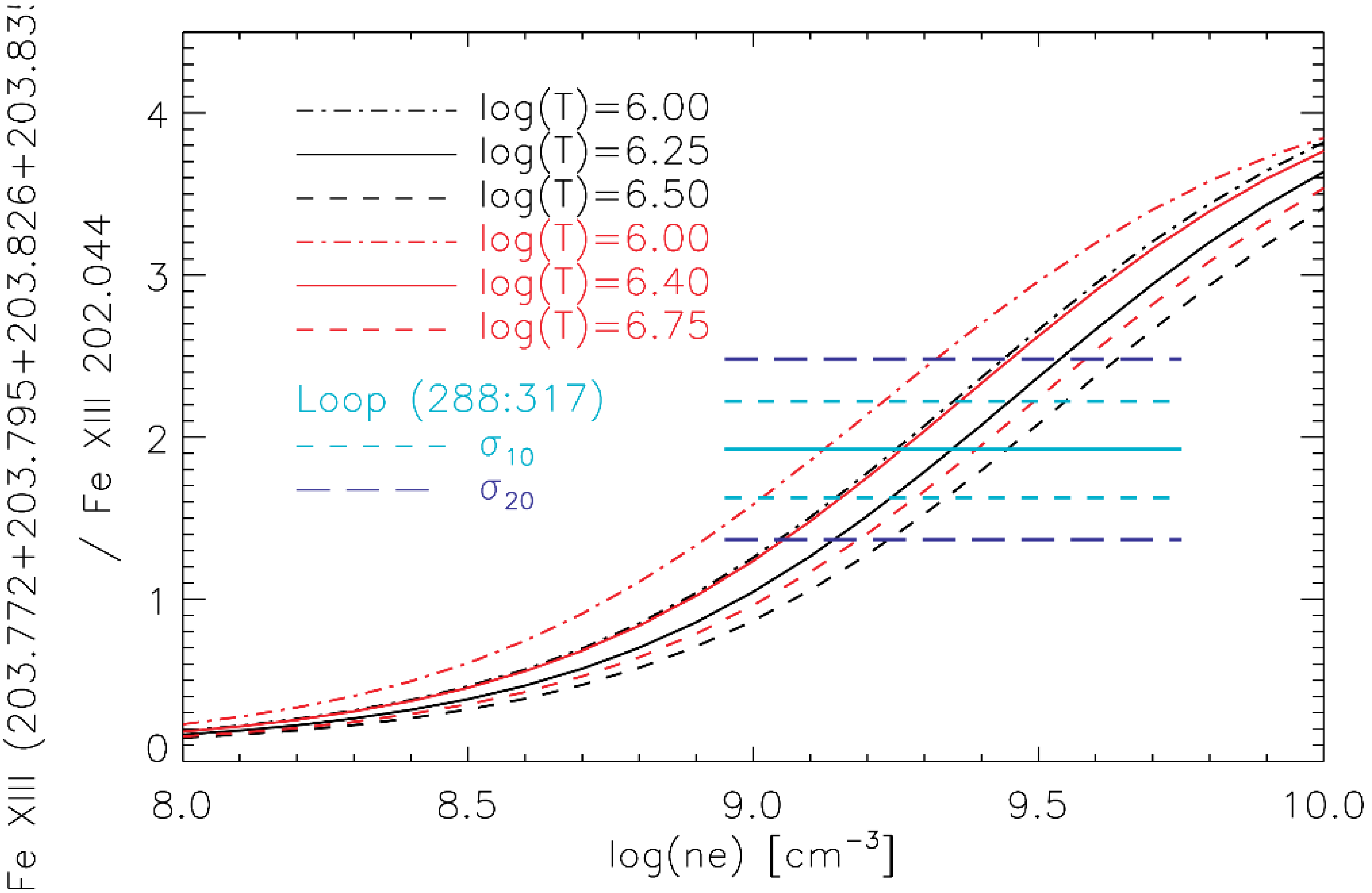


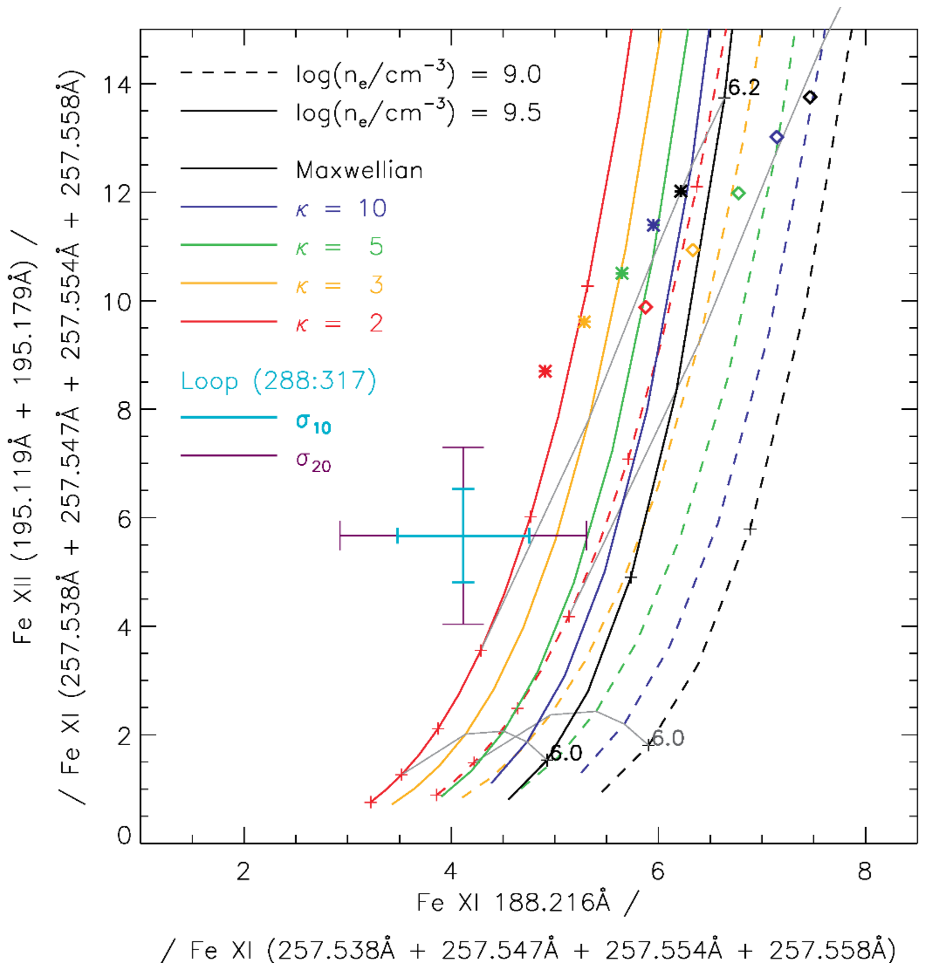
# Density Diagnostics: Fe XI



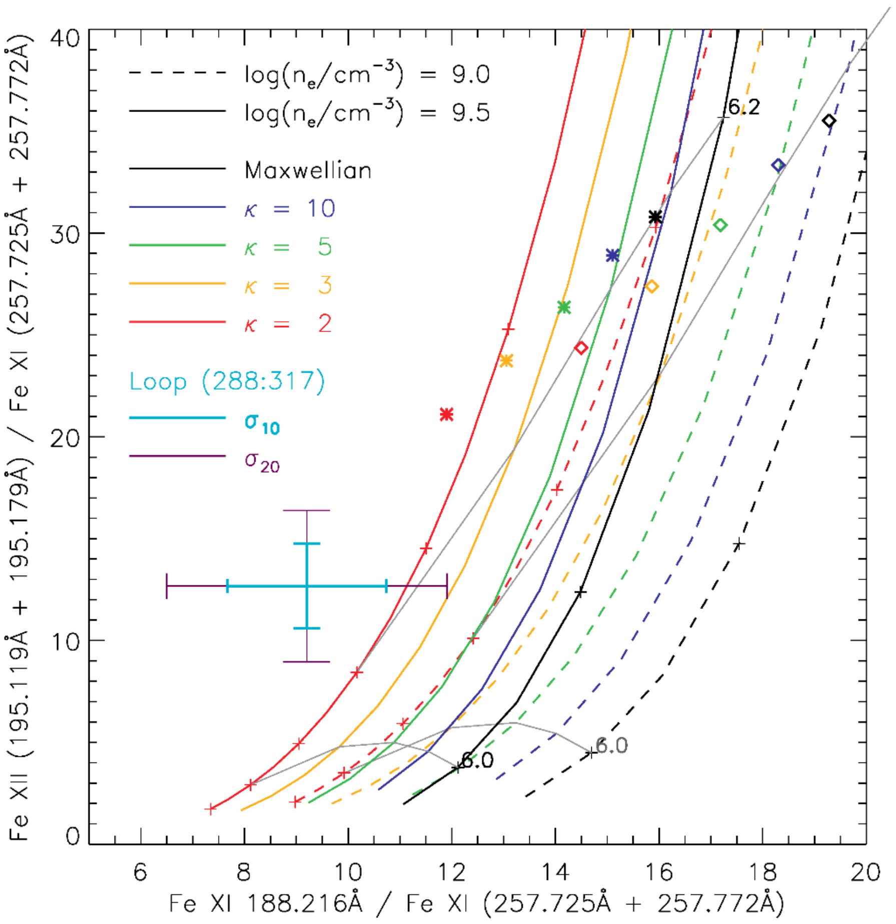
# Density Diagnostics: Fe XIII



# Non-Maxwellian Diagnostics

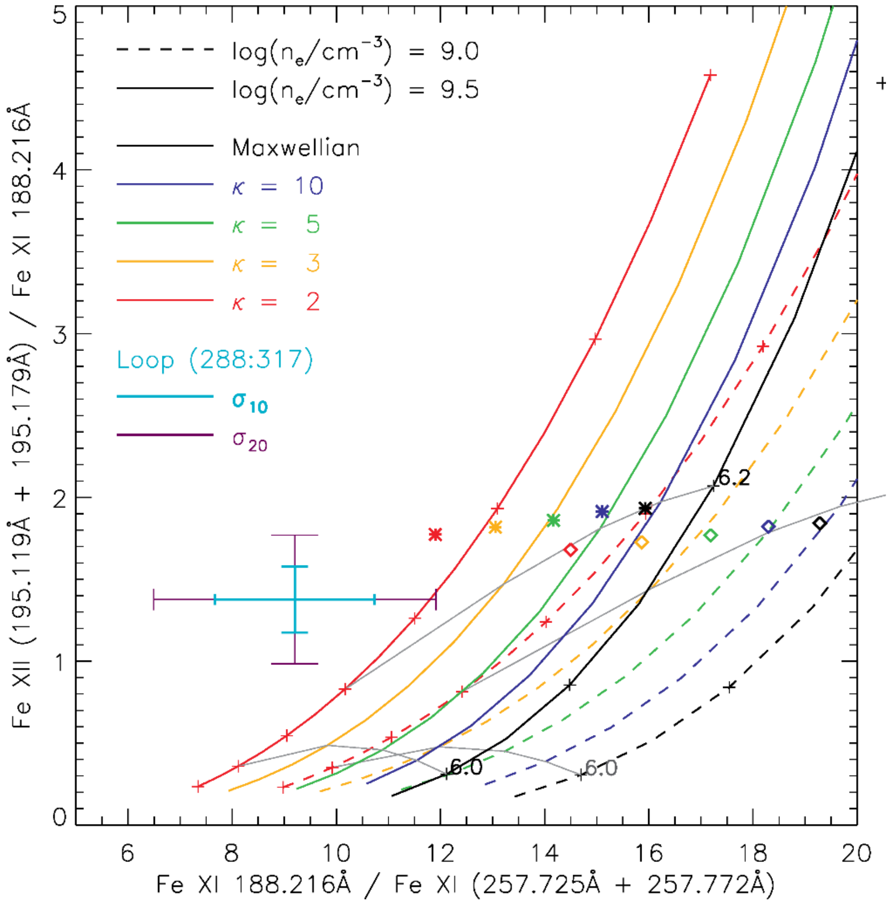


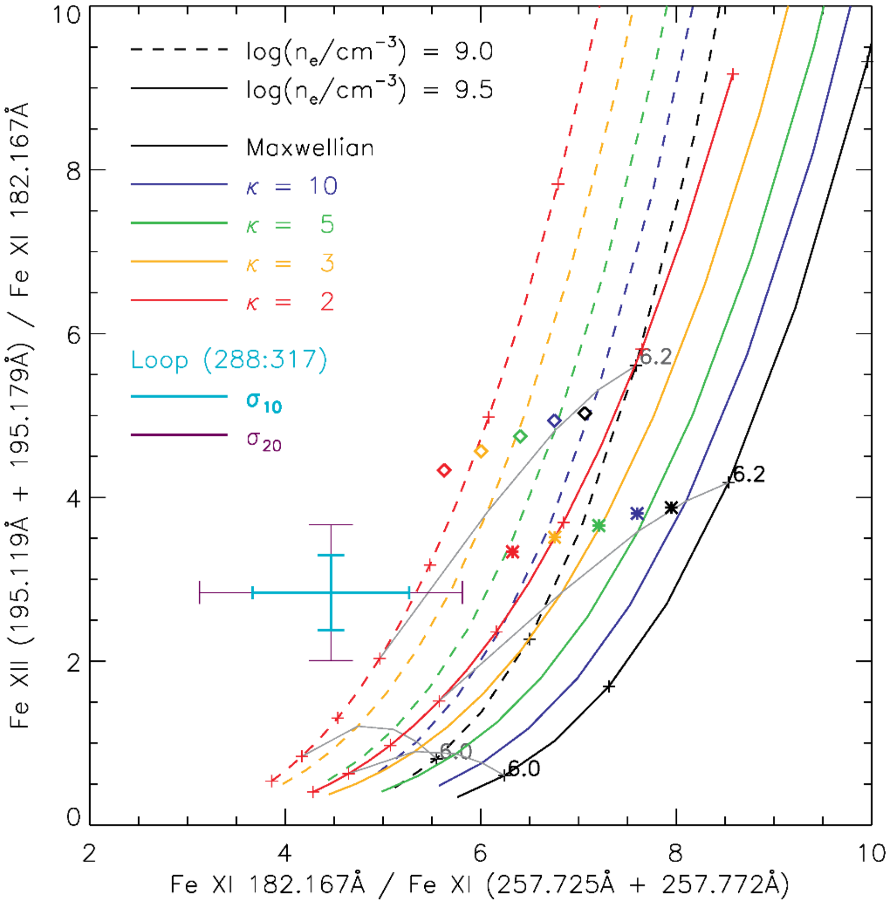

**I1/I2 vs. I3/I2**




**I1/I4 vs. I3/I4**

# Non-Maxwellian Diagnostics



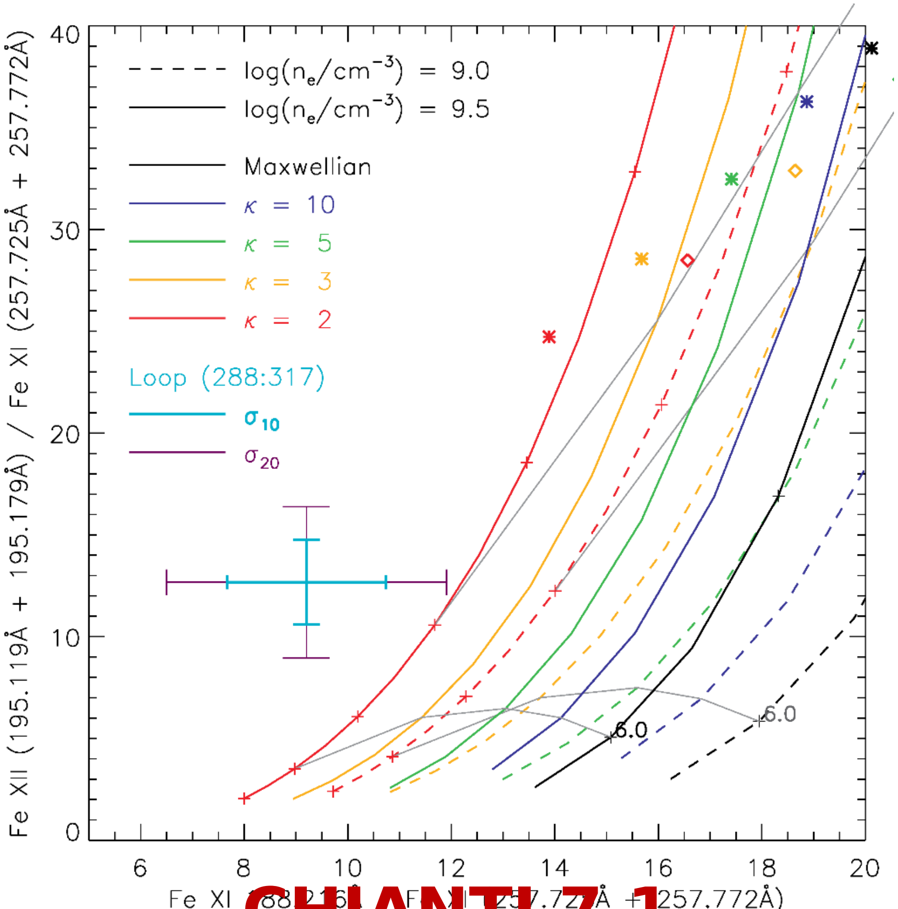




**$I_1/I_4$ vs. $I_3/I_1$**

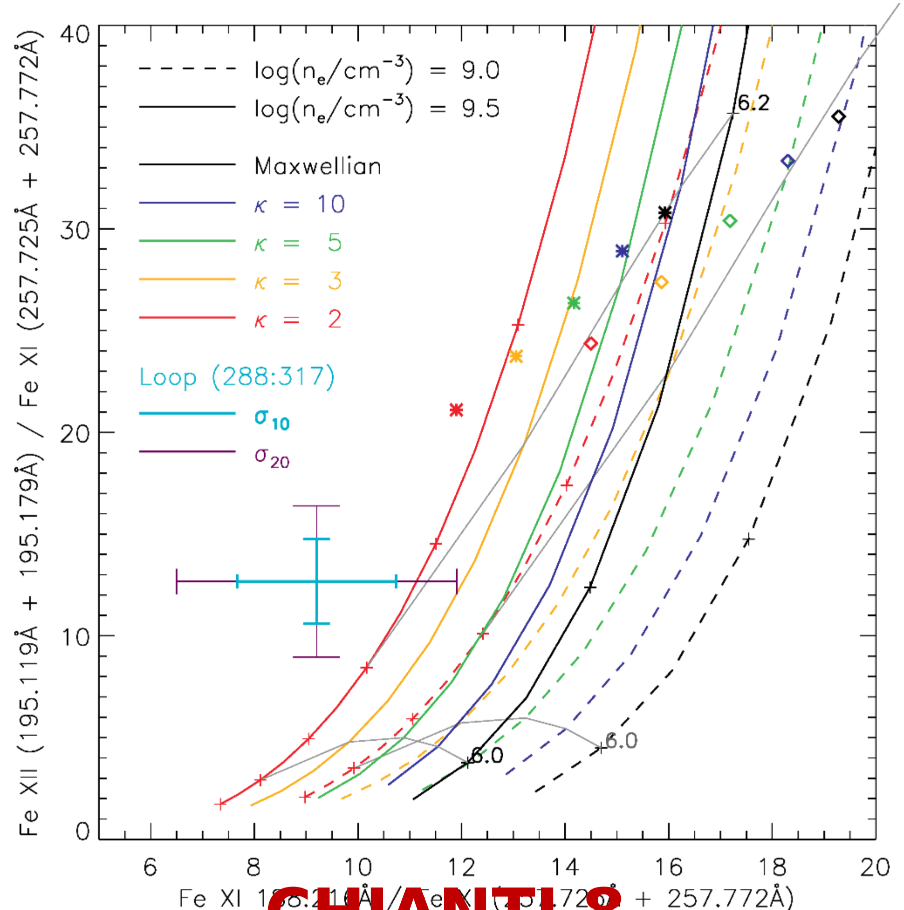
**$I_5/I_4$ vs. $I_3/I_5$**

- **Loop has κ ≤ 2**
- **This does not change if DEM is considered**

# Influence of Atomic Data




**CHIANTI 7.1**




**CHIANTI 8**

- **Chianti 8 – includes n≤4 – more transition than in v. 7.1**
- **Still, our calculations are missing *n* ≥ 5 levels: Cascading & Resonances - but we expect only less than 10 %: *Del Zanna et al. (2014, A&A 543, A139)***

# Summary

**We observed a transient coronal loop**
- **at the same place there a B8.9 flare occurred previously**

- **The loop is evolving and multi-thermal**
- **Jetting activity near the loop right foot-point**
- **DEMs derived from SDO/AIA**

- **EIS densities: log(ne) = 9.0 – 9.5**

- **The loop is non-Maxwellian with *κ* ≤ 2 - we are able to observe strong non-thermal effects**
- **This does not change if DEM is taken into account**

**Calibration is a problem: especially the 20% uncertainty**

**Dudík J., *et al*.: 2015, The Astrophysical Journal 807, p. 123.**