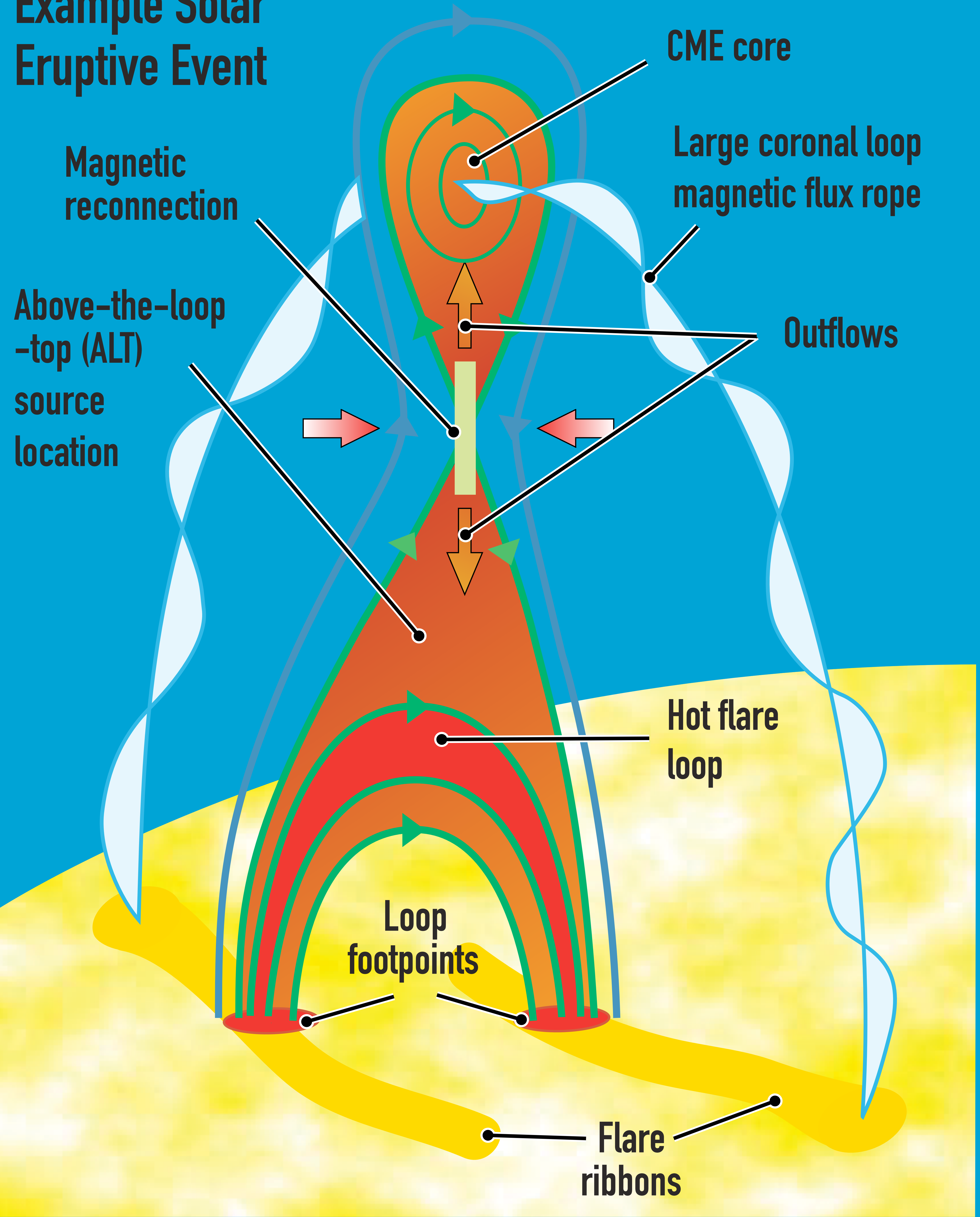
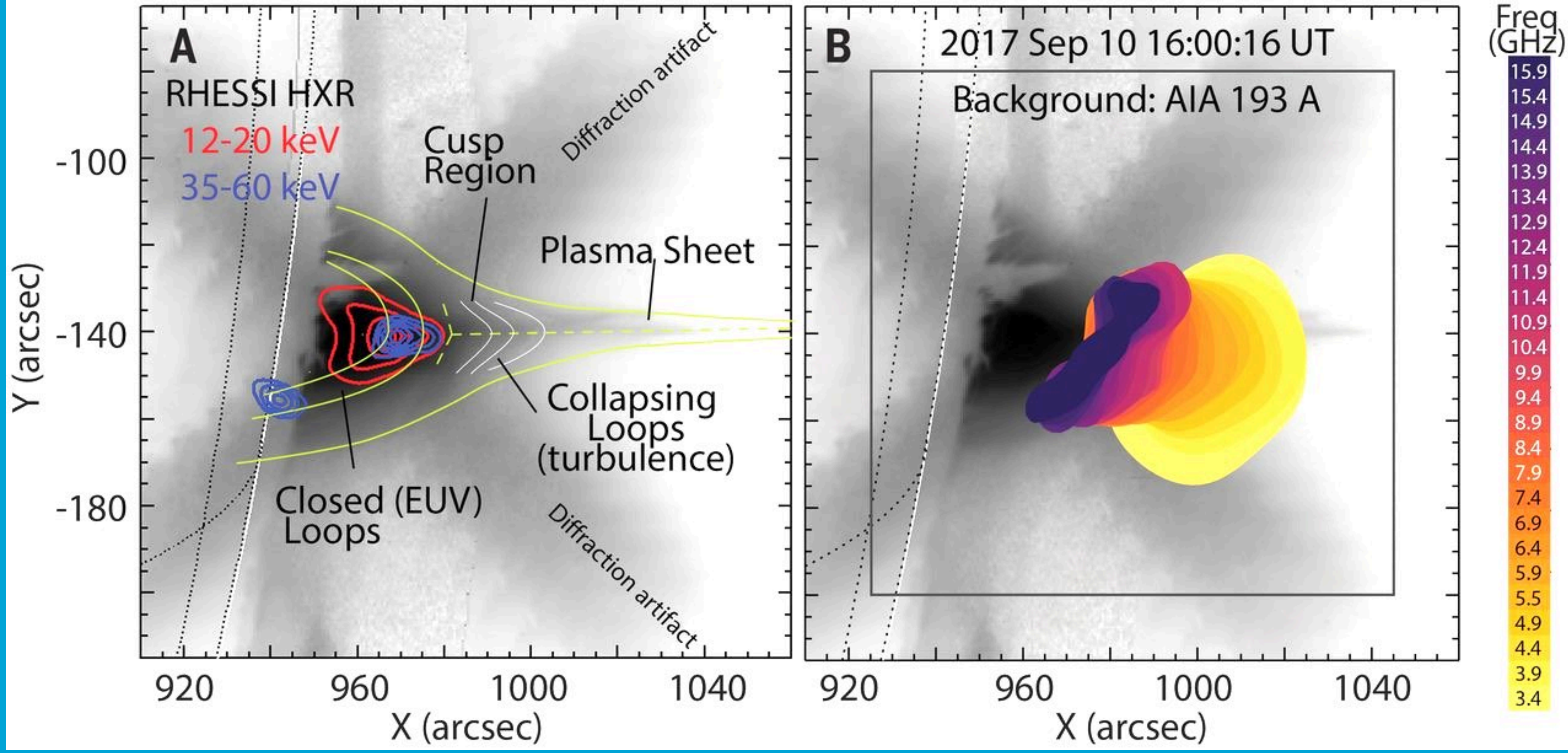
GRAHAM S. KERR (CATHOLIC UNIV. OF AMERICA / NASA GSFC)

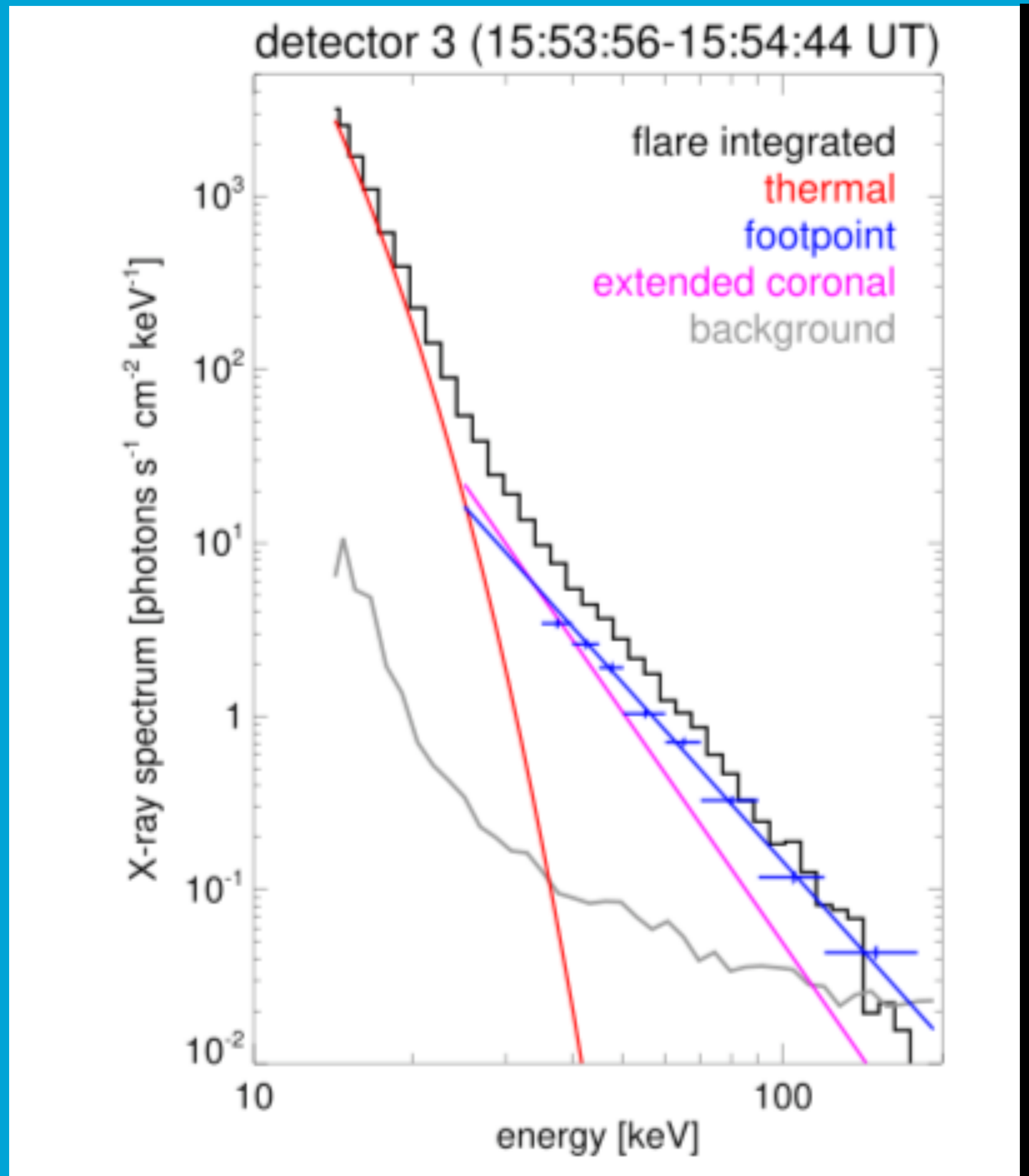
SOLAR FLARE RIBBON FRONTS AS A WINDOW ONTO FLARE ENERGETICS

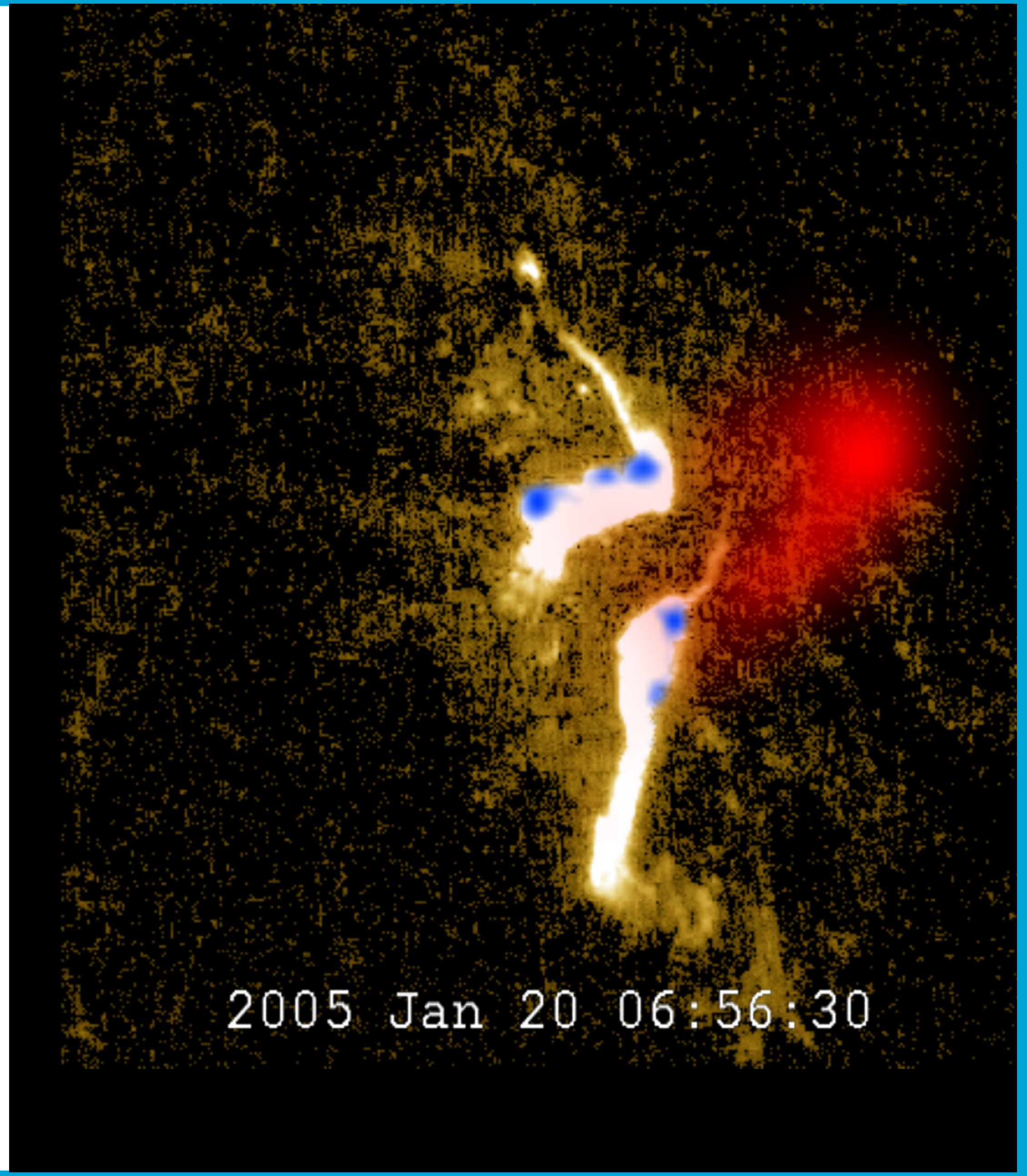
With Vanessa Polito (LMSAL), Joel C. Allred (NASA GSFC), Yan Xu (NJIT)

Example Solar Eruptive Event



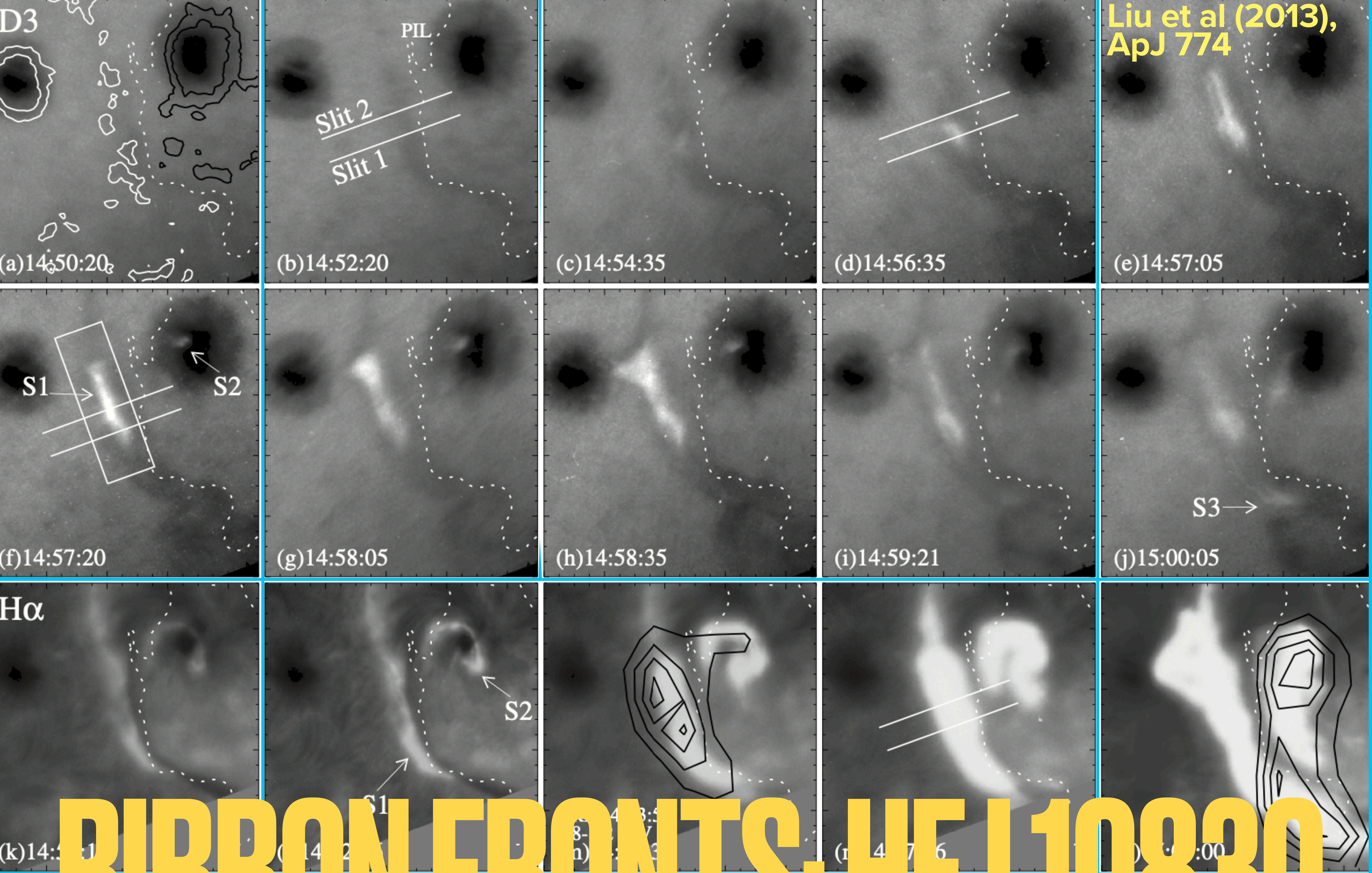






OVERVIEW OF SOLAR FLARE RIBBON FRONT OBSERVATIONS

HE I 10830 & MG II RESONANCE LINES



Liu et al (2013), ApJ 774

RIBBON FRONTS: HE I 10830

Observations in the 1980s of He I D3 dimming before emission in flares — possibly related to hard X-ray properties (HXR were weaker in dimming phase).

More recently very high spatial resolution flare imaging from Big Bear Solar Observatory (BBSO) found that ahead of flare ribbons the He I 10830Å line dimmed before brightening.

The dimming lasted for ~100s, and the 'negative' ribbon was 300-500km wide.

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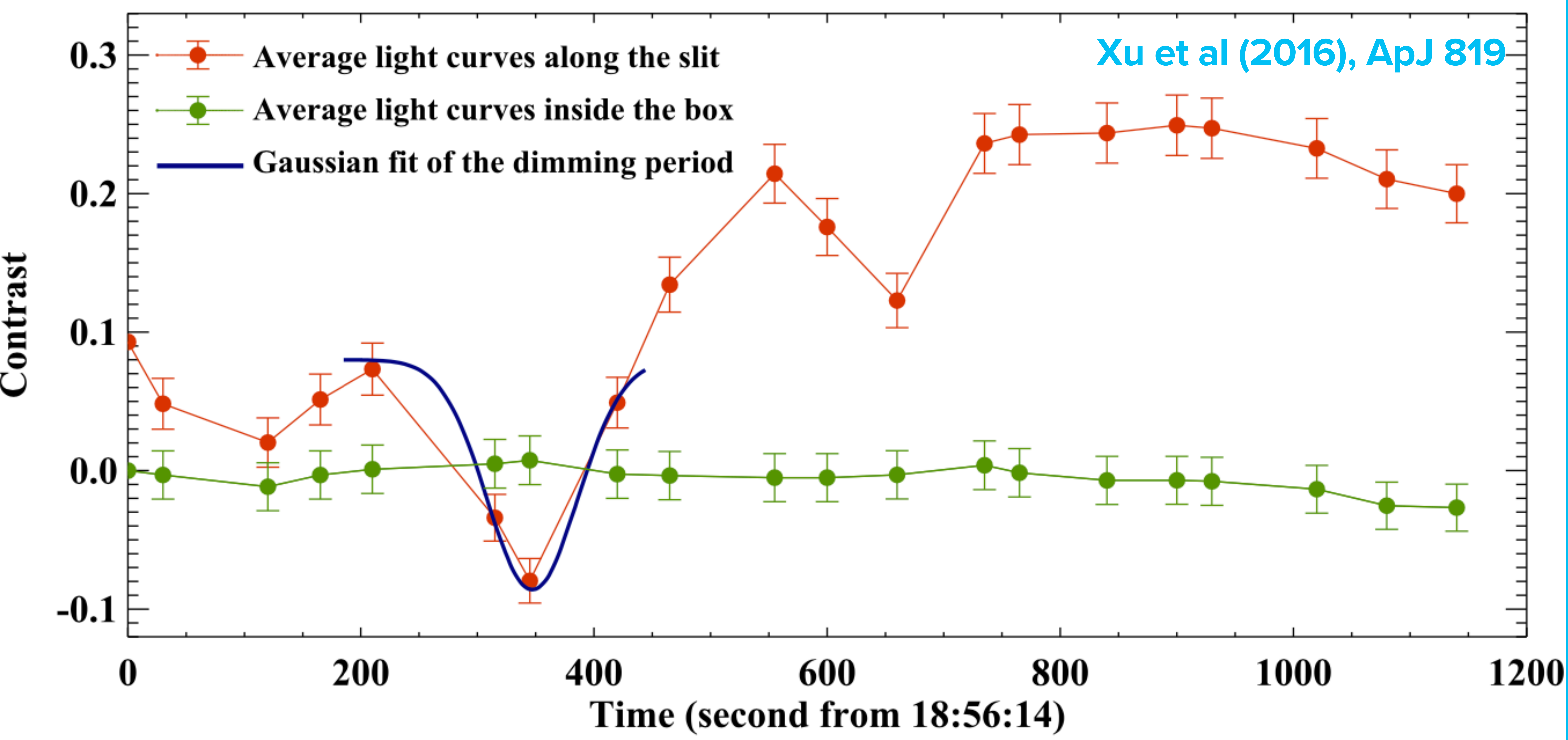

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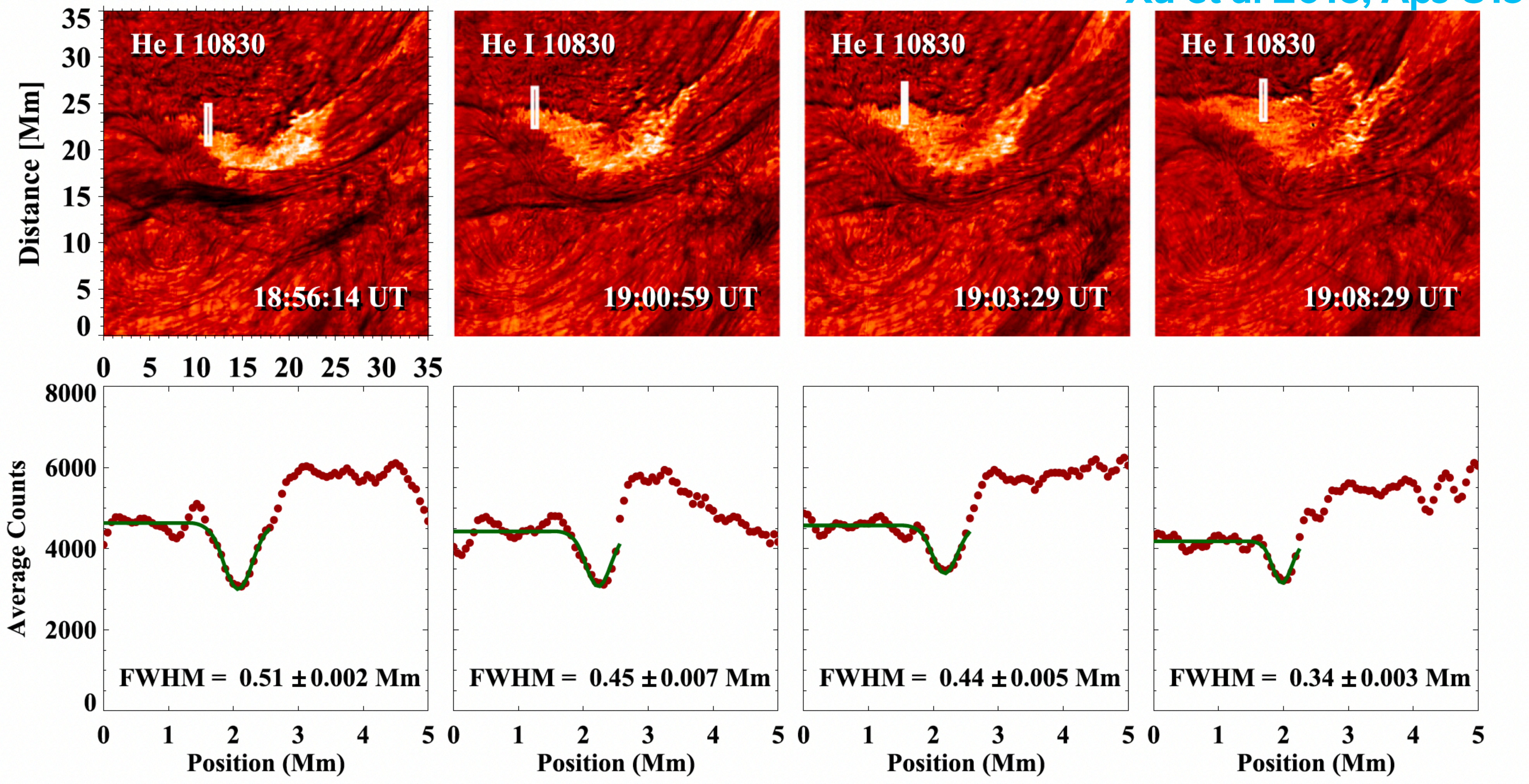

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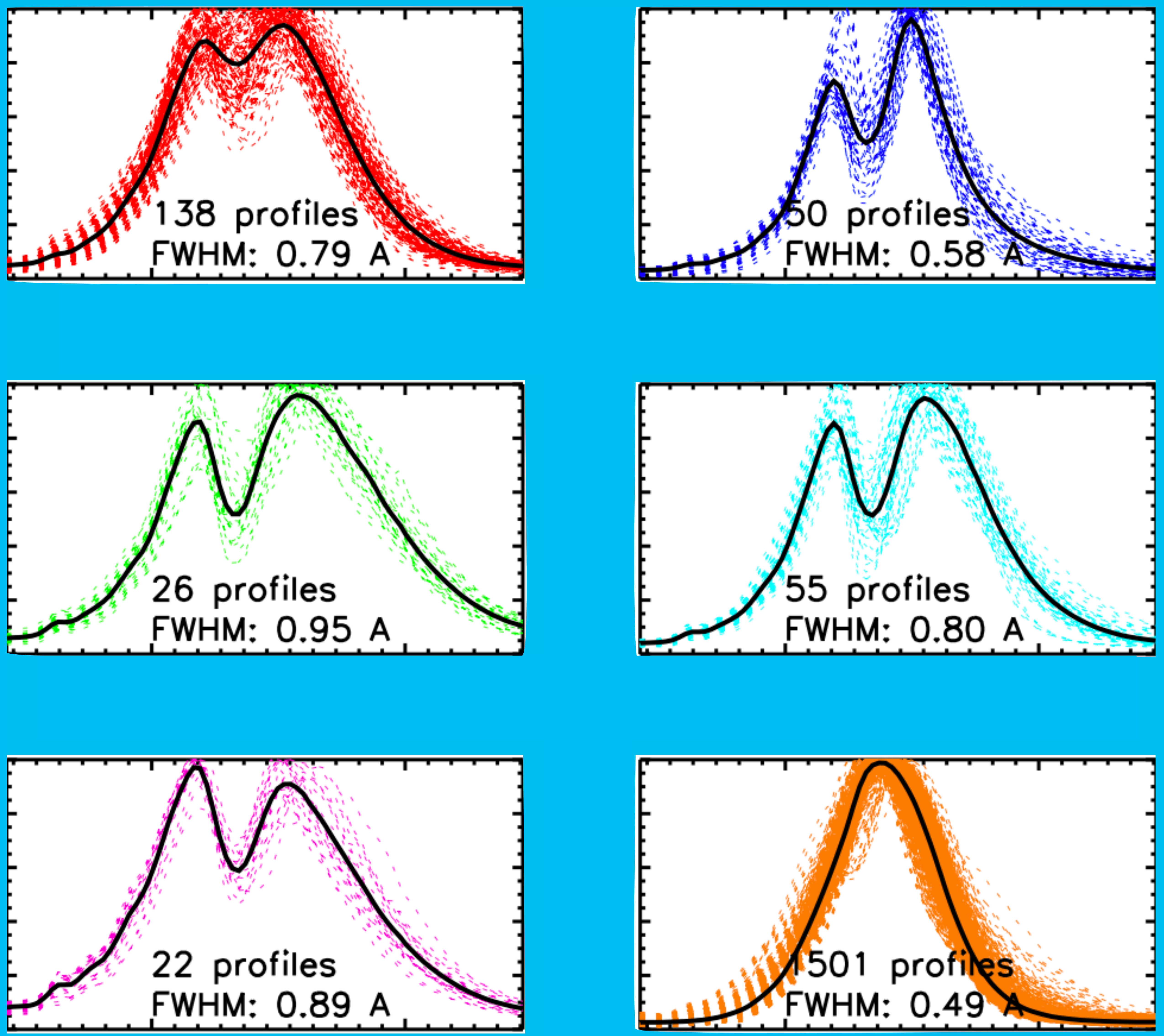
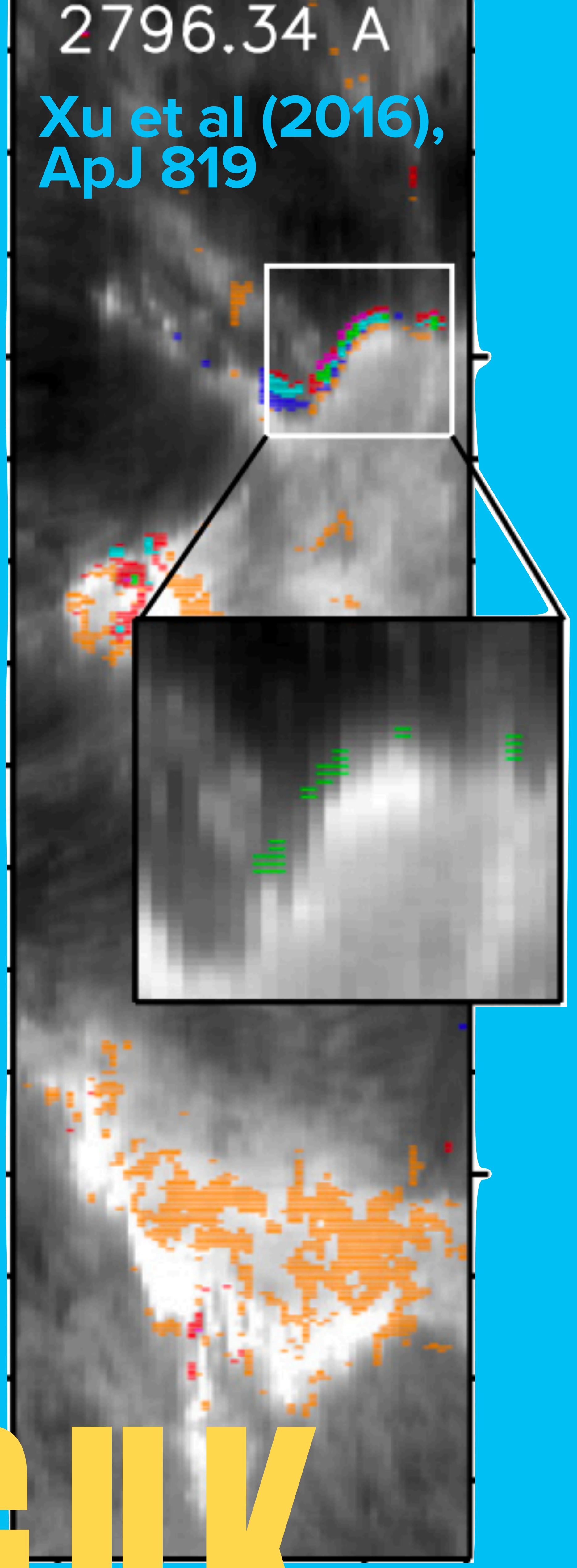
RIBBON FRONTS: MG II K





Xu et al (2016), ApJ 819

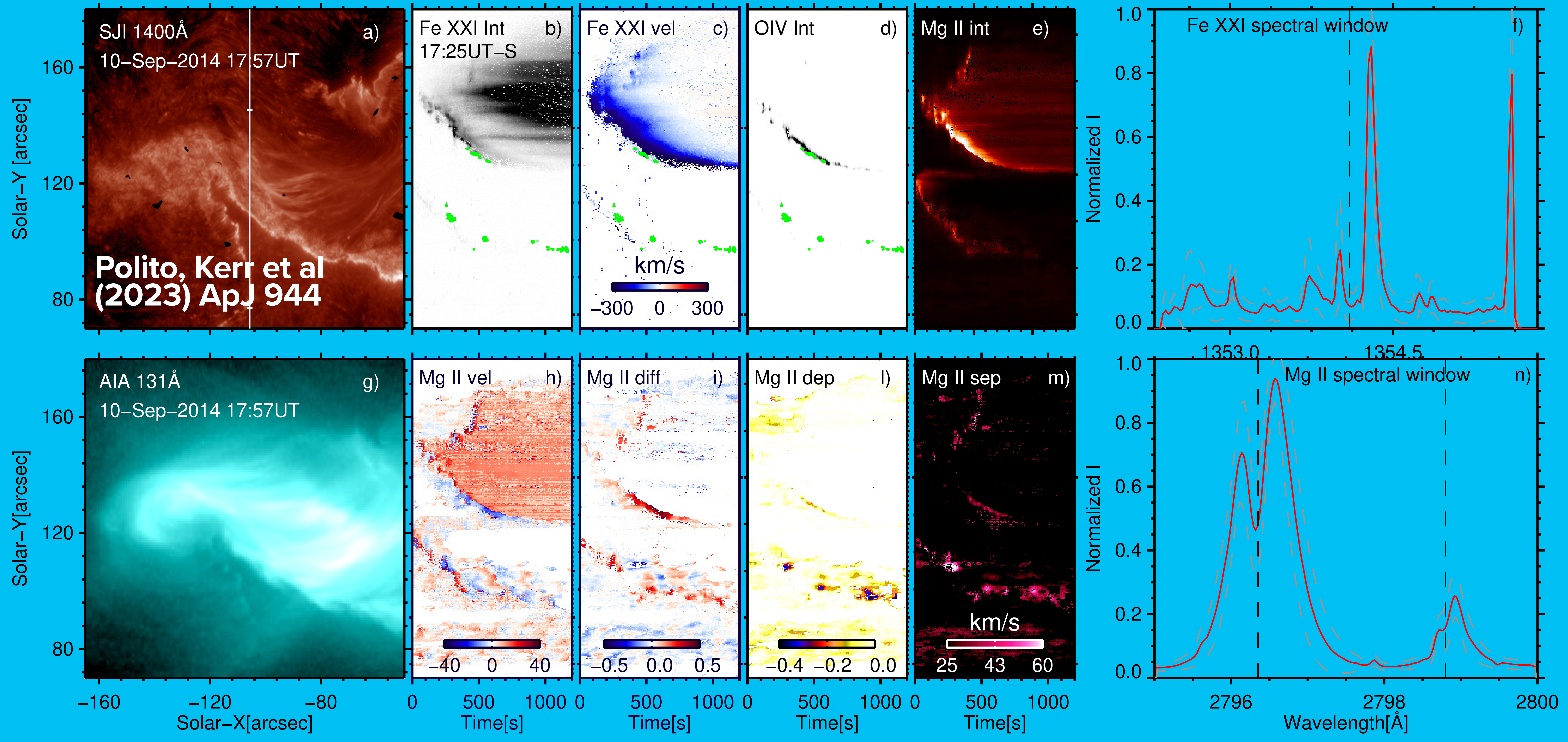
Ribbon front Mg II near-UV spectra exhibit different characteristics than in the main bright ribbons:

- ✳Deeper central reversals;
- ✳Extremely broad profiles;
- ✳Slight blueshift of line core (k3);
- ✳Asymmetric peaks (k2r > k2v);
- ✳Increased peak separation;
- ✳Subordinate lines in emission.

These are transient, and do not uniformly appear along the ribbon — it is somewhat patchy.

Note that evaporation is not present in ribbon front pixels.

Evaporation occurred later (~20-300s), when the pixels where in their bright phase.



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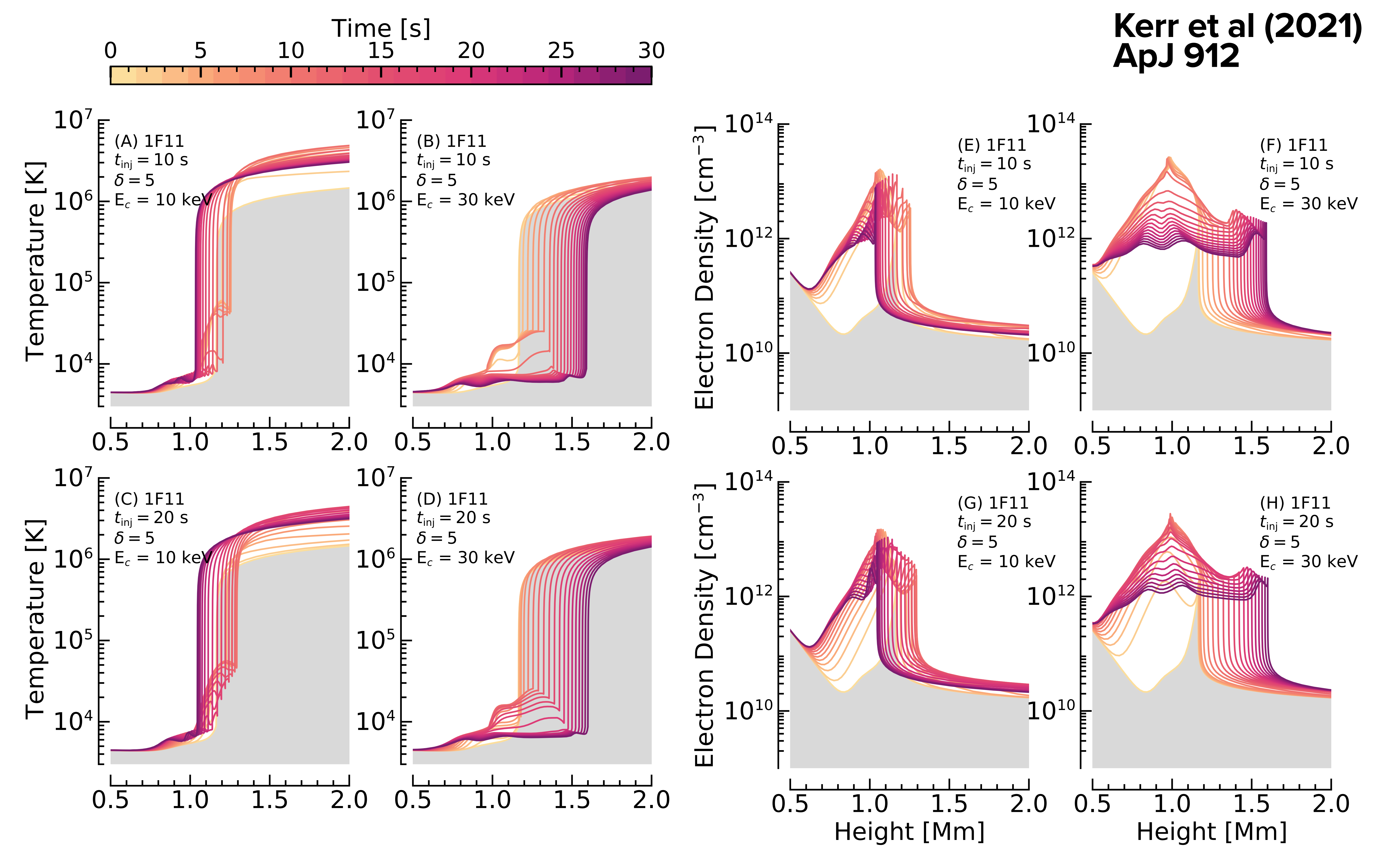
WHAT CAUSES THE RIBBON FRONT CHARACTERISTICS ?

MODELLING RIBBON FRONTS VS BRIGHT RIBBONS

RAN MANY FLARE LOOP MODELS, WITH AND WITHOUT NONTHERMAL COLLISIONAL IONIZATION OF HELIUM INCLUDED.

THE STRENGTH OF THE FLARES, THE PROPERTIES OF THE NONTHERMAL ELECTRONS, AND THE IMPULSIVENESS WERE VARIED.



HE I 10830 DIMMING

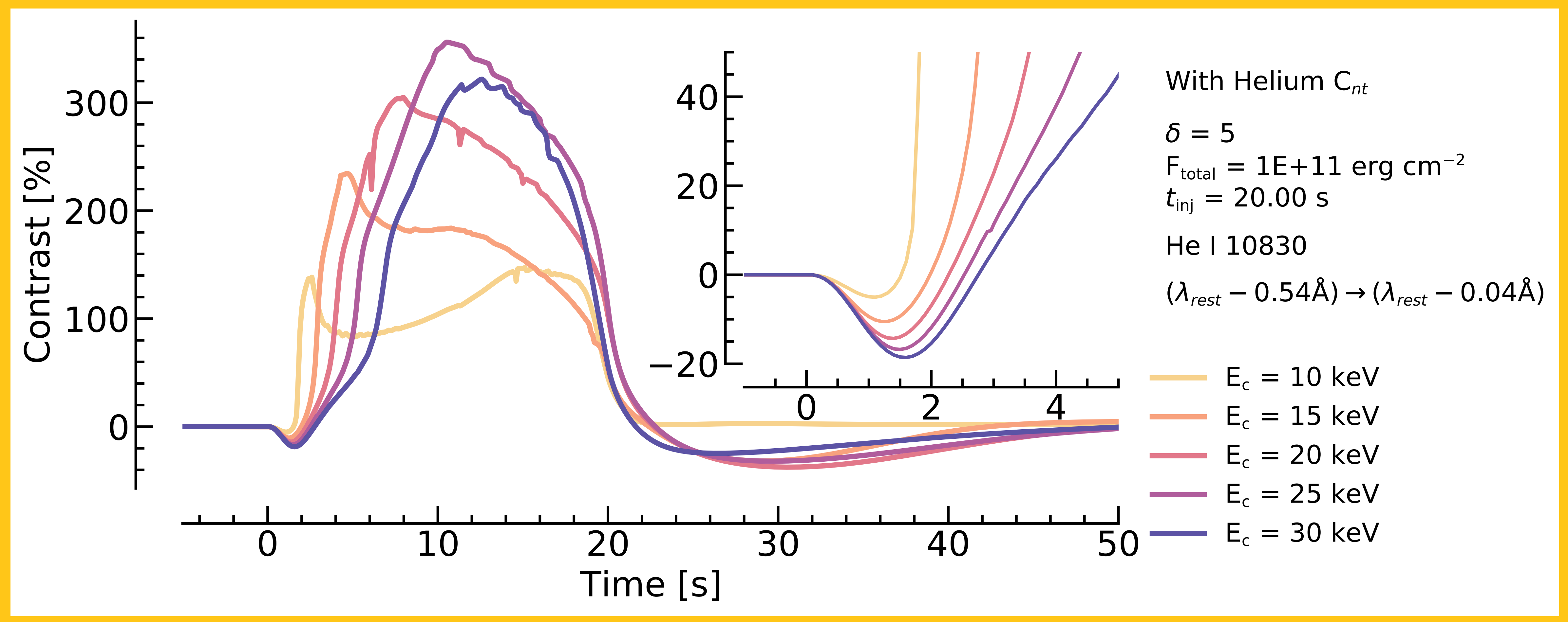
- Successfully reproduced pattern of dimming then emission.
- ONLY if nonthermal collisional excitation was included!

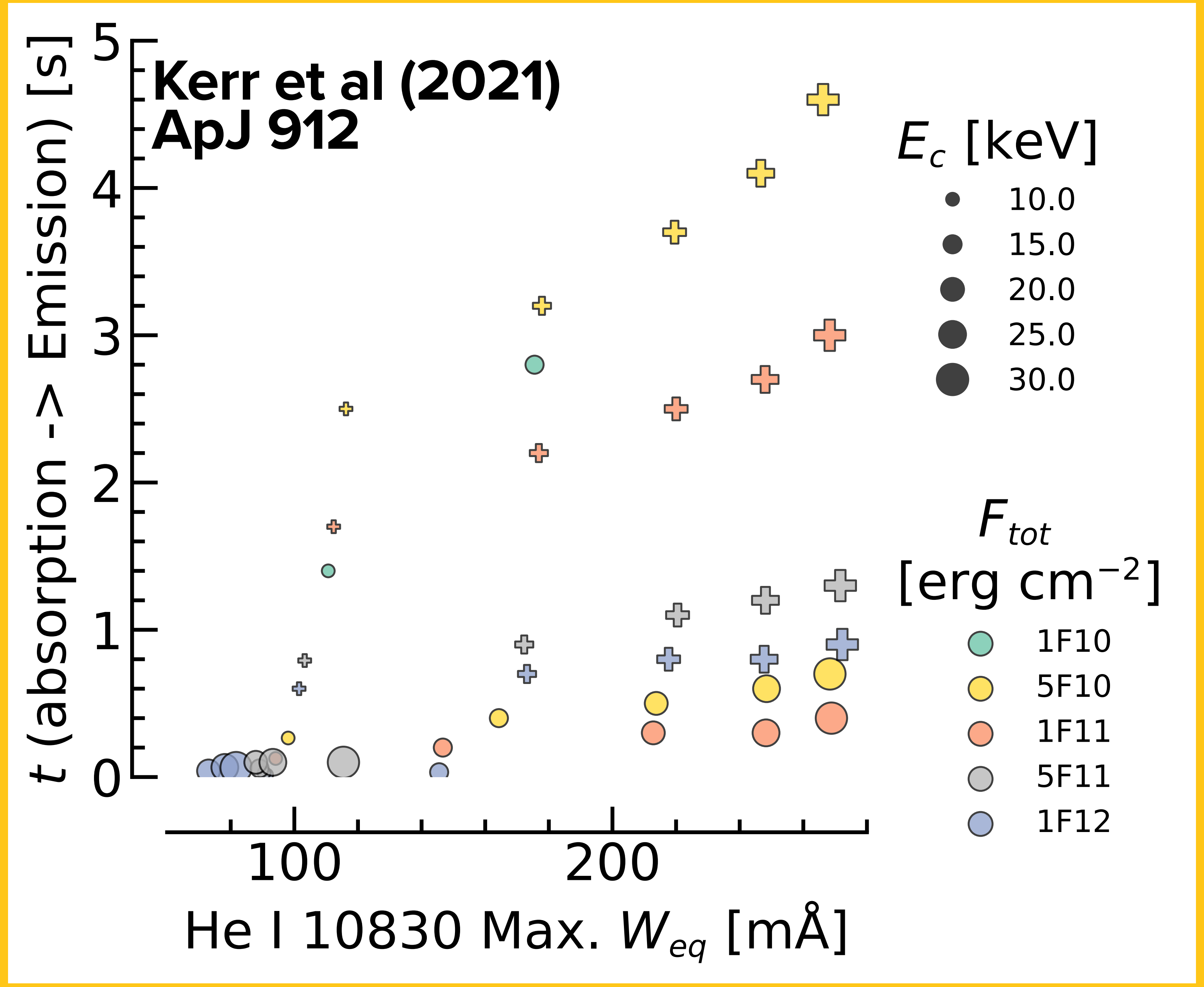
  ✳Omitting the collisions, or running only conduction-driven flares failed to produce initial dimming.

- Properties of the dimming were related to the injected particles.

  ✳Harder energy spectra, and weaker flares were better at producing dimming.

  ✳Injecting energy more gradually also helped.

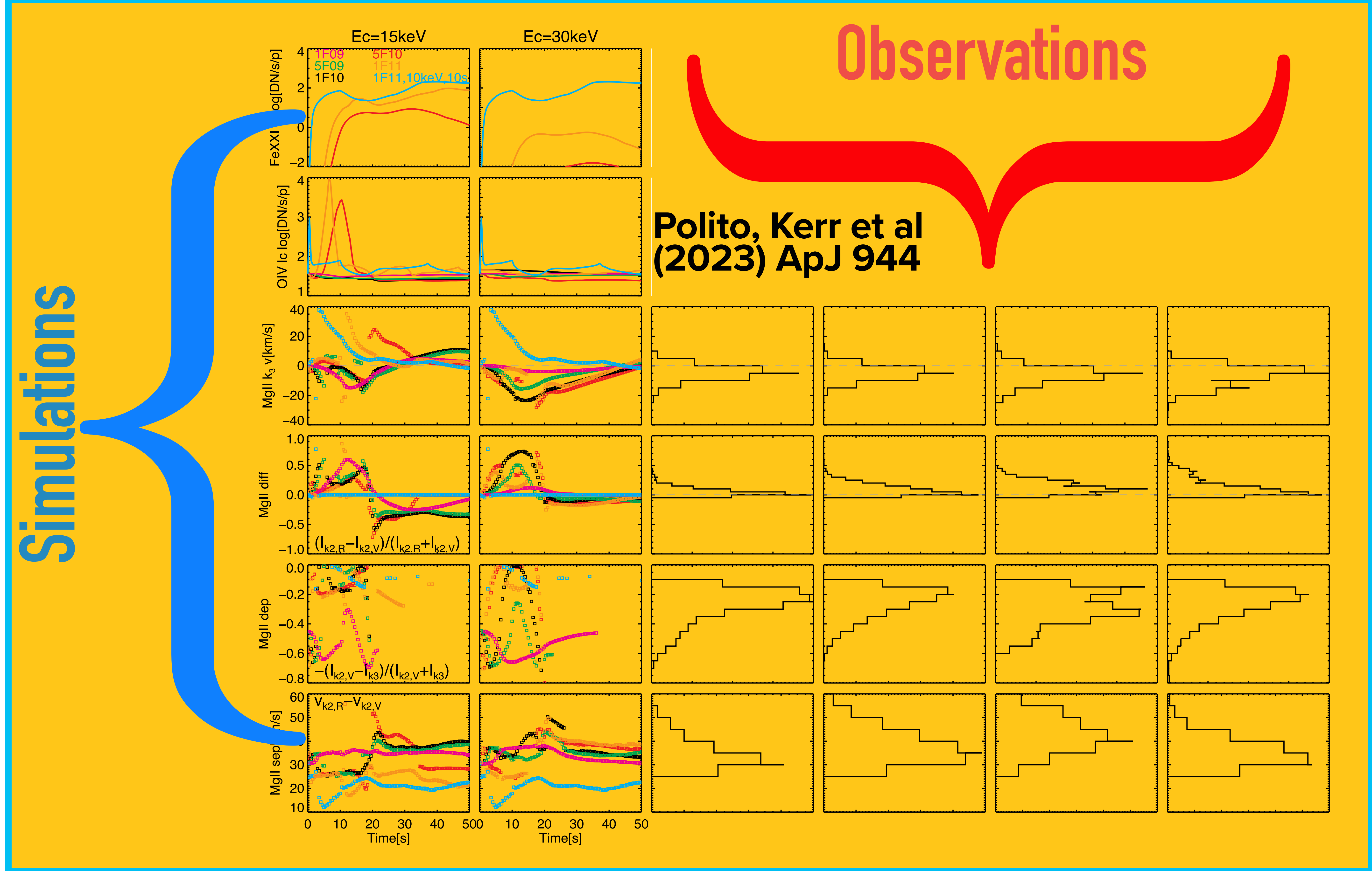




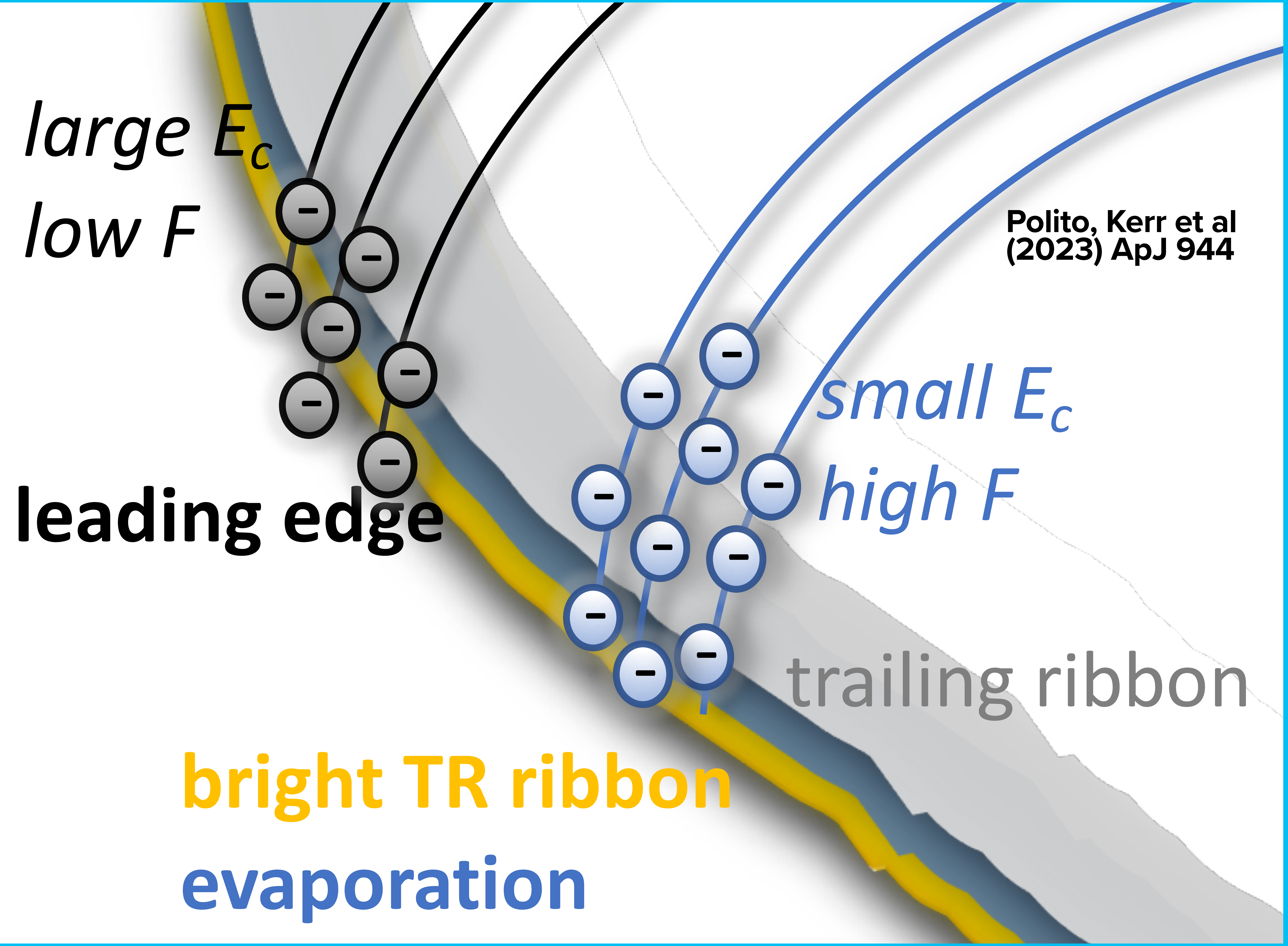
MG II CHARACTERISTICS

- The same simulations that produced He I 10830 dimming produced Mg II spectra consistent with ribbon front observations.

  ✳Evaporation only occurred in flares in which energy injection was large and fast.



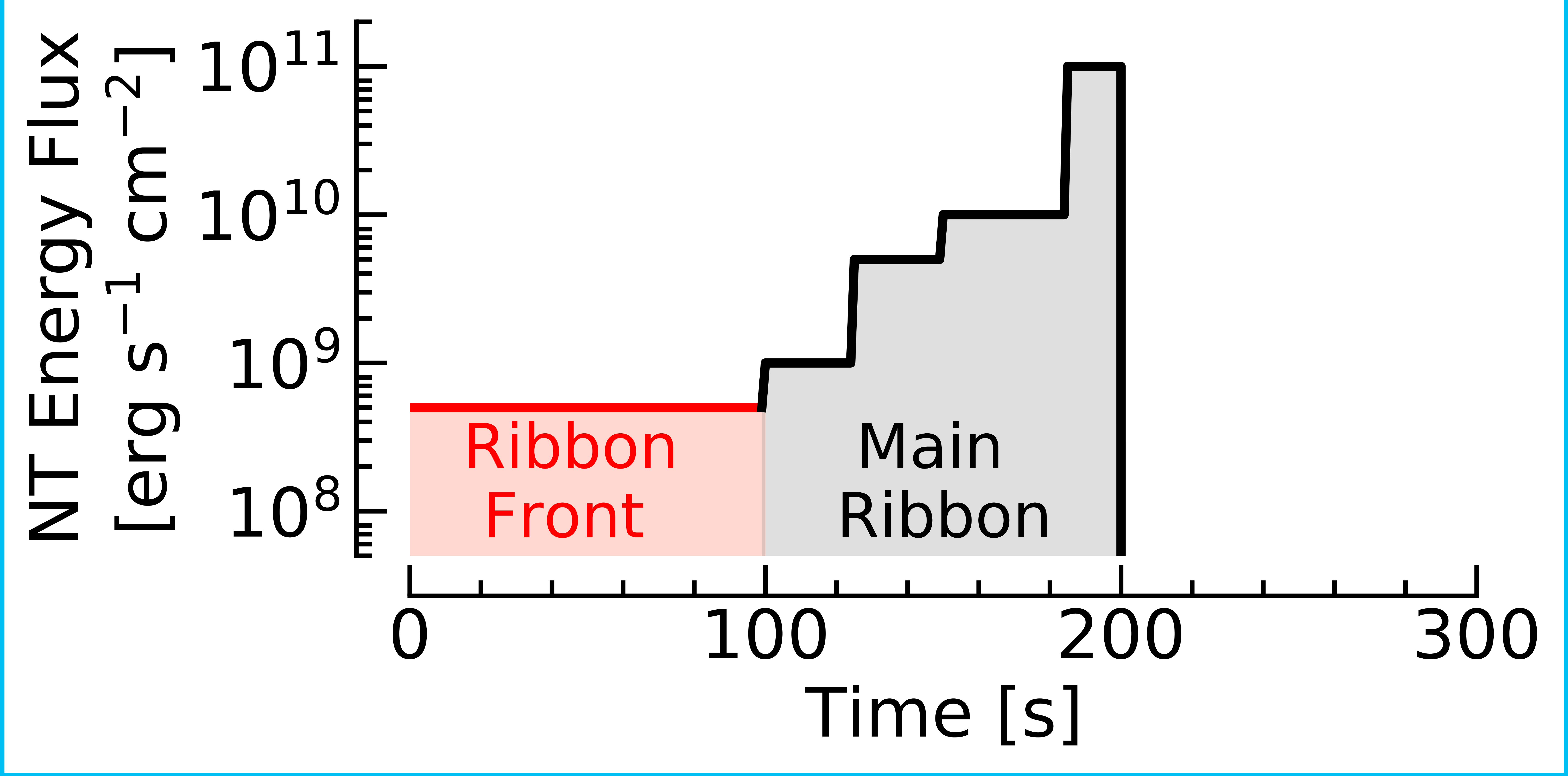
TWO DIFFERENT HEATING REGIMES?



ADDRESSING MODEL-DATA DISCREPANCY: LIFETIMES OF RIBBON FRONTS

MODELLING THE EXTENDED RIBBON FRONT REGIME

- OBSERVATIONS SHOW RIBBON FRONT LIFETIMES ~20-300 SECONDS.
- OUR FIRST MODEL GRID ONLY PRODUCED 1-4 SECONDS OF RIBBON FRONT CHARACTERISTS!
- TRIED A SIMPLE SET OF EXPERIMENTS WHERE THE INJECTED ENERGY FLUX STARTED VERY WEAK, AND WAS RAMPED-UP.

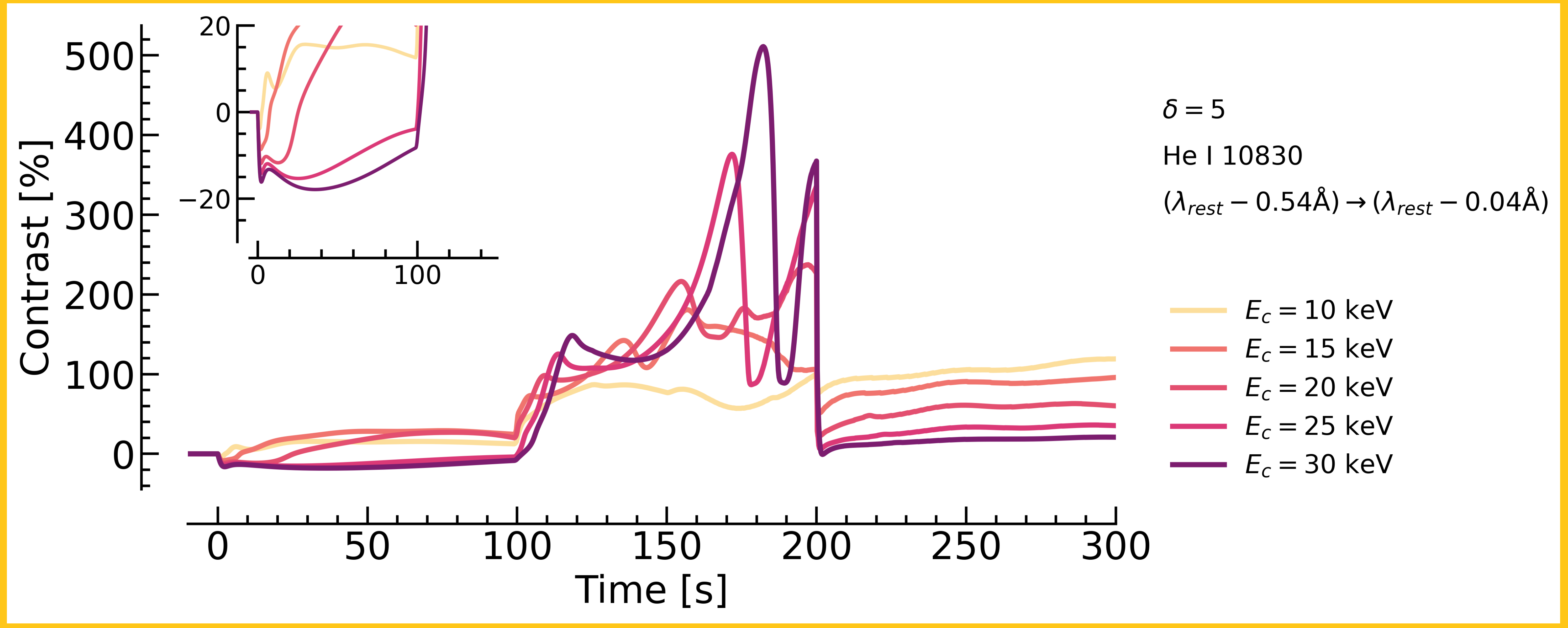


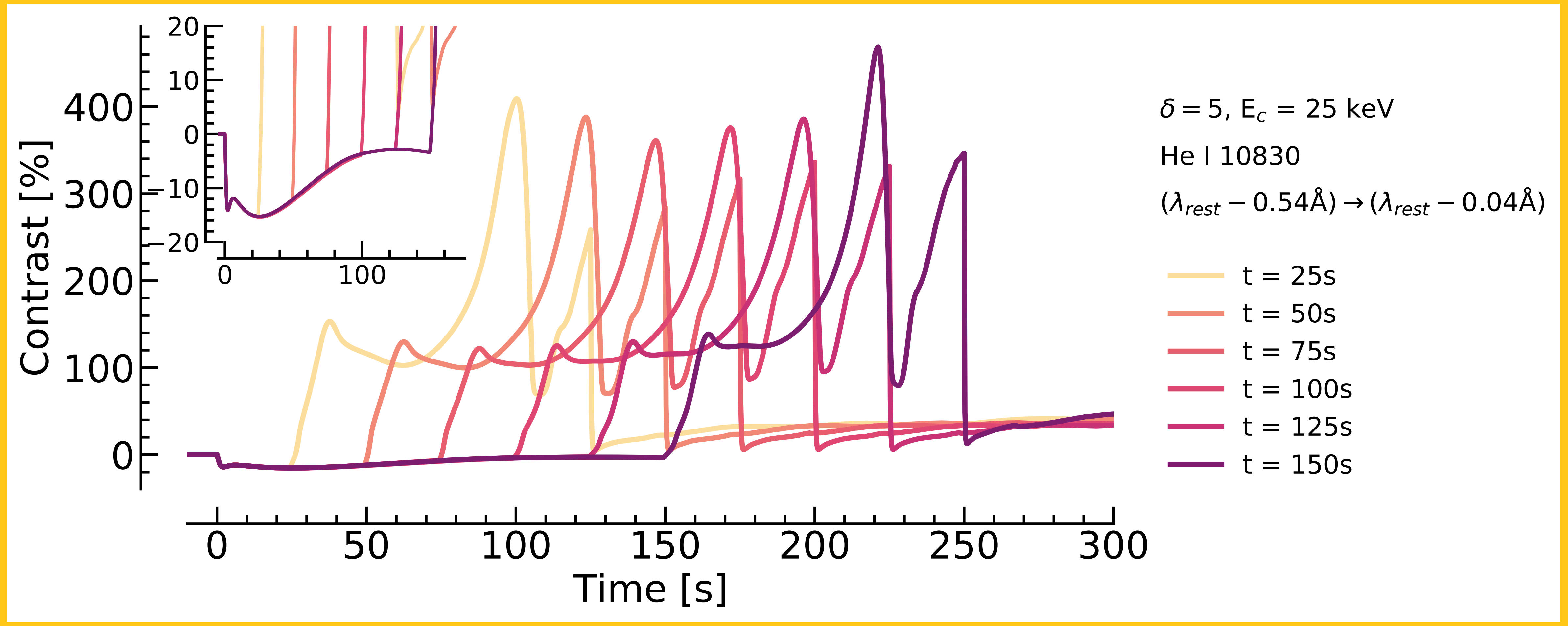
HE I 10830 EXTENDED DIMMING

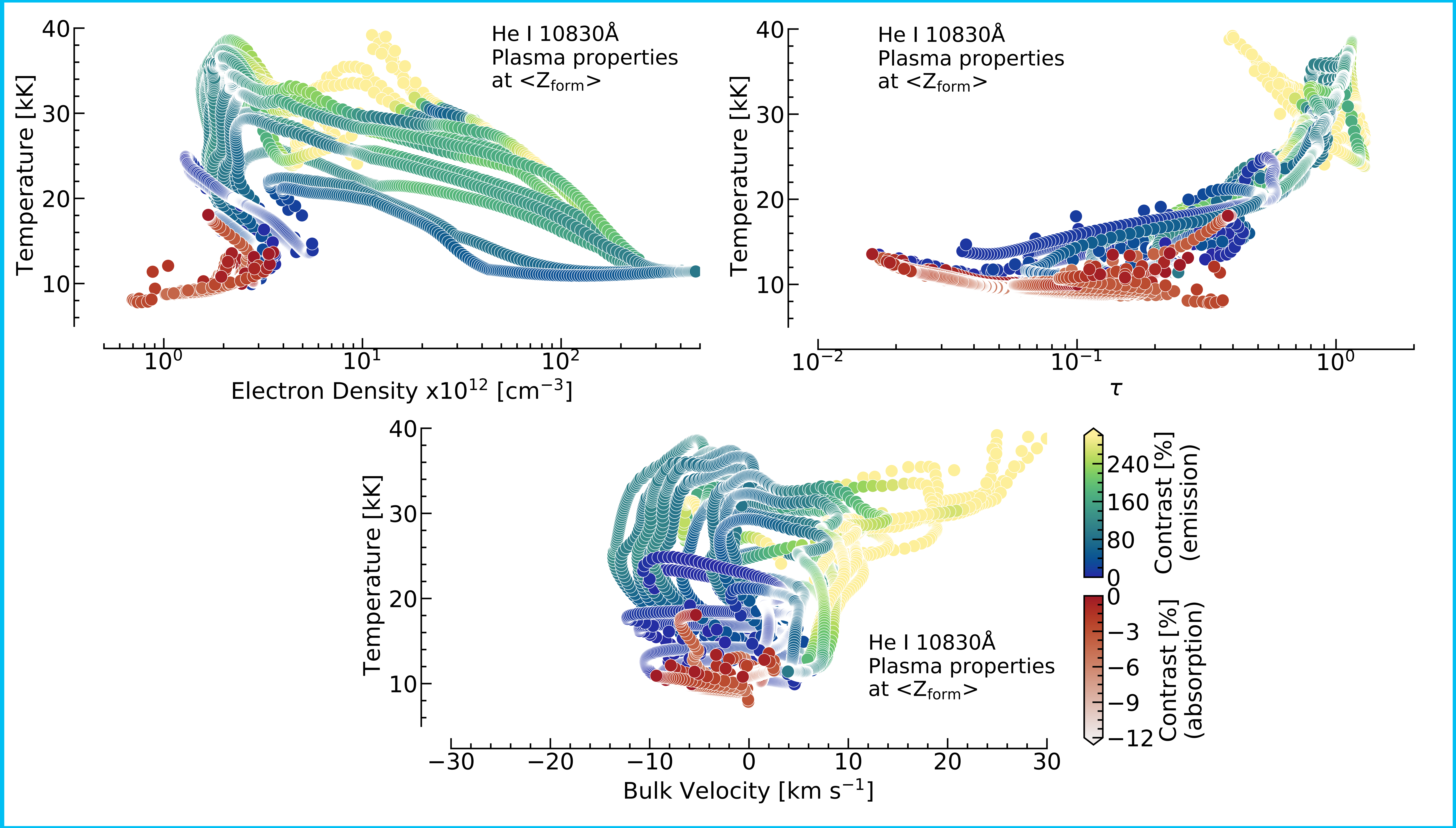
- Successfully reproduced the extended lifetime!

  ✳Only the harder simulations persisted with ribbon fronts throughout the weak-heating phase.

- Varying the duration of the weak heating phase has a direct impact on the duration of the ribbon front lifetime.







He I 10830Å driven into emission once the upper chromospheric temperature exceeds

T~15kK

and the electron density exceeds

$n_e \sim 3.5\times10^{12}$ cm-1

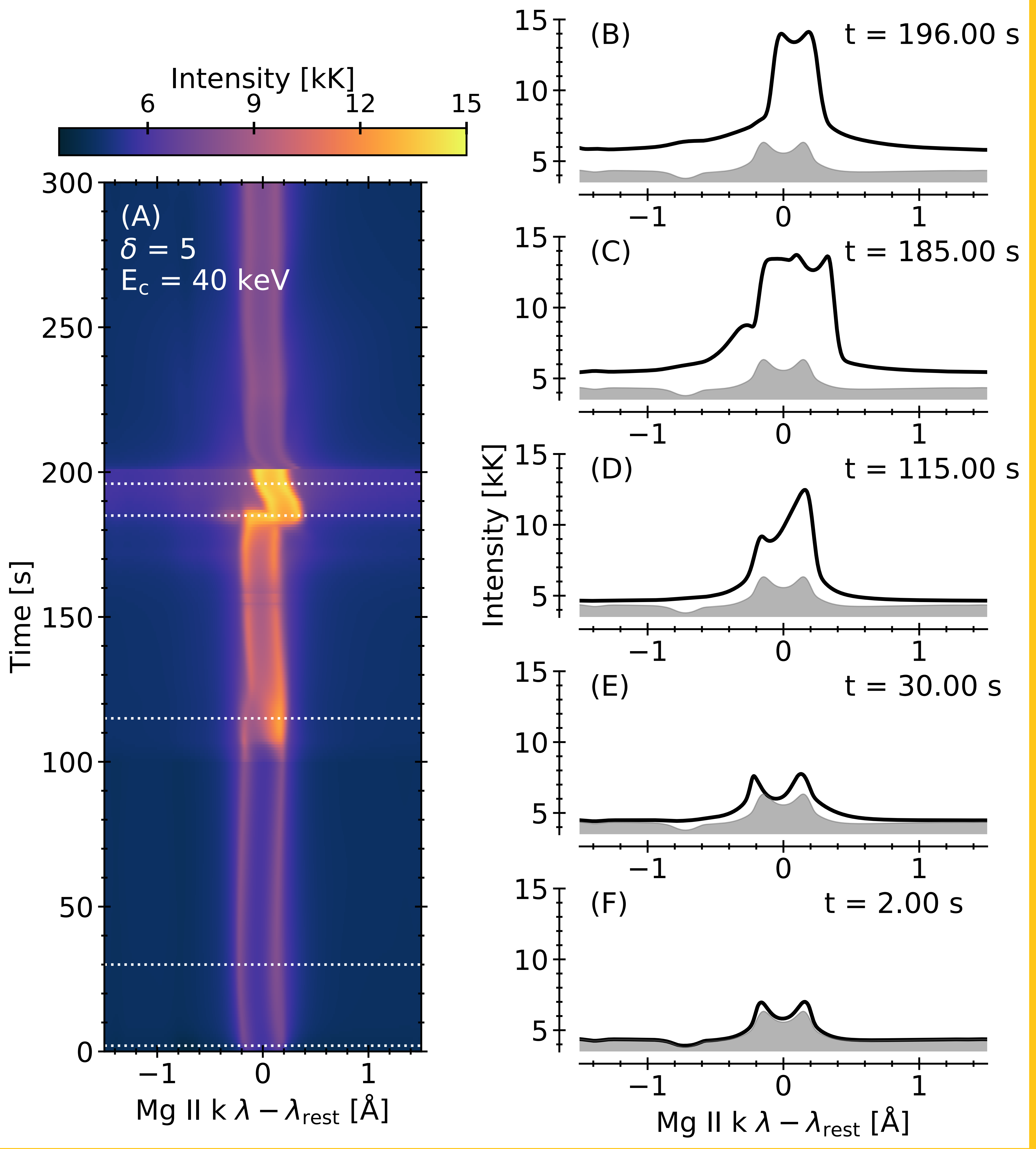
If the density gets very high then this can happen at cooler temperatures.

The He I 10830 line also forms within a modest upflow during the ribbon front phase -- little to no redshifts at those times.

ABSORPTION -> EMISSION

MG II NUV EXTENDED RIBBON FRONTS

- Mg II ribbon front characteristics also qualitatively match ribbon fronts during the weak heating phase.
  - ✳Not every metric lasted the whole duration.
  - ✳The ‘best’ were deeper reversal and blueshift of line core.



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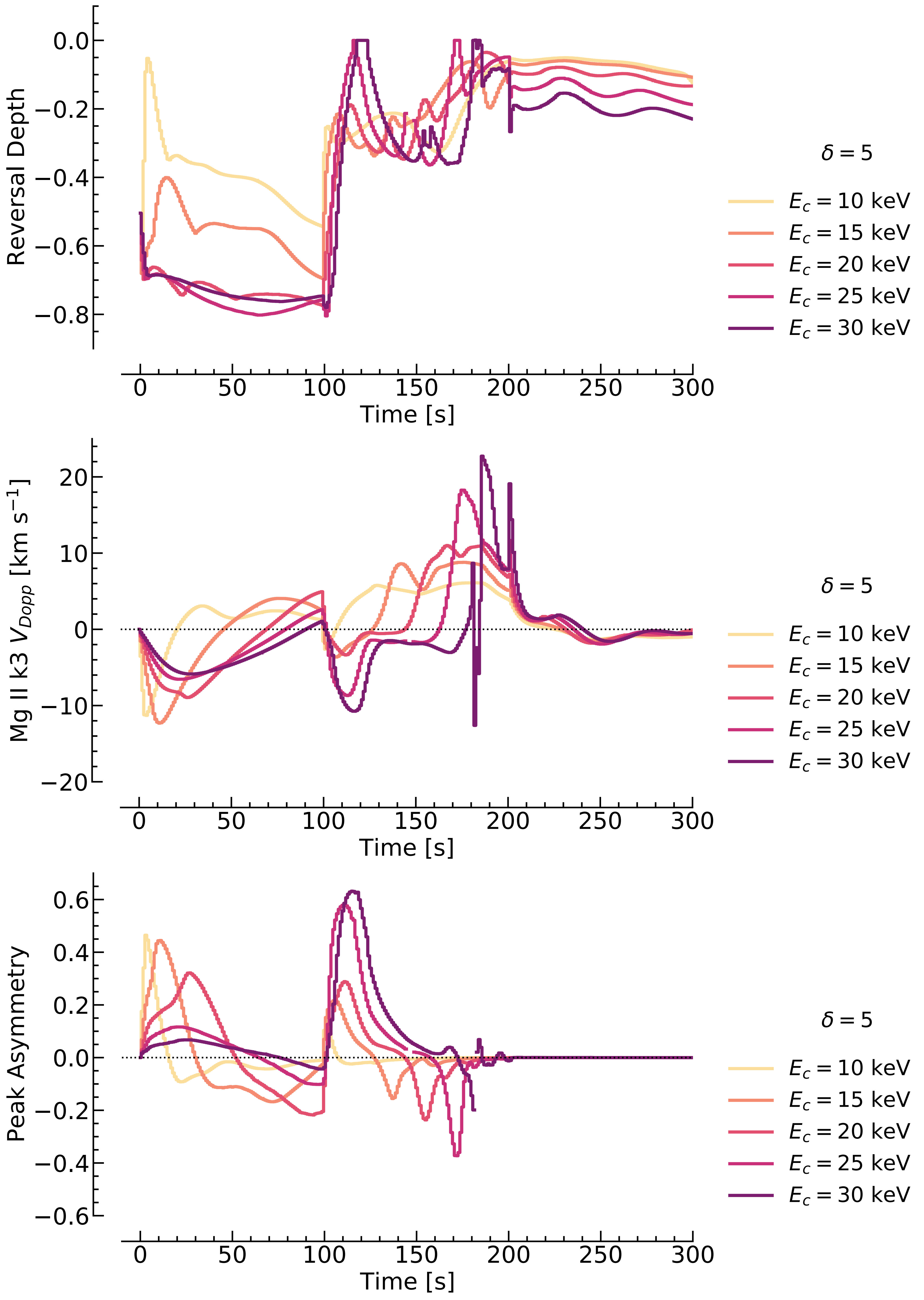
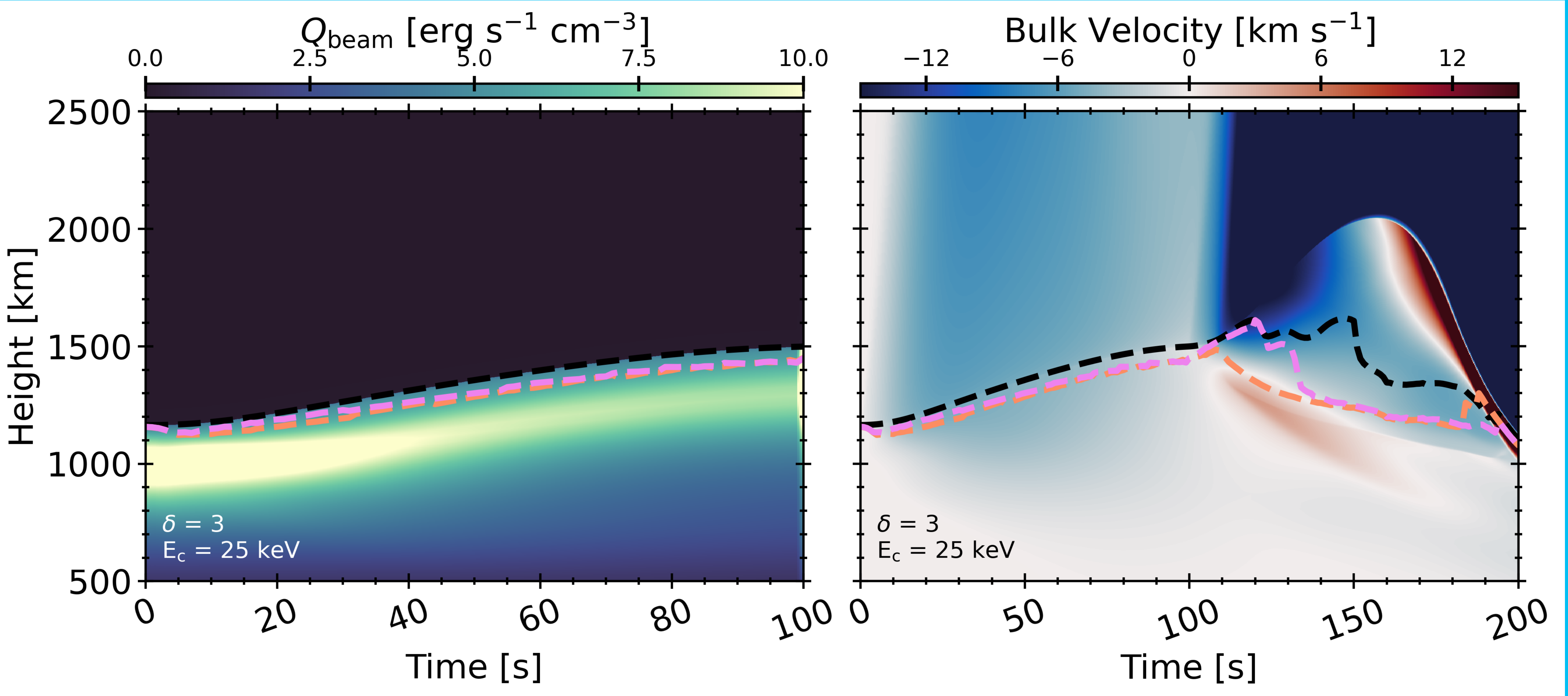




LOCATION OF ENERGY DEPOSITION IS KEY

In the weak heating phase (ribbon fronts) the beam deposits a modest amount of energy *below* the formation height of the Mg II line core.

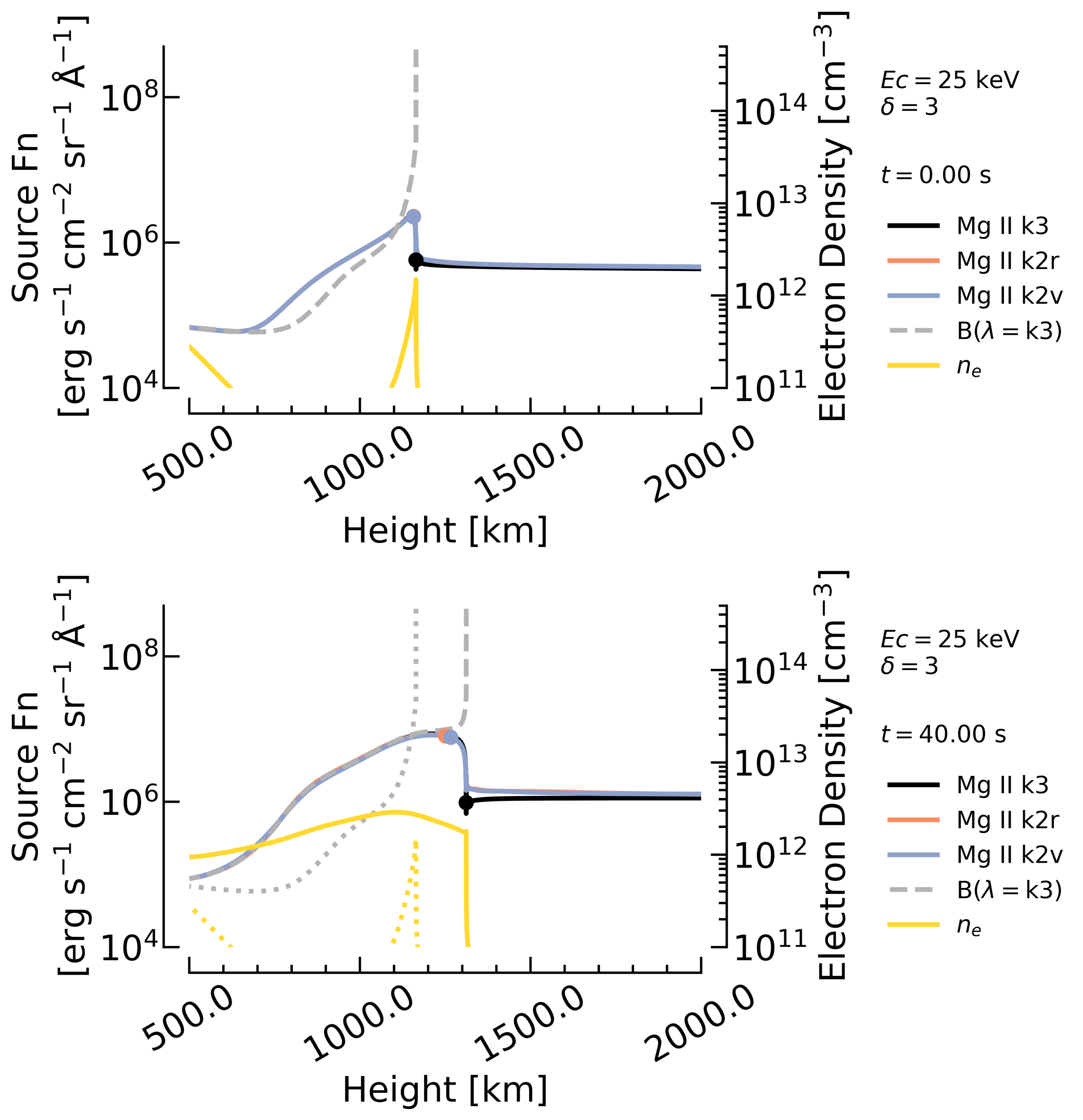
That is, the mid chromosphere is heated.

The region where the flanking peaks form experience much larger increase in T and n_e.

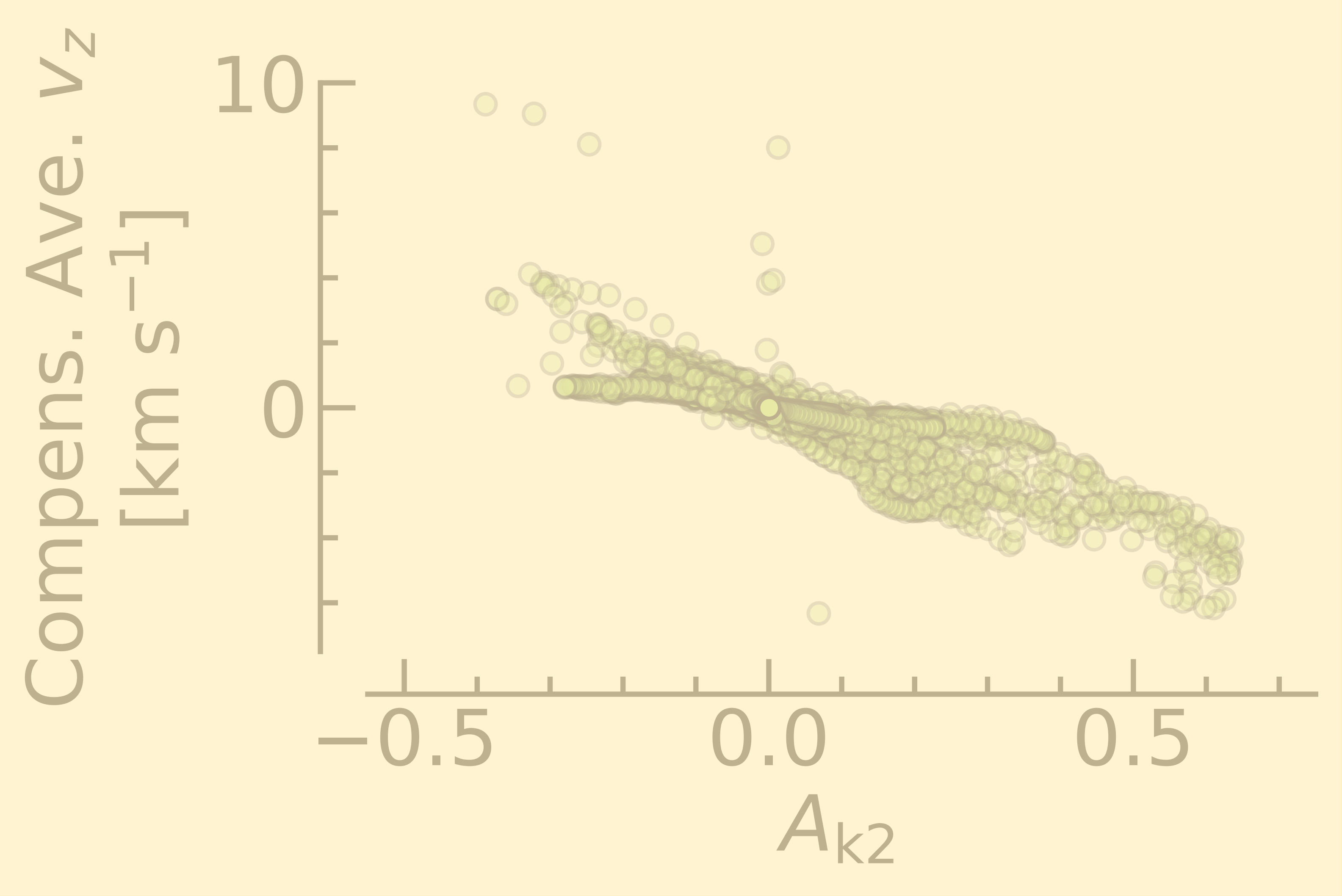
Later, when energy injection increases, the beam directly deposits energy in the formation region of the core (upper chromosphere).

DEEPER CENTRAL REVERSAL

The source function of the k2 peaks increases, and they form further from the k3 line core. Thus the difference in the emergent intensity of the components increases and the core deepens.



K2 PEAK ASYMMETRY



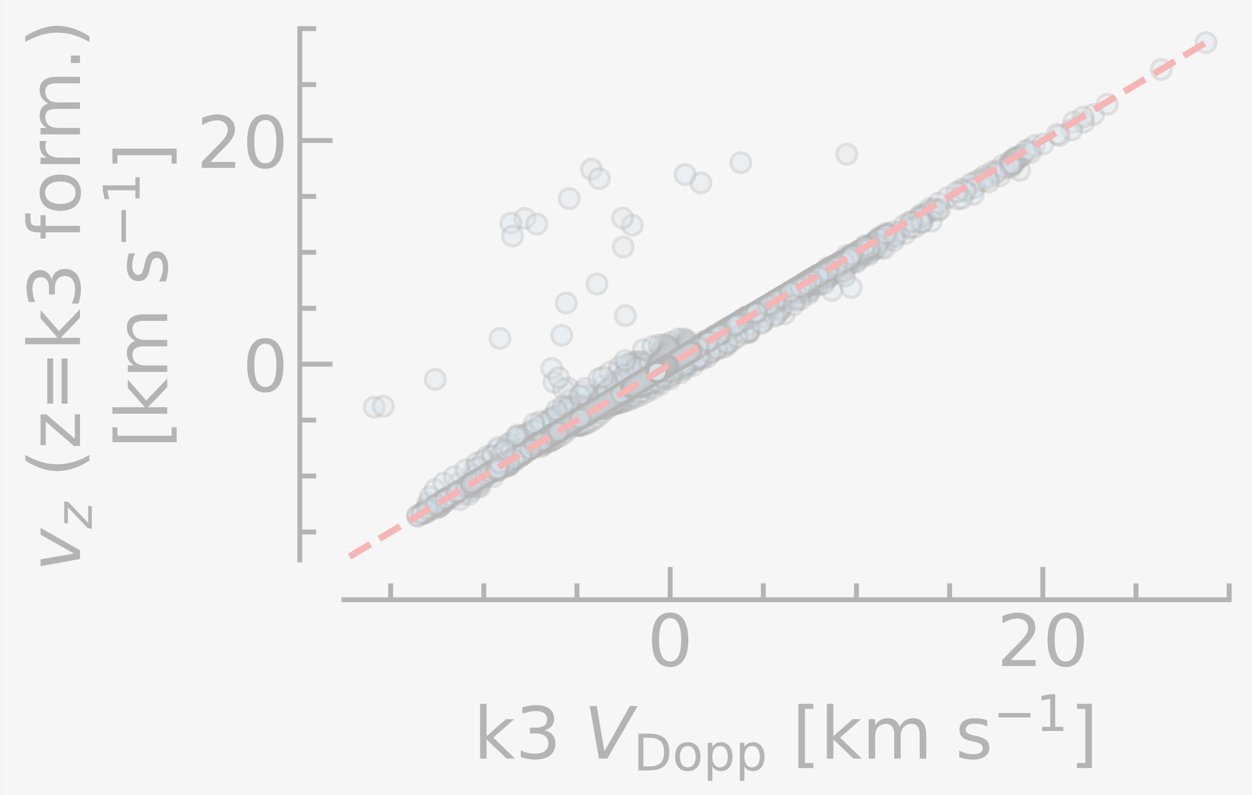
It may seem counterintuitive, but a gentle *upflow* in the region between the k2 and k3 formation heights results in a brighter red peak.

This is because the absorption profile of the line is blueshifted. More blue peak photons are absorbed than red, making the red peak appear brighter.

The velocity difference is directly proportional to the level of asymmetry.

During the bright ribbon phase the opposite scenario is at work.

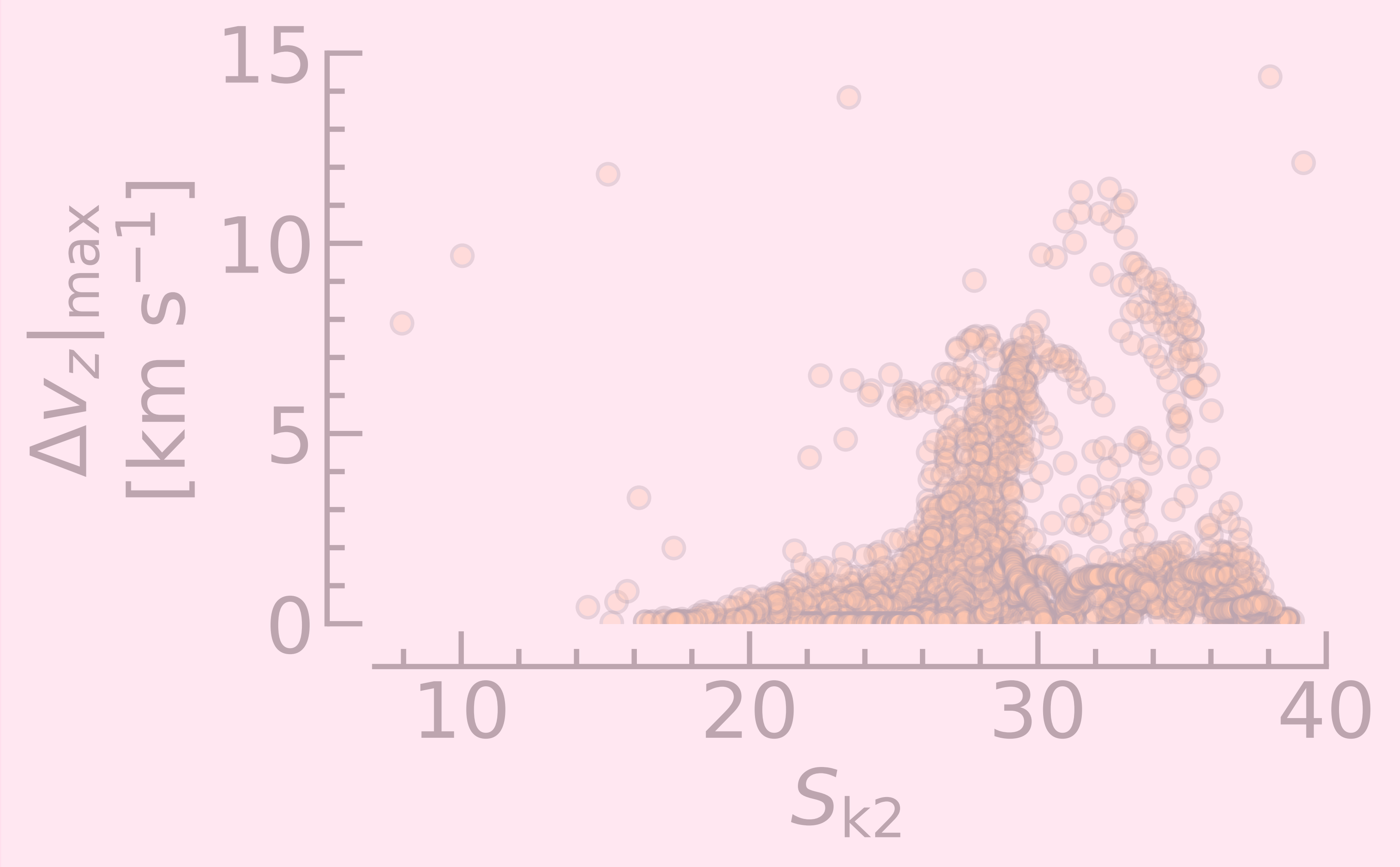
BLUESHIFTED LINE CORE



Line core Doppler speed tracks the velocity at the formation height well.

During ribbon front phase, the deeply penetrating, but modest, beam drives gentle upflows through the mid-upper chromosphere.

K2 PEAK SEPARATION



Multiple processes can increase the k2 peak separation:

1) Microturbulence
2) A large velocity in the k2 formation region (that affects the height-dependent wavelength shifts).
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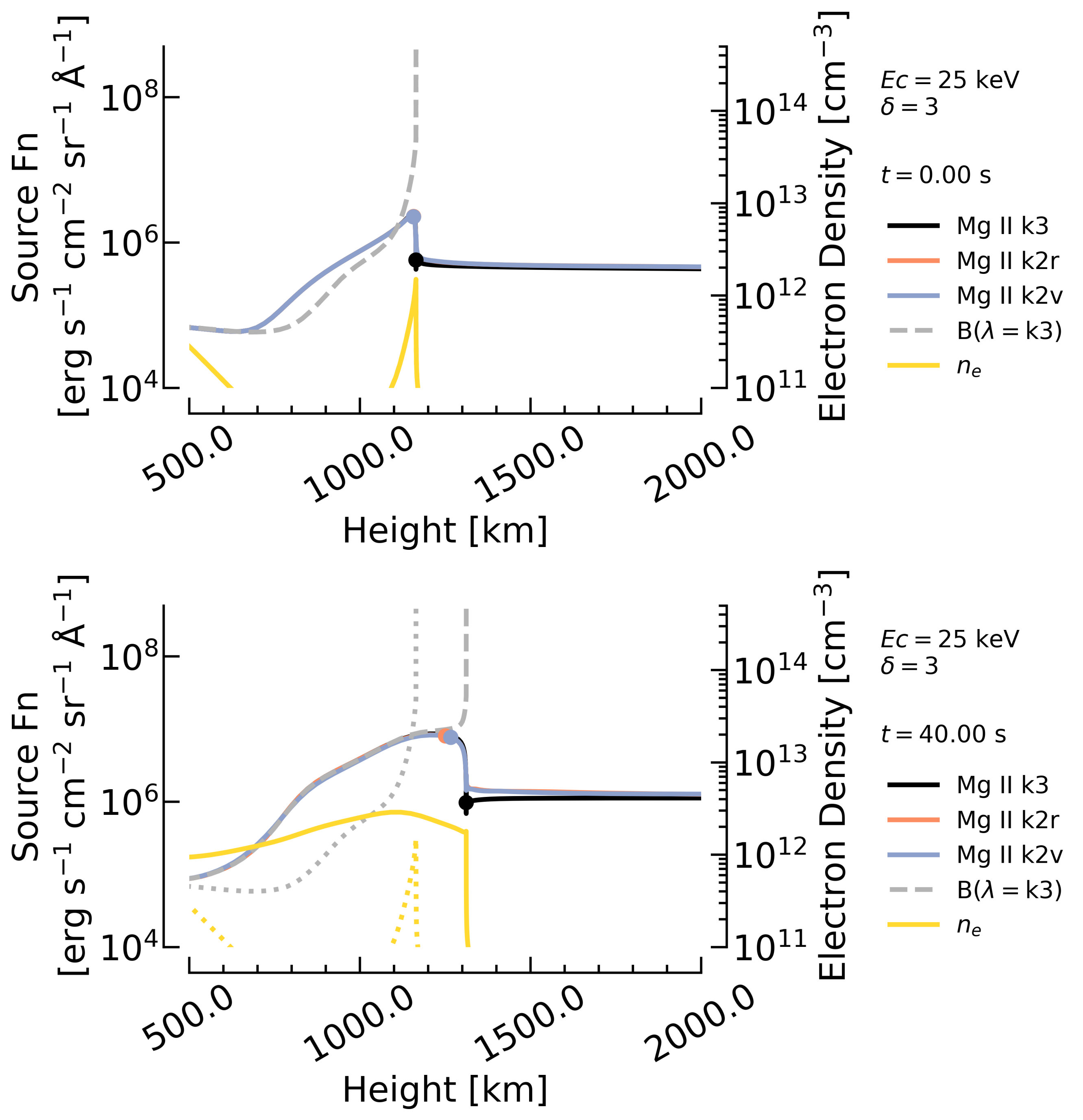

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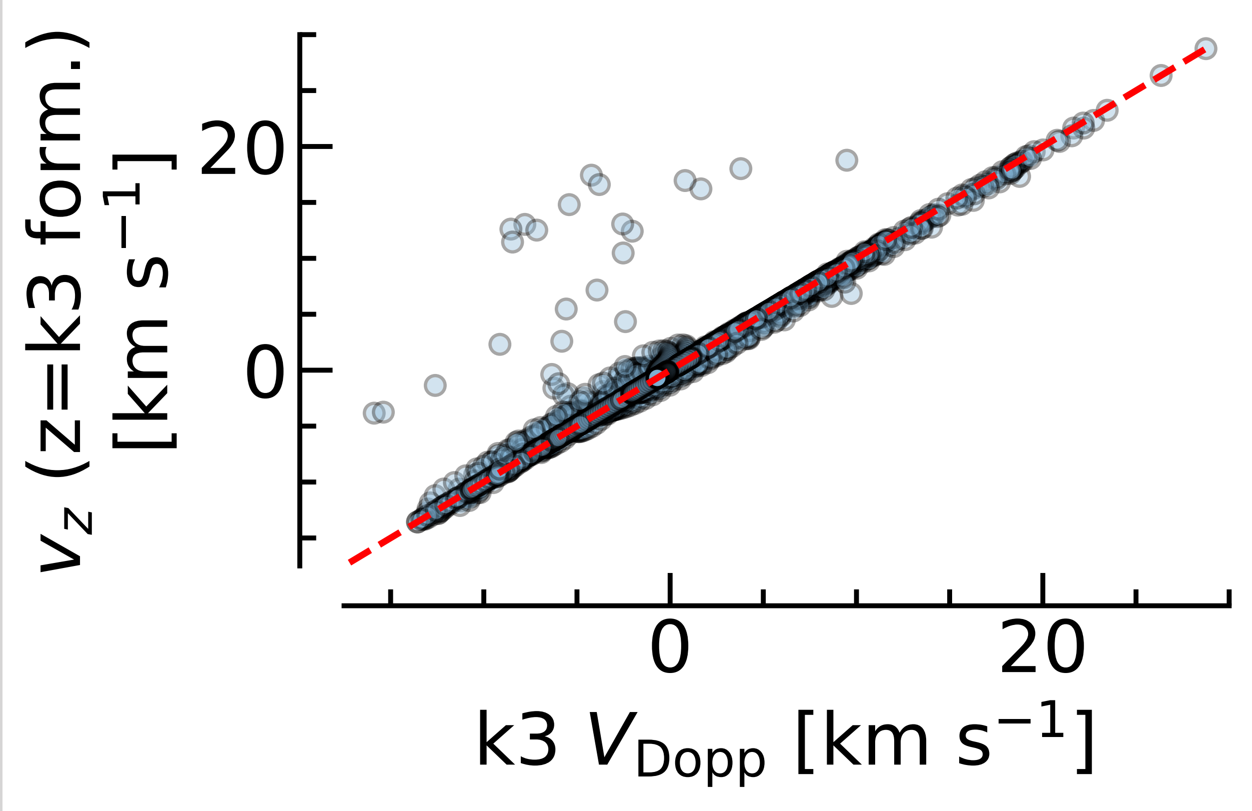

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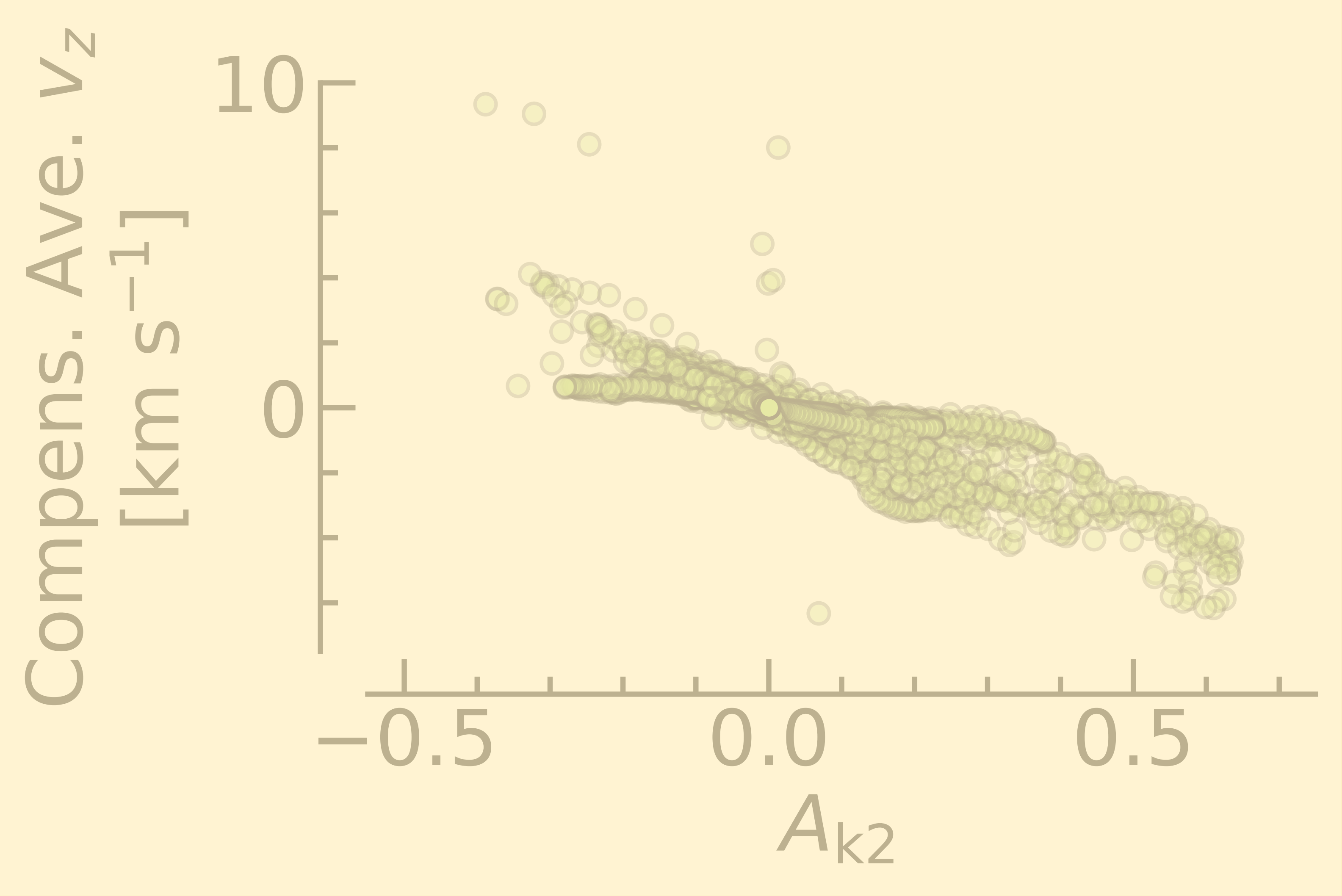

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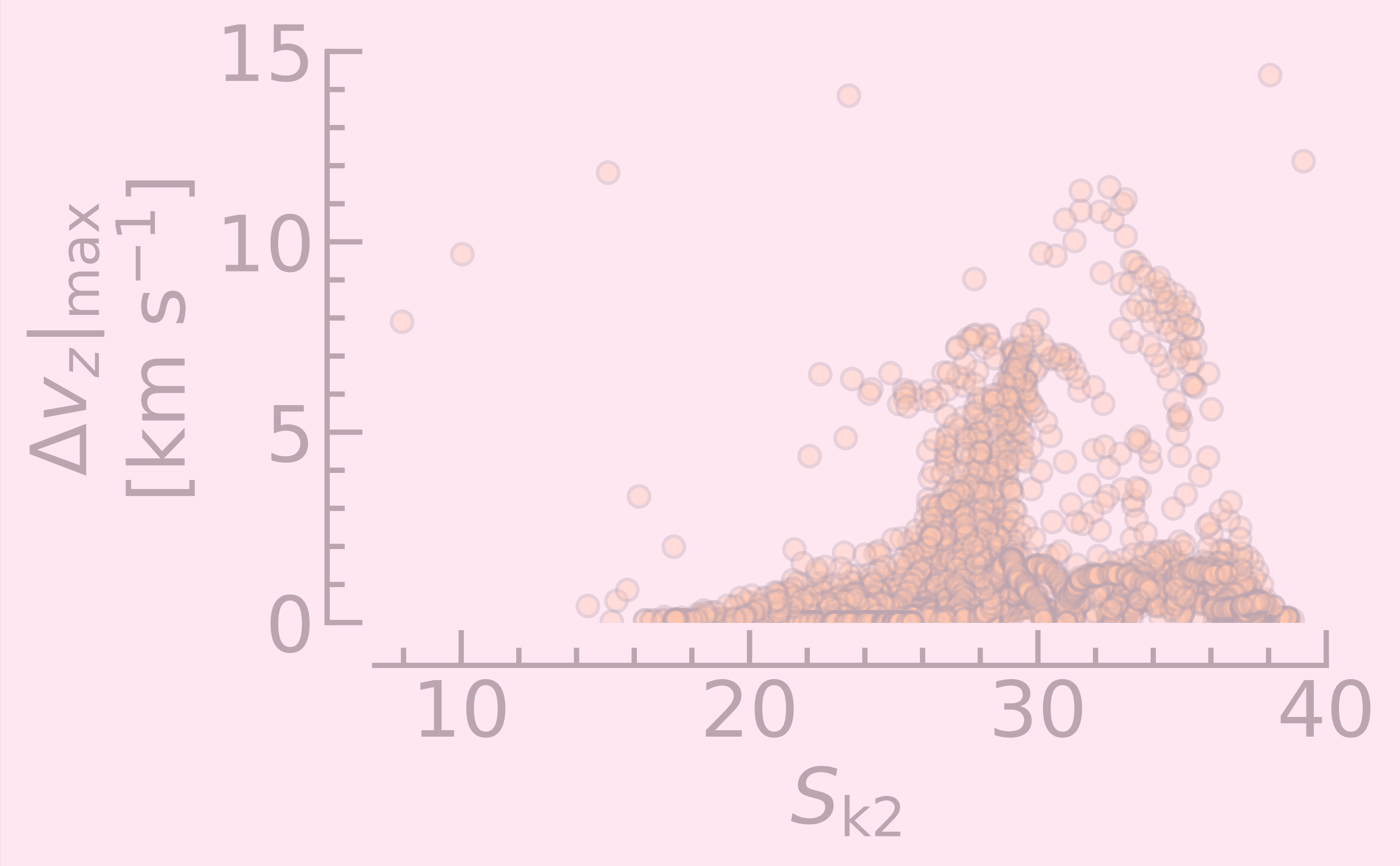

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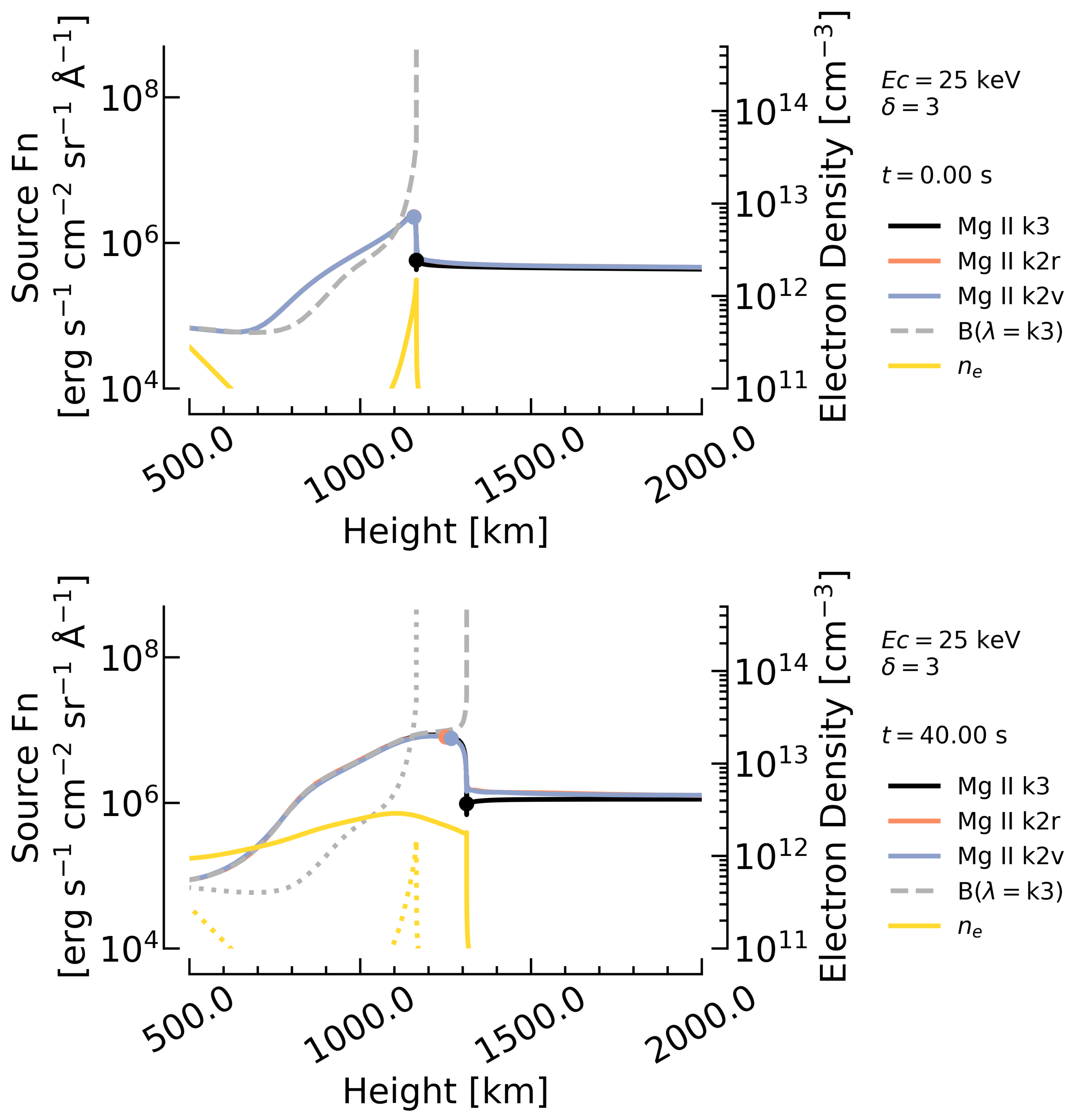

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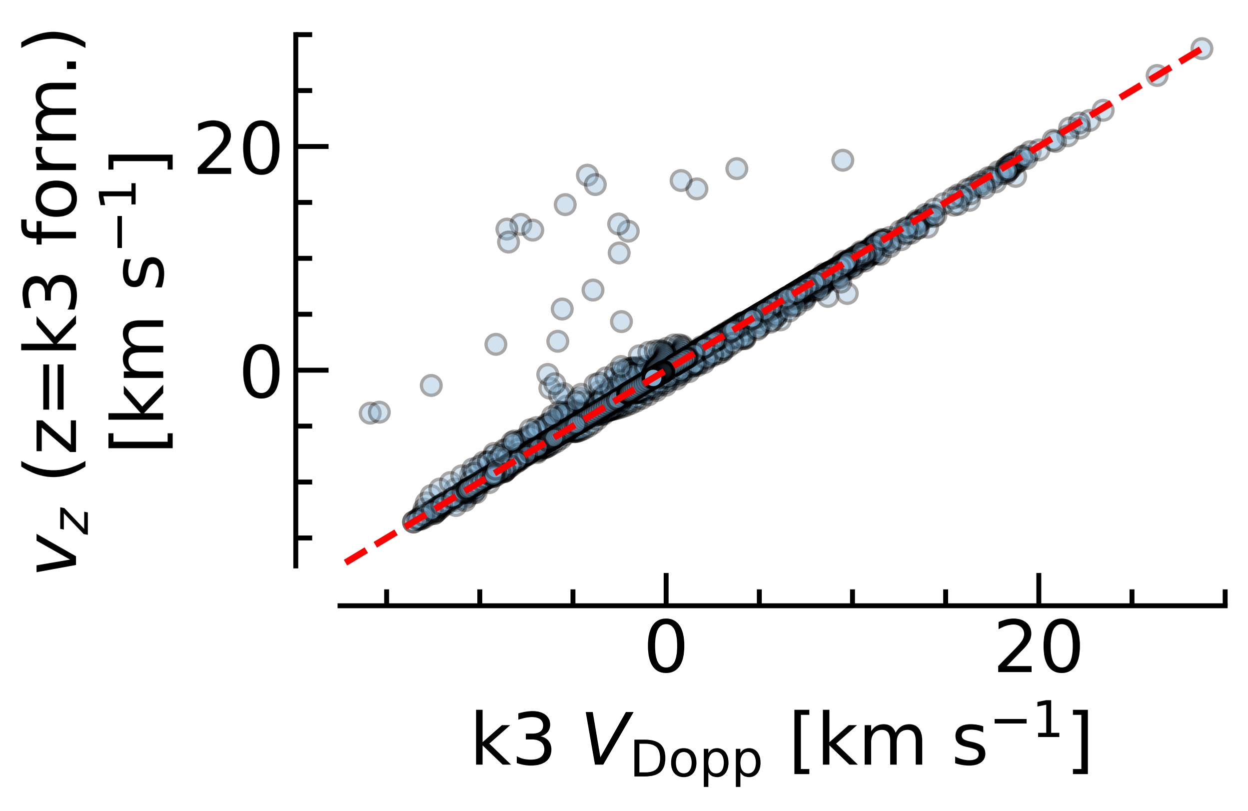

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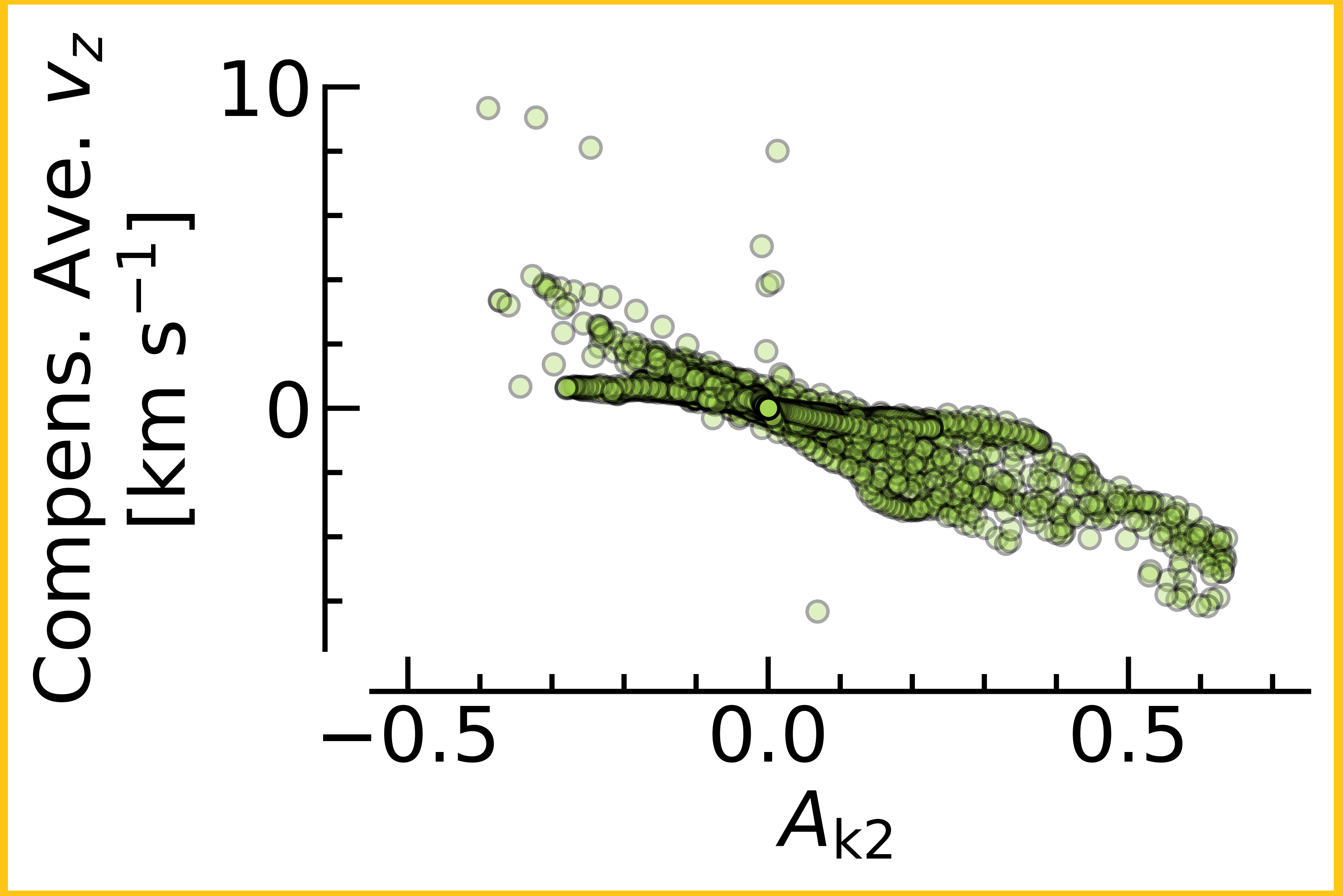

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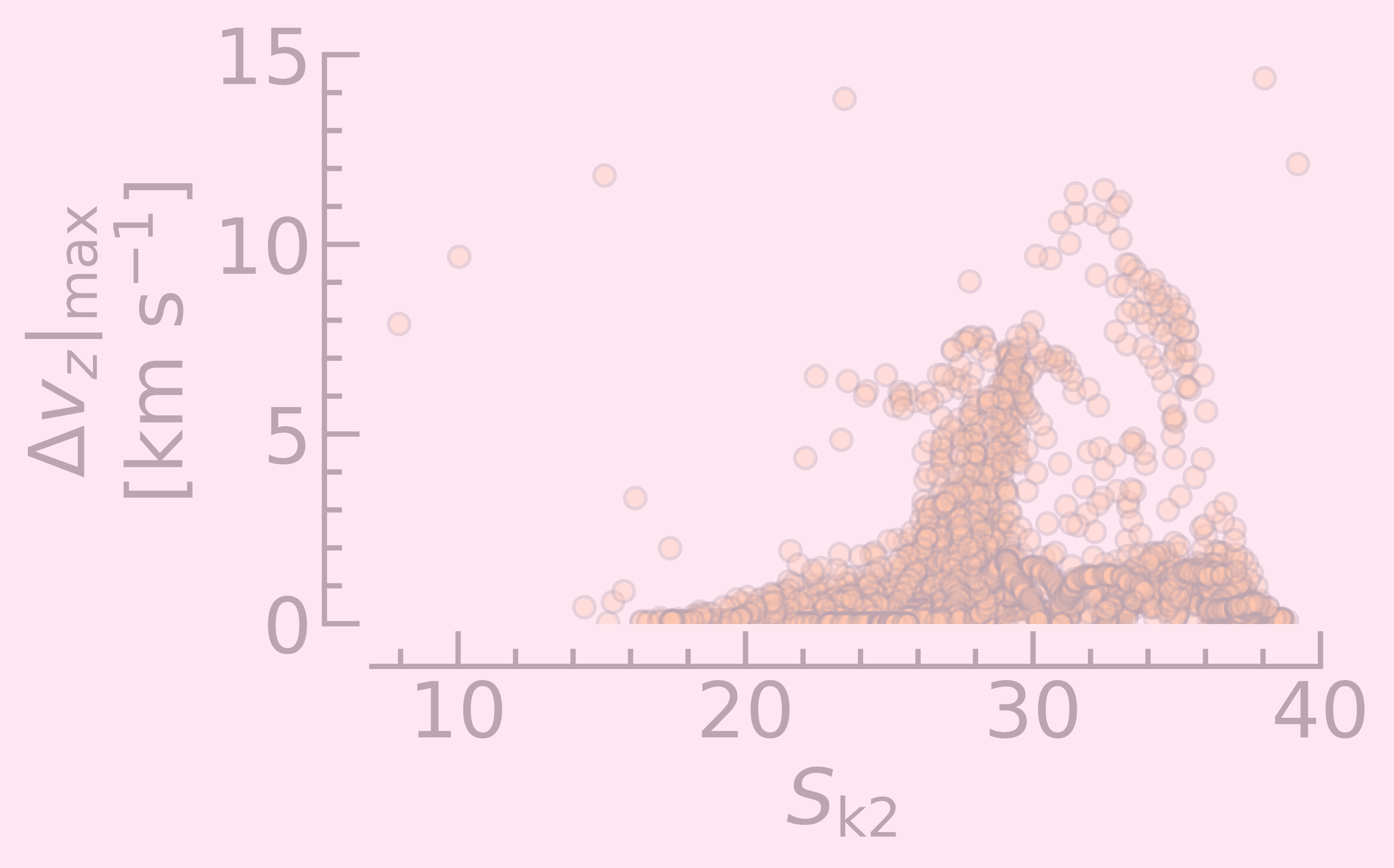

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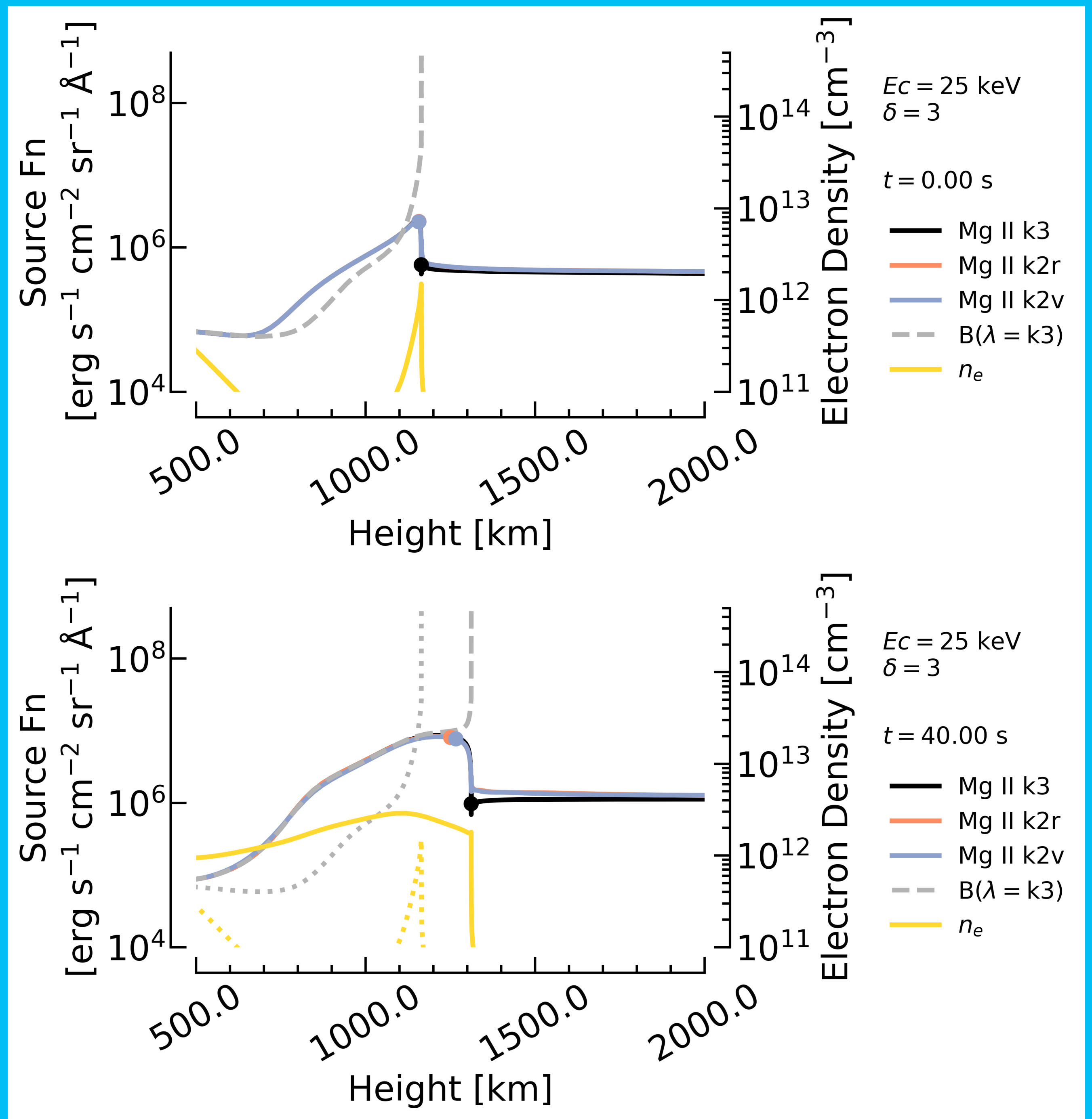

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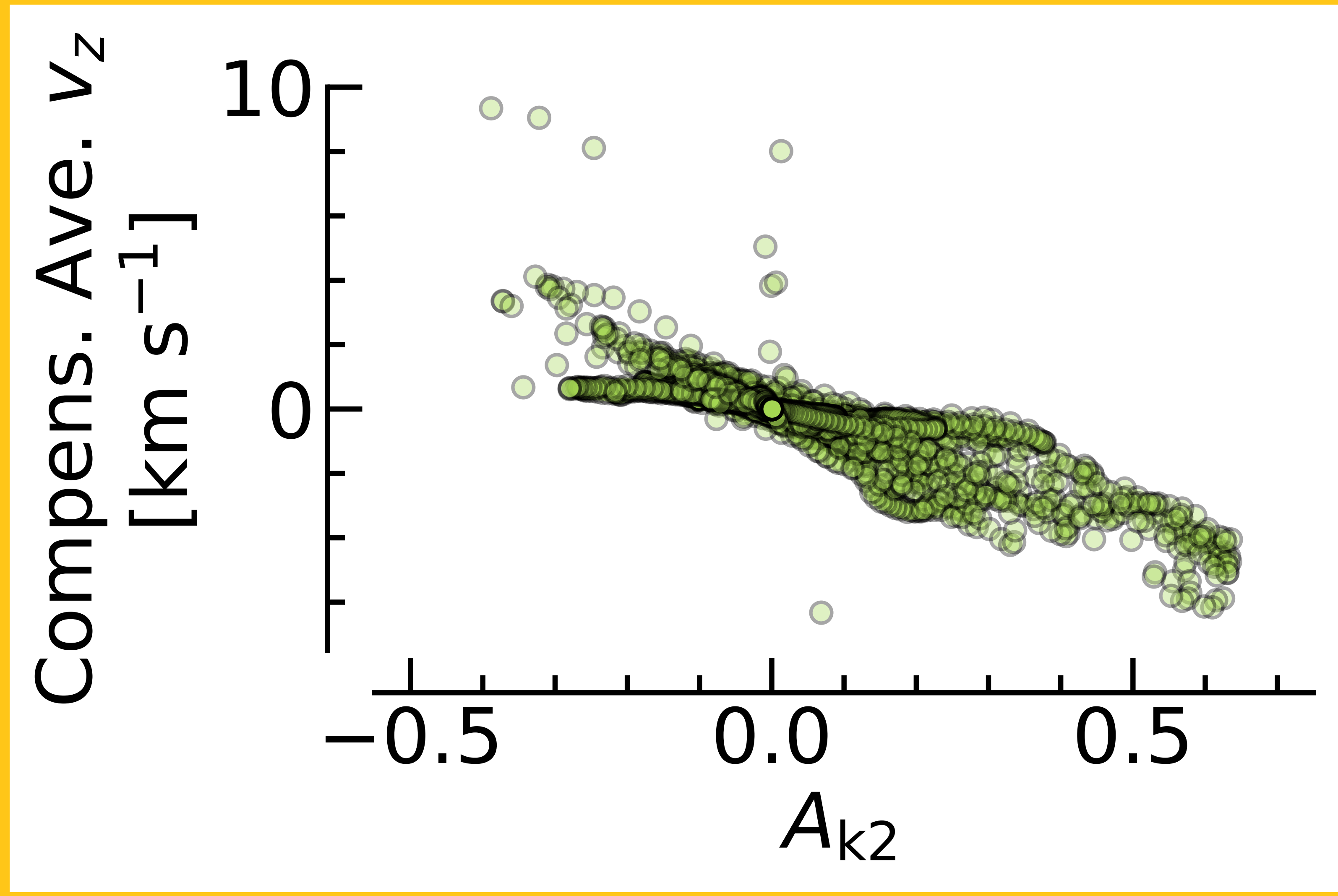

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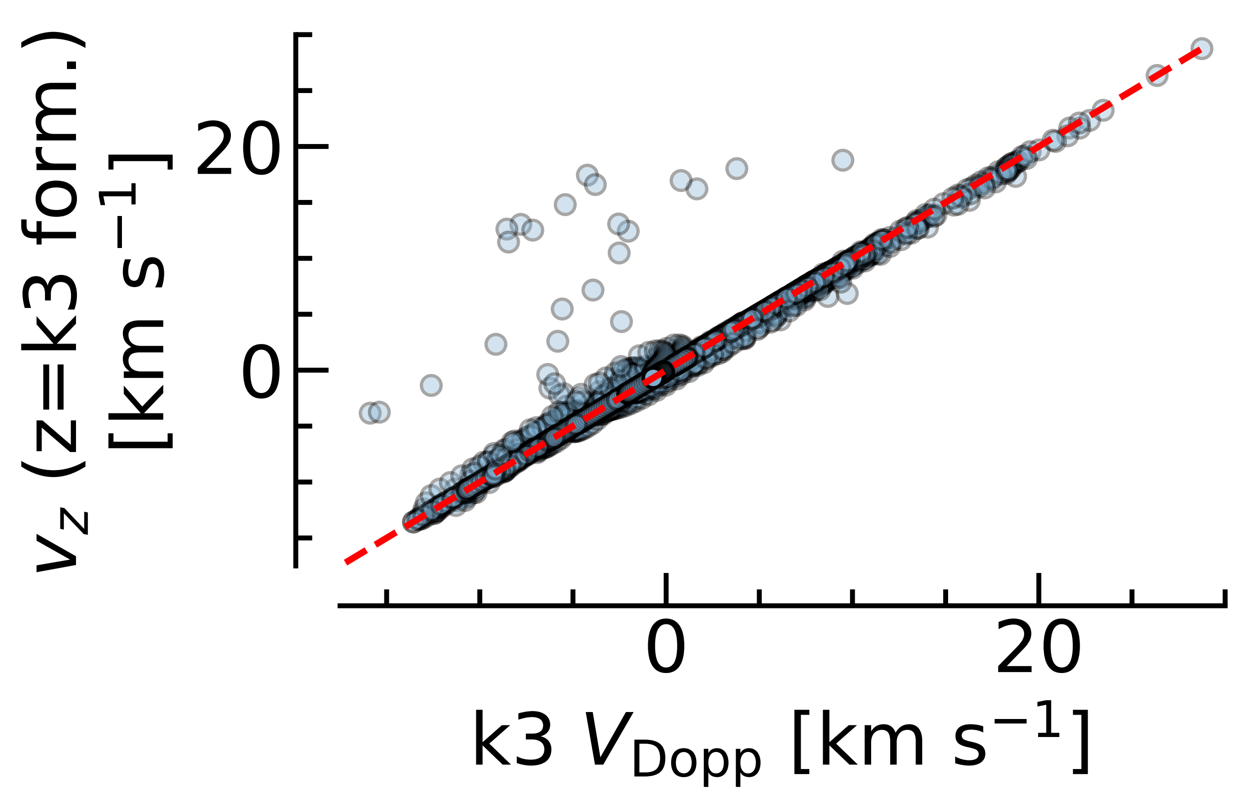

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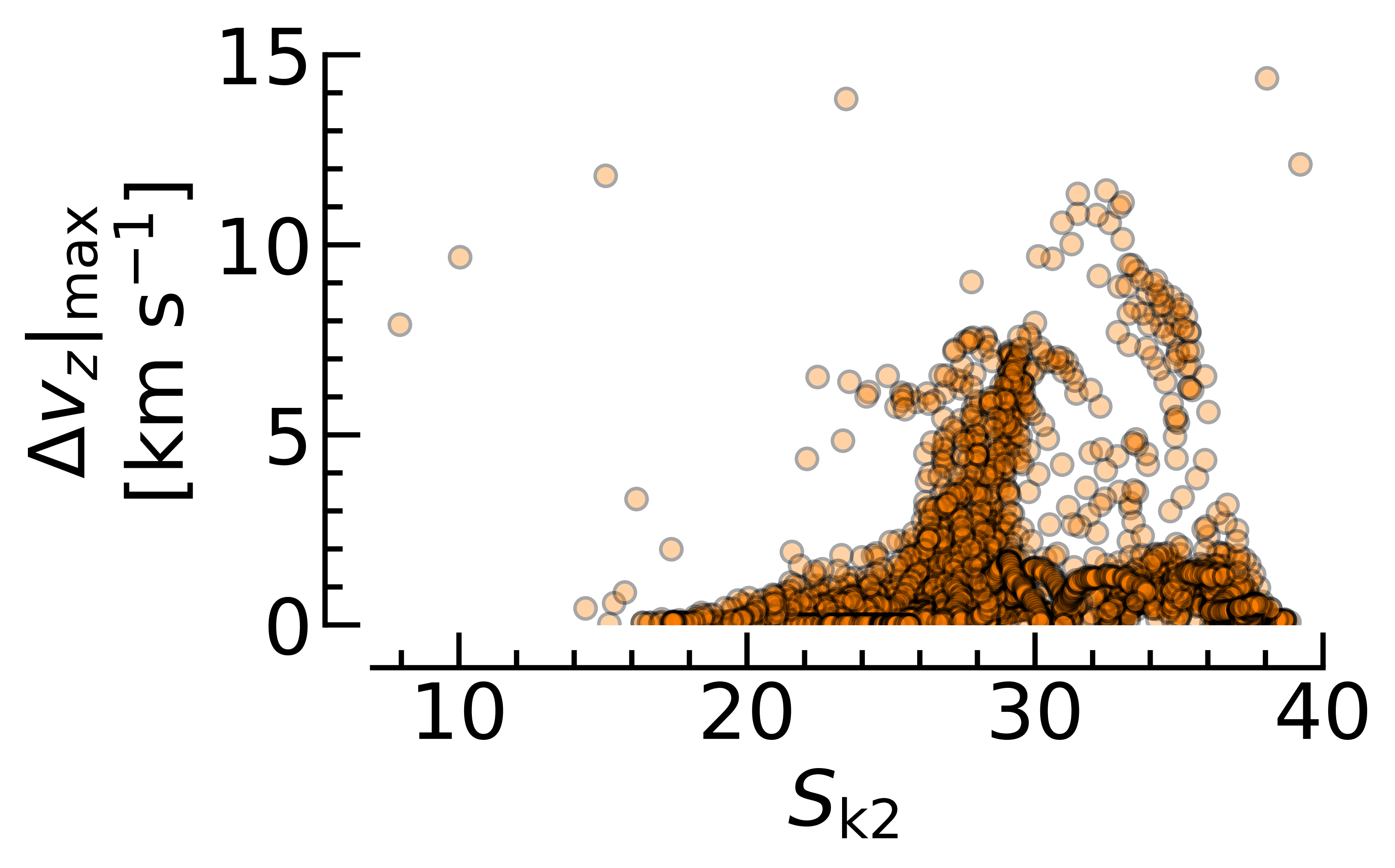

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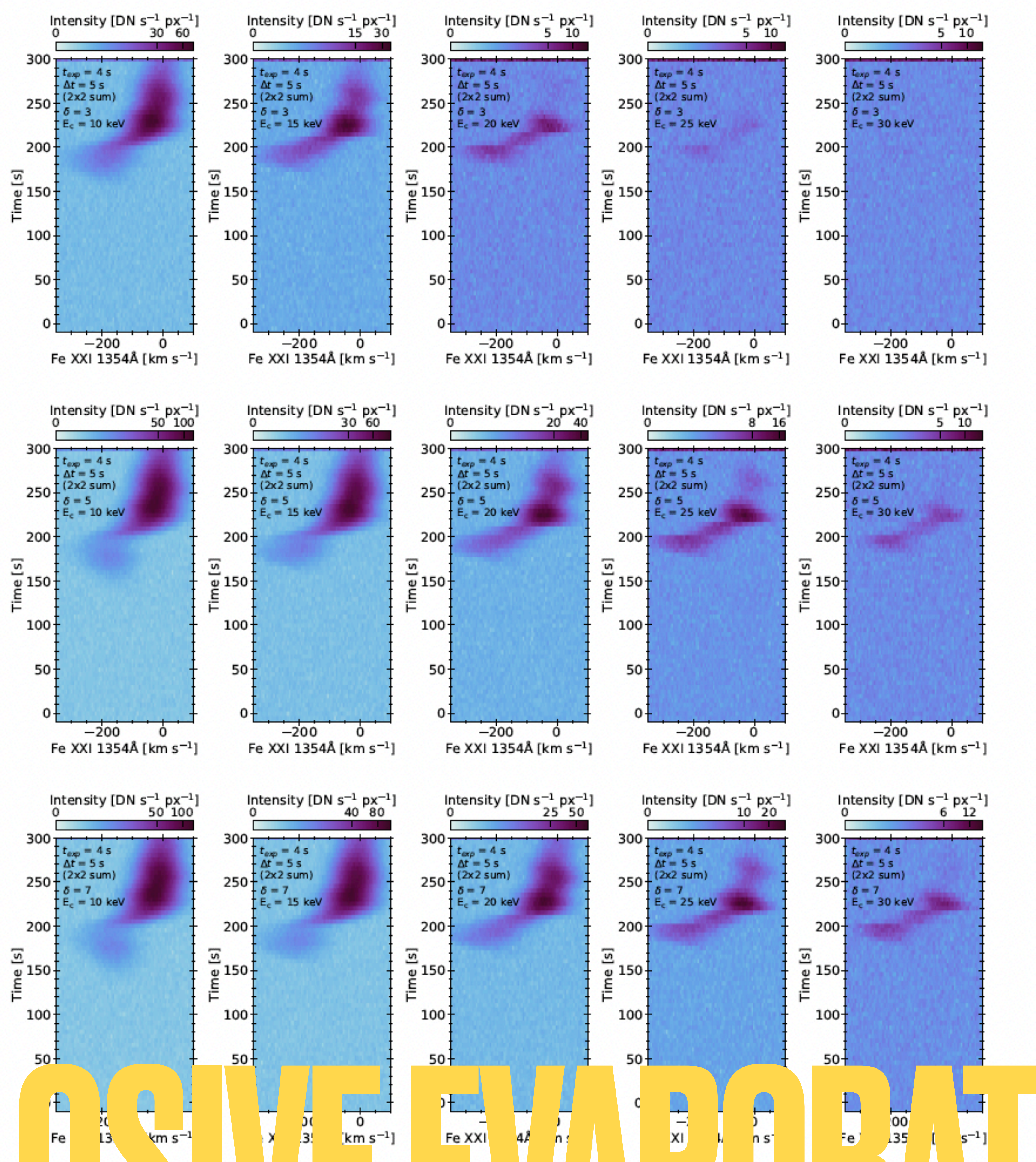
EXPLOSIVE EVAPORATION?



Fe XXI (11MK) emission typically exhibits explosive evaporation in bright ribbons, but not ribbon fronts.

During the ribbon front phase, there is no explosive evaporation, and no meaningful Fe XXI emission.

In most of the simulations Fe XXI transitions to being bright and strongly blue shifted once the energy input is large enough.

This is consistent with observations… including that not every ribbon front ultimately leads to explosive evaporation.

SUMMARY

- High resolution observations indicate that at some locations ahead of the bright propagating ribbon, we find 'ribbon fronts'. These ribbon fronts:
  - ➡...can be long lived (20-300s);
  - ➡... exhibit rather different properties compared to pre-flare and bright ribbons;
  - ➡... typically transition to becoming bright ribbons.
- Modelling has revealed:
  - ➡... nonthermal electrons are required to explain He I 10830 dimming;
  - ➡... a weak energy flux that heats the mid-chromosphere more than the upper chromosphere is required (e.g. a harder nonthermal electron energy distribution);
  - ➡... at these locations there may be some period of weak particle precipitation, preceding the main event.

What causes this evolution of heating rates into individual locations?