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GRAHAM KERR (CUA & NASA GSFC)

YAN XU (NJIT), JOEL ALLRED (NASA GSFC), VIACHESLAV SADYKOV (GSU), NENGYI HUANG (NJIT), VANESSA POLITO (BAERI/LMSAL), HAIMIN WANG (NJIT)

NEGATIVE FLARE RIBBONS & NONTHERMAL PARTICLES: ENHANCED ABSORPTION OF HE I 10830Å

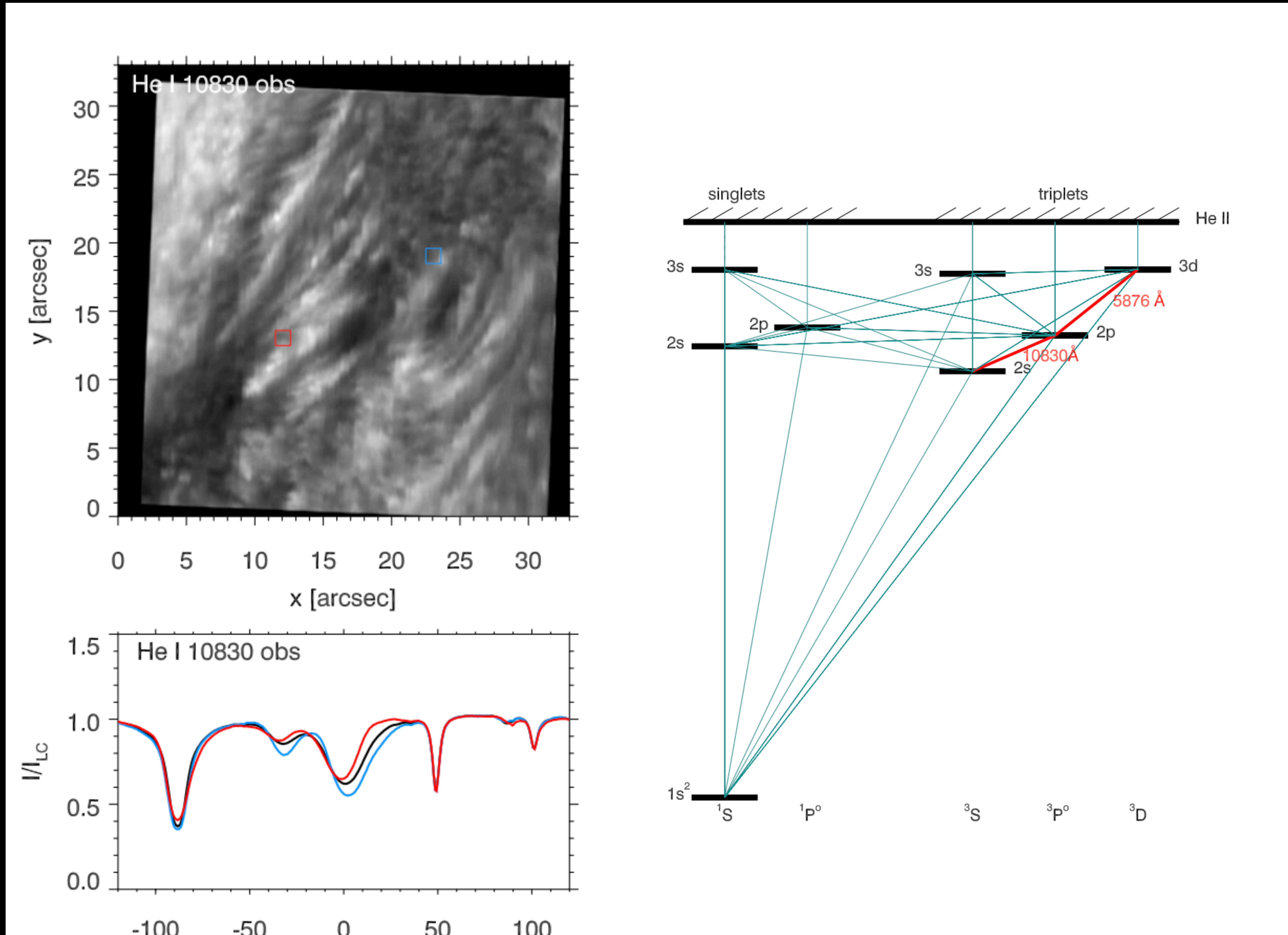
ORTHOHELIUM SPECTRAL LINES

- Orthohelium is an excited state of helium, with several useful transitions, giving rise to absorption features in the infrared (10830Å) and optical (5876Å; the D3 lines).

- Populating these levels with only direct thermal collisions (CM) is difficult in the quiet Sun, given the high excitation potential (T > ~20kK is required).

- Transition region and coronal photons (a few 100k to > 1MK) with wavelengths < 504Å can photoionise He I. Electrons quickly recombine with He II back to He I. Cascades and direct recombinations to the multiplet leads to the population of orthohelium. This is the photoionisation-recombination mechanism (PRM).

- Continuum photons are then absorbed by the overpopulated 3S level, leading to absorption profiles forming in the upper chromosphere. The 10830Å triplet, and D3 lines, are sensitive to both extreme-UV (EUV) flux illumination (corona/TR) and to electron density (chromosphere).



Libbrecht et al 2020

See Andretta & Jones 1997;
Centeno et al 2008;
Avrett et al 1994;
Leenaarts et al 2016

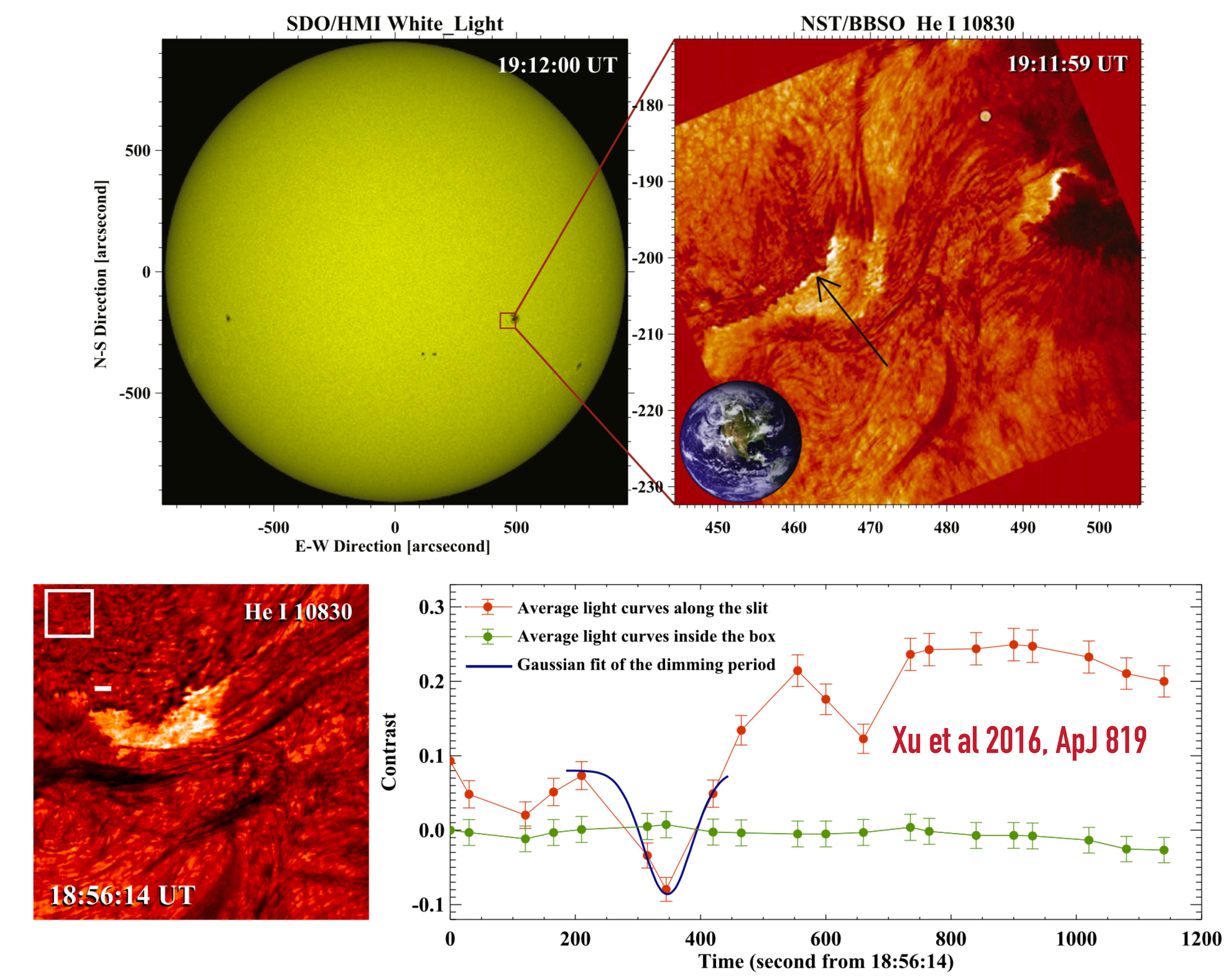
ORTHOHELIUM IN SOLAR FLARES

- He I 10830 and D3 lines have been observed to be in both emission and absorption during flares. Though flare observations are not common this will hopefully change with upcoming solar cycle with BBSO, DKIST, and SST.

- The leading edge of He I 10830 flare ribbons have been observed to undergo a period of enhanced absorption, before the line goes into emission. Similarly, D3 sources have been observed to go through period of enhanced absorption before emission.

- There has been speculation that this is due to the either
(1) enhanced EUV emission from the corona and TR (PRM) or
(2) bombardment by nonthermal electrons leading to nonthermal collisional ionisations then recombinations (CRM).

- **To exploit these probes of flare energy transport into the lower solar atmosphere we must understand their formation properties during flares.**

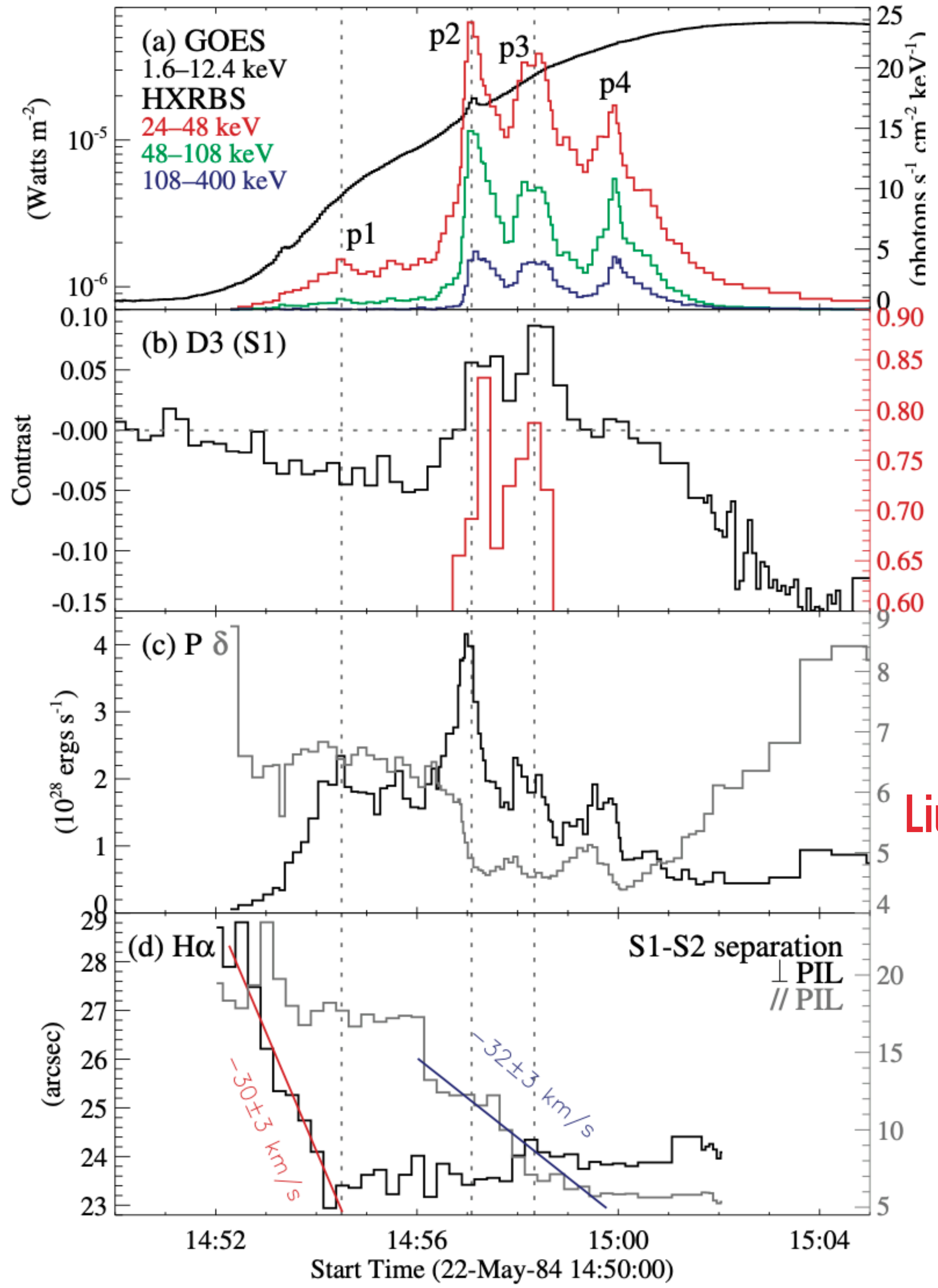


See also:
Zirin 1980; Li et al 2007; Du & Li 2008; Liu et al 2013; Xu et al 2016; Kobanov 2018; Fuhrmeister et al 2020; Ding et al 2005; Huang et al 2020.

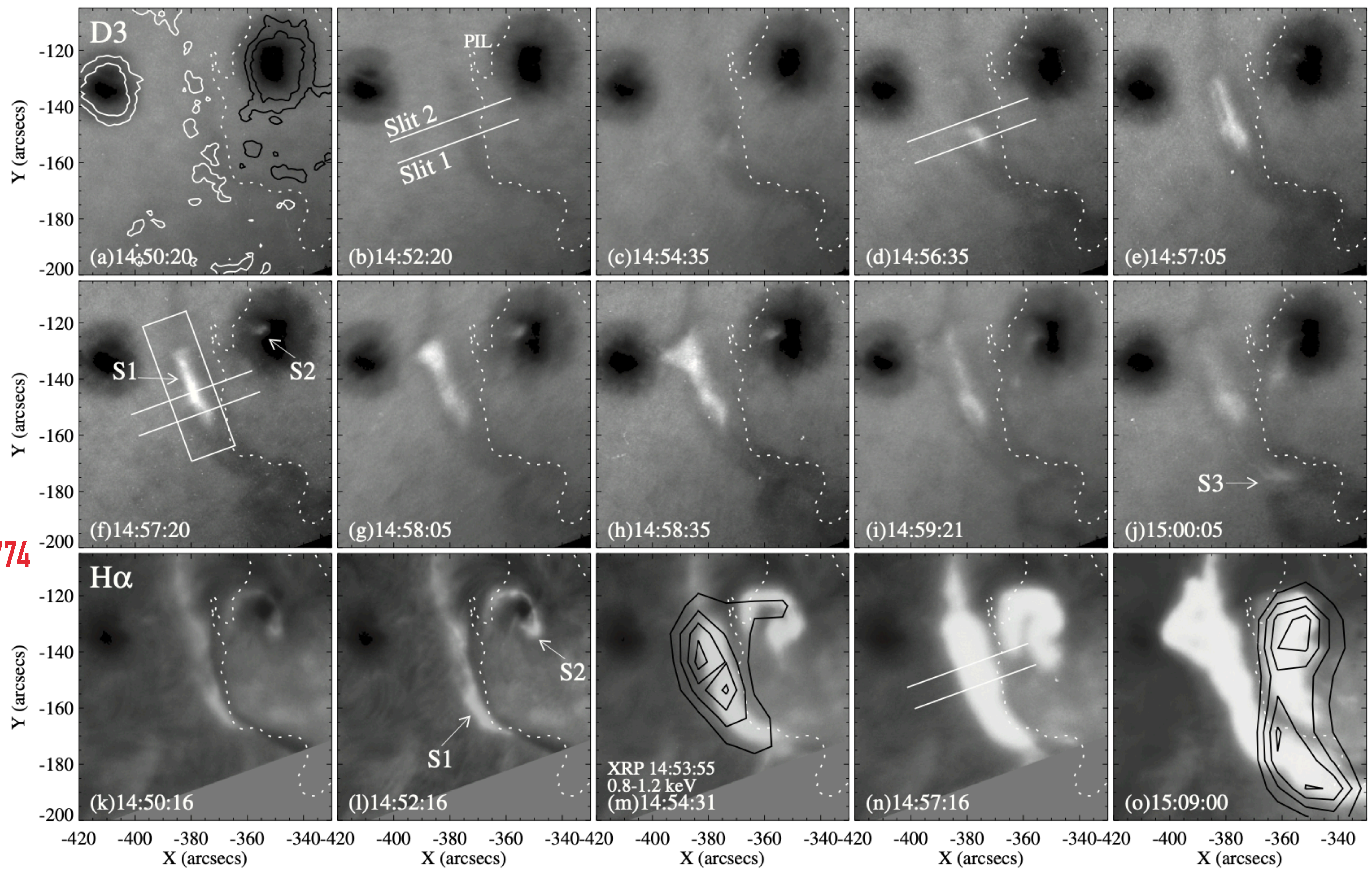
ORTHOHELIUM IN SOLAR FLARES

Kerr et al 2021, ApJ 912 summarises other He 10830 and D3 obs in both solar and stellar flares

- Dimming and emission are related to hard X-ray (i.e. electron beam) properties.



Liu et al 2013, ApJ 774



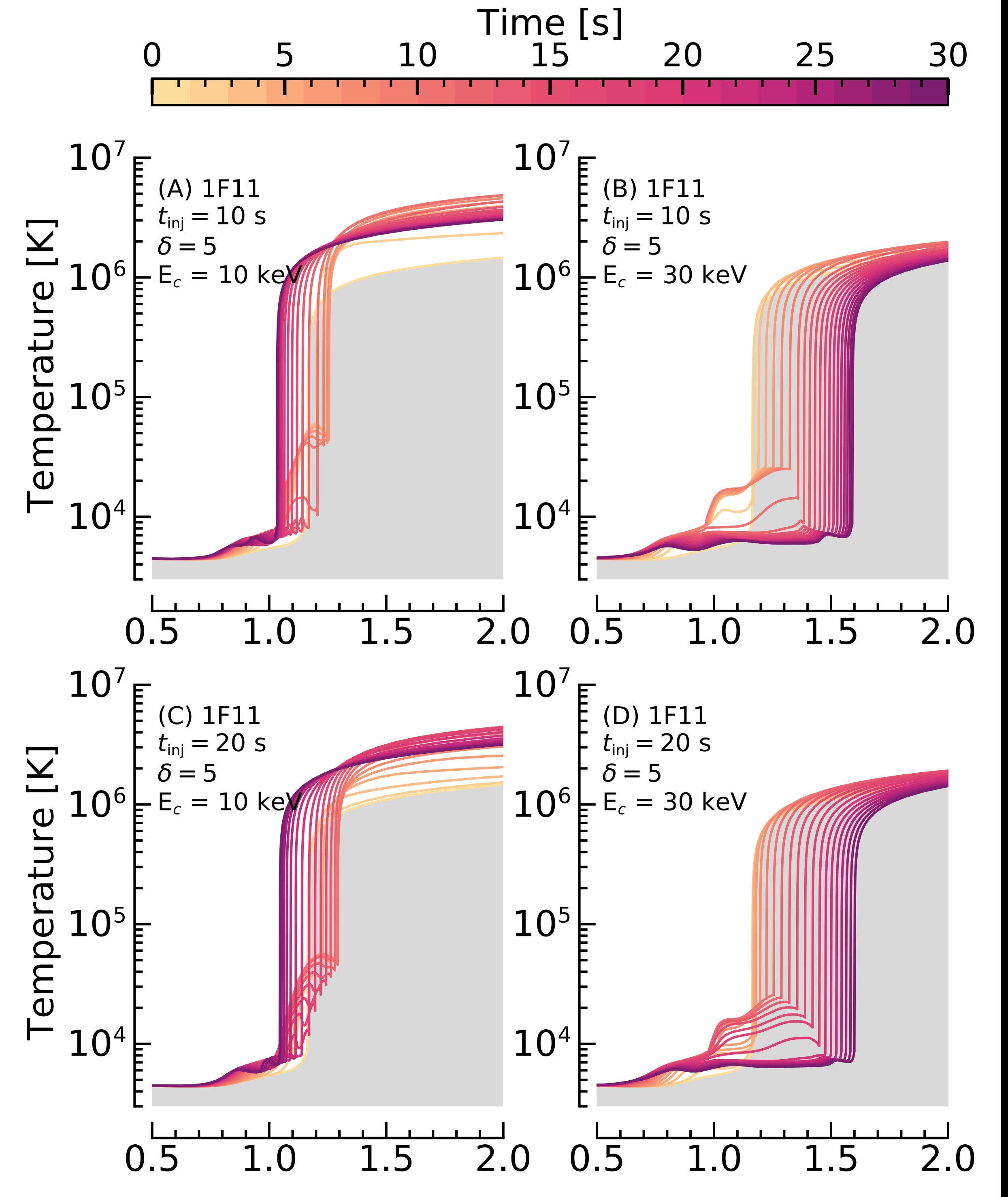
RADYN FLARE SIMULATIONS

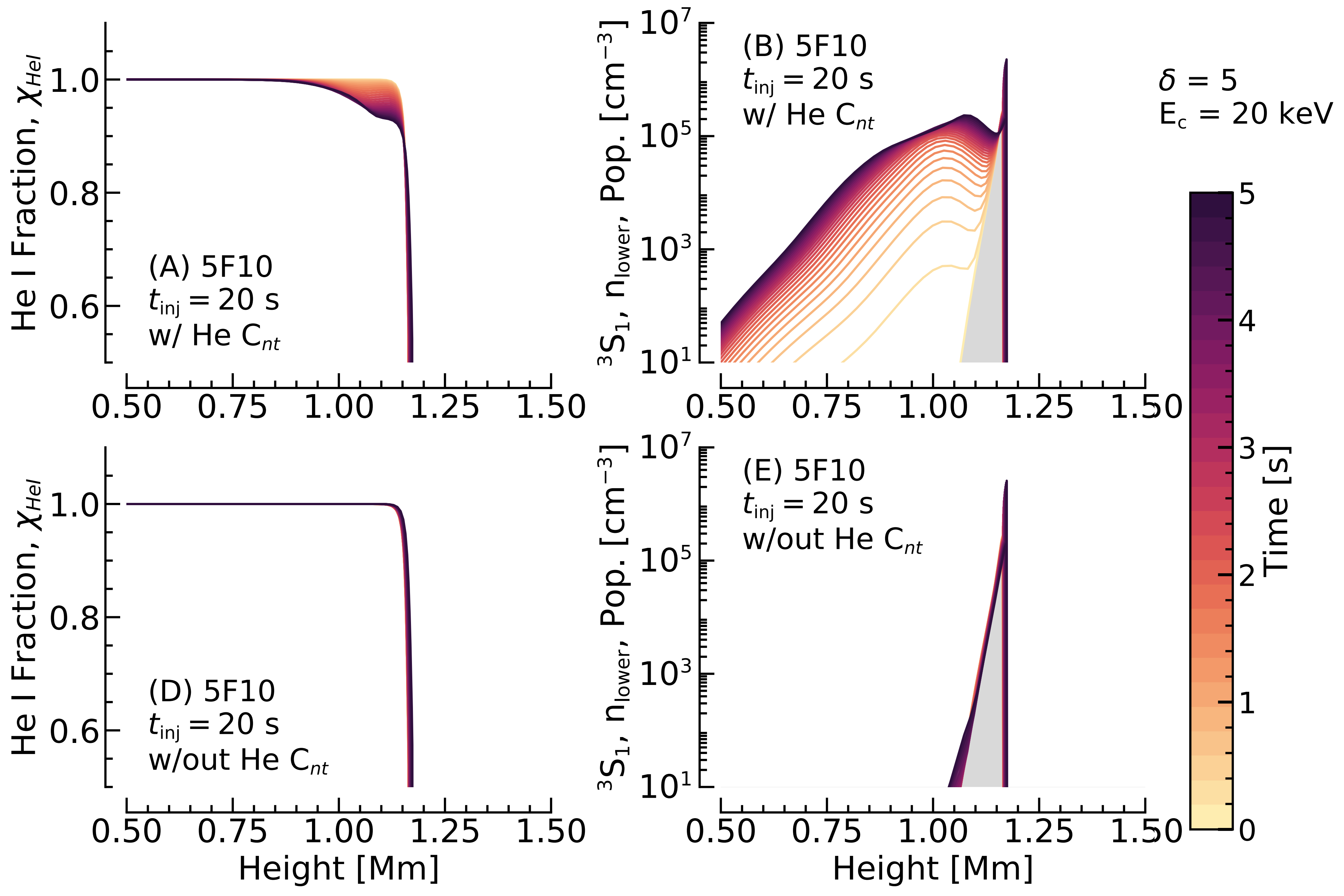
- 50 electron beam driven flare simulations were produced:
  - The spectral slope of the nonthermal electron distribution was fixed at δ = 5.
  - the low energy cutoff values were E_c = [10,15,20,25,30] keV.
  - Total energy fluxes were F = [1×10^{10}, 5×10^{10}, 1×10^{11}, 5×10^{11}, 1×10^{12}] erg cm^{-2}.
  - Energy was injected for τ = [10,20] s.
- Simulations were repeated with nonthermal collisional ionisation of helium (He C_{nt}) switched off.
- Omission of He C_{nt} resulted in only minor differences in the hydro response.

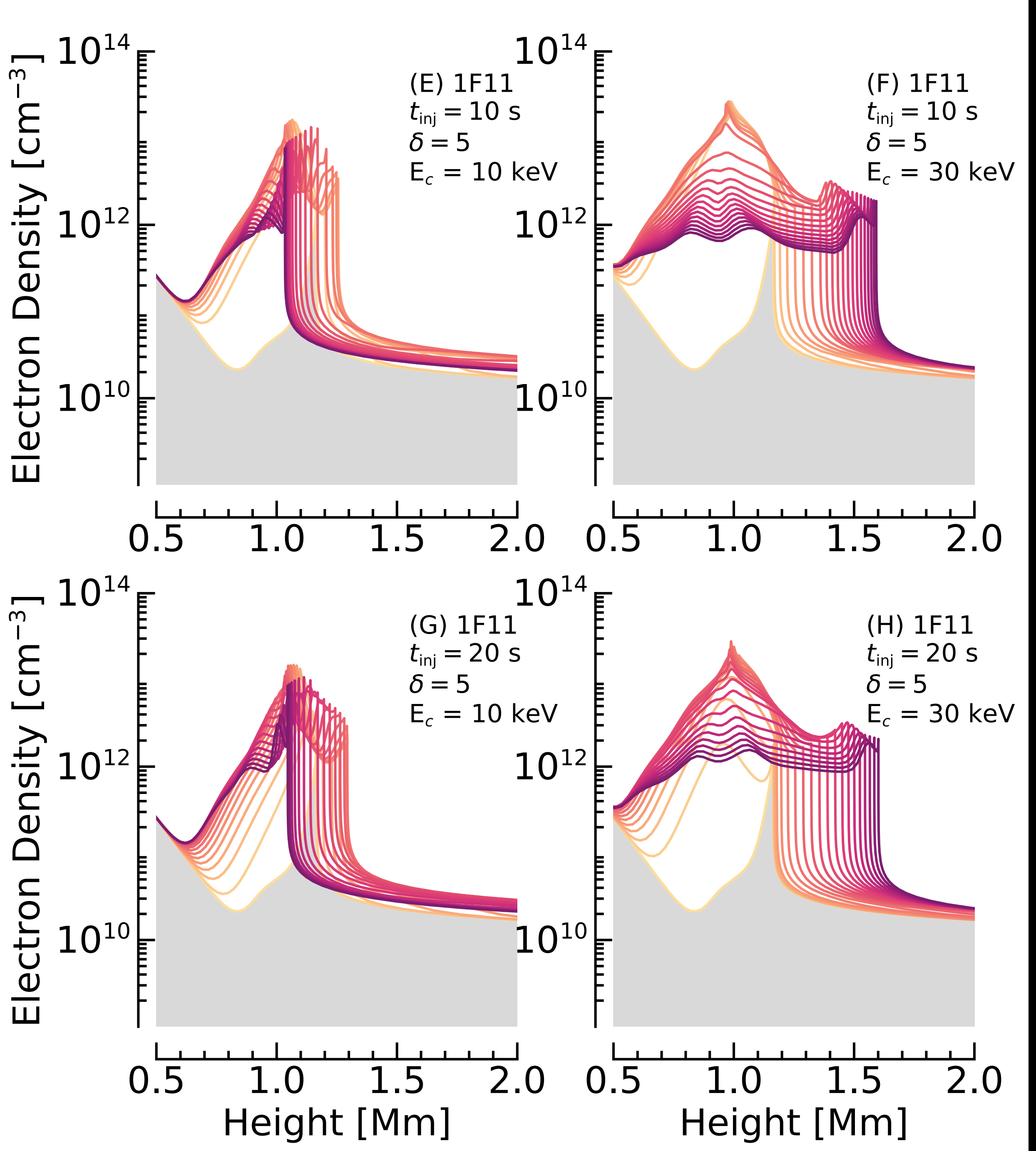
Simulations performed with RADYN+FP

- Radiation hydro code with non-thermal particle transport.
- NLTE chromosphere w/ non-equilibrium pops.
- Includes Non-thermal He collisions.
- Includes coronal/TR irradiation.

(Allred et al 2015, 2020)

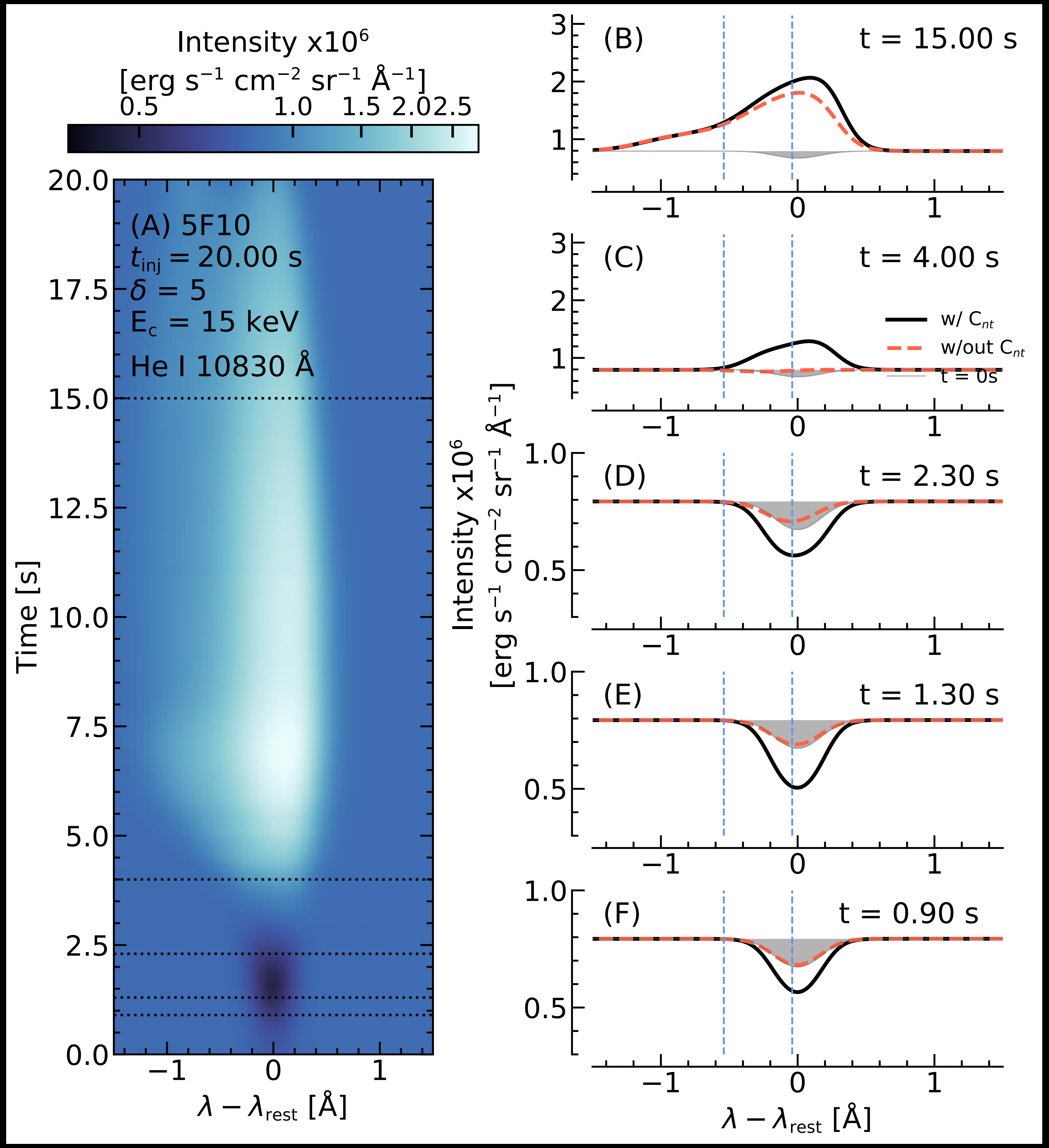


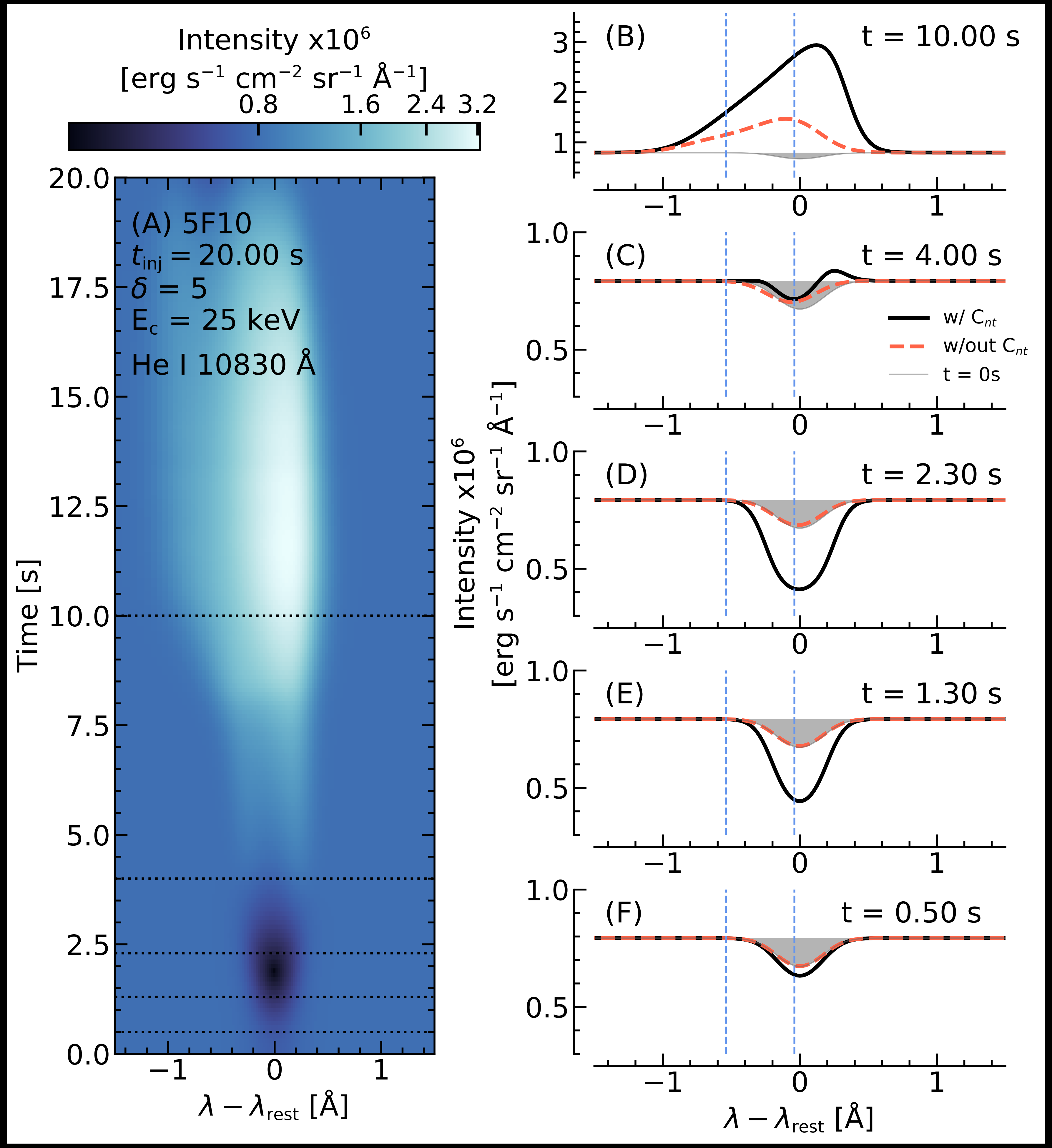




DO WE SEE ENHANCED ABSORPTIONS?

- Yes! … but ONLY if we include nonthermal collisional ionisation C_{nt}. Therefore CRM is the cause of the enhanced absorption, and the properties of the impinging electrons are related to the magnitude and duration of the absorption.





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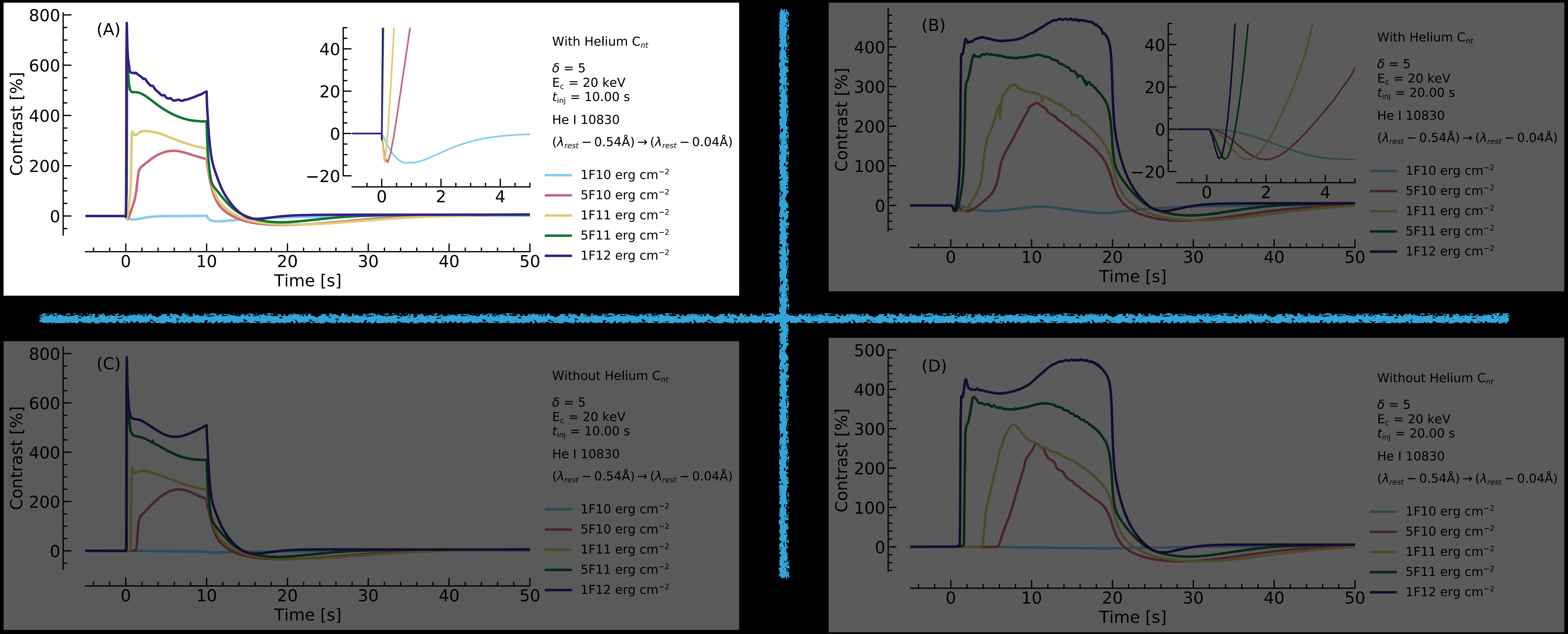
- The effect is longer lived for weaker flares.



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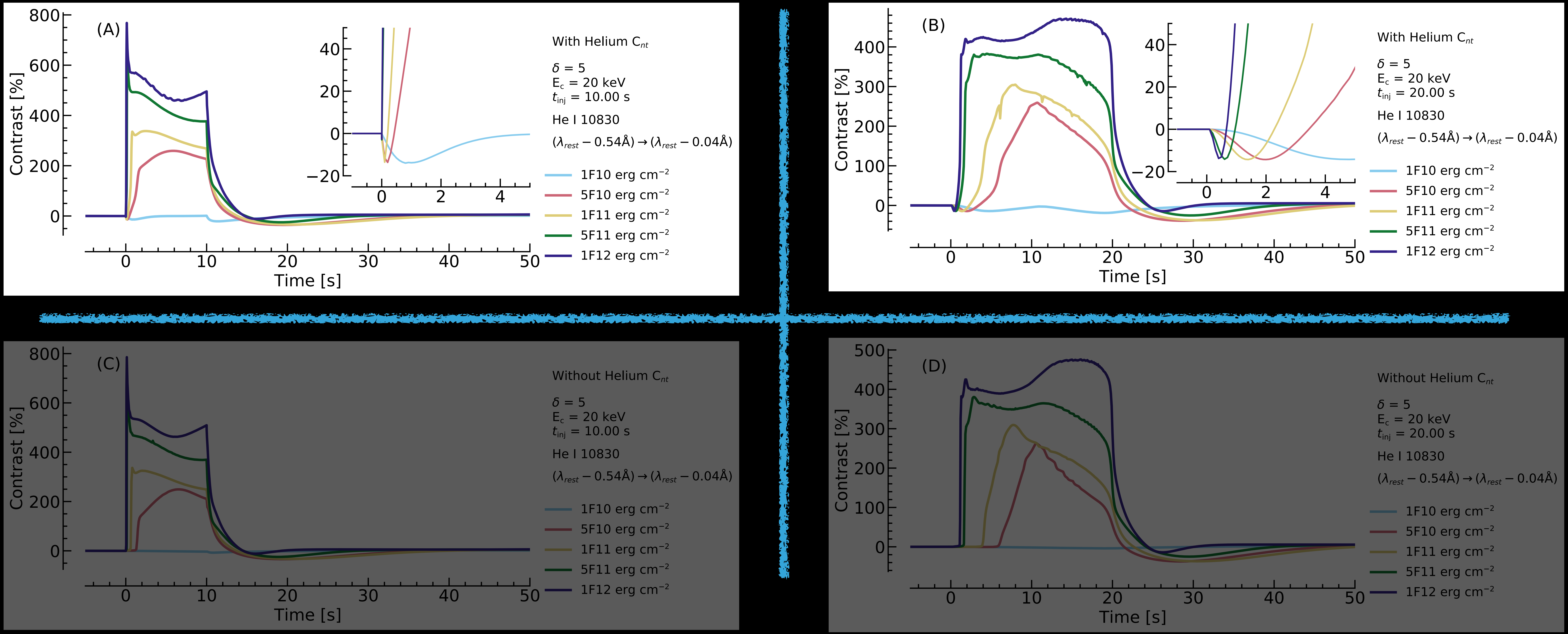

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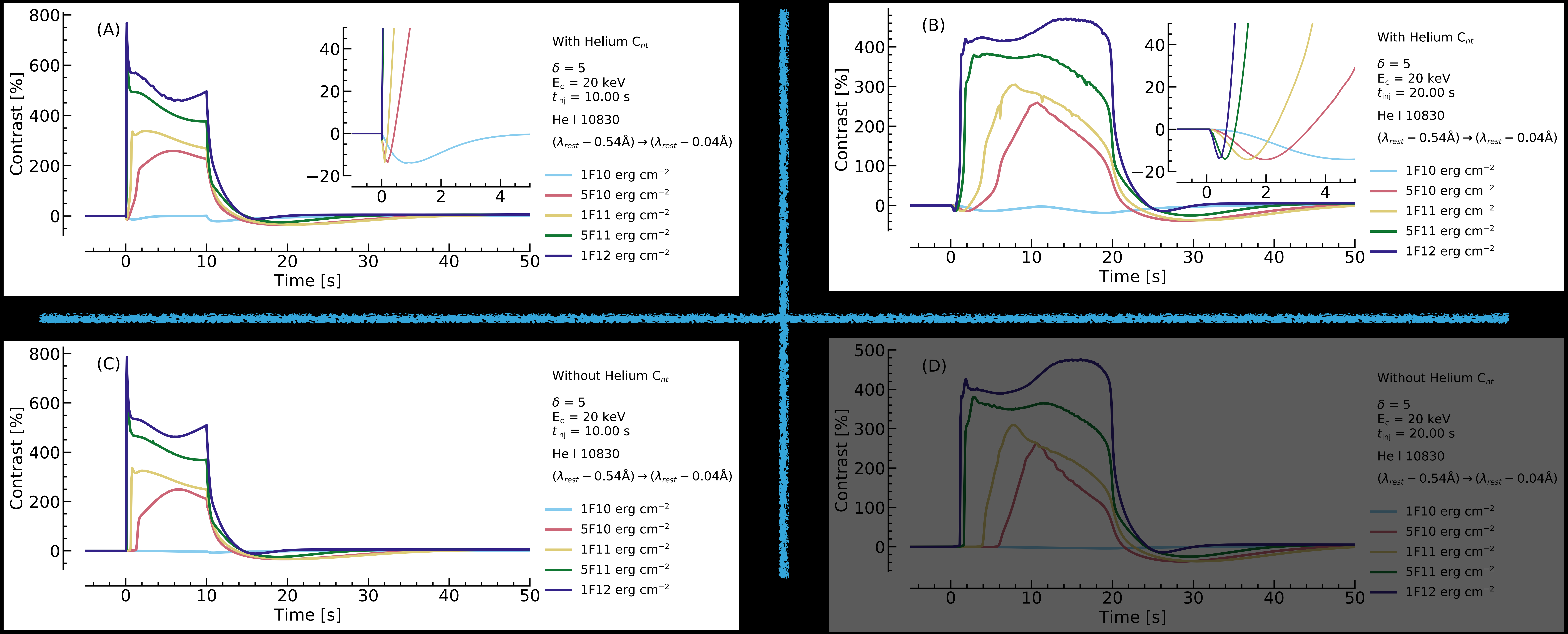

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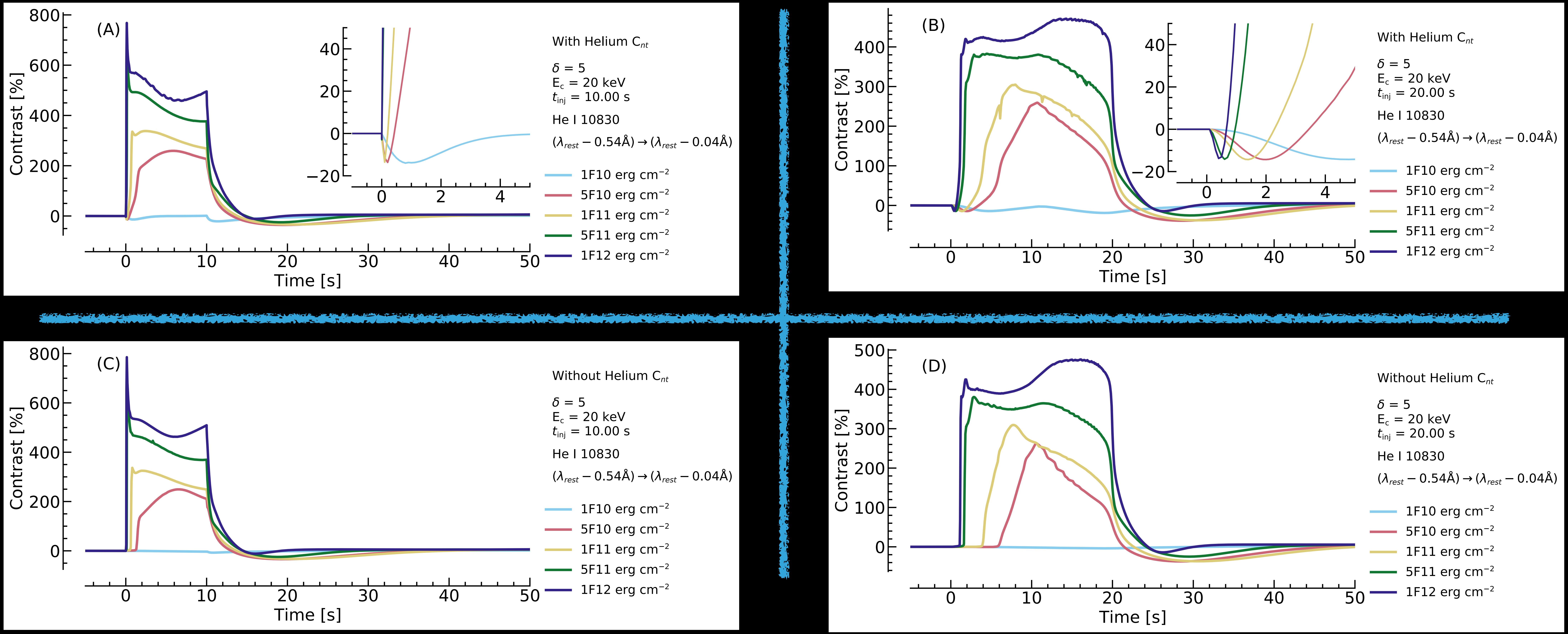
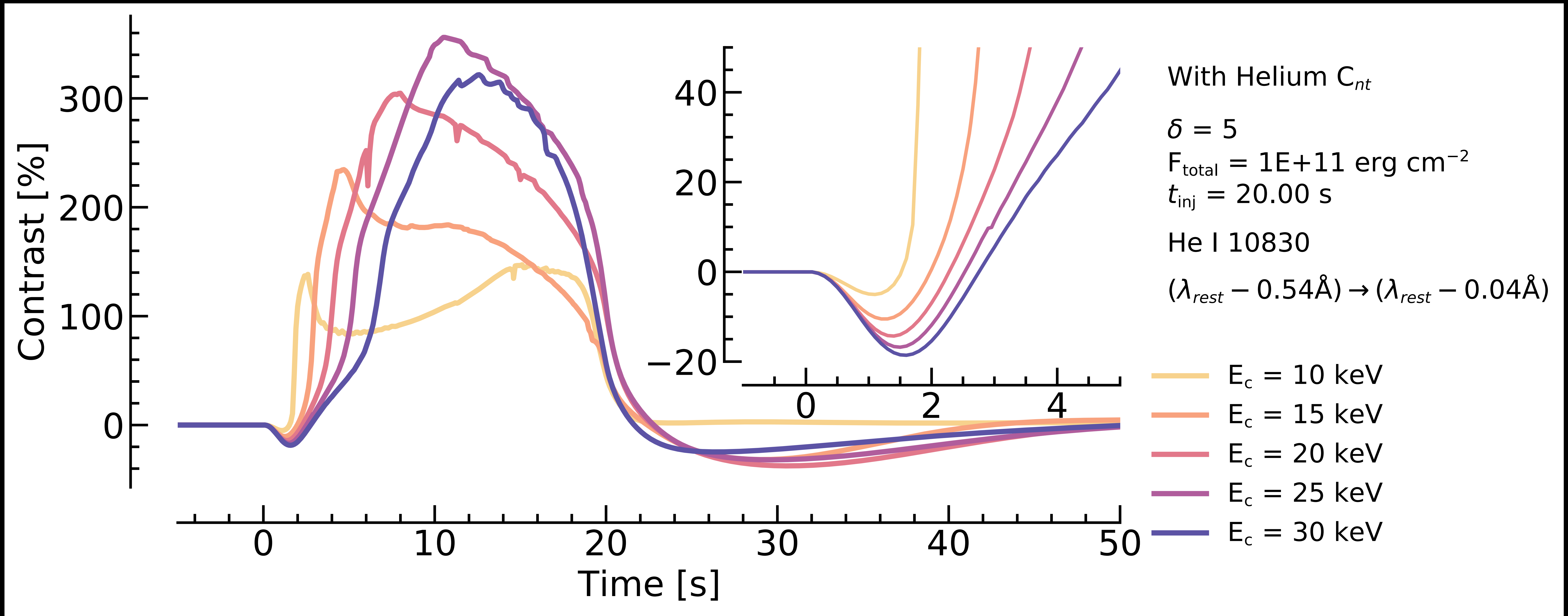


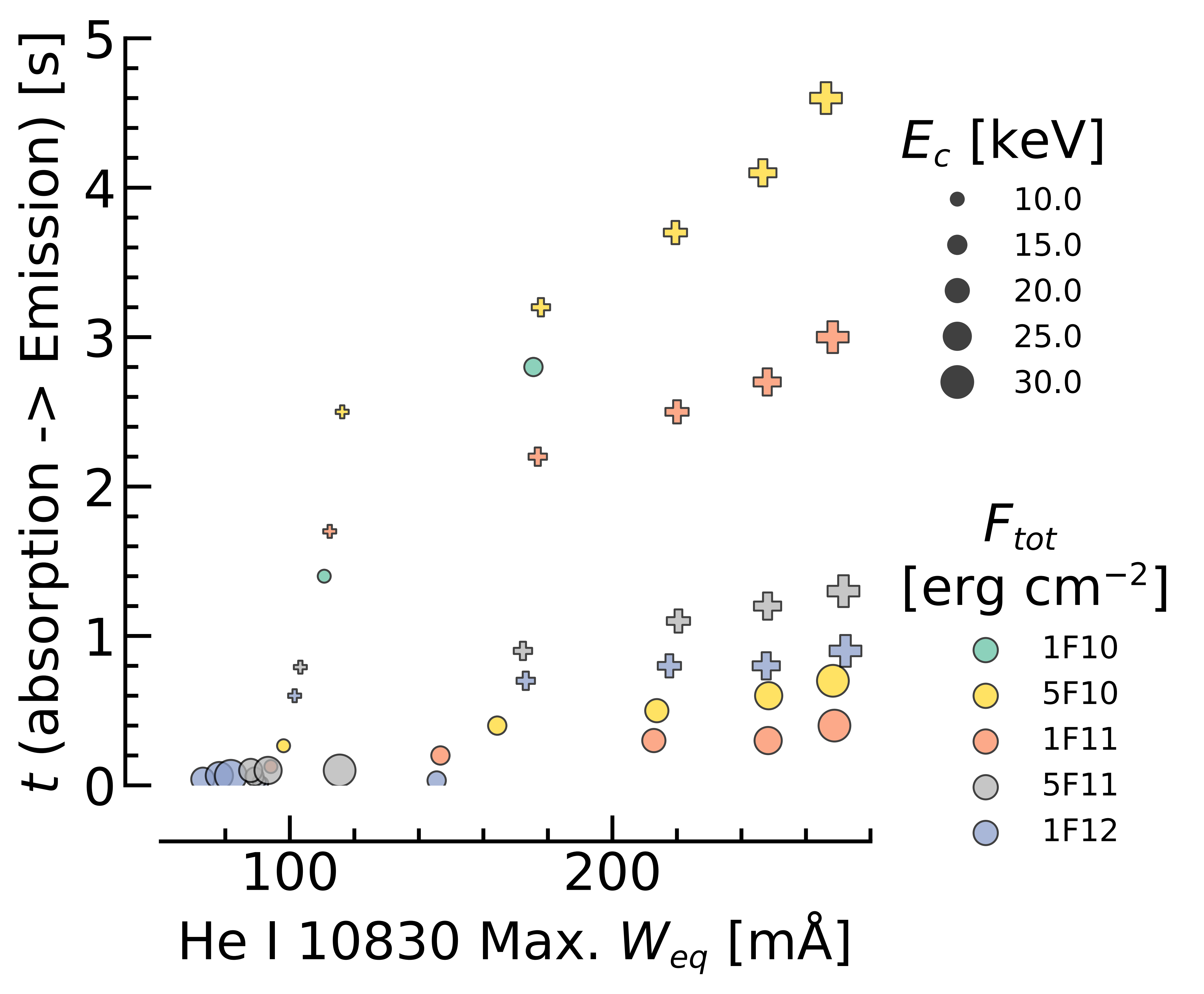
DO WE SEE ENHANCED ABSORPTIONS?

- Strength and duration of absorption depends on the spectral properties of the non-thermal distribution.
- Harder electron energy spectrum (more deeply penetrating) results in stronger, more sustained absorptions. This is because it takes longer for upper chromosphere temperature to exceed ~20kK, at which point thermal collisions are more important in populating orthohelium.



DO WE SEE ENHANCED ABSORPTIONS?

- Strength and duration of absorption depends on beam properties. Harder electron energy spectrum (more deeply penetrating) results in stronger, more sustained absorptions. This is because it takes longer for upper chromosphere temperature to exceed ~20kK, at which point thermal collisions are more important in populating orthohelium.



+ $t_{inj} = 20s$

• $t_{inj} = 10s$

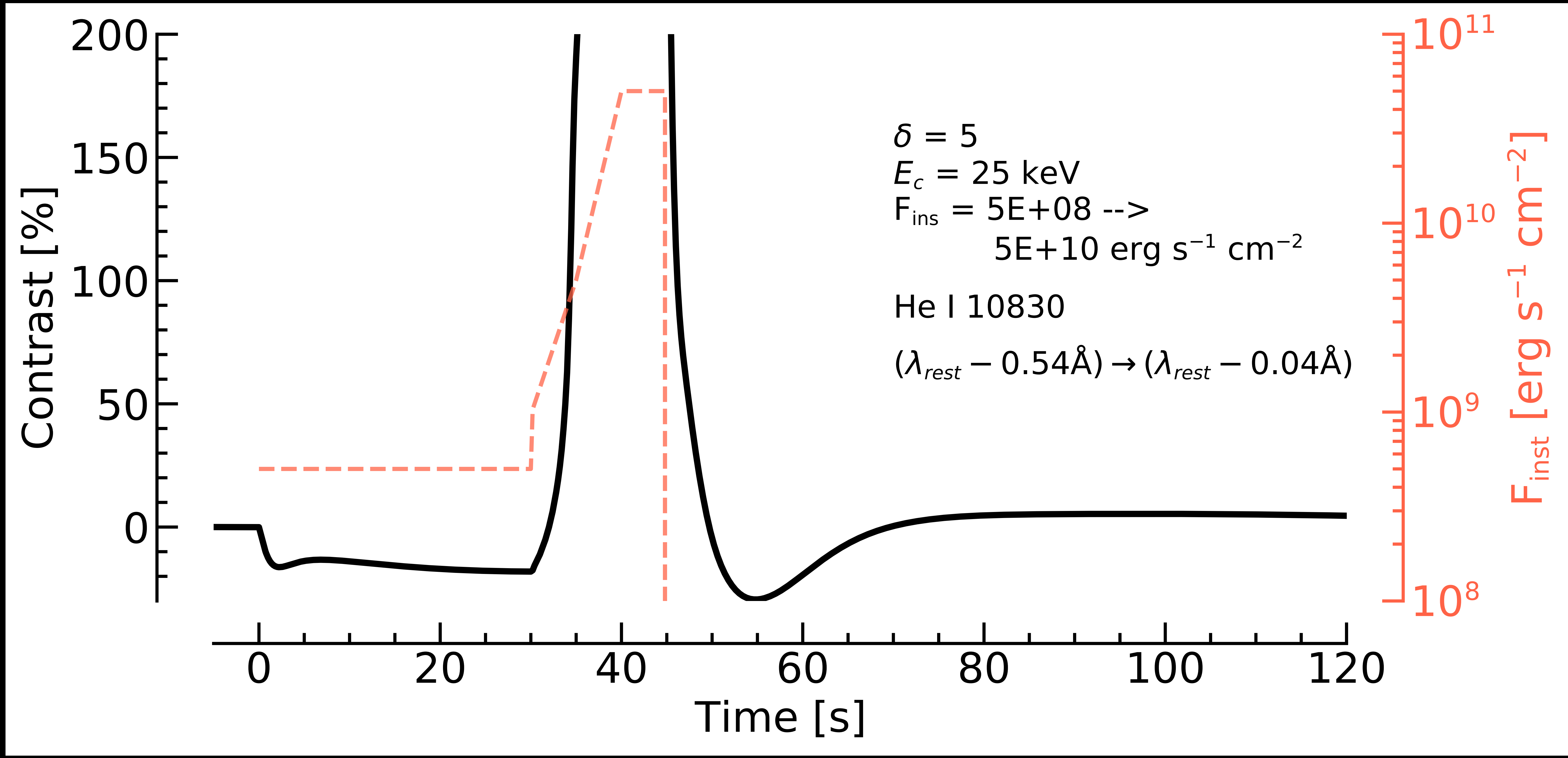
1F10 with Ec > 15 keV don't go into emission

More gradual heating ($t_{inj} = 20s$) extends period of enhanced absorption.

DIMMING IS TOO SHORT

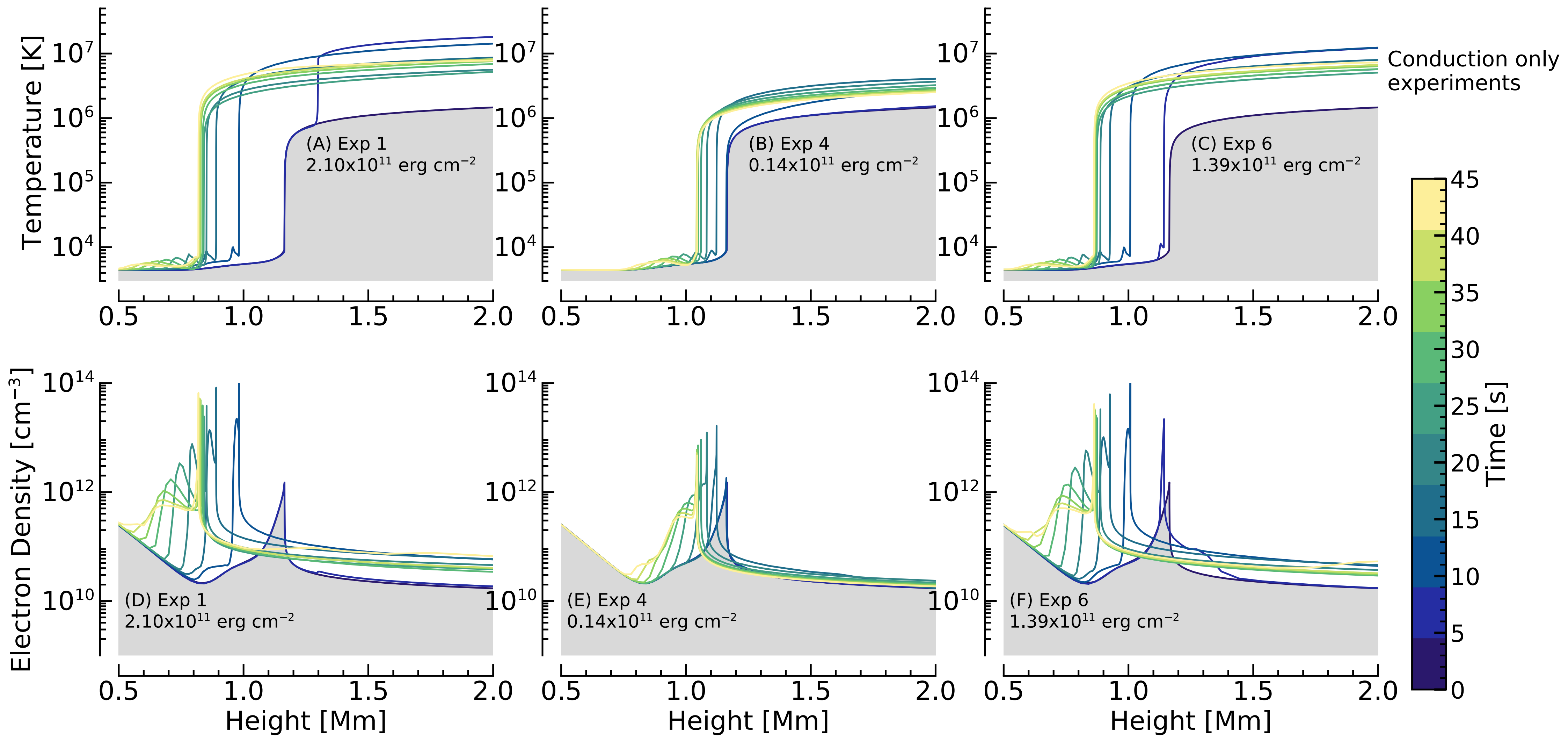
- The modelled dimming is of the right magnitude, but is too short lived. The only way we could have a sustained dimming was to have an extended period of weak non-thermal electron bombardment before the main flare. Simulations that only had in-situ coronal heating led only to emission.

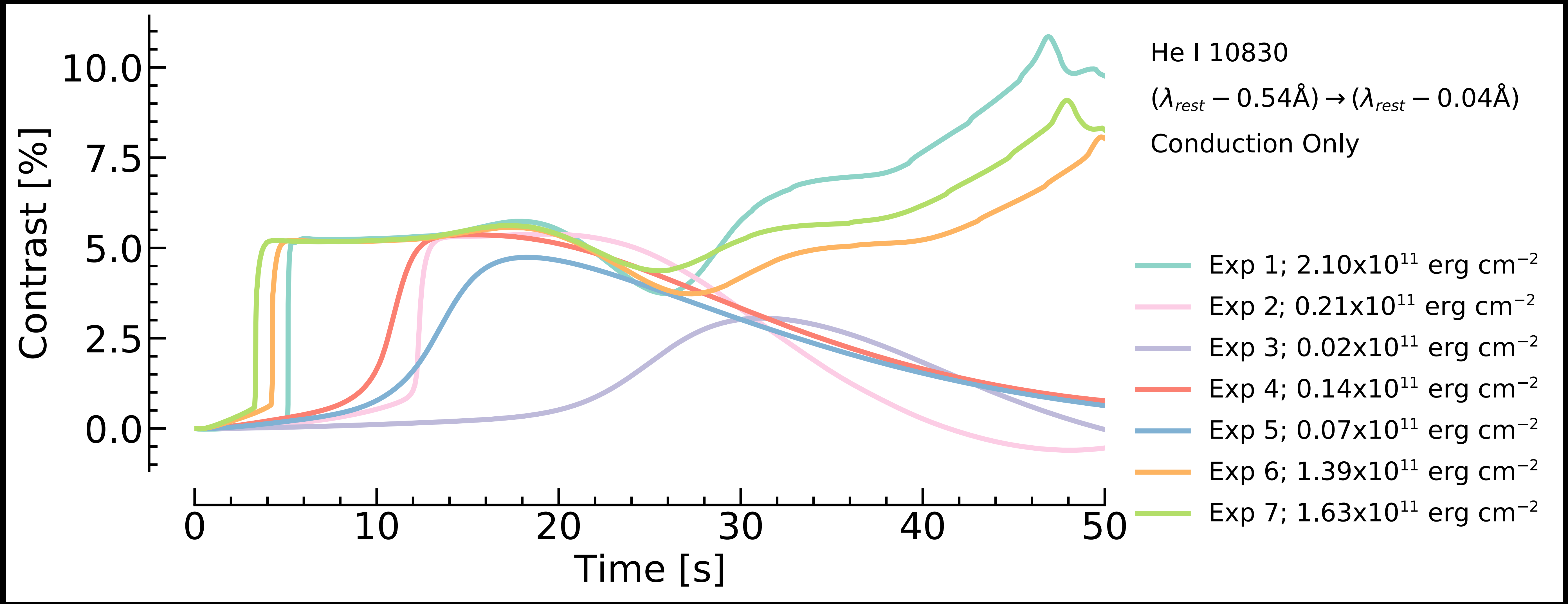
- In our model the non-thermal particles came from a beam of precipitating electrons, but could other sources exist – local acceleration via Alfvenic waves for example (Fletcher & Hudson 2008).



ENERGY TRANSPORT VIA CONDUCTION ONLY DOES NOT PRODUCE DIMMING

- Dimming at flare onset is not present in flares driven by in-situ heating + conduction.





FLARE RIBBON FRONTS — HIGH SPATIOTEMPORAL RESOLUTION NEEDED

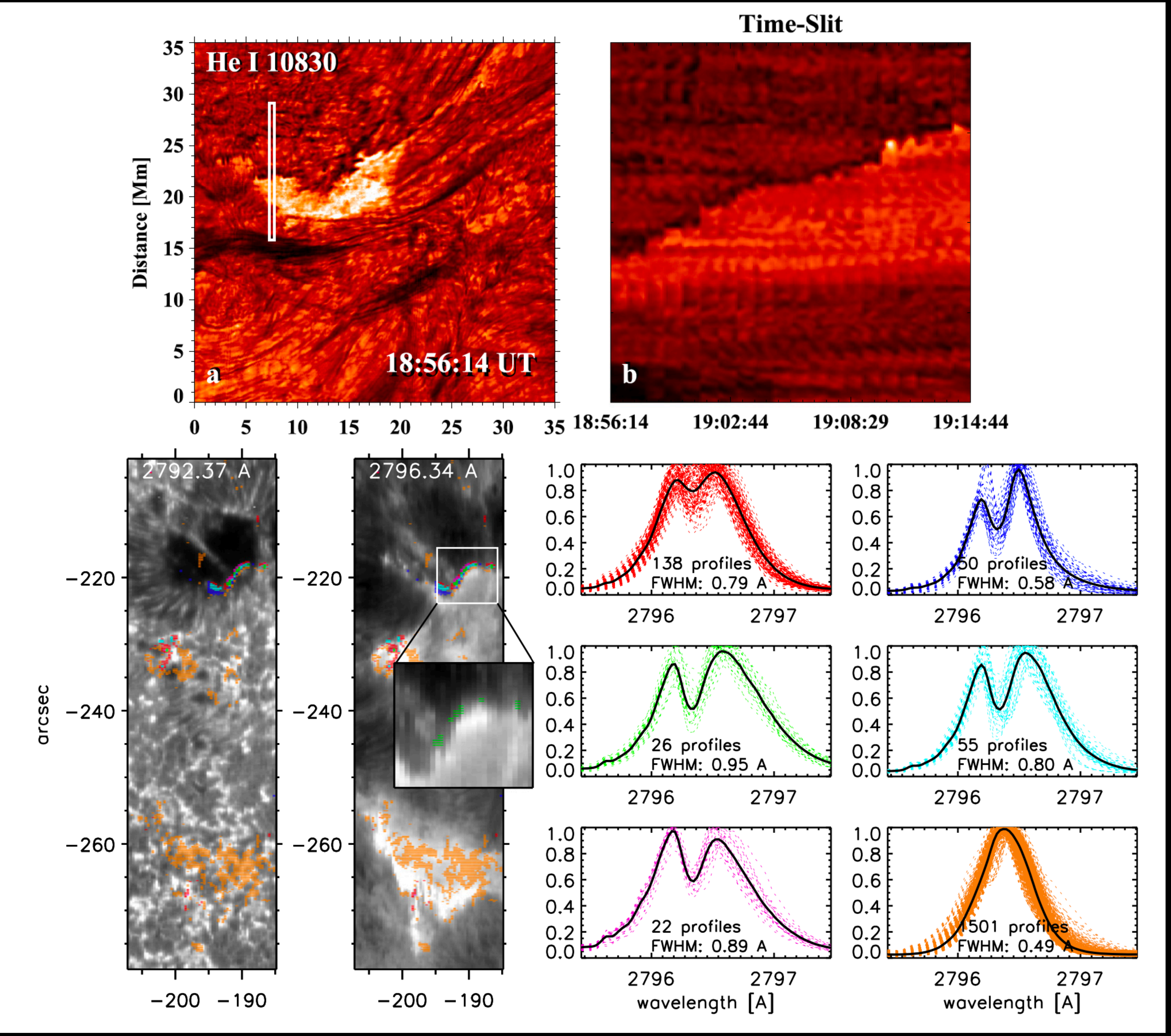
- There have recently been a number of interesting observations of the leading edge of flare ribbons, where newly reconnected field lines deposit their energy. This should be the focus of future studies with high spatiotemporal resolution over the full flaring region. Ideally with simultaneous hard X-ray obs (with high dynamic range).

Negative contrast at flare leading edge

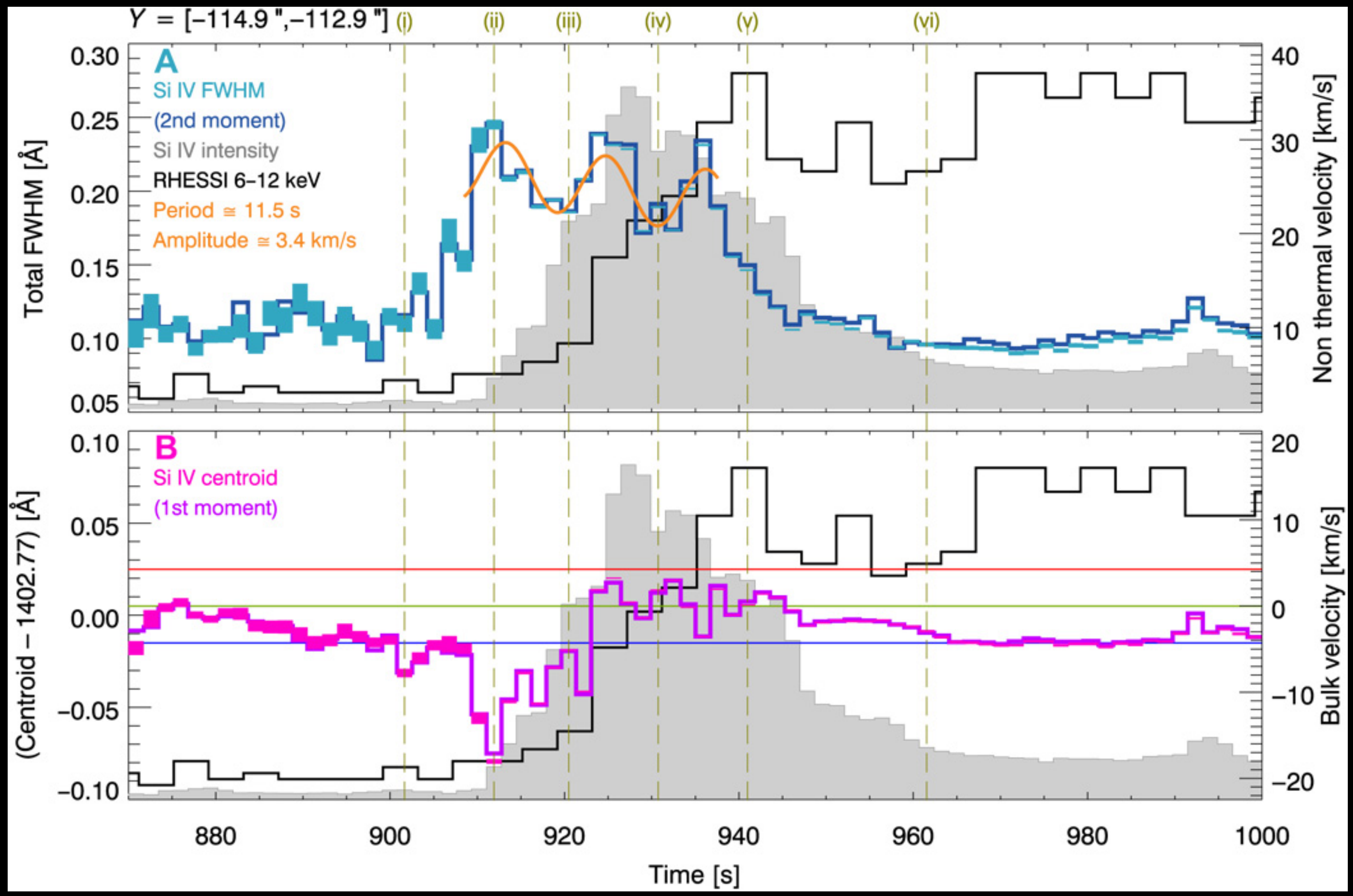
Xu et al 2016

Unique profiles at leading edge

See also Panos et al 2018, 2021

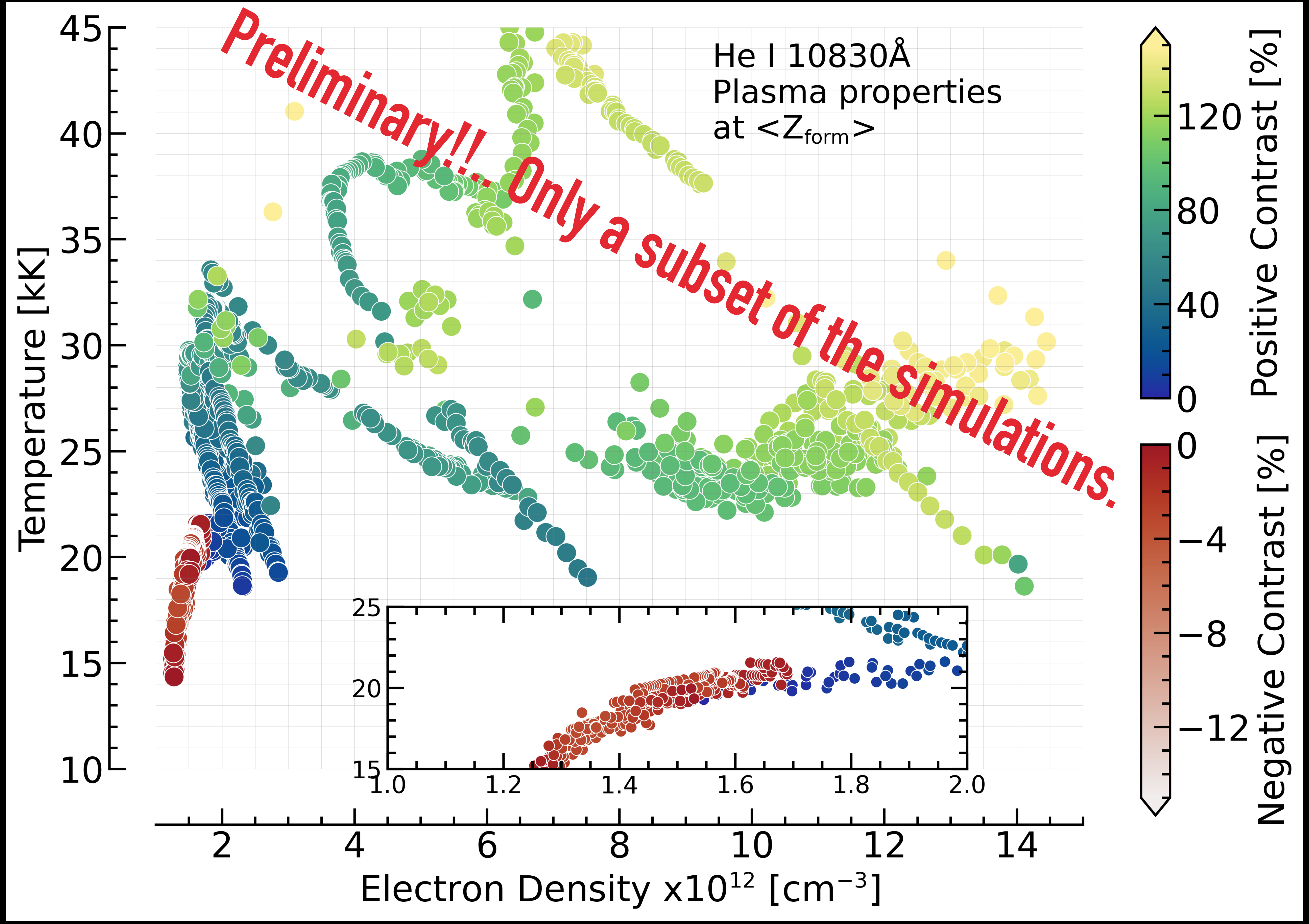


Non-thermal line width increases before line intensity Jeffrey et al 2018



CONCLUSIONS AND NEXT STEPS

- Non-thermal collisional ionisation of He I -> He II is required to produce flare-induced dimming of the He I 10830Å triplet.
- Properties of the dimming are related to the spectral distribution of the non-thermal particles.
- Currently a discrepancy related to timing of dimming – need a period of weak bombardment in the model to produce sustained dimming.
- Observational study underway to look at differences in IRIS lines from the ribbons associated with He dimming, and those from ribbons without. Will be followed up by modelling of Mg II, Si IV, C II.
- Expanding to model He I D3 also – preliminary results suggest similar response fo 10830Å triplet, but with differences that could lead to potential diagnostics of both the plasma properties and the non-thermal particles. Could we use relative behaviour He I 10830 and He I D3 lines to infer plasma temperatures and densities in the upper chromosphere?



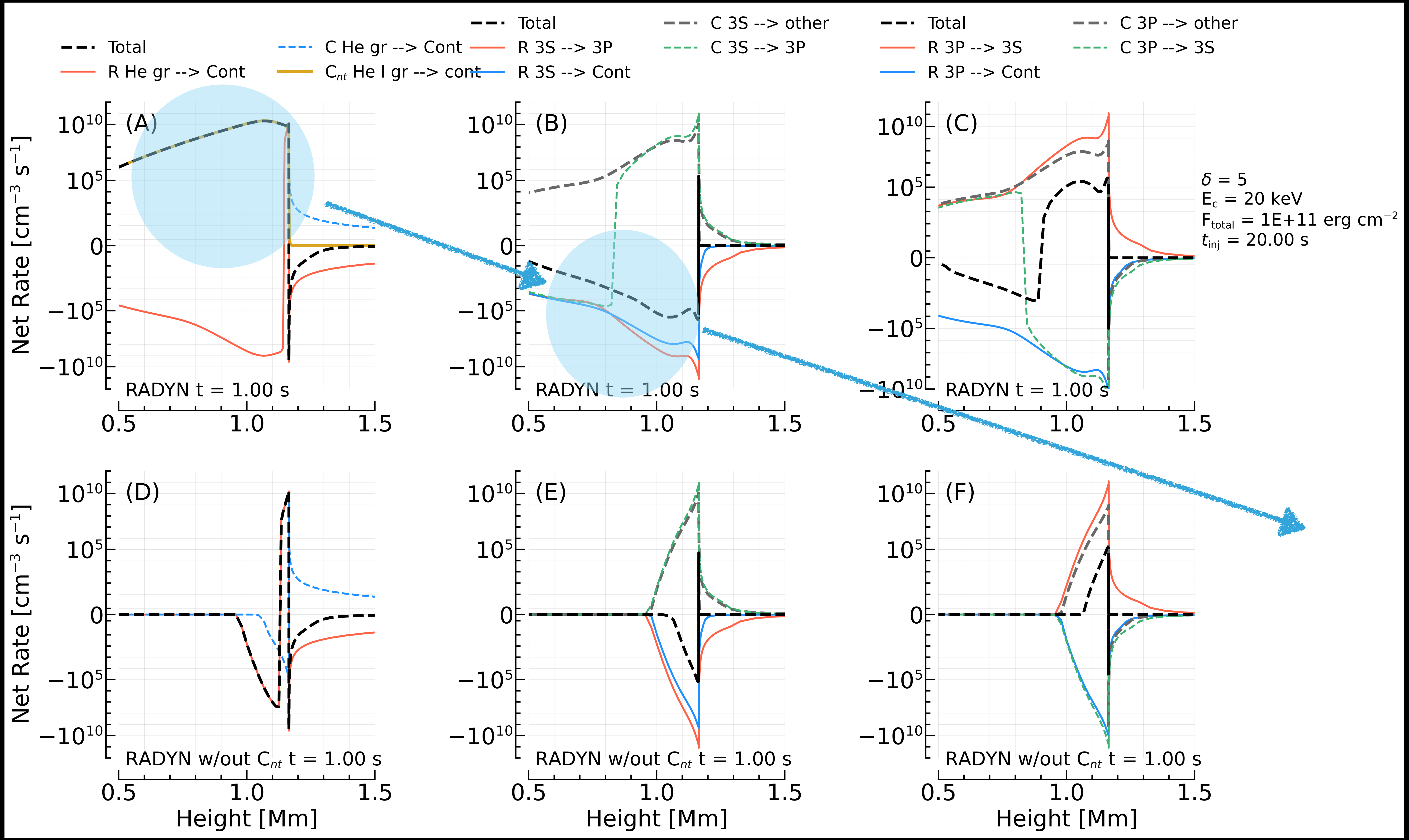
Additional Material

WHEN DOES THE LINE GO INTO EMISSION

- Why is the effect shorter lived for stronger flares, and only present when nonthermal collisions are present?

With C_{nt}

Without C_{nt}



Net rates, N = Nr + Nc

Nr = R↑ - R↓

Nc = C↑ - C↓

Positive = transitions *out of* level

Negative = transitions *into* level

Excess population due to nonthermal collisional ionisation followed by recombinations.

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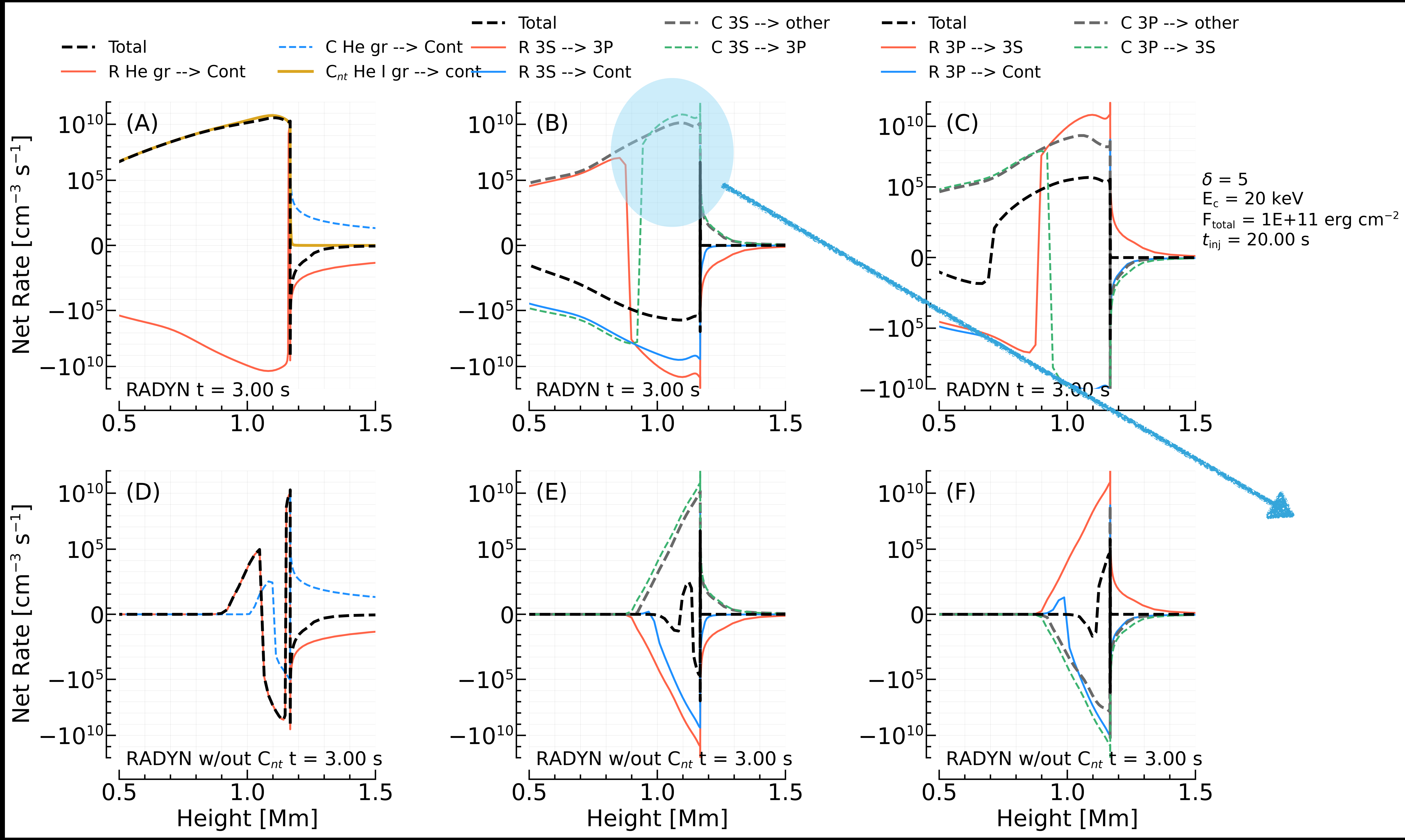

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As temperature rises thermal collisions drive electrons from He I ^{3}S –> He I ^{3}P, bringing line into emission.

This happens faster in stronger flares.

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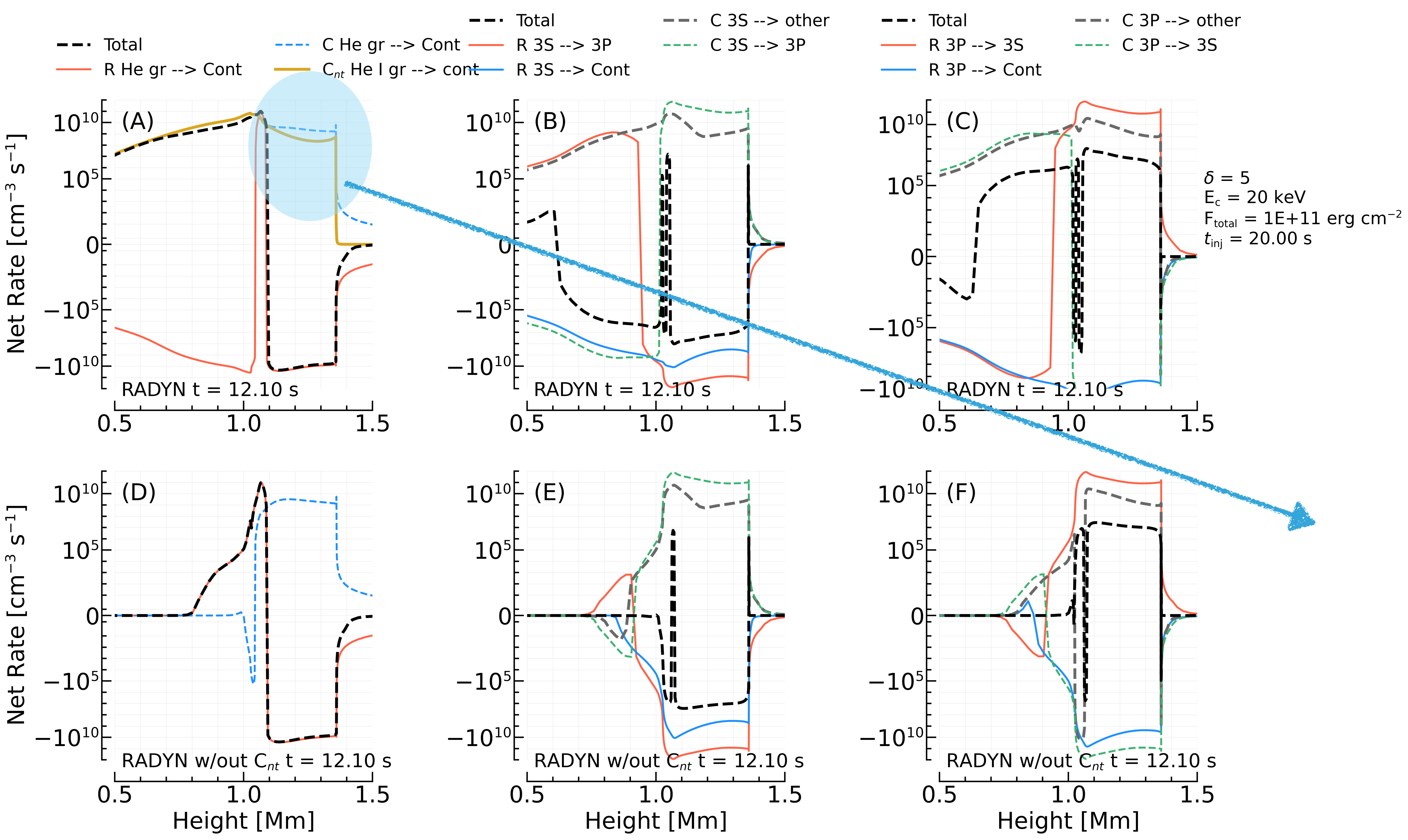

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Later in flare, temperature is > 20kK, and thermal collisions dominate in parts of atmosphere.

This happens faster in stronger flares.