

Atomic Modelling in the UV for stellar atmospheres

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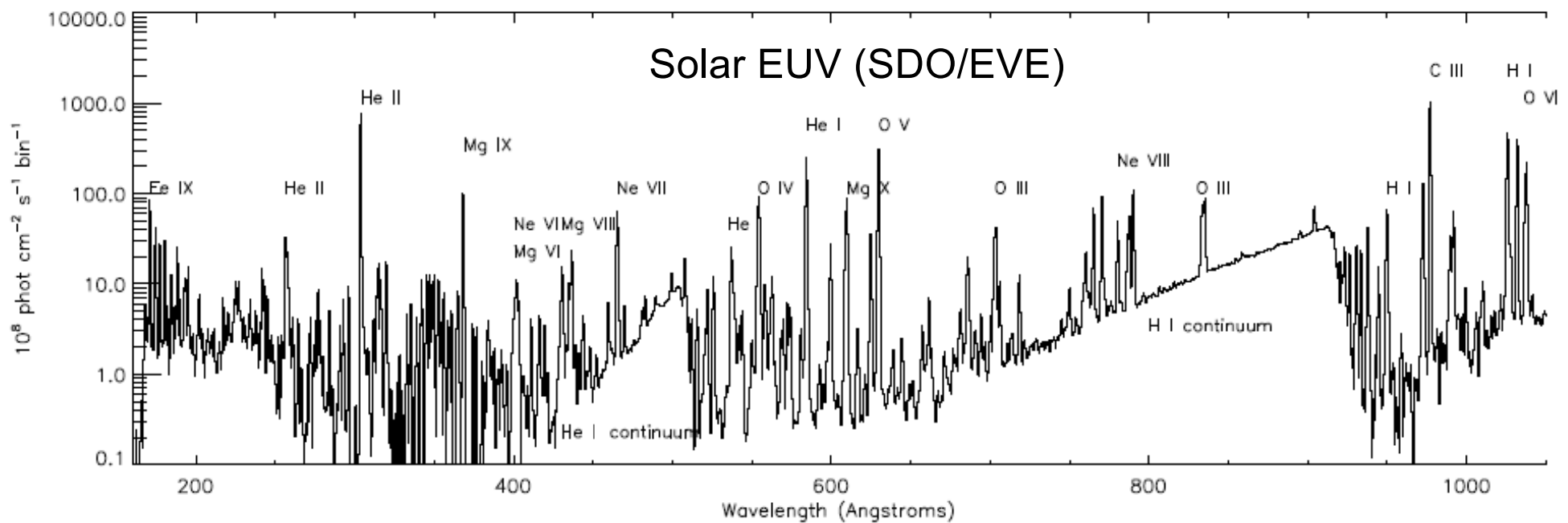
A quick summary of some recent improvements
produced by my group



R. Dufresne E. Deliporanidou



Collaborators: P.J. Storey N.R. Badnell



The EUV is mostly optically thin coronal lines – atomic data are now better than some observations, but the strongest lines from H, He are yet to be understood.

We are currently improving the models for H, He as very simplified ones are still currently widely used.

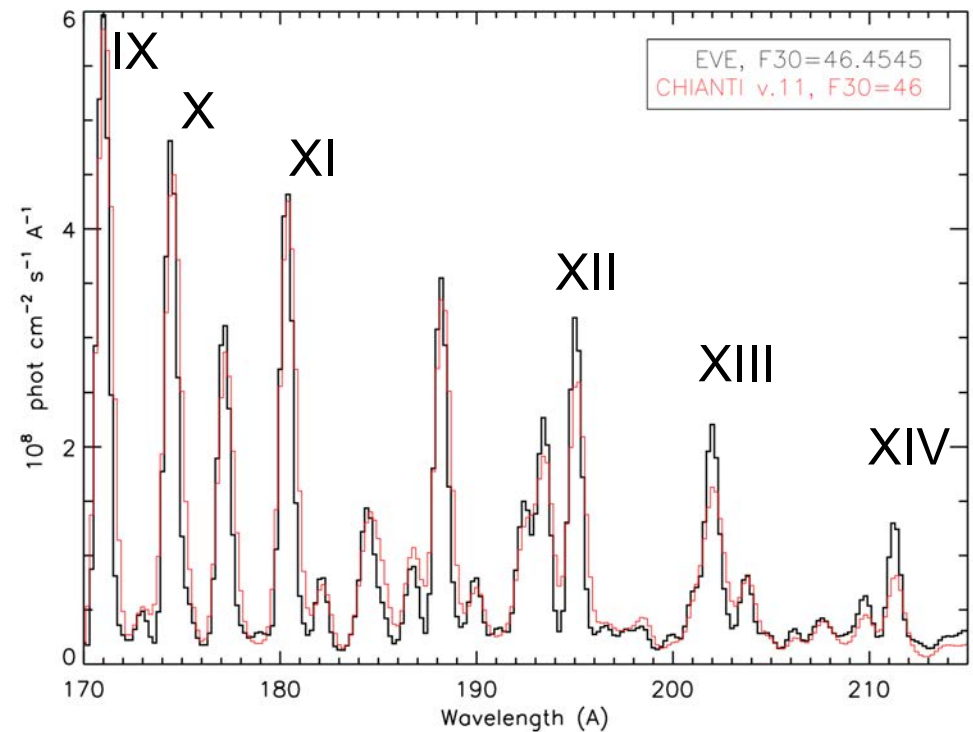
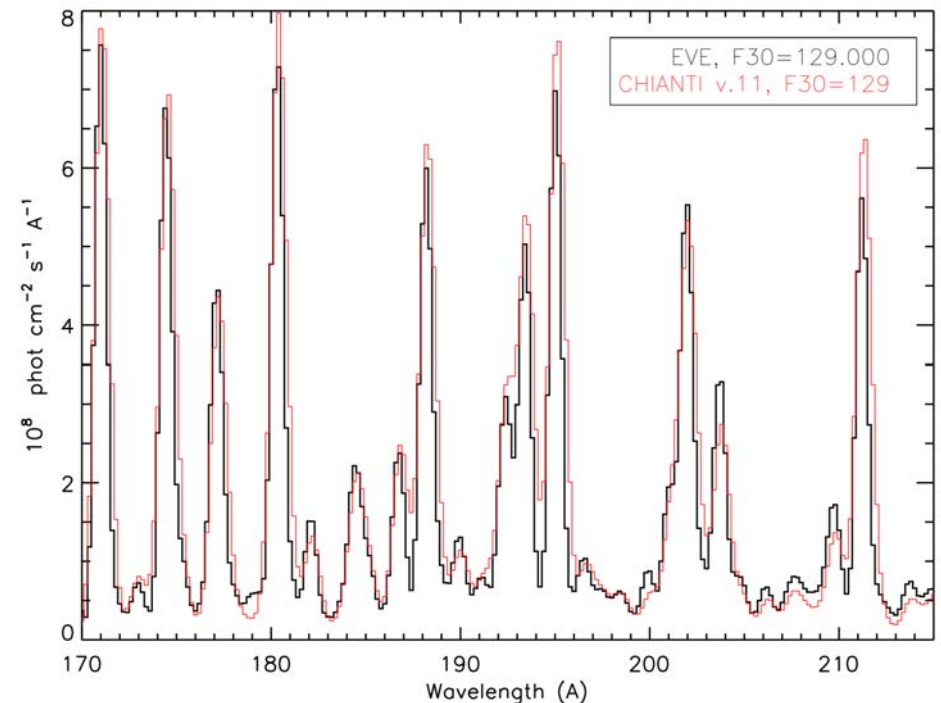
The UV is mostly emitted by the chromosphere - transition region with mostly low charge states/neutrals that are difficult to model -atomic data are NOT complete.

Modelling EUV irradiances

- We have built a model of the EUV solar irradiance building on atomic data.
- It provides values better than most observations...

(Deliporanidou & Del Zanna, MNRAS)

We are extending the models to stars, to be benchmarked with future EUV Observations (SIRIUS ESA proposal, PI Barstow, ESCAPE proposal, PI France, etc.)

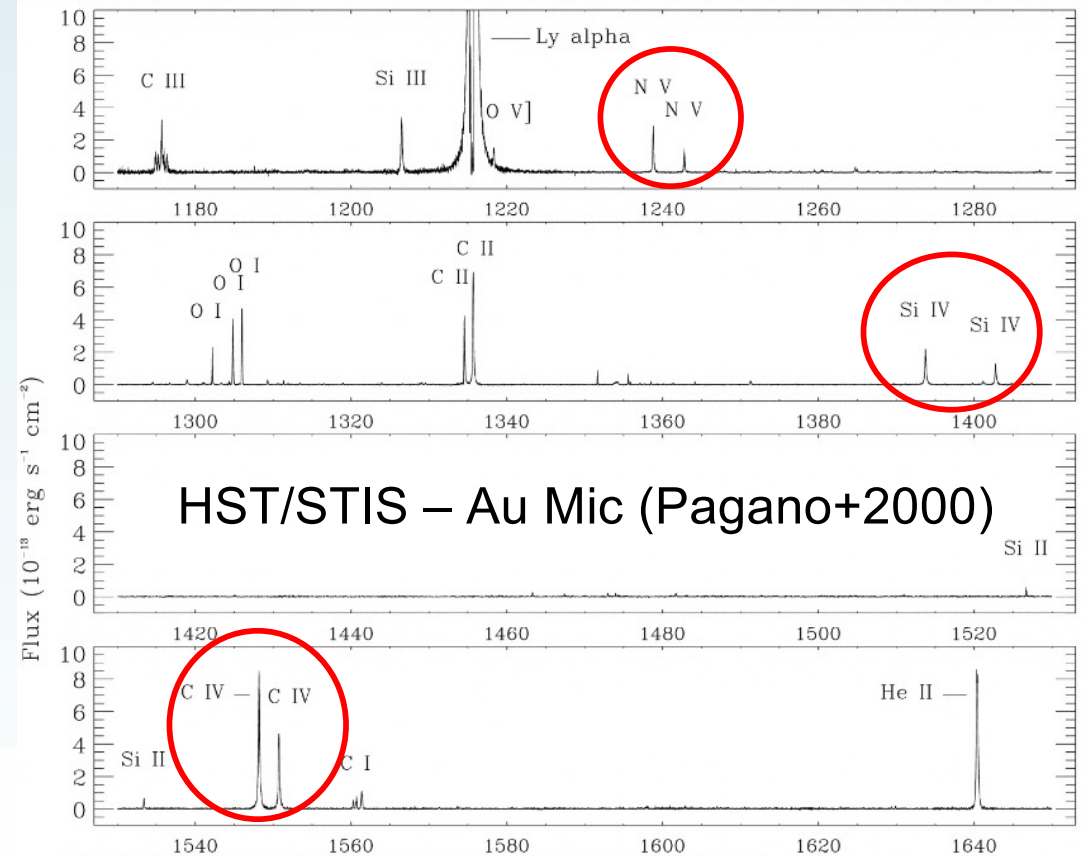
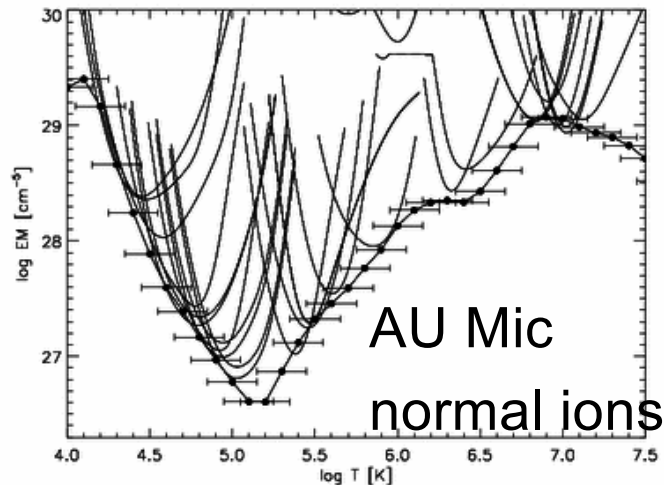
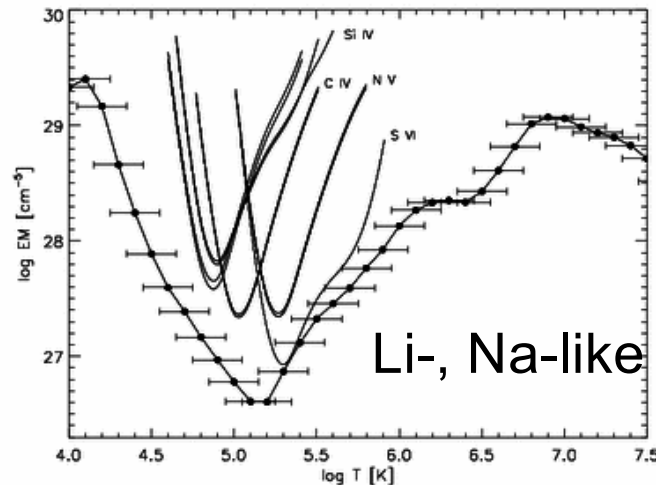


Anomalous ions in all UV stellar spectra

The strongest UV lines from Li- and Na-like ions are 2—5 times brighter than predicted; the EUV helium lines are stronger by ~15

On the Sun, the problem was known since the 1970's.

Del Zanna+(2002) was the first to show that **this is a general problem in all stellar UV spectra. Problem remain unsolved for 50 years.**

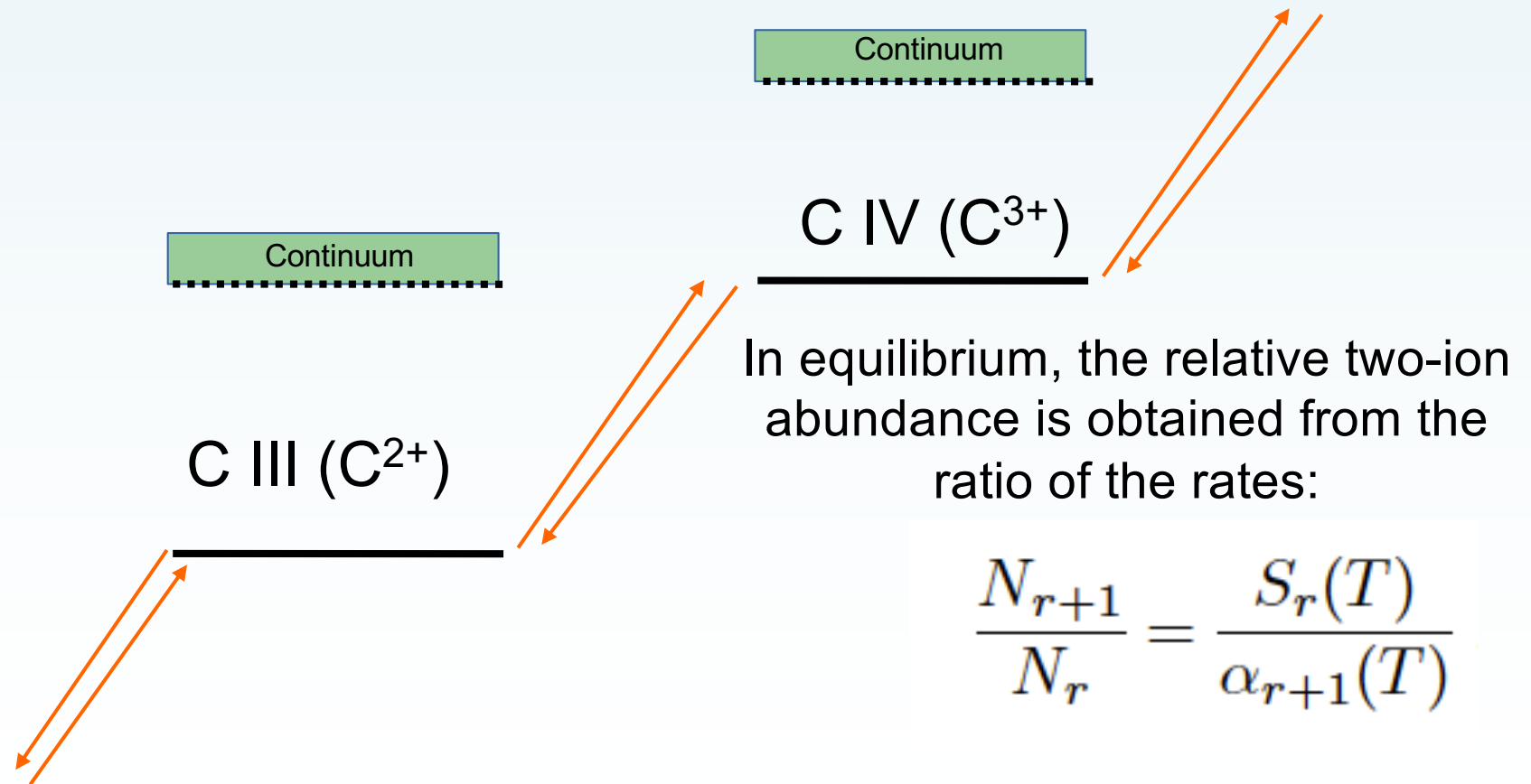


$$EMLoc_i = \frac{I_{obs}}{Ab(X) G_{ji}(T_e)}$$

`Zero' density approximation in astrophysics

Astrophysical codes assume that each ion is in the ground state and rates only depend on T_e

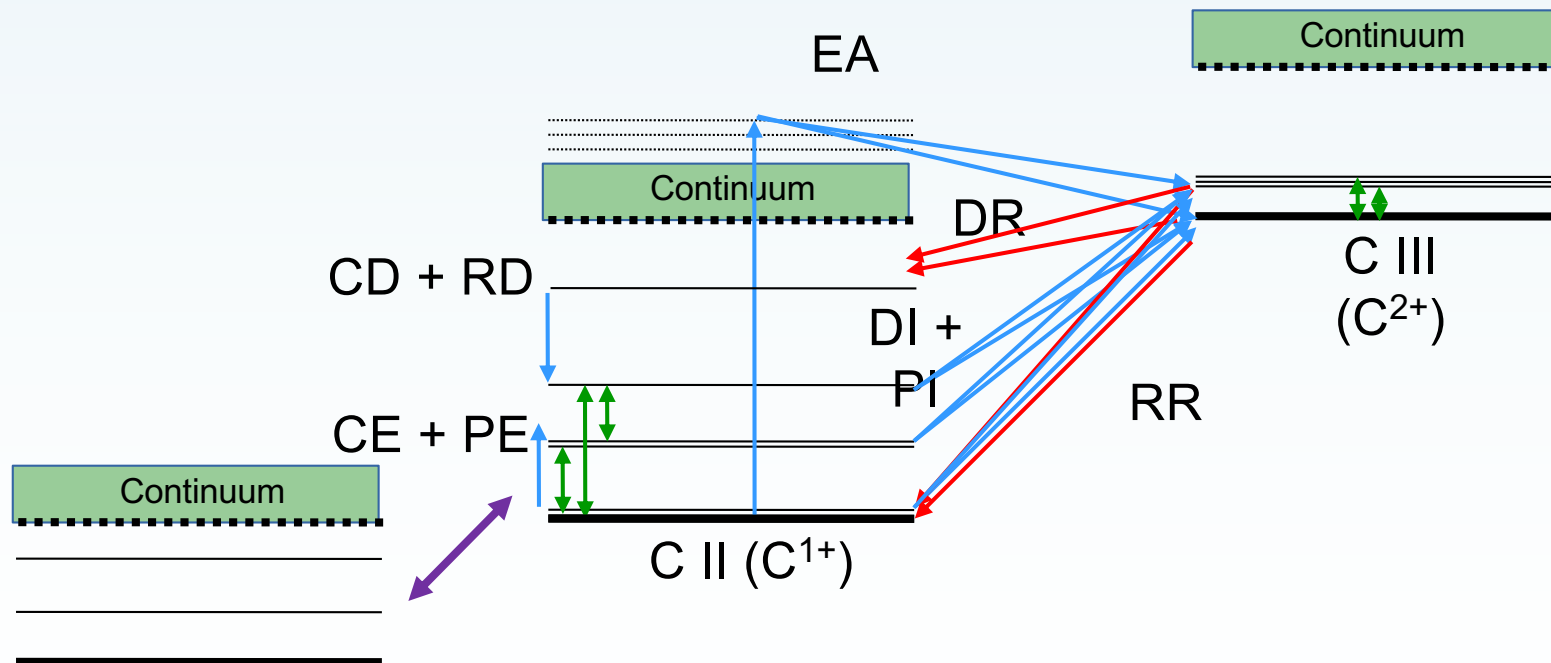
Usually called coronal approximation, but in reality it is a **zero density**



CRM models (Del Zanna)

I developed a new approach: collisional-radiative models, level-resolved matrix with all the main levels for all the ions. First CRM for coronal helium adapted to other elements.

- 1) suppression of DR, the main recombination (Burgess 1964+)
- 2) Collisional Ionization (CI) from metastable levels (cf Raymond, Storey 1976+)
- 3) Charge transfer (CT) Dufresne +
- 4) Photo-ionization / recombination Badnell, Storey (2019,2020,2021a,b).

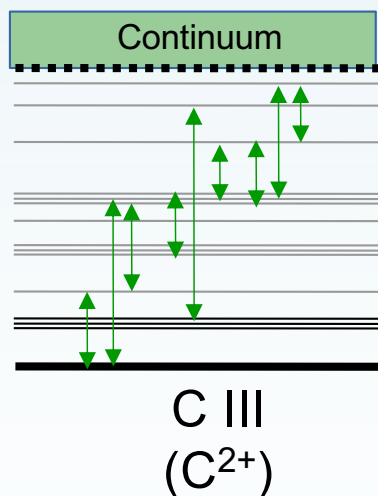
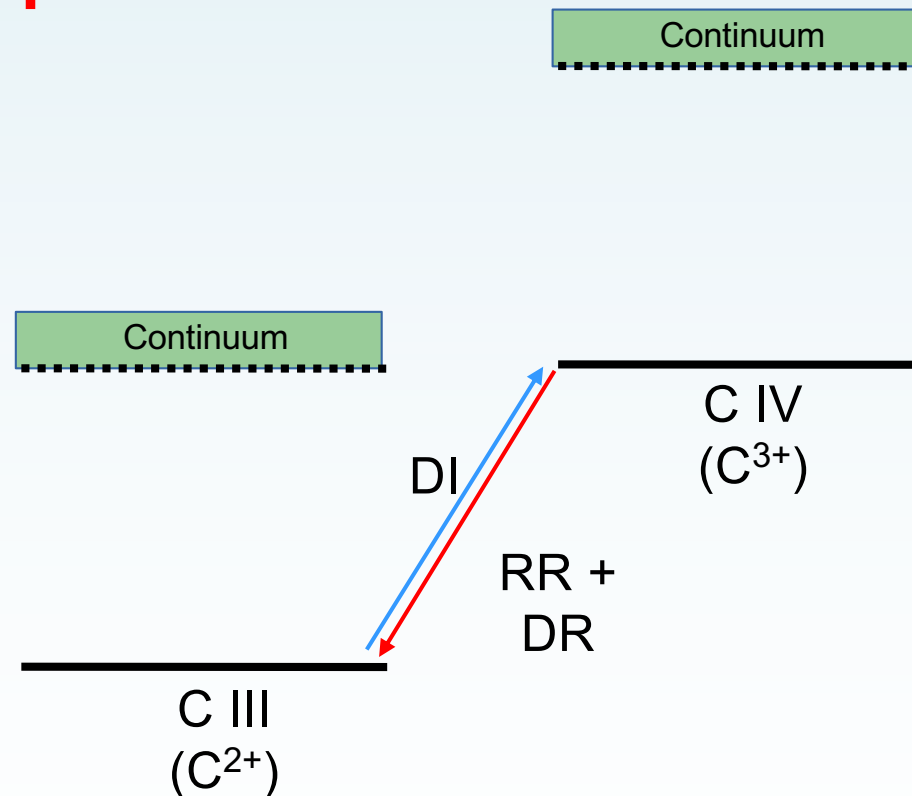


C I

DI – Direct Ionisation PI – Photo-ionisation EA – Excitation-Autoionisation
 RR/RD – Radiative Recombination/Decay DR – Dielectronic Recombination
 CE/CD – Collisional Excitation/De-excitation PE – Photo-excitation

Simplification for CHIANTI v.11

Solve level populations for each ion and calculate effective total ionization/recombination rates approximating the DR suppression



CHIANTI v.11:
Dufresne+ 2024, ApJ

$$R^{z+1} = R_1 n_1 + R_2 n_2 + R_3 n_3 + \dots$$

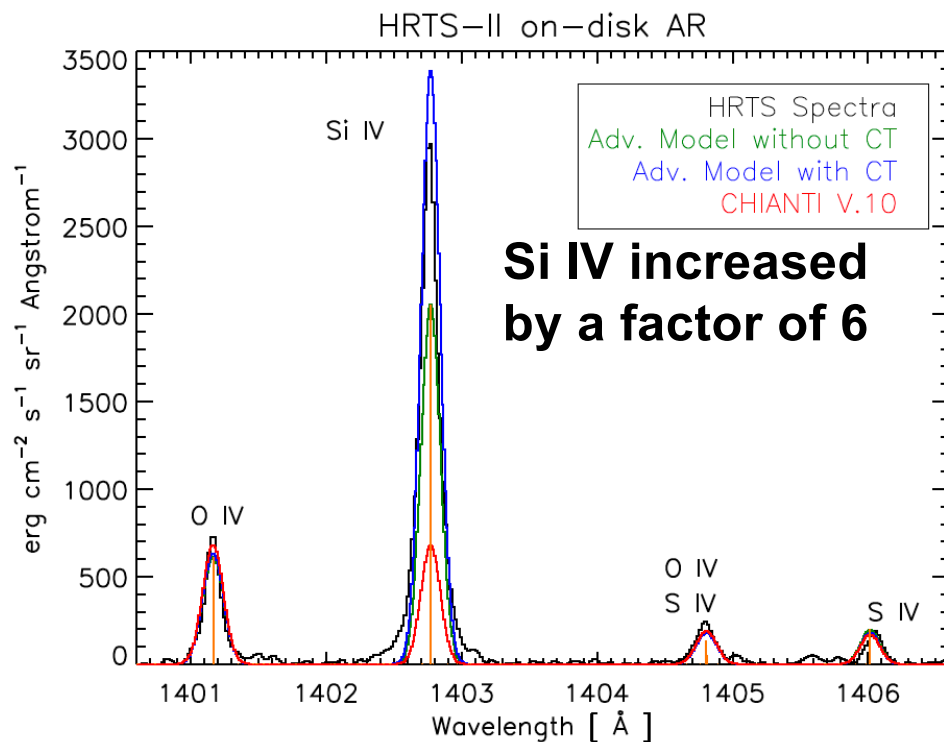
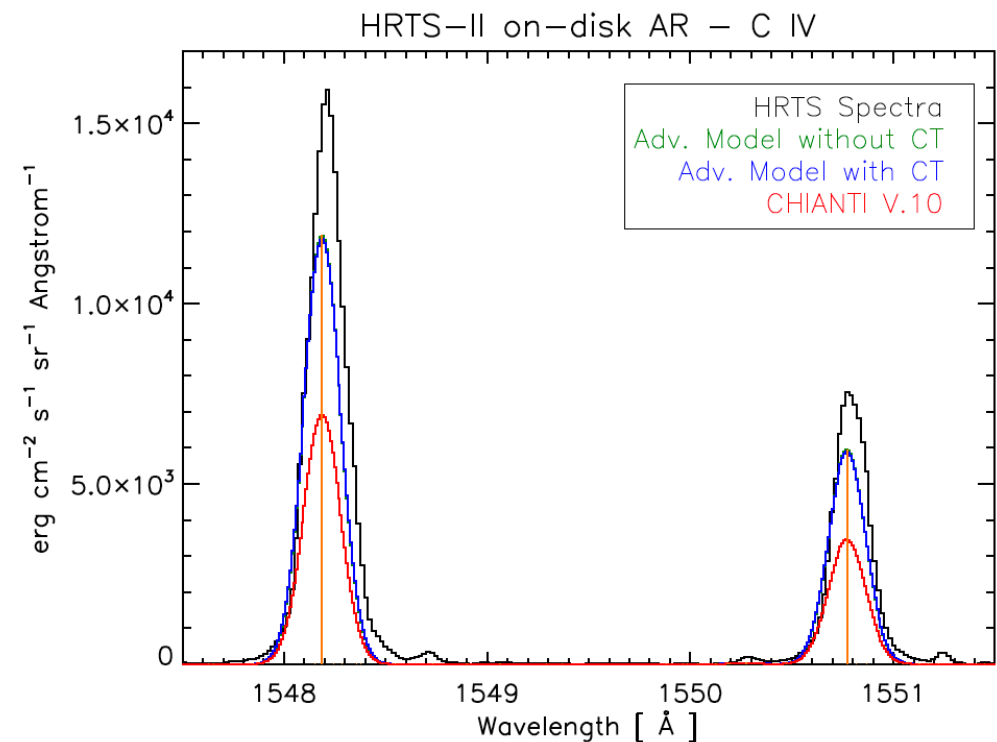
$$S^{z+1} = S_1 n_1 + S_2 n_2 + S_3 n_3 + \dots$$

$$\frac{dN^z}{dt} = R^{z+1} N^{z+1} - S^z N^z = 0$$

AR plage – UV – large increases in Si IV, C IV

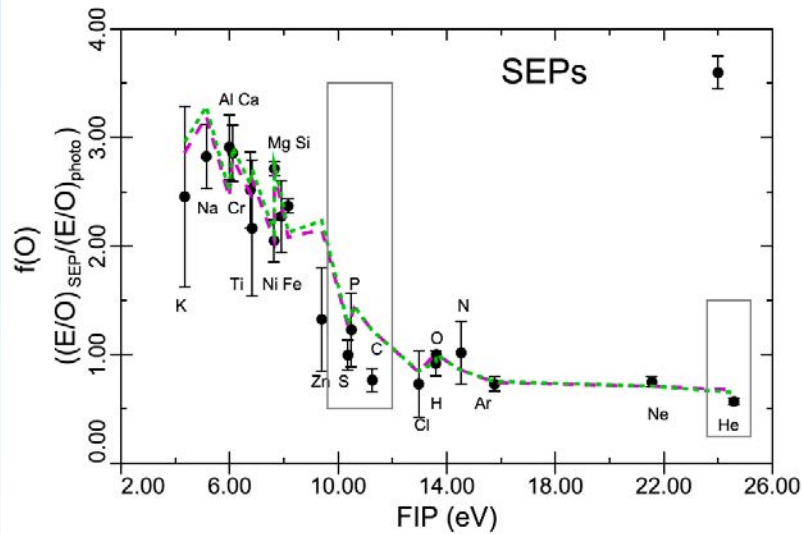
Surprisingly, at the high densities of the plage, we find agreement within 30% between observed and predicted radiances for all anomalous lines with simple – unphysical – static plane-parallel atmosphere modelling.

More physics is needed but this is a big effect.



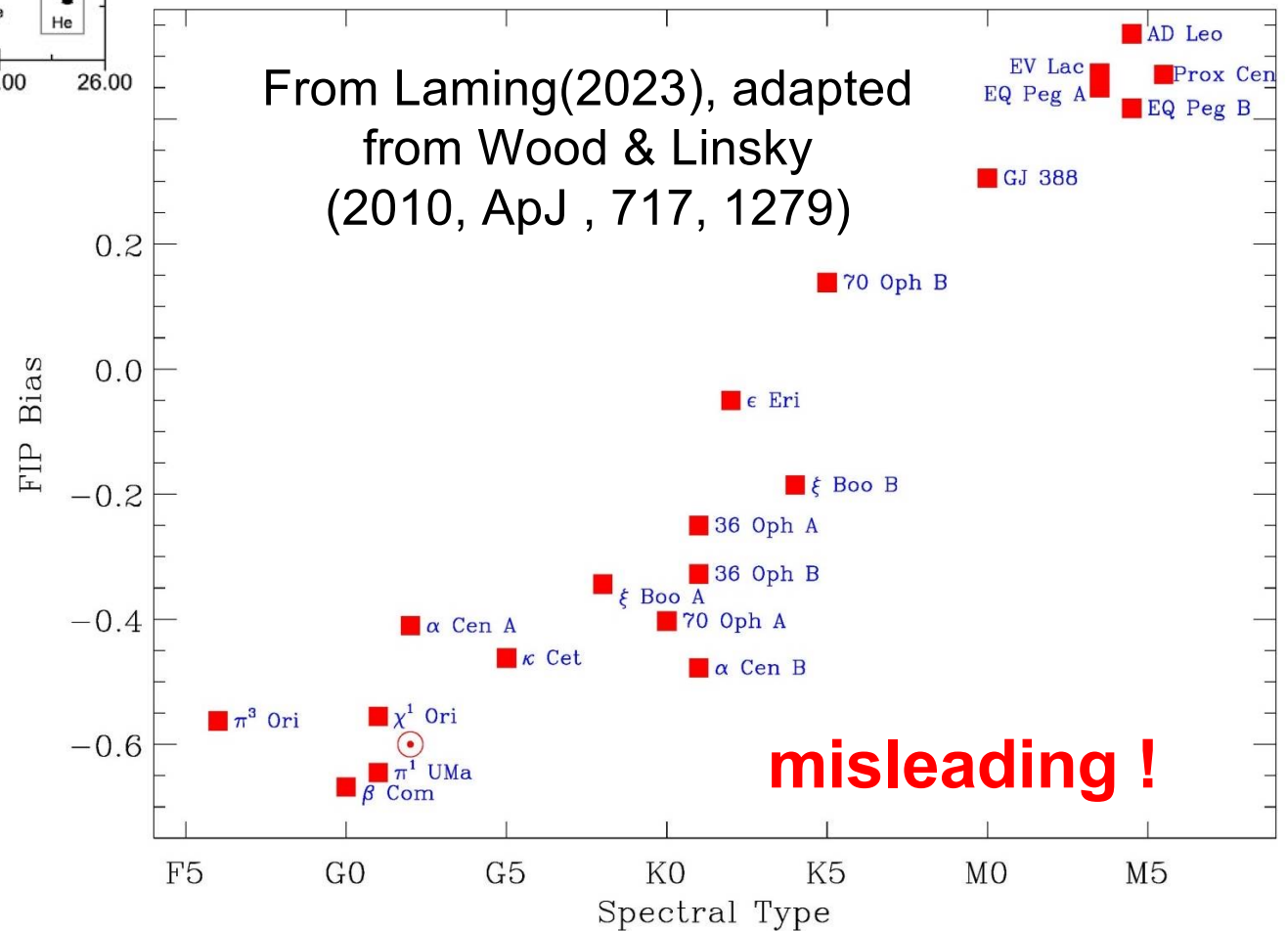
Plage region from the HRTS II flight. We found photospheric abundances (Asplund+2009), which is contrary to expectation based on FIB bias !

FIP / inverse FIP in stars

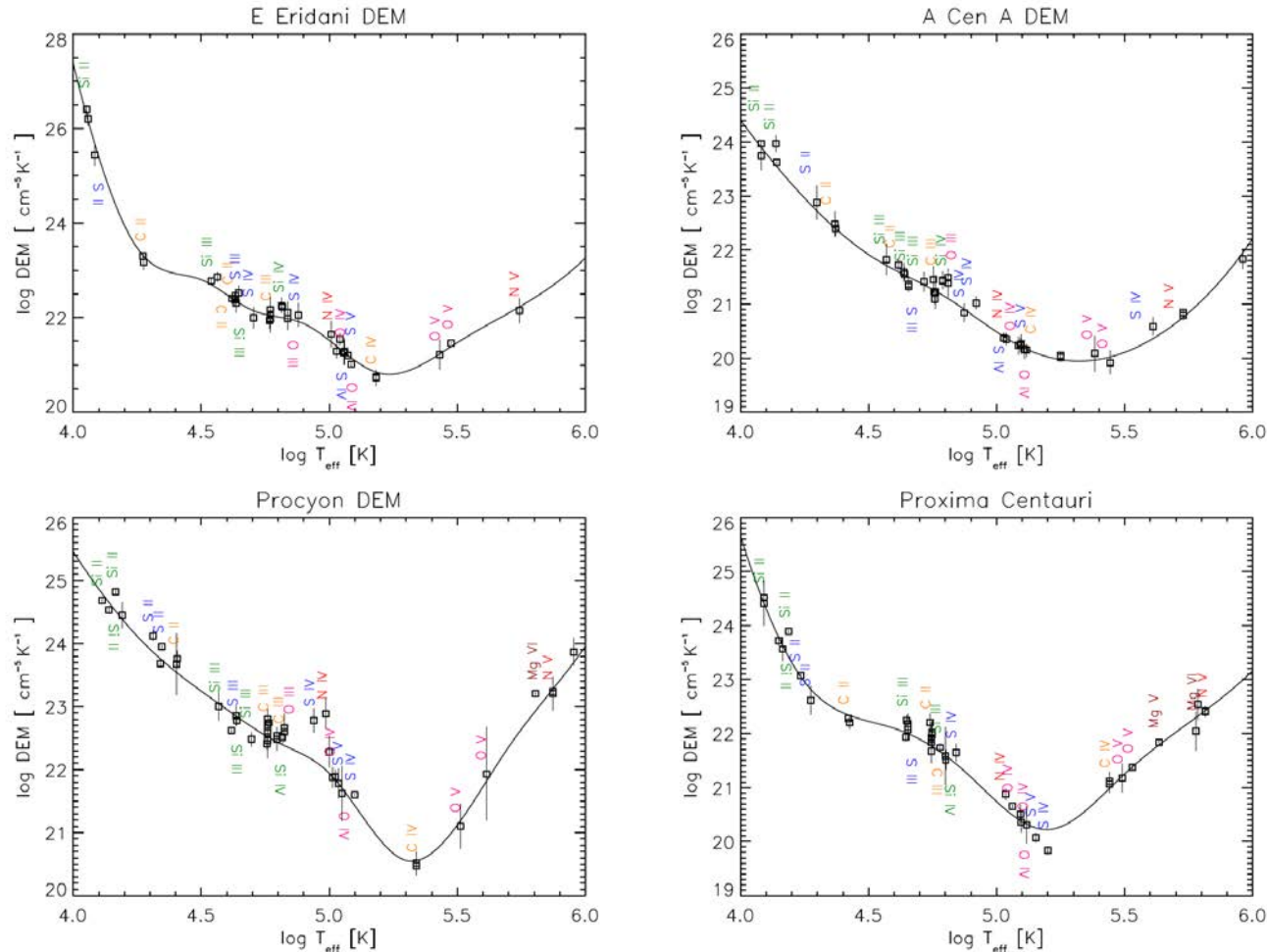


Solar Energetic Particles
(Reames 2018)

See Living Review (Del Zanna & Mason 2018)



NO FIP bias in stellar TR



The CHIANTI V.11 has allowed us to attempt the first measurements of relative abundances in the transition regions with a DEM approach.

We took HST/STIS observations of a sample of stars, compared the abundances with up-to-date photospheric values, finding **no FIP bias (as in the Sun)**.

Deliporanidou and Del Zanna, 2024, MNRAS

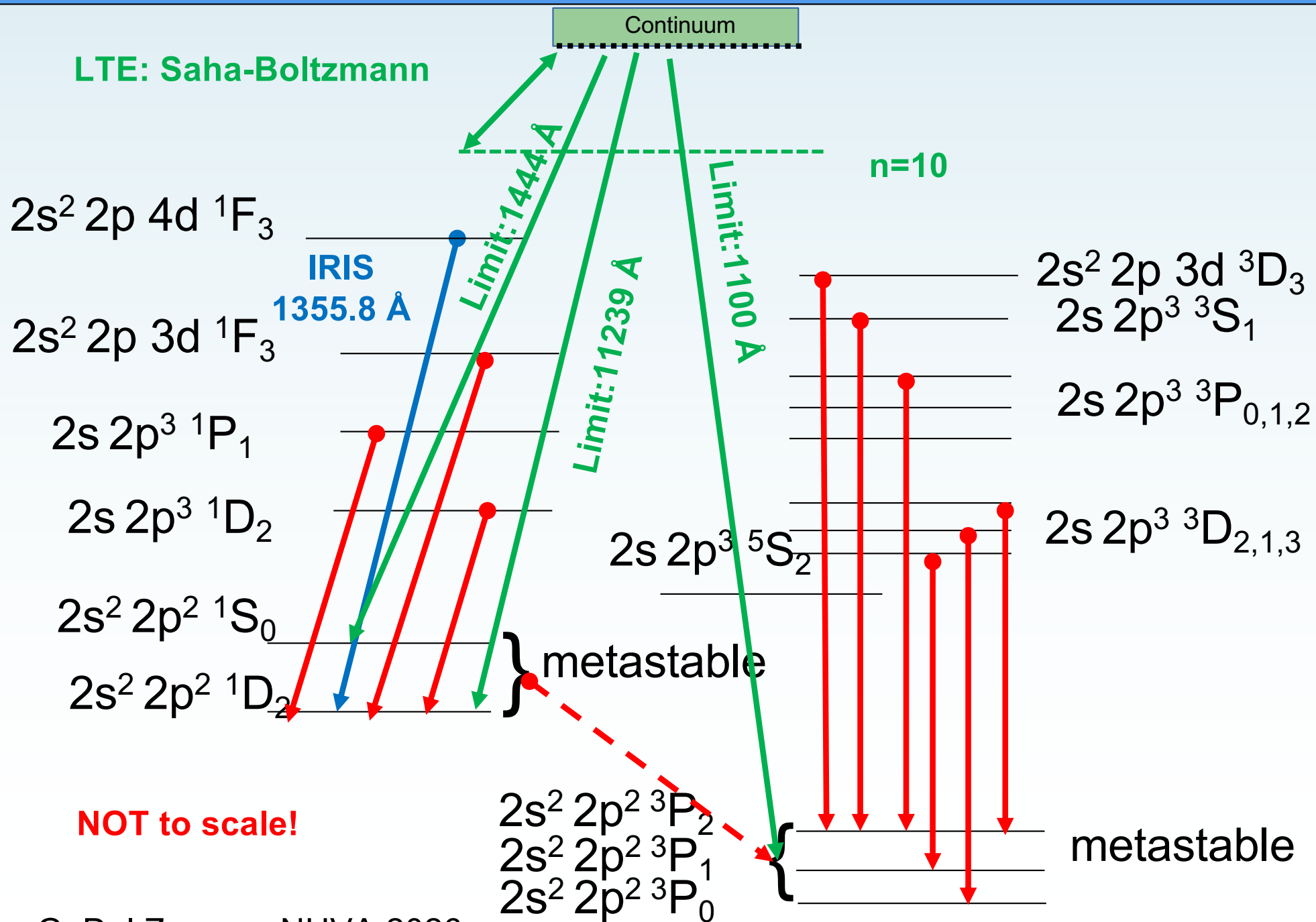
Emission lines from neutrals

In the UV there are thousands of emission lines from neutrals and singly-ionized atoms with missing atomic data and identifications. About 250 from just C I.

They offer unexplored diagnostics. Different series of lines form in the low or mid chromosphere, from the temperature minimum, probing a region not explored.

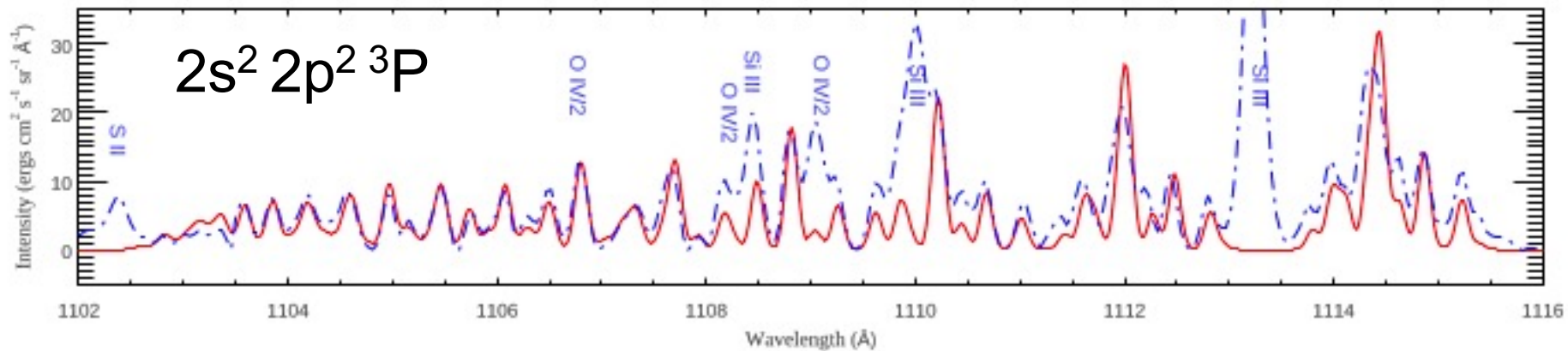
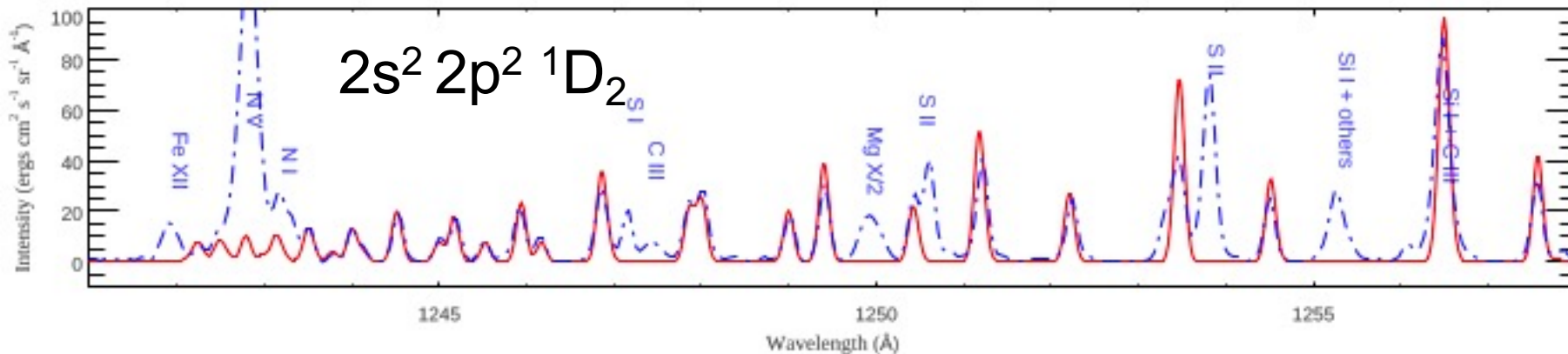
Lines from high n are in Saha-Boltzmann equilibrium with the continuum so are more simple to model. They are still affected by opacity (Dufresne, Del Zanna, Osborne, 2025, MNRAS).

Neutral C



C I

- Provided atomic data that were missing; found mistakes in NIST A-values
- Identified over 40 new UV lines not reported.
- Great Potential for diagnostics. Storey, Dufresne, Del Zanna MNRAS 2024



Blue: solar SOHO SUMER spectrum
Red: scaled theoretical C I spectra

UV continuum problems

The UV continuum with static 1D Radiative transfer (RT) has always been overestimated, requiring fudges (missing opacity).

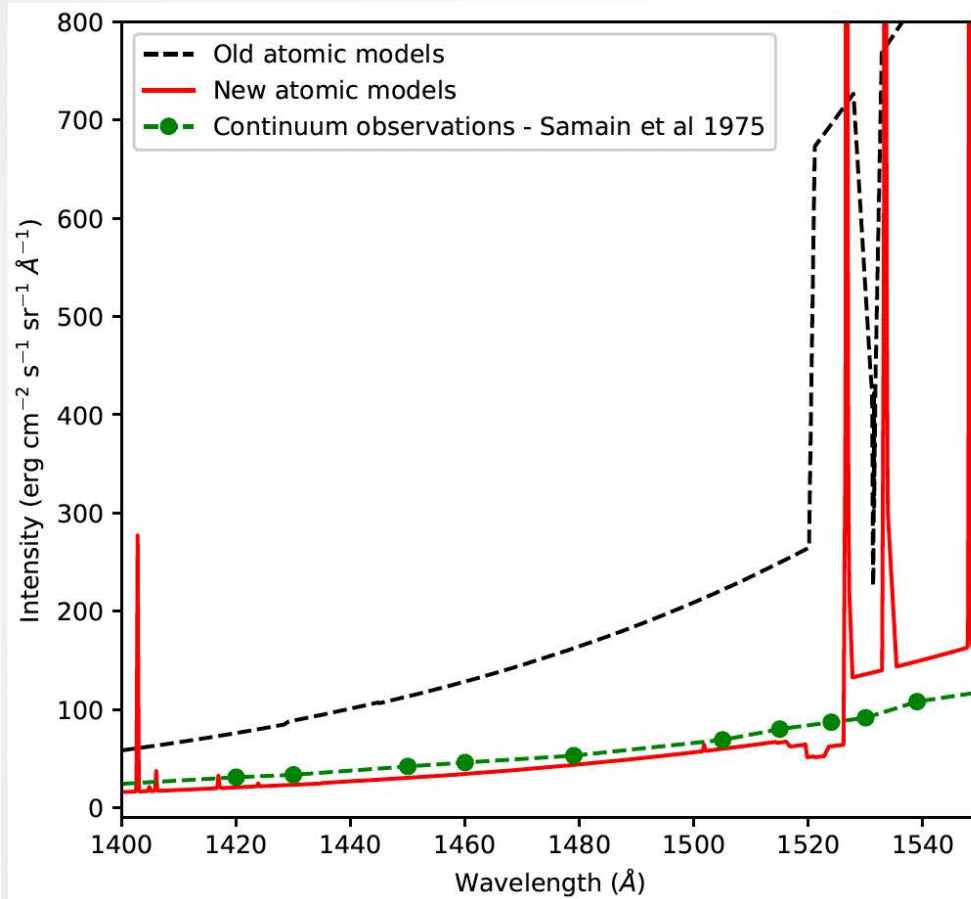
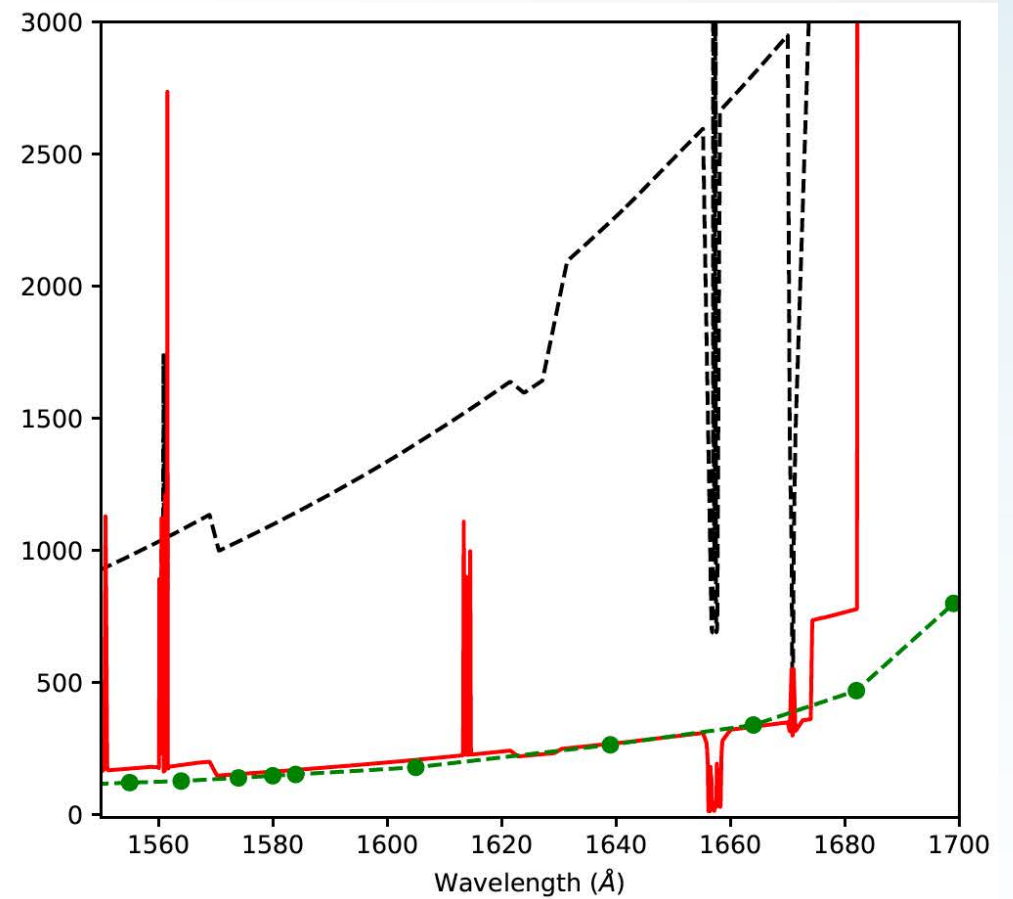
All the RT codes used in solar physics and astrophysics

- use very old atomic rates, often approximated.
- have very small atomic models, missing ionization/recombination
- model incorrectly the recombination.

We adopted updated atomic data from the UK APAP network, plus PI, CT rates we have calculated (cf. data on ZENODO).

We have run 1D RT calculations for the quiet Sun with the Lightweaver code (Osborne and Milic 2021).

UV continuum

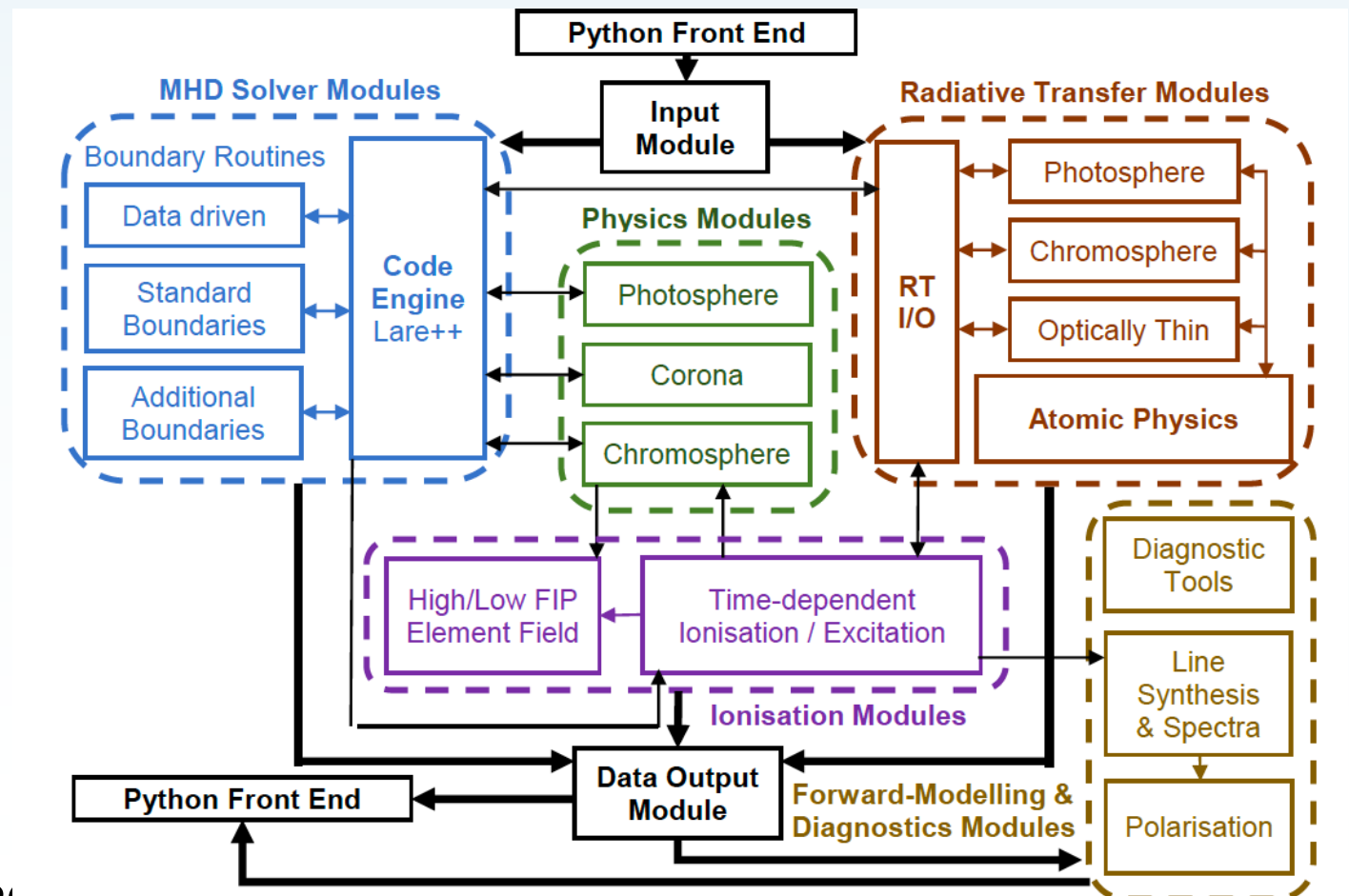


Improved by a factor of 10
Dufresne, Del Zanna, Osborne (2025)

More physics

Obtained a large grant award from STFC (UK) for the Solar Atmospheric Modelling Suite (SAMS), a collaboration of UK researchers with funding for 5 years to tackle the chromosphere. **We welcome contributions.**

- Calculate plasma dynamics, photon and atomic processes self-consistently with 3-D RT, MHD.
- Open source, modular. Exascale computing. **General use for stellar atmospheres.**



Laboratory astrophysics – any future?

Astronomers use codes as black boxes – The providers of theoretical and laboratory studies have nearly disappeared. We have entered the dark ages in atomic physics (Gary Ferland, CLOUDY photo-ionization code).



Example: the CHIANTI database received a NASA award, but most of the data were produced by the UK-funded APAP network www.apap-network.org, also used by all plasma codes for astrophysics.

National Aeronautics and Space Administration

Presents the

Group Achievement Award

to

CHIANTI Consortium

For outstanding contributions to the scientific productivity of NASA missions and the creation of a uniquely valuable tool for spectroscopic scientists worldwide.

Giulio Del Zanna



Signed and Sealed at Washington, DC
March Two Thousand Twenty Four

Bill Nelson
Administrator, NASA

The network is now closed after Nigel Badnell passed away.
I made available on ZENODO updated e-ion cross-sections (20+years)

Atomic databases are not sustainable, not coordinated, they rely on few efforts.
Knowledge in atomic physics has disappeared in most countries.

The future of astrophysical spectroscopy depends on sustained support for theory and experiment and training of young researchers.

If anyone is able to help out do get in contact with me soon, before I retire.