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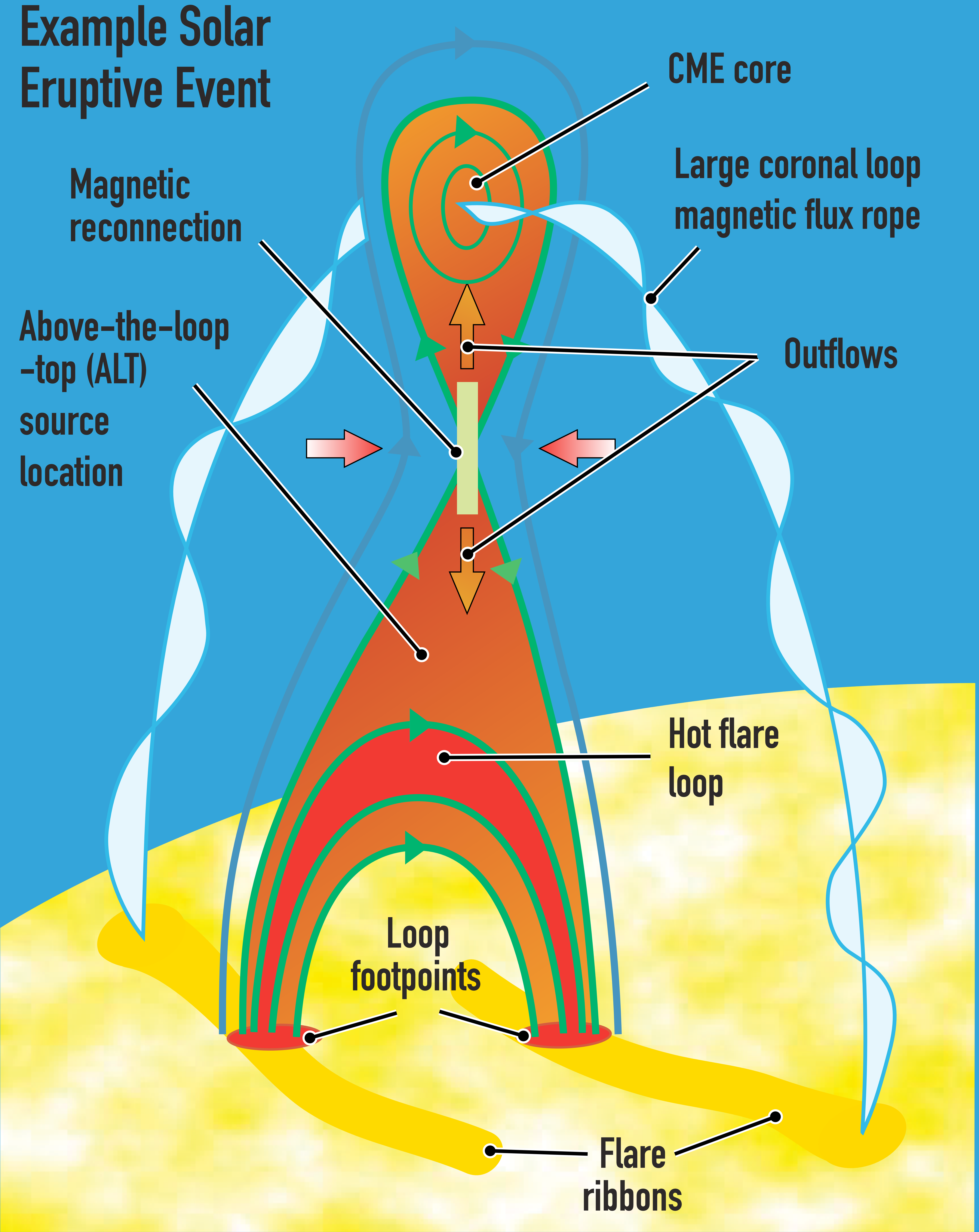
SUPRATHERMAL PROTONS AND LYMAN LINE EMISSION IN SOLAR FLARES: REVISITING THE ORRALL-ZIRKER EFFECT



SOLAR FLARES - STANDARD MODEL

Transient, yet dramatic energy release in the solar atmosphere that, together with CMEs, drive space weather.

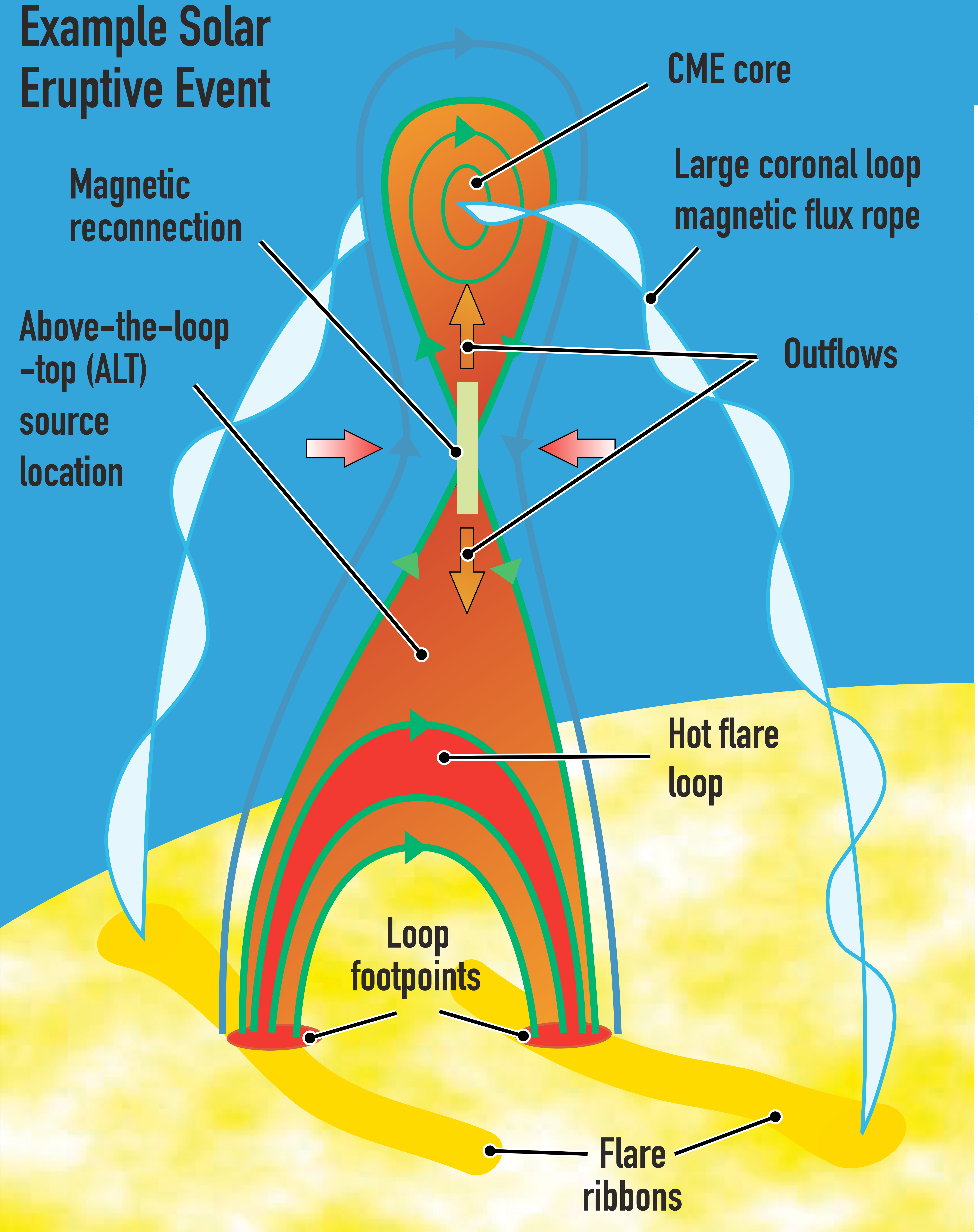
Magnetic reconnection liberates signifiant amounts of energy ($>10^{32}$ ergs) in the corona, causing in situ heating and accelerating particles out of the thermal background.

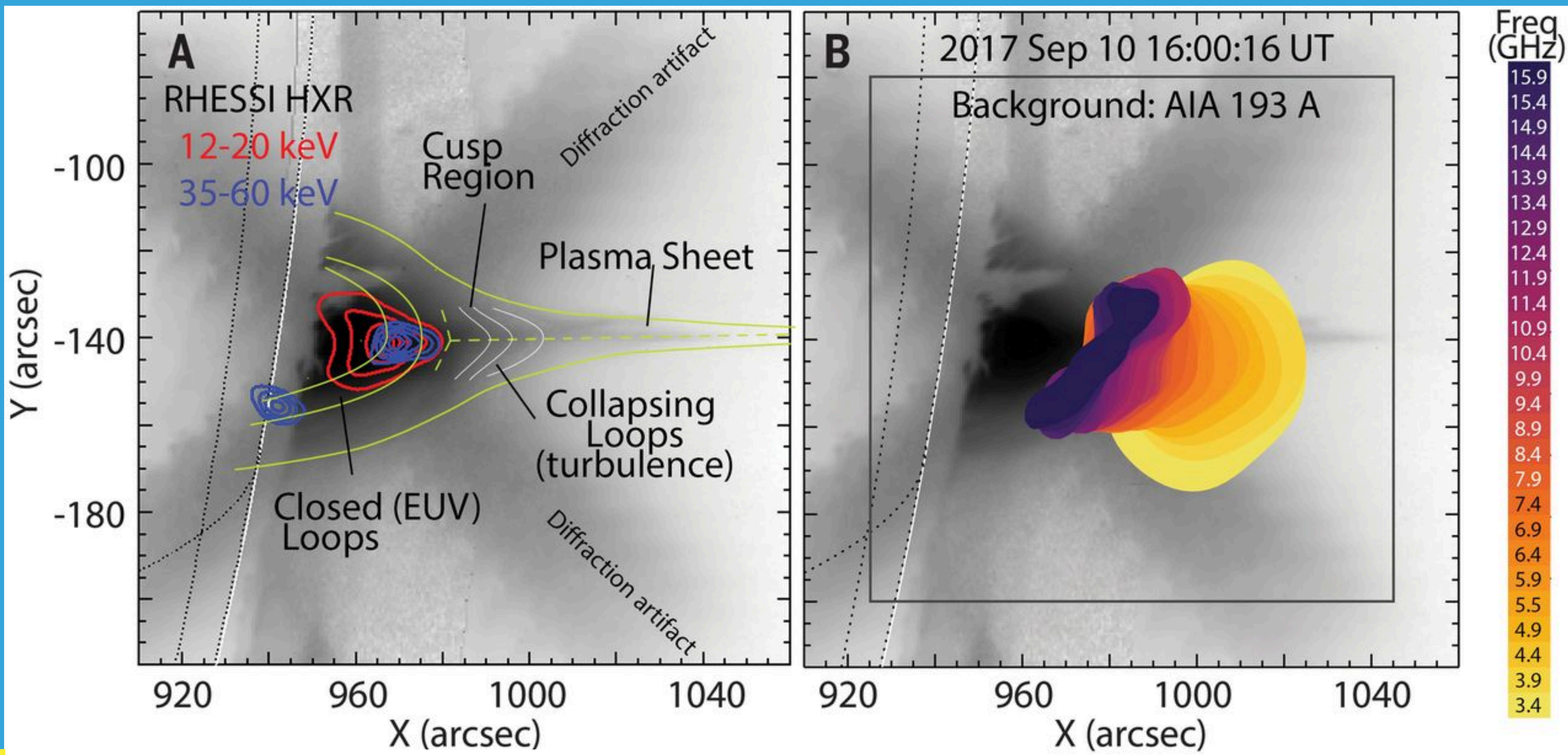
Usually we just talk about electrons but very likely protons and other ions are also accelerated — indeed we may be ignoring a substantial fraction of the energy transported in flares.

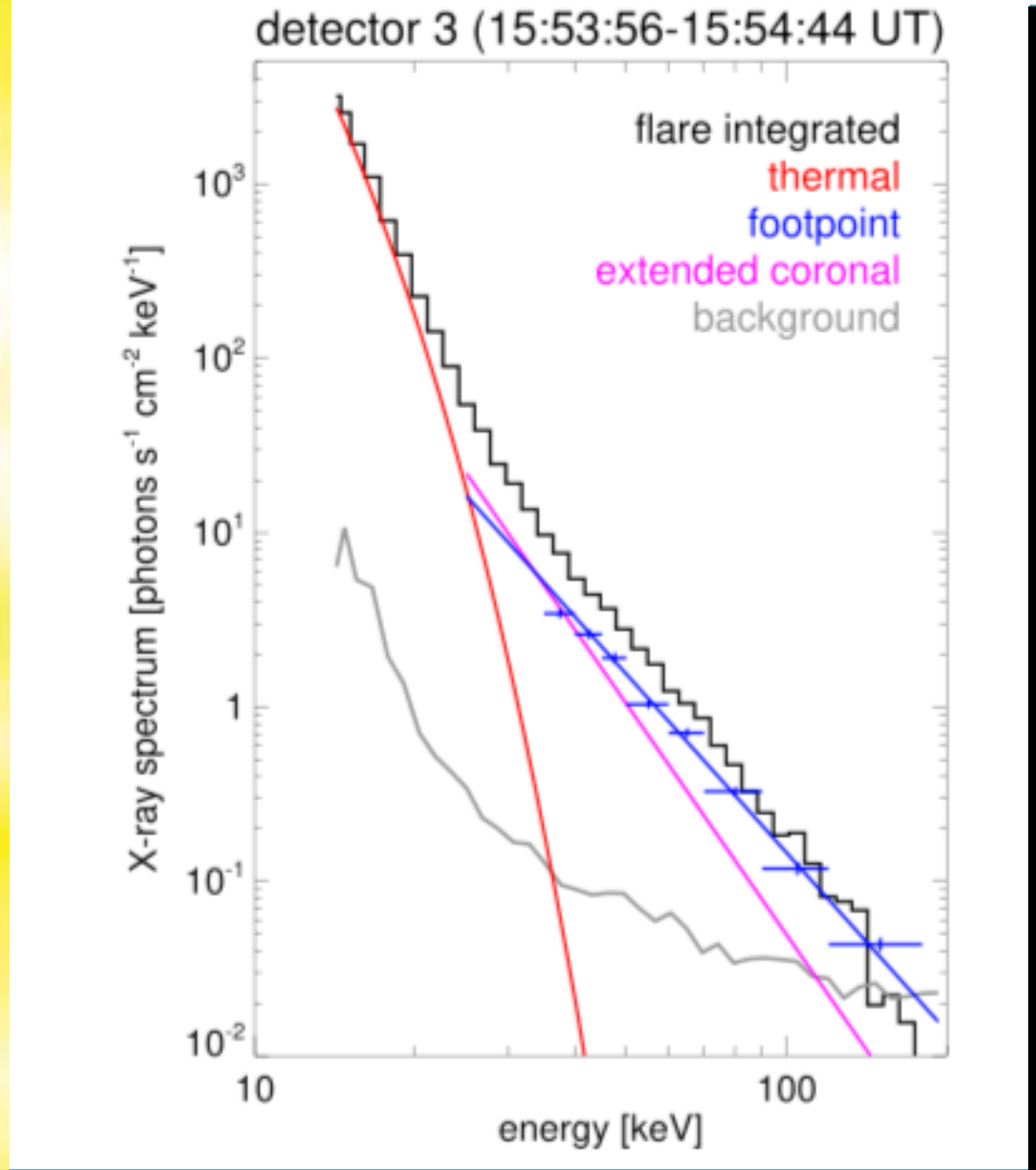
These non-thermal particles are ducted along the magnetic field lines to the lower atmosphere (transition region and chromosphere), where they undergo Coulomb collisions.

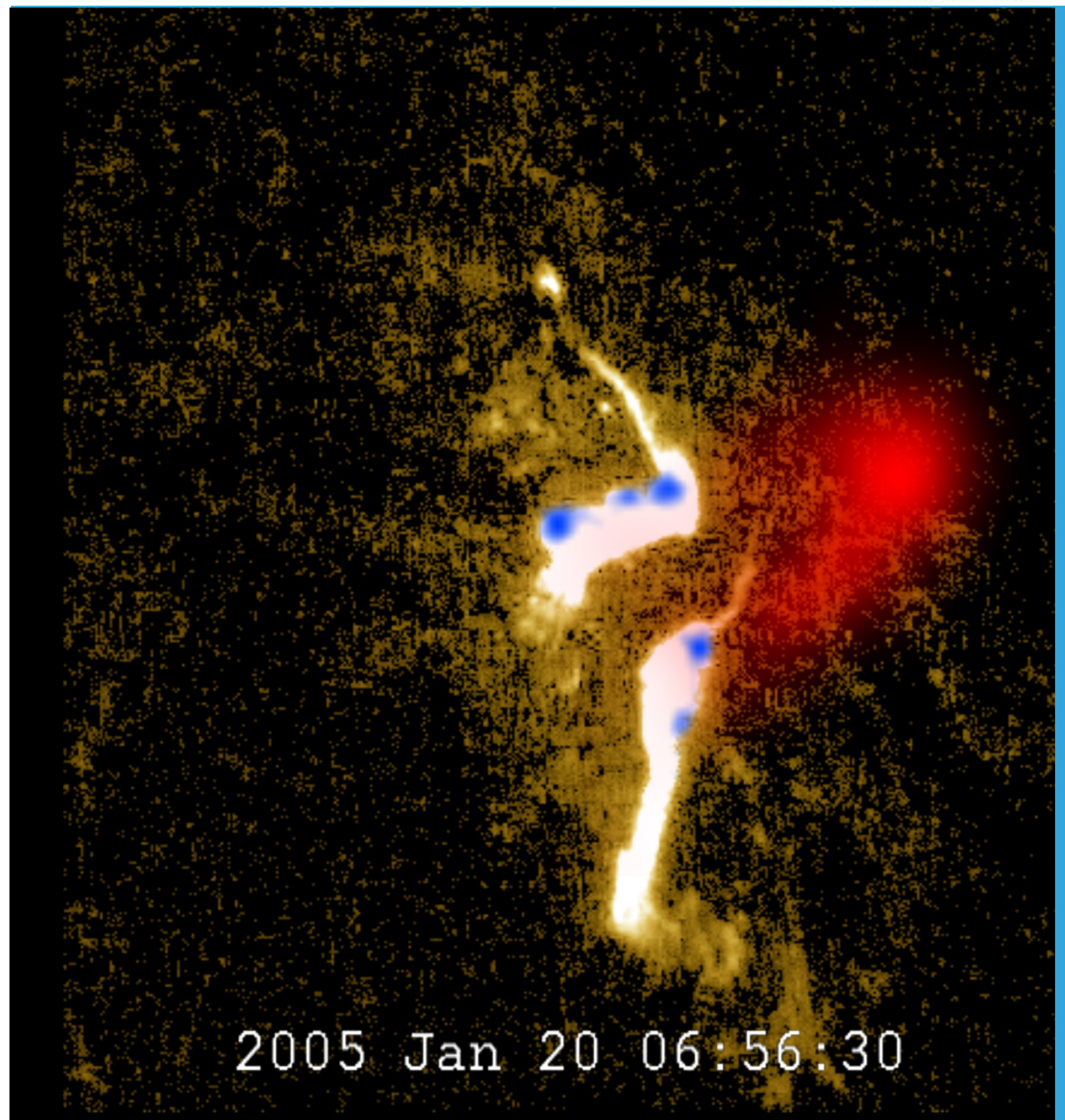
Intense plasma heating and and ionisation results in a broadband enhancement to the solar radiative output and mass flows.

SOLAR FLARES – OBSERVATIONS

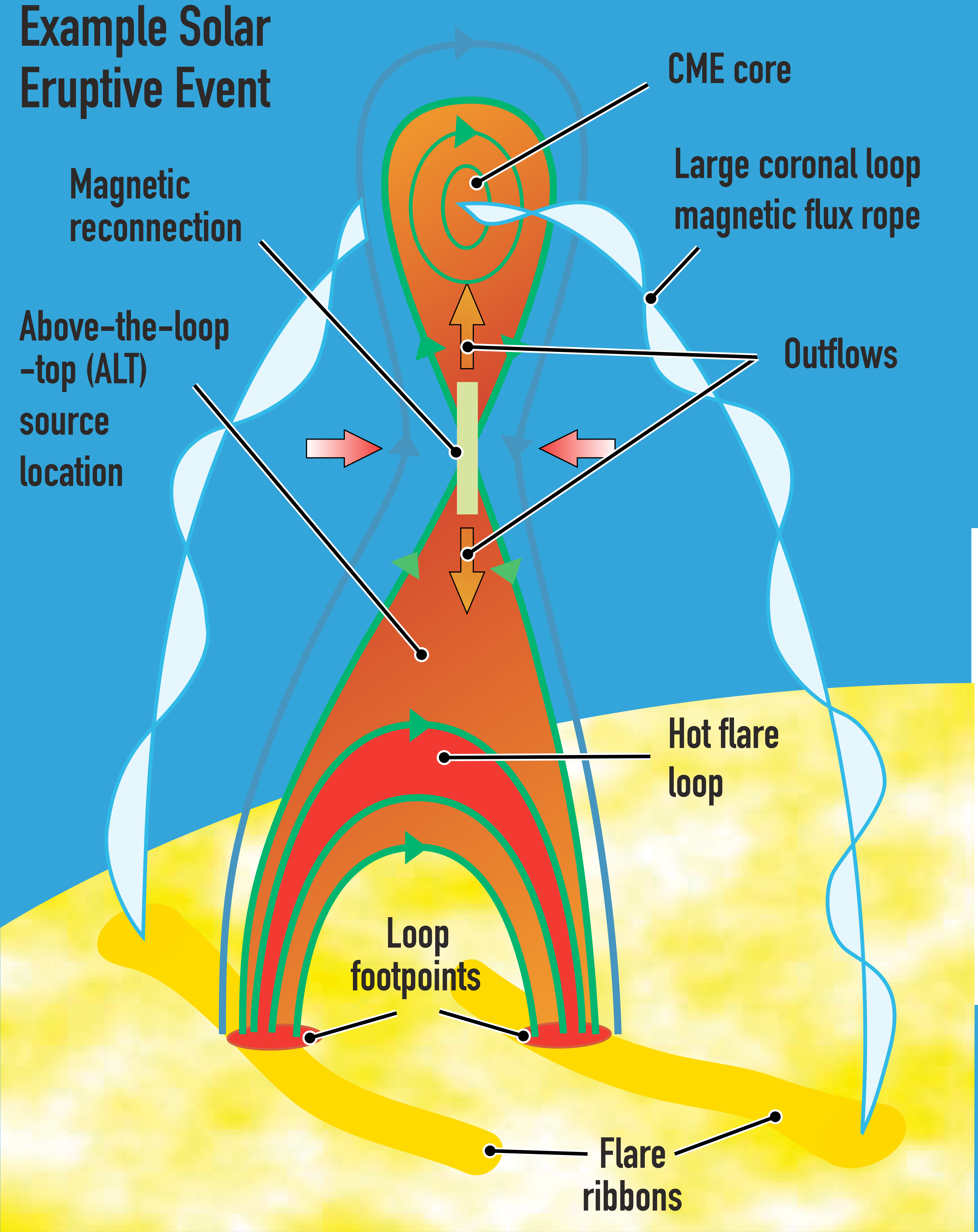








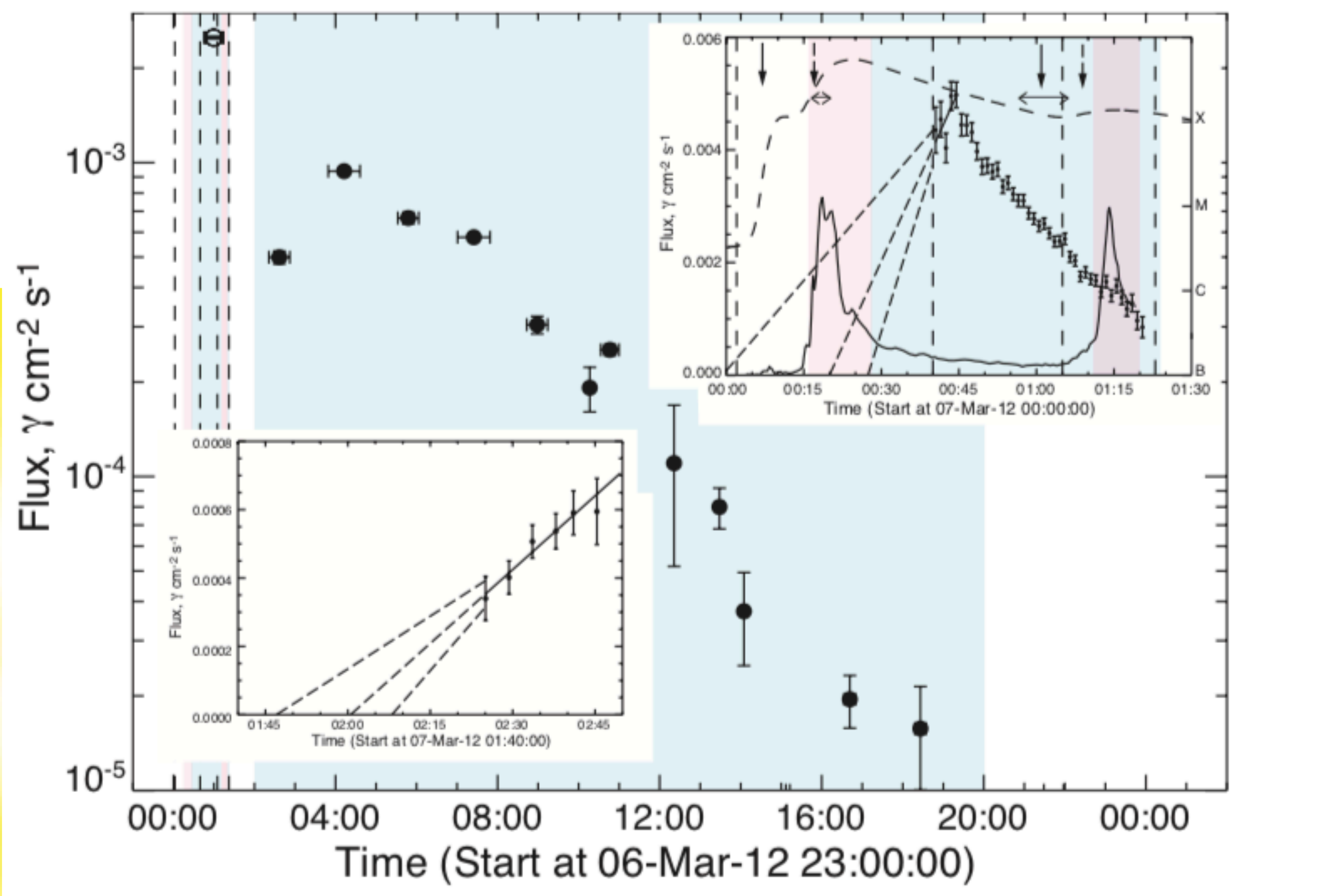
X-ray obs can be used to derive non-thermal electron distributions (which are then used to drive flare models).

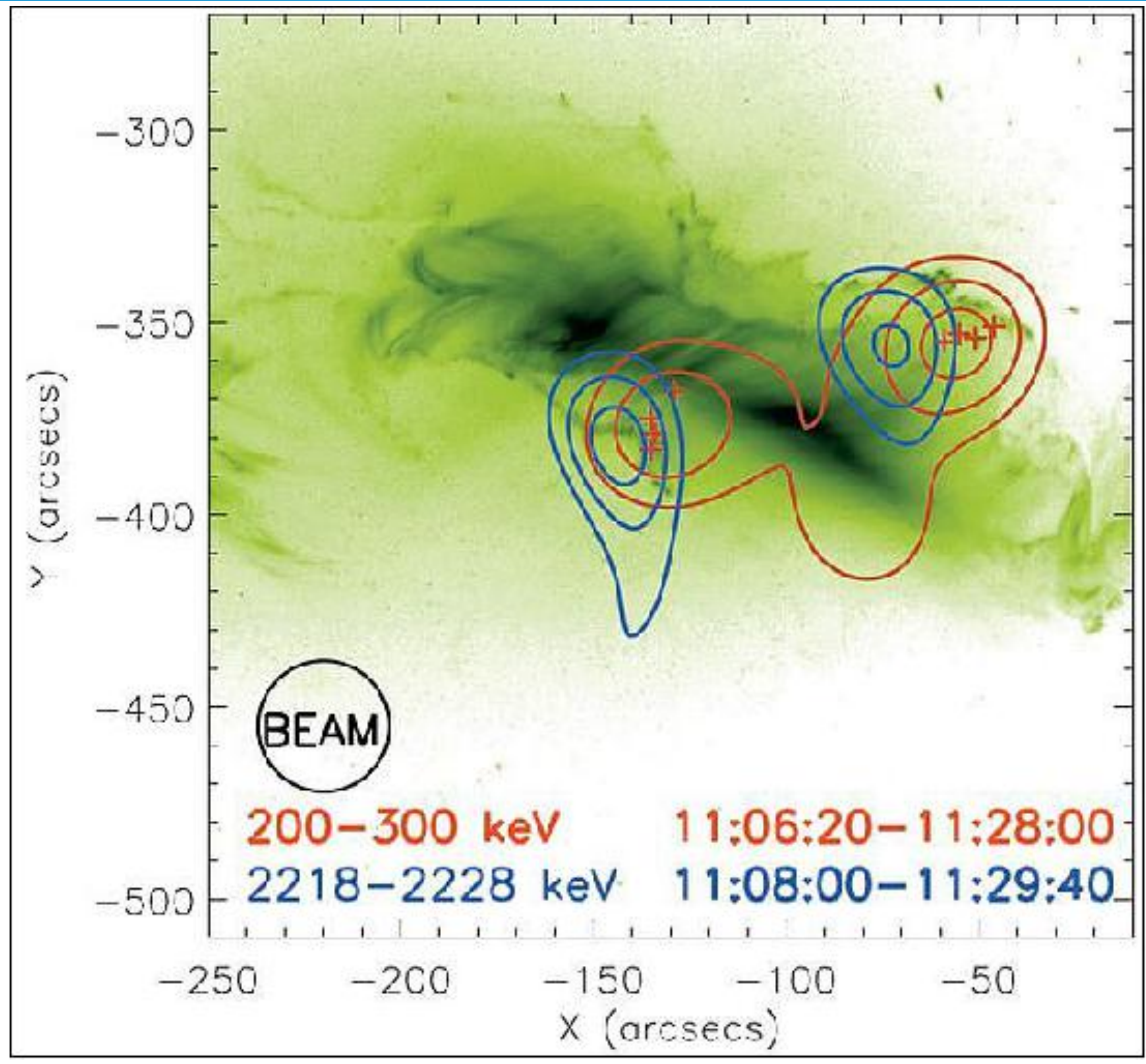


SOLAR FLARES - OBSERVATIONS

γ-ray observations (e.g. RHESSI, GRIPS, FERMI/LAT) offer a window on high energy protons (> MeV)

However, observations are not common and we don't have a clear picture on spectral properties, e.g. energy content and spectral distribution, of non-thermal protons.

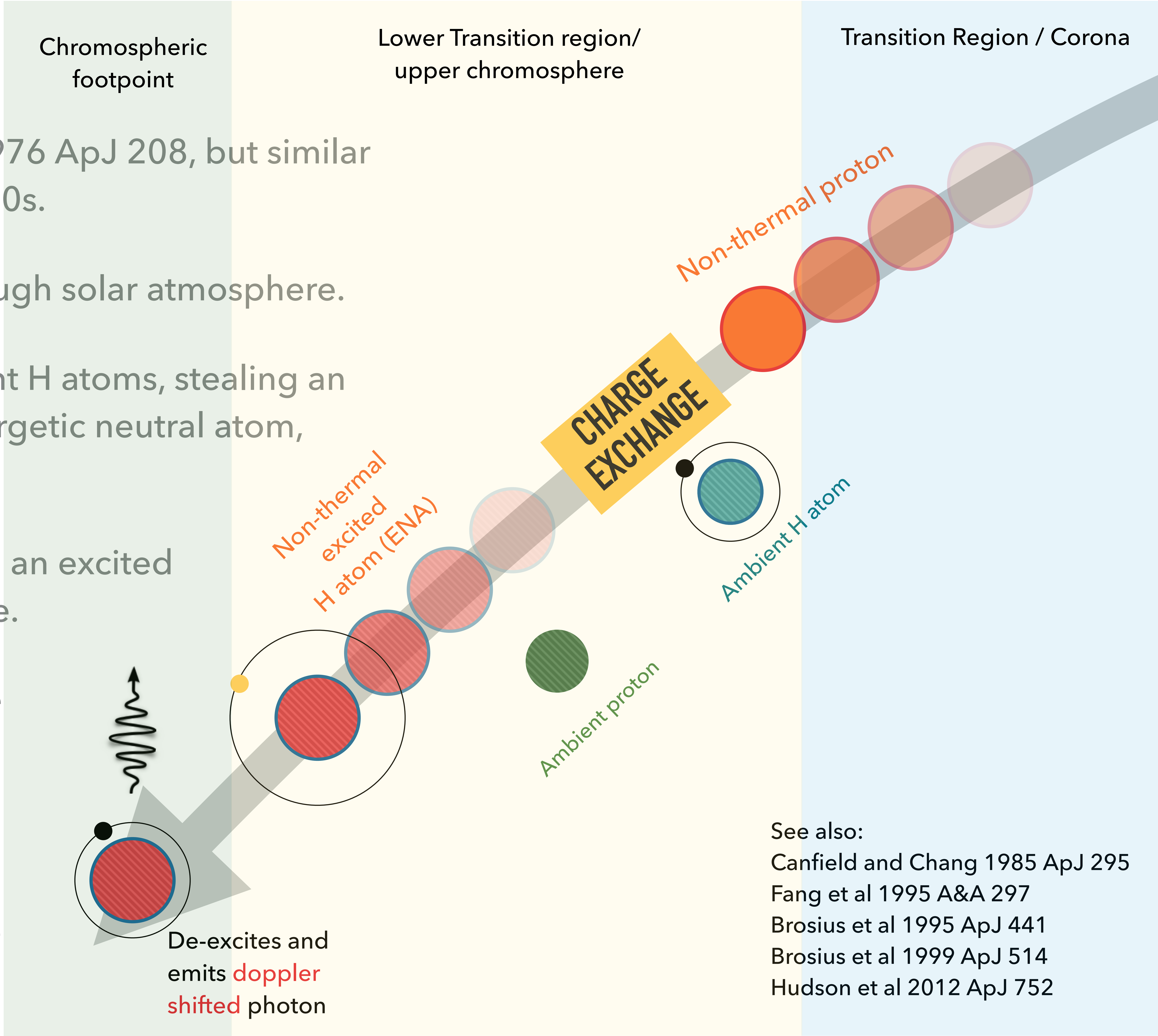




In addition to γ-ray observations, we need a means to observe and diagnose the properties of lower energy 10–100s keV non-thermal protons!

ORRALL-ZIRKER EFFECT OVERVIEW

- 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).



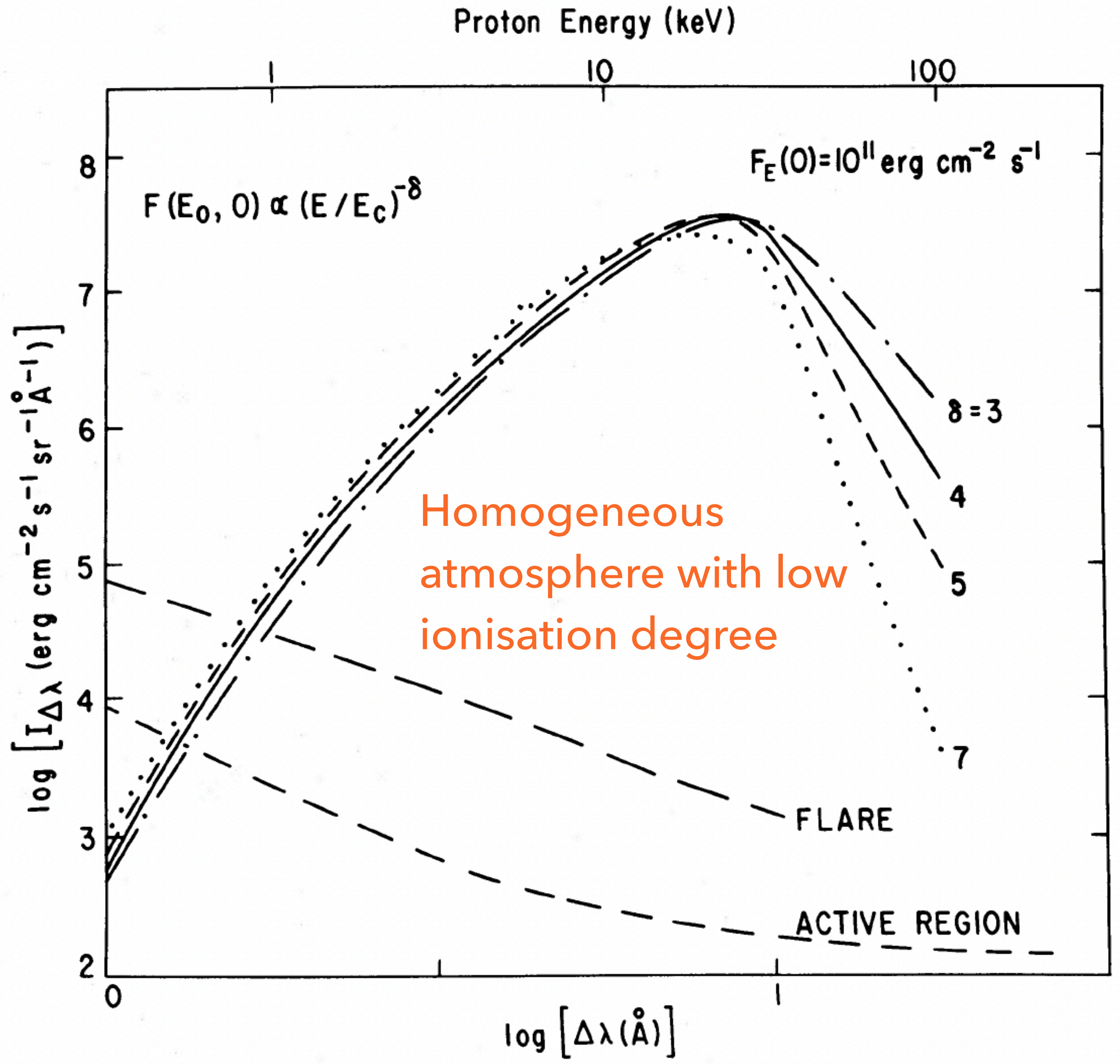
See also:
Canfield and Chang 1985 ApJ 295
Fang et al 1995 A&A 297
Brosius et al 1995 ApJ 441
Brosius et al 1999 ApJ 514
Hudson et al 2012 ApJ 752

ORRALL-ZIRKER EFFECT OVERVIEW

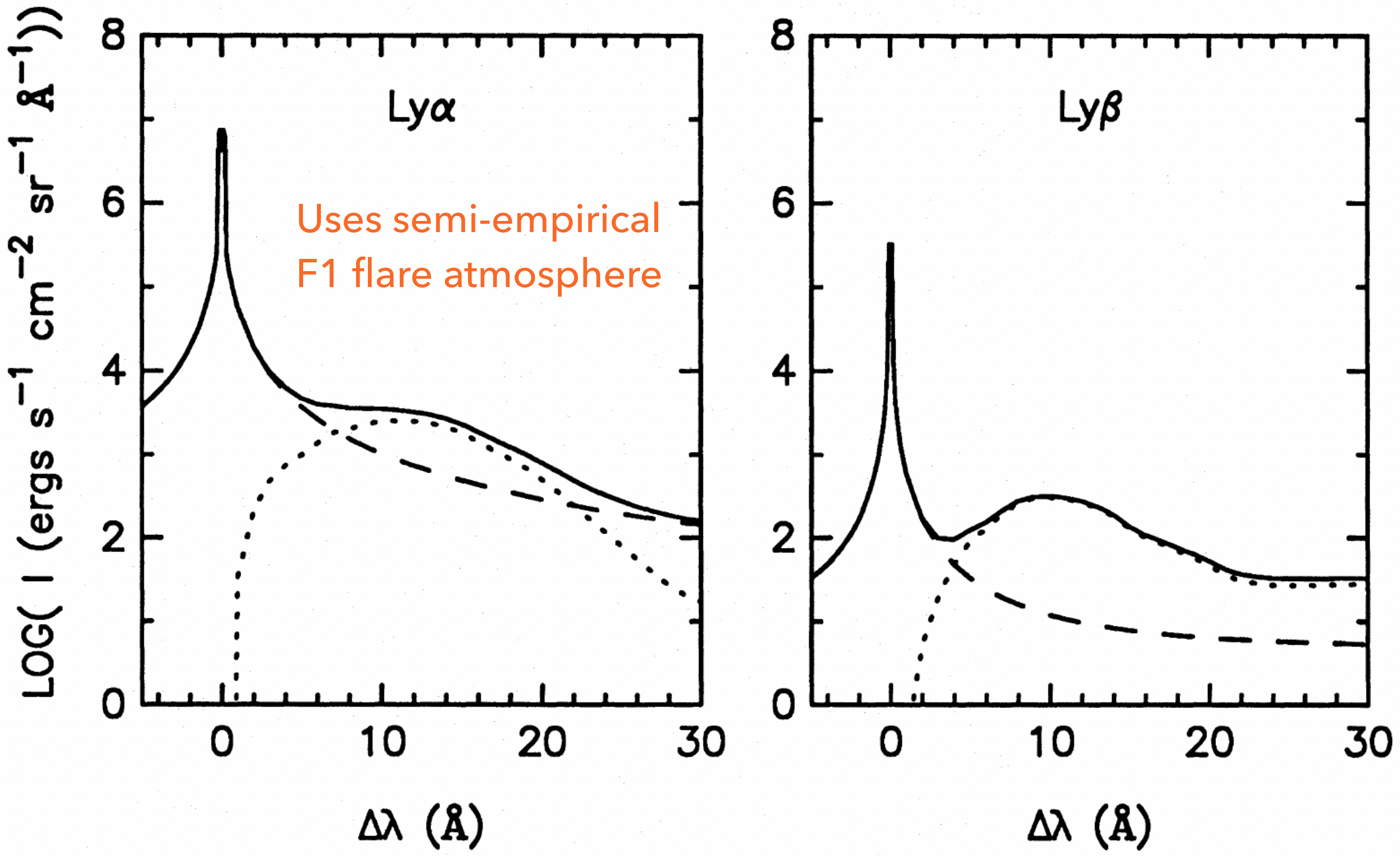
- Theoretical results suggested that non-thermal Ly α and Ly β emission would be detectable. These earlier works used semi-empirical flare atmospheres to predict ‘regular’ Lyman flare emission.

- 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

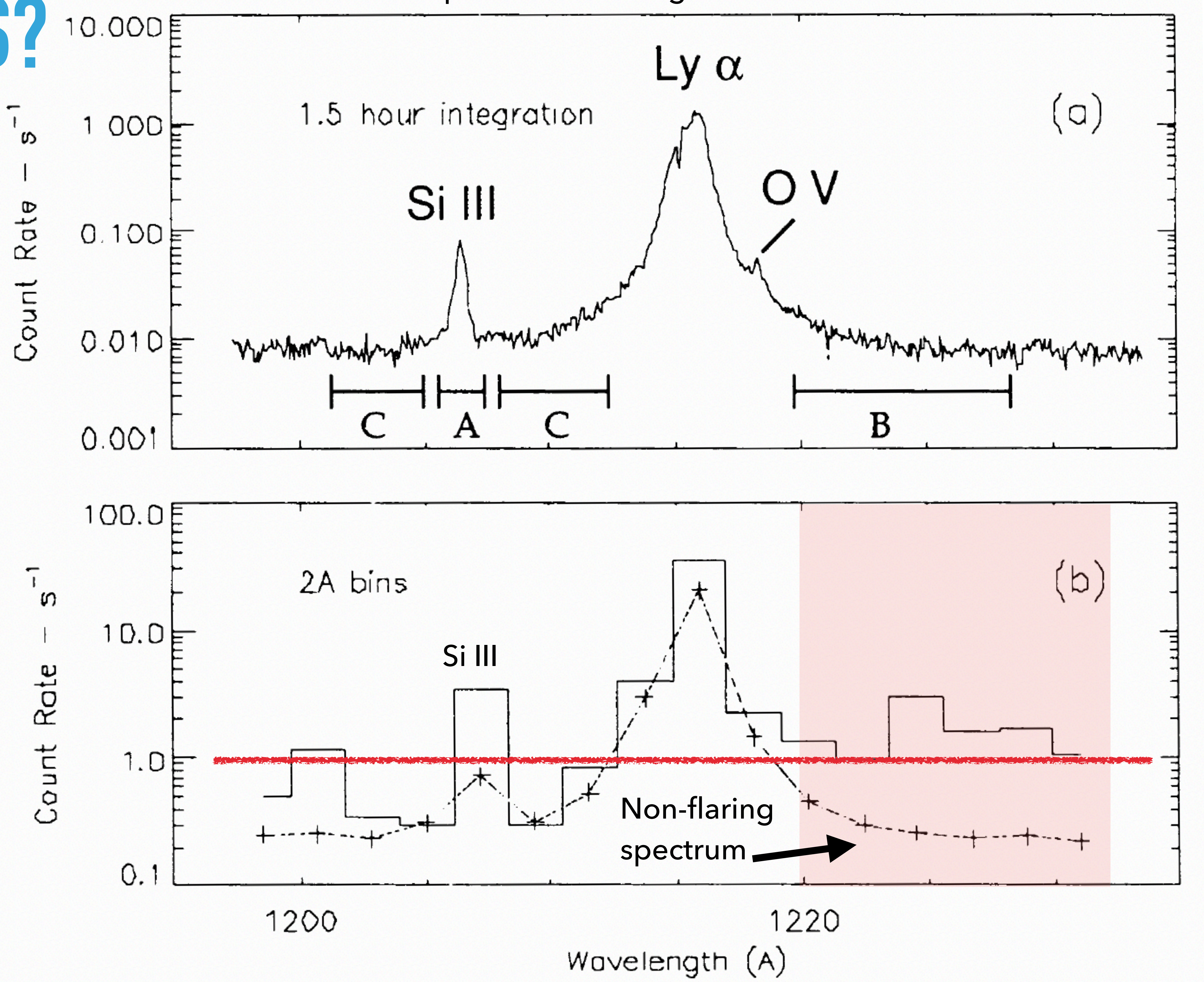
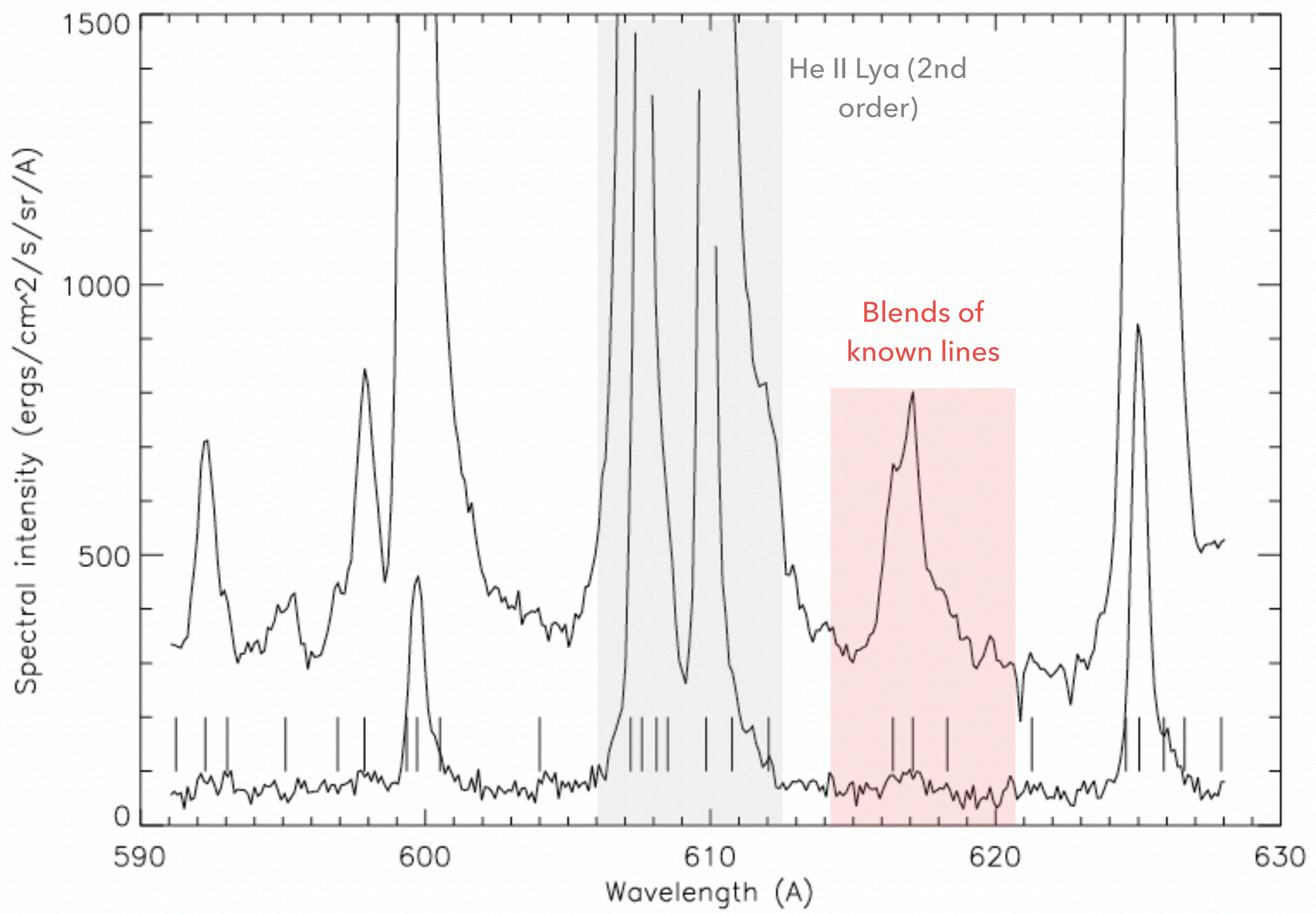


FIG. 1.—(*a*) An integration of all spectra taken during 1.5 hr of observing. The bars indicate regions of integration used in the analysis. Geocoronal emission affects only the central 0.6 Å of the line. (*b*) Integration of the spectrum over the 3.2 s of the peak Lyman-α red wing enhancement, in 2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

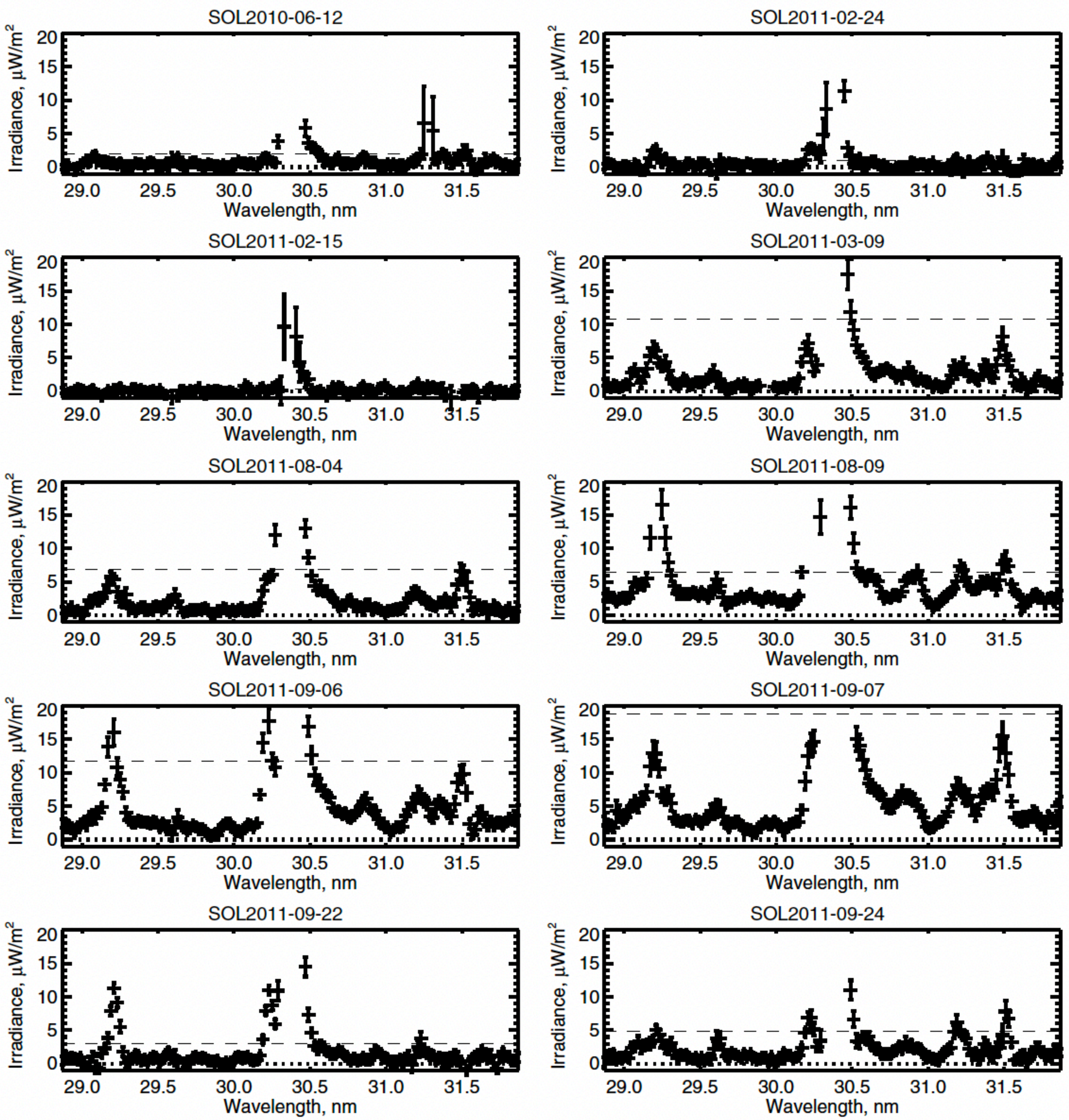
Flare spectrum observed by SOHO/CDS, with He II 304Å emission observed in second order. Adapted from Brosius 2001



ORRALL-ZIRKER EFFECT — OBSERVATIONS?

- Hudson et al 2012 ApJ 752 also searched for the OZ effect in He II 304Å, using disk integrated SDO/EVE flare excess spectra.
- Despite selecting known γ-ray events and a flare that produced solar energetic particles, the He II 304Å line showed no sign of enhanced red-wing emission of the type expected from the OZ effect.

Flare excess irradiance spectra from Hudson et al 2012

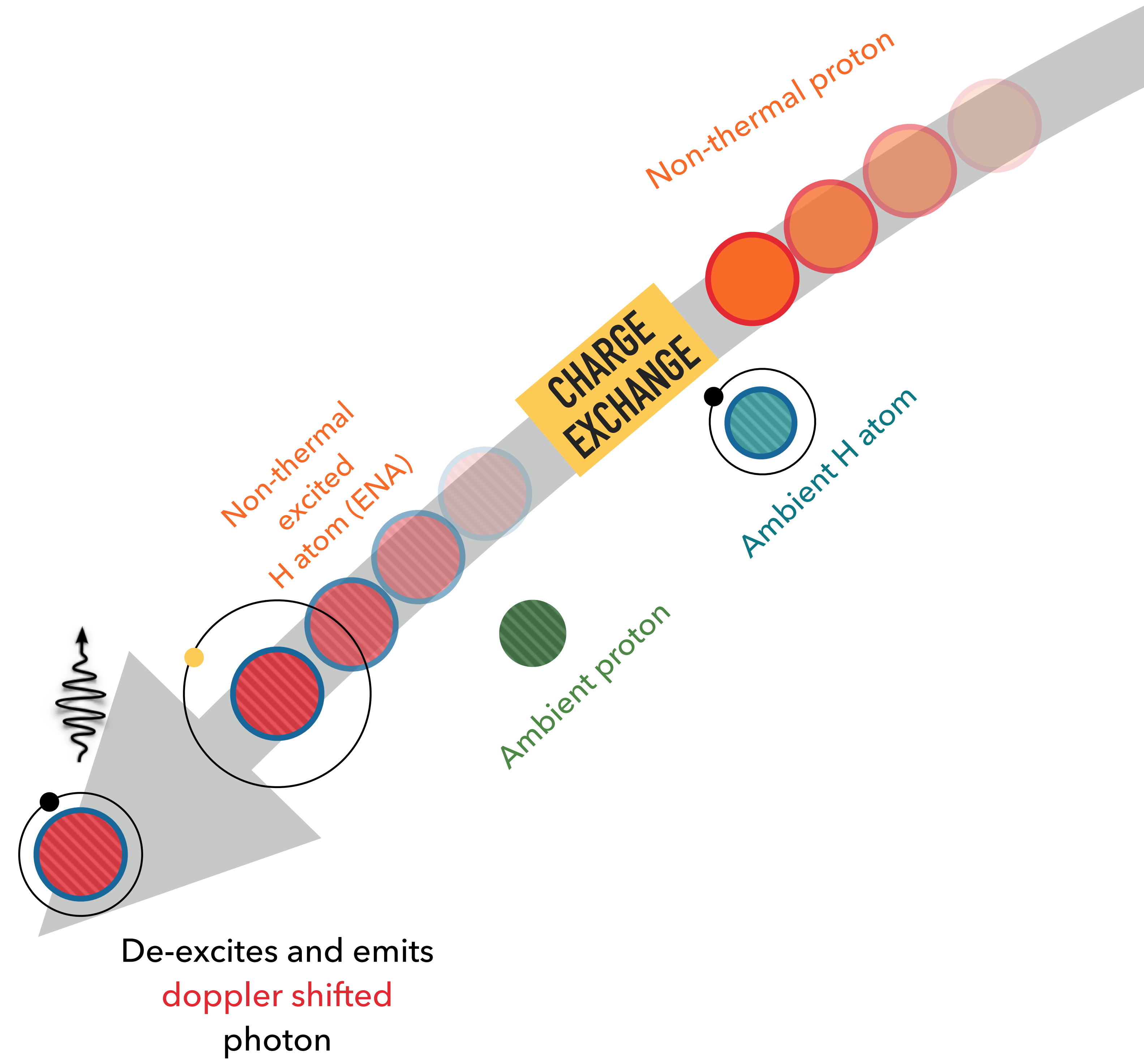


REVISITING OZ WITH RADYN + FP

- 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, the **RADYN** (Carlsson & Stein 1995, Allred et al 2015) code **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

- We produced a large grid of proton beam driven flare simulations with the following parameters:

E_c = [25, 50, 100, 150, 250, 500, 1000, 3000] keV

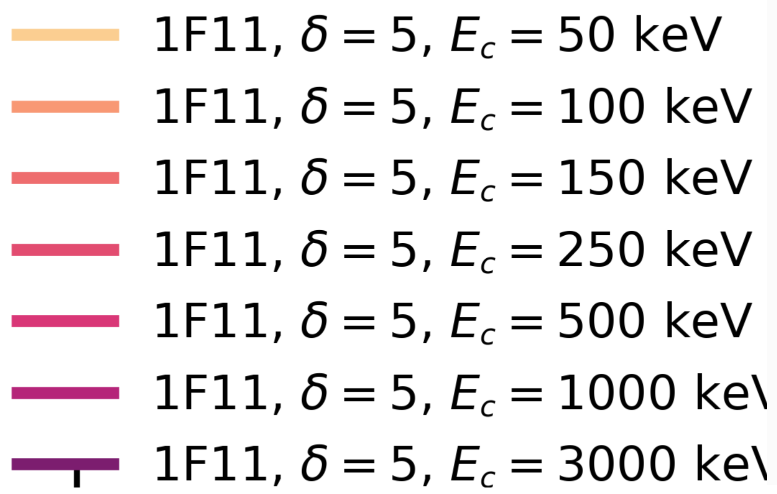
δ = [3, 4, 5, 6, 7, 8]

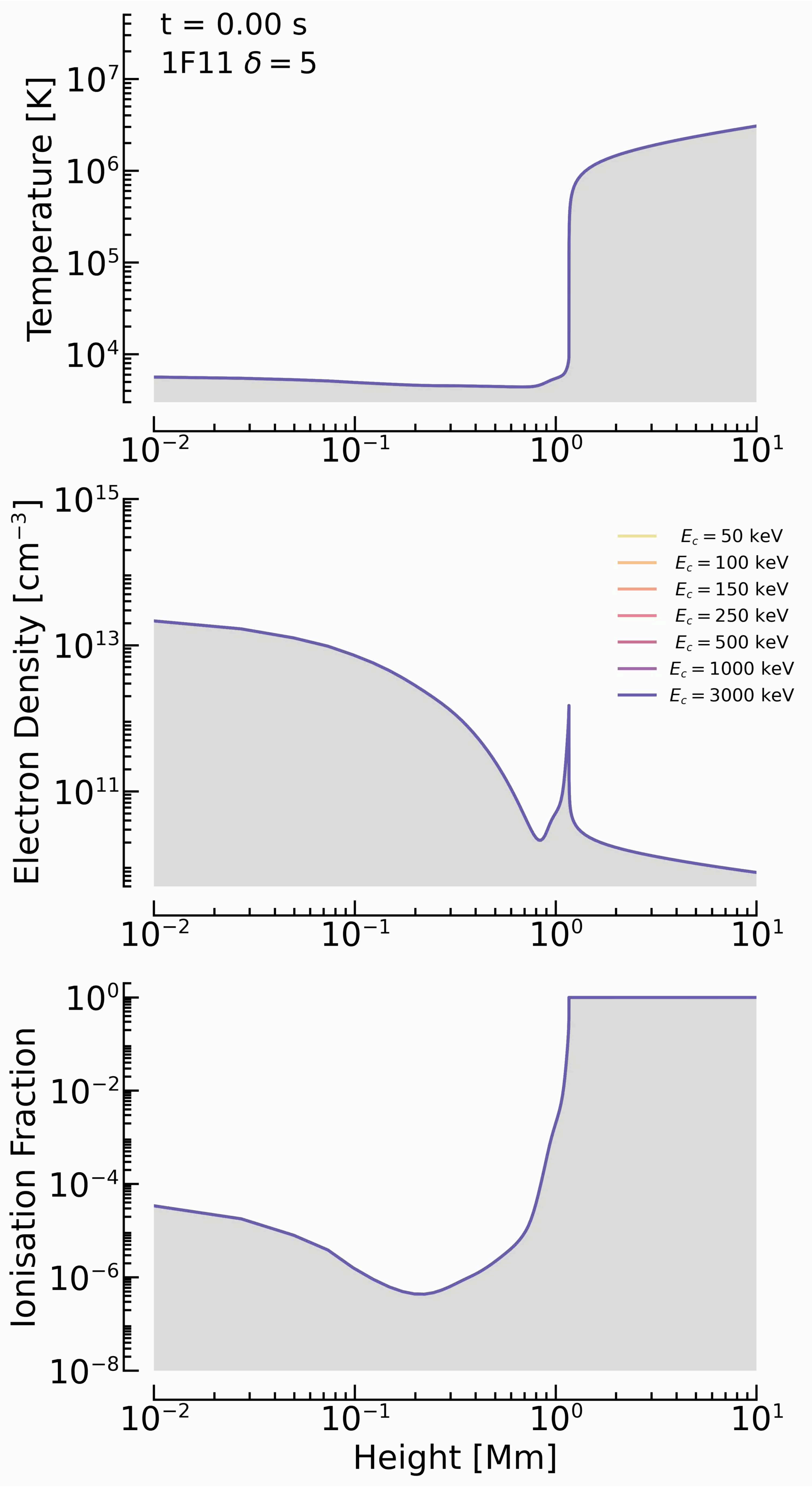
Flux = [1×10^{9}, 1×10^{10}, 1×10^{11}] erg s^{-1} cm^{-2}

- We don't discuss the dynamics of the proton beam driven flares here, but Joel Allred has a talk in this same session on that topic!

- Also, only a subset have been explored with regards to the OZ effect so far.

- Movie shows effect of varying the E_c of the proton distribution for fixed δ = 5 and flare strength of 1×10^{11} erg cm^{-2} s^{-1}.

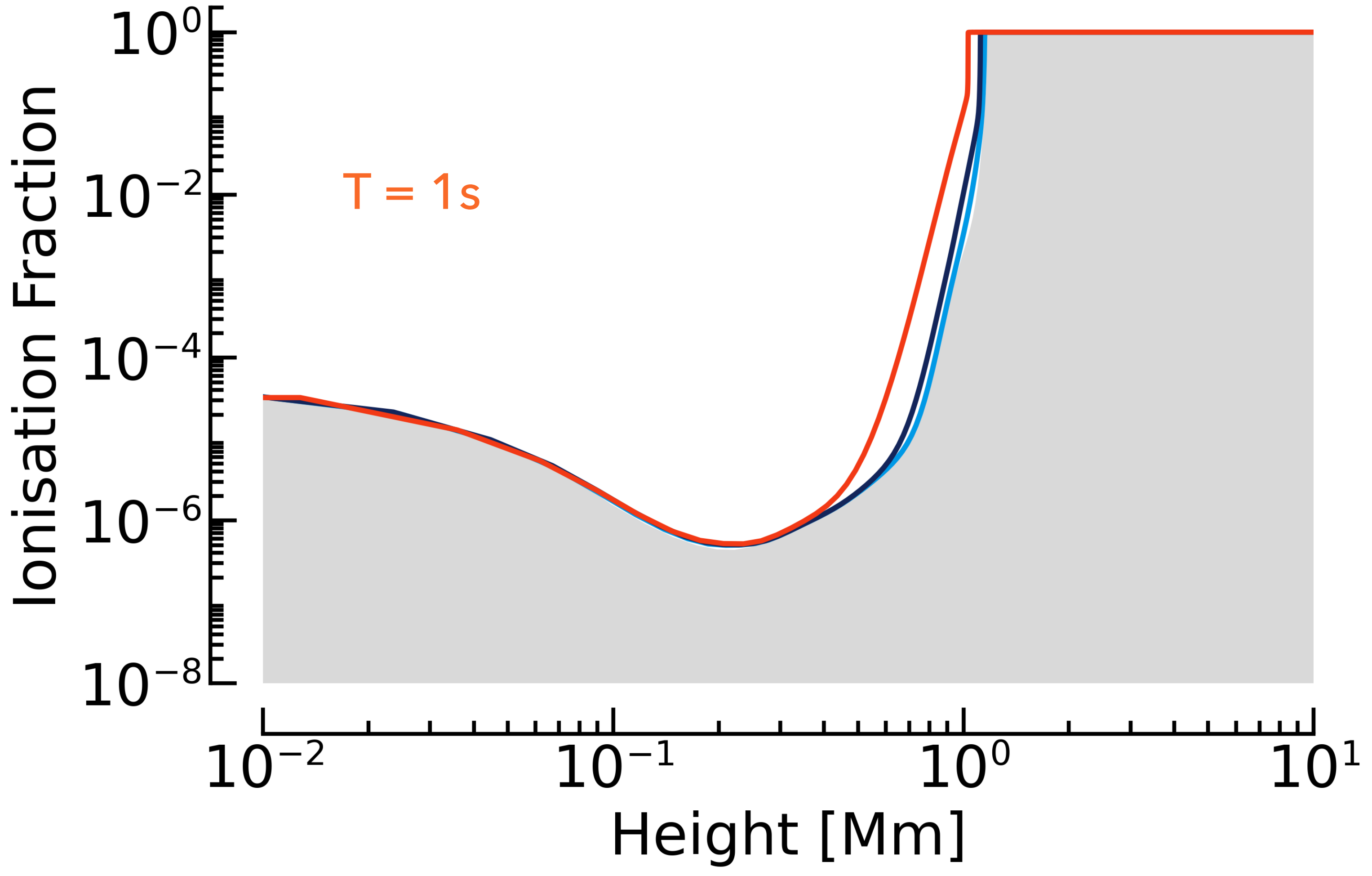


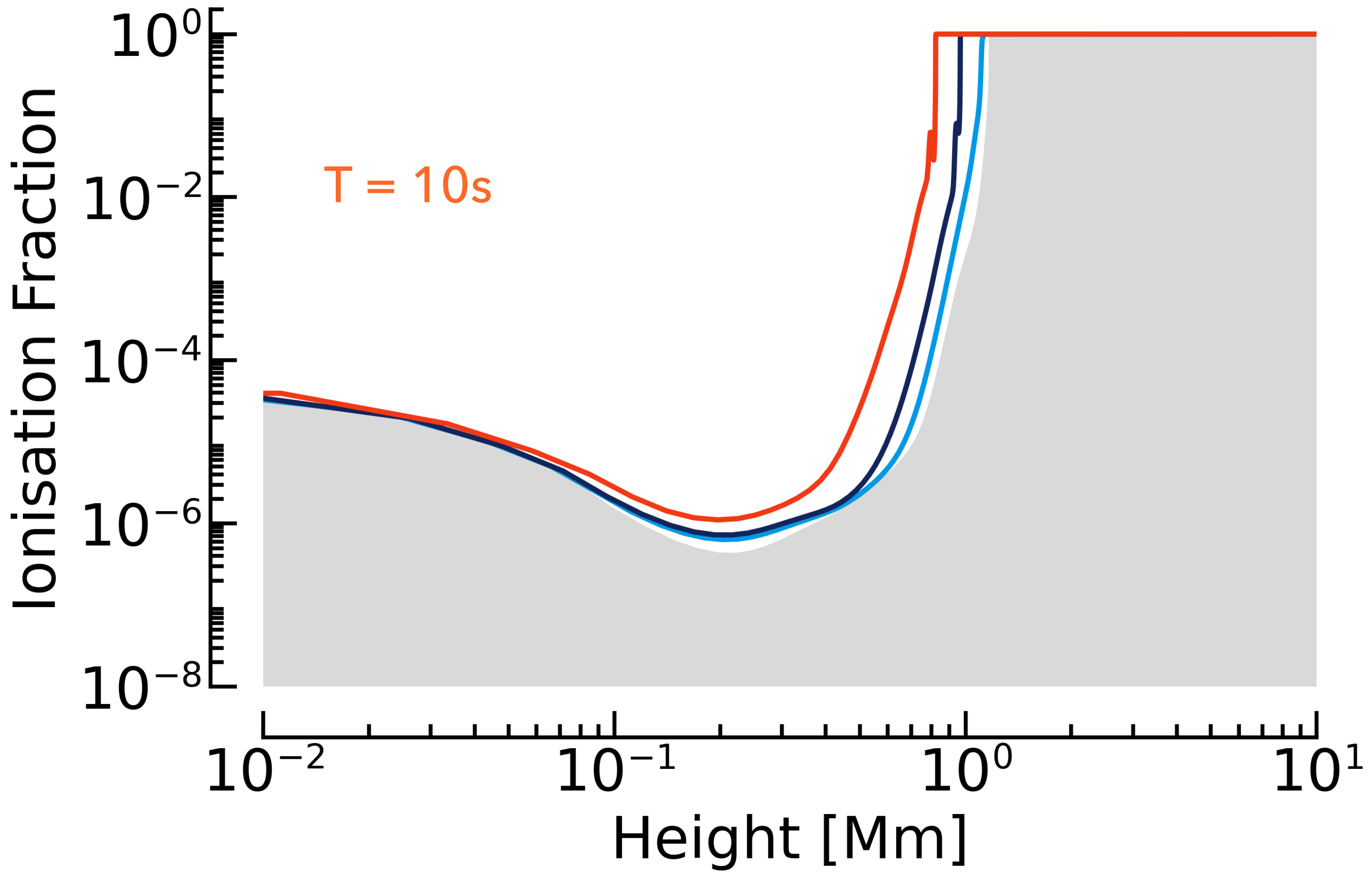


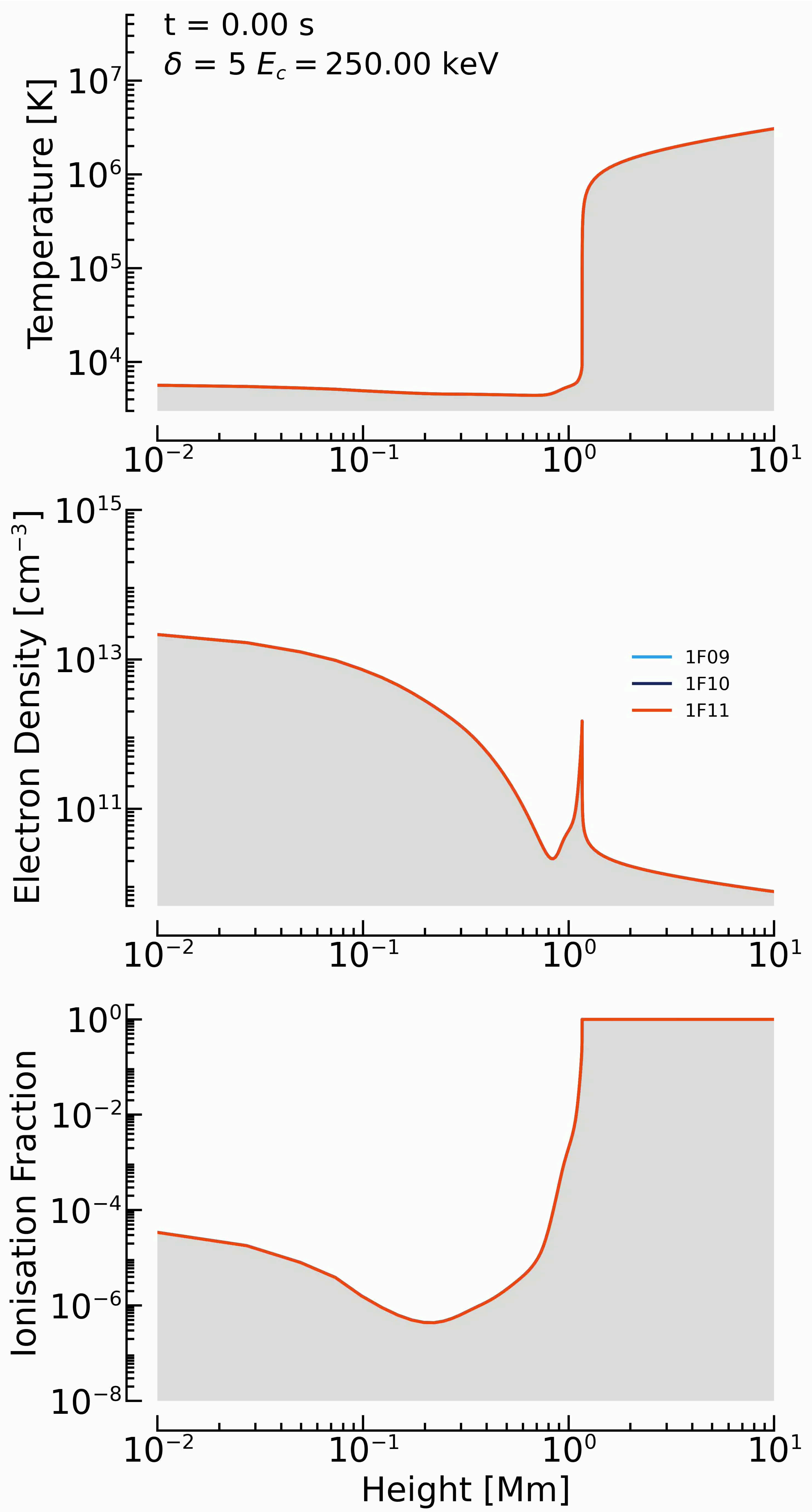
PROTON BEAM SIMULATIONS FROM RADYN+FP

- Here we vary the flare strength, for fixed proton δ = 5 and E_c = 250 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





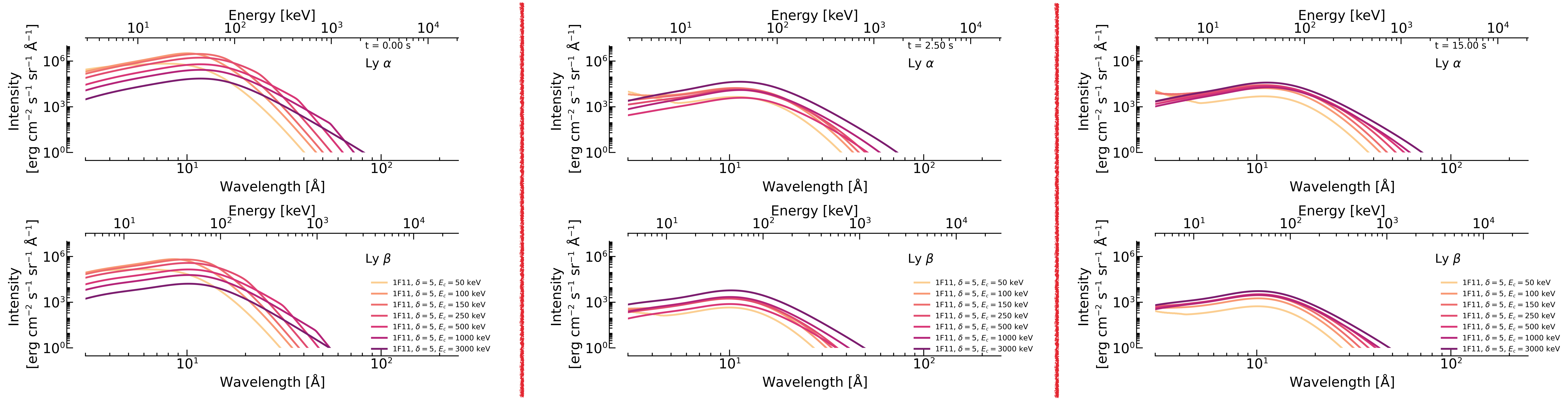


NONTHERMAL HYDROGEN LINE EMISSION

- Here we show the OZ emission from Ly α and Ly β in simulations that vary the E_c of the proton distribution for fixed δ = 5 and injected flux of 1×10^{11} erg cm^{-2} s^{-1}.

- As ionisation begins, strength of OZ emission diminishes as much fewer charge exchange interactions occur.

1F11, $\delta = 5$, $E_c = 50$ keV
1F11, $\delta = 5$, $E_c = 100$ keV
1F11, $\delta = 5$, $E_c = 150$ keV
1F11, $\delta = 5$, $E_c = 250$ keV
1F11, $\delta = 5$, $E_c = 500$ keV
1F11, $\delta = 5$, $E_c = 1000$ keV
1F11, $\delta = 5$, $E_c = 3000$ keV

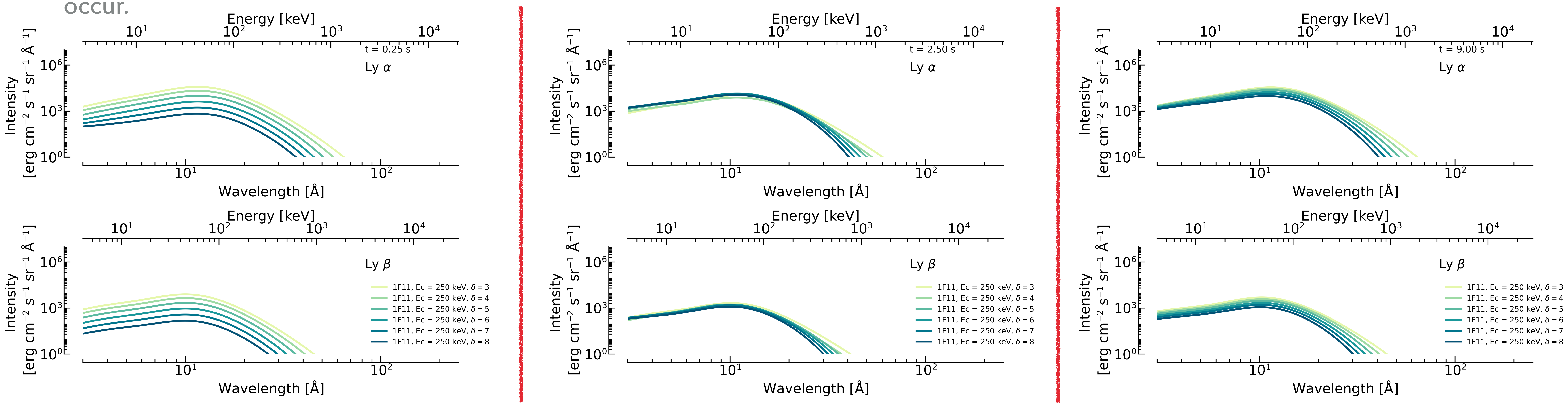


T = 0s T = 2.5s T = 15s

NONTHERMAL HYDROGEN LINE EMISSION

- 1F11, Ec = 250 keV, $\delta = 3$
- 1F11, Ec = 250 keV, $\delta = 4$
- 1F11, Ec = 250 keV, $\delta = 5$
- 1F11, Ec = 250 keV, $\delta = 6$
- 1F11, Ec = 250 keV, $\delta = 7$
- 1F11, Ec = 250 keV, $\delta = 8$

- Here we show the OZ emission from Ly α and Ly β in simulations that vary the δ of the proton distribution for fixed E_c = 250 keV and injected flux of 1×10^{11} erg cm^{-2} s^{-1}.
- As ionisation begins, strength of OZ emission diminishes as much fewer charge exchange interactions occur.



T = 0.25s

T = 2.5s

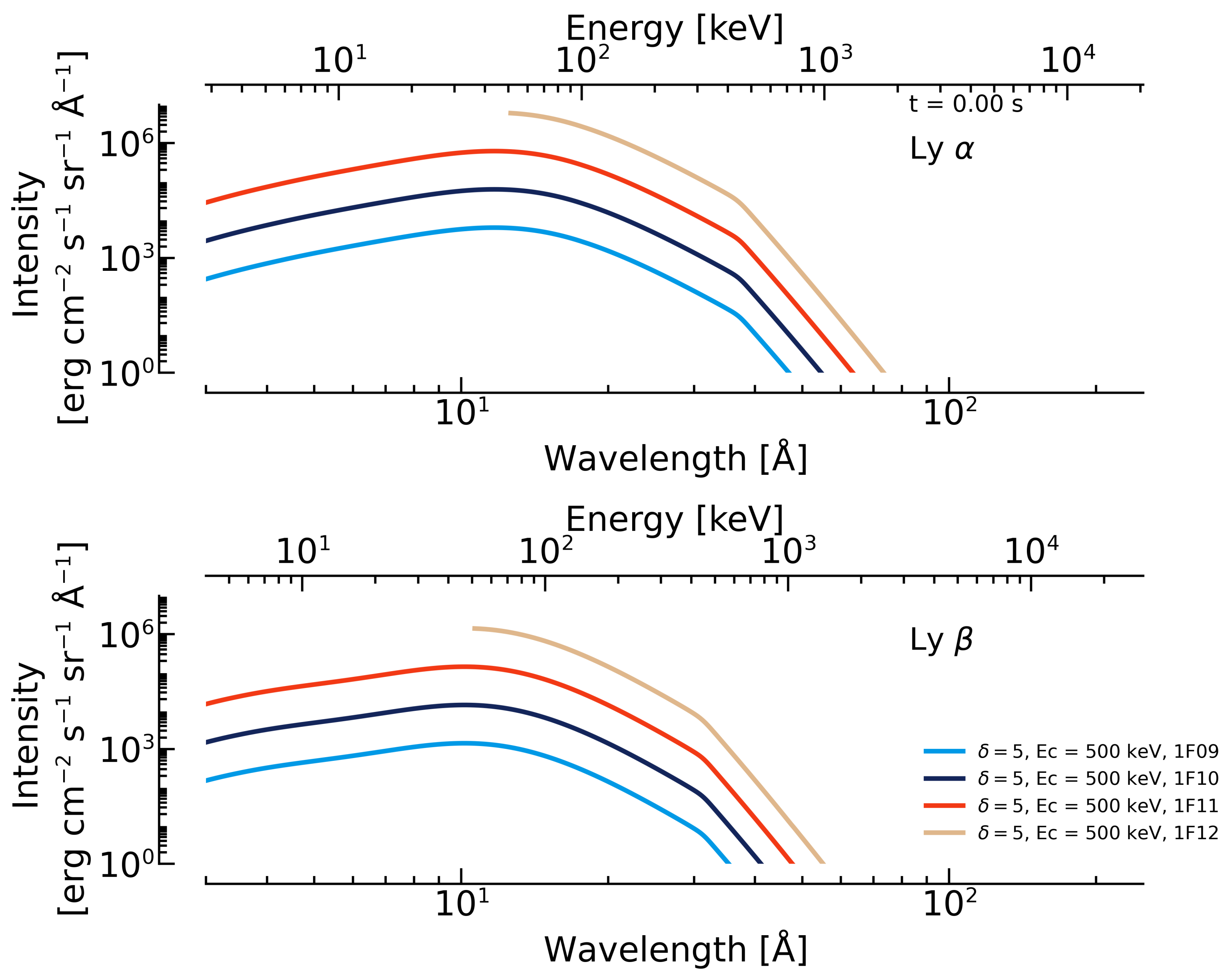
T = 9s

NONTHERMAL HYDROGEN LINE EMISSION

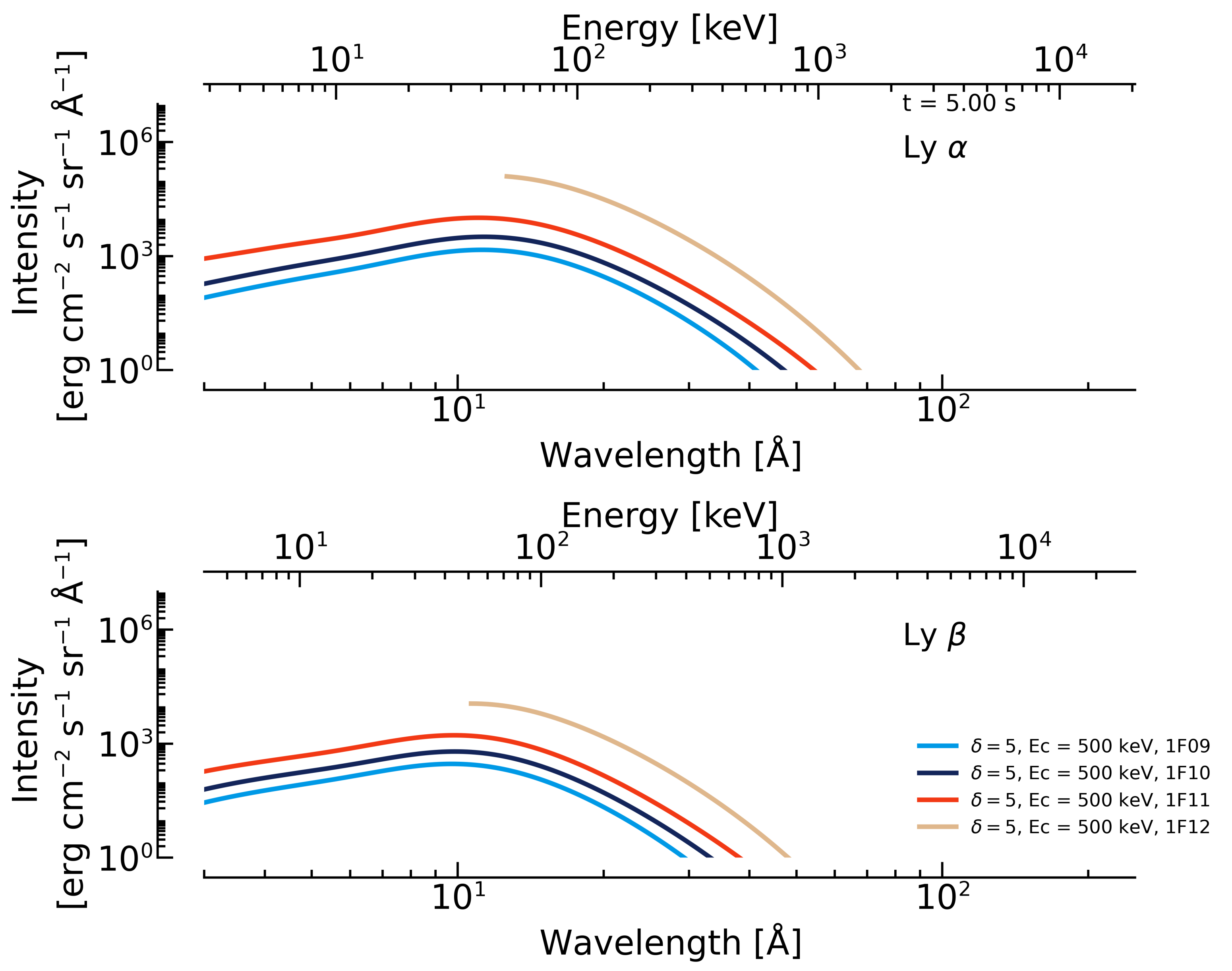
$\delta = 5$, Ec = 500 keV, 1F09
$\delta = 5$, Ec = 500 keV, 1F10
$\delta = 5$, Ec = 500 keV, 1F11
$\delta = 5$, Ec = 500 keV, 1F12

- Here we show the OZ emission from Ly α and Ly β in simulations that vary the injected flux of the proton distribution for fixed E_c = 250 keV and δ = 5.

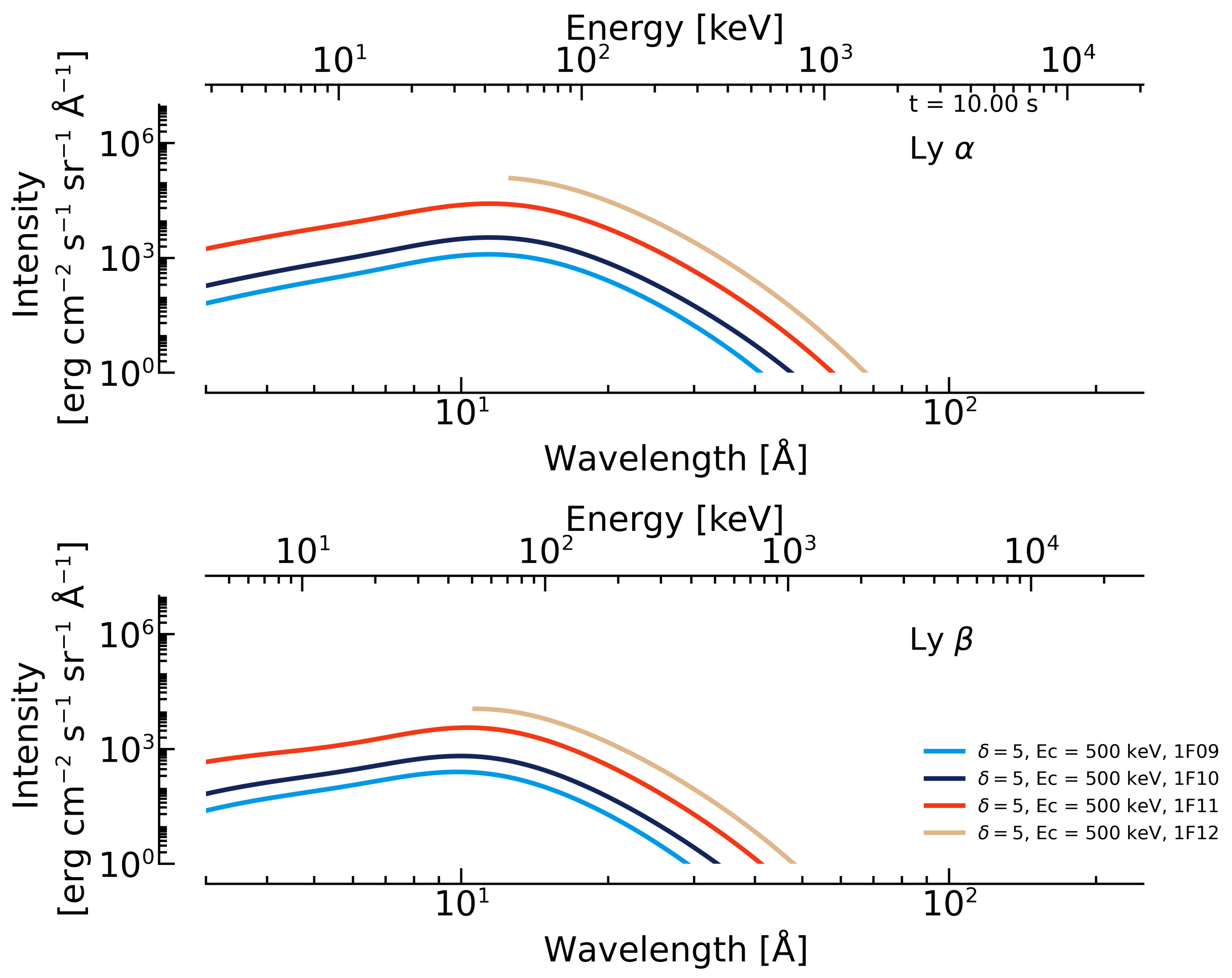
- As ionisation begins, strength of OZ emission diminishes as much fewer charge exchange interactions occur.



T = 0s



T = 5s



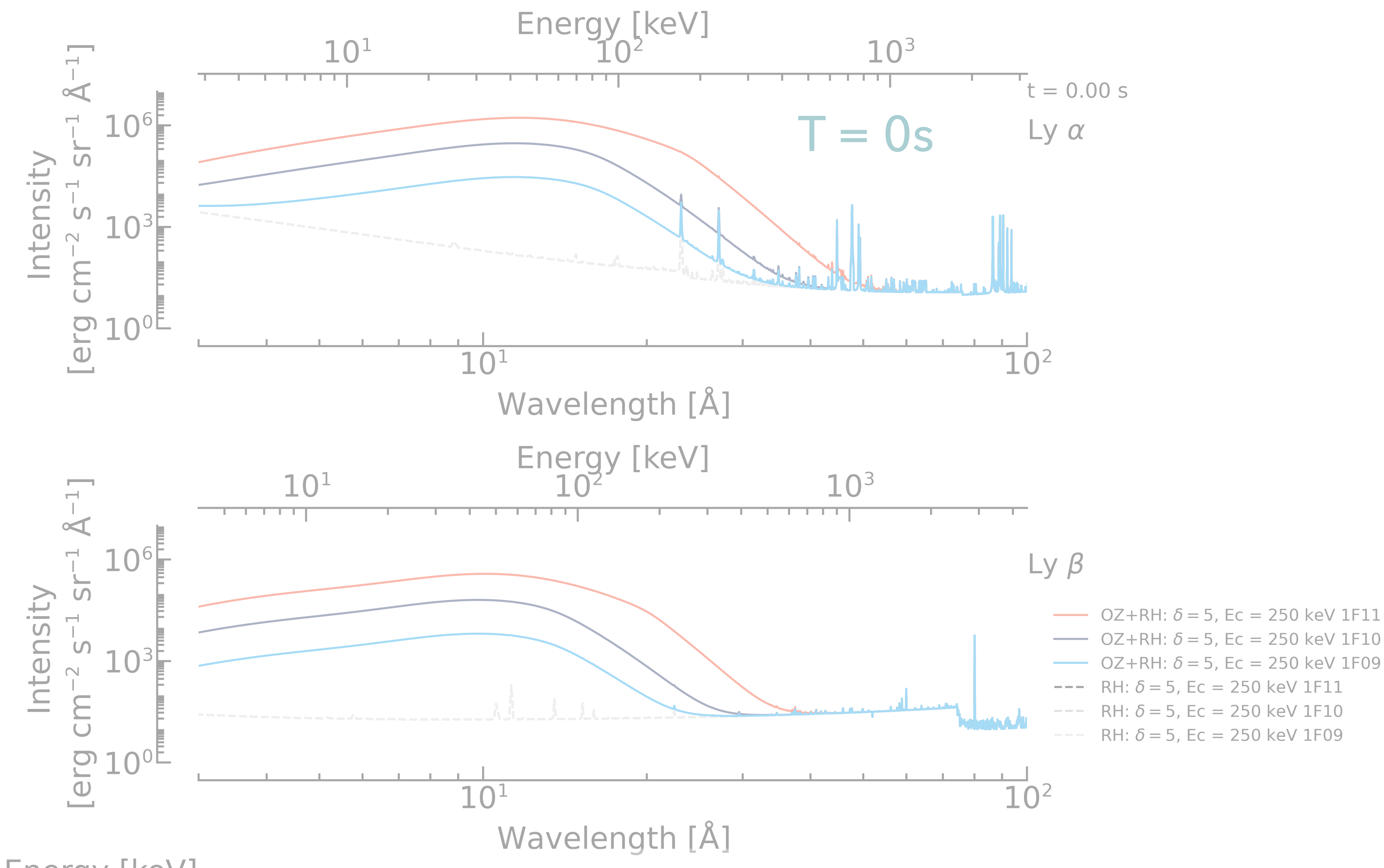
T = 10s

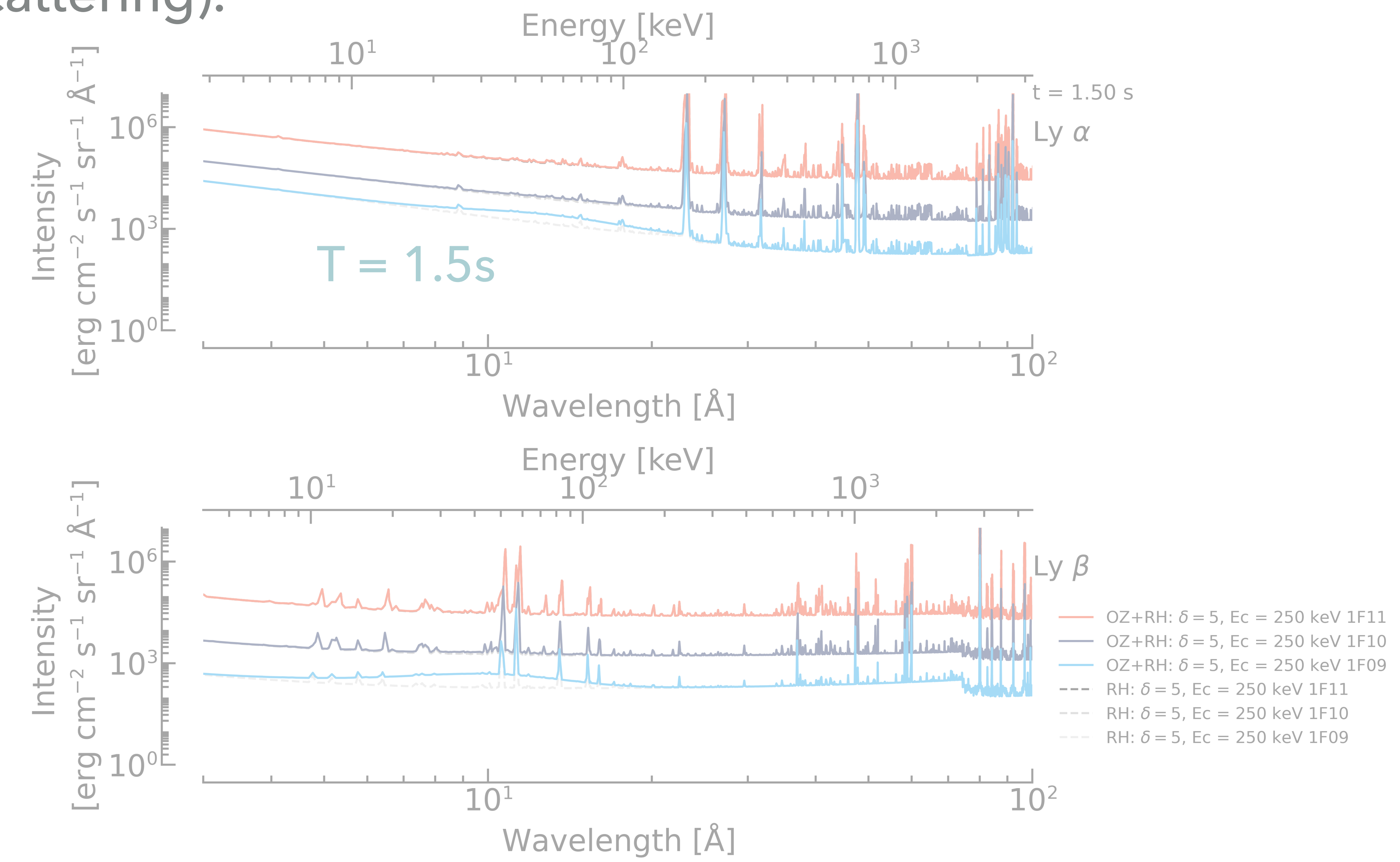
OBSERVATIONAL PROSPECTS

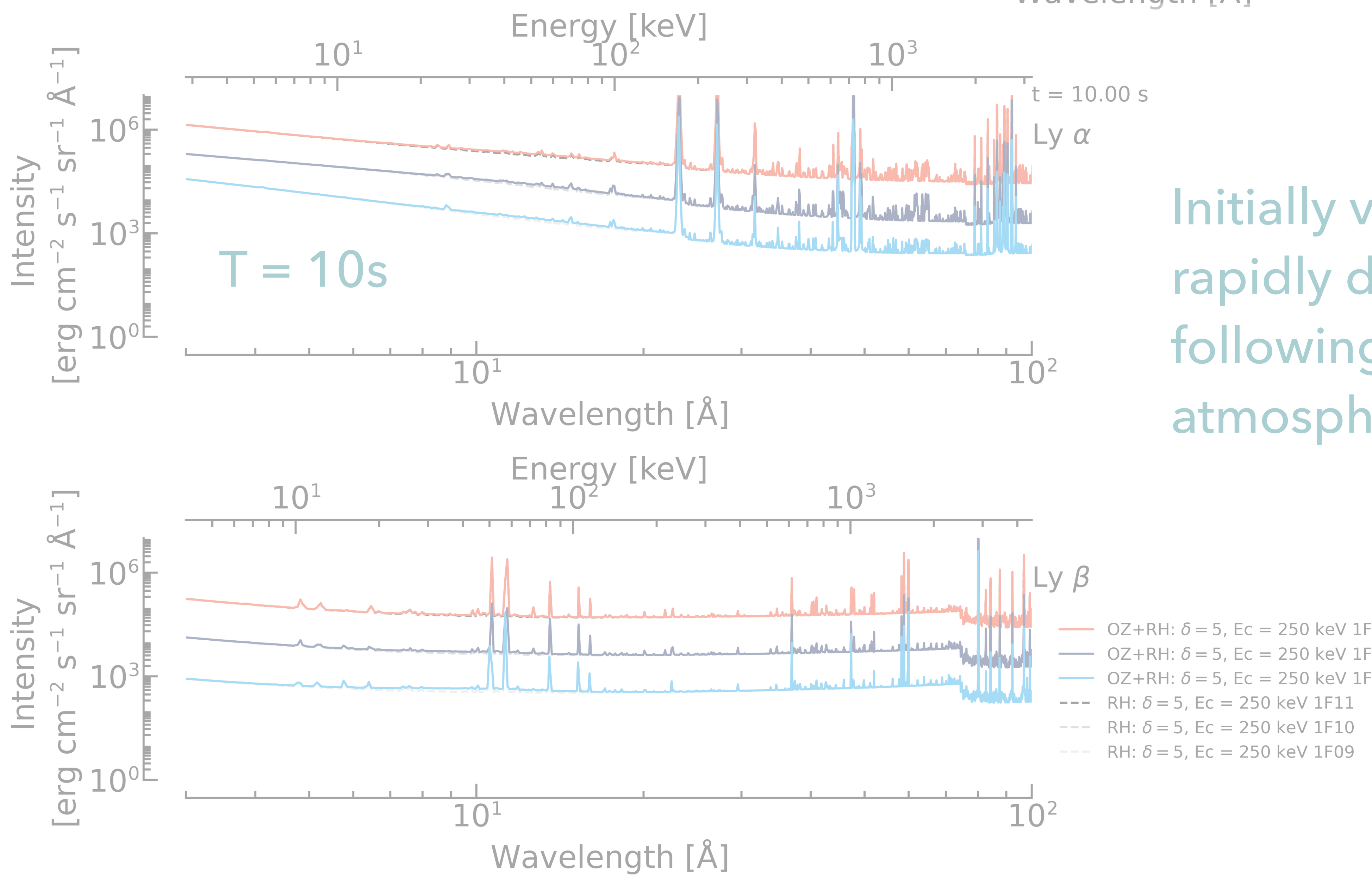
- Can this emission be seen above the background flaring emission?

- Using RADYN flare atmospheres with RH1.5D, we synthesised the spectrum near the Lyα and Lyβ lines for three of our flares (so far): $\delta = 5$, $E_c = 250$keV, $F = [1\times10^{9}, 1\times10^{10}, 1\times10^{11}]$ erg s^{-1} cm^{-2}.

- H, Ca II, Si, C, O I, Mg II, Al solved in NLTE, several other species in LTE, with Kurucz linelists included to account for opacity from forest of lines (LTE, but with scattering).

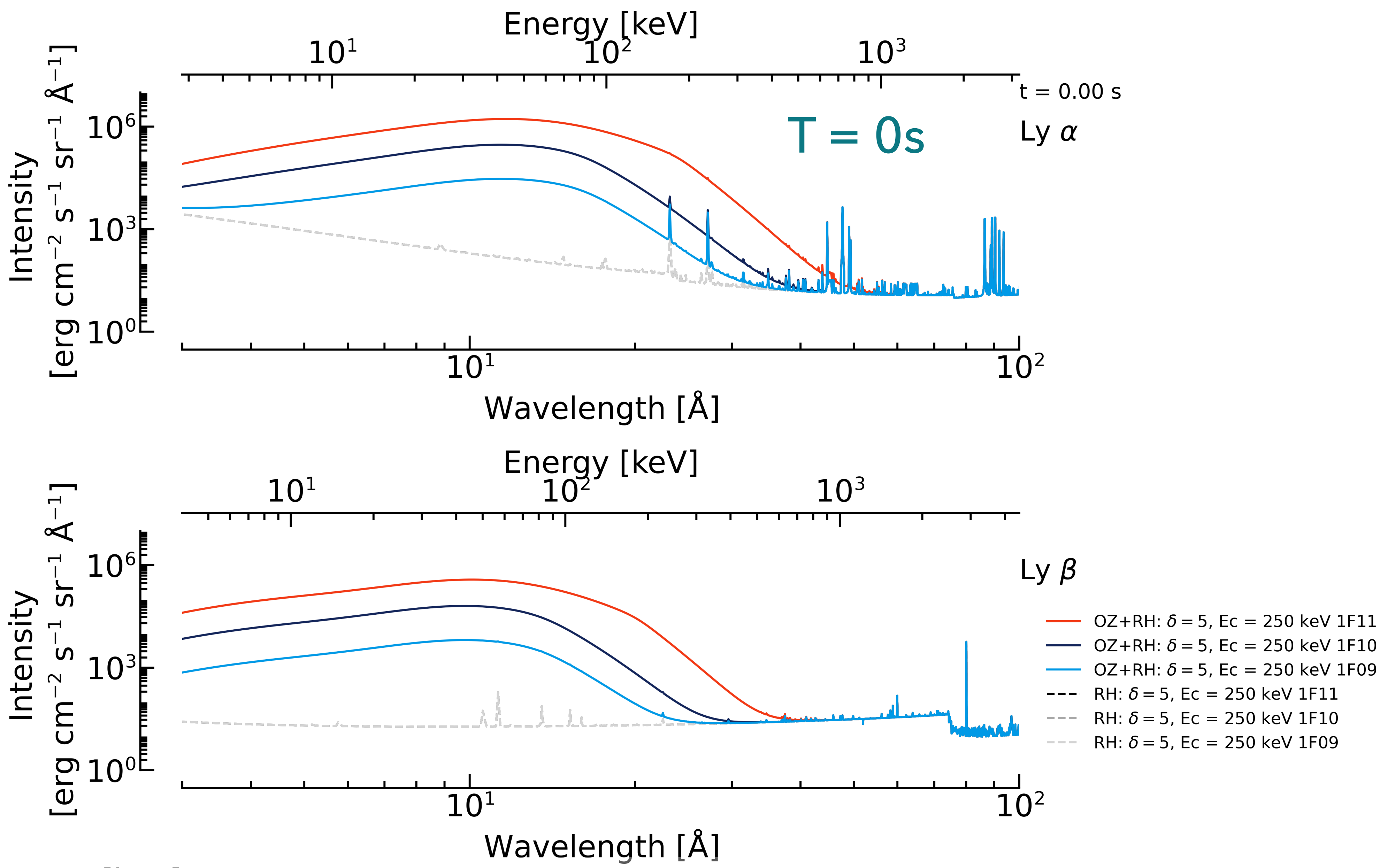






Initially very strong, but rapidly decreases in strength following ionisation of flaring atmosphere.

OBSERVATIONAL PROSPECTS



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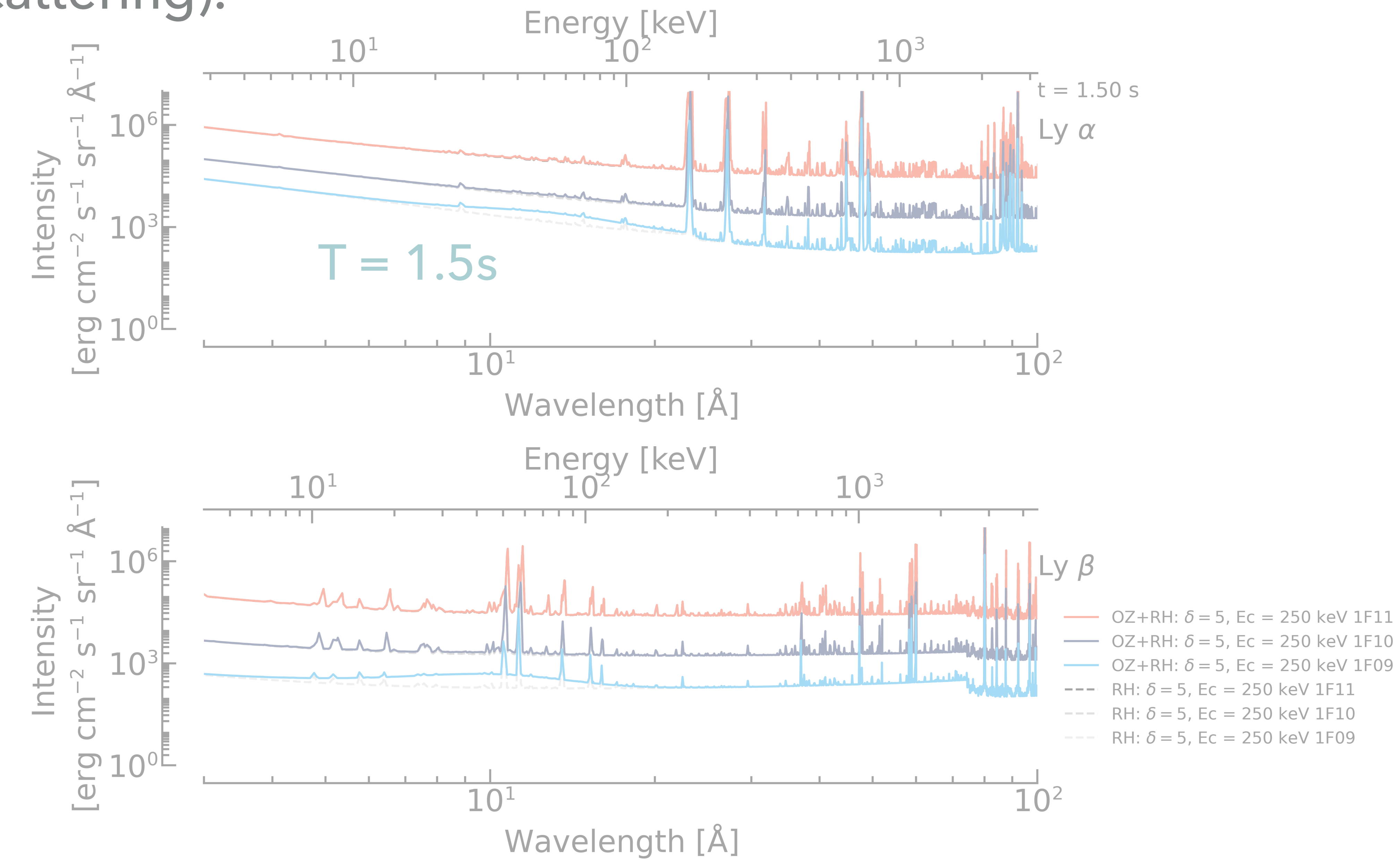

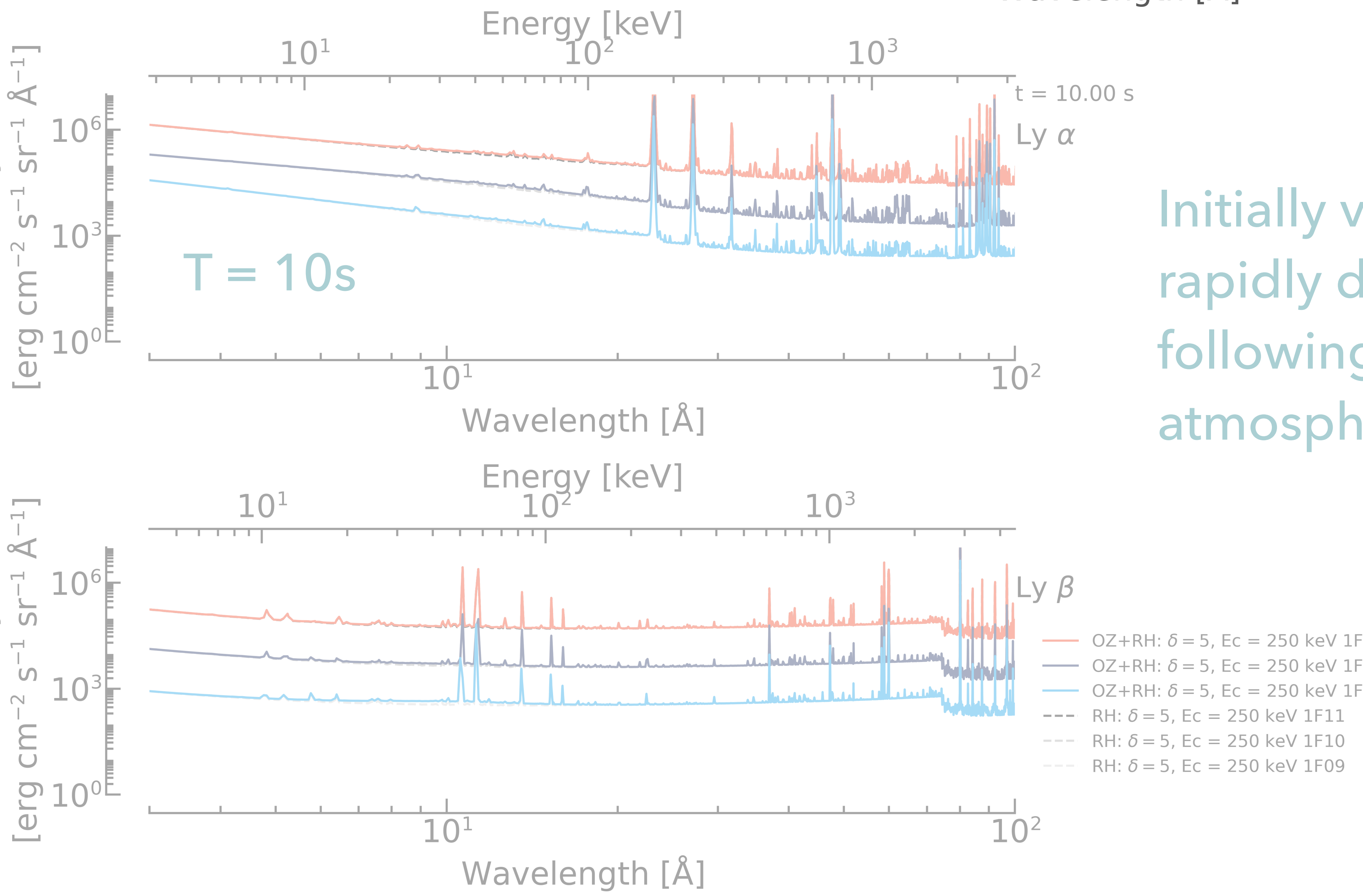

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OBSERVATIONAL PROSPECTS

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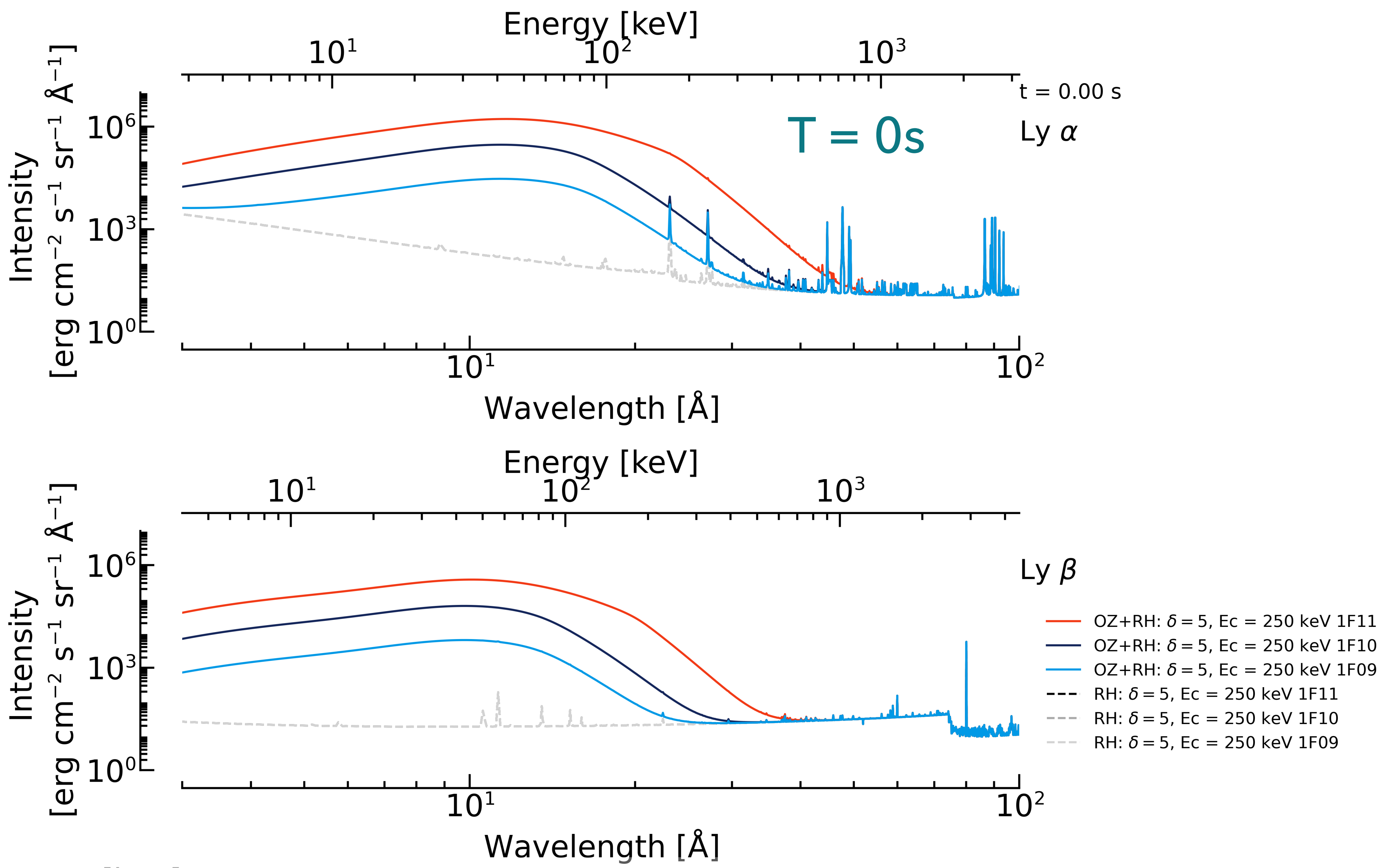

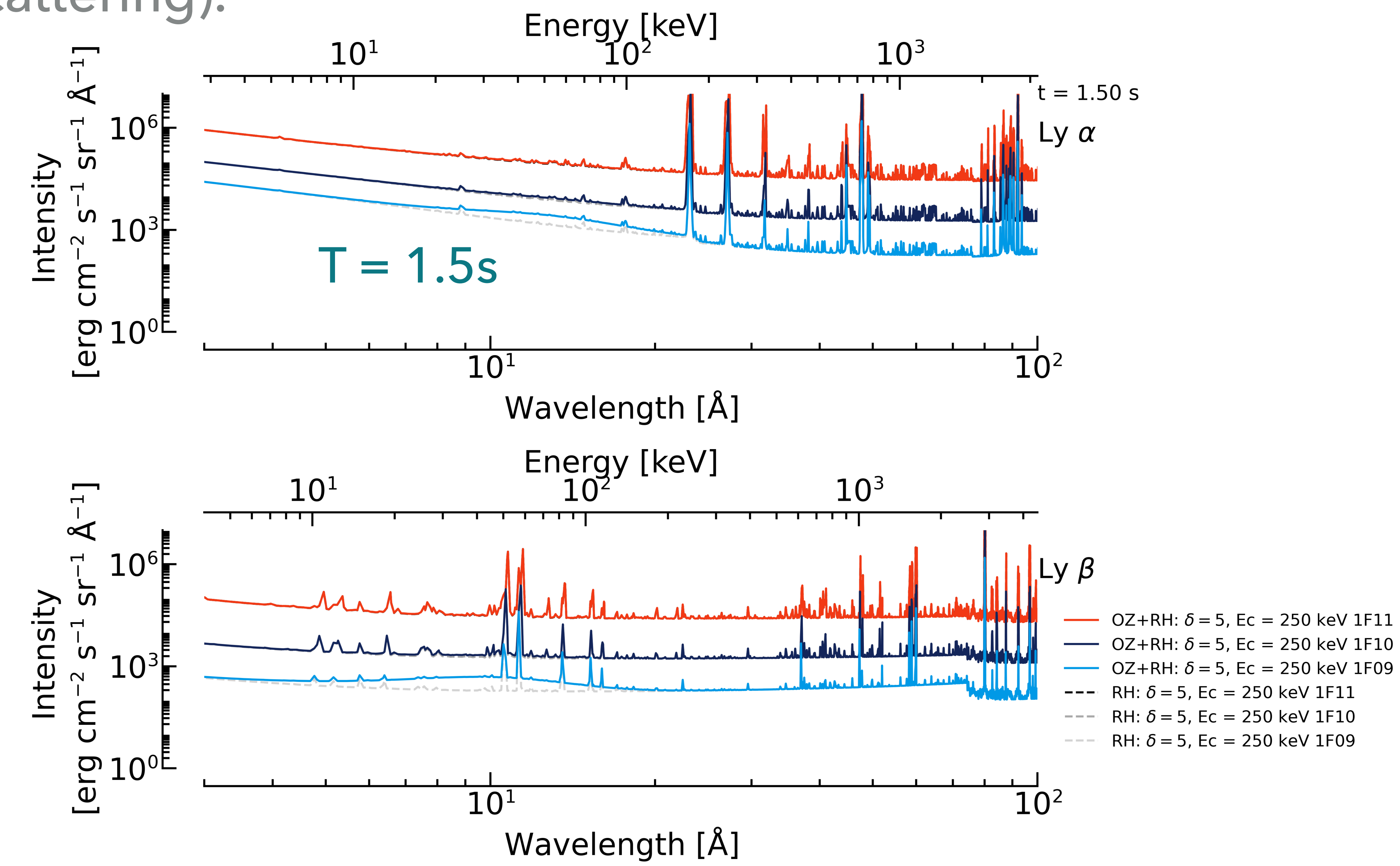

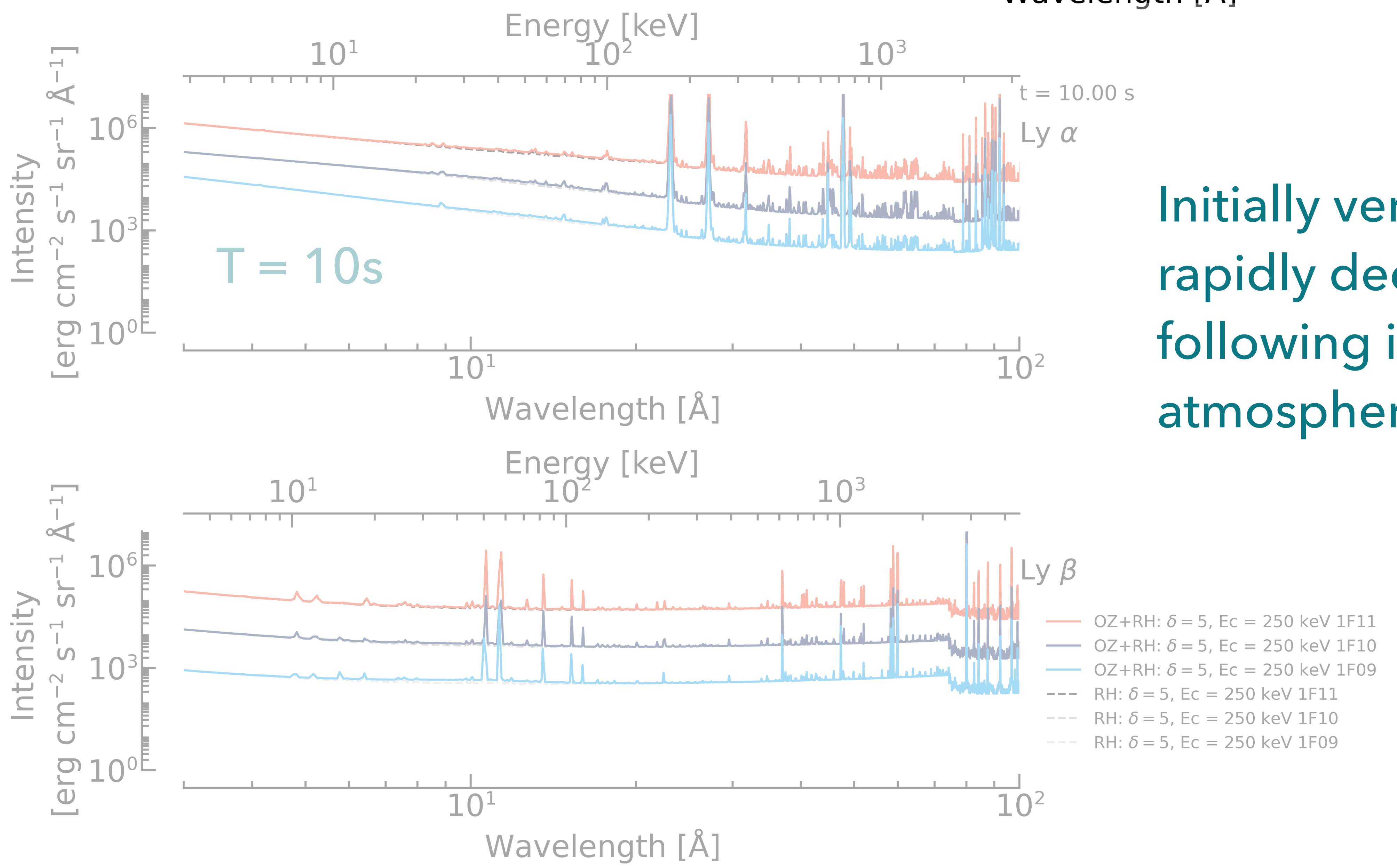

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OBSERVATIONAL PROSPECTS

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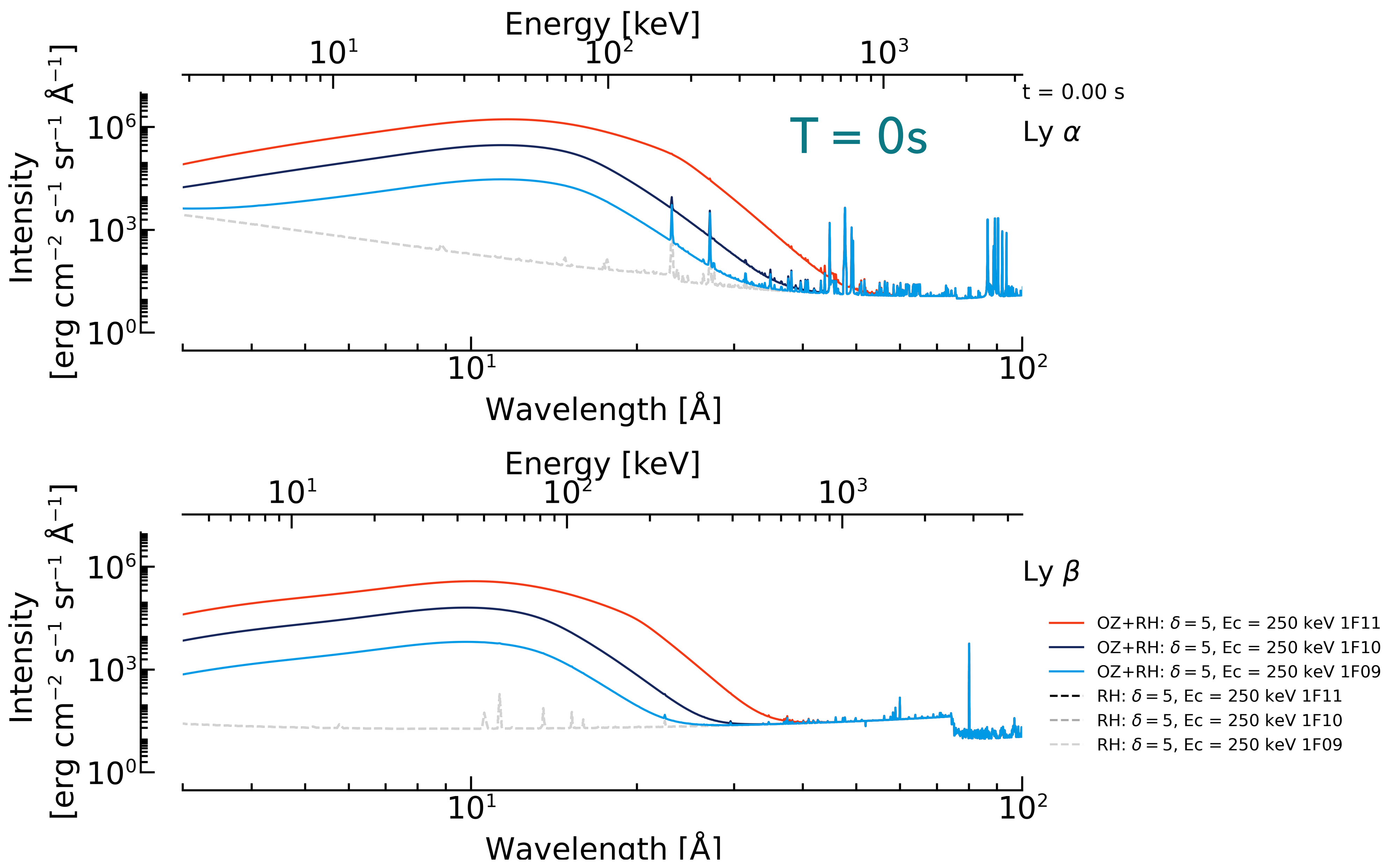

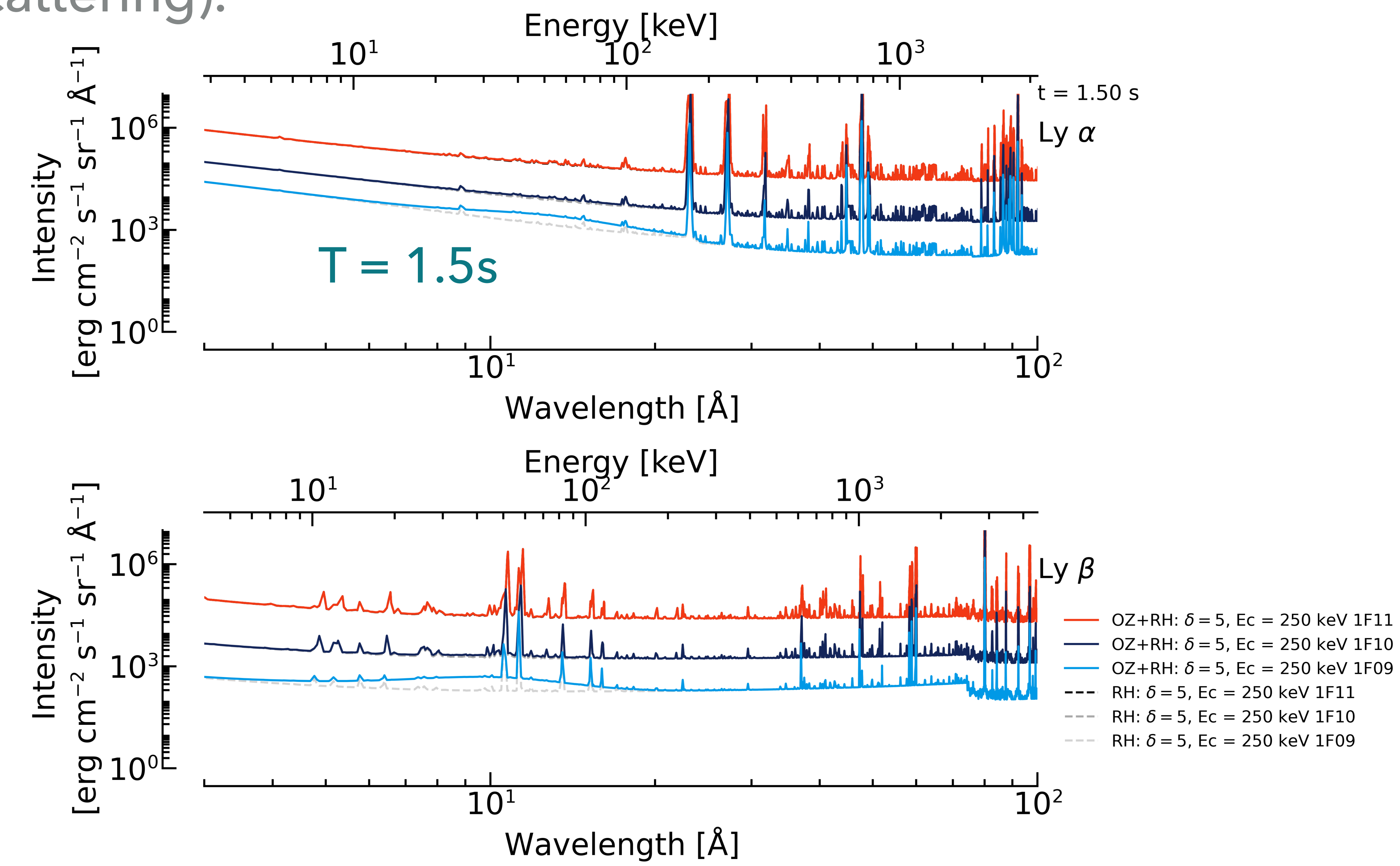

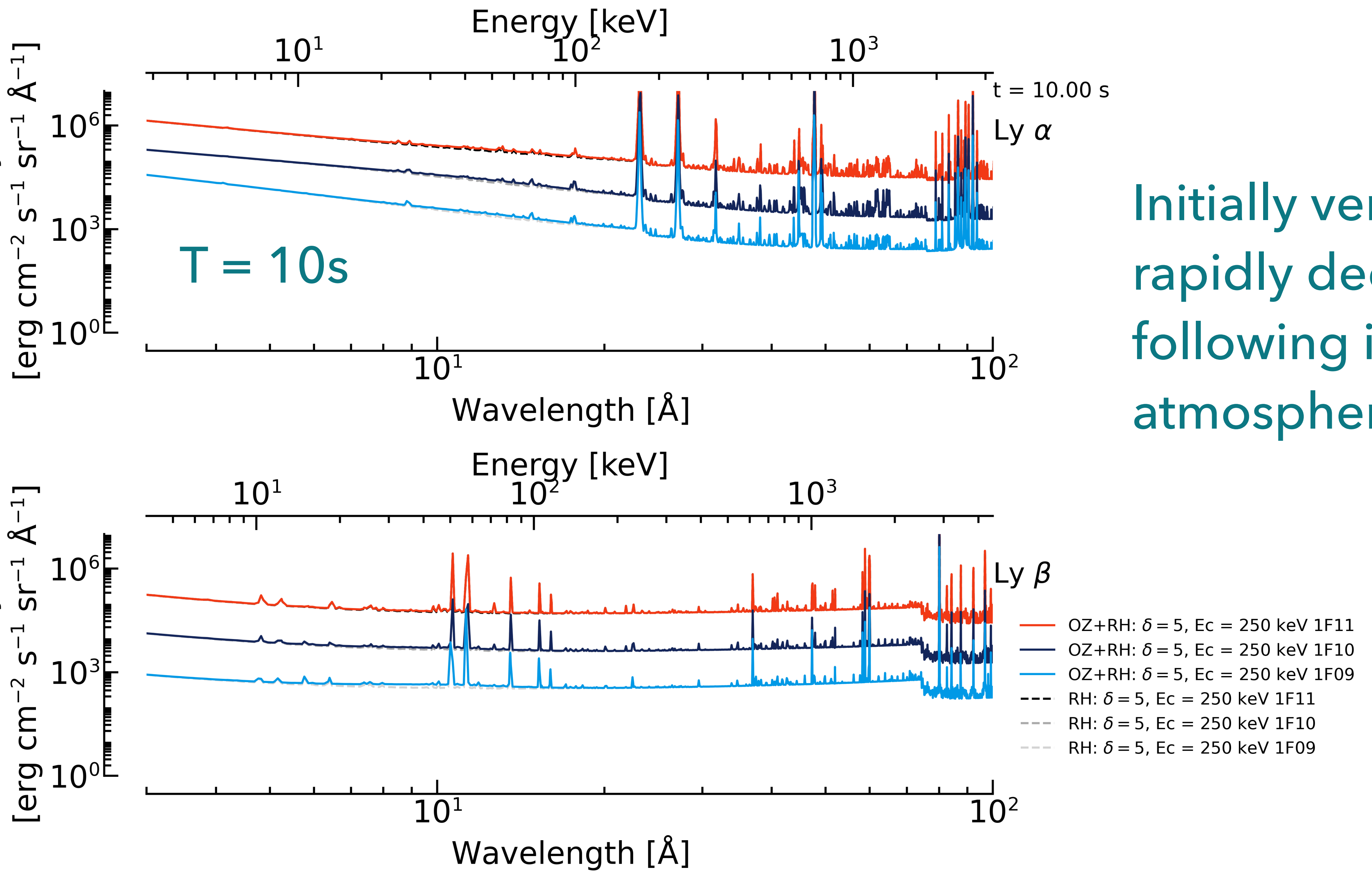

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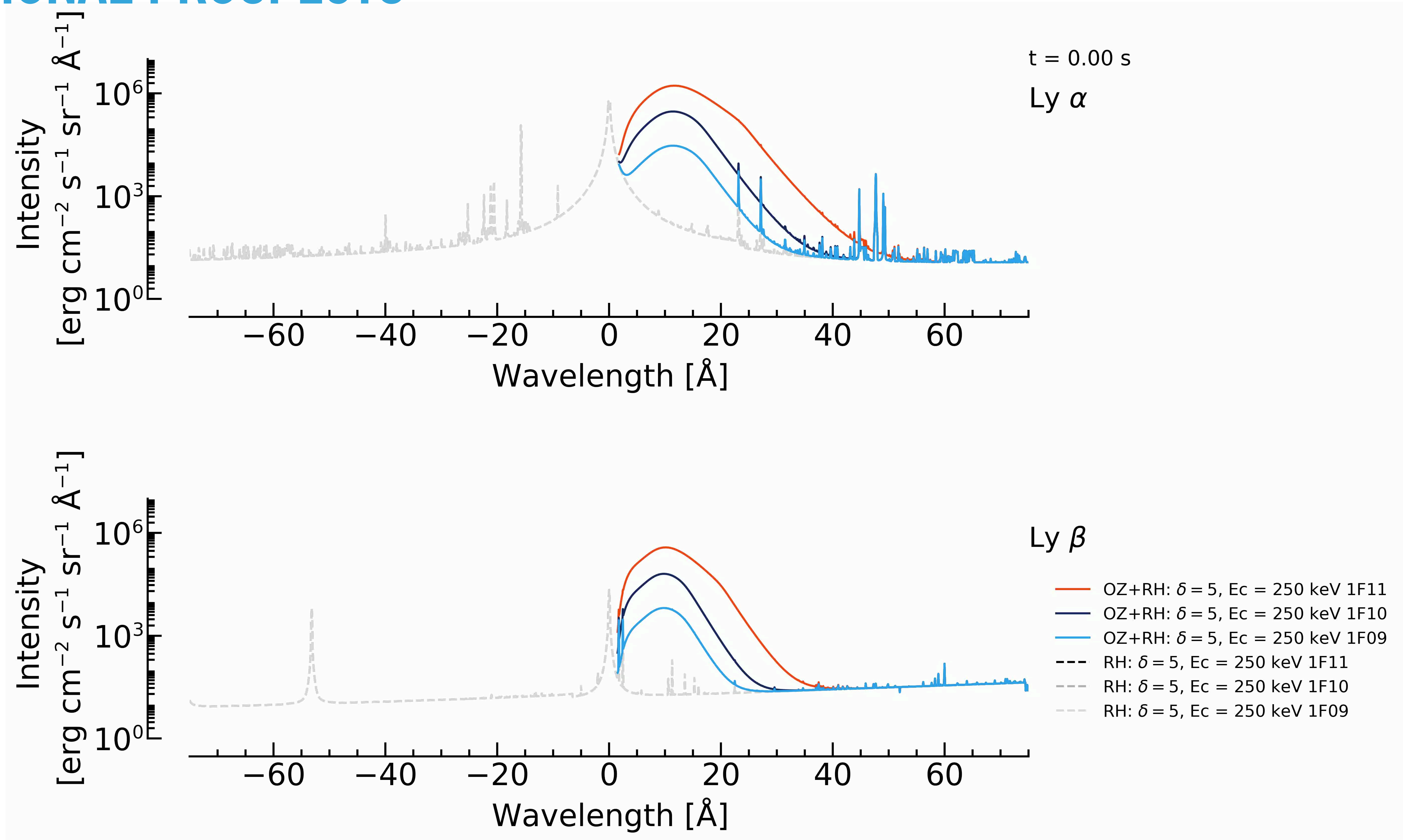
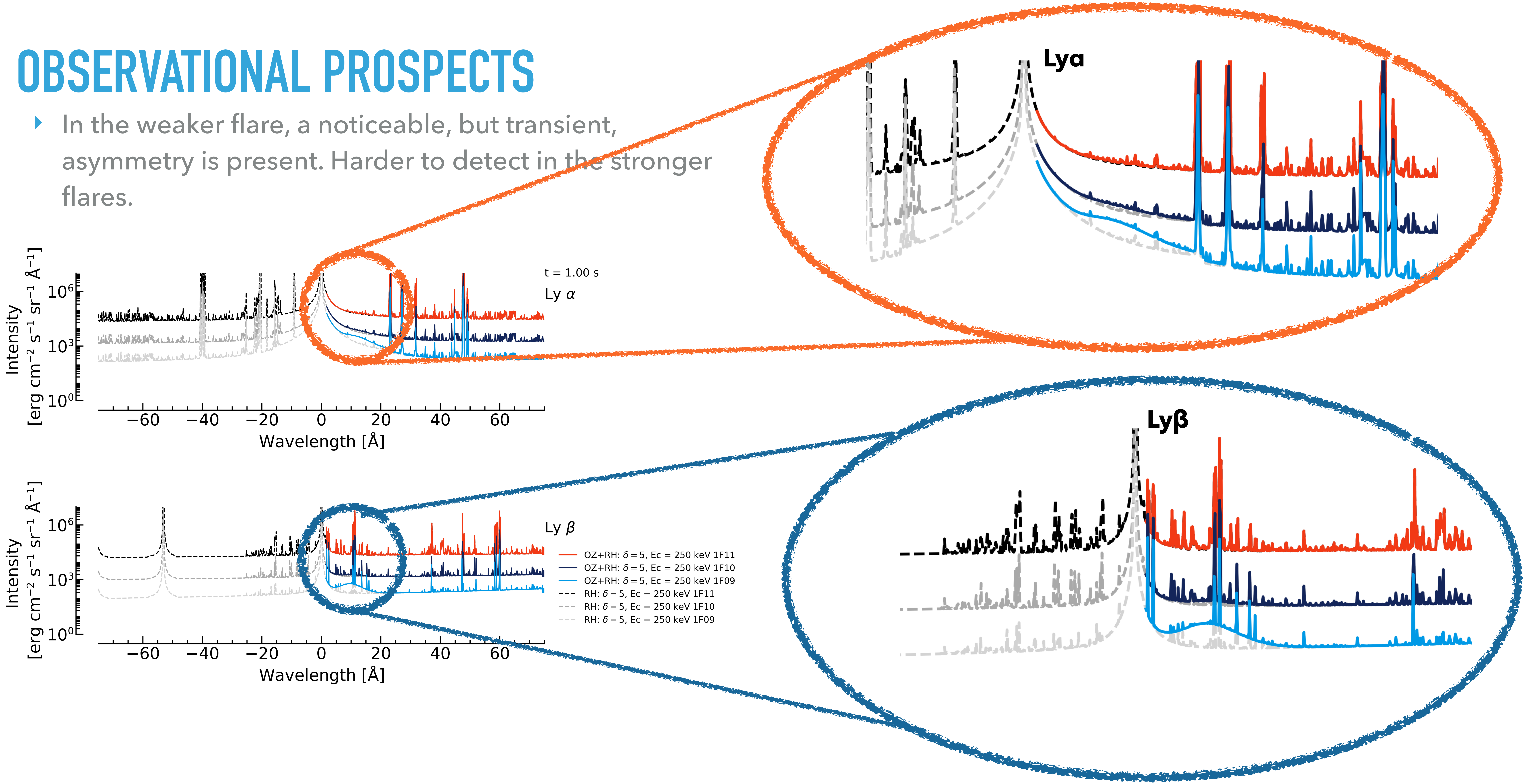
OBSERVATIONAL PROSPECTS



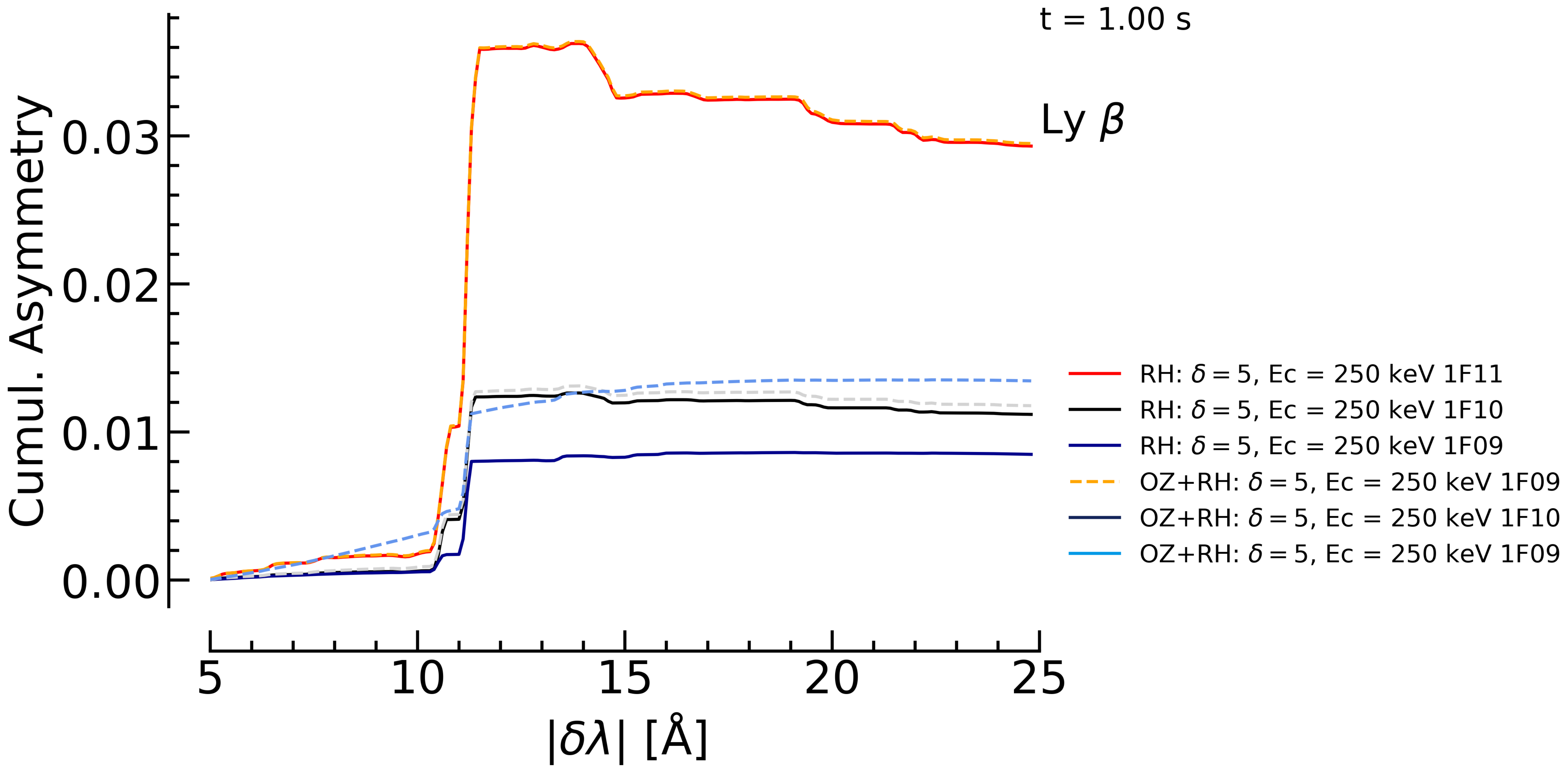
OBSERVATIONAL PROSPECTS

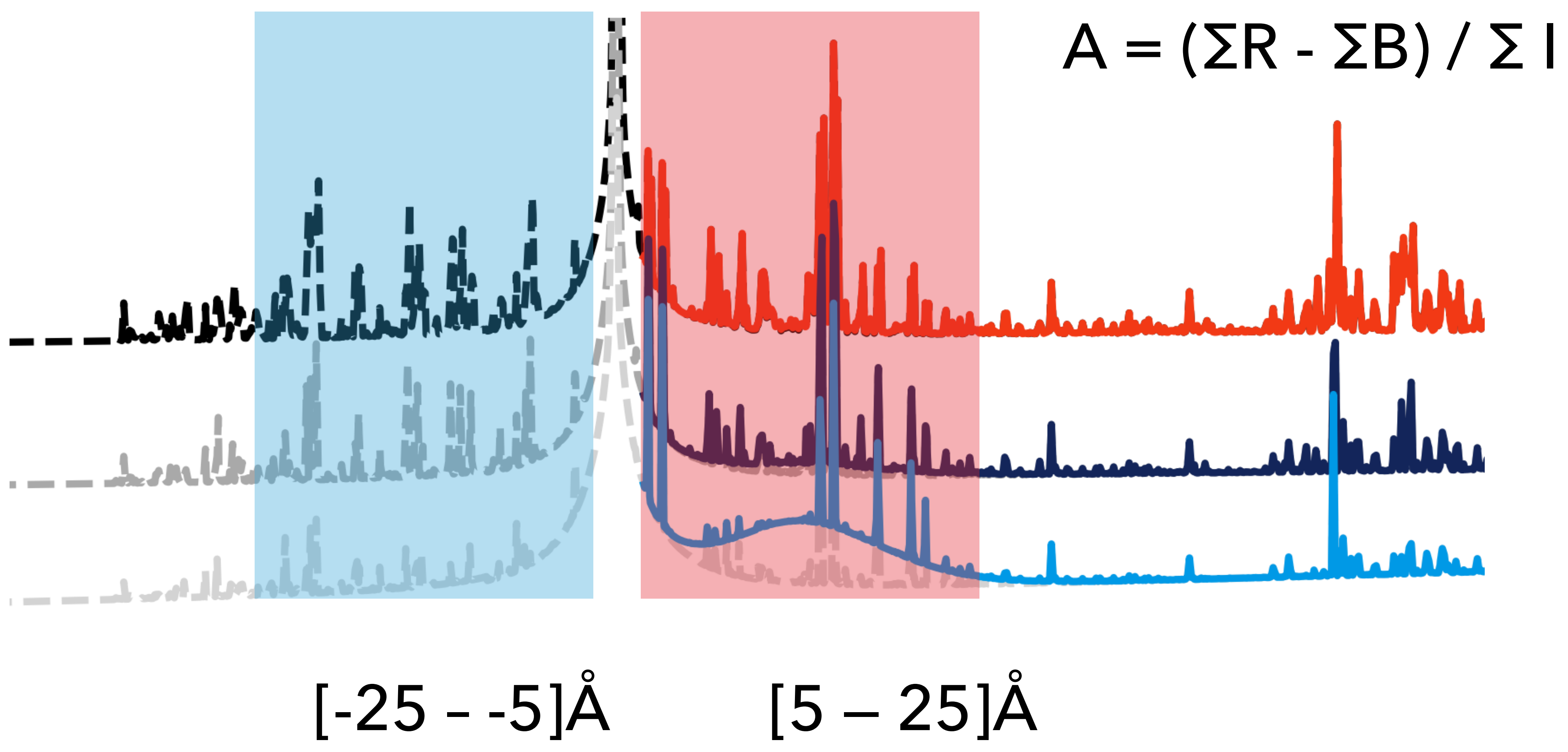
- In the weaker flare, a noticeable, but transient, asymmetry is present. Harder to detect in the stronger flares.



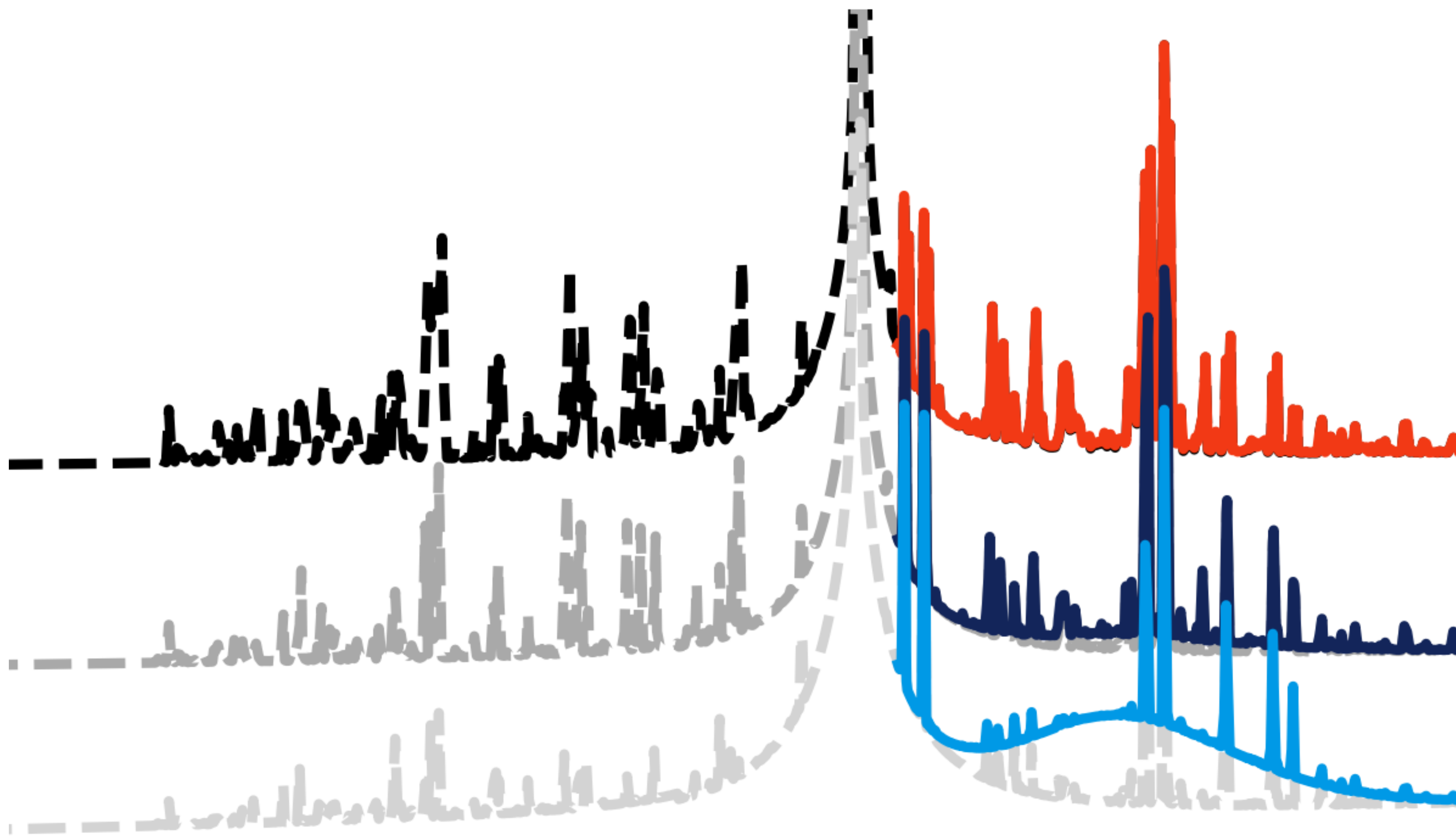
OBSERVATIONAL PROSPECTS

- Tracking asymmetry over time hints that we can see something in weaker flares (and that there is still an ‘excess’ asymmetry in stronger flares).
- Here we measure the asymmetry in the red wing vs blue wing in a cumulative way moving away from line core. We have not fit the wings or continuum under the forrest of lines, so a future analysis will carefully remove their influence. Instead we just compare the asymmetry when including OZ (dashed lines) to the asymmetry without OZ emission.
- There is a ‘natural’ asymmetry present due to the other lines in the wings/near continuum, but comparing the asymmetry with and without OZ emission shows that around 5-10Å the asymmetry in the weaker flare simulation asymmetry sharply increases.
- More work is needed here to determine if it is useful in detecting the OZ effect.





OBSERVATIONAL PROSPECTS



- In this talk we are not going into detail about observatories that might detect the signal in weak flares, but do note that EUVST, SolO/SPICE, SolO/EUI, SNIFS, and SDO/EVE could potentially detect this effect.
- The question is sensitivity, so determining that requirement is a next step.
- SDO/EVE flare excess irradiance can reveal flaring Lyβ emission. So far, no detection but we have only looked at a couple of larger flares, and have not done any systematic survey.

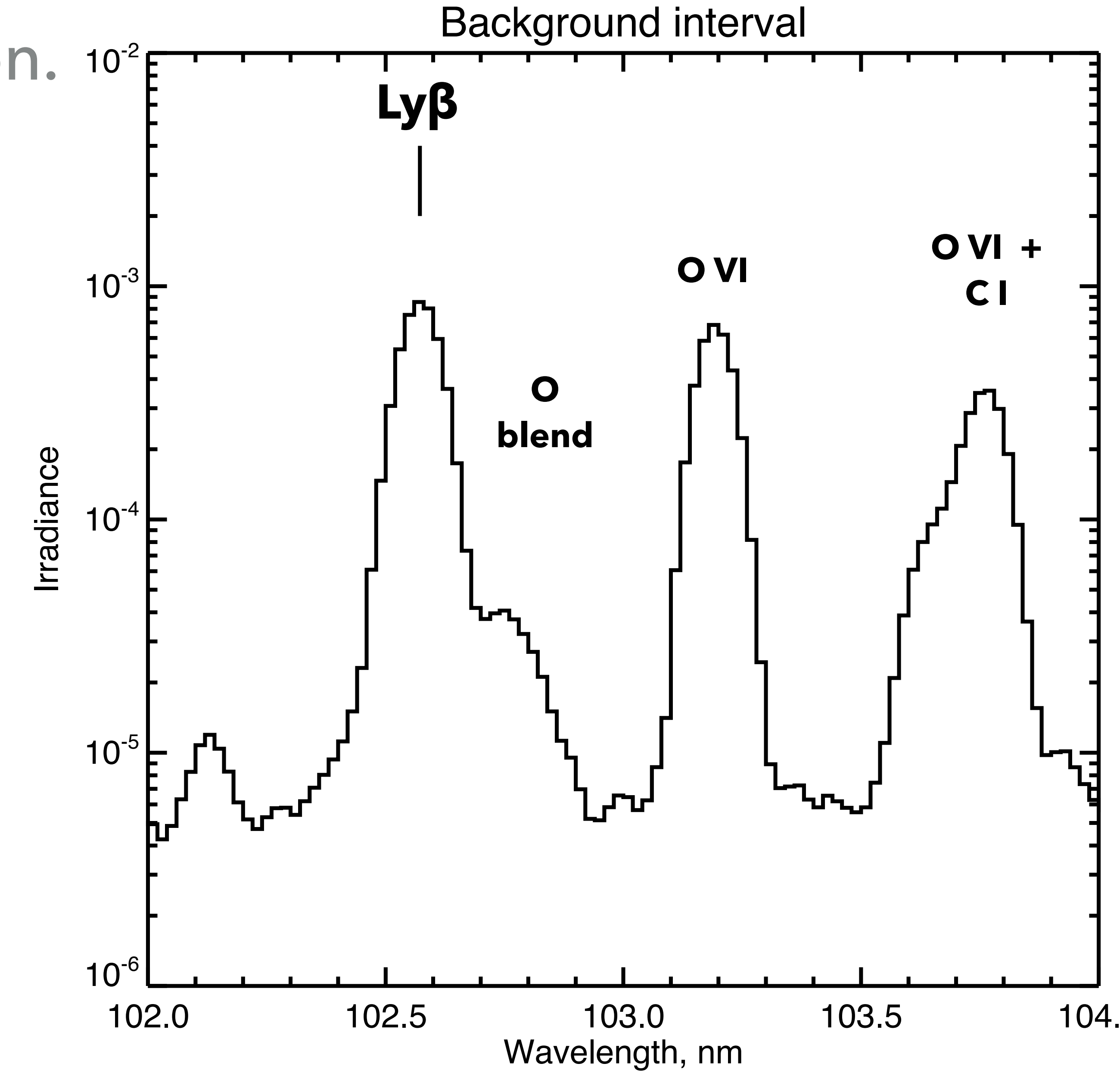
SDO/EVE Analysis

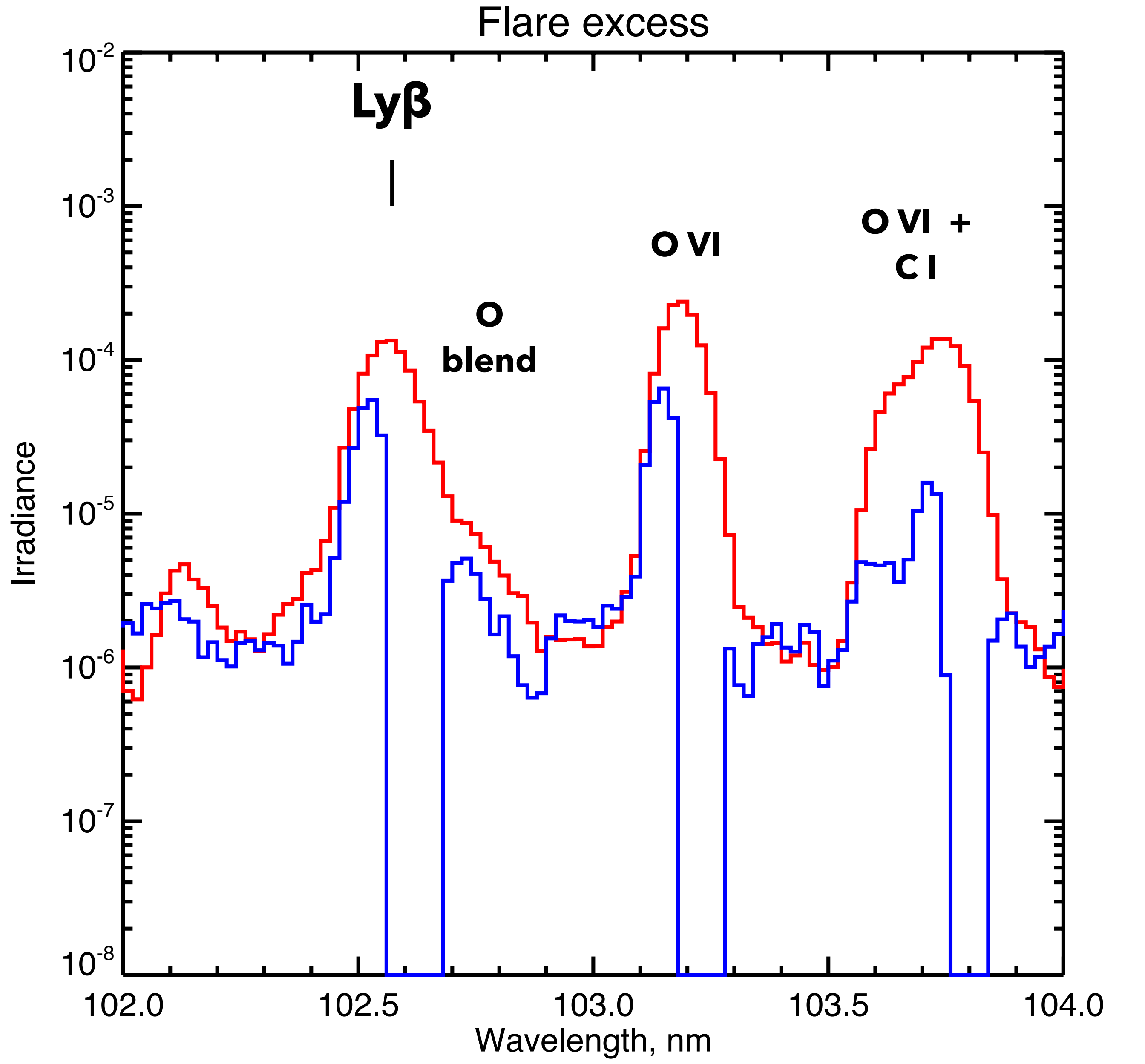
Black line is the full spectrum, from the background interval.

The red curve is the flare excess irradiance spectra from the impulsive phase.

The blue curve is the flare excess irradiance spectra from the gradual phase (this flare was a long duration gamma ray event).

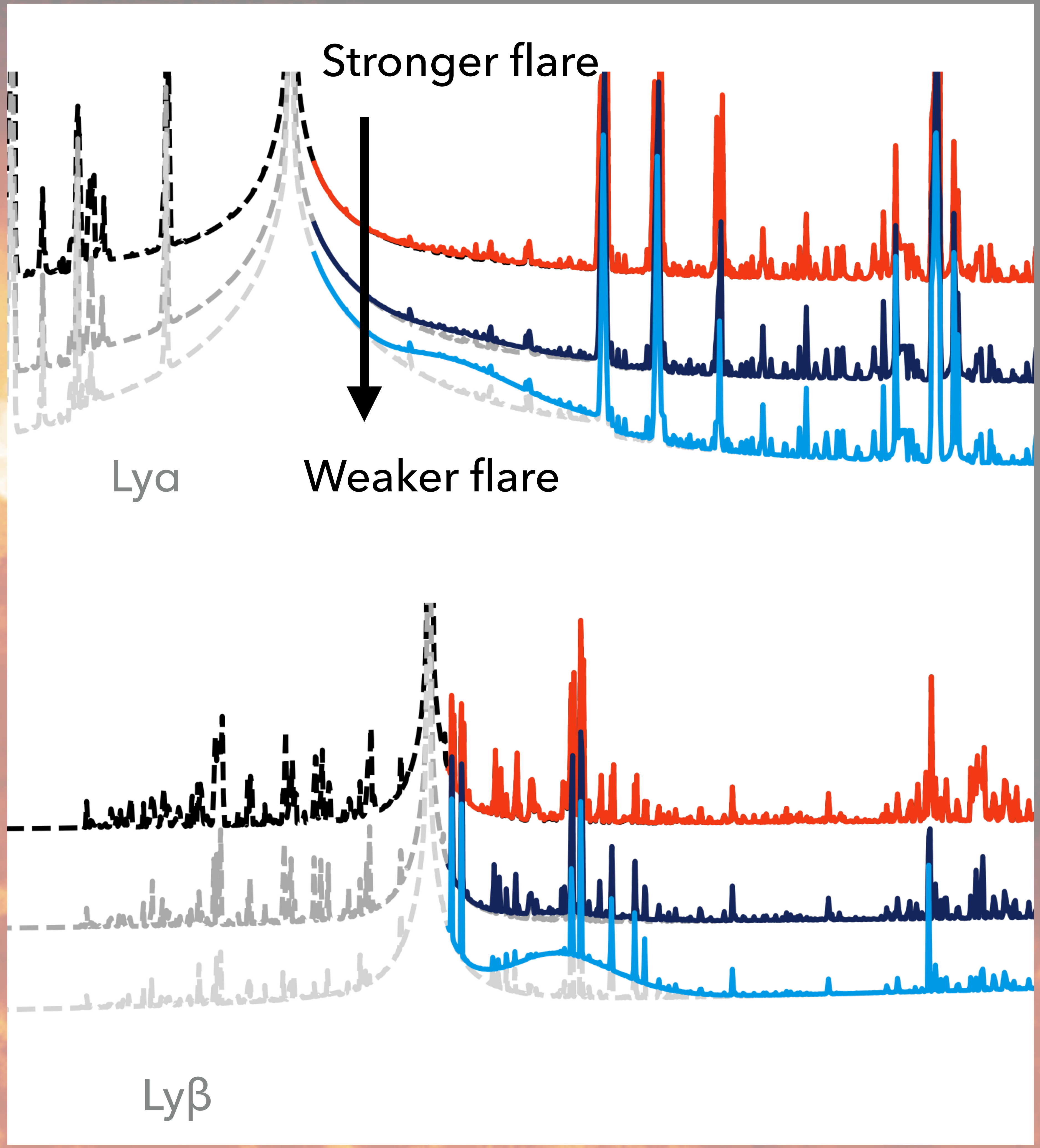
No obvious asymmetry is present – at EVE's resolution Oxygen lines are blended in the wing of Lyβ.





Conclusions

- We revisit the Orrall-Zirker effect with up to date numerical resources, capable of tracking the ionisation stratification and non-thermal proton populations.
- Preliminary investigation sampling a large grid of proton beam driven flares suggests that the atmosphere ionises very quickly driving down ENA production and emission.
- Proton beam charge exchange emission will likely be difficult to observe against ambient flare emission in stronger flares. Weaker events do show emission that could be detected as a transient asymmetry at the flare leading edge.
- Other model updates such as suppression of thermal conduction are underway and may allow us some respite. Also need to run electron+proton (multi-species) beams.
- Much more work is needed so watch this space!



Extra Slides

RELEVANT CROSS SECTIONS

- I can provide details to people off-line if you are interested, but in brief here is a description of cross sections used. We compiled from various sources in the literature, both experimental and theoretical where necessary. We fit Chebyshev functions to data, and extended with a linear fit in log-E space to high energy.

- Cross sections were compared to those found in older work on OZ effect, with some important differences identified when using up-to-date cross sections.

Creation of suprathermal states: Charge exchange direct to that state, collisional excitation from a lower lying state

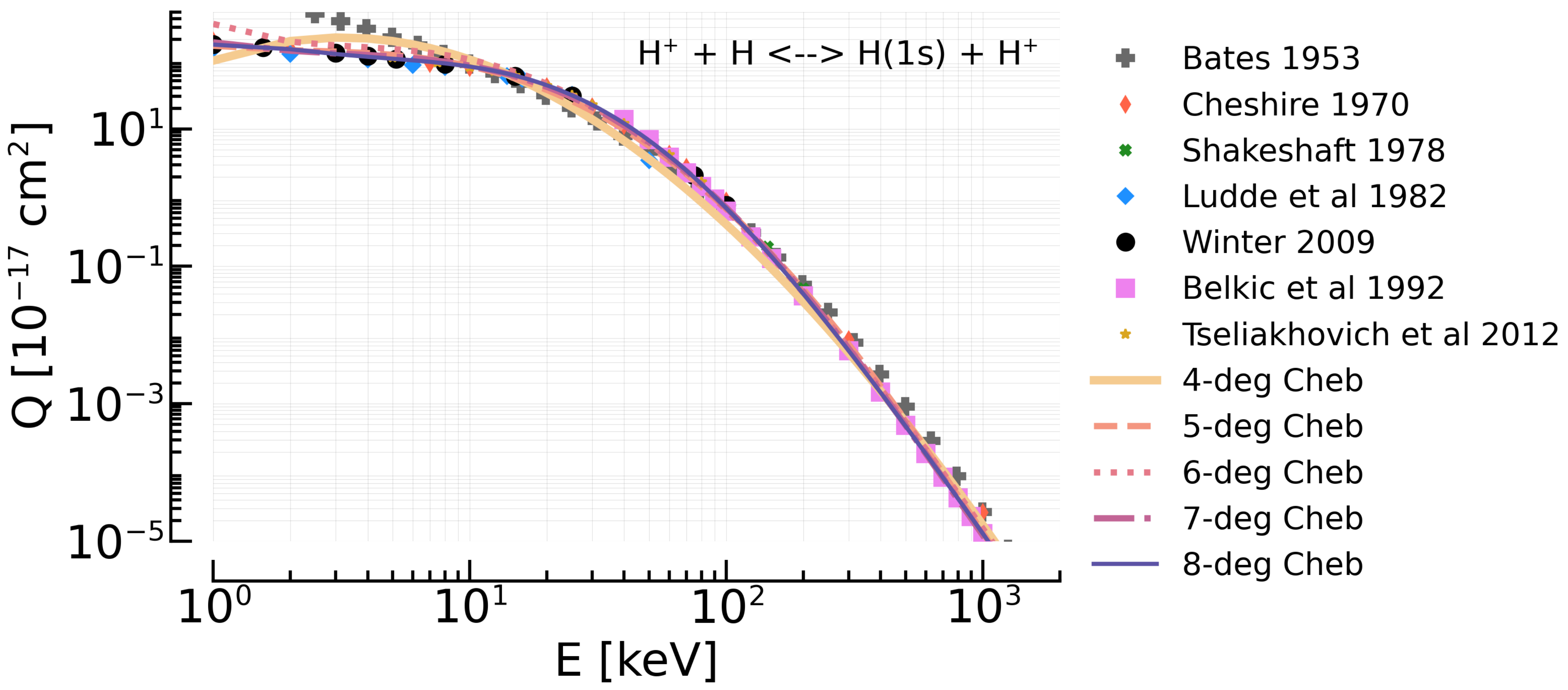
Destruction of suprathermal states: Collisional excitation to a higher lying state, collisional ionisation, spontaneous emission

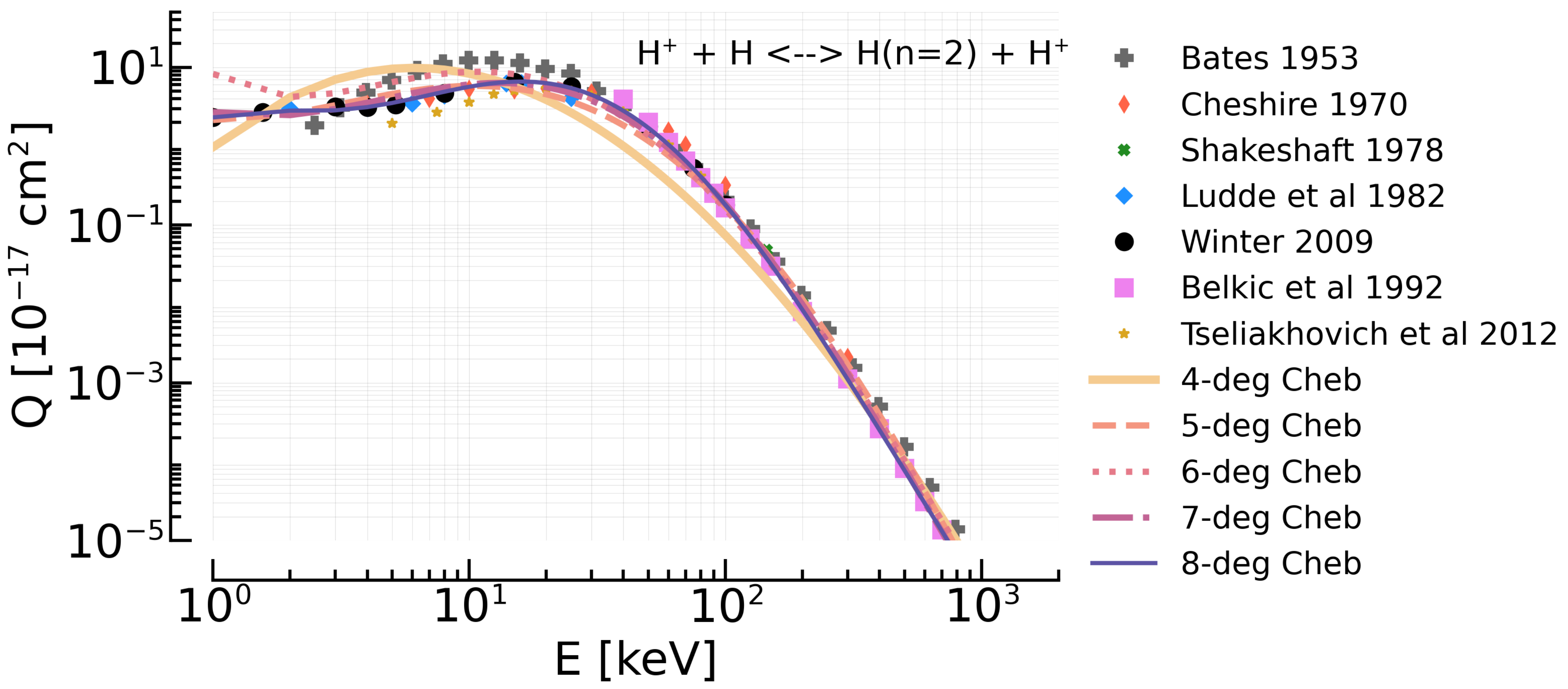
Charge exchange cross sections are shown on next slides, but I don't show the collisional cross sections here for brevity.

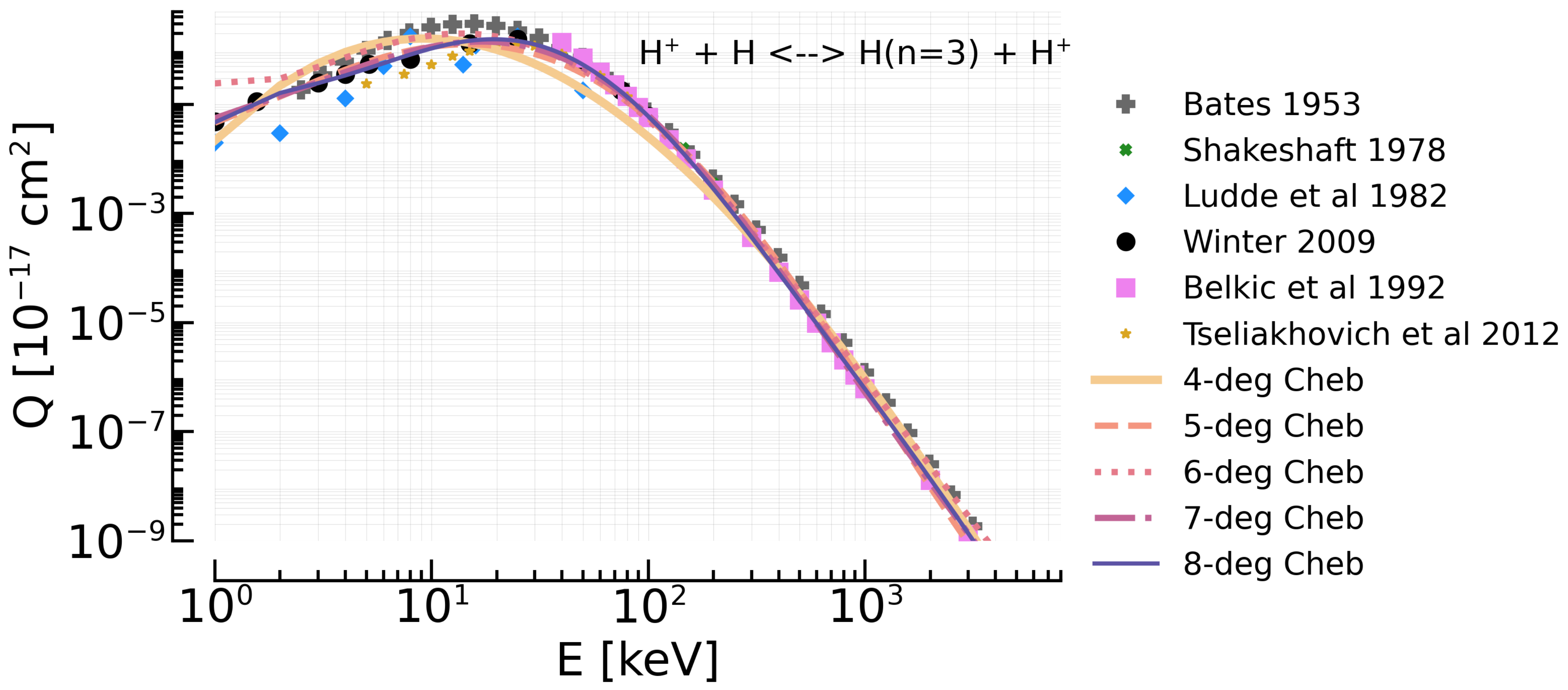
Collisions with protons, electrons and neutral H were considered for excitation and ionisations, from various sources including the well established International Atomic Energy Agency, where available. Others were from recent data or numerical studies.

RELEVANT CROSS SECTIONS

Charge exchange cross sections to n = 1 , 2, 3

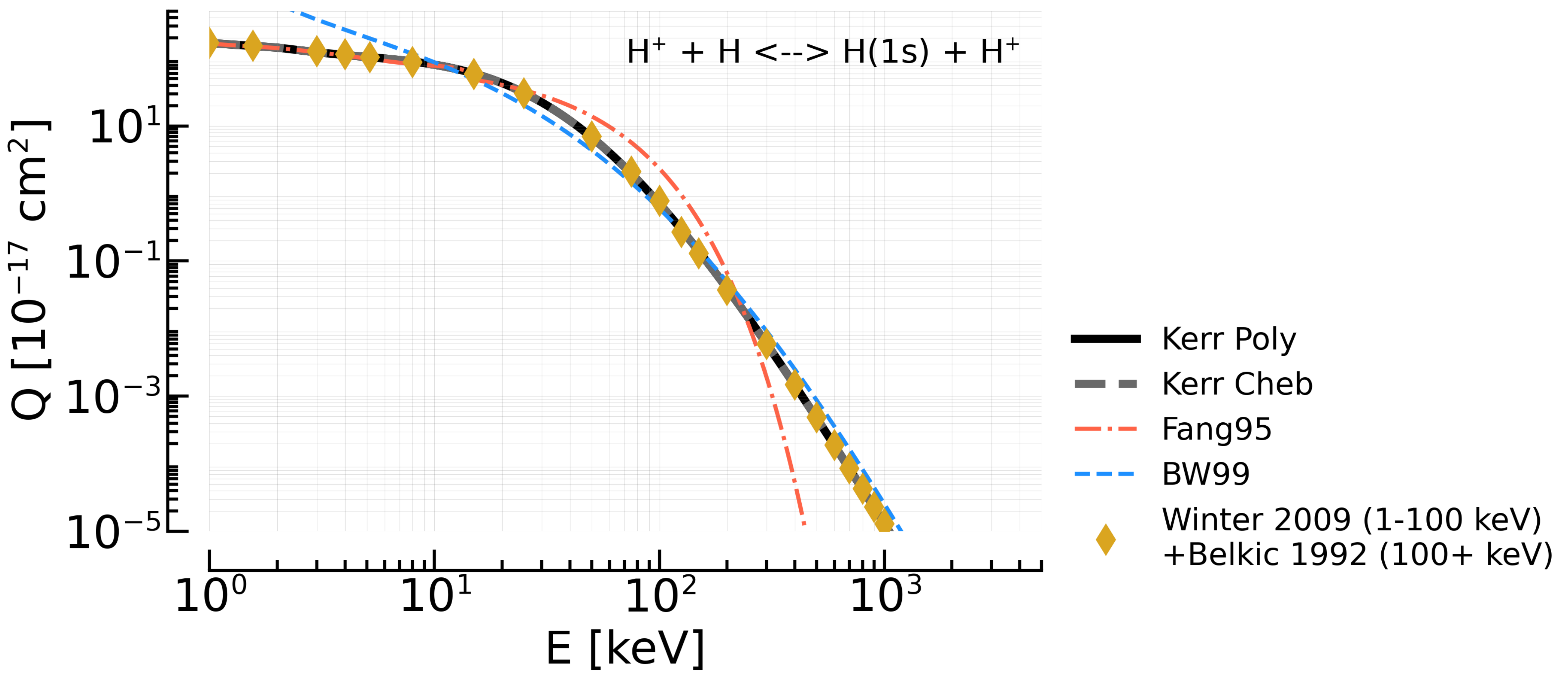


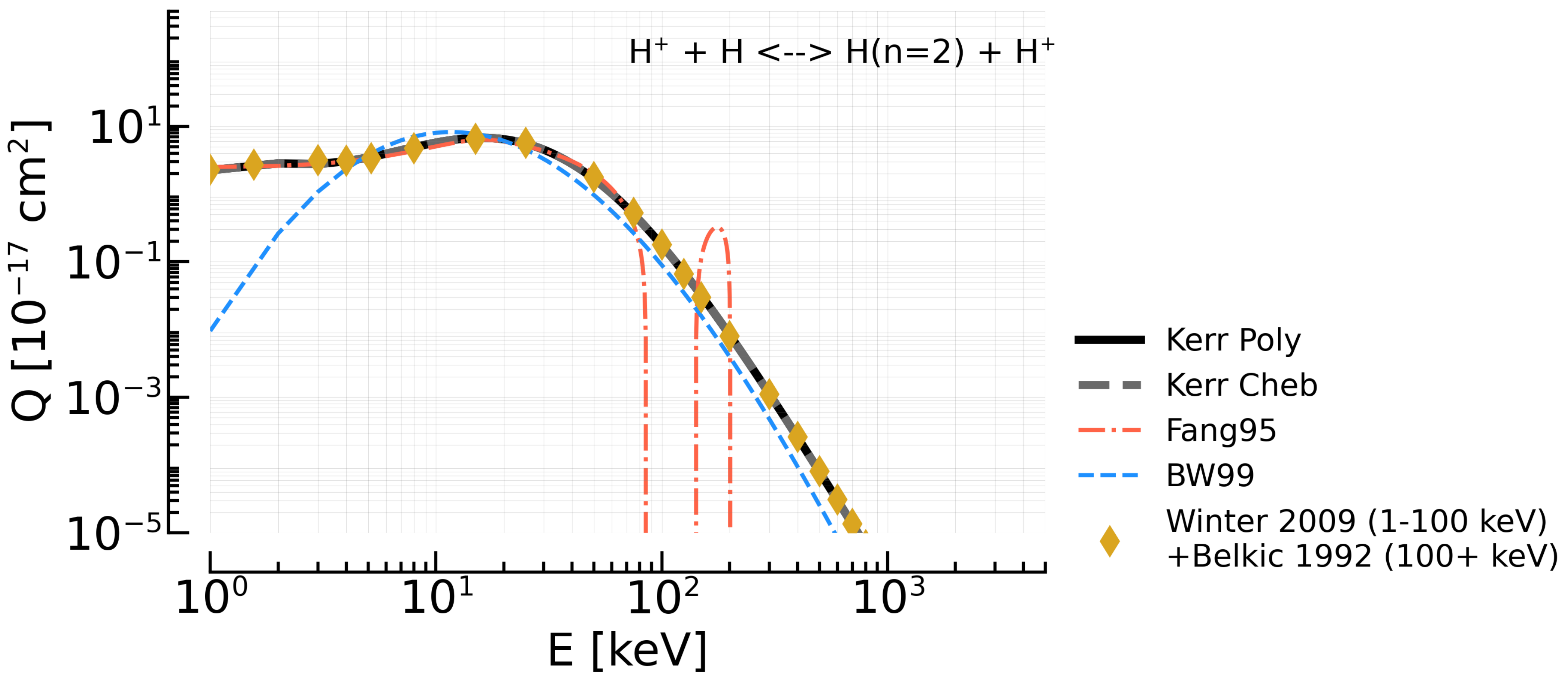


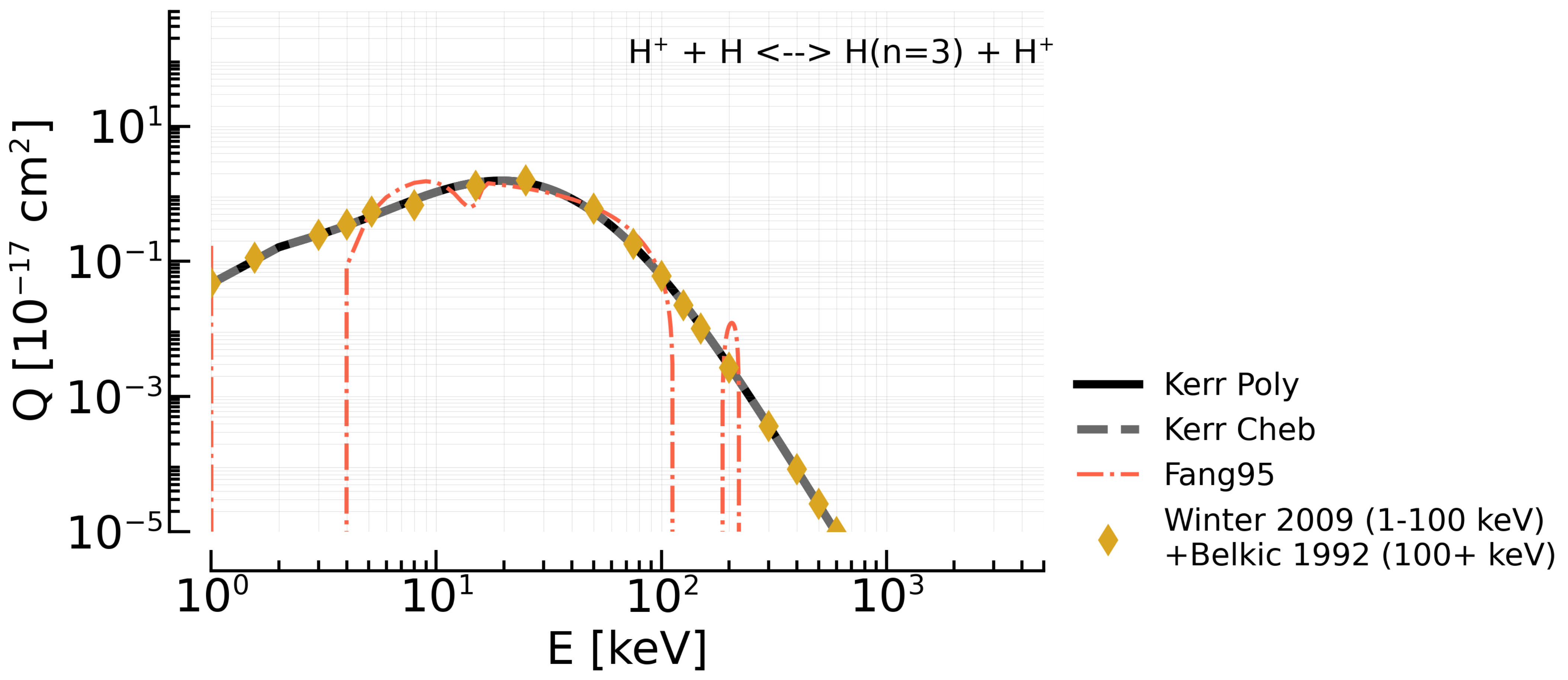


Data and the functions fit

RELEVANT CROSS SECTIONS







Comparing my fits of more recent data to those used in prior studies of OZ effect: Fang et al 1995, Brosius & Woodgate 1999.

Orral & Zirker 1976 mostly used the Bates data on the previous slide, and Canfield and Cheng 1985 used similar values.