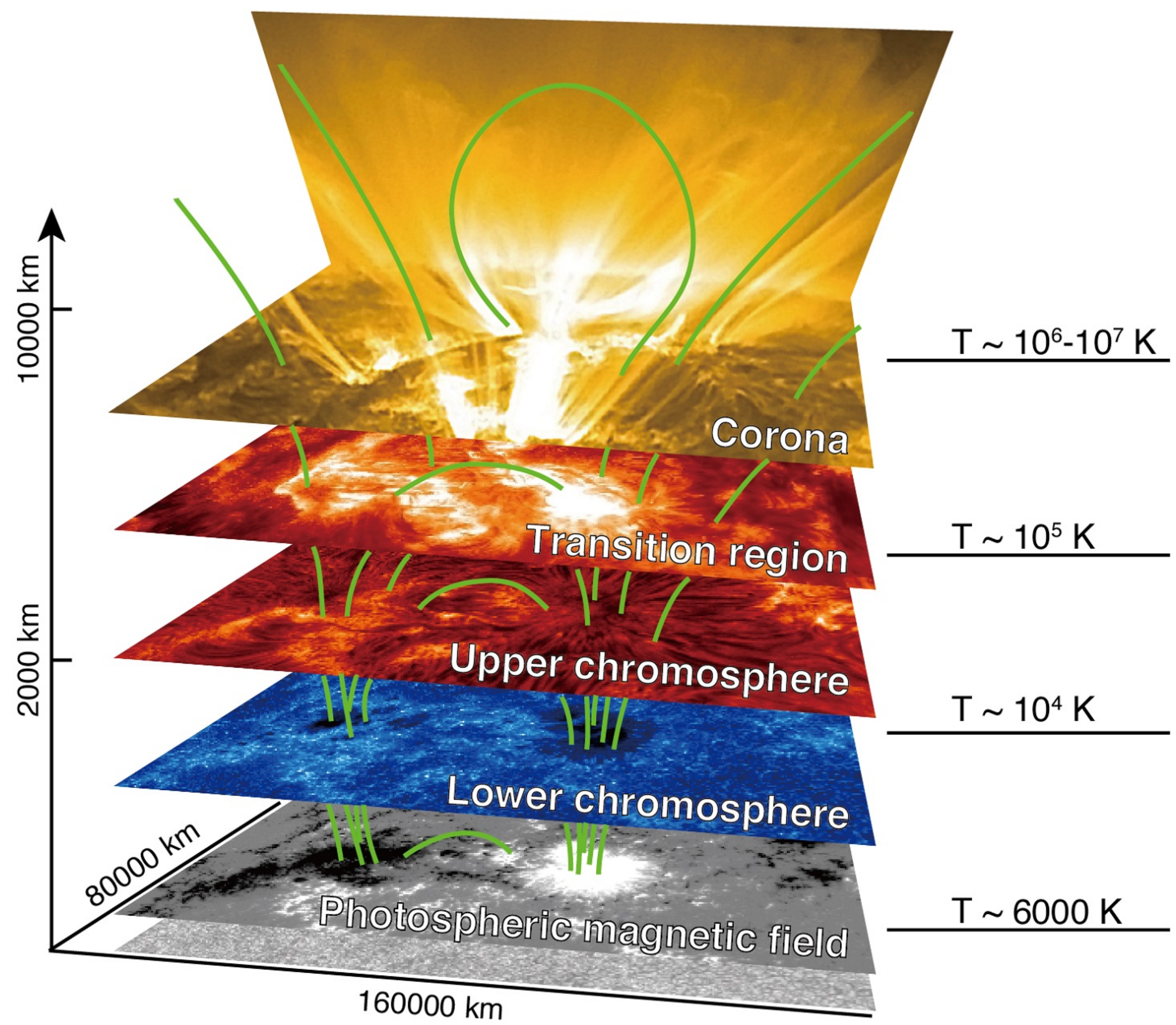
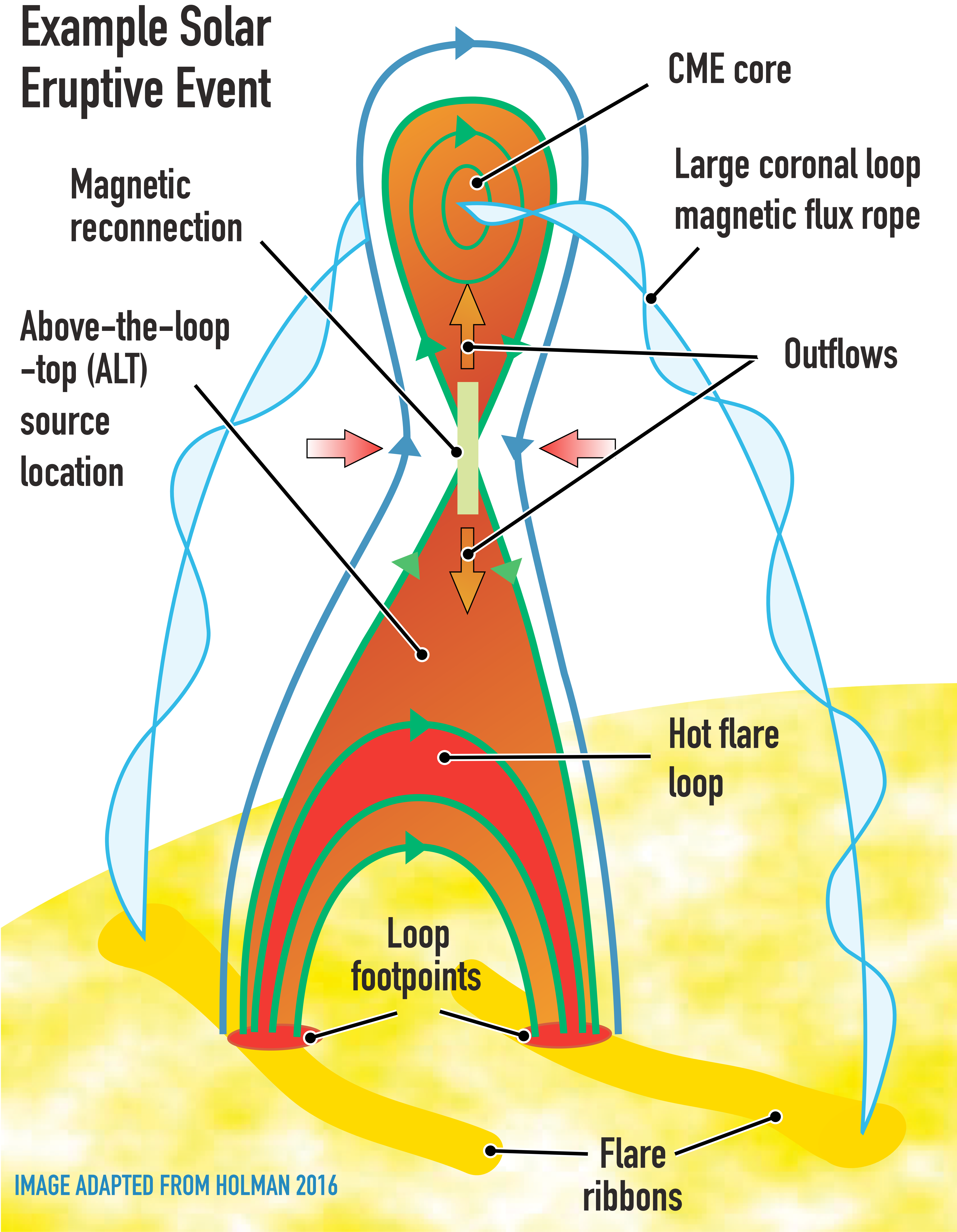
GRAHAM KERR NASA/GSFC & CUA (HE/HIM/HIS)

PROSPECTS OF DETECTING NON-THERMAL PROTONS DURING SOLAR FLARES WITH SPICE: LYMAN LINE SPECTROSCOPY AND THE OZ EFFECT

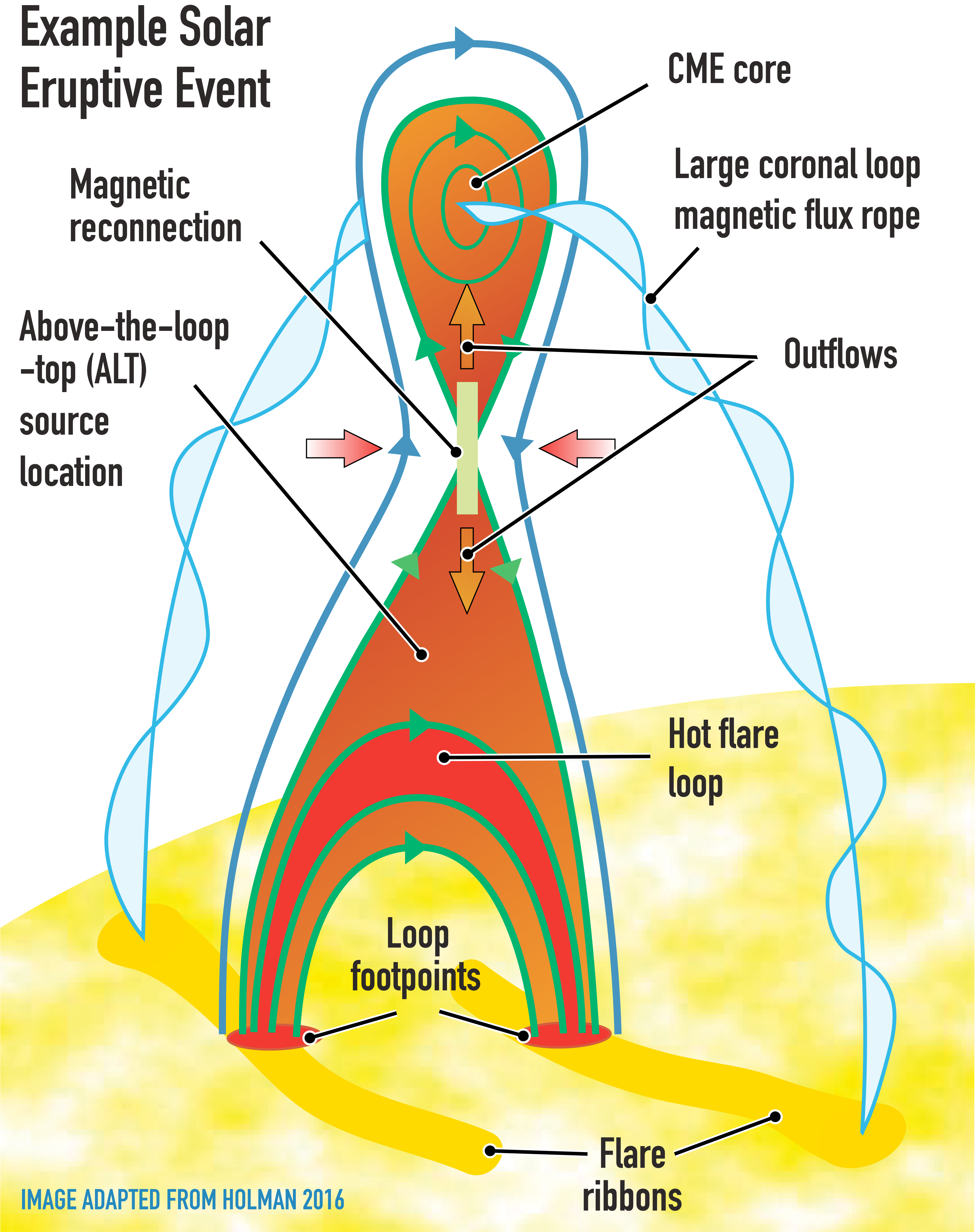
SOLAR FLARES

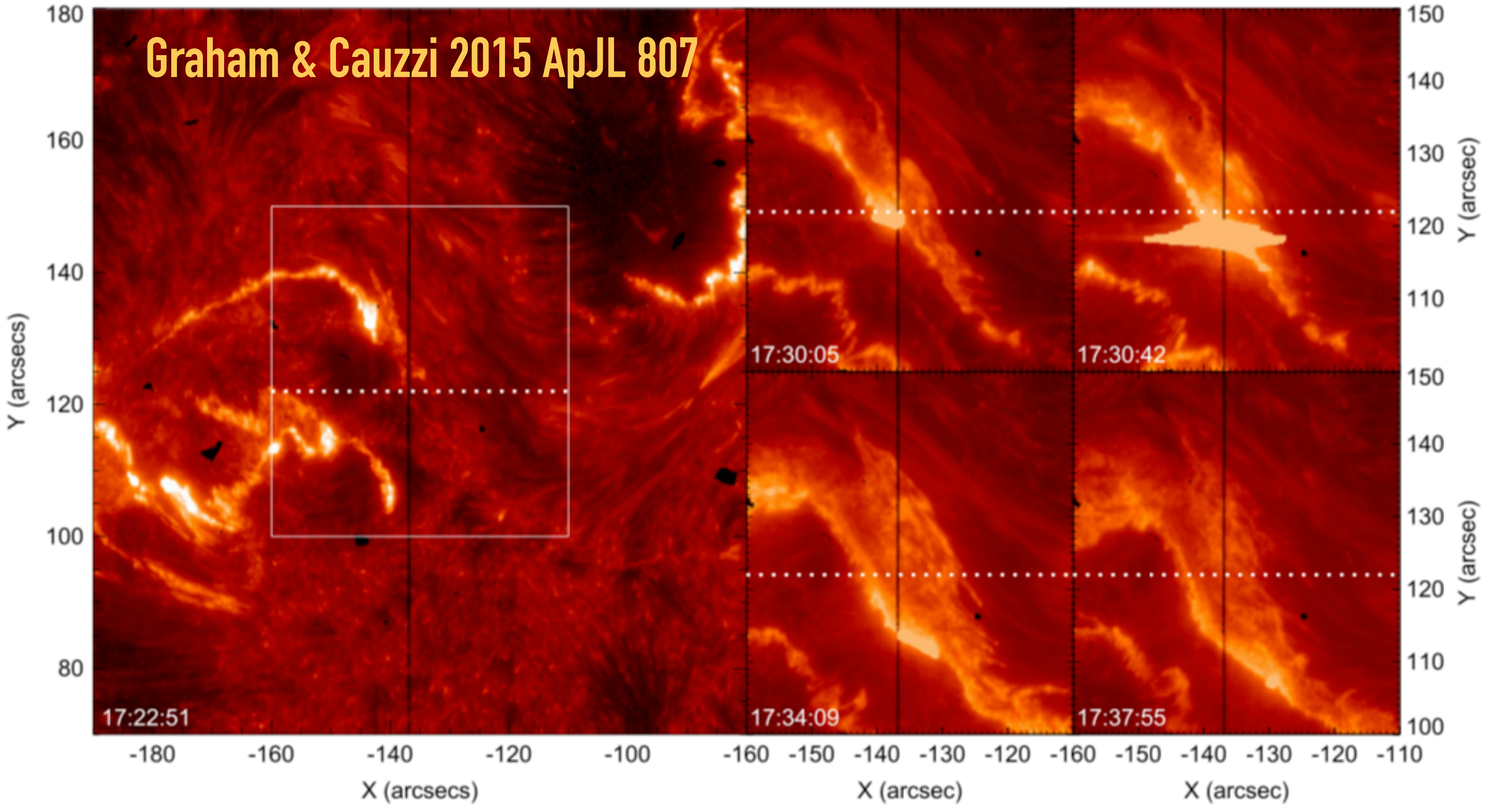


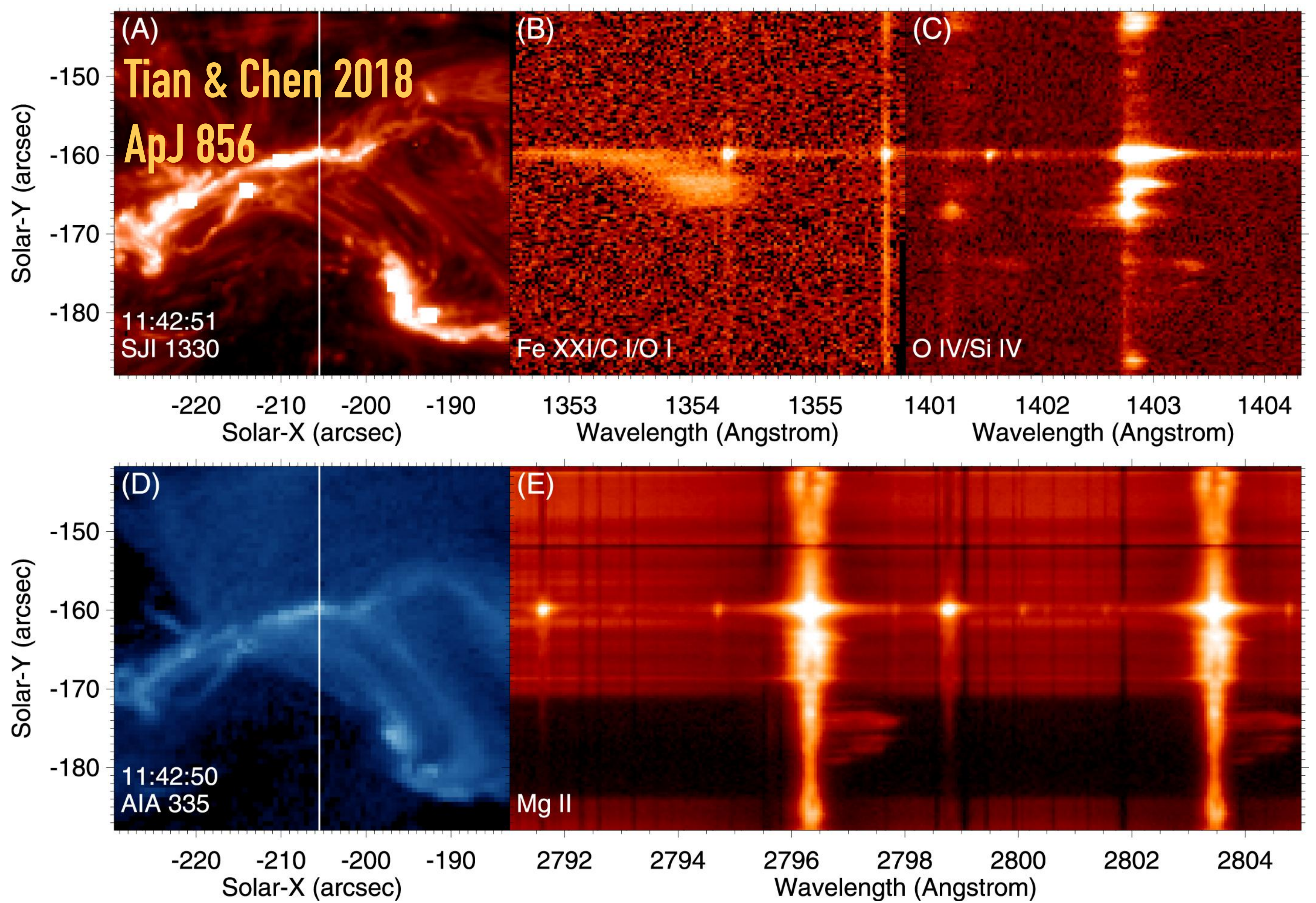


X1.6 CLASS FLARE 10TH SEPT 2014

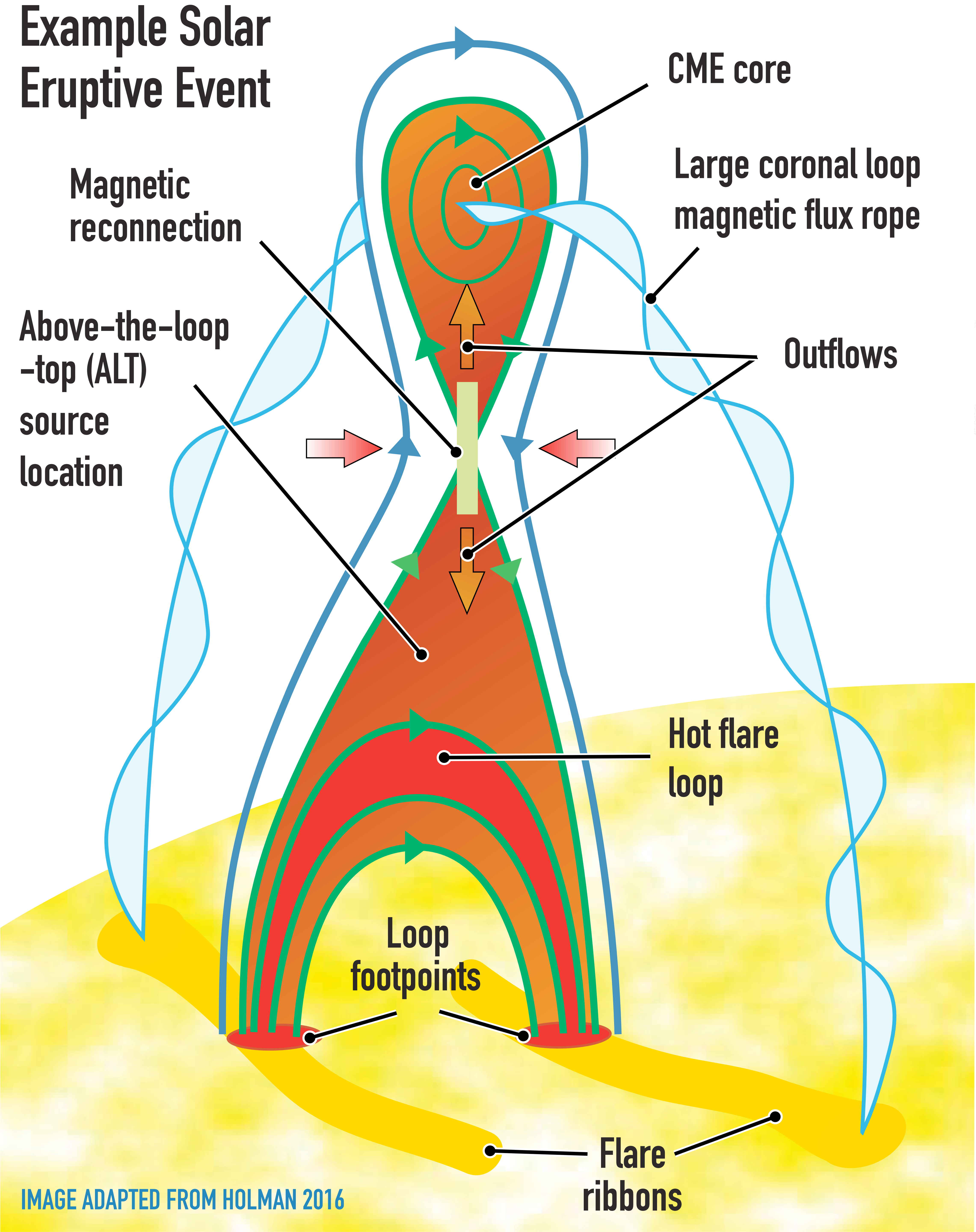
SOLAR FLARES

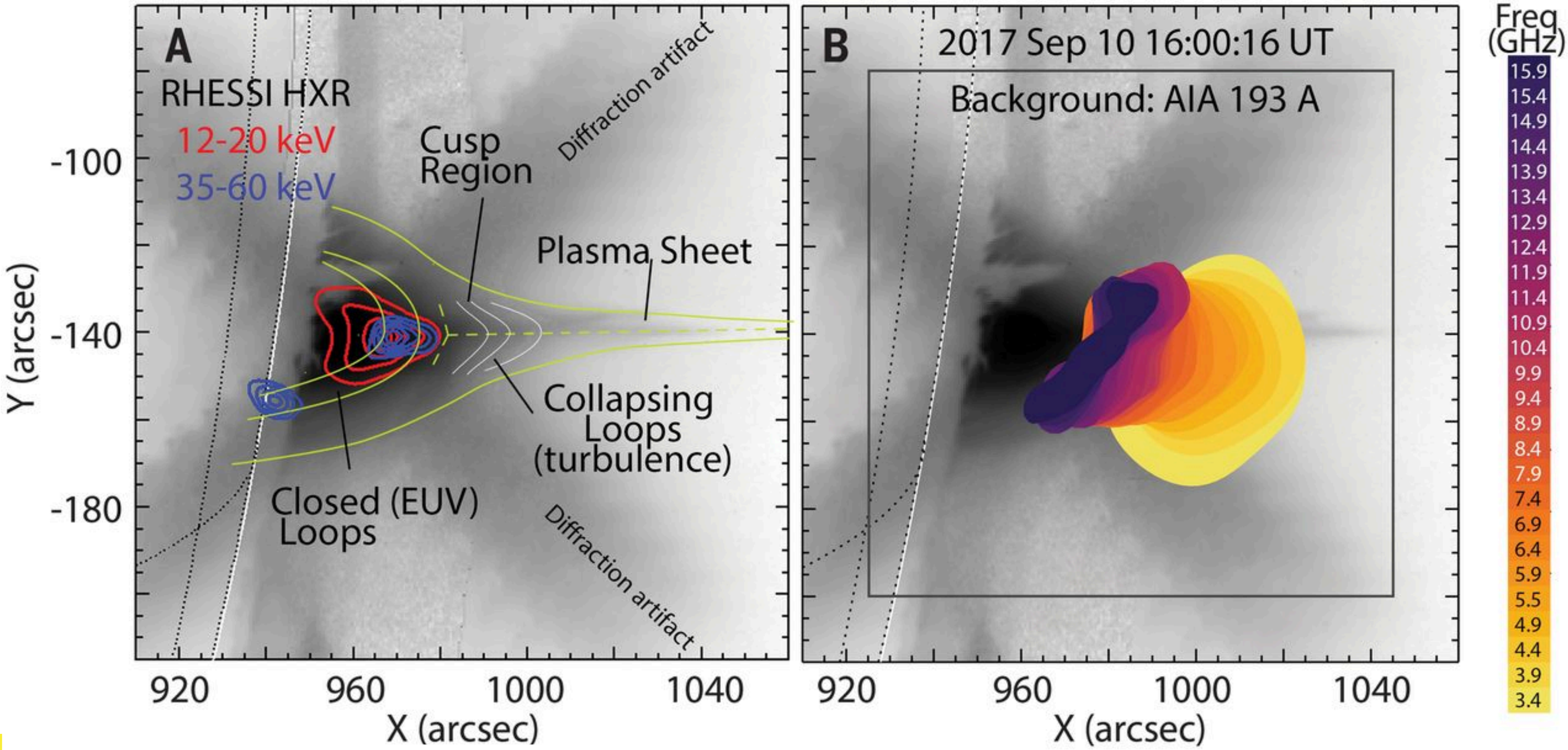


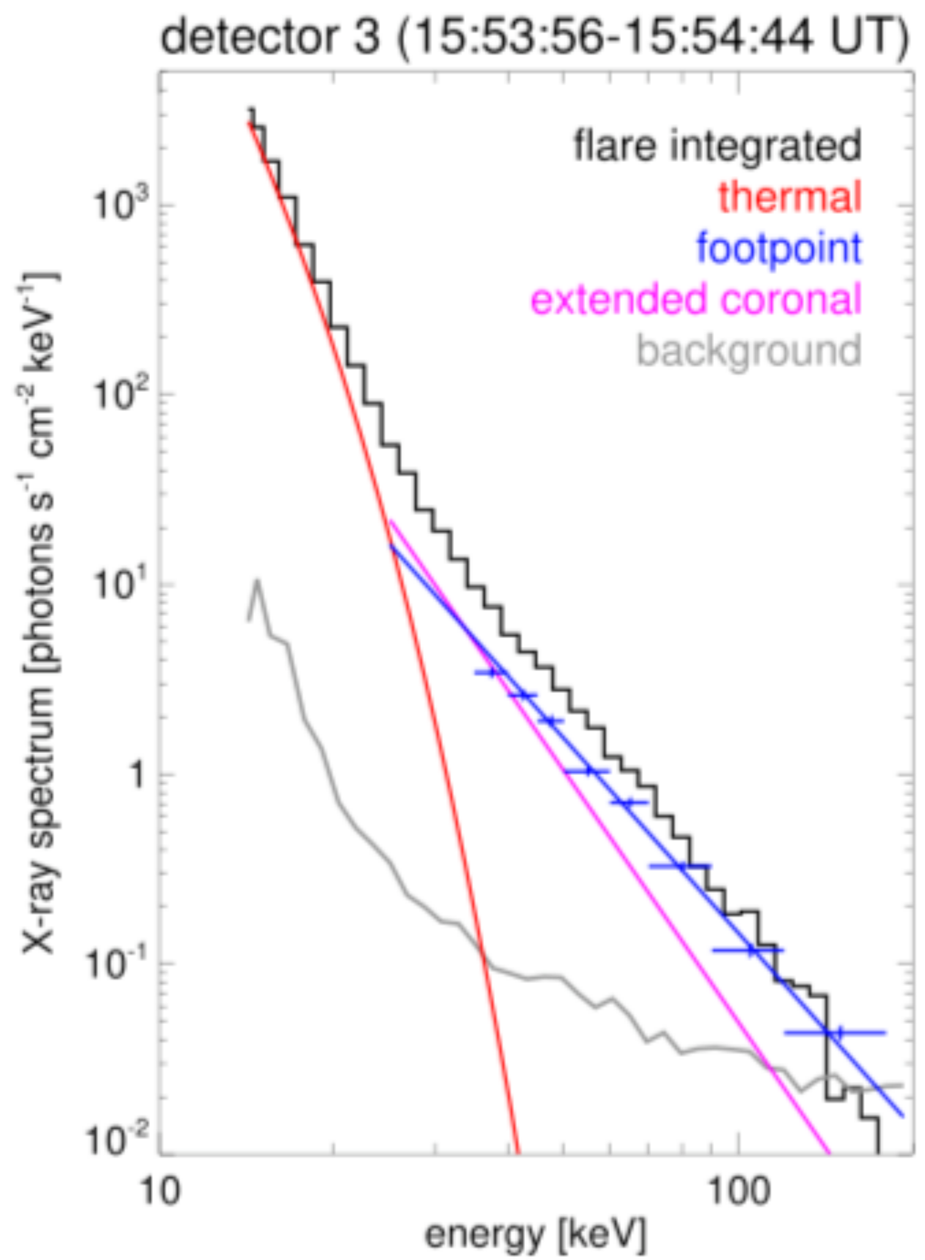


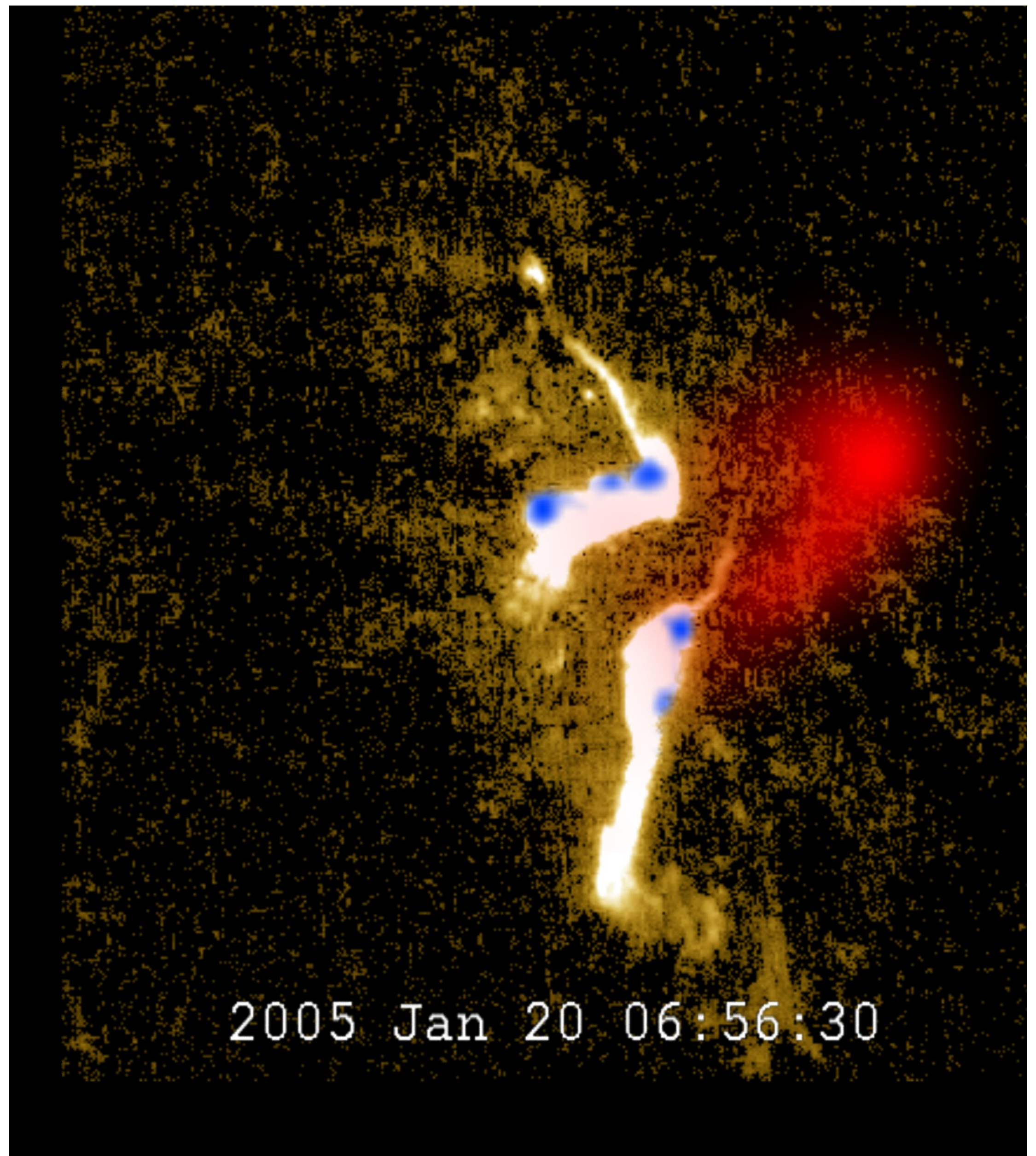


SOLAR FLARES









X-ray obs can be used to derive non-thermal electron distributions (which are then used to drive flare models).

Example Solar Eruptive Event

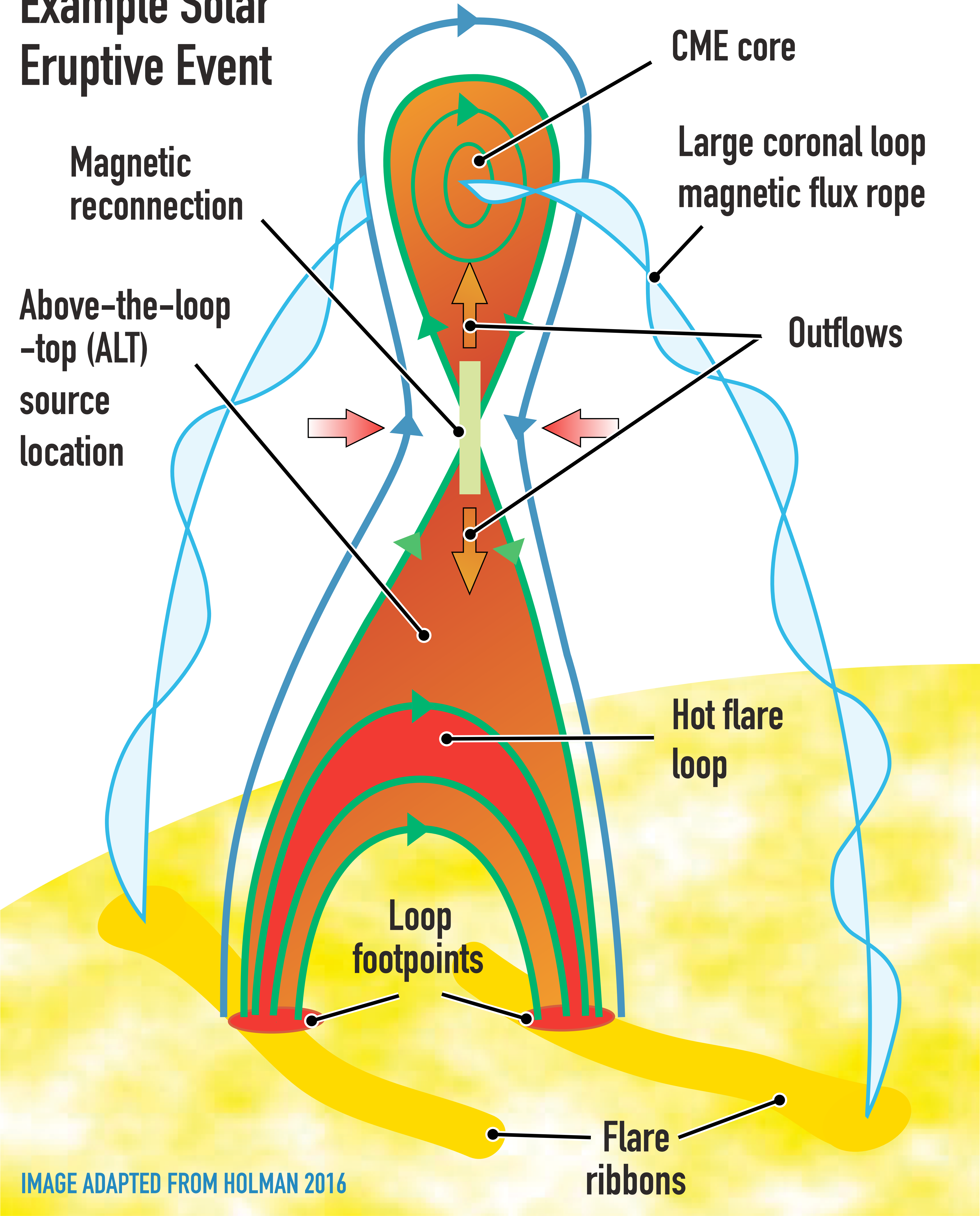
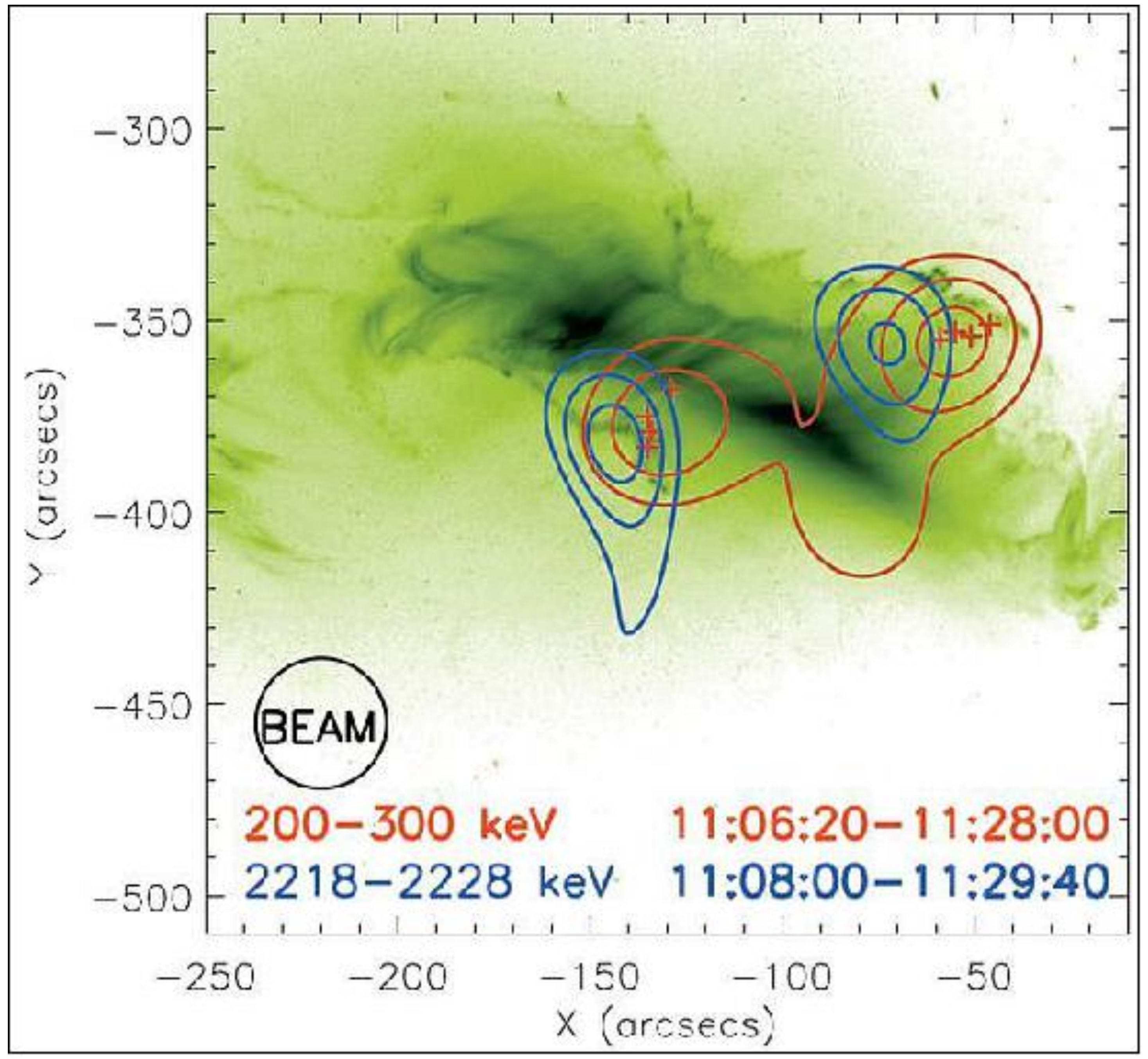


IMAGE ADAPTED FROM HOLMAN 2016

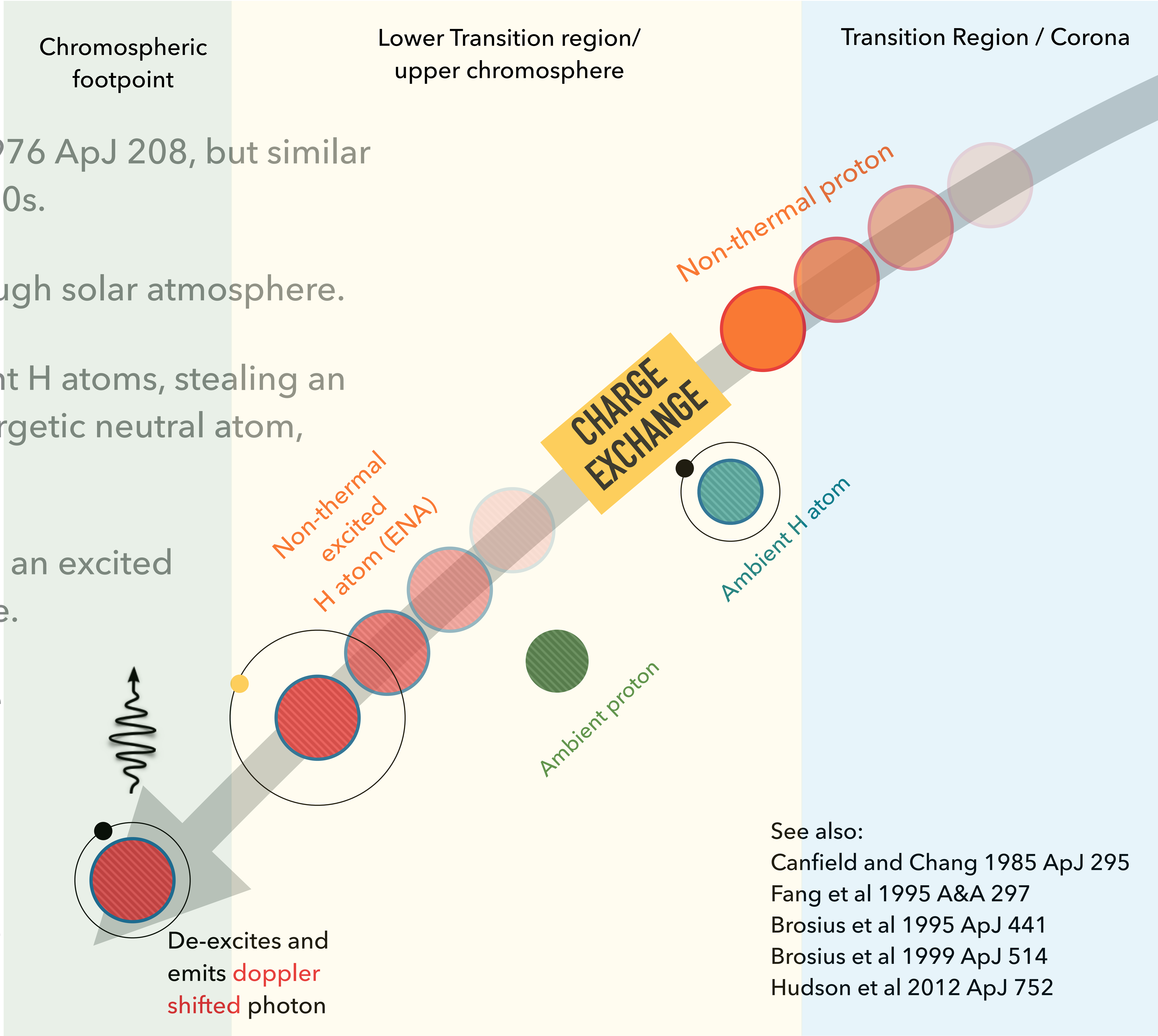
SOLAR FLARES

- Very likely that protons are accelerated in flares in addition to electrons.
- They may even carry a substantial fraction of the energy released in a flare (potentially equal to that of electrons!) and can penetrate deeper.
- However they are generally ignored in flare models, partly due to very poor constraints of their energy distribution, particularly at low energy.
- There is a danger that we are missing up to half of the flare energy transported to the lower atmosphere!



ORRALL-ZIRKER EFFECT

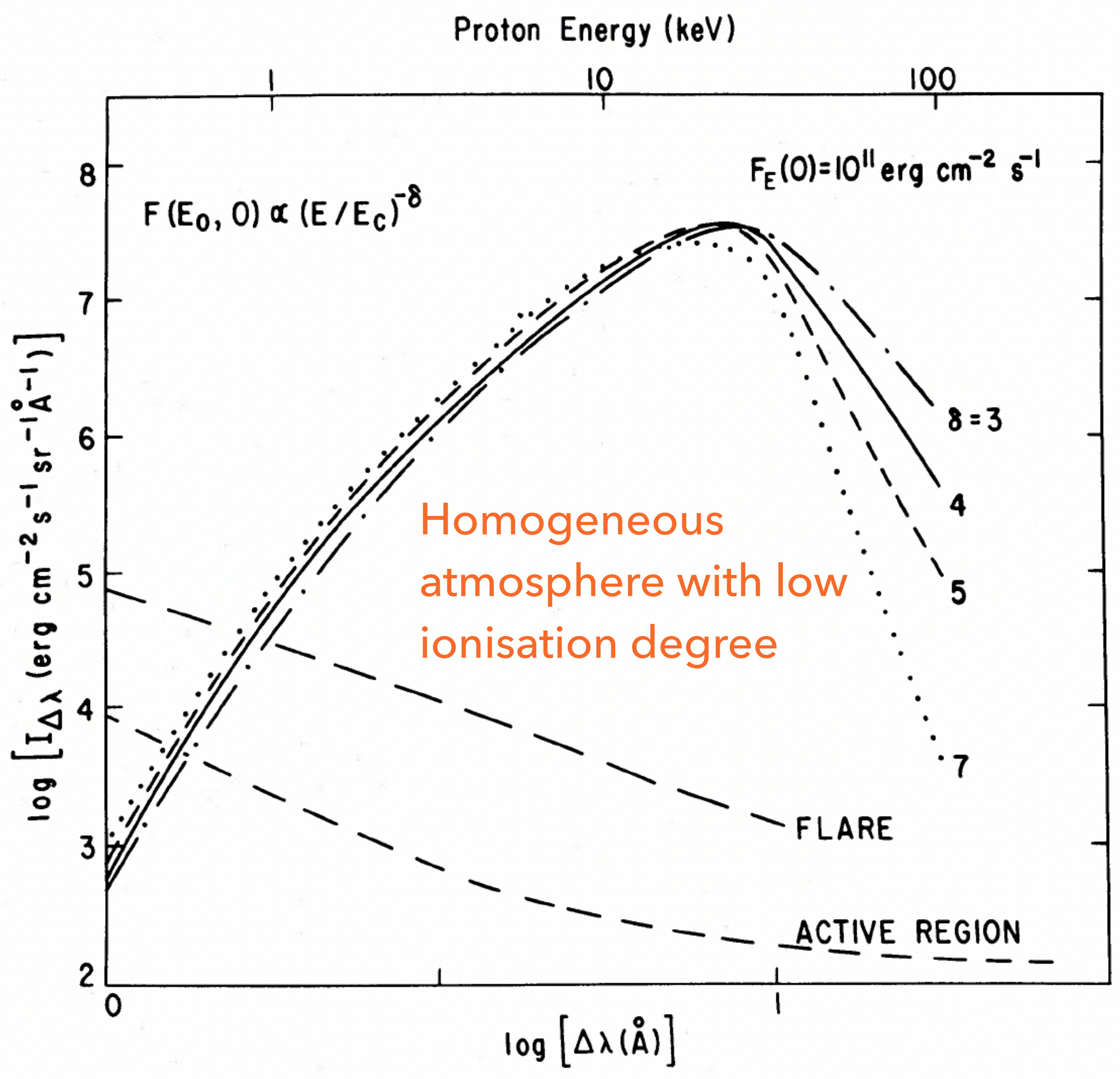
- First proposed for flare science by Orral & Zirker 1976 ApJ 208, but similar process observed in proton aurora in Hα in the 1930s.
- Flare accelerated non-thermal protons stream through solar atmosphere.
- Via charge exchange, they can interact with ambient H atoms, stealing an electron. This produces a non-thermal H atom (energetic neutral atom, ENA), leaving behind an ambient proton.
- The ENA either undergo charge exchange direct to an excited state, or can undergo a collisions to an excited state.
- The excited non-thermal H atom will then de-excite spontaneously, emitting a photon.
- Since the atom is suprathermal, this photon is very red-shifted, and may be detected in the red wings of H Ly α, H Ly β, or He II 304 (in the case of α-particle contribution to the ion beam).



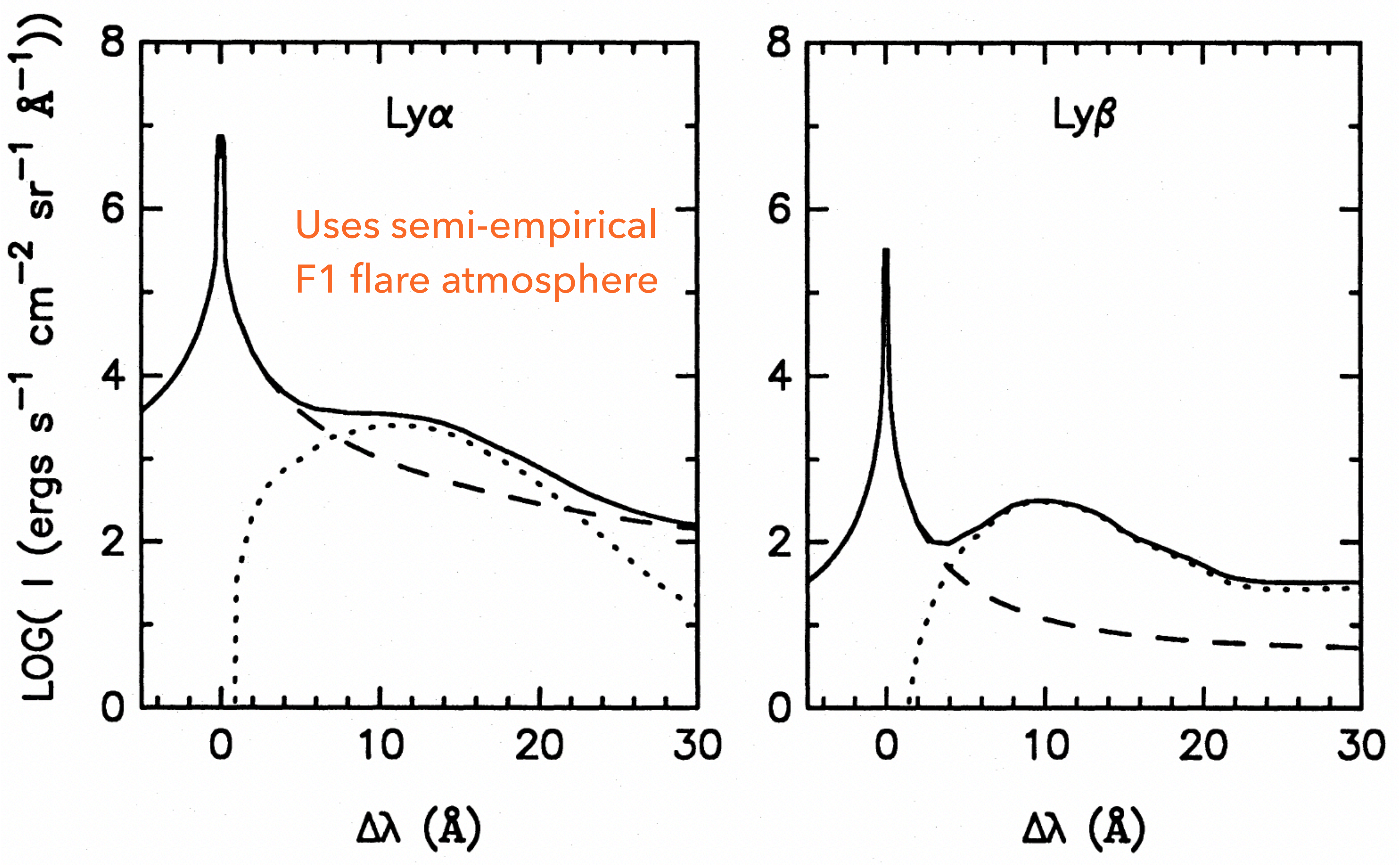
See also:
Canfield and Chang 1985 ApJ 295
Fang et al 1995 A&A 297
Brosius et al 1995 ApJ 441
Brosius et al 1999 ApJ 514
Hudson et al 2012 ApJ 752

ORRALL-ZIRKER EFFECT OVERVIEW

- Theoretical results suggested that non-thermal Ly α and Ly β emission would be detectable. These earlier works used semi-empirical flare atmospheres to predict ‘regular’ Lyman flare emission.
- Varying initial parameters of the proton distribution resulted in noticeable differences in shape of non-thermal Lyman line features.
- Different cross-sections and ionisation stratification resulted in varying strengths of emission.



Canfield and Chang 1985 ApJ 295



Fang et al 1995 A&A 297

Note the much weaker emission when using a non-homogeneous atmosphere with more flare-like ionisation fraction.

See also:
Canfield and Chang 1985 ApJ 295
Fang et al 1995 A&A 297
Brosius et al 1995 ApJ 441
Brosius et al 1999 ApJ 514
Hudson et al 2012 ApJ 752

ORRALL-ZIRKER EFFECT — OBSERVATIONS?

- Stellar flare Lyman α observation from Hubble Space Telescope interpreted as OZ effect emission by Woodgate et al 1992, ApJ 397.
- Very transient enhanced red wing (~3s) near 1223Å (δλ~7-10Å), without a similar blue wing enhancement, during a moderately sized flare on the dMe star AU Microscopii.
- Only known detection of the OZ effect.

Adapted from Woodgate et al 1992

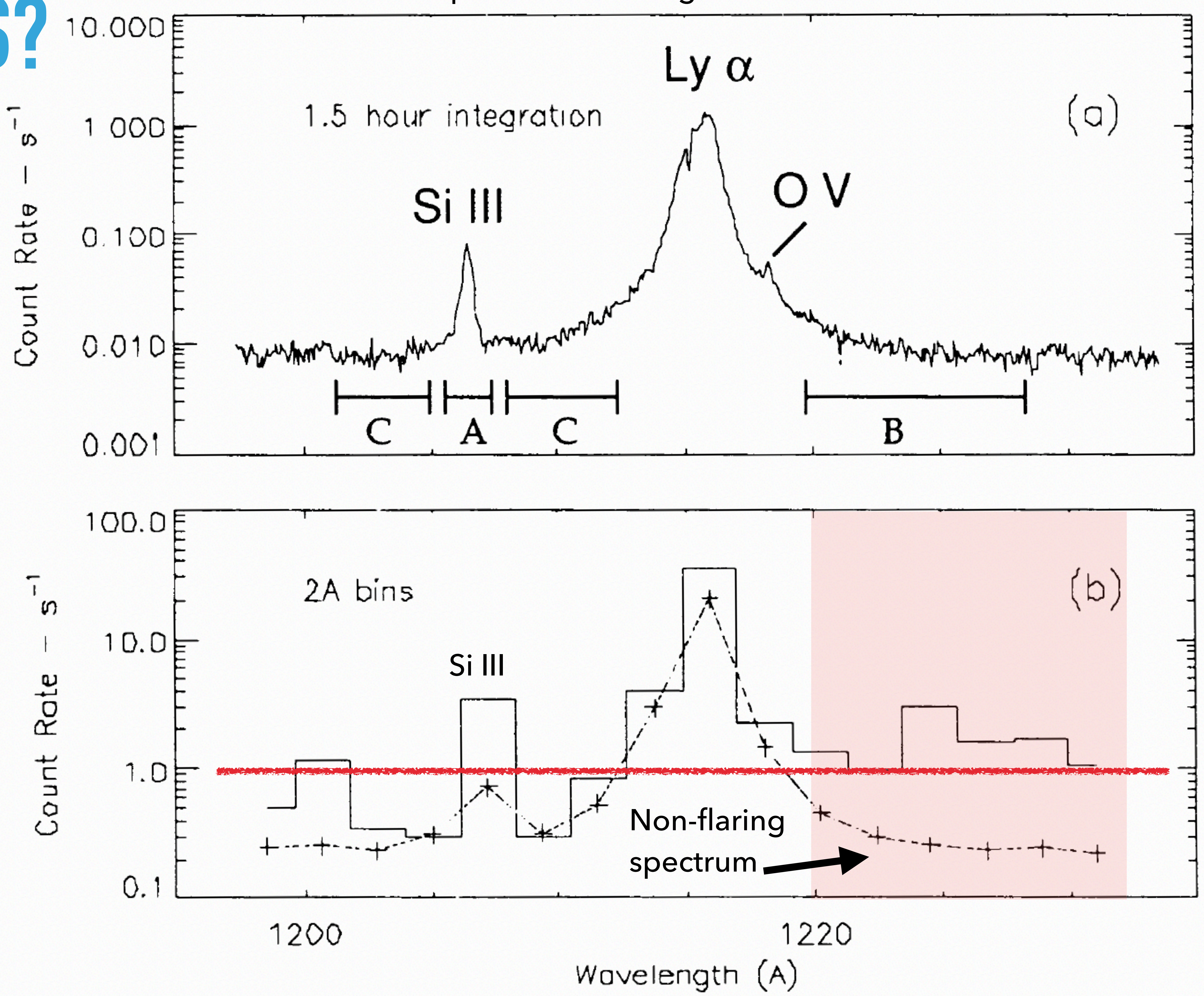
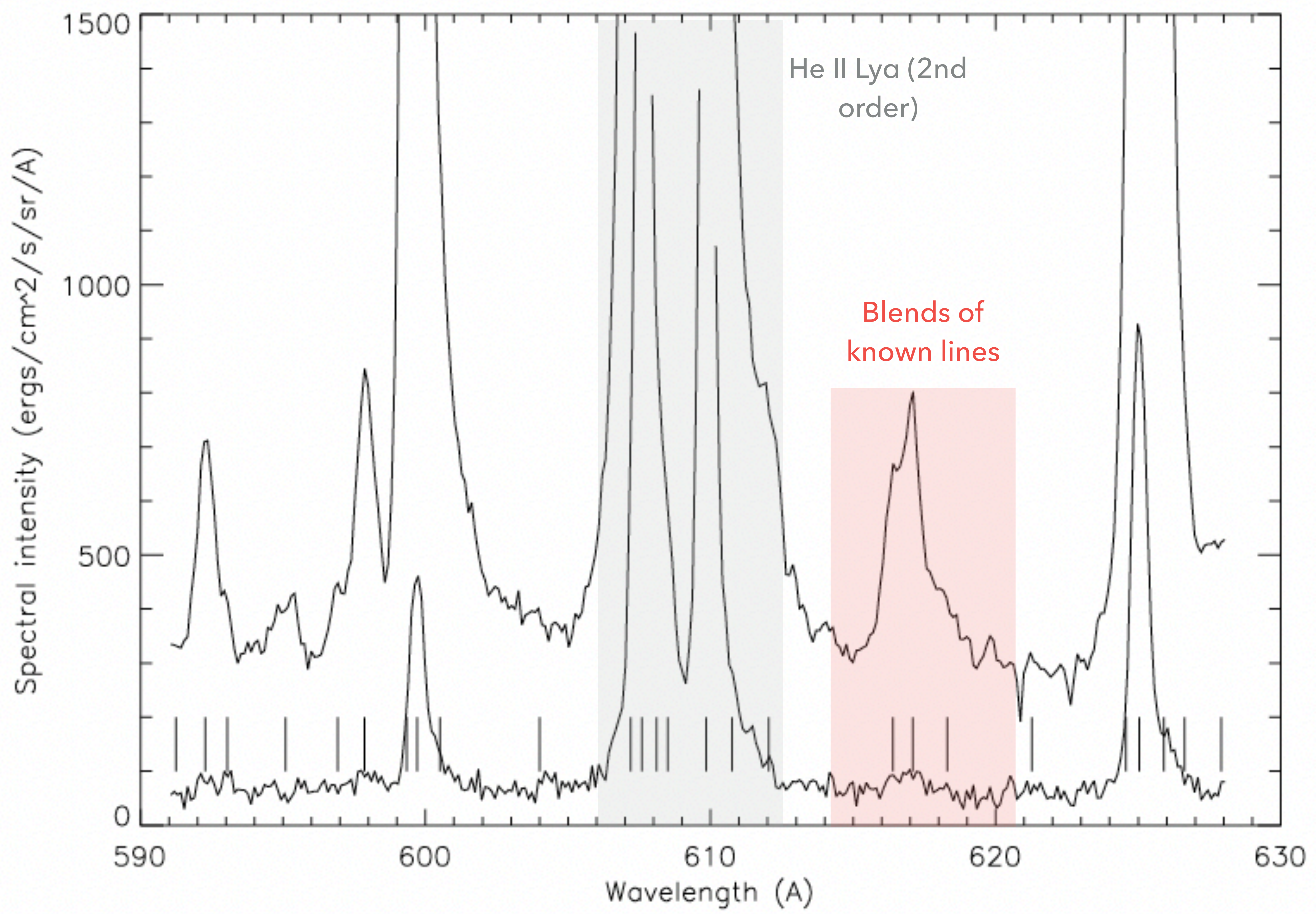


FIG. 1.—(*a*) An integration of all spectra taken during 1.5 hr of observing. The bars indicate regions of integration used in the analysis. Geocoronal emission affects only the central 0.6 Å of the line. (*b*) Integration of the spectrum over the 3.2 s of the peak Lyman-α red wing enhancement, in 2 Å bins. The dashed line is the spectrum from (*a*) binned to 2 Å resolution.

ORRALL-ZIRKER EFFECT — OBSERVATIONS?

- Brosius 2001, ApJ 555 investigated He II 304Å, using SOHO/CDS data (note that it is second order, so appears at 608Å in the CDS spectra).
- The red wing feature indicated is actually a blend of several known lines that became enhanced in the flare.
- No charge-exchange induced emission was detected by comparing blue and red wings, with an upper limit < 1% of the He II 304Å peak intensity at flare onset established.

Flare spectrum observed by SOHO/CDS, with He II 304Å emission observed in second order. Adapted from Brosius 2001

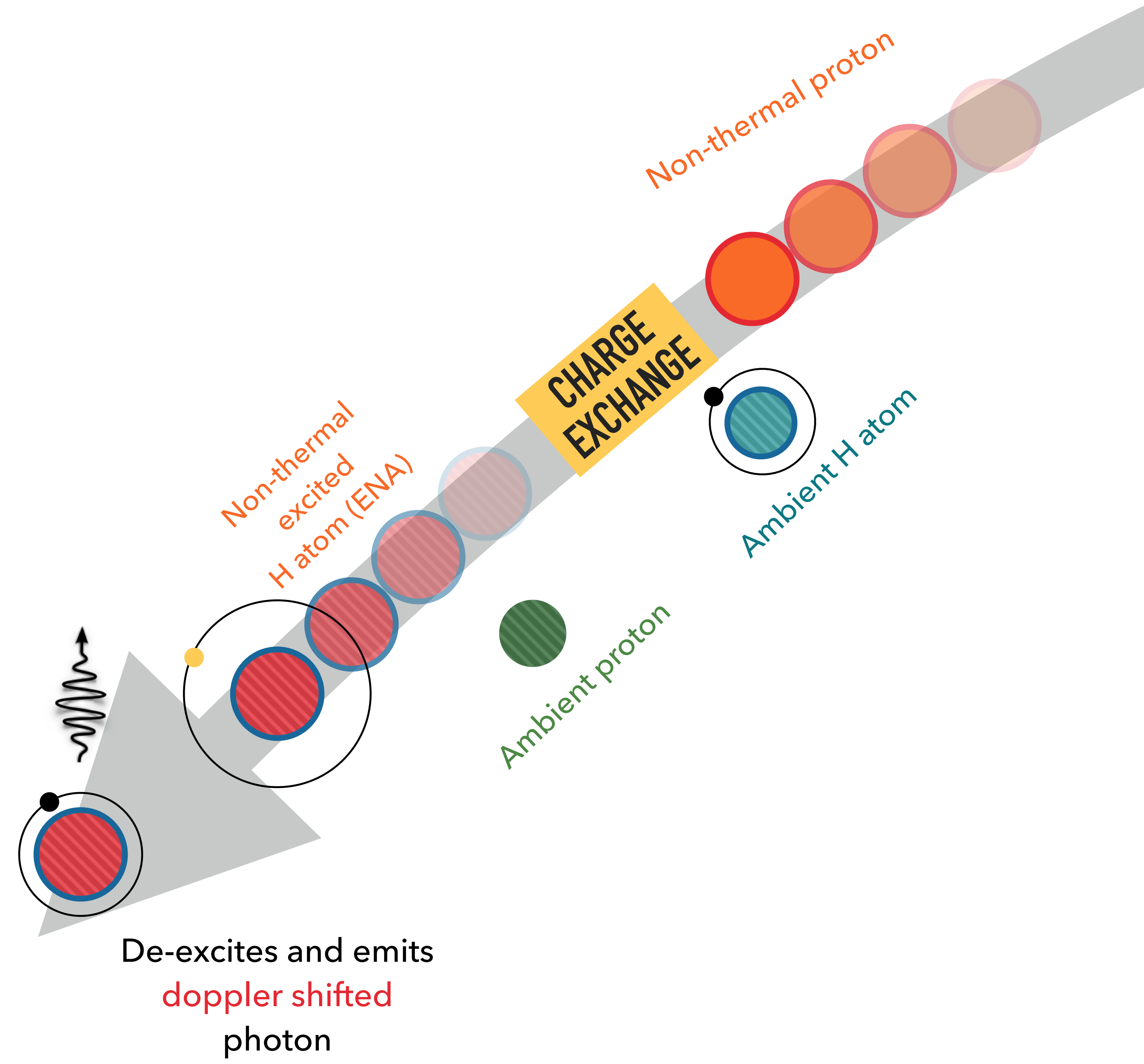


REVISITING OZ WITH RADYN + FP

- Using a state-of-the-art flare radiation hydrodynamics numerical code coupled with particle transport code we now revisit the OZ effect to make modern predictions and determine if it is a viable means to diagnose deka-keV protons in flares.

- Crucially, **RADYN** (Carlsson & Stein 1995, Allred et al 2015) **models a much more realistic non-equilibrium ionisation stratification (including non-thermal ionisations)** than employed by prior experiments with the OZ effect. We couple **RADYN** with **FP** (Allred et al 2020), a code that models the **non-thermal particle transport through the flaring atmosphere, providing us with the distribution function at each time**.

- **RADYN** models the Lyman lines, but we also model these using **RADYN's** flare atmospheres (plus non-equilibrium atomic level populations) with the **RH** code (Uitenbroek 2001) to **obtain the extended Lyman line profiles and nearby lines and continua including overlapping transitions and partial frequency redistribution**.

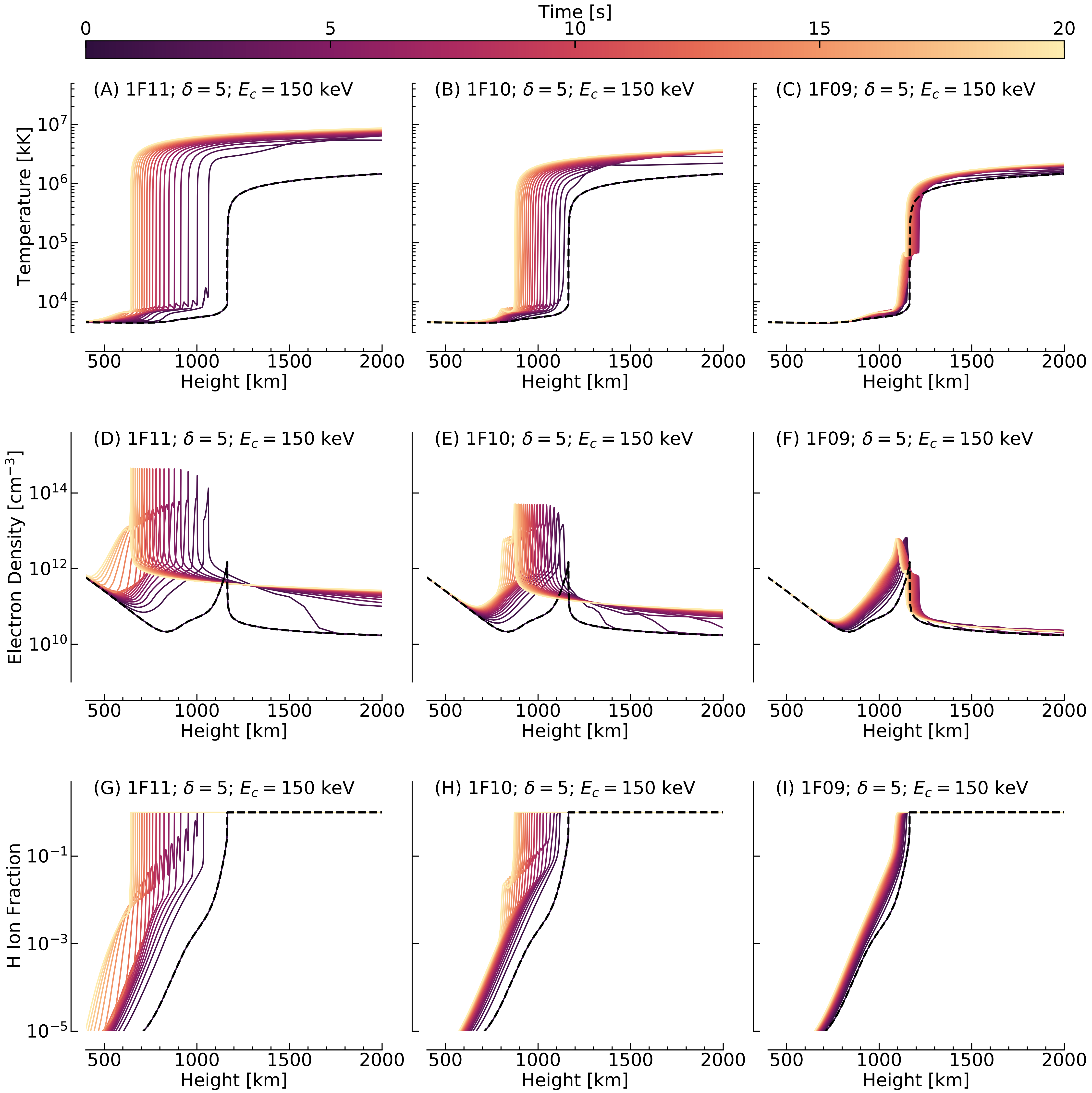


- We wrote an open-source python package (still in development but available) to model the OZ effect **using up-to-date interaction cross-sections** (the user can select alternative cross-sections in a straightforward manner).

- It is easy to use, and can employ any atmosphere and particle distribution. We provide it RADYN+FP output.

- Currently models Lyα, Lyβ, and Hα, but can be easily extended to He II 304Å (or to any ion of interest).

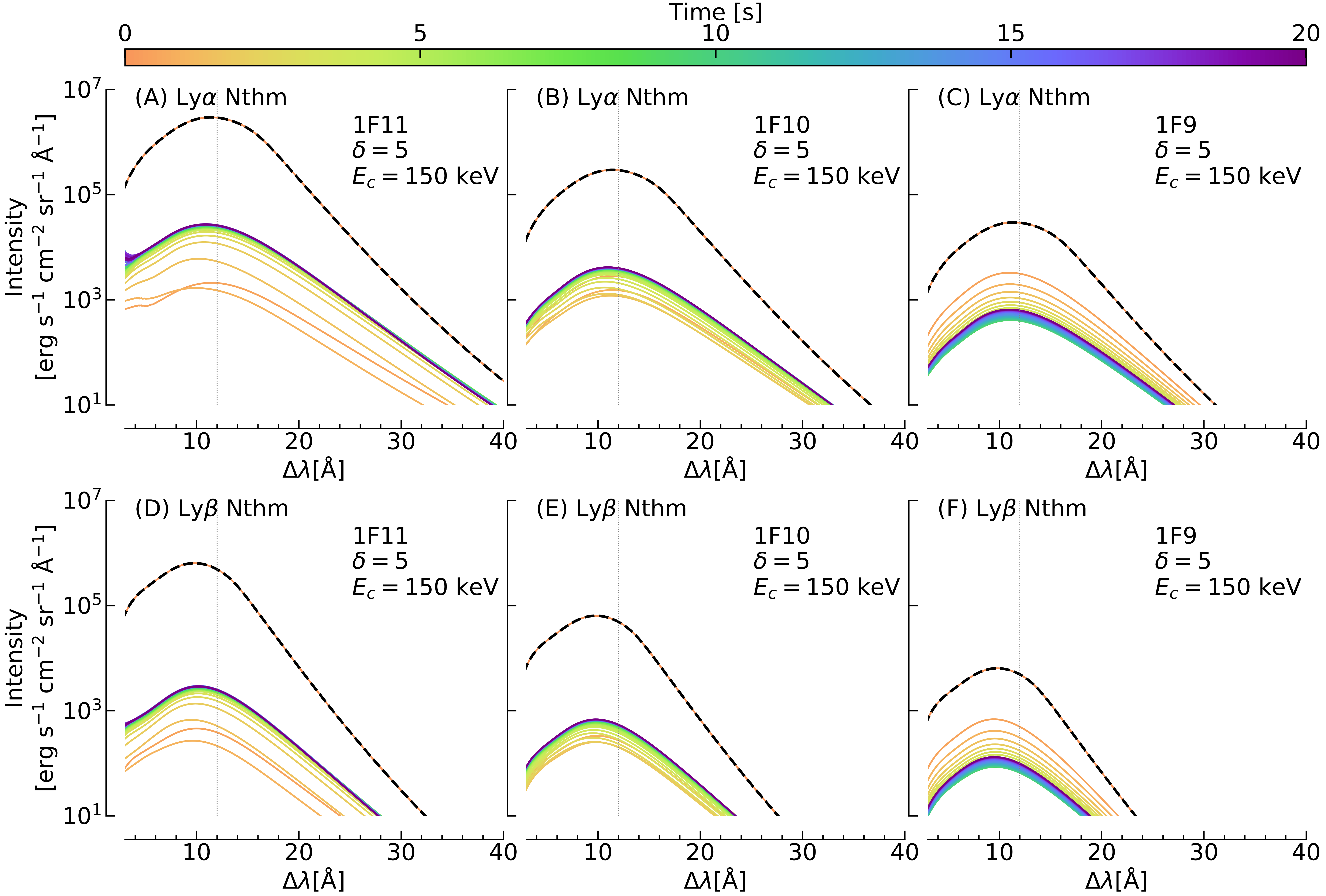
PROTON BEAM SIMULATIONS FROM RADYN+FP

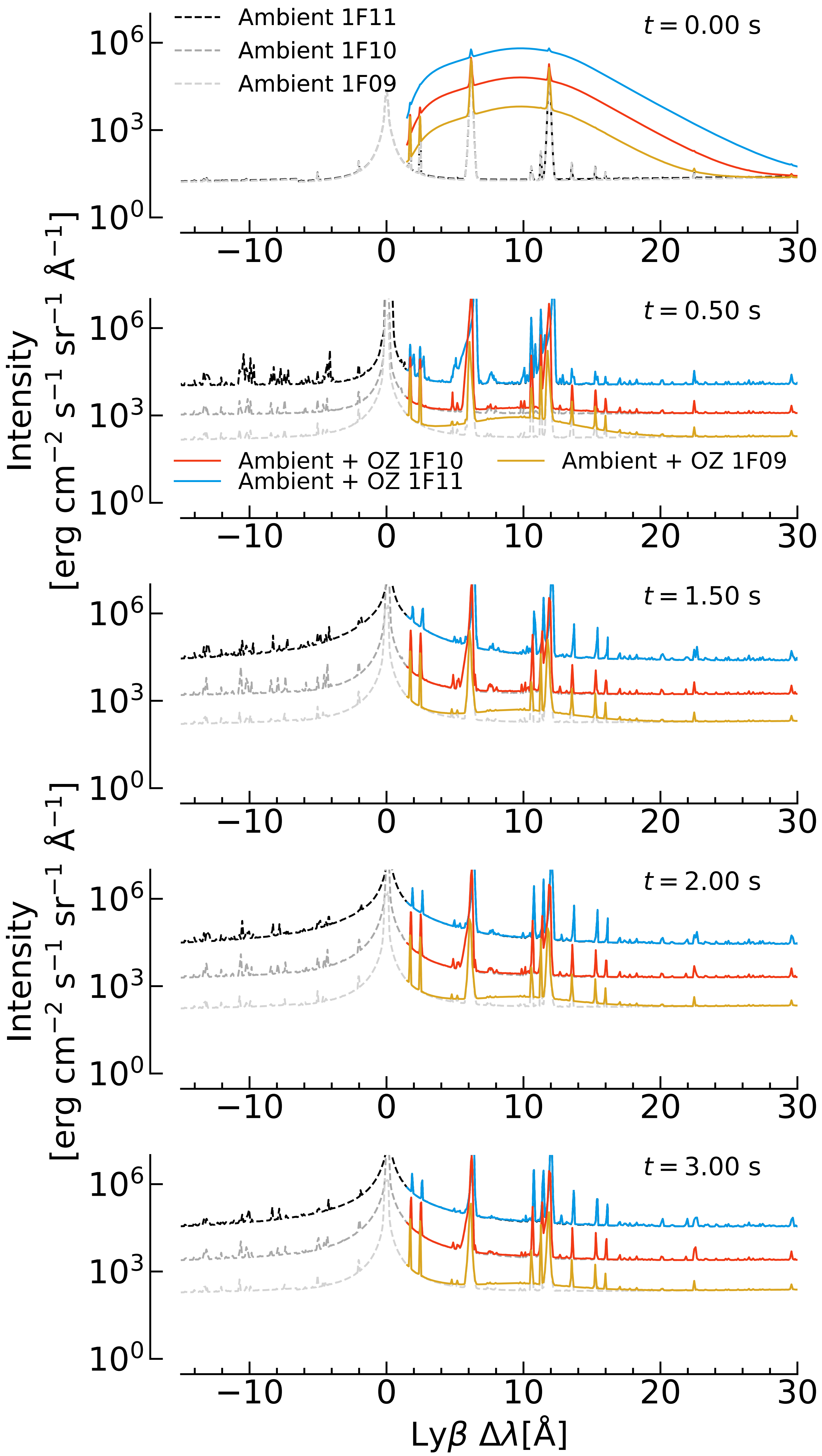


- Here we vary the flare strength, for fixed proton δ = 5 and E_c = 150 keV.
- Note the deeper penetration of the ionisation wall, and larger ionisation in general, in the stronger flare simulation.

Modelling the ionisation stratification self-consistently is essential for this project, making RADYN+FP the best suited codes for this task

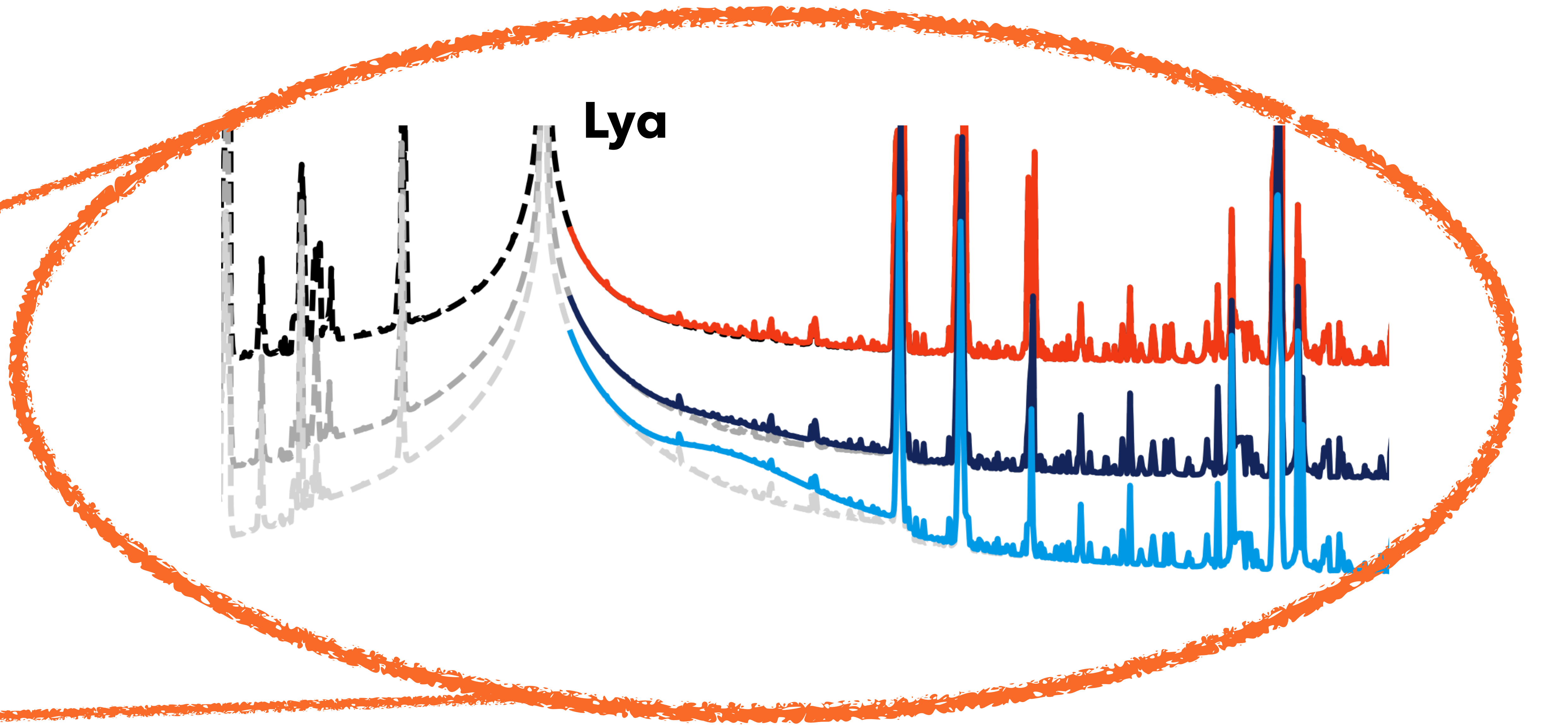
OBSERVATIONAL PROSPECTS

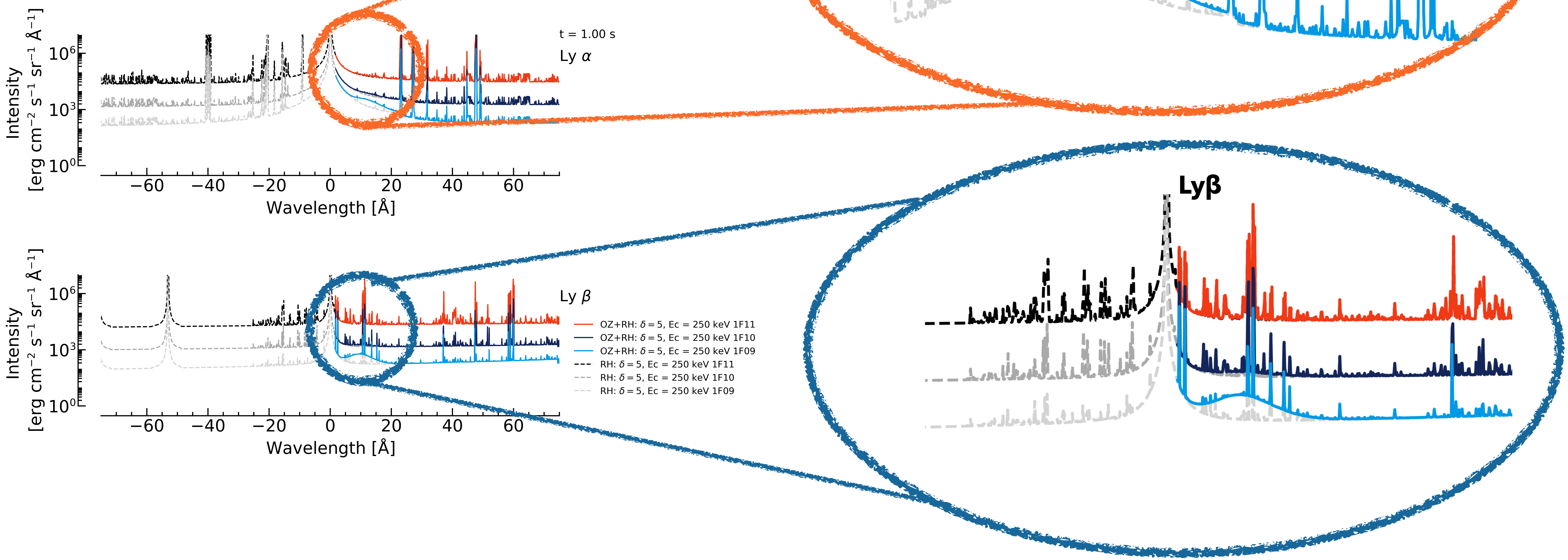




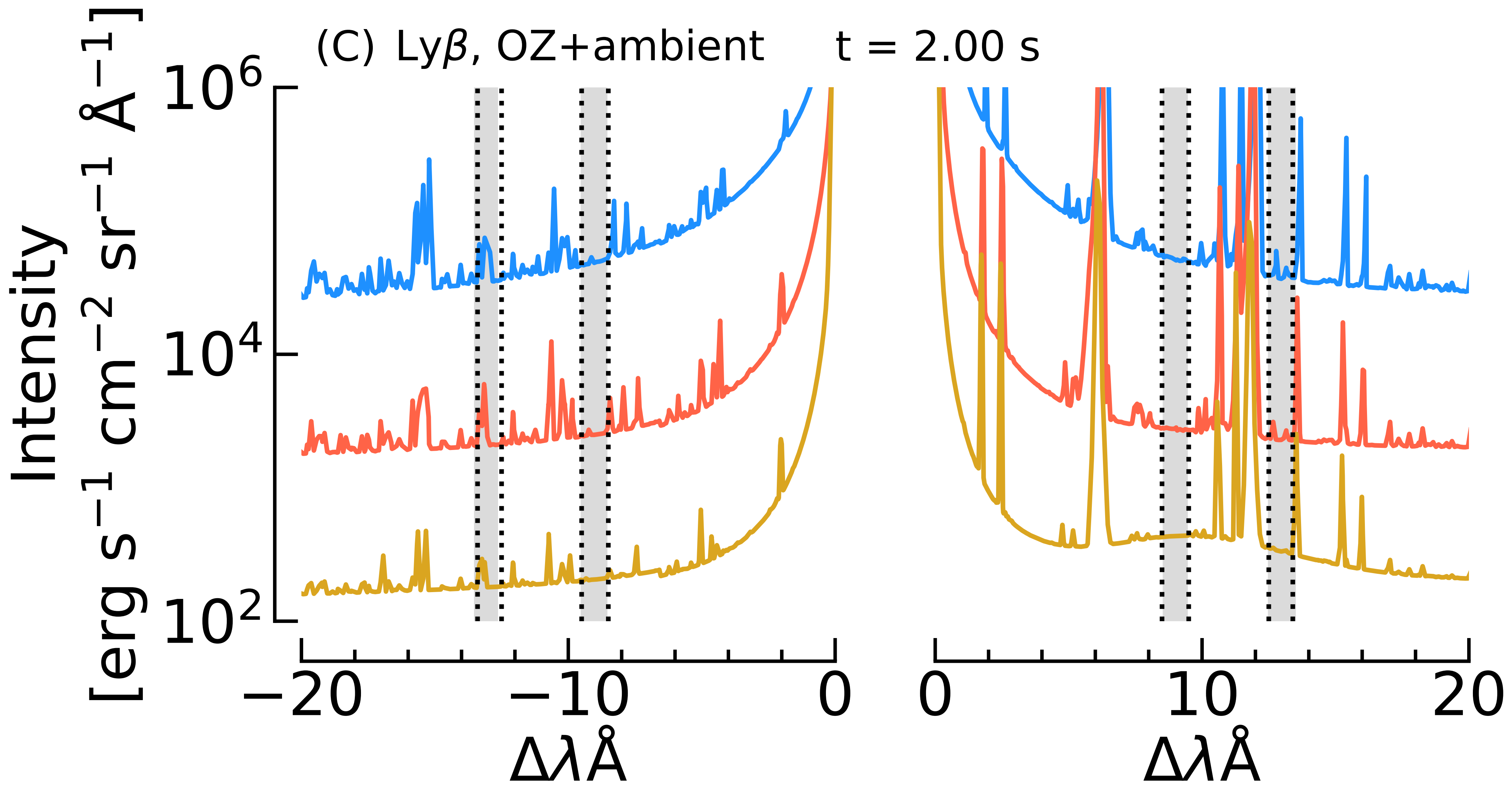
OBSERVATIONAL PROSPECTS

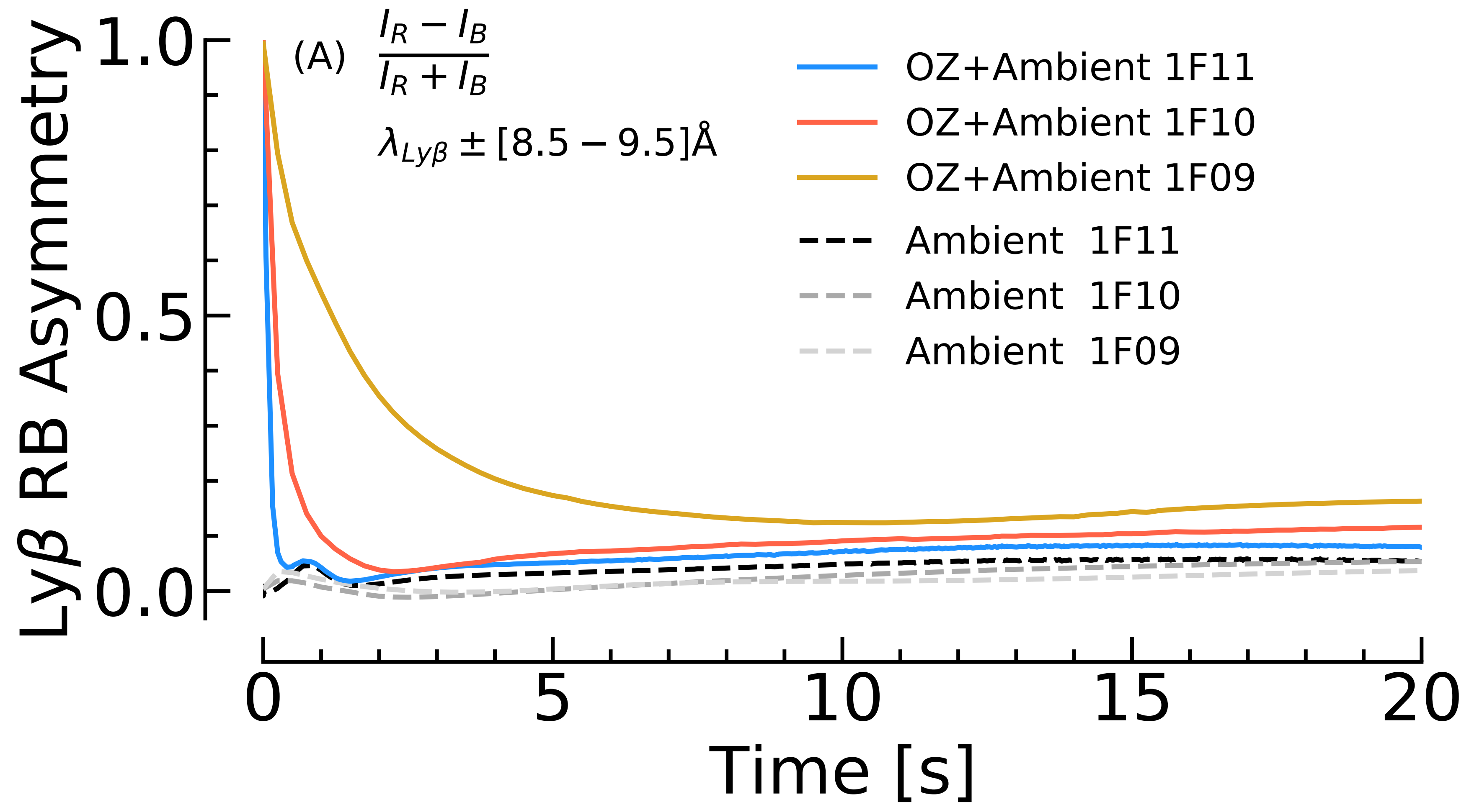
- In the weaker flare, a noticeable, but transient, asymmetry is present. Harder to detect in the stronger flares.

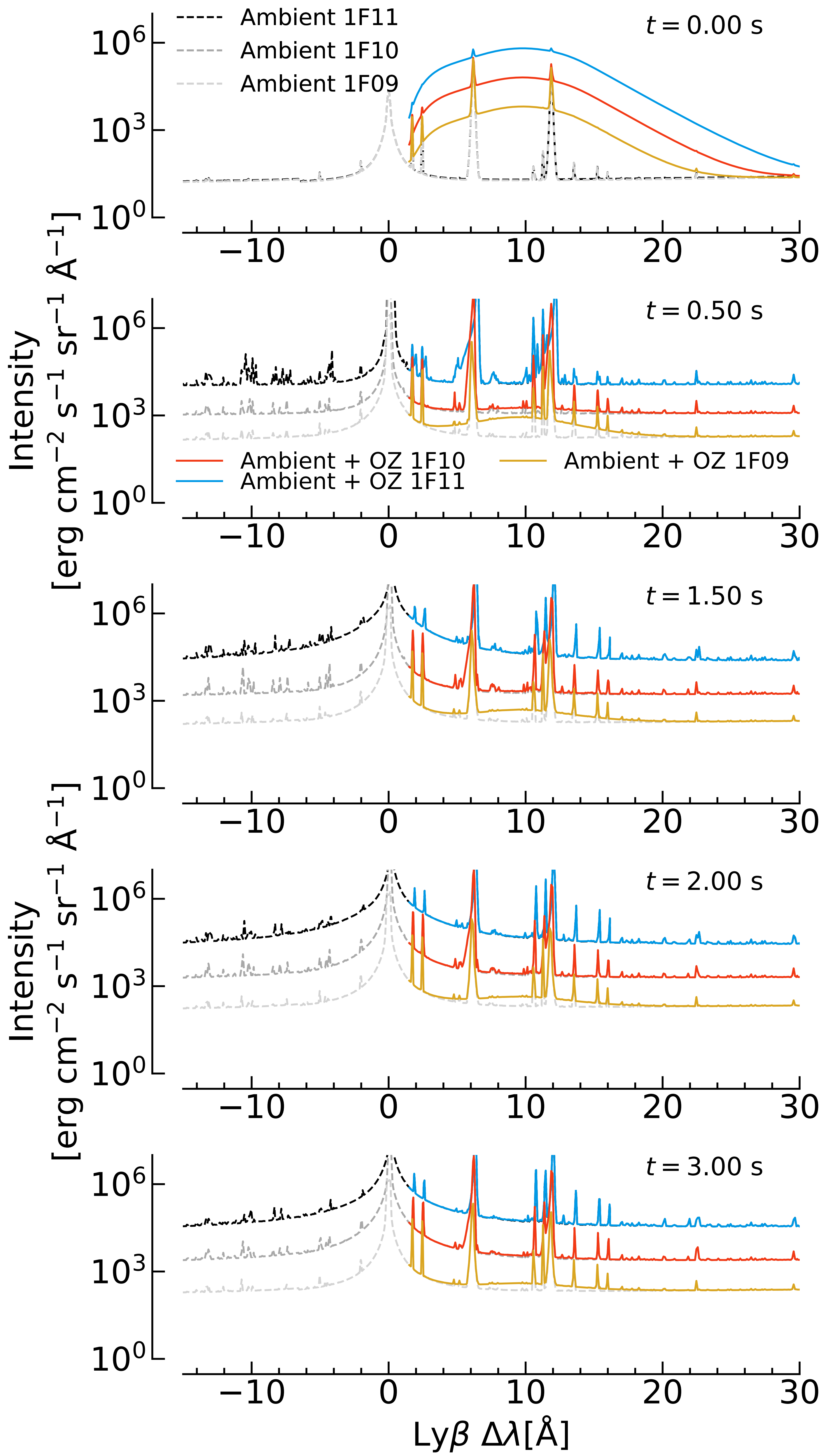




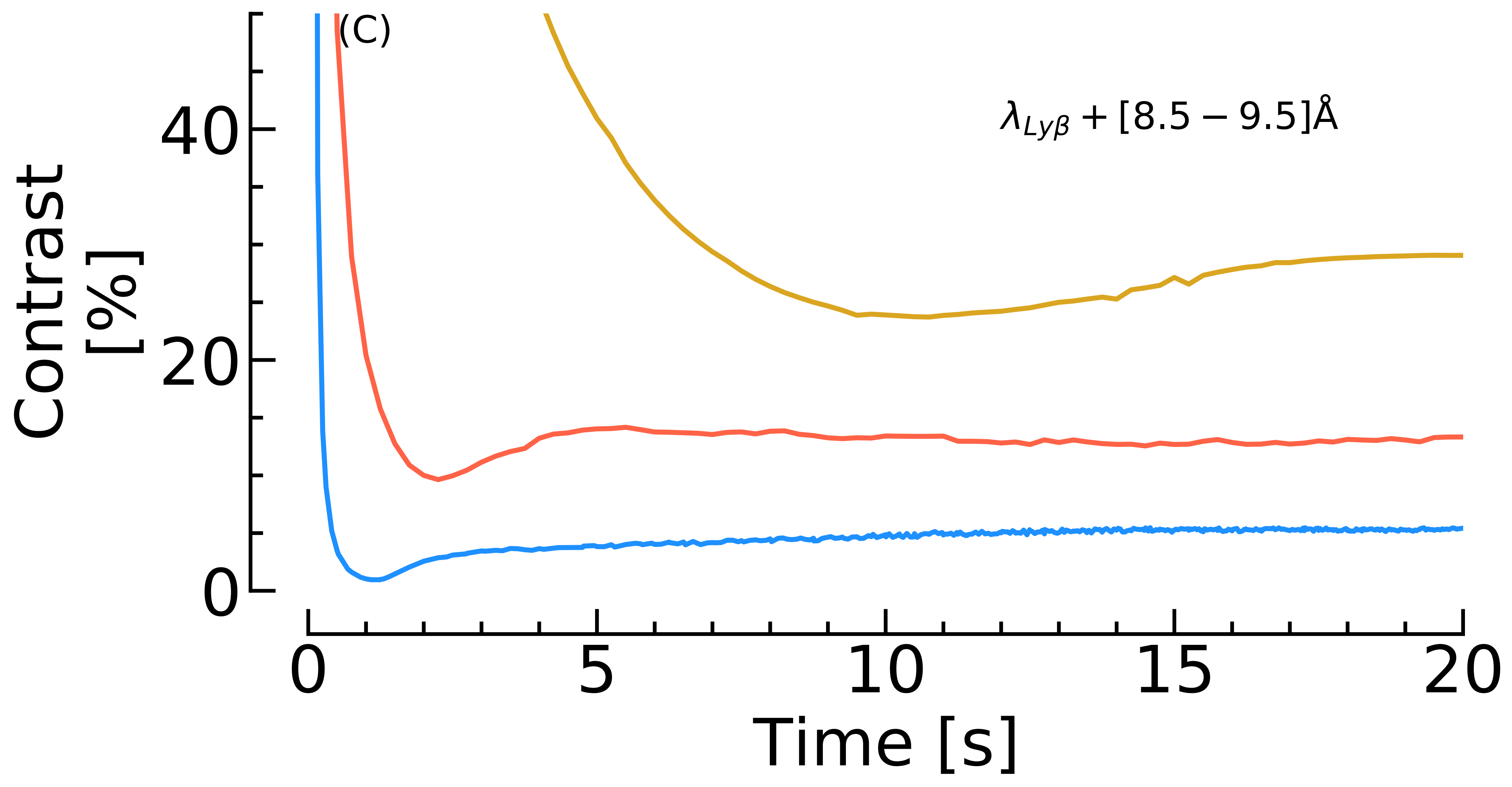
OBSERVATIONAL PROSPECTS

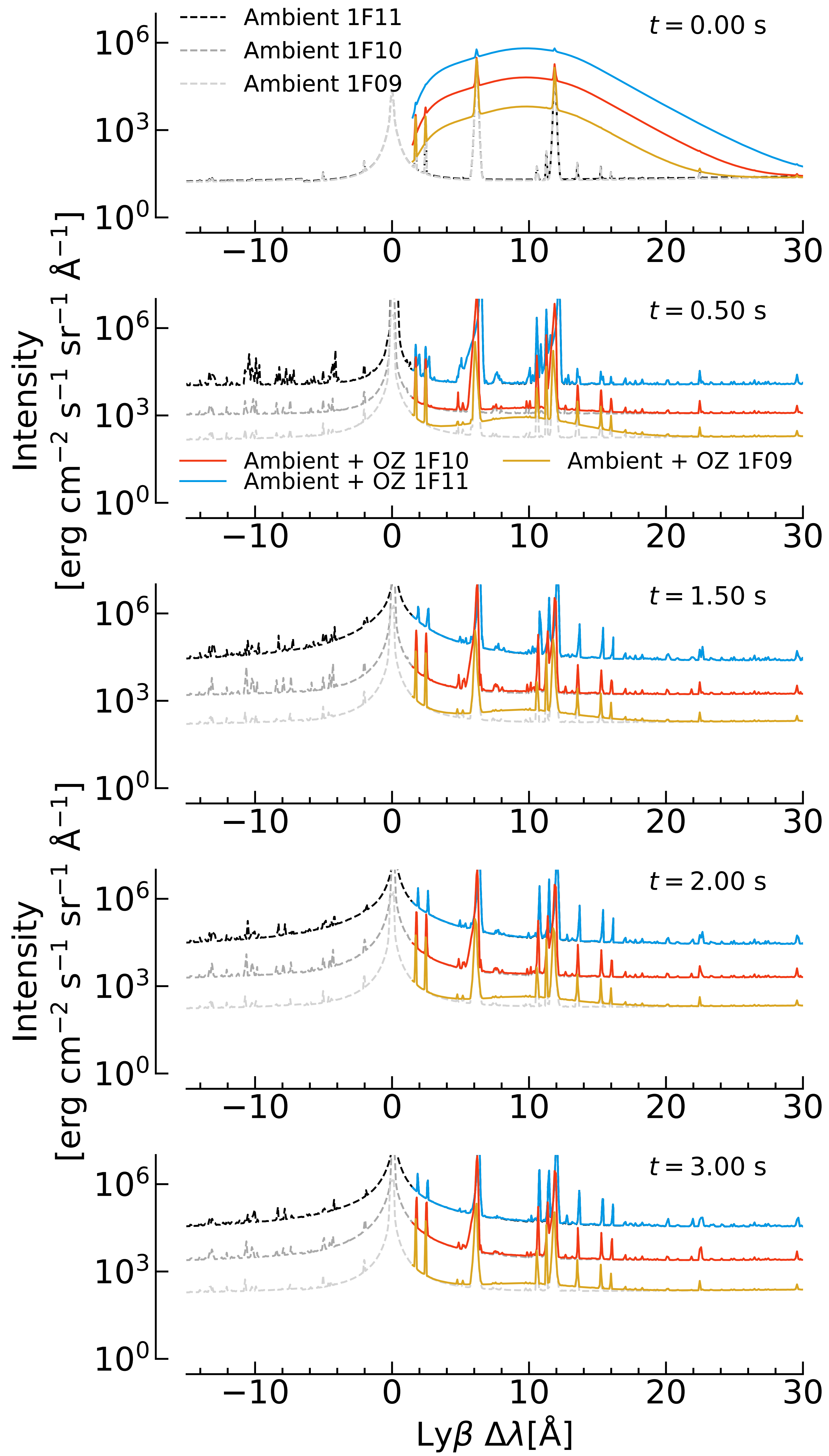




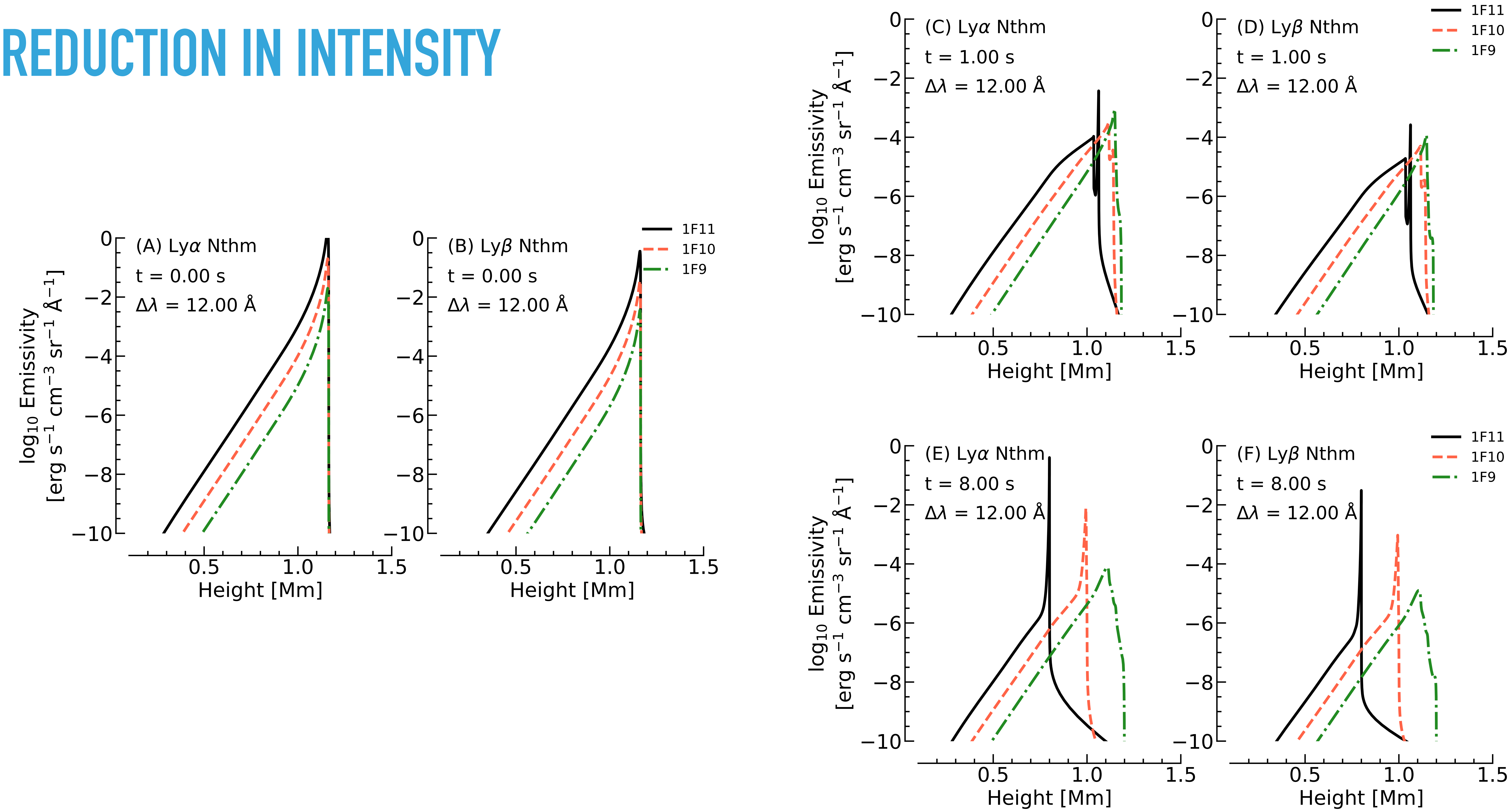


OBSERVATIONAL PROSPECTS

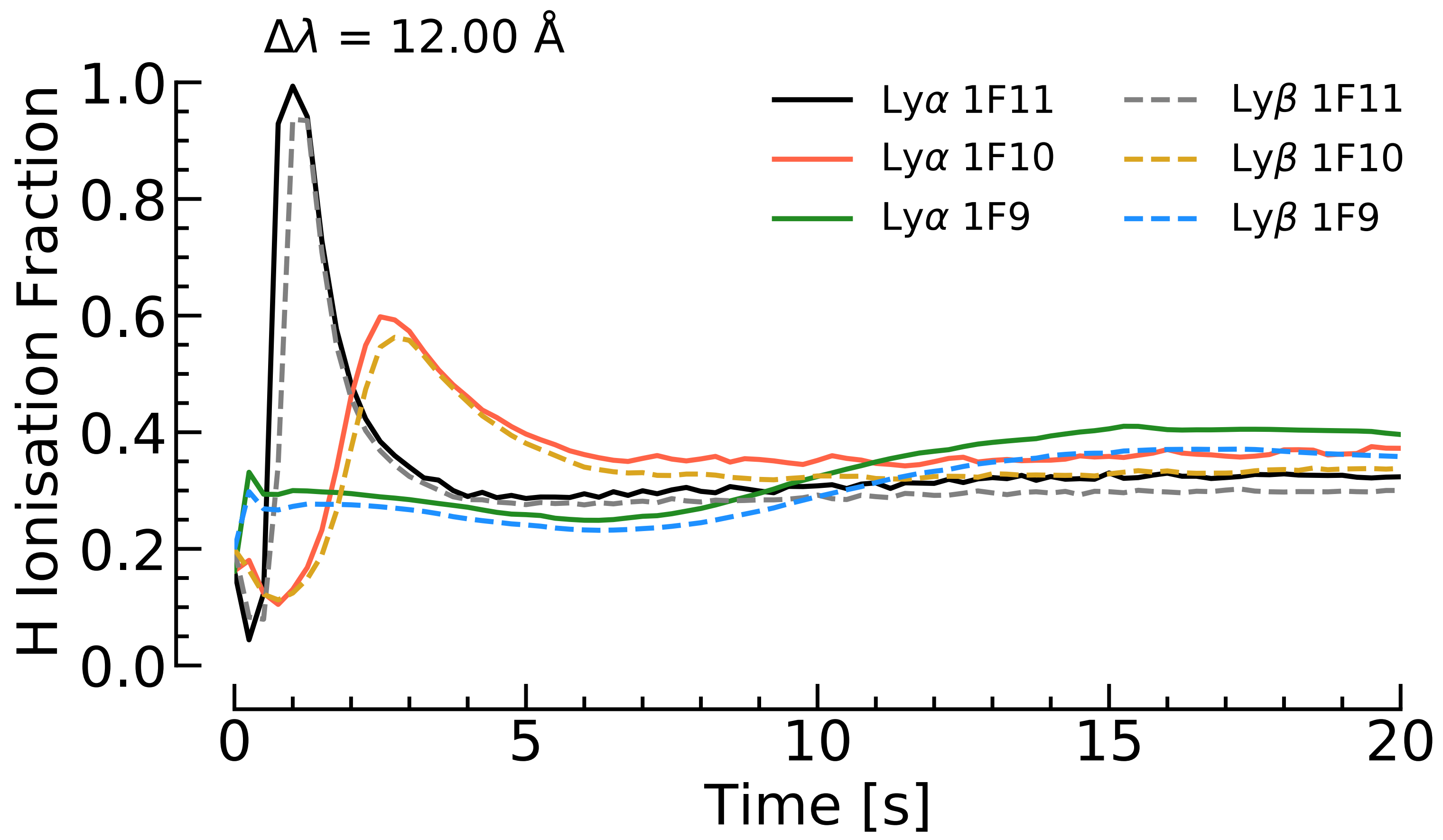


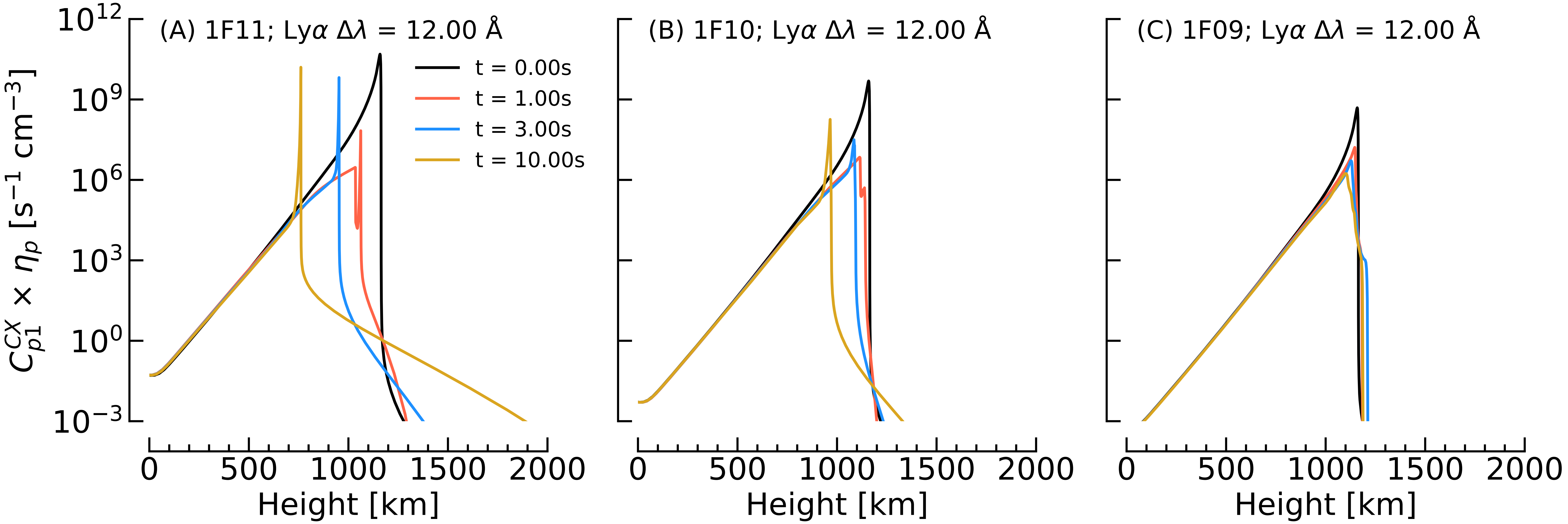


REDUCTION IN INTENSITY



IONISATION FRACTION AND # OF CHARGE EXCHANGE INTERACTIONS

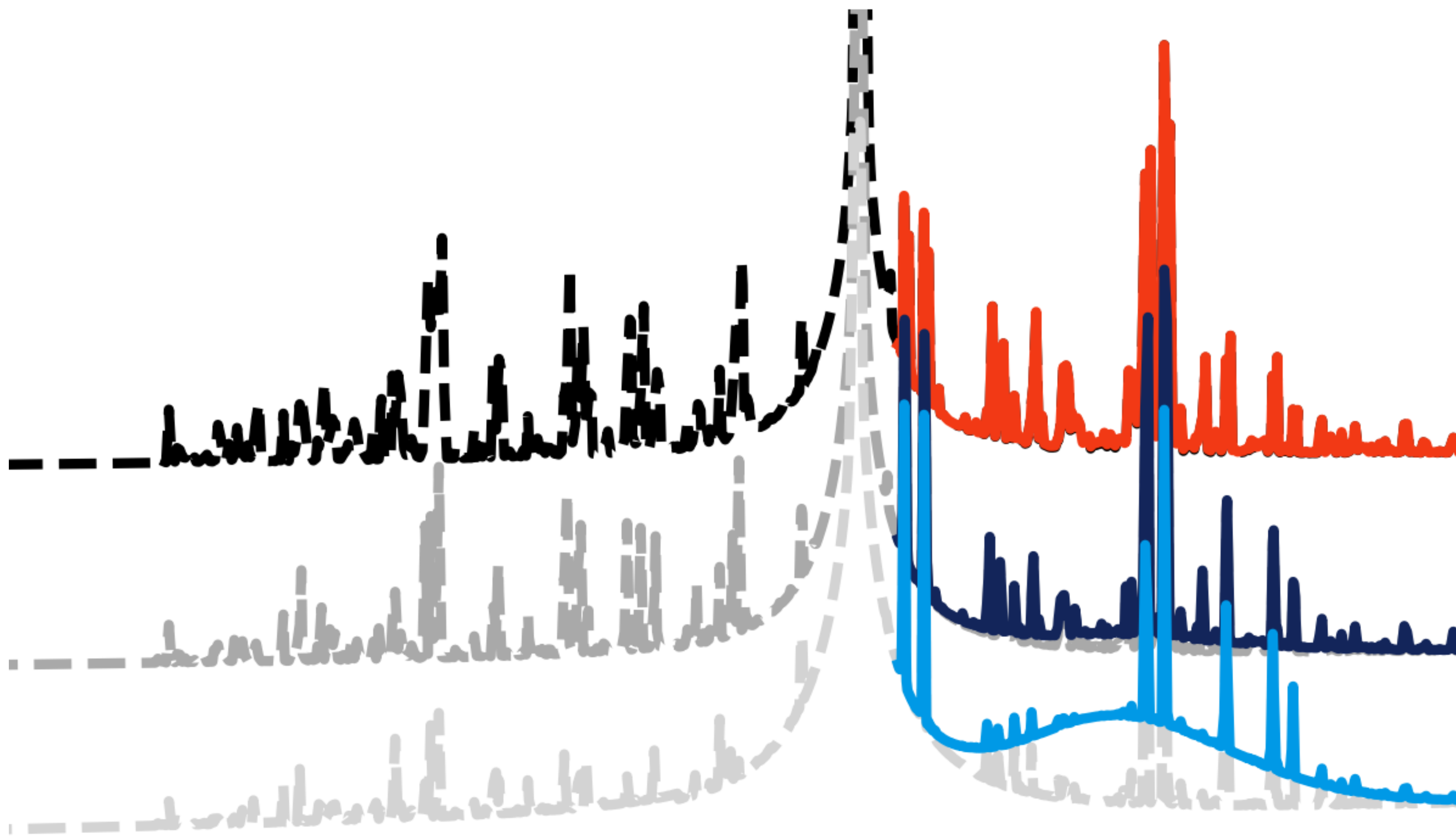


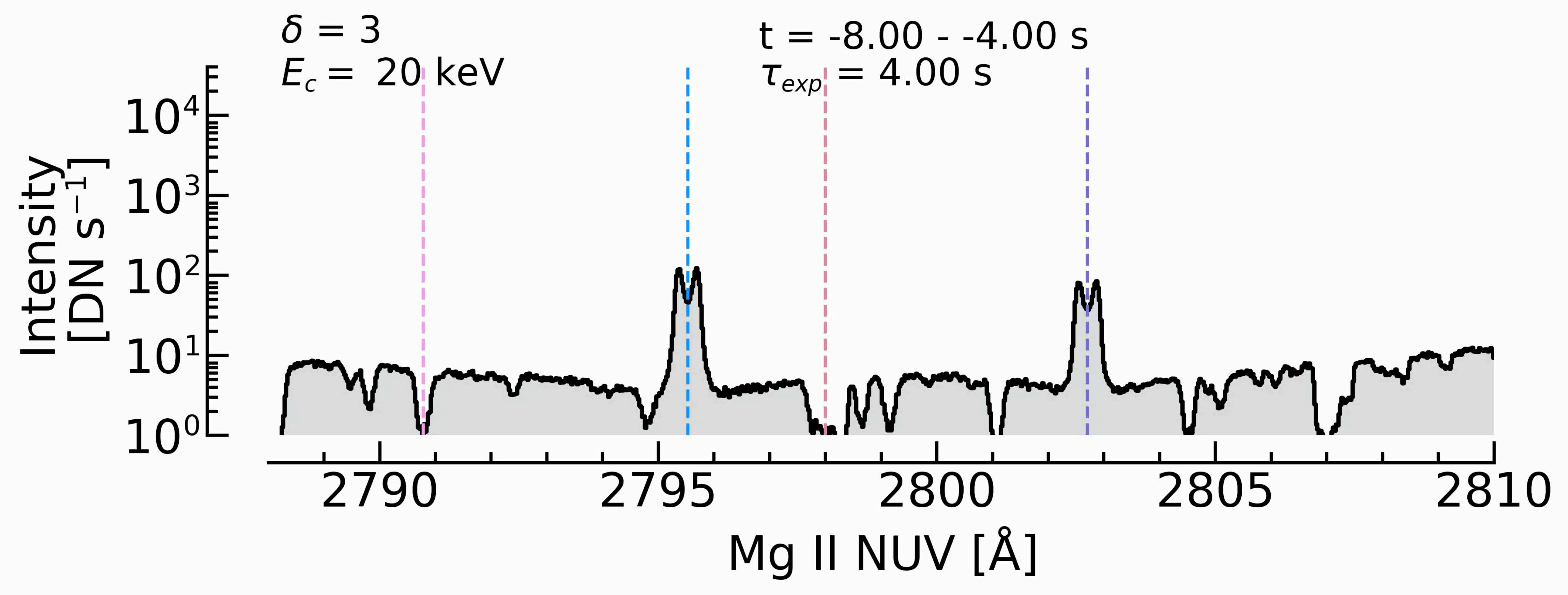


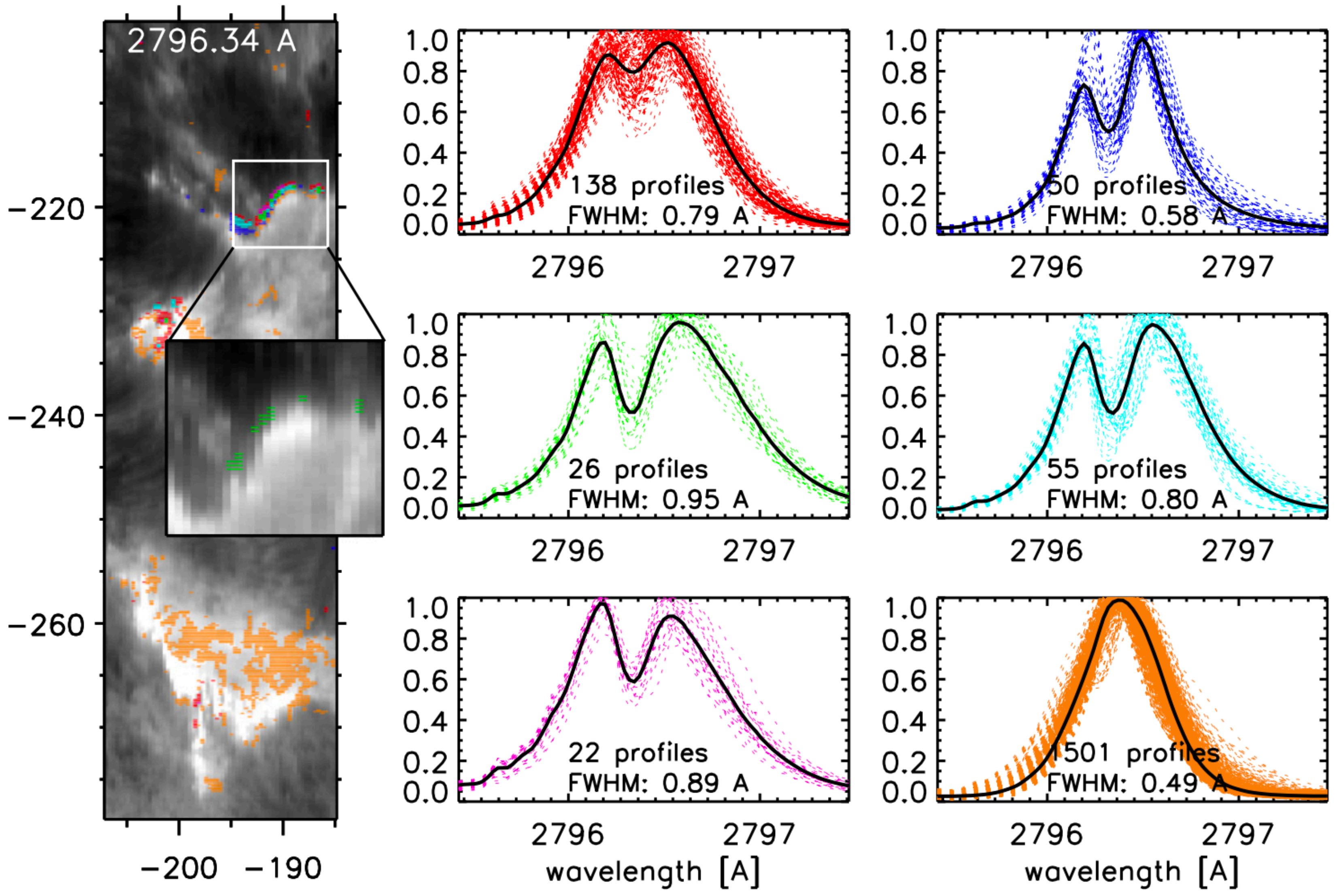
OBSERVATIONAL PROSPECTS

- Our other work on observations and modelling of the He I 10830 IR lines, and Mg II NUV lines in flares has suggested that there could be a period of weak energy injection into the leading edge of the flare ribbon – Flare ribbon leading edges are an ideal target for Lyman line observations to ID the OZ effect!

Xu et al 2016 ApJ;
Kerr et al 2021 ApJ;
Xu et al 2022 ApJ;
Polito, Kerr et al 2022
Kerr, Polito et al 2023 (in prep)



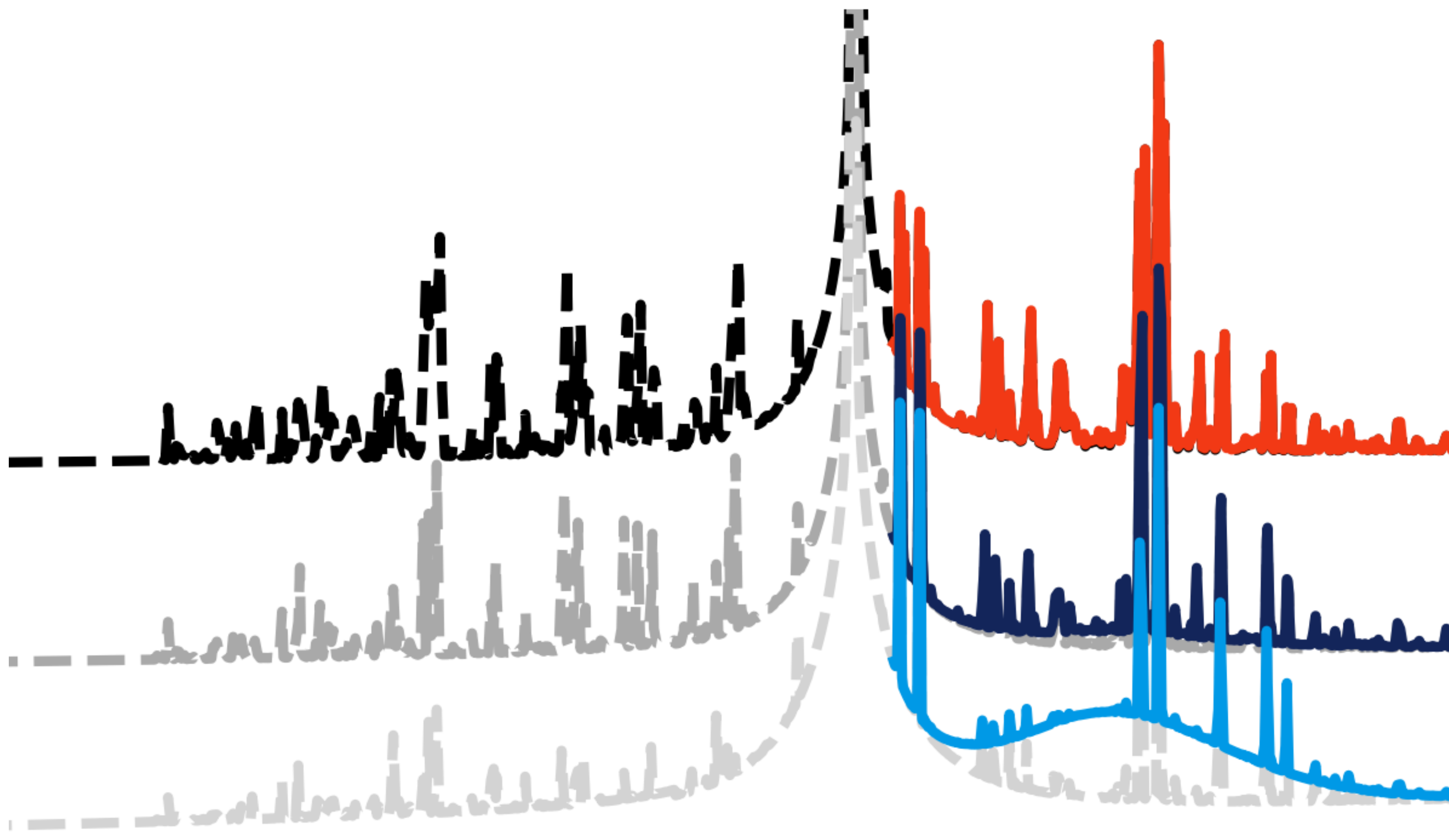




Xu et al 2016, ApJ 819

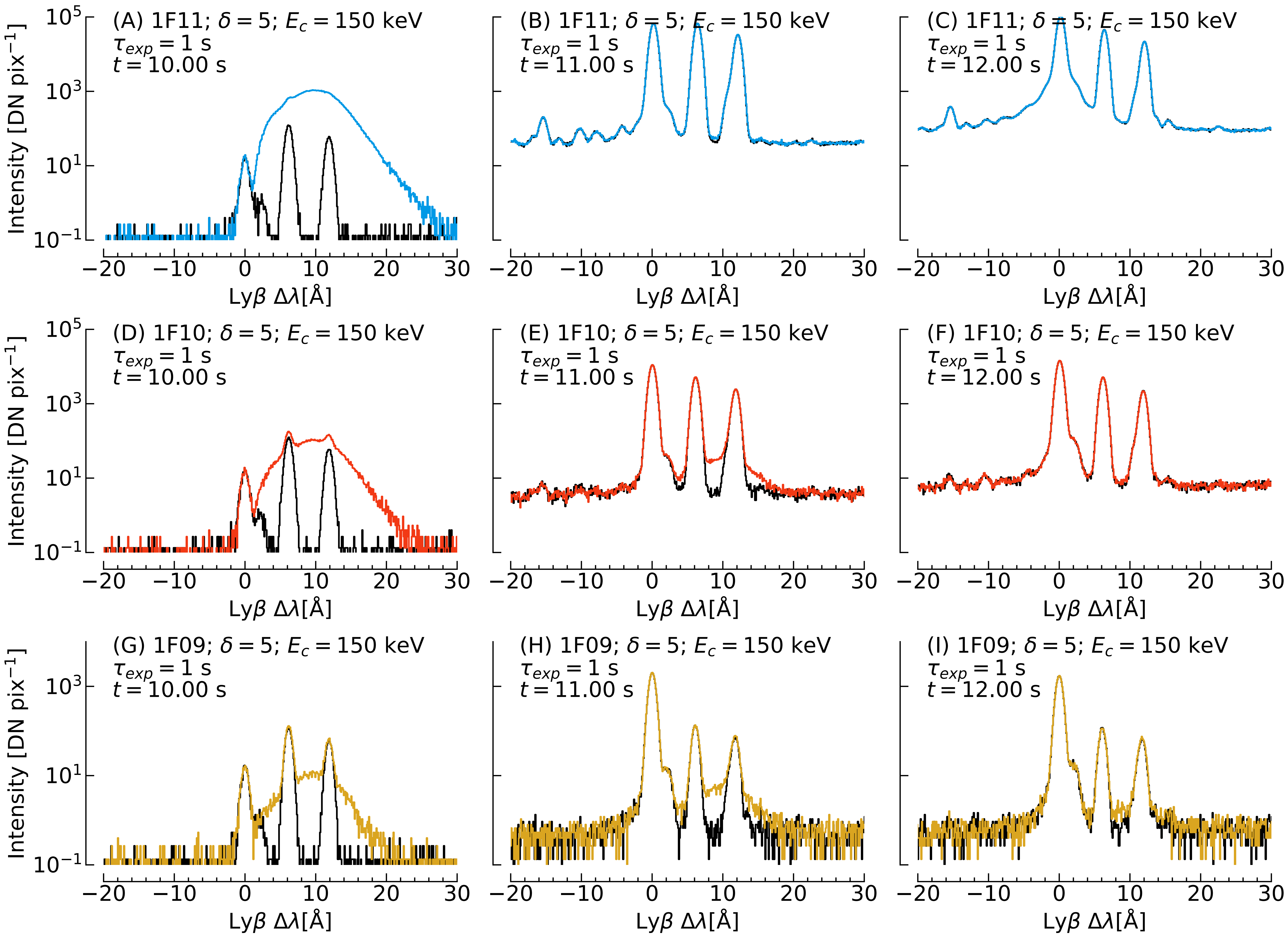
DEGRADING SYNTHETIC SPECTRA TO SOLO/SPICE

- Spectra output at least every 0.25s, sometimes faster.
- They were:
  - ➡ Re-cast (conserving flux) to SPICE level 2 plate scale;
  - ➡ Convolved with Gaussian with FWHM 9.4 SPICE spectral pixels;
  - ➡ Converted from physical units to photons;
  - ➡ Degraded by the effective area and spectral dispersion;
  - ➡ Corrected for size of SPICE pixel;
  - ➡ Integrated through time to account for smearing due to exposure time;
  - ➡ Poisson noise added to the intensity in Photons/px;
  - ➡ Converted to DN/px



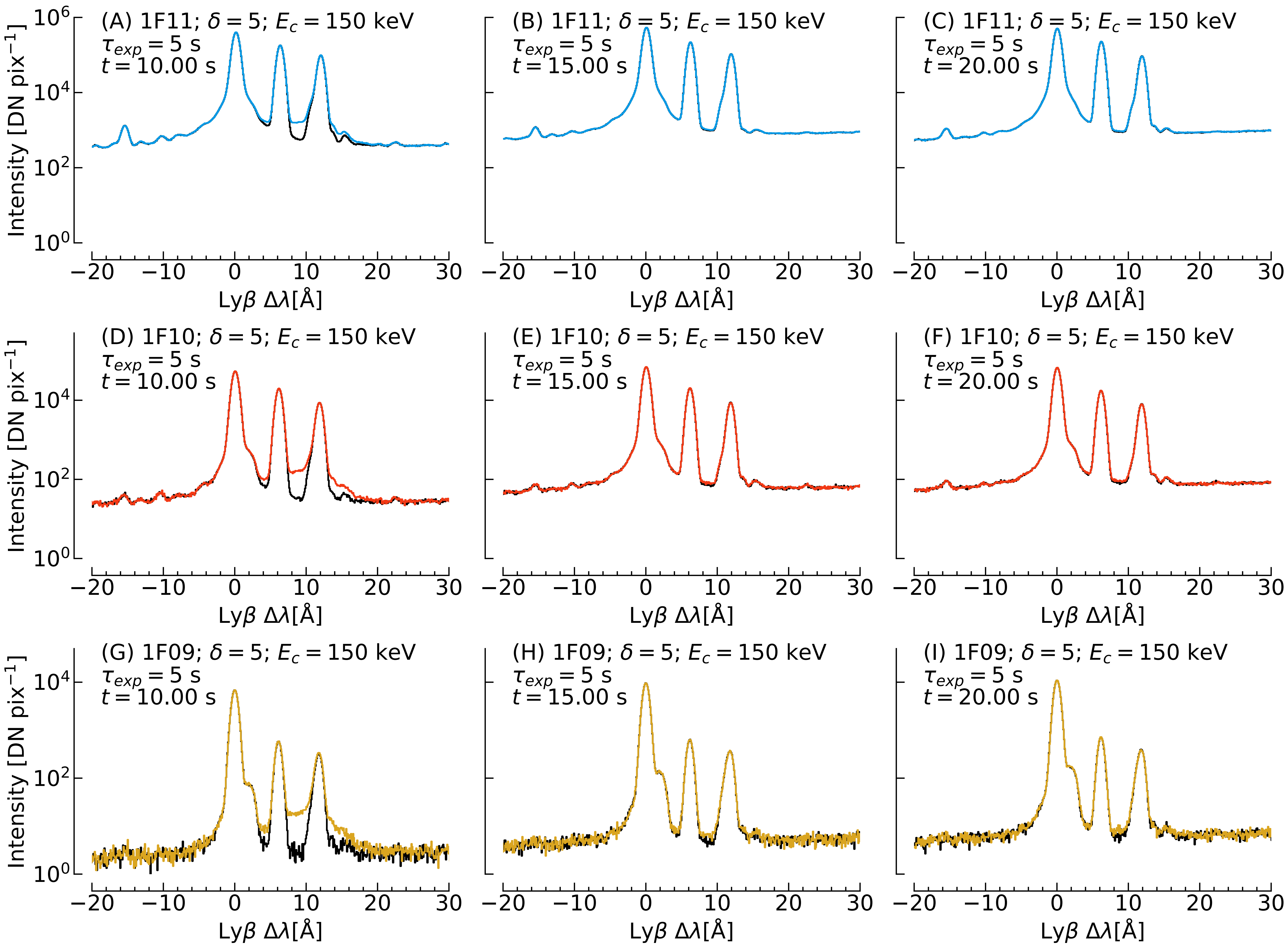
- Have not accounted for spatial PSF, and we assume for now a filling factor of 1 at 0.5AU
  - ➡ Ribbon front profiles are around 350-500km, so 1″ on Sun when SolO is at 0.5AU is comparable to this width.

DEGRADING SYNTHETIC SPECTRA TO SOLO/SPICE



DEGRADING SYNTHETIC SPECTRA TO SOLO/SPICE

- Even with a 5s exposure time, there is a reasonably strong signal, albeit for only one frame.



Summary

- We revisit the Orrall-Zirker effect with up to date numerical resources, capable of tracking the ionisation stratification and non-thermal proton populations.
- While initially very strong, rapid ionisation of the ambient chromosphere quickly drives down ENA production and emission.
- Proton beam charge exchange emission will likely be difficult to observe against ambient flare emission in stronger flare sources. Weaker sources should show emission that could be detected as a transient asymmetry (target flare ribbon fronts?).
- SPICE could observe this! 1 or 5s exposures should work.
- Need to run electron+proton (multi-species) beams.