Atomic spectroscopy (needs mostly for ions)

Giulio Del Zanna

DAMTP, CMS, University of Cambridge, UK

High-resolution spectroscopy and broad-band imaging requires

-completeness and accuracy in the atomic data (e-ion scattering and A-values)

-accurate wavelengths (Doppler measurements)

-line identifications

Science & Technology Facilities Council

SEVENTH FRAMEWORK PROGRAMME

solid

UNIVERSITY OF CAMBRIDGE

Atomic data

CALCULATION:

UK **APAP Network** http://www.apap-network.org/
has become the main ion atomic data provider
for fusion and astrophysics
(Strathclyde, UCL, Cambridge)

BENCHMARK:

EUV line identifications and benchmark

DISTRIBUTION:

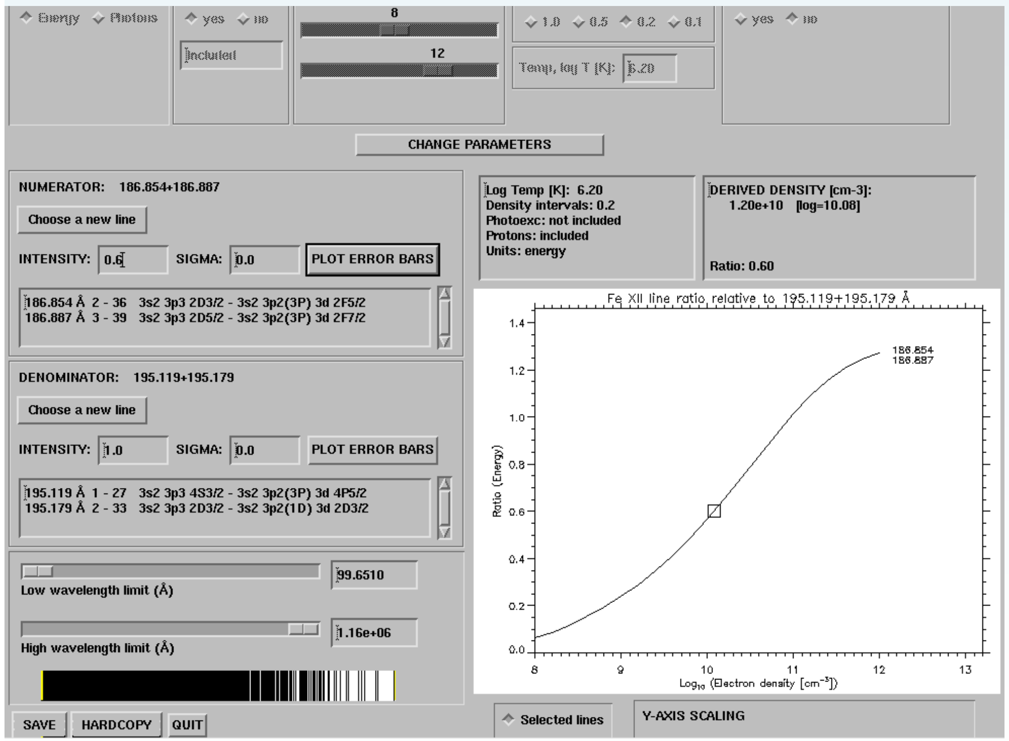
CHIANTI (www.chiantidatabase.org) has now become the reference atomic database for ions (often better than NIST), included in most atomic spectral codes for astrophysics (hundreds of citations per year).

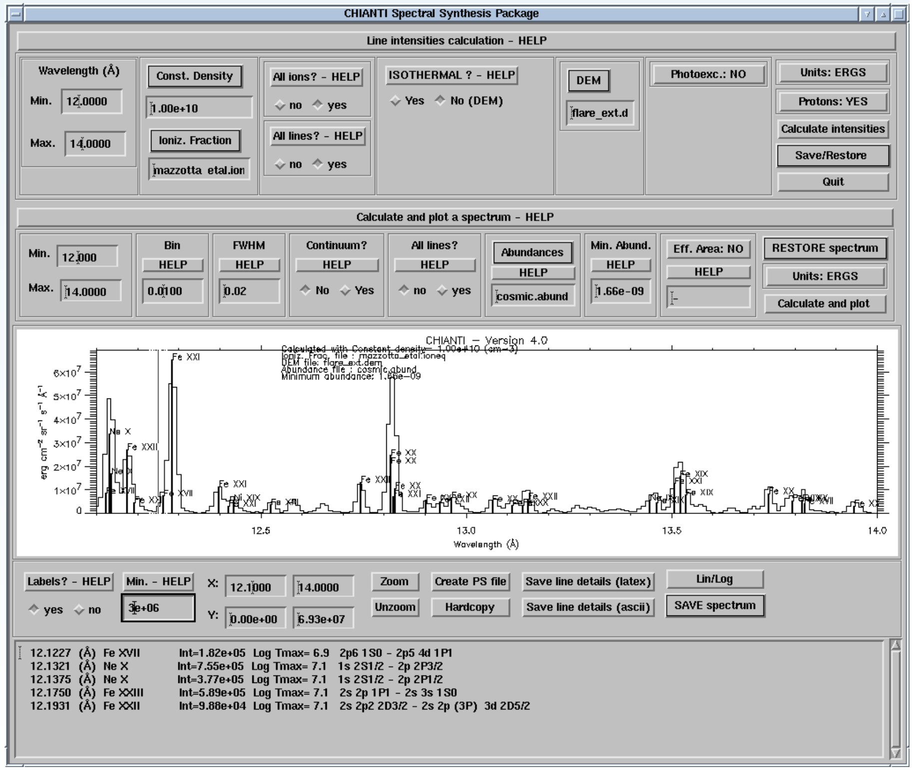
CHIANTI v.7 are available in VAMDC (Virtual Atomic and Molecular Data Center: http://portal.vamdc.eu)

1) Many users (e.g. modellers) need. e.g. the emissivities to calculate the radiative lossess for plasma.
2) Ne or Te from line ratios
3) Simulated spectra

The CHIANTI programs are mostly in IDL, not directly accessible.

GUIs will be made available to access the data via VAMDC



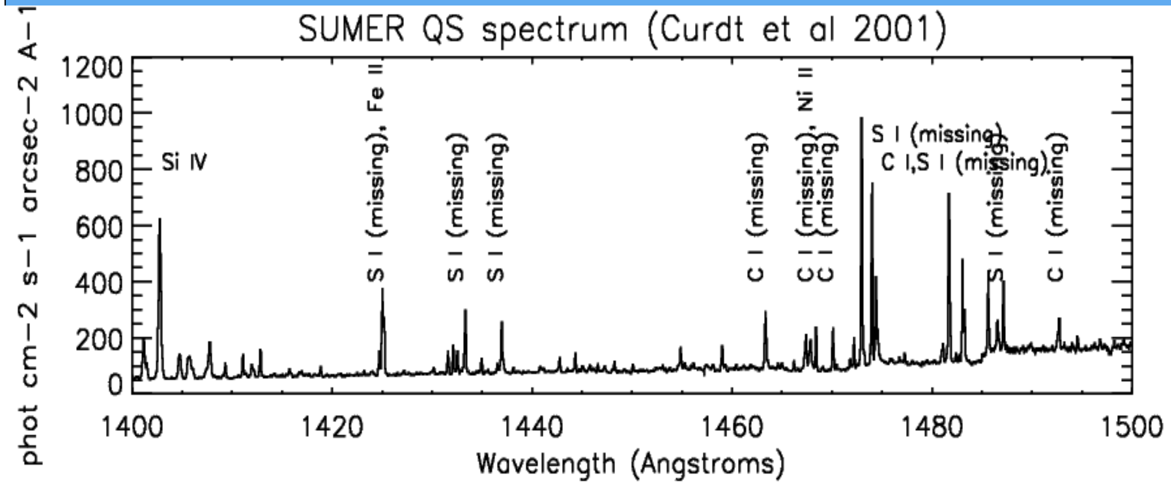


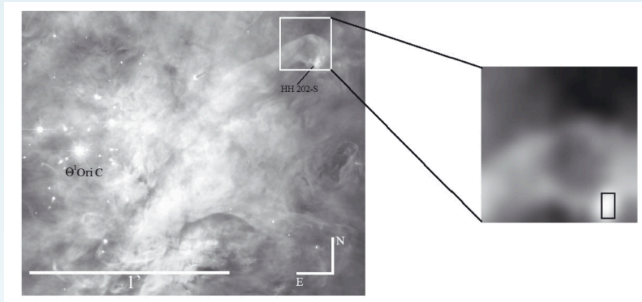
CHIANTI v.8 (Del Zanna et al. 2015)

V.8 will be included into VAMDC.

- New format for energy and rates files.
- Rates: not spline fitted, but actual values in the Burgess-Tully (1992) scaled domain. Good for low-T (photoionized plasma).
- All excitations included (data usable for high-Ne plasmas)
- Data for a few isoel. seq.from UK APAP network.

UV/visible – neutral and low charge states





New additons to CHIANTI v.8:

- S I – new (Tayal 2004)
- N I (Tayal 2006)
- C I – new neutral (Wang+2013)
- Fe III – new ion (Badnell 2014)
- S II (Tayal & Zatsarinny 2010)
- S III: Hudson et al. (2012)

A-values from various sources.

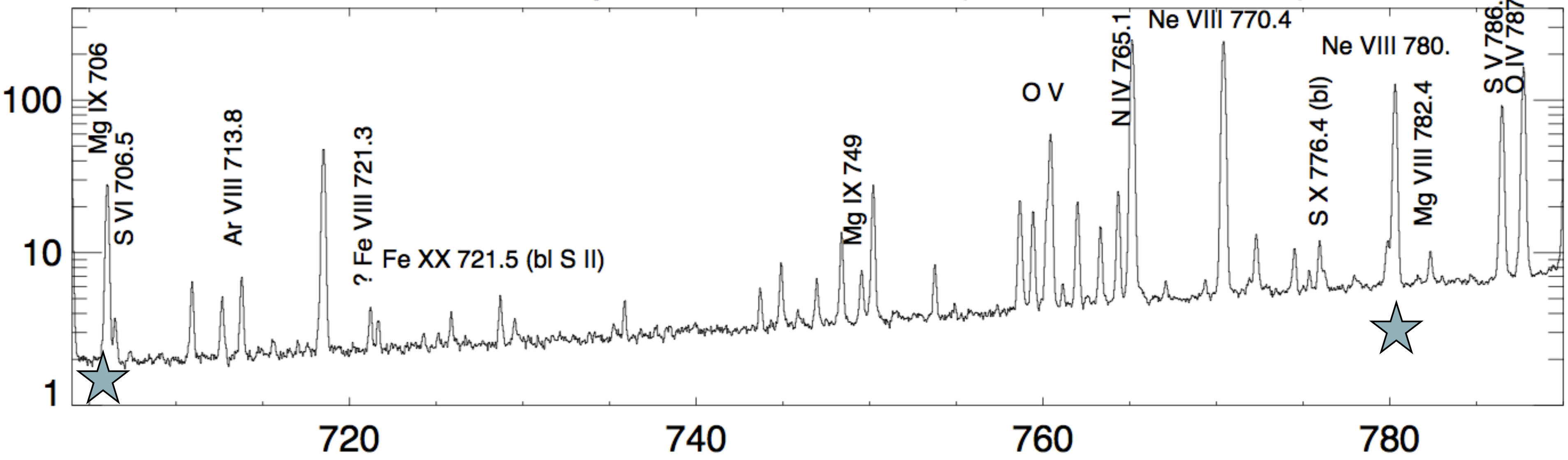
Table 2. Physical conditions.

Indicator		Nebular component	Shock component
n_e (cm^{-3})	[O II]	3490 ± 810	18 810 ± 8280
	[S II]	2350 ± 910	> 14 200
	[Cl III]	2470 ± 1240	23 780 ± 13 960
	[Fe III]	11 800 ± 9000	17 100 ± 2500
	[Ar IV]	5800 :[a]	–
	Adopted	2890 ± 550	17 430 ± 2360
T_e (K)	[N II]	9610 ± 390	9240 ± 300
	[O II]	8790 ± 250	9250 ± 280
	[S II]	8010 ± 440	8250 ± 540
	[O III]	8180 ± 200	8770 ± 240
	[S III]	8890 ± 270	9280 ± 300
	[Ar III]	7920 ± 450	8260 ± 410
	He I	8050 ± 150	7950 ± 200

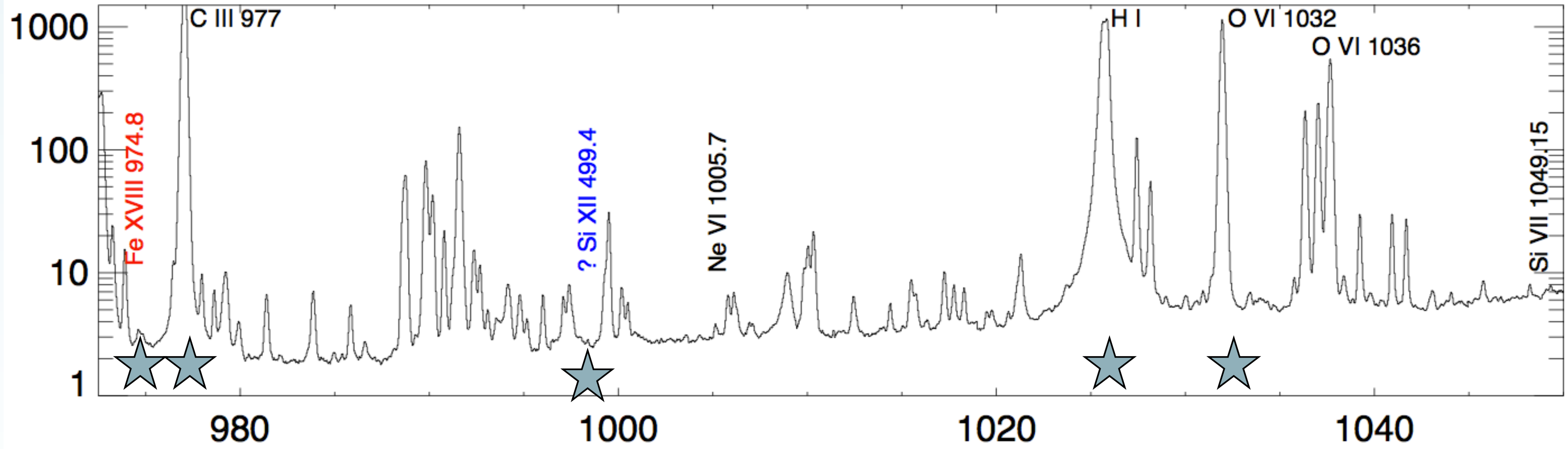
More data are needed

Orion Nebula
(Mesa Delgado et al, 2009).

SUMER QS spectrum 704-790 (Curdt et al 2001)

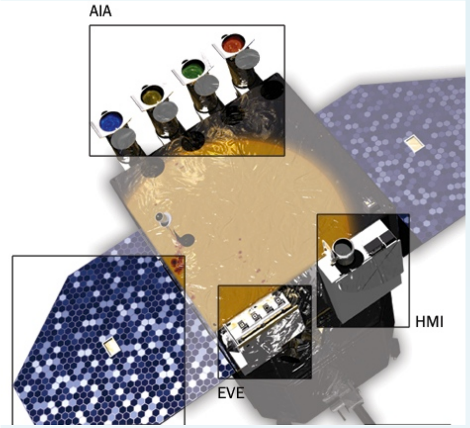


SUMER QS spectrum 972.5-1050 (Curdt et al 2001)

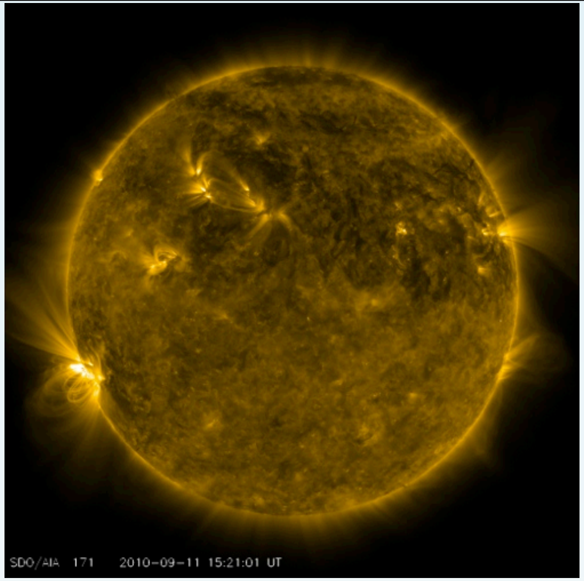


Solar Orbiter (2018-) next ESA/NASA solar major mission UV/EUV spectroscopy

Solar corona: EUV

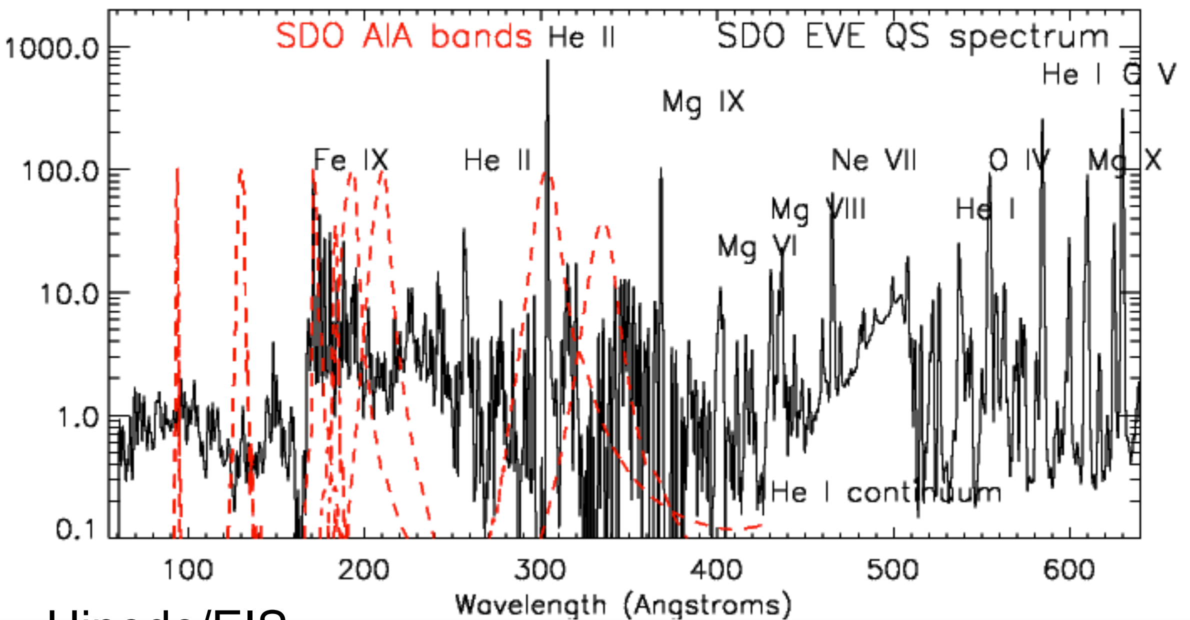


From 2010:SDO



Six broad-band EUV images every 12s

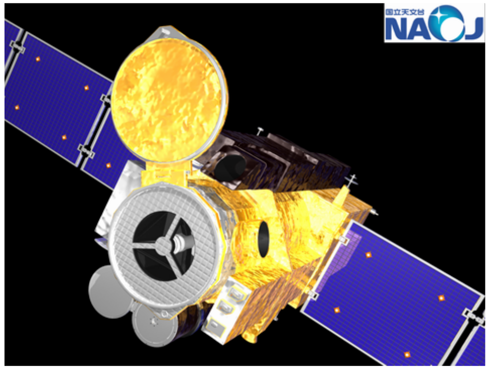
EUV spectra every 10s

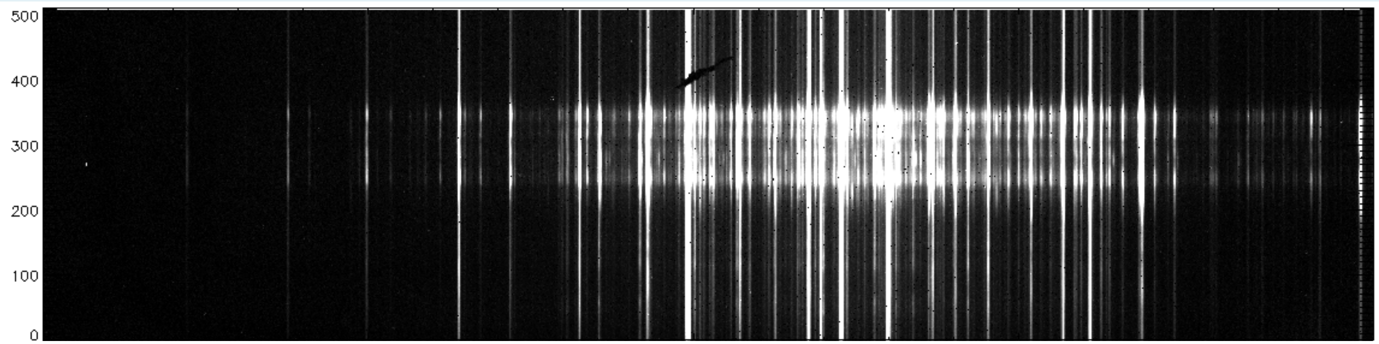


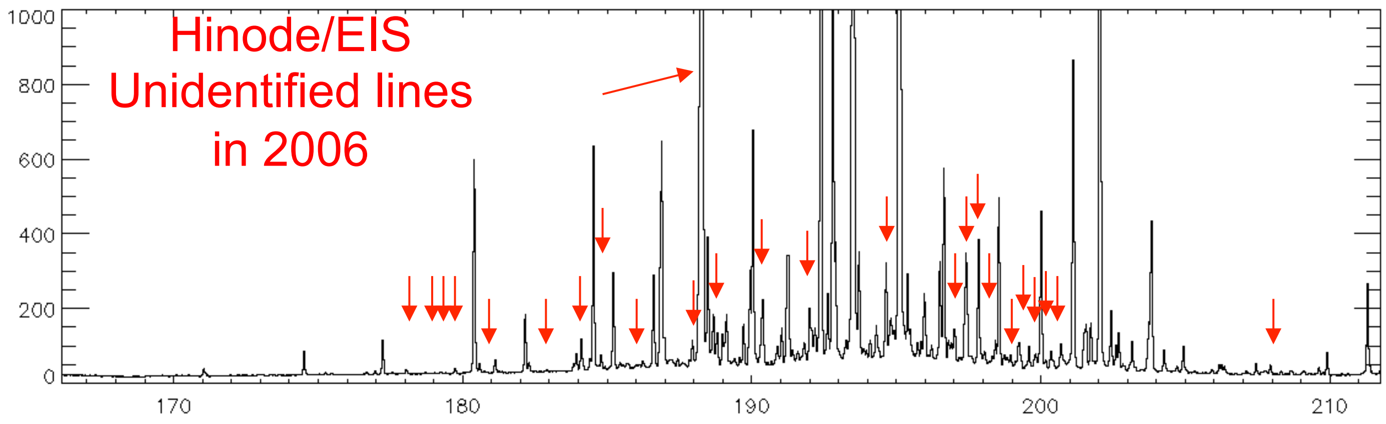
Hinode/EIS ↔ ↔

Used to study the heating of the solar corona. Ne, Te, chemical abundances

Hinode EIS and iron unidentified lines



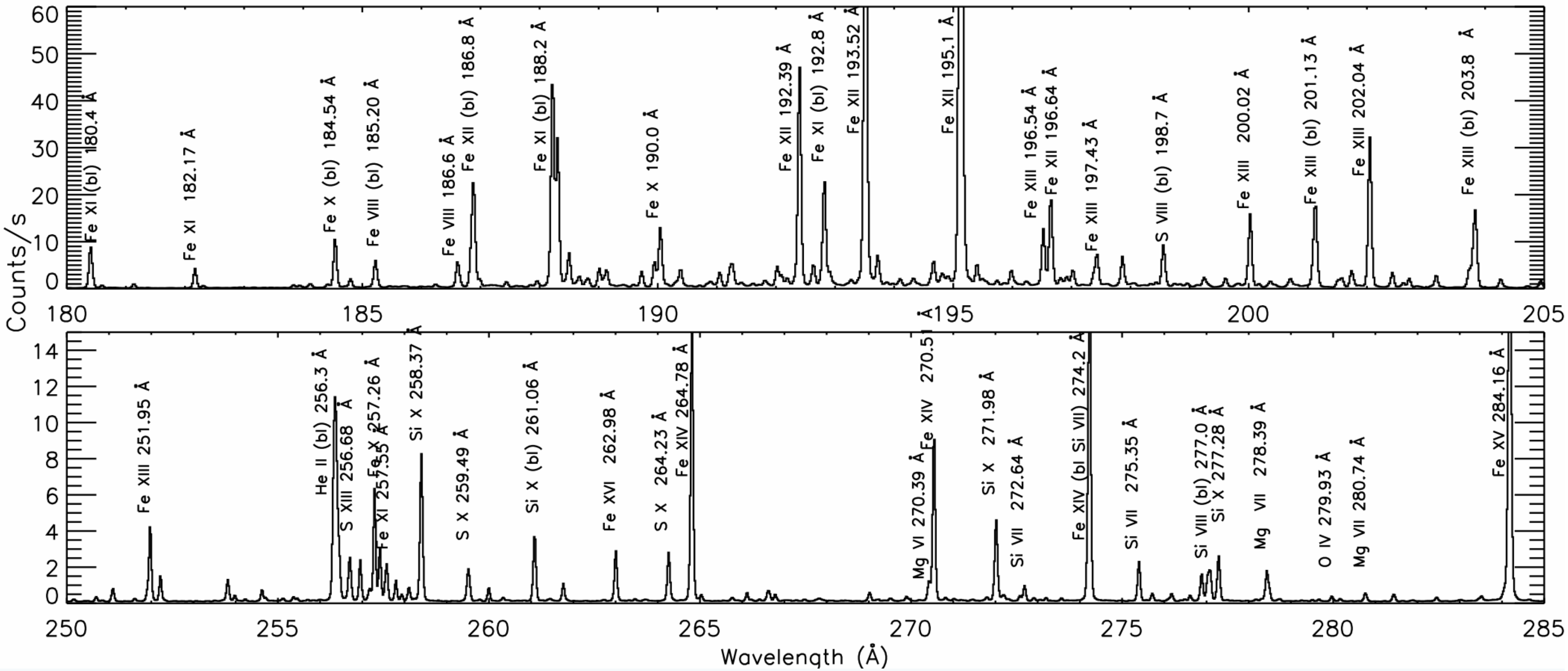




Del Zanna (2011): most brightest iron coronal lines finally identified with the help of laboratory plates after 8 years!
More work still needed.

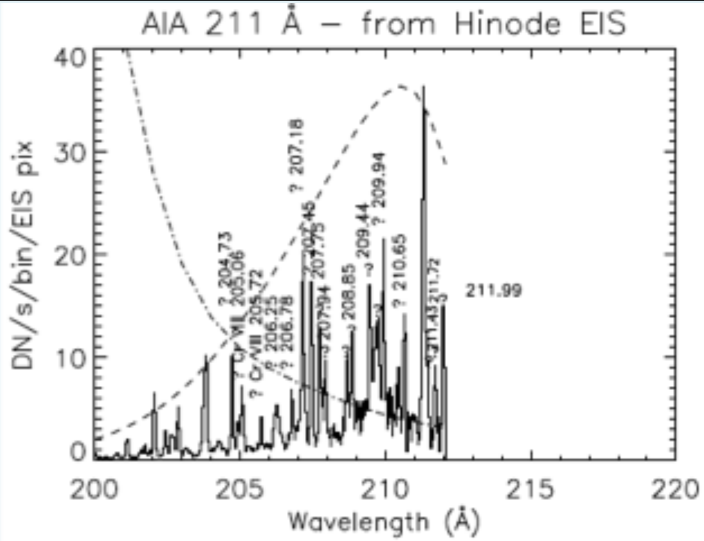
B.Fawcett 166 – 212 Angstroms

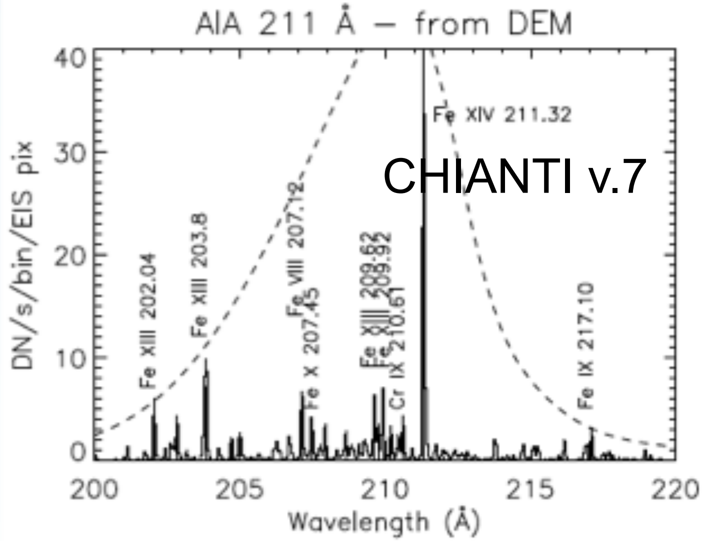
Hinode EIS spectrum of an active region



Mostly from iron !

AIA EUV bands





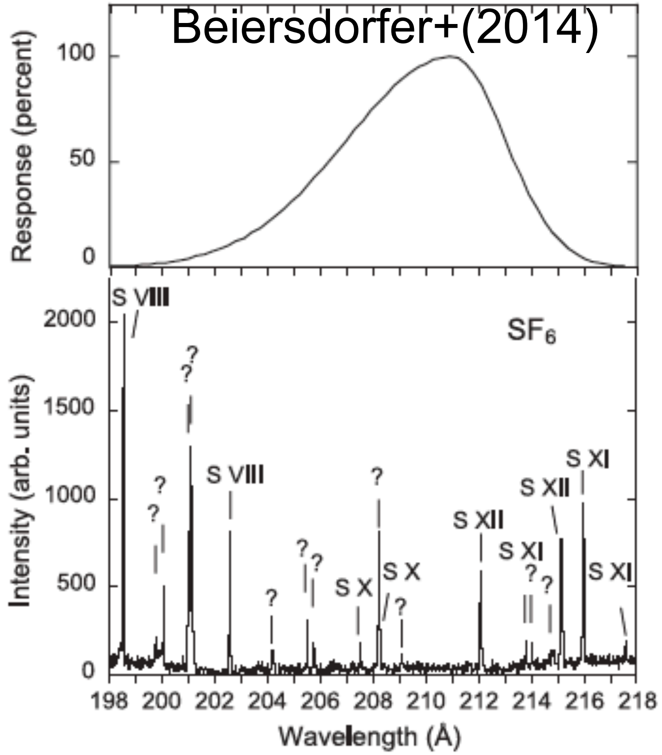


Figure 3. EUV spectrum of fluorine and sulfur produced by injecting SF_6 into the EBIT-I electron beam ion trap covering the spectral range λ198–λ218. The electron beam energy was 1000 eV, but the spectrum differs very little from observations at 600 eV. Identified spectral features are labeled by the corresponding spectrum. Unidentified features are labeled by a question mark. The response of the *SDO*/AIA λ211 channel is indicated on top.

A lot of cool/unidentified lines in AIA bands (Del Zanna+2011).
more work needed.

CHIANTI v.8 – isoelectronic sequences

He-like (Whiteford et al. 2001, up to n=5)

Li-like (Liang & Badnell 2011, 204 levels up to n=5 + inner-shell)

B-like (Liang+2012, 204 levels, up to n=4)

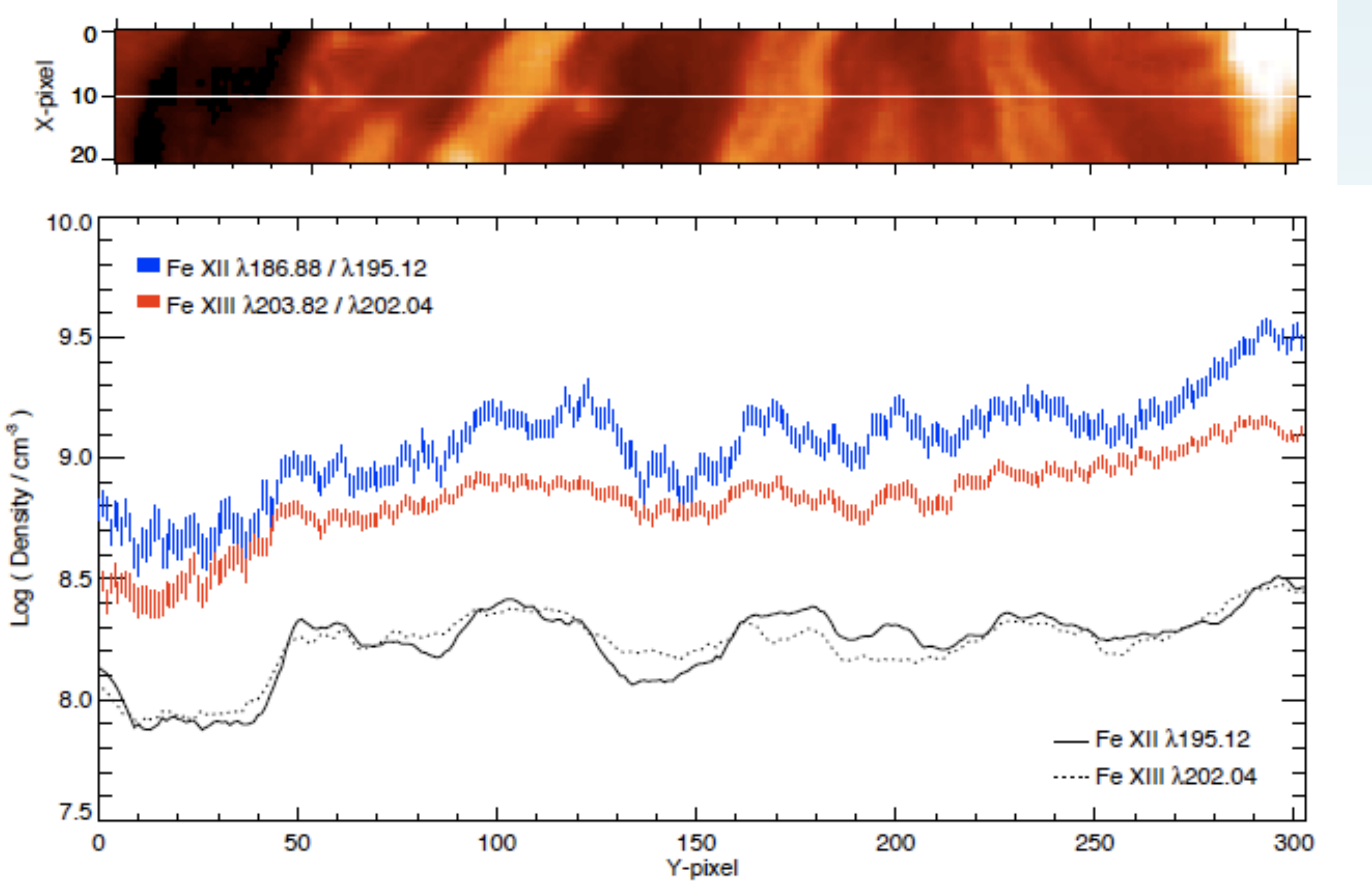
Na-like (Liang+2009, 161 levels, up to n=6 + inner-shell)

Ne-like (Liang+Badnell 2010, 207 levels, up to n=7)

C		II 37	III 20	IV 15	V 49	VI 25																
N	I 26	II 58	III 20	IV 20	V 15	VI 49	VII 25															
O	I 7	II 35	III 46	IV 75	V 166	VI 40	VII 49	VIII 25														
F																						
Ne		II 3	III 86	IV 22	V 49	VI 180	VII 46	VIII 40	IX 49	X 36												
Na			III 3	IV 10	V 13	VI 20	VII 15	VIII 10	IX 20	X 49	XI 25											
Mg		II 15		IV 3	V 86	VI 72	VII 46	VIII 125	IX 108	X 40	XI 49	XII 25										
Al		II 20	III 21		V 3	VI 10	VII 15	VIII 20	IX 125	X 10	XI 40	XII 49	XIII 25									
Si		II 29	III 20	IV 21	V 27	VI 195	VII 86	VIII 72	IX 46	X 125	XI 92	XII 40	XIII 49	XIV 25								
P					V 19		VII 3	VIII 10	IX 15	X 20	XI 15	XII 10	XIII 20	XIV 45	XV 25							
S		II 43	III 49	IV 52	V 16	VI 21	VII 27	VIII 195	IX 86	X 72	XI 72	XII 125	XIII 92	XIV 40	XV 49	XVI 25						
Cl		II 5	III 5	IV 5						X 10	XI 15	XII 20		XIV 10		XVI 49	XVII 25					
Ar			III 5	IV 30	V 5		VII 16	VIII 21	IX 89	X 195	XI 86	XII 72	XIII 15	XIV 125	XV 92	XVI 40	XVII 49	XVIII 25				
K					V 5	VI 5			IX 19		XI 3	XII 10	XIII 15	XIV 20	XV 15	XVI 10	XVII 20	XVIII 49	XIX 25			
Ca		II 41			V 5	VI 5	VII 27	VIII 40	IX 283	X 21	XI 89	XII 195	XIII 86	XIV 91	XV 46	XVI 125	XVII 92	XVIII 40	XIX 49	XX 25		
Sc																						
Ti											XI 16	XII 19		XIV 3	XV 10	XVI 72	XVII 20	XVIII 15	XIX 10	XX 20		
V																						
Cr							VII 13	VIII 31	IX 48				XIII 16	XIV 19		XVI 3	XVII 10	XVIII 15	XIX 20	XX 15	XXI 10	XXI
Mn								VIII 13	IX 31	X 48					XV 19		XVII 3	XVIII 10	XIX 15	XX 20	XXI 15	XXI
Fe		II 142	III 219	IV 37	V 34	VI 80	VII 9	VIII 104	IX 379	X 825	XI 999	XII 898	XIII 950	XIV 739	XV 283	XVI 21	XVII 267	XVIII 337	XIX 636	XX 375	XXI 620	XXI
Co																	XVII 19		XIX 3	XX 10	XXI 15	XXI
Ni		II 17									XI 180	XII 31	XIII 48	XIV 143	XV 126	XVI 40	XVII 159	XVIII 21	XIX 89	XX 195	XXI 58	XXI

Accurate data needed for Ne diagnostics

Hinode EIS spectra have pushed the needs for more accurate atomic data.
A discrepancy in Ne from Fe XII has been noted.



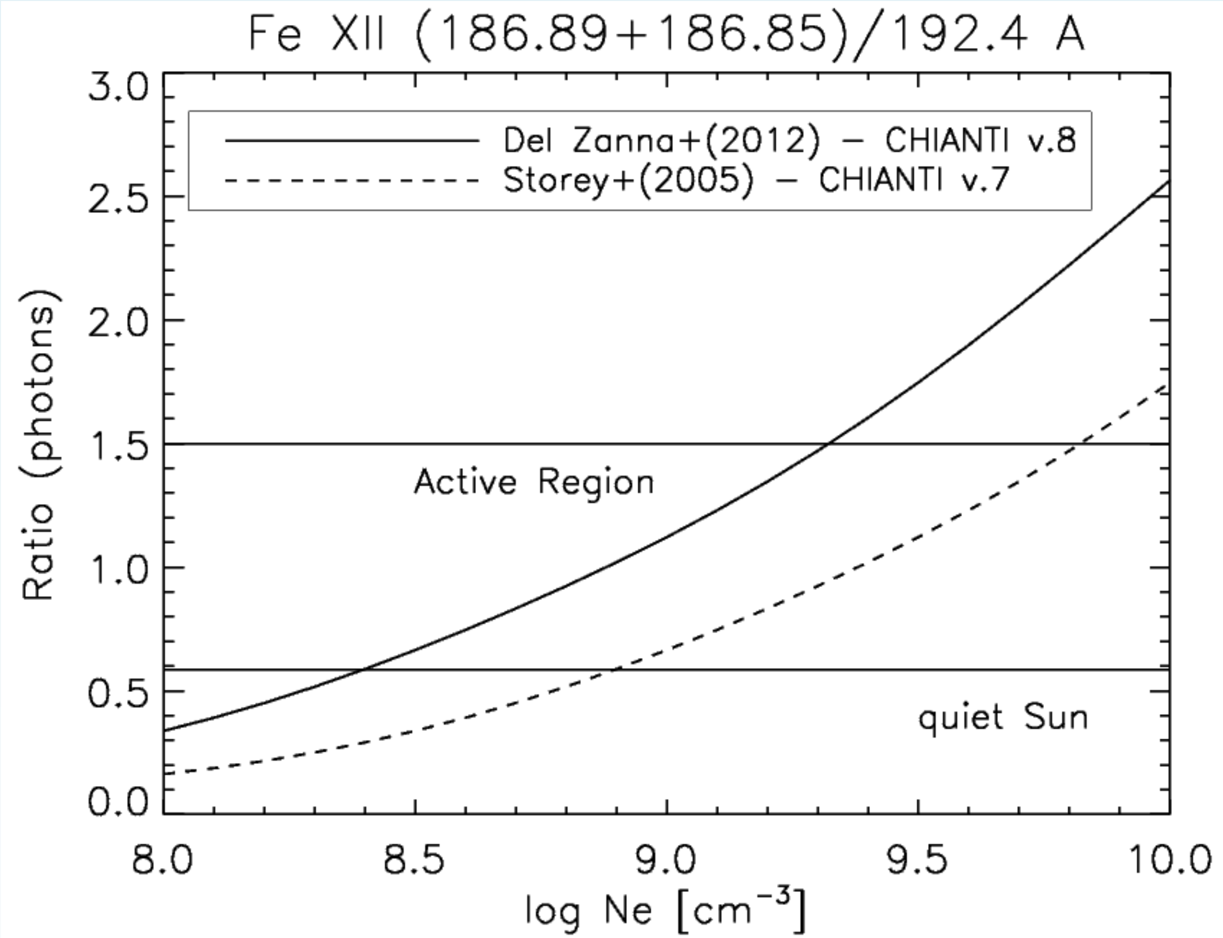
Young et al. (2009)

New large-scale R-matrix calculations

- DW calculations for some n=4 levels significantly underestimate collision strengths. Soft X-rays
- Cascading from higher levels significantly increases the populations of lower levels. EUV

- Fe VIII (new ICFT+STJK – TEC): Del Zanna & Badnell 2014
- Fe IX: Del Zanna et al. (2014) up to n=5
- Ni XI up to n=4 (Del Zanna et al. 2014)
- Fe X: Del Zanna et al. (2012) up to n=4
- Fe XI: Del Zanna & Storey (2012) up to n=4, merged with Del Zanna et al. (2010)
- Fe XII: Del Zanna et al. (2012) up to n=4
- Fe XIII: Del Zanna & Storey (2012) up to n=4
- Ni XV, same target as Fe XIII (Del Zanna et al. 2012)

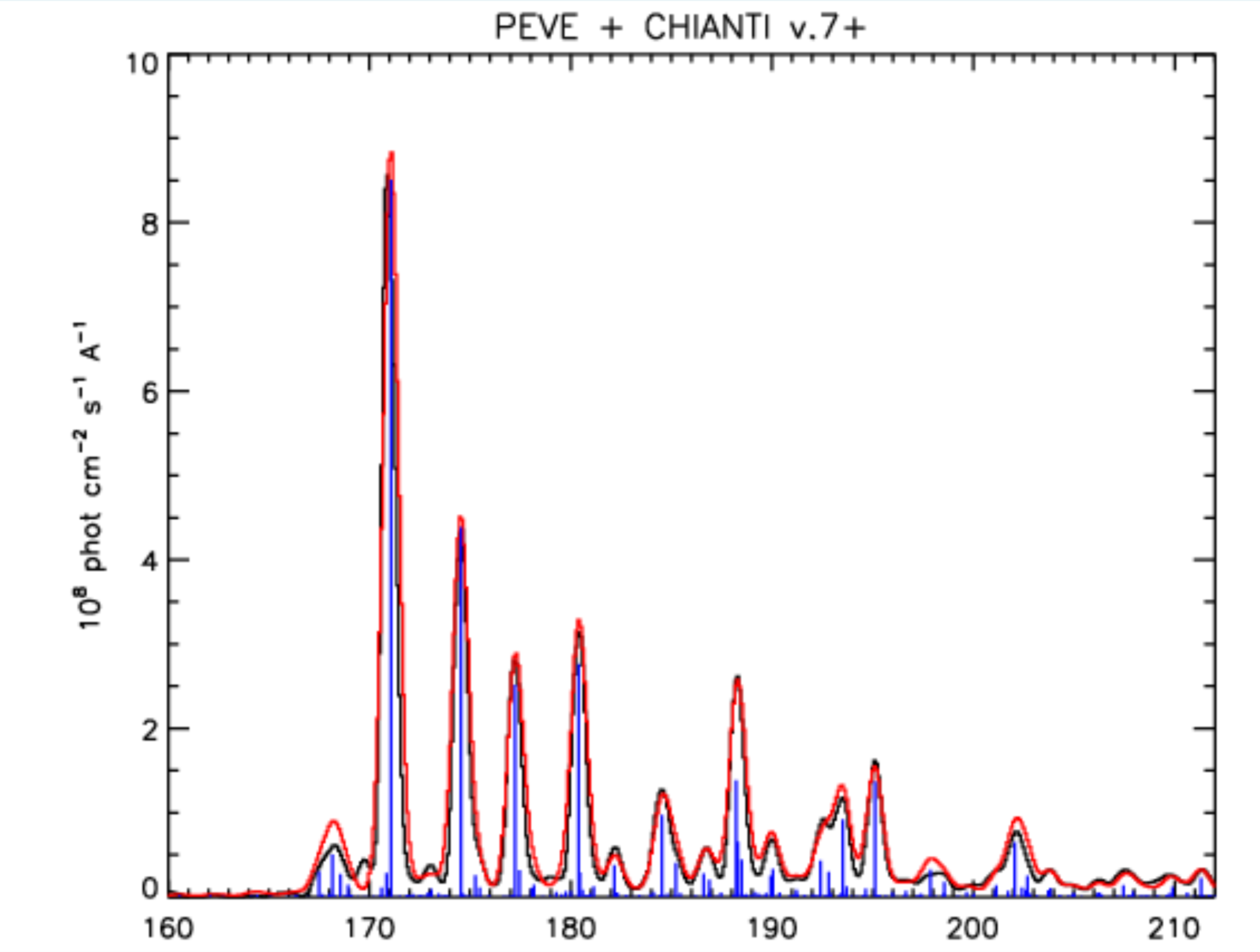
More calculations of this kind are needed.



- The new atomic data produce lower densities.

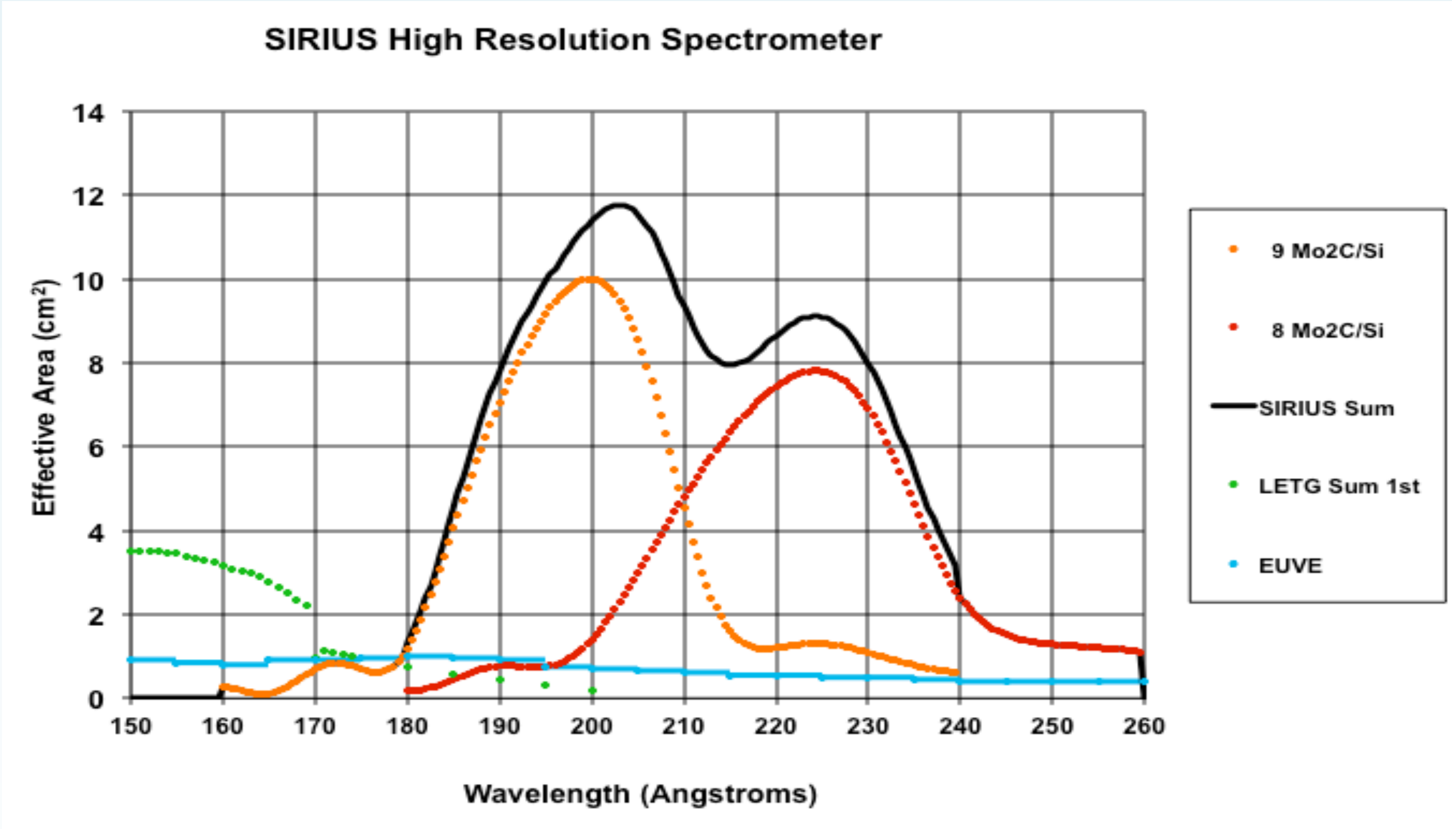
Quiet Sun EUV irradiance spectrum

Modelling (red) shows overall very good agreement within 10-20%



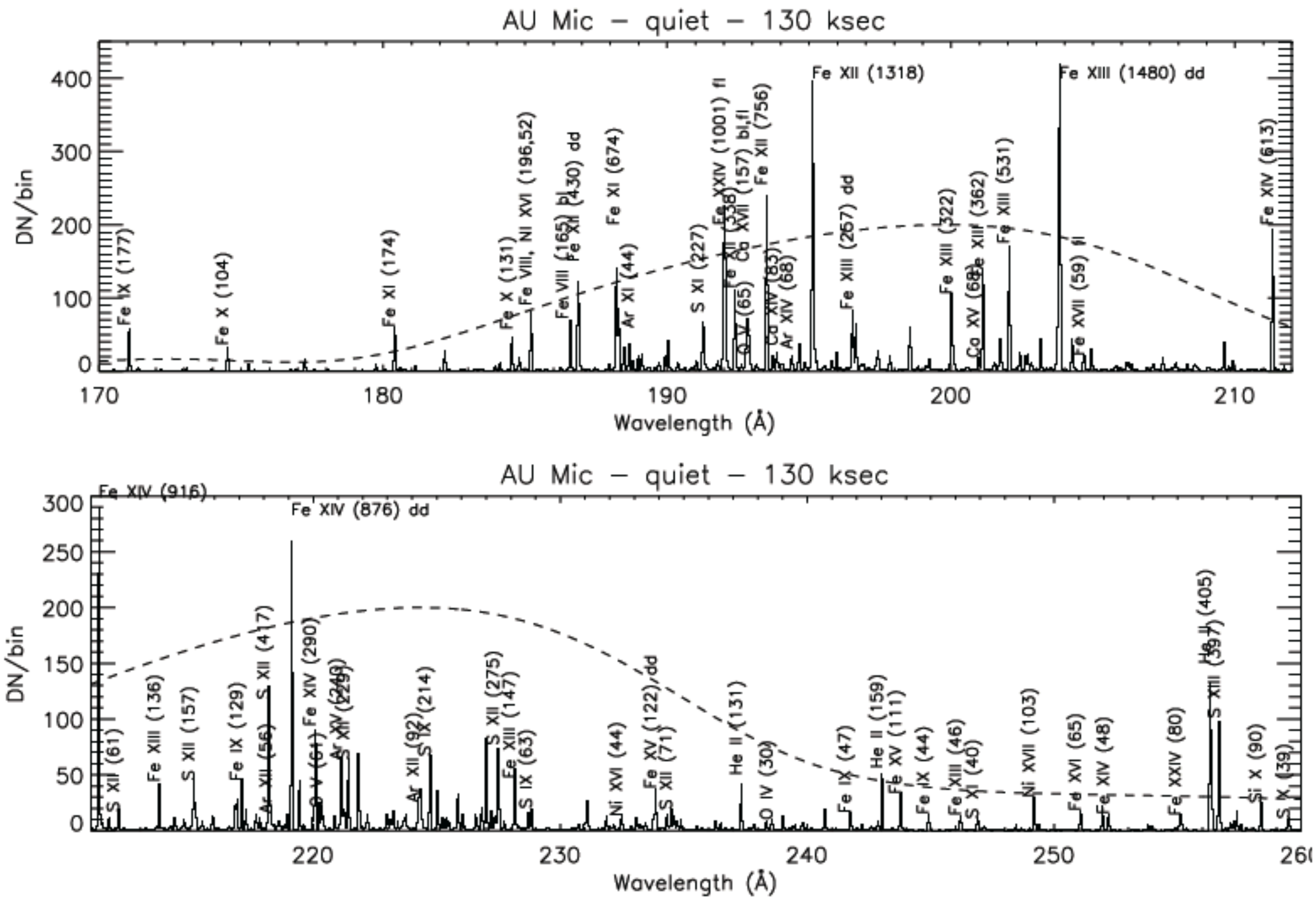
SIRIUS

Stellar & **I**SM **R**esearch via **I**n-orbit **U**ltraviolet **S**pectroscopy
First high-resolution EUV spectroscopic astrophysical mission
(ESA-CAS proposal, led by M. Barstow – Leicester Univ.)



Slitless, normal incidence off-axis EUV spectrograph
R~5000, peak A_{eff} > 10 cm^2, λλ 180-240 Å

SIRIUS

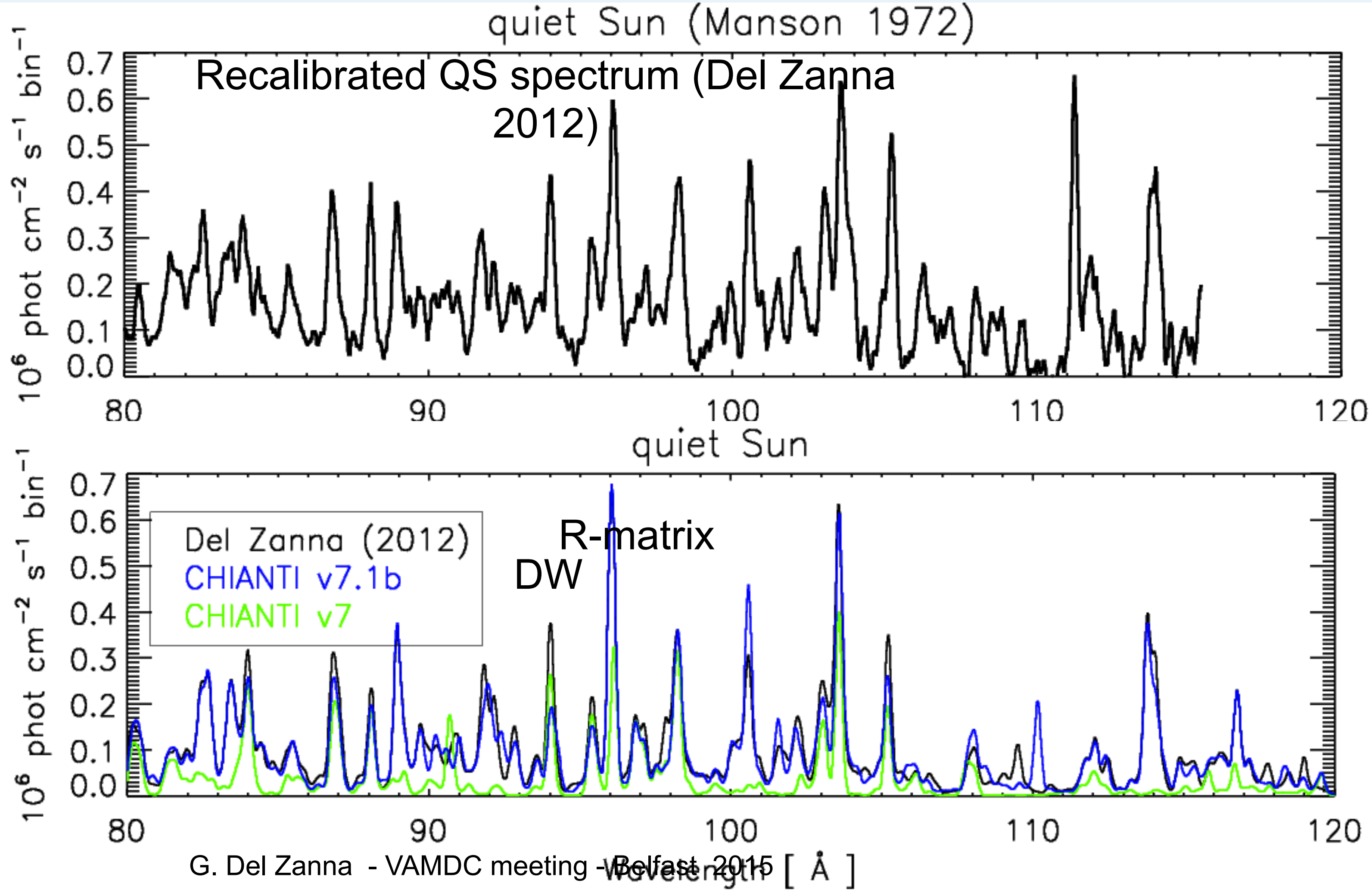


Simulation using CHIANTI v.8.

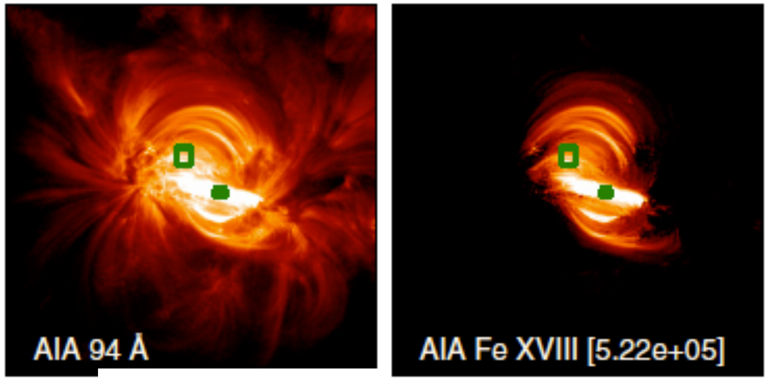
The 210-250 A region is largely unexplored.

Soft X-rays - a lot more of missing data

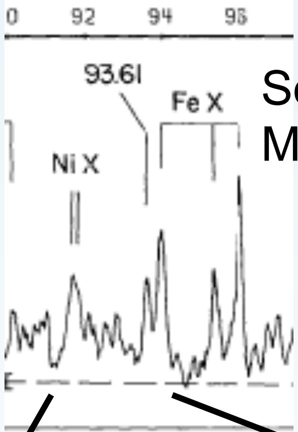
CHIANTI v.7.1: DW data + identifications (Del Zanna 2012).
V.8: R-matrix data



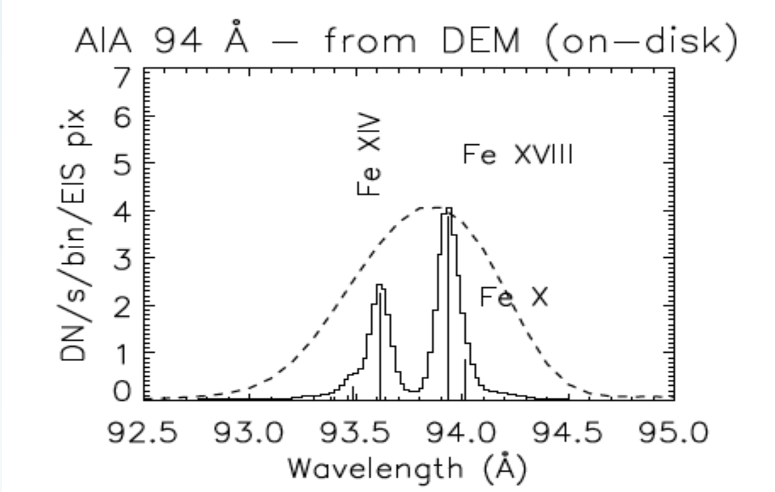
How many years to sort out 1 A bin ?

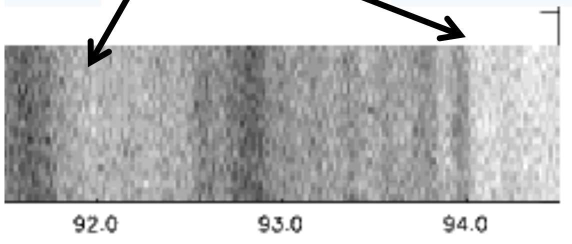


AIA 94 A images show ubiquitous presence of Fe XVIII (Warren et al. 2012) and provide for the first time detailed information of hot plasma in active regions.



Solar spectrum Manson (1972)





Laboratory spectrum. One line still to be identified!

New DW calculations for Fe VIII, Fe IX (O'Dwyer+2012)
New Fe XIV identification (Del Zanna 2012)
First scattering Fe X calculations (Del Zanna+ 2012)

Conclusions

Would be useful to produce a `laboratory astrophysics' approach where all the UK groups (laboratory and theoretical calculations) are coordinated to support the astrophysics community.

Significant laboratory and theoretical work is still needed to reach completeness and accurate wavelengths.

Significant international interest in providing uncertainties on atomic data