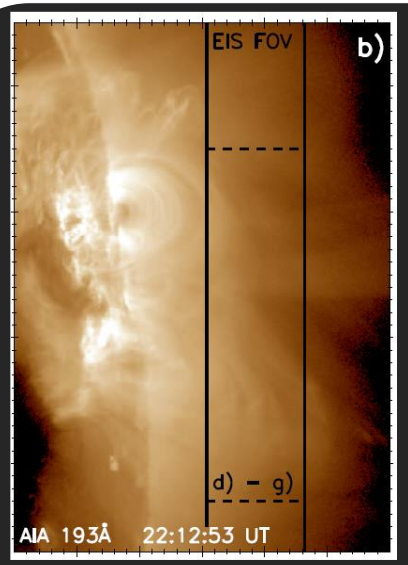


Diagnostics from EUV and Forbidden Lines

Jaroslav Dudík

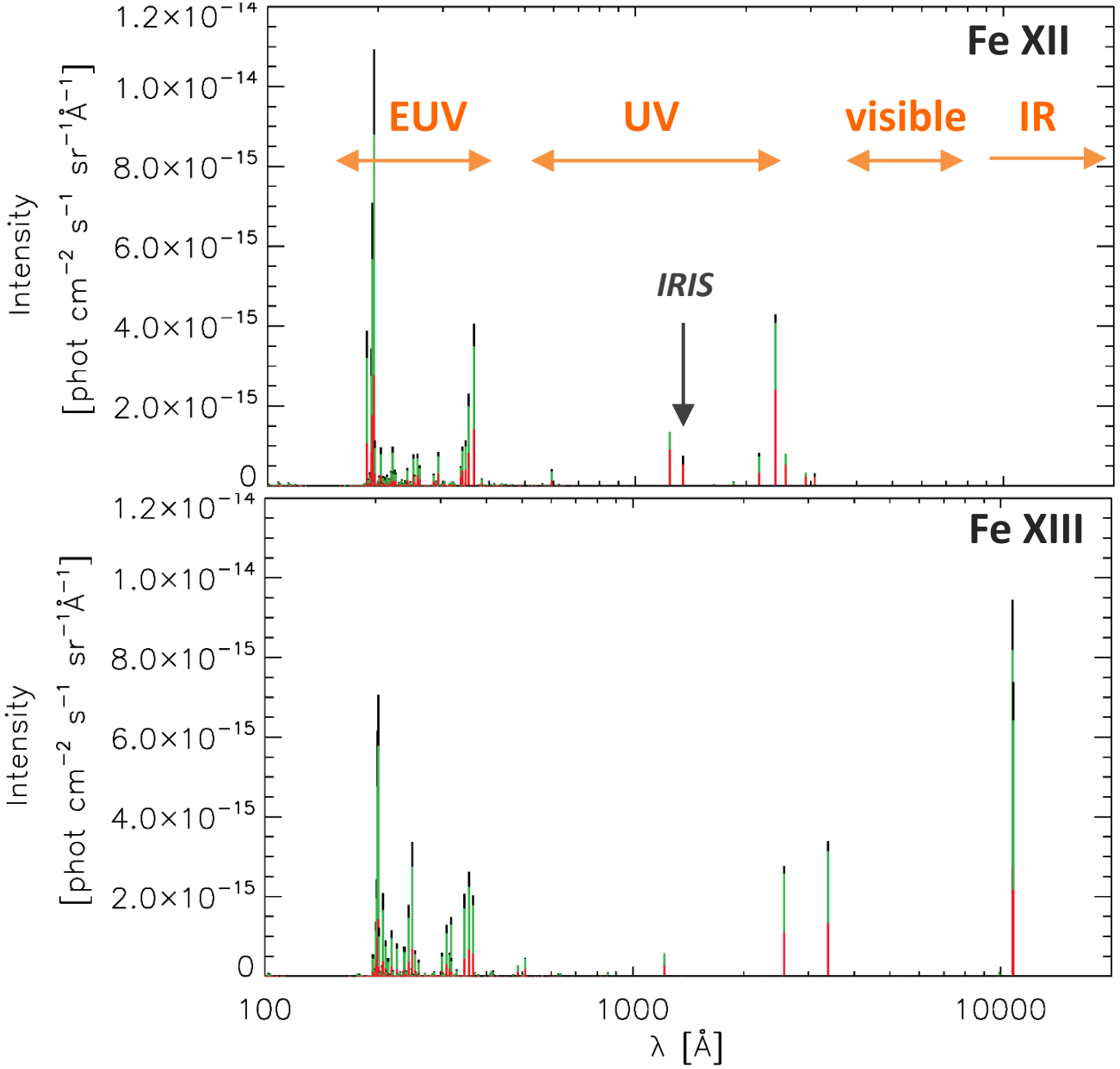
Astronomical Institute of the Czech Academy of Sciences

with

Giulio Del Zanna,	**Helen E. Mason**	*DAMTP,*	*University of Cambridge, UK*
Vanessa Polito		*BAERI & LMSAL,*	*California, USA*
Jan Rybák		*AI SAV,*	*Tatranská Lomnica, SK*
Elena Dzifčáková,	**Juraj Lörinčík**	*ASU CAS,*	*Ondřejov, CZ*
Steven Tomczyk,	**Michael Galloy**	*HAO,*	*NCAR, Boulder, USA*

ISSI Preparation Meeting 1, 2023–10–23

Allowed and forbidden lines



Coronal Fe ions produce many emission lines across the solar spectrum:

- ***Allowed lines***
  mostly in EUV (at about 200 – 400 Å)
  observed by *Hinode*/EIS

- ***Forbidden lines***
  located at larger wavelengths (UV, visible, IR)

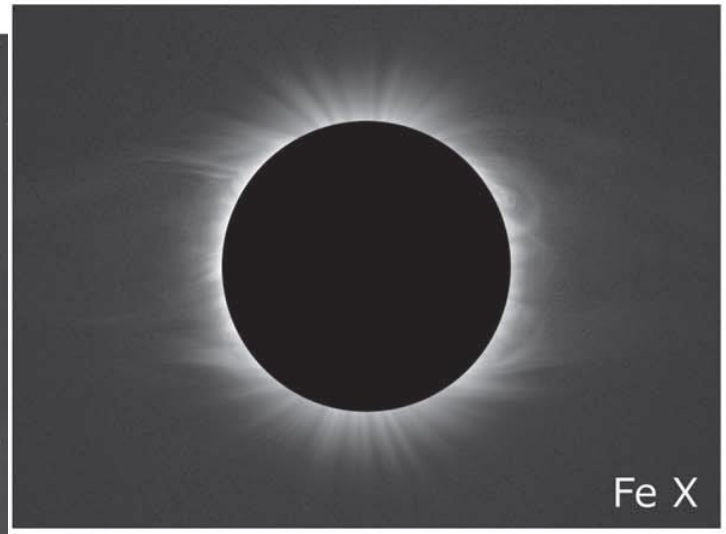
  Fe XII 1349 Å: *IRIS* (talk by Giulio Del Zanna)

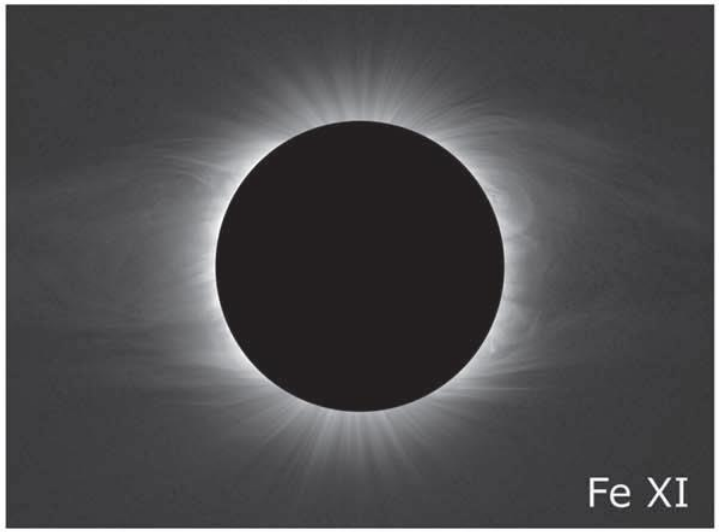
  Fe XIII 10747 & 10801 Å in near-infrared
  observed by *COMP*

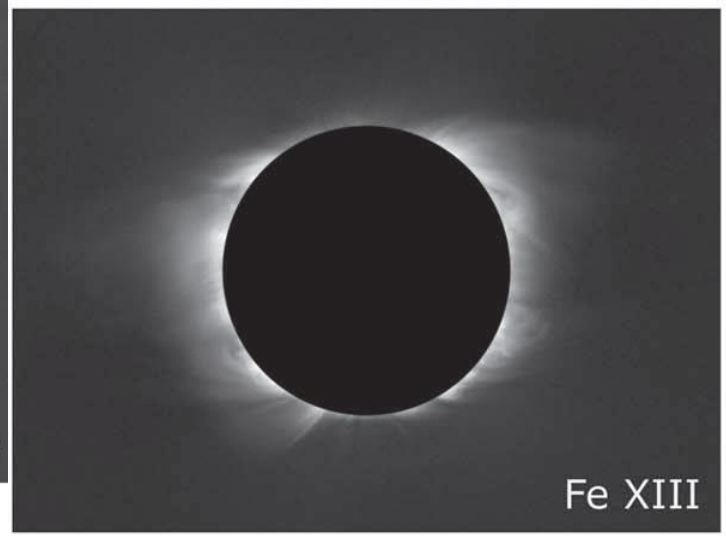
- **Requires coordinated observing campaigns:**
  IHOPs 246 and 316

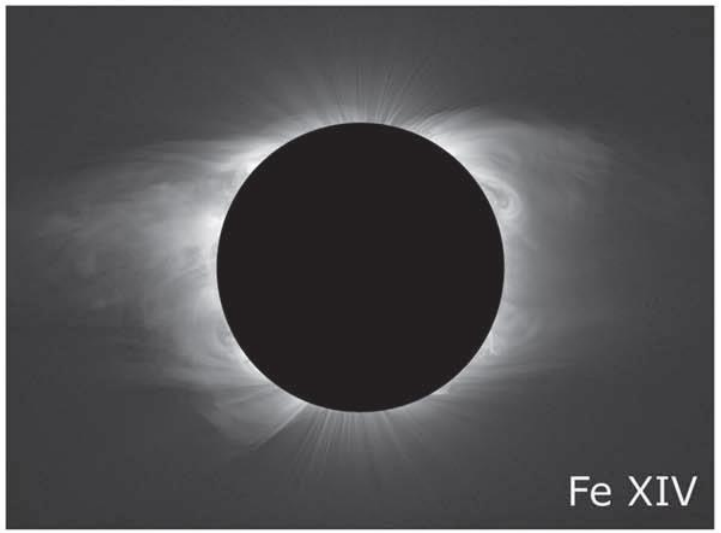
images from Dudík et al. (2014) A&A, 570, A124
see also Del Zanna & DeLuca (2018) ApJ, 852, 52

Corona in forbidden lines









Habbal et al. (2021), ApJL, 911, L4

Coronal Multichannel Polarimeter (COMP)

Tomczyk et al. (2008), SoPh, 247, 411

- **Ground-based coronagraph and polarimeter @ MLSO, Hawaii**
- **20 cm f/11 singlet objective**
- **Tunable birefringent filter + beam splitter, 1.3 Å FWHM**
- **Fe XIII 10747 Å and 10801 Å lines**

Tian et al. (2013), SoPh, 288, 637

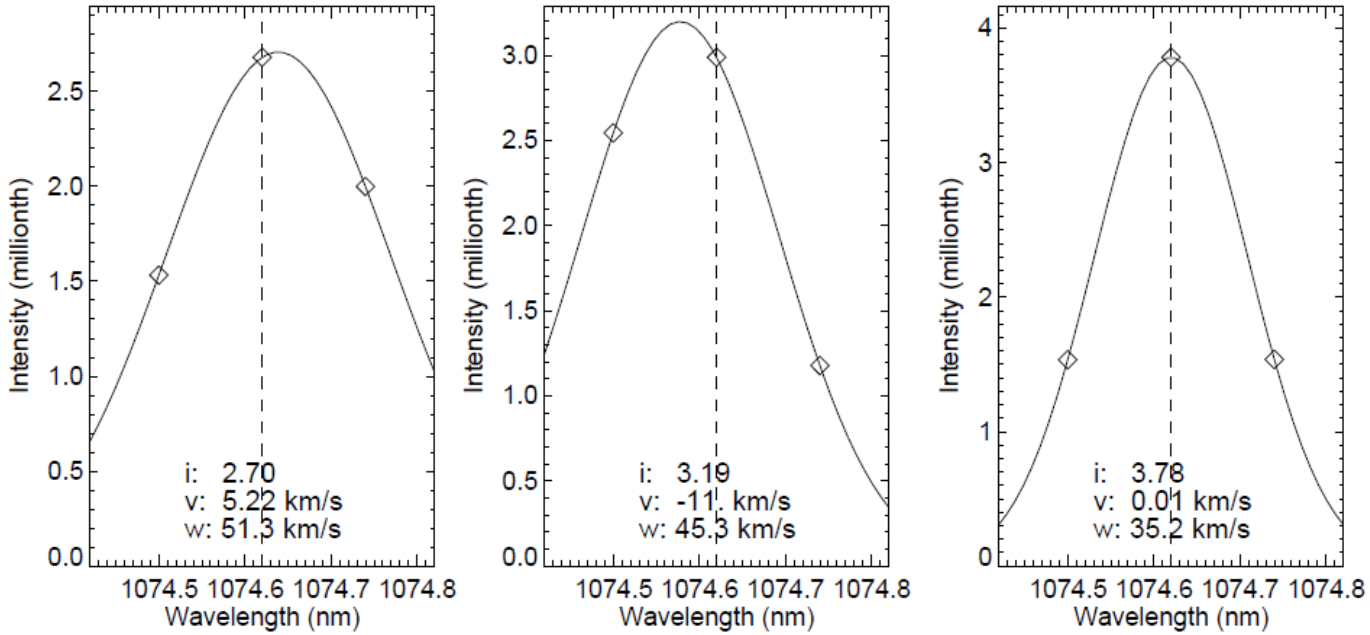
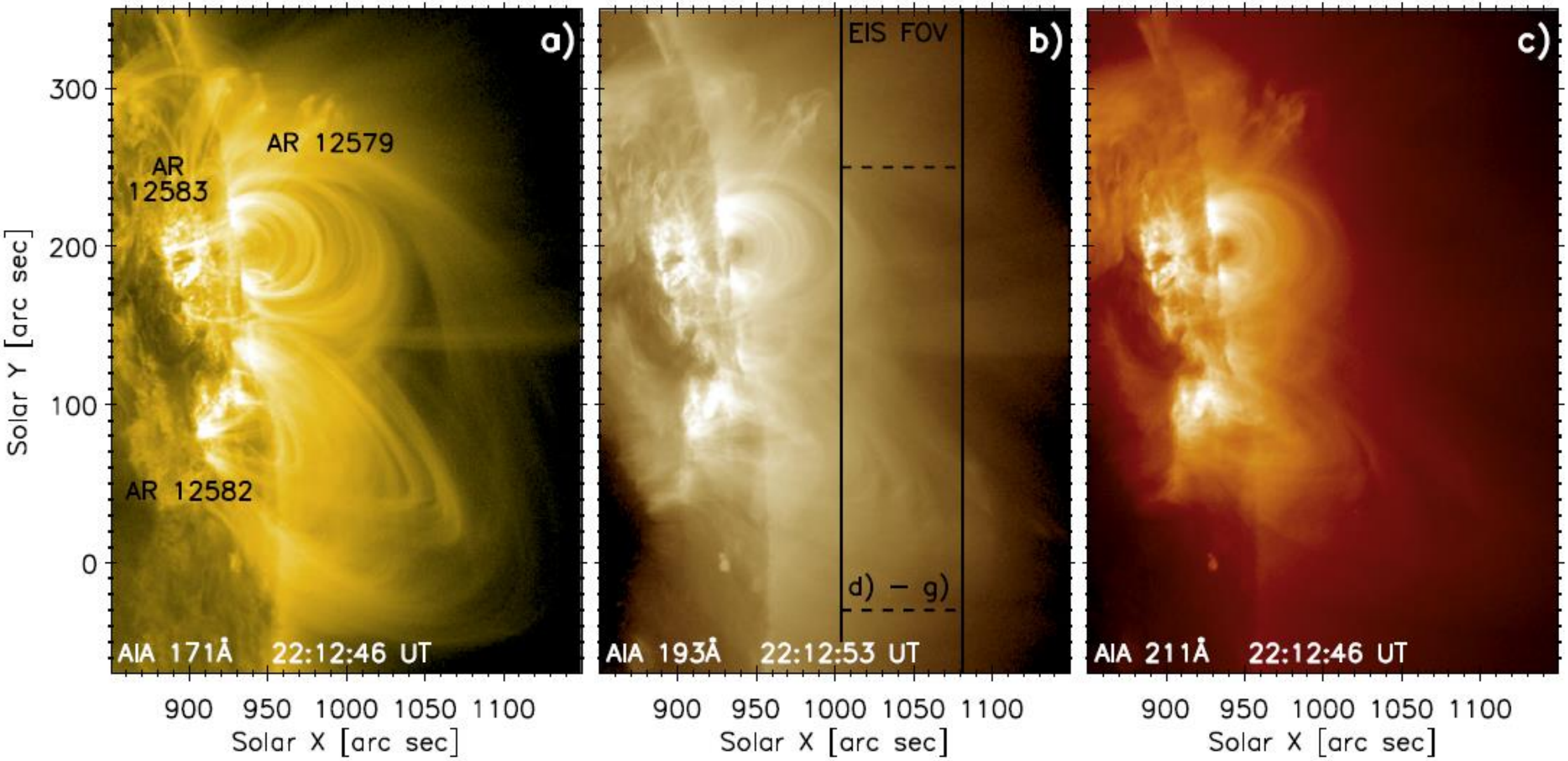
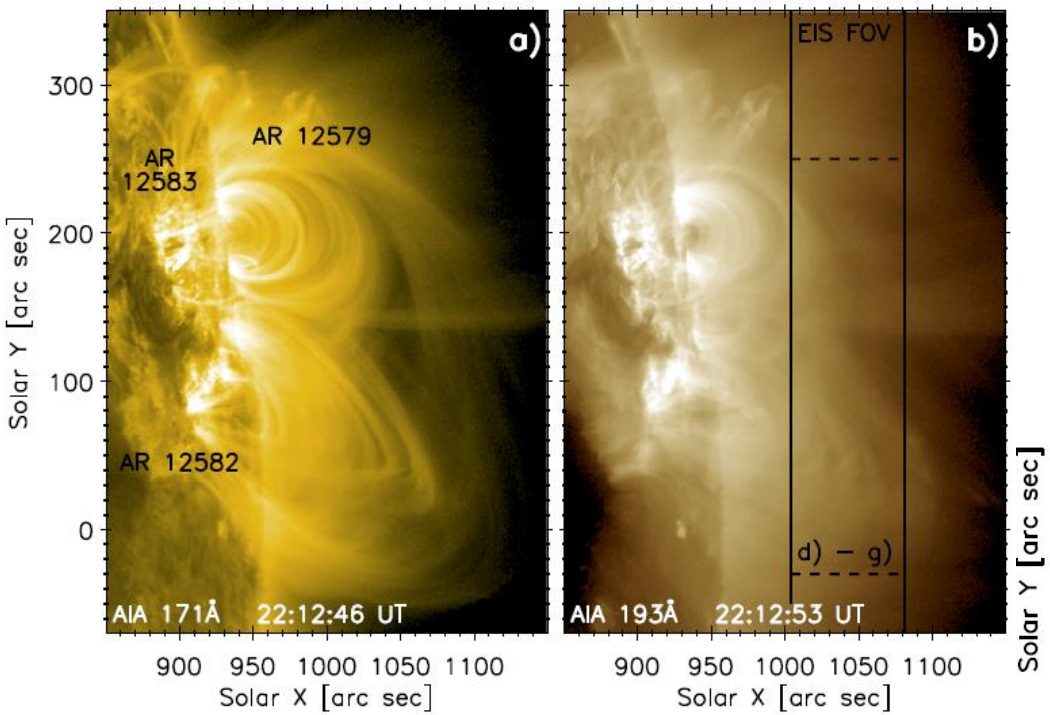


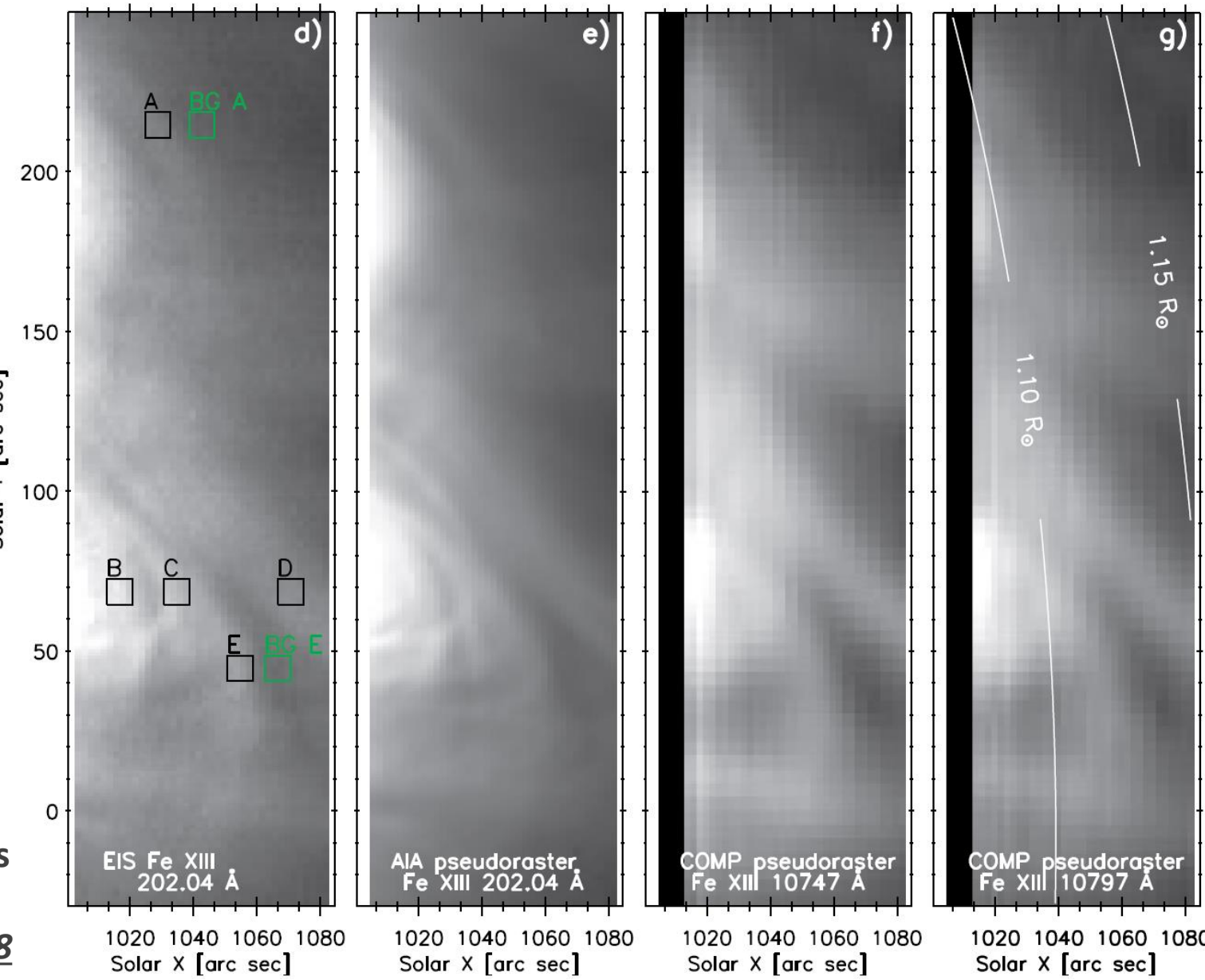
Figure 1. Three examples of observed emission line profiles (diamonds) and the analytical solution (solid line). The dashed line indicates the rest wavelength of the line. The line center intensity [i], Doppler shift [v] and line width [w] are marked in each panel.

IHOP 316 target: 2016–08–30



Fe XIII: *Hinode*/EIS and *COMP*



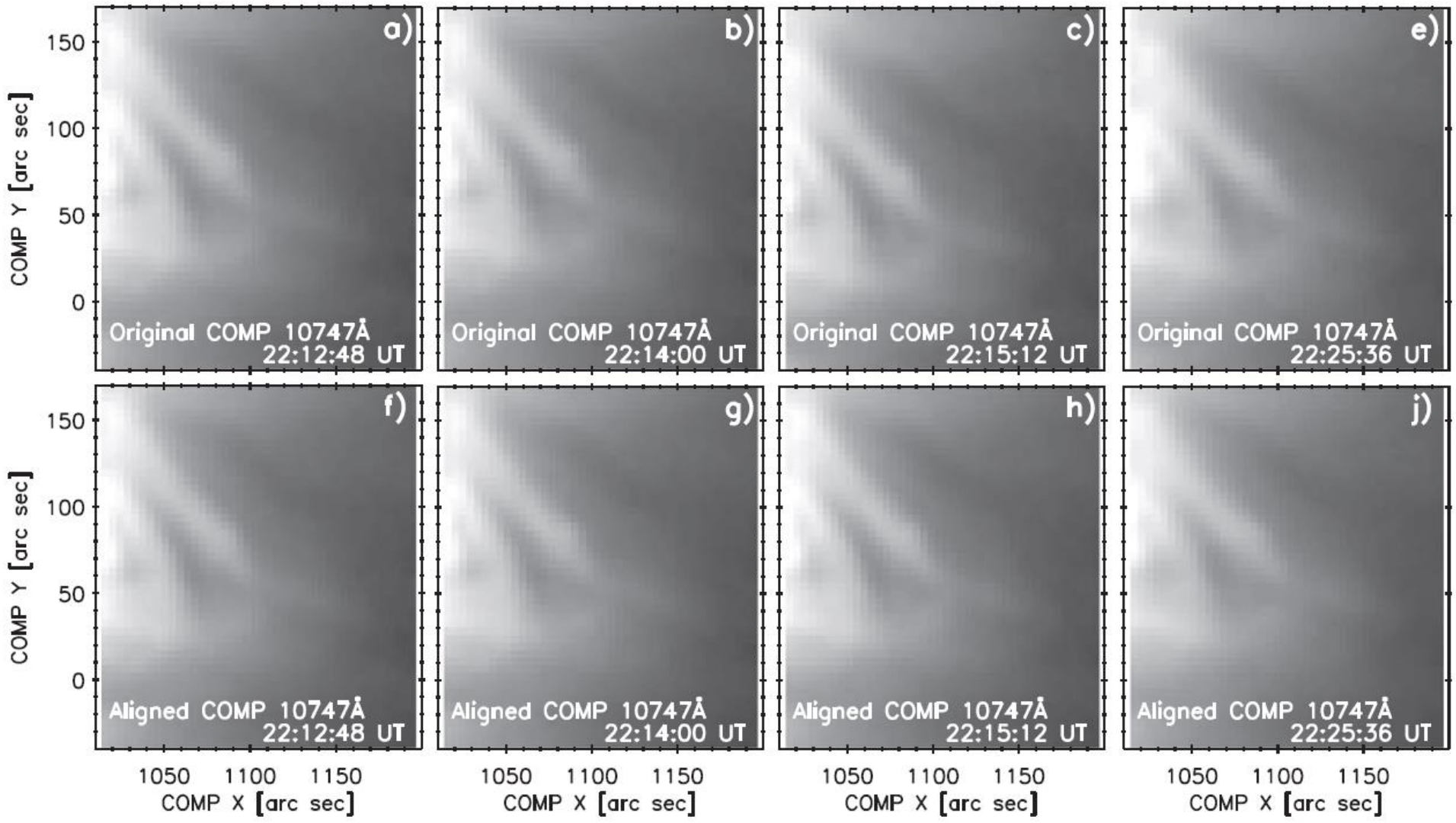


- IHOP 316, 2016 August 30

- EIS resolution 2–3”
- COMP resolution >5”, much coarser than EIS
- COMP line-center intensities I_0 not affected by stray light: Use instead of integrated line profiles

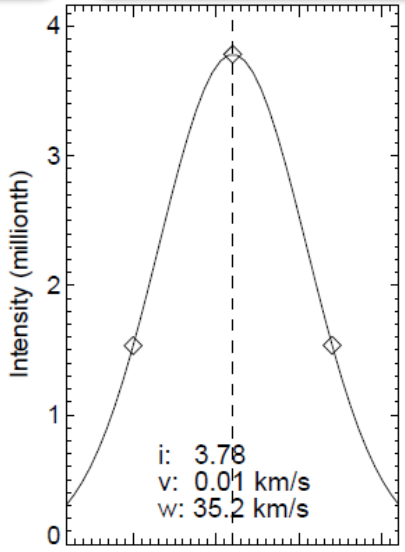
Dudík et al. (2021), ApJ, 906, 118

COMP: Alignment



- Tracking inaccuracies, seeing deformations
- Chosen first 10747 Å image as reference
- *i+1* image to *i*-th one
- *Shifted, rotated,* and stretched
- 10801 Å processed same way as 10747 Å
- The *COMP* is rotated with respect to AIA by about 0.5°

COMP: Uncertainties



- 3-point fits: Standard measurements
- We measured 7-points per profile, which allows us to derive uncertainties
- Consistent with scatter in time

- Stray light?
- Line center I_0 not sensitive to stray light

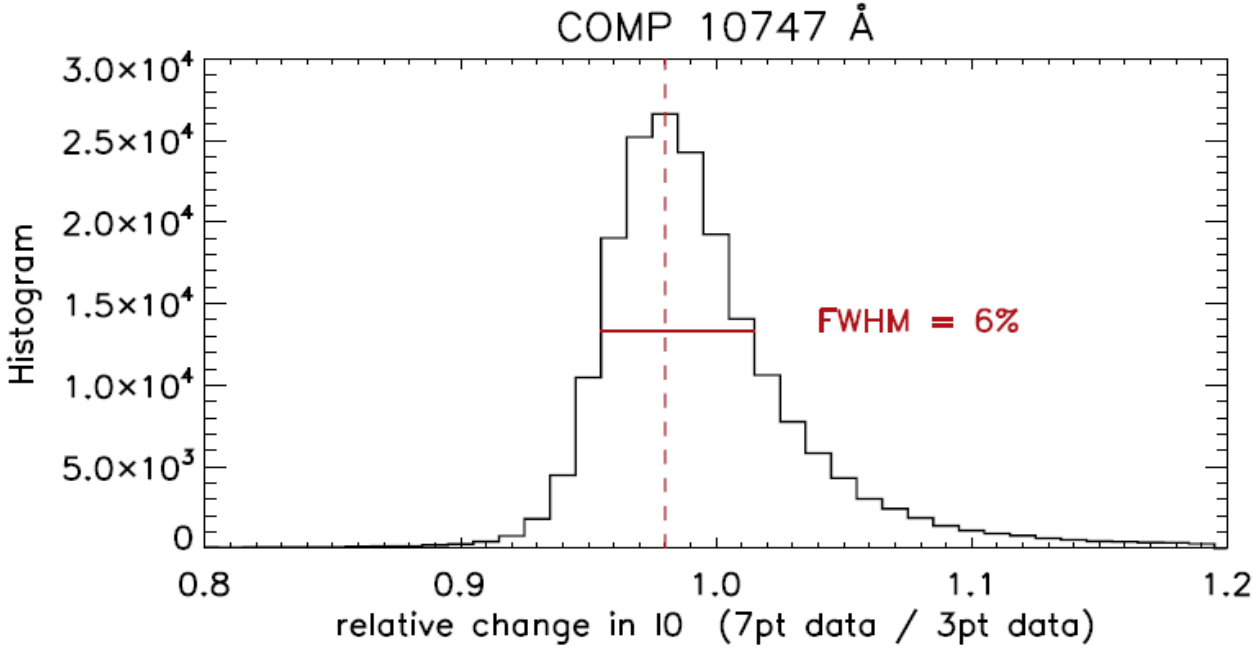
$$I_{\rm obs} = I_{\rm true} - sI_{\rm true} + s\langle I\rangle, \quad (1)$$

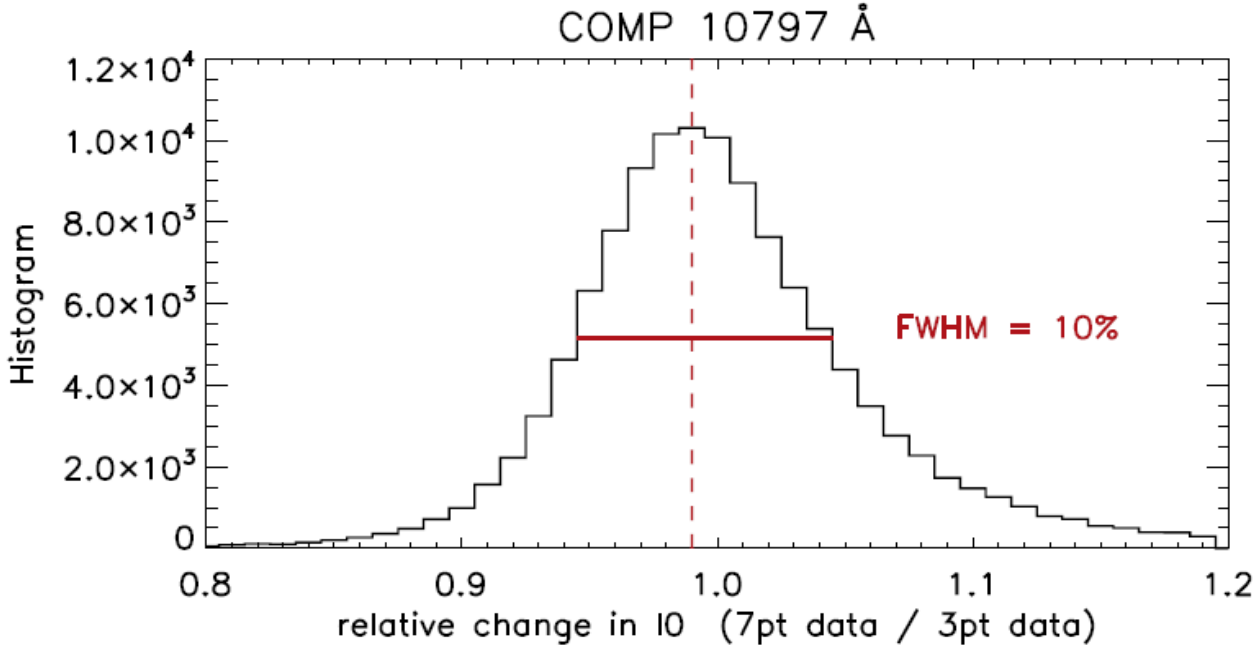
or

$$I_{\rm true} = \frac{I_{\rm obs} - s\langle I\rangle}{1-s}. \quad (2)$$

With respect to the local continuum $I_{\rm true,c}$ one can then write

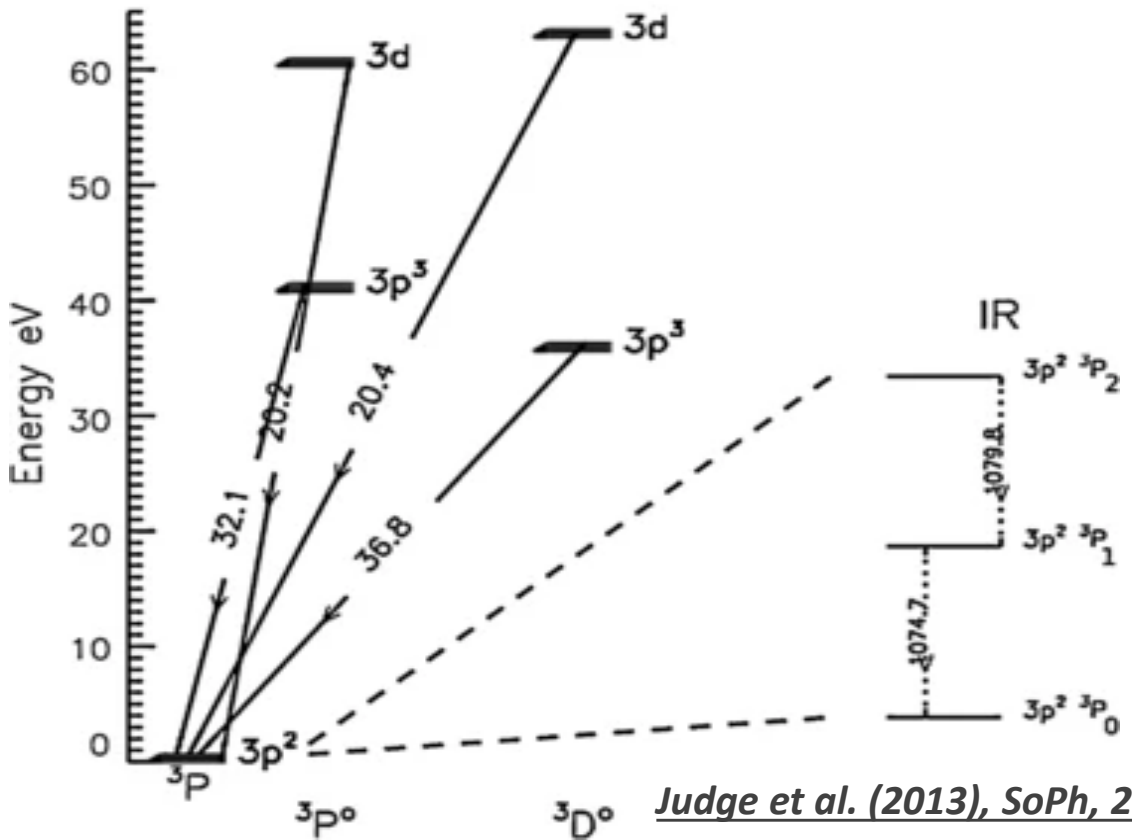
$$\frac{I_{\rm true}}{I_{\rm true,c}} = \frac{I_{\rm obs} - s\langle I\rangle}{I_{\rm obs,c} - s\langle I\rangle} = \frac{I_{\rm obs}/I_{\rm obs,c} - s}{1-s}, \quad (3)$$





Fe XIII: Electron density diagnostics

λ [Å]	Levels	Level Description	Self-blends	Notes
196.53	4–26	$3s^2 3p^2\ ^1D_2$–$3s^2 3p 3d\ ^1F_3$	…	…
202.04	1–20	$3s^2 3p^2\ ^3P_0$–$3s^2 3p 3d\ ^3P_1$	…	…
203.83	3–25	$3s^2 3p^2\ ^3P_2$–$3s^2 3p 3d\ ^3D_3$	203.77 (7–60)	bl Fe XII
…	…	…	203.80 (3–24)	…
…	…	…	203.84 (8–60)	…
10747	1–2	$3s^2 3p^2\ ^3P_0$–$3s^2 3p^2\ ^3P_1$	…	…
10797	2–3	$3s^2 3p^2\ ^3P_1$–$3s^2 3p^2\ ^3P_2$	…	…

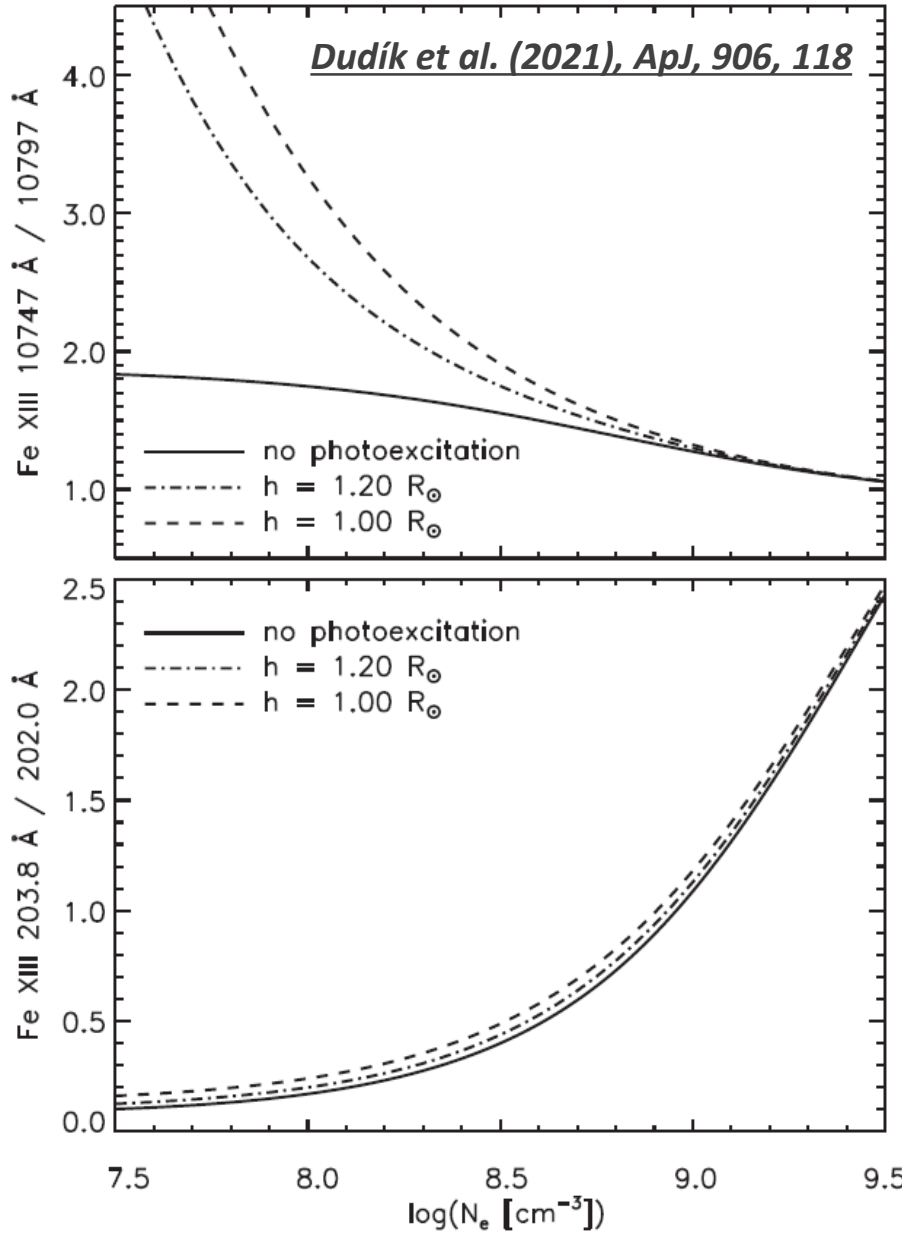


Judge et al. (2013), SoPh, 288, 467

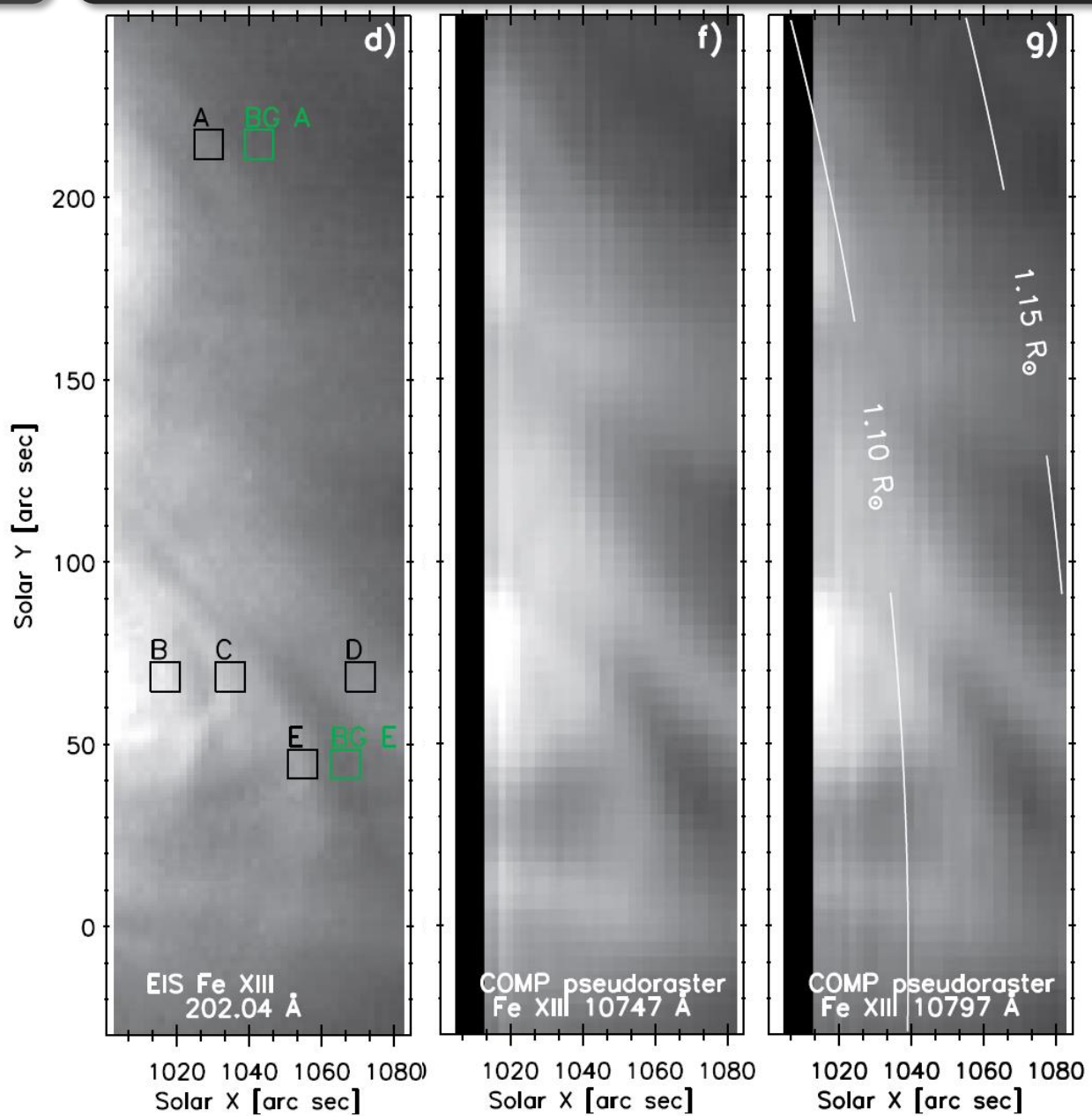
Fe XIII produces both EUV and IR lines

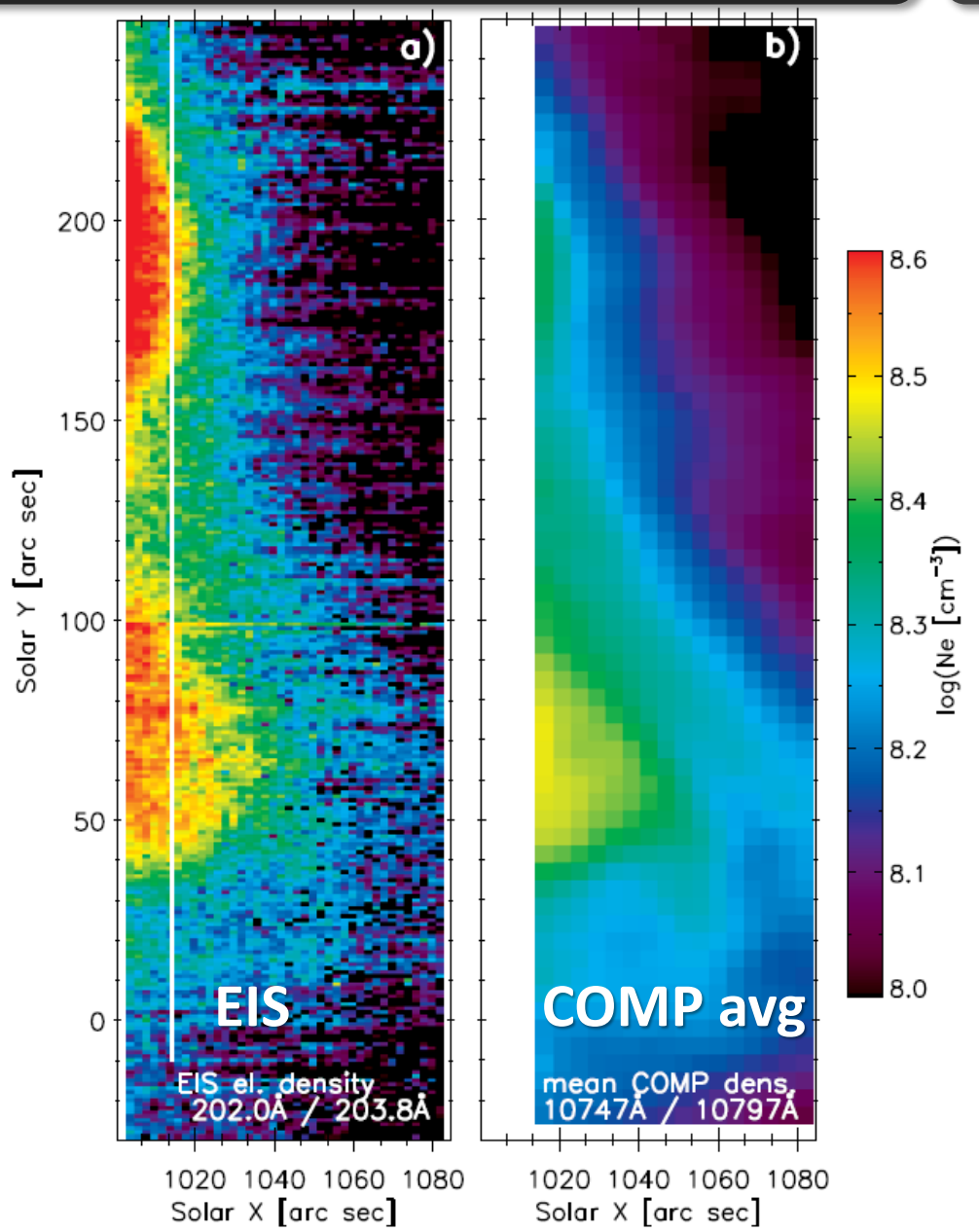
- Three strong EUV lines
- 2 IR lines (forbidden)
- **IR lines can be photoexcited**
- **Knock-on effects for EUV lines**
  Young et al. (2009), ApJ, 495, 587

Dudík et al. (2021), ApJ, 906, 118



Electron density maps





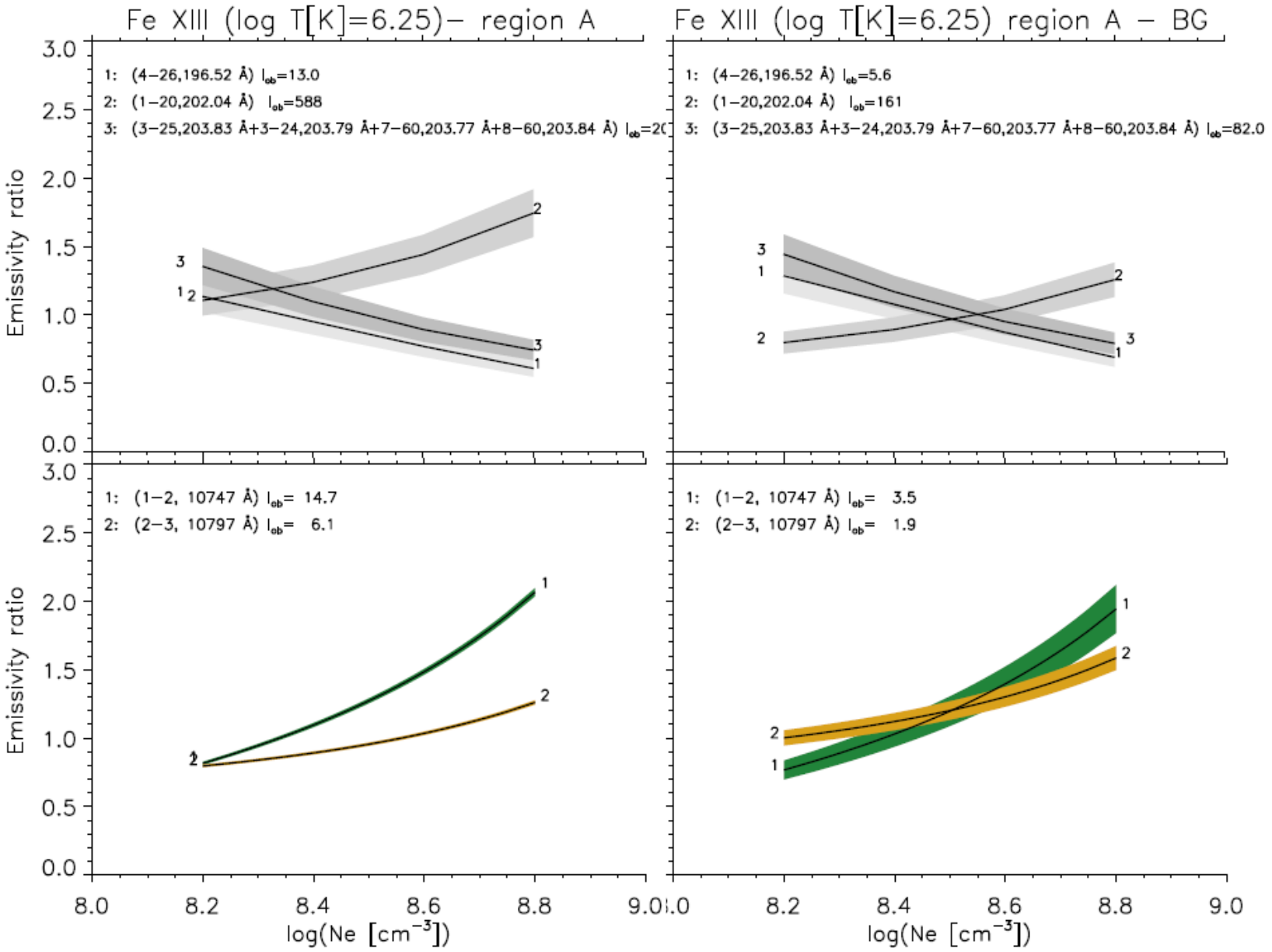
Background subtraction

We chose several 8” x 8” boxes to improve the S/N

- About 2x2 COMP pixels
- Many EIS pixels, whose size is 2”x1”

- EIS: Photon noise uncertainties
- COMP: Uncertainties estimated to be about 5% (3-point vs 7-point fits)

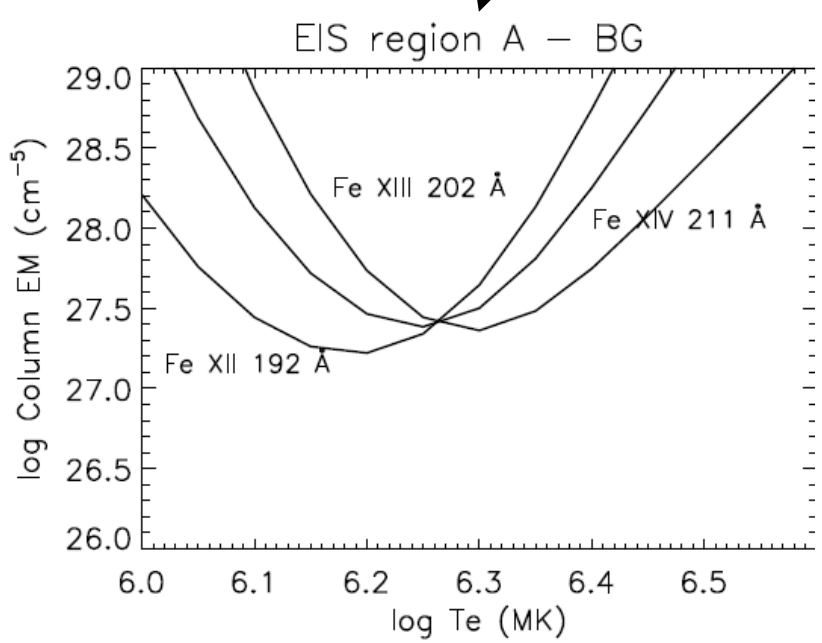
- **BG subtraction increases densities significantly (factor 2)**
- BG contributes >75% of signal for the forbidden lines
- Least affected are the 196.5 and 203.8 Å, where BG is <60%

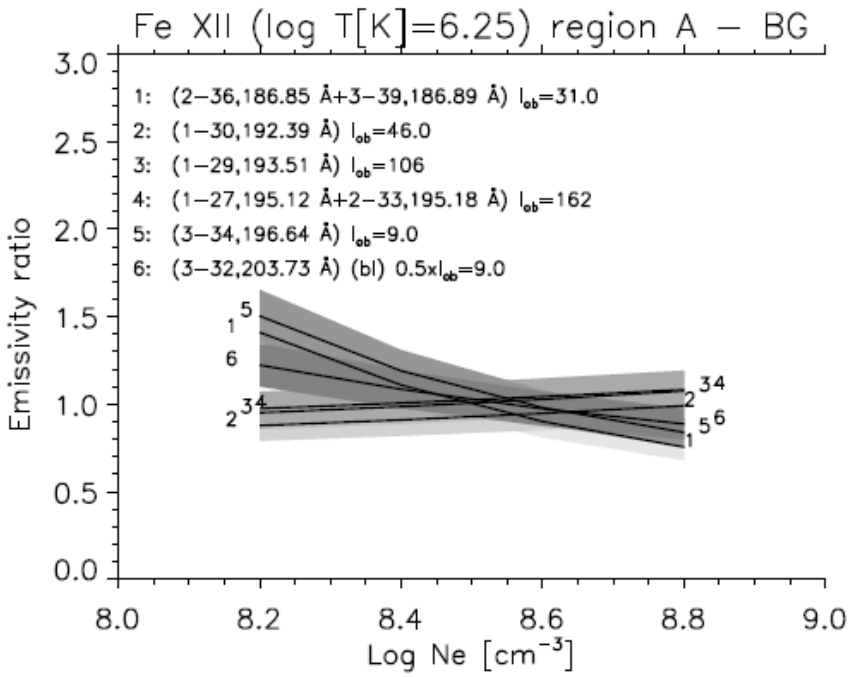


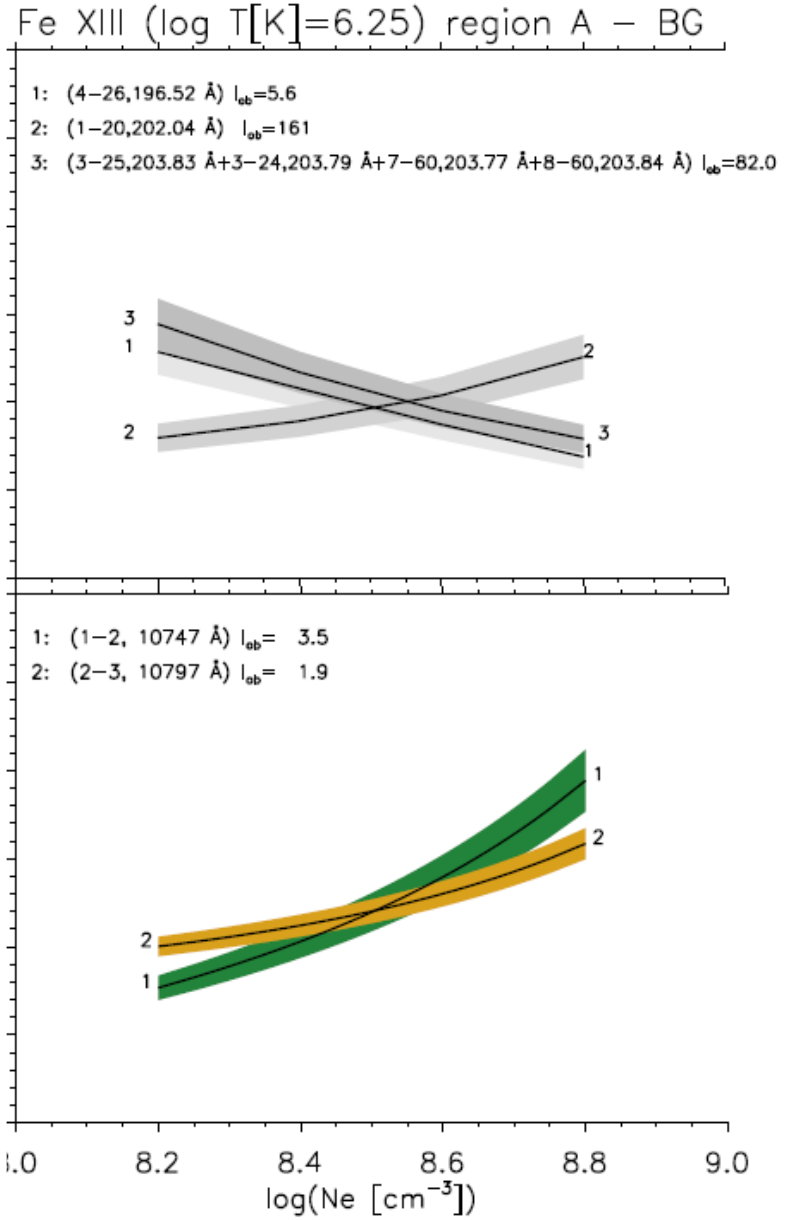
Electron densities from Fe XIII and XII

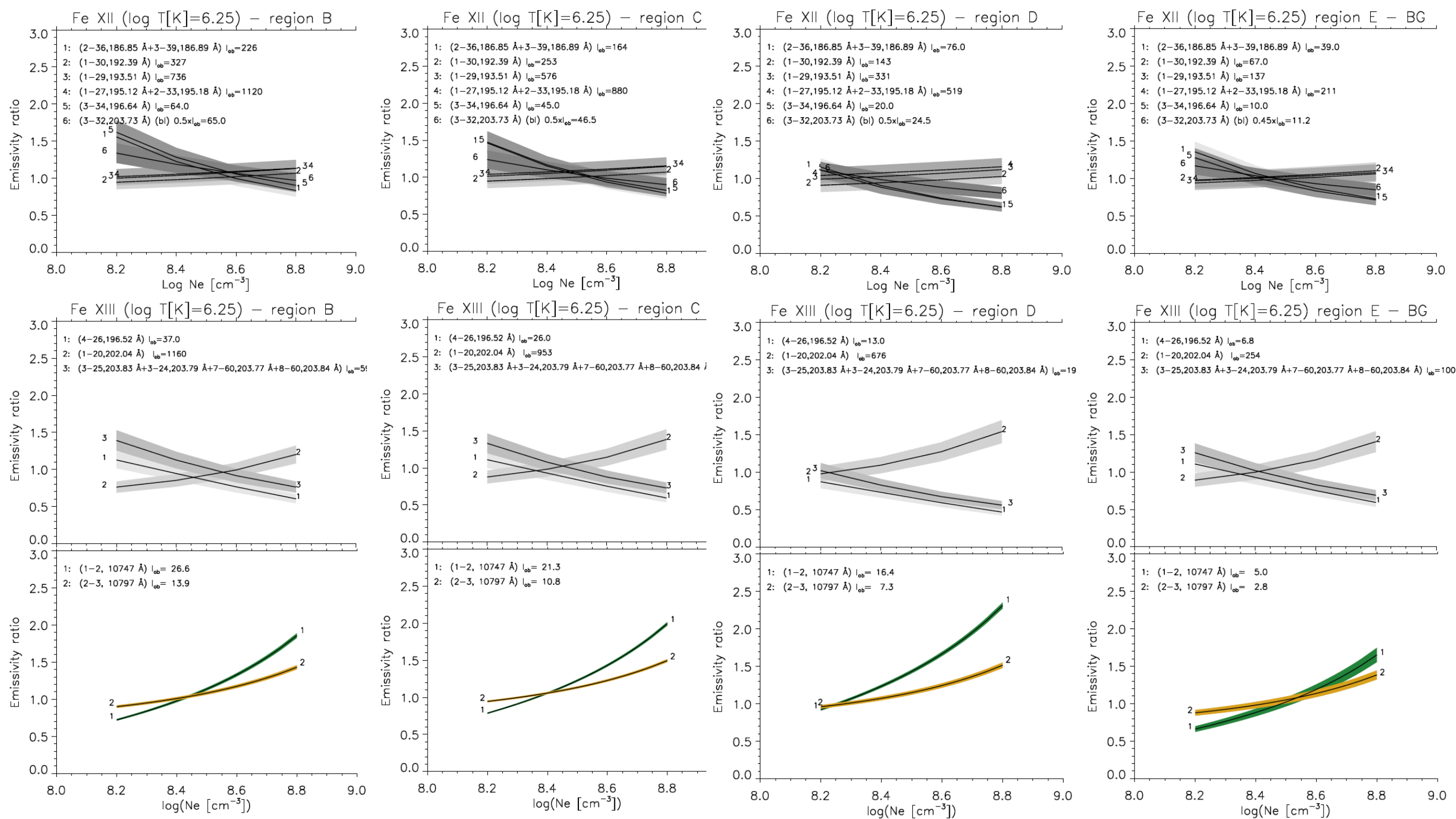
EIS observes several Fe XII lines that can be used for density diagnostics

- **Fe XII with Fe XIII densities are in good agreement** →
- **EM loci plots indicate isothermal plasmas with logT = 6.25**

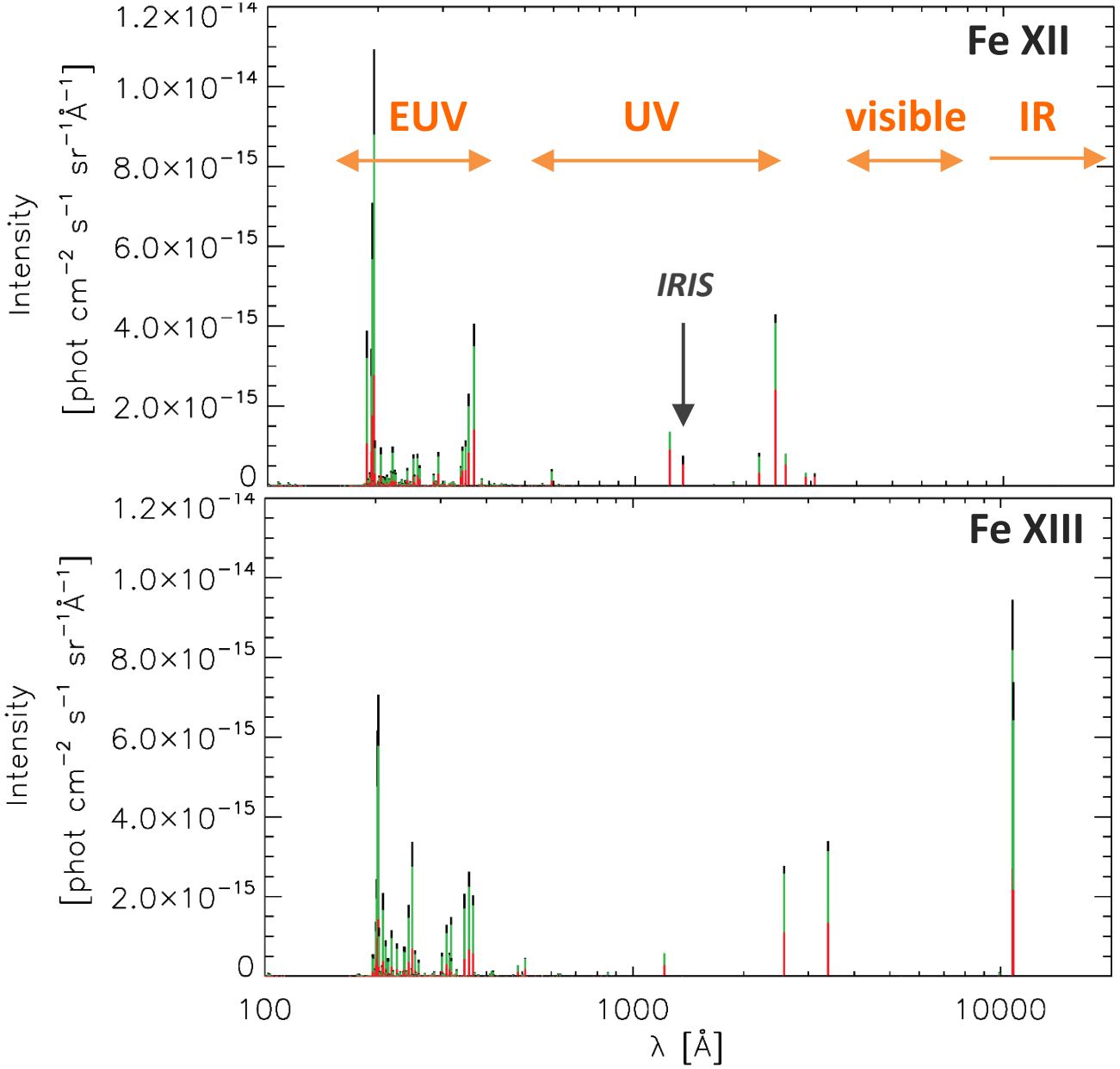







Fe XII (log T[K]=6.25) – region B
1: (2–36,186.85 Å+3–39,186.89 Å) I_ob=226
2: (1–30,192.39 Å) I_ob=327
3: (1–29,193.51 Å) I_ob=736
4: (1–27,195.12 Å+2–33,195.18 Å) I_ob=1120
5: (3–34,196.64 Å) I_ob=64.0
6: (3–32,203.73 Å) (bl) 0.5xI_ob=65.0
Fe XII (log T[K]=6.25) – region C
1: (2–36,186.85 Å+3–39,186.89 Å) I_ob=164
2: (1–30,192.39 Å) I_ob=253
3: (1–29,193.51 Å) I_ob=576
4: (1–27,195.12 Å+2–33,195.18 Å) I_ob=880
5: (3–34,196.64 Å) I_ob=45.0
6: (3–32,203.73 Å) (bl) 0.5xI_ob=46.5
Fe XII (log T[K]=6.25) – region D
1: (2–36,186.85 Å+3–39,186.89 Å) I_ob=76.0
2: (1–30,192.39 Å) I_ob=143
3: (1–29,193.51 Å) I_ob=331
4: (1–27,195.12 Å+2–33,195.18 Å) I_ob=519
5: (3–34,196.64 Å) I_ob=20.0
6: (3–32,203.73 Å) (bl) 0.5xI_ob=24.5
Fe XII (log T[K]=6.25) region E – BG
1: (2–36,186.85 Å+3–39,186.89 Å) I_ob=39.0
2: (1–30,192.39 Å) I_ob=67.0
3: (1–29,193.51 Å) I_ob=137
4: (1–27,195.12 Å+2–33,195.18 Å) I_ob=211
5: (3–34,196.64 Å) I_ob=10.0
6: (3–32,203.73 Å) (bl) 0.45xI_ob=11.2
Fe XIII (log T[K]=6.25) – region B
1: (4–26,196.52 Å) I_ob=37.0
2: (1–20,202.04 Å) I_ob=1160
3: (3–25,203.83 Å+3–24,203.79 Å+7–60,203.77 Å+8–60,203.84 Å) I_ob=5
1: (1–2, 10747 Å) I_ob= 26.6
2: (2–3, 10797 Å) I_ob= 13.9
Fe XIII (log T[K]=6.25) – region C
1: (4–26,196.52 Å) I_ob=26.0
2: (1–20,202.04 Å) I_ob=953
3: (3–25,203.83 Å+3–24,203.79 Å+7–60,203.77 Å+8–60,203.84 Å
1: (1–2, 10747 Å) I_ob= 21.3
2: (2–3, 10797 Å) I_ob= 10.8
Fe XIII (log T[K]=6.25) – region D
1: (4–26,196.52 Å) I_ob=13.0
2: (1–20,202.04 Å) I_ob=676
3: (3–25,203.83 Å+3–24,203.79 Å+7–60,203.77 Å+8–60,203.84 Å) I_ob=19
1: (1–2, 10747 Å) I_ob= 16.4
2: (2–3, 10797 Å) I_ob= 7.3
Fe XIII (log T[K]=6.25) region E – BG
1: (4–26,196.52 Å) I_ob=6.8
2: (1–20,202.04 Å) I_ob=254
3: (3–25,203.83 Å+3–24,203.79 Å+7–60,203.77 Å+8–60,203.84 Å) I_ob=100
1: (1–2, 10747 Å) I_ob= 5.0
2: (2–3, 10797 Å) I_ob= 2.8
Emissivity ratio
Log Ne [cm^-3]
log(Ne [cm^-3])

Allowed and forbidden lines



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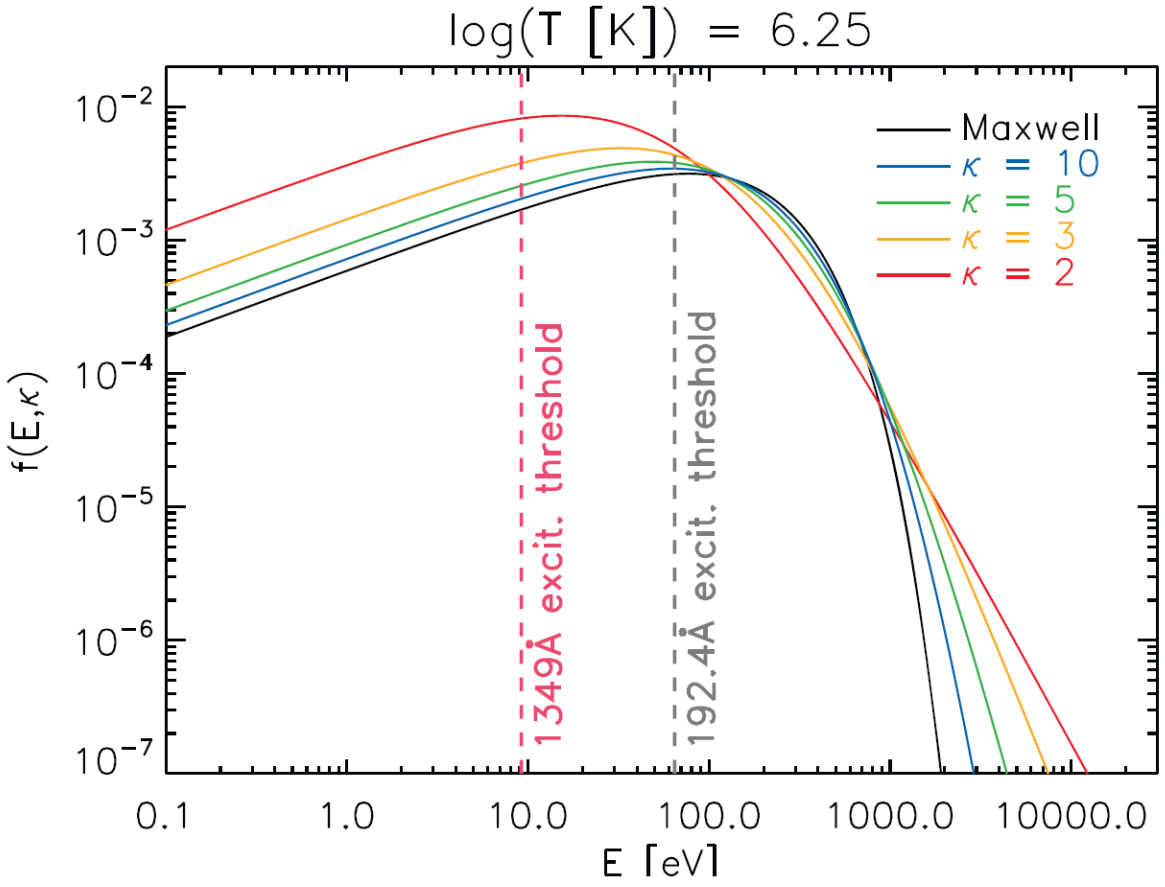
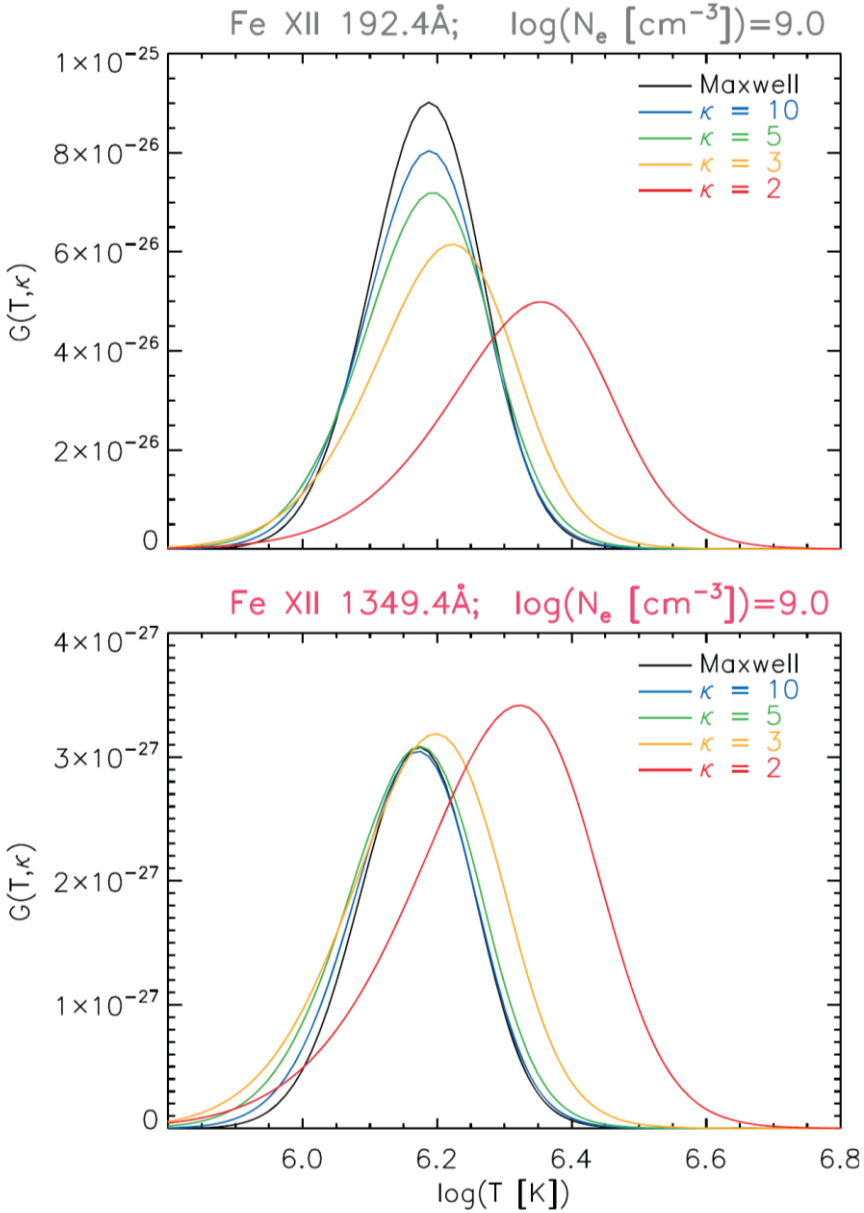
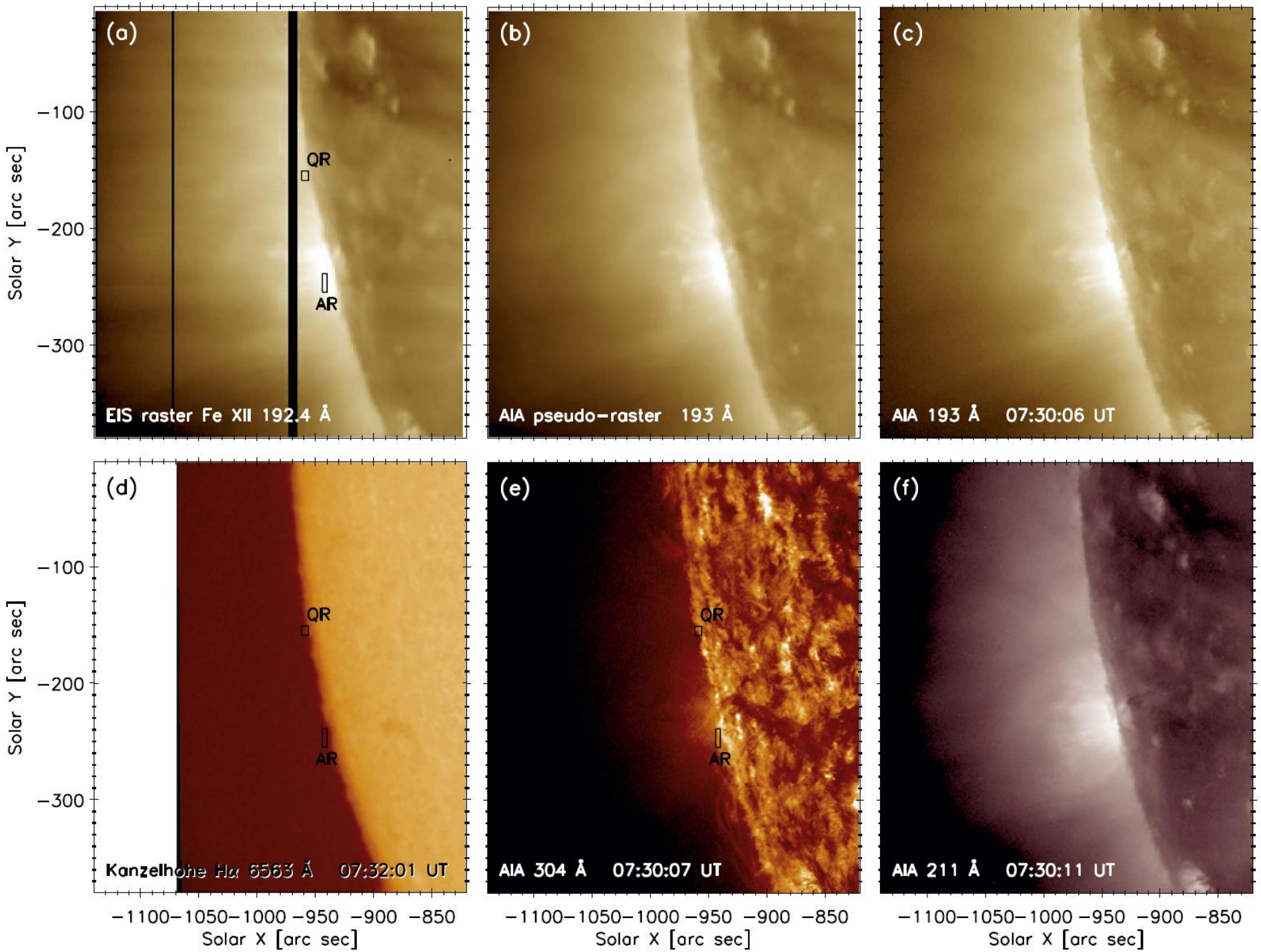
images from Dudík et al. (2014) A&A, 570, A124
see also Del Zanna & DeLuca (2018) ApJ, 852, 52

Diagnostics from Fe XII

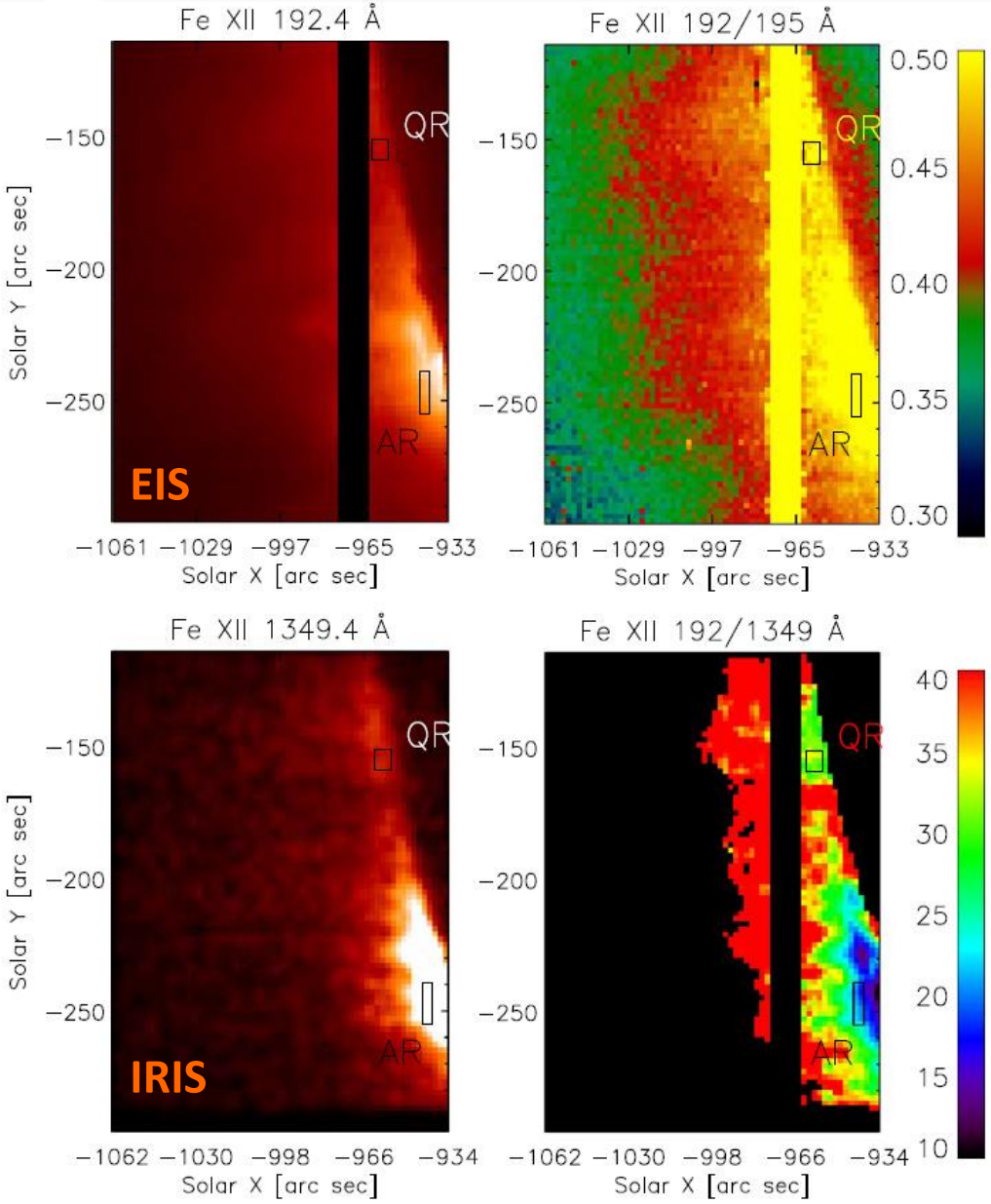


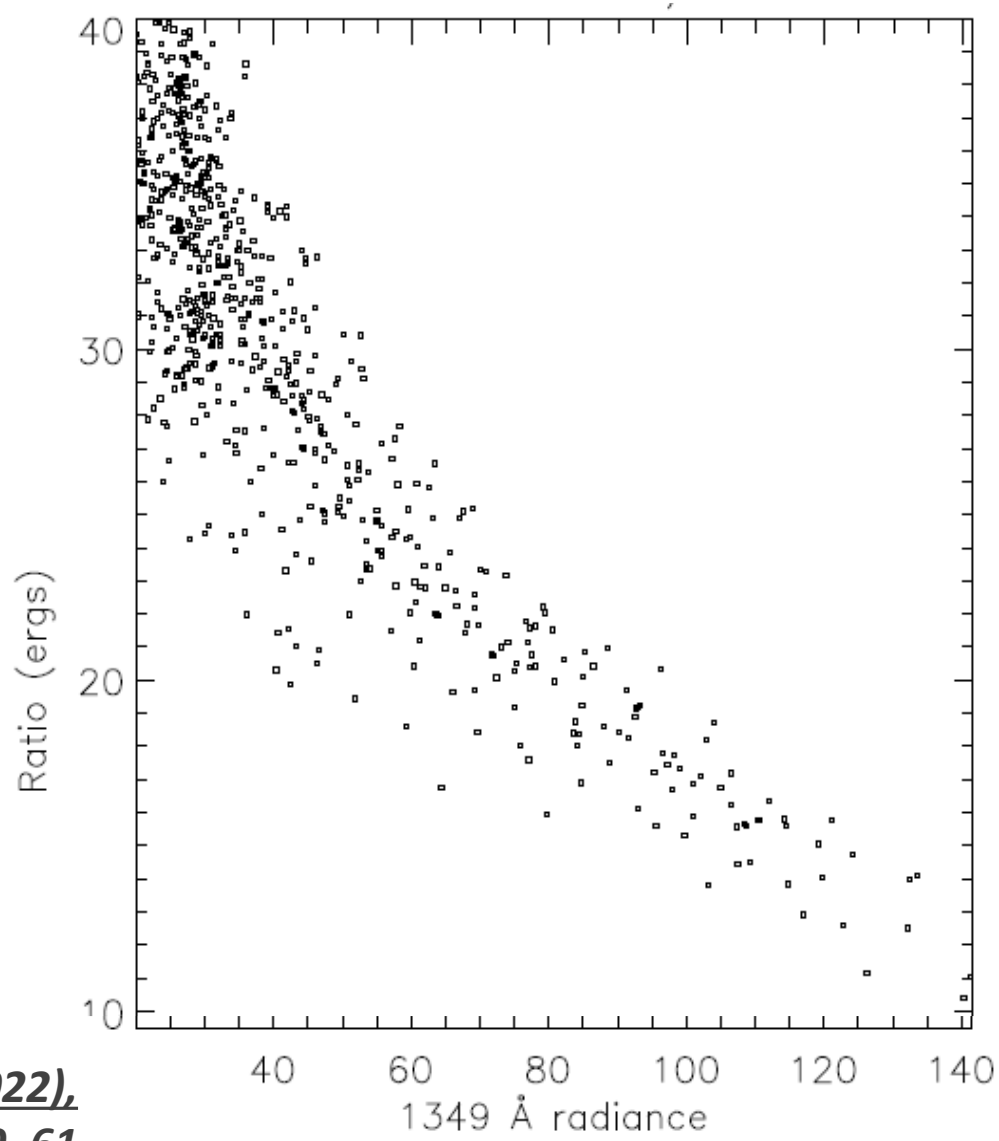


- **Forbidden lines are excited by electrons with much lower *E***
- **This allows for diagnostics of the electron distribution (in equilibrium this is the same as diagnostics of T_e)**

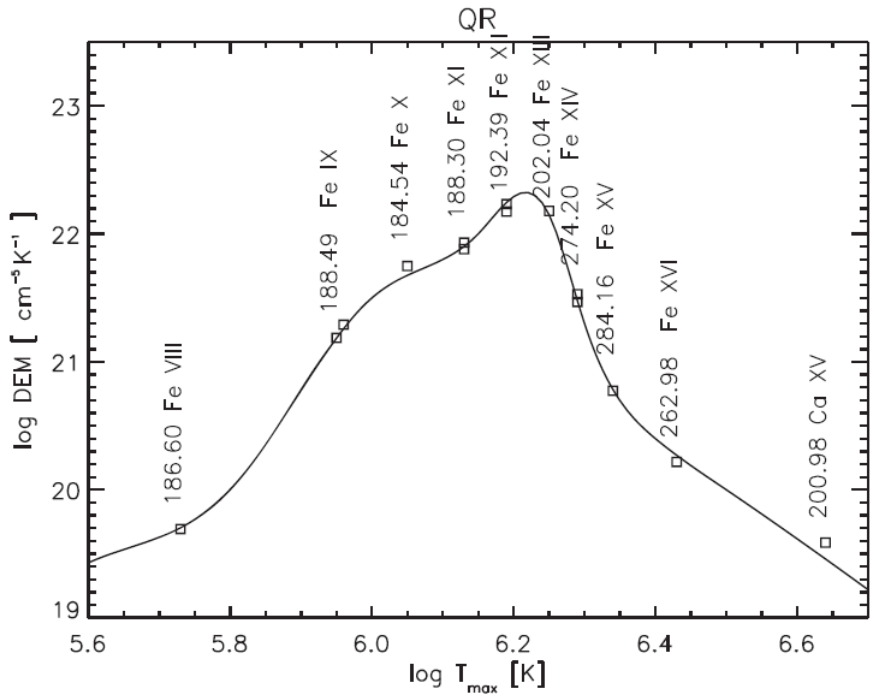

(a)
(b)
(c)
(d)
(e)
(f)
QR
AR
EIS raster Fe XII 192.4 Å
AIA pseudo−raster 193 Å
AIA 193 Å 07:30:06 UT
Kanzelhohe Hα 6563 Å 07:32:01 UT
AIA 304 Å 07:30:07 UT
AIA 211 Å 07:30:11 UT
Solar Y [arc sec]
−100
−200
−300
Solar X [arc sec]
−1100 −1050 −1000 −950 −900 −850

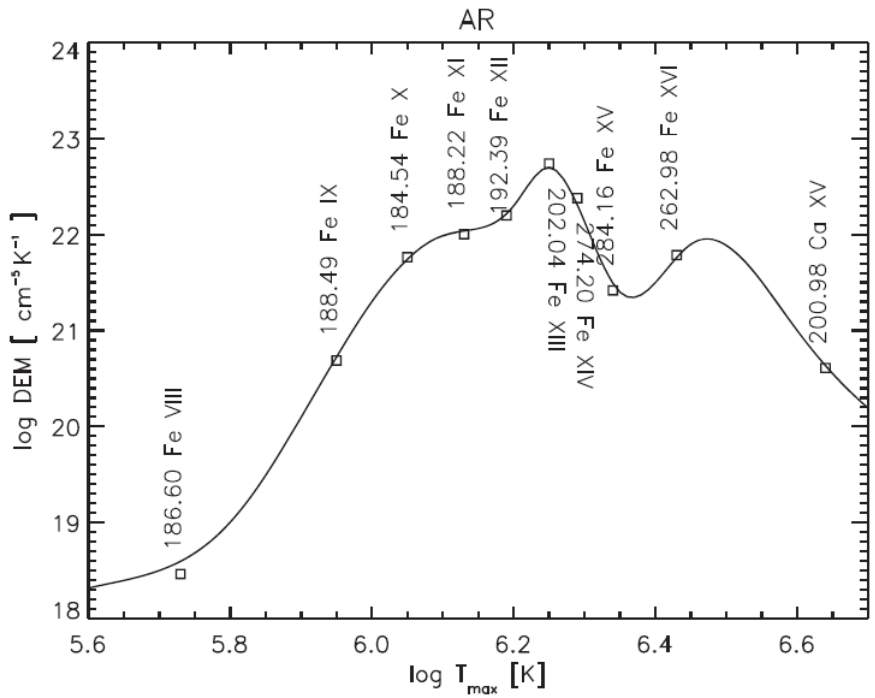
Co-spatial EIS and IRIS observations of Fe XII





Del Zanna et al. (2022), ApJ, 930, 61


QR
log DEM [cm⁻⁵K⁻¹]
log T_max [K]
186.60 Fe VIII
188.49 Fe IX
184.54 Fe X
188.30 Fe XI
192.39 Fe XII
202.04 Fe XIII
274.20 Fe XIV
284.16 Fe XV
262.98 Fe XVI
200.98 Ca XV


AR
log DEM [cm⁻⁵K⁻¹]
log T_max [K]
186.60 Fe VIII
188.49 Fe IX
184.54 Fe X
188.22 Fe XI
192.39 Fe XII
202.04 Fe XIII
274.20 Fe XIV
284.16 Fe XV
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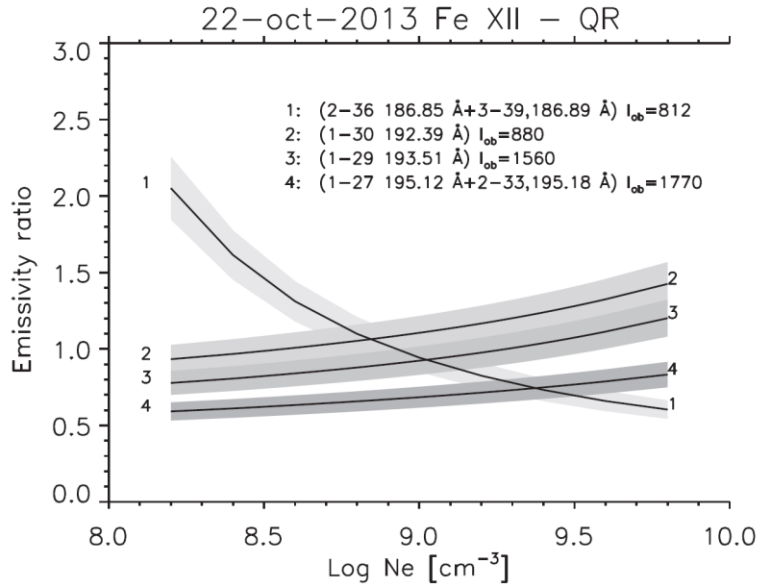
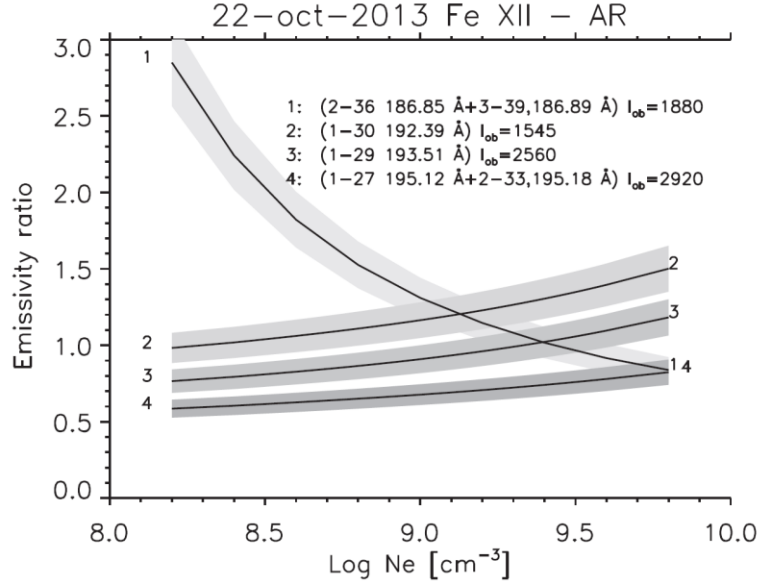
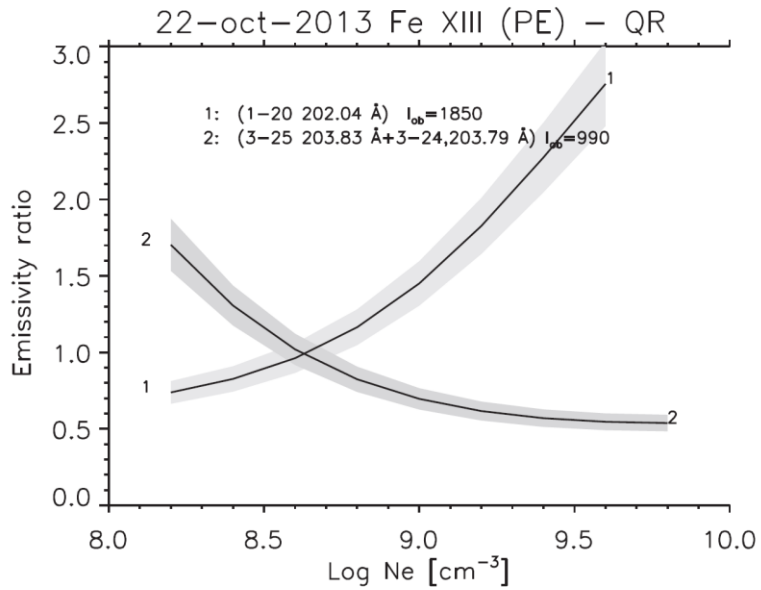
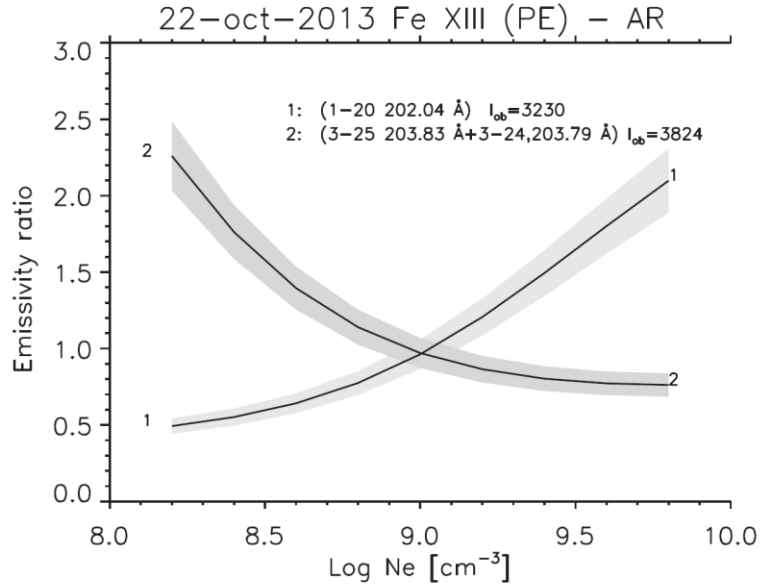
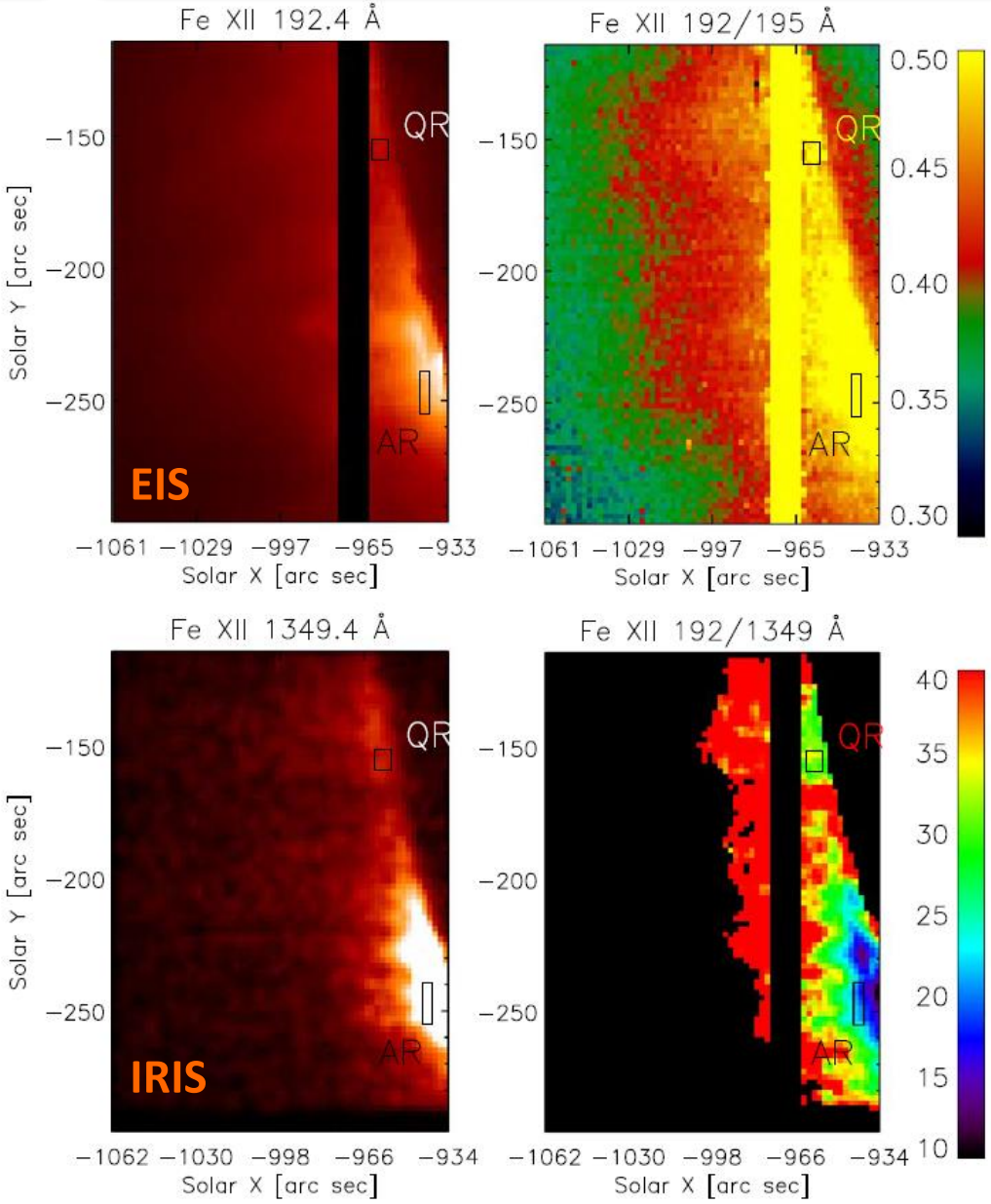

22−oct−2013 Fe XII − QR
1: (2−36 186.85 Å+3−39,186.89 Å) I_ob=812
2: (1−30 192.39 Å) I_ob=880
3: (1−29 193.51 Å) I_ob=1560
4: (1−27 195.12 Å+2−33,195.18 Å) I_ob=1770
Emissivity ratio
Log Ne [cm⁻³]

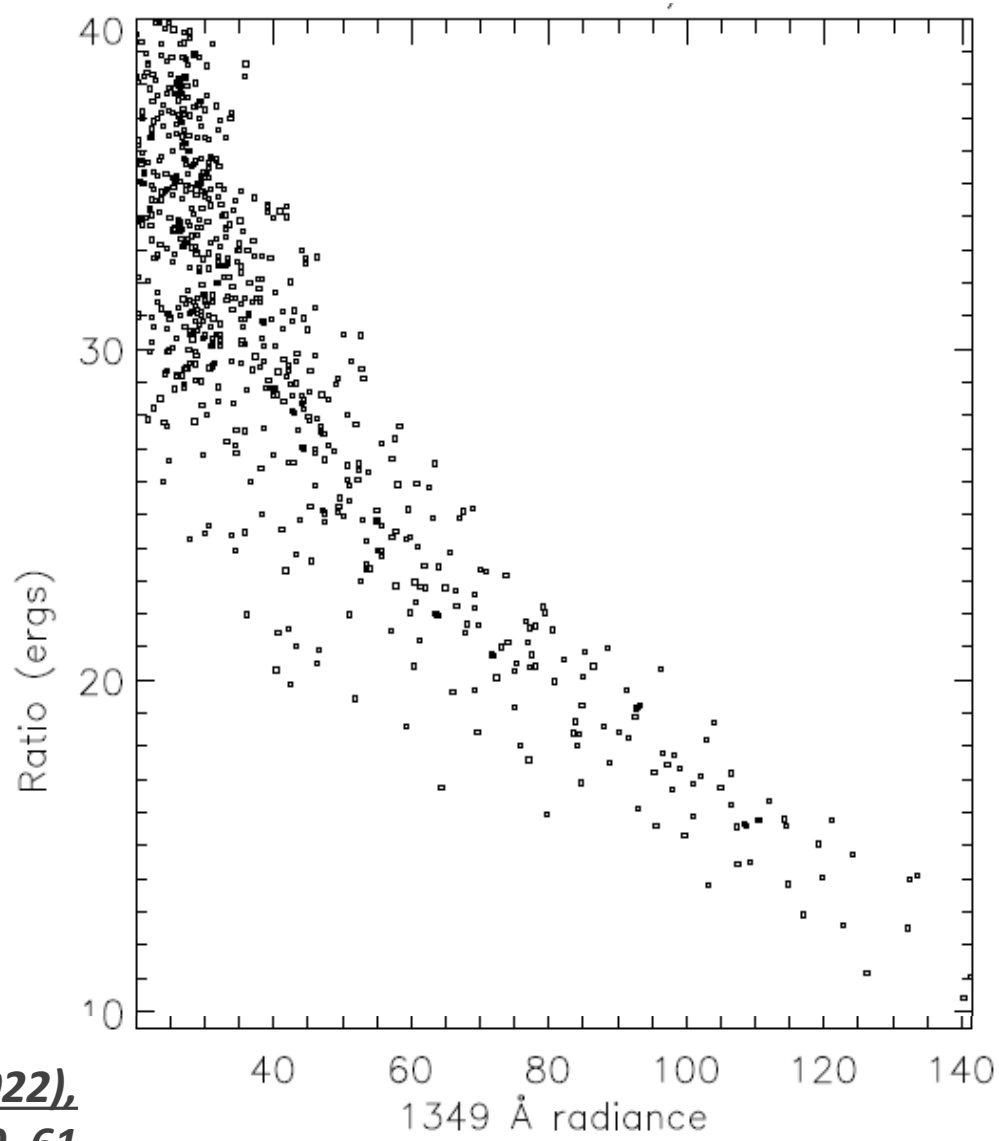

22−oct−2013 Fe XII − AR
1: (2−36 186.85 Å+3−39,186.89 Å) I_ob=1880
2: (1−30 192.39 Å) I_ob=1545
3: (1−29 193.51 Å) I_ob=2560
4: (1−27 195.12 Å+2−33,195.18 Å) I_ob=2920
Emissivity ratio
Log Ne [cm⁻³]


22−oct−2013 Fe XIII (PE) − QR
1: (1−20 202.04 Å) I_ob=1850
2: (3−25 203.83 Å+3−24,203.79 Å) I_ob=990
Emissivity ratio
Log Ne [cm⁻³]

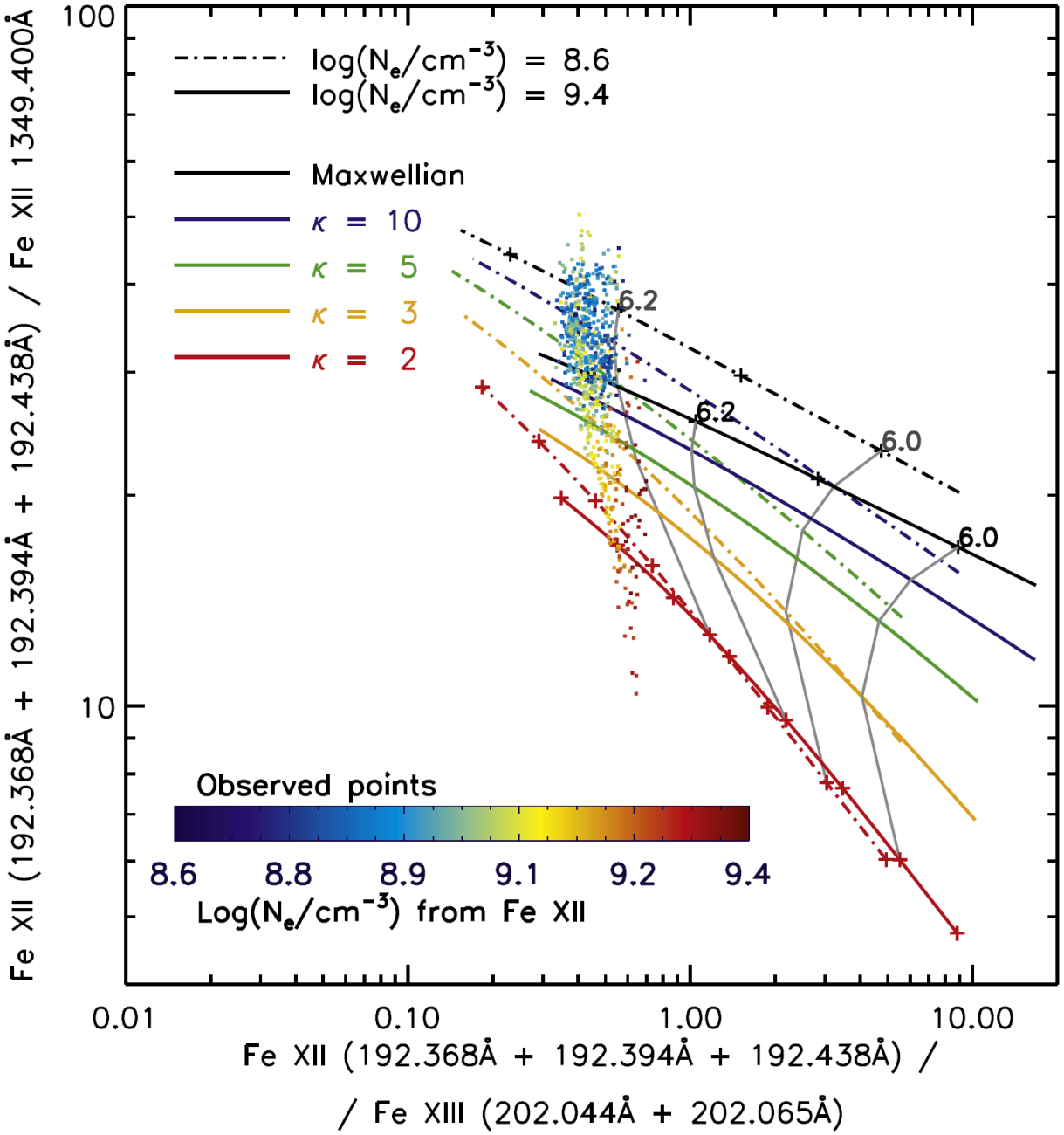

22−oct−2013 Fe XIII (PE) − AR
1: (1−20 202.04 Å) I_ob=3230
2: (3−25 203.83 Å+3−24,203.79 Å) I_ob=3824
Emissivity ratio
Log Ne [cm⁻³]

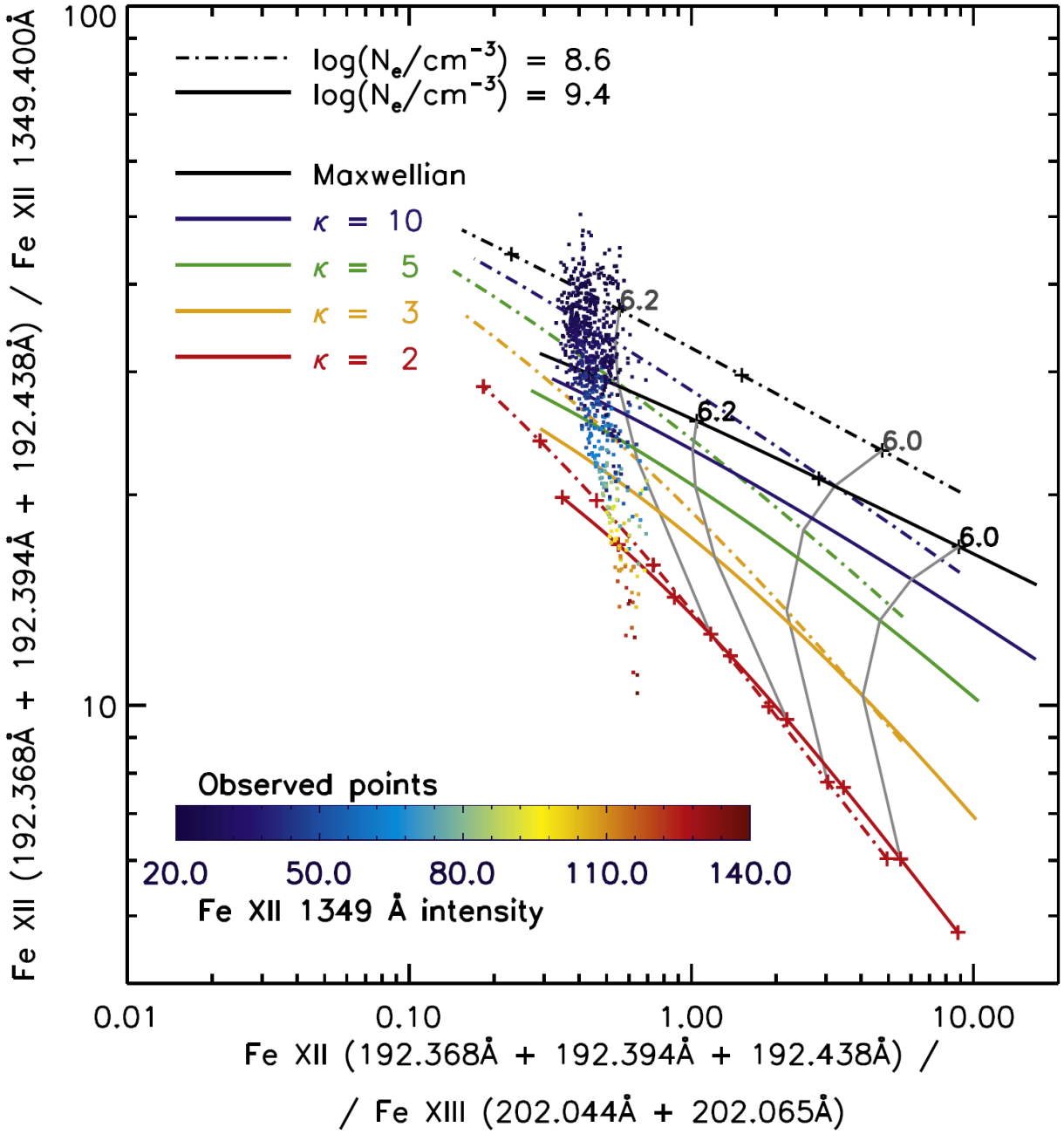
Co-spatial EIS and IRIS observations of Fe XII





Del Zanna et al. (2022), ApJ, 930, 61

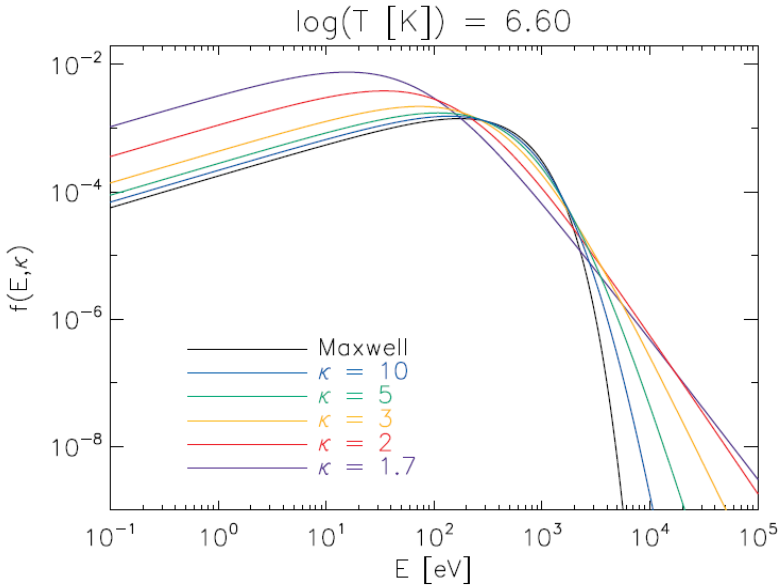

log(N_e/cm^-3) = 8.6
log(N_e/cm^-3) = 9.4
Maxwellian
κ = 10
κ = 5
κ = 3
κ = 2
6.2
6.2
6.0
6.0
Observed points
8.6 8.8 8.9 9.1 9.2 9.4
Log(N_e/cm^-3) from Fe XII
100
10
0.01
0.10
1.00
10.00
Fe XII (192.368Å + 192.394Å + 192.438Å) / Fe XII 1349.400Å
Fe XII (192.368Å + 192.394Å + 192.438Å) /
/ Fe XIII (202.044Å + 202.065Å)


log(N_e/cm^-3) = 8.6
log(N_e/cm^-3) = 9.4
Maxwellian
κ = 10
κ = 5
κ = 3
κ = 2
6.2
6.2
6.0
6.0
Observed points
20.0 50.0 80.0 110.0 140.0
Fe XII 1349 Å intensity
100
10
0.01
0.10
1.00
10.00
Fe XII (192.368Å + 192.394Å + 192.438Å) / Fe XII 1349.400Å
Fe XII (192.368Å + 192.394Å + 192.438Å) /
/ Fe XIII (202.044Å + 202.065Å)

Ad: The KAPPA package

- Maxwellian (equilibrium) spectra calculated with CHIANTI v10
- KAPPA package based on CHIANTI v10 allows for calculation of NMED spectra for κ-distributions

https://kappa.asu.cas.cz



Dzifčáková, Dudík et al. (2023), ApJS, accepted