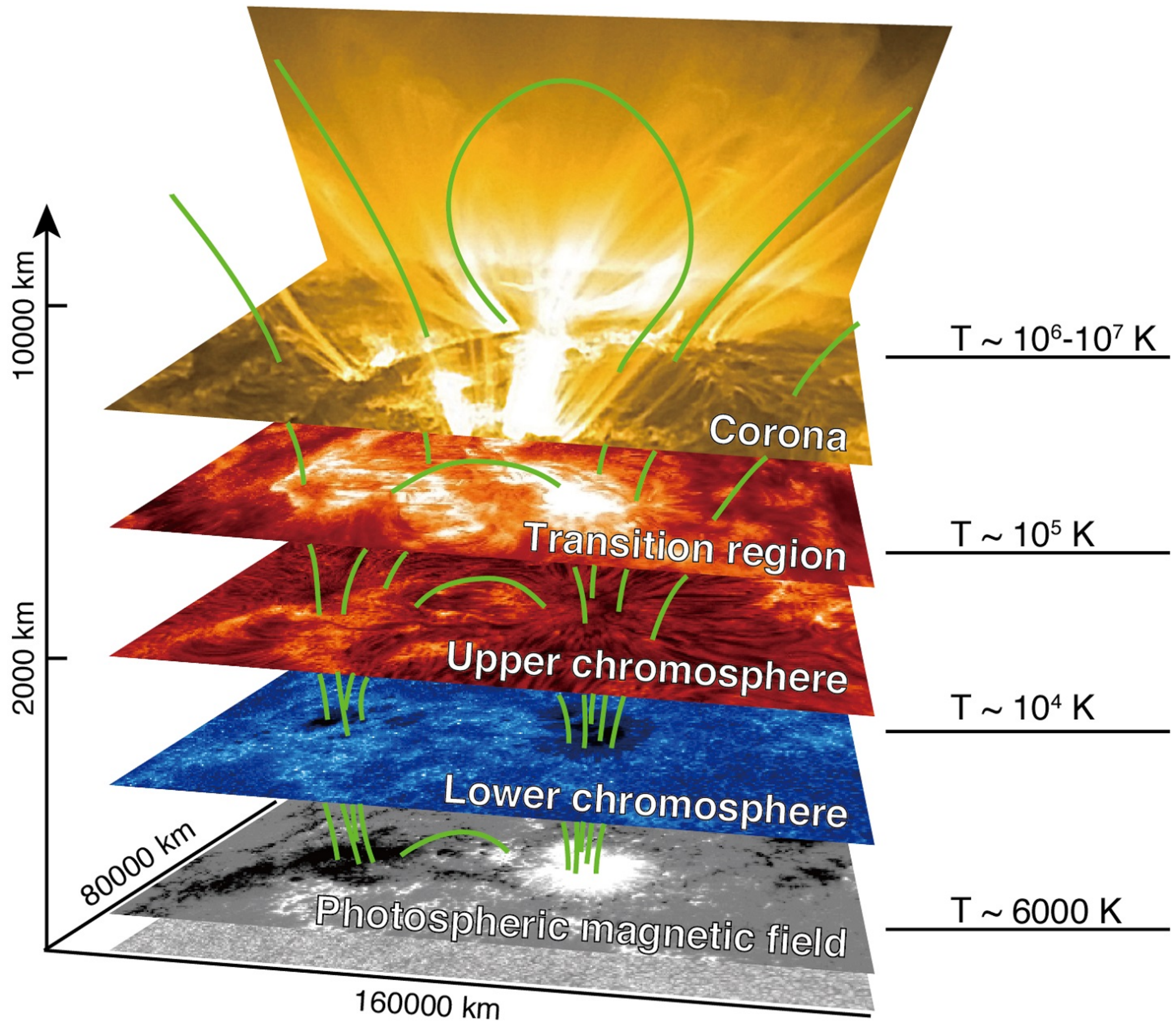
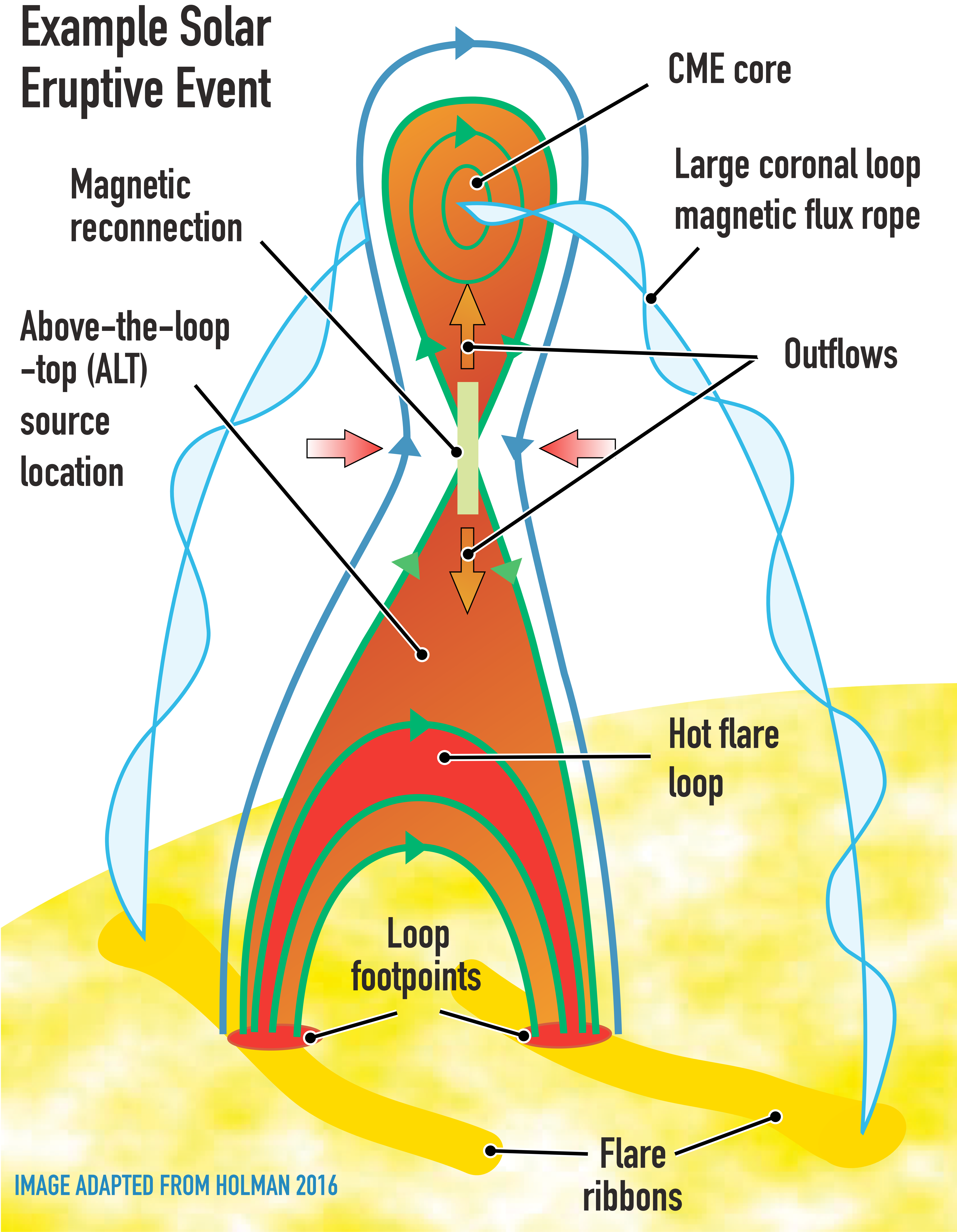
GRAHAM KERR CUA & NASA/GSFC (HE/HIM/HIS)

INTERROGATING SOLAR FLARE LOOP MODELS WITH OBSERVATIONS: RECENT SUCCESSES, CURRENT PROBLEMS, AND FUTURE DIRECTIONS

SOLAR FLARES





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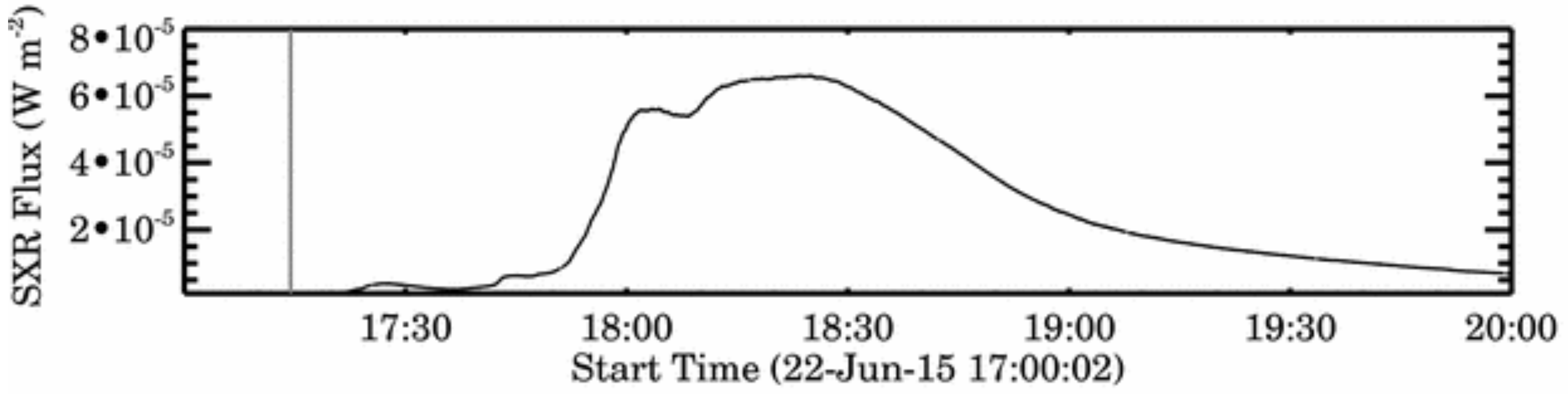
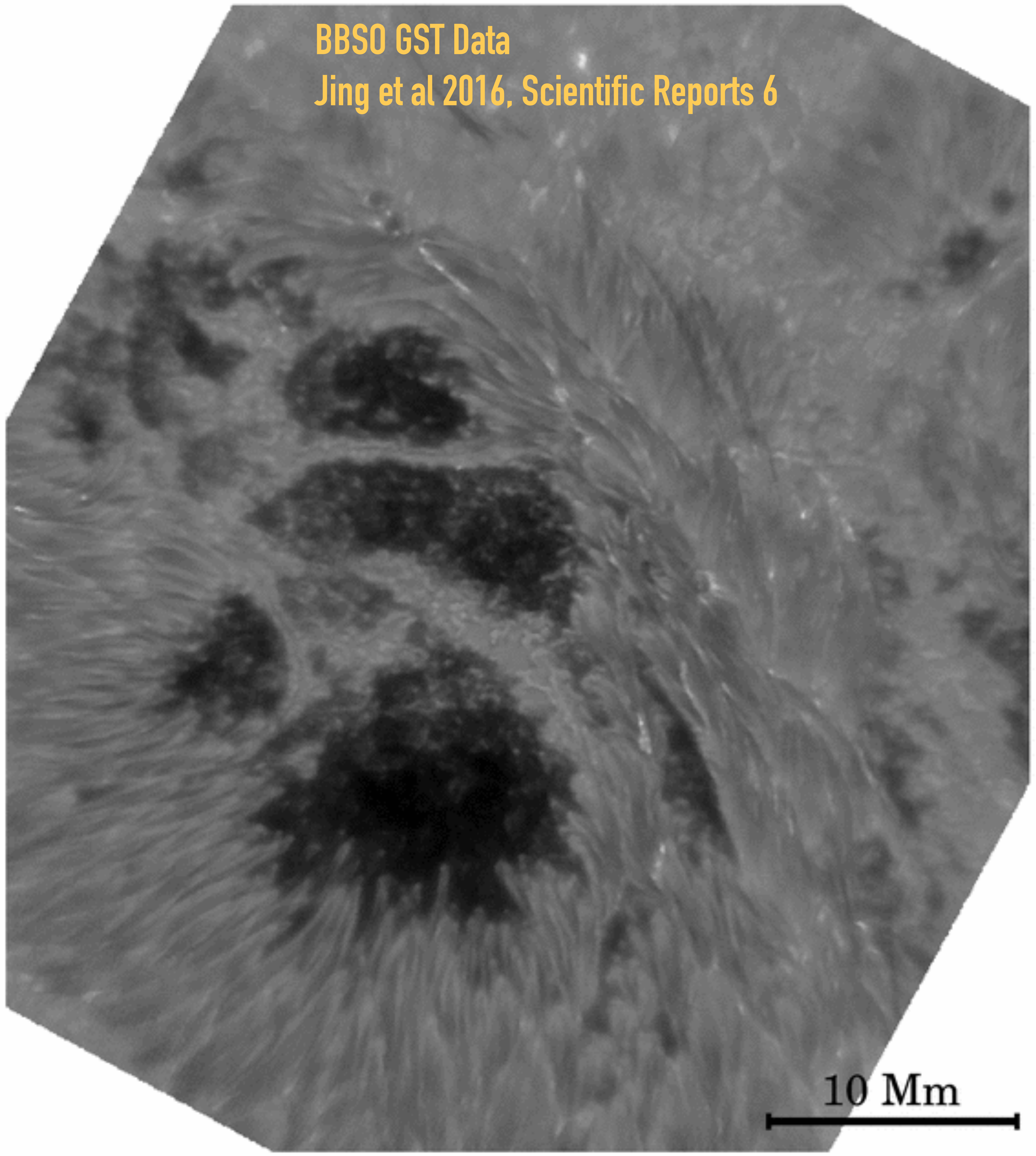
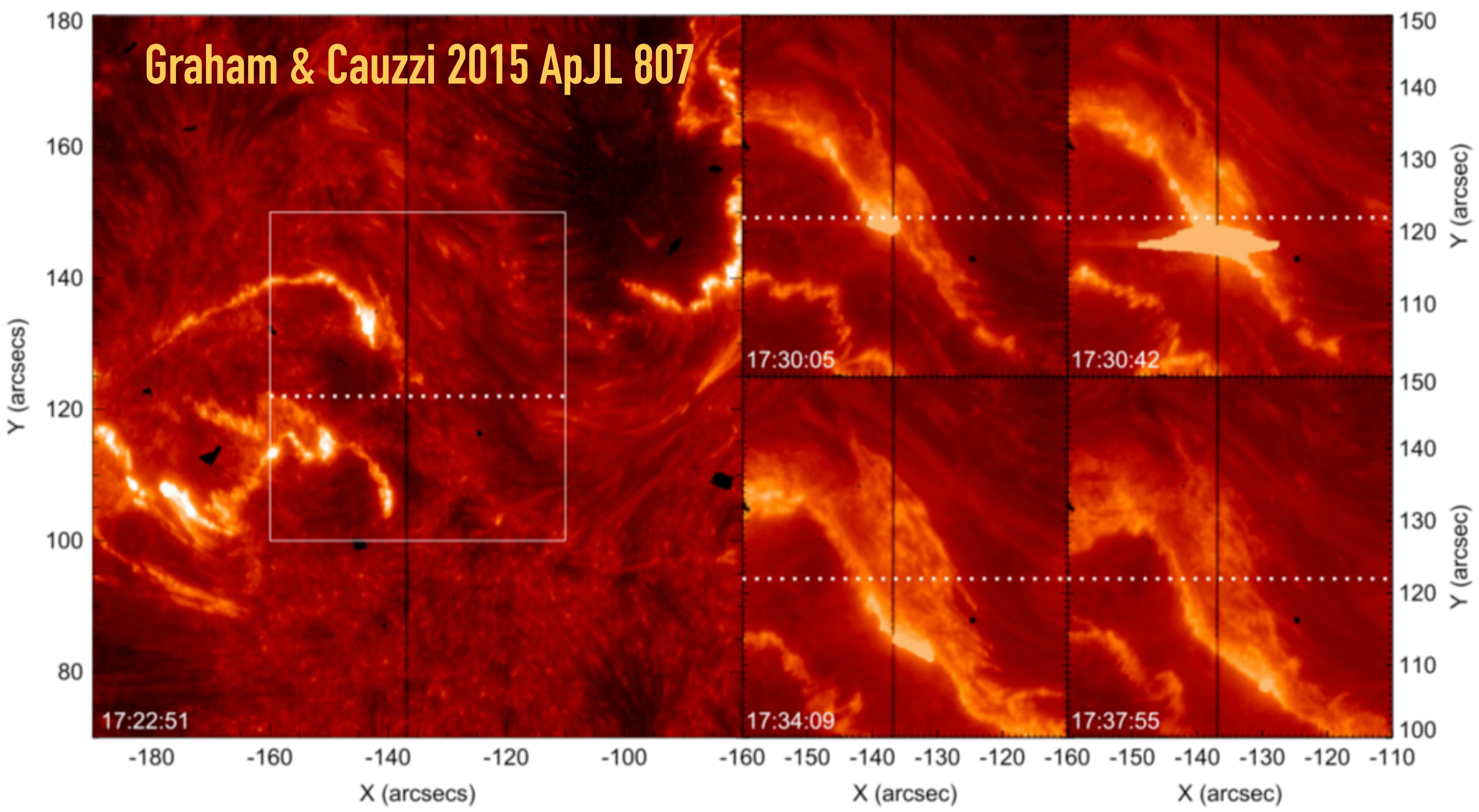
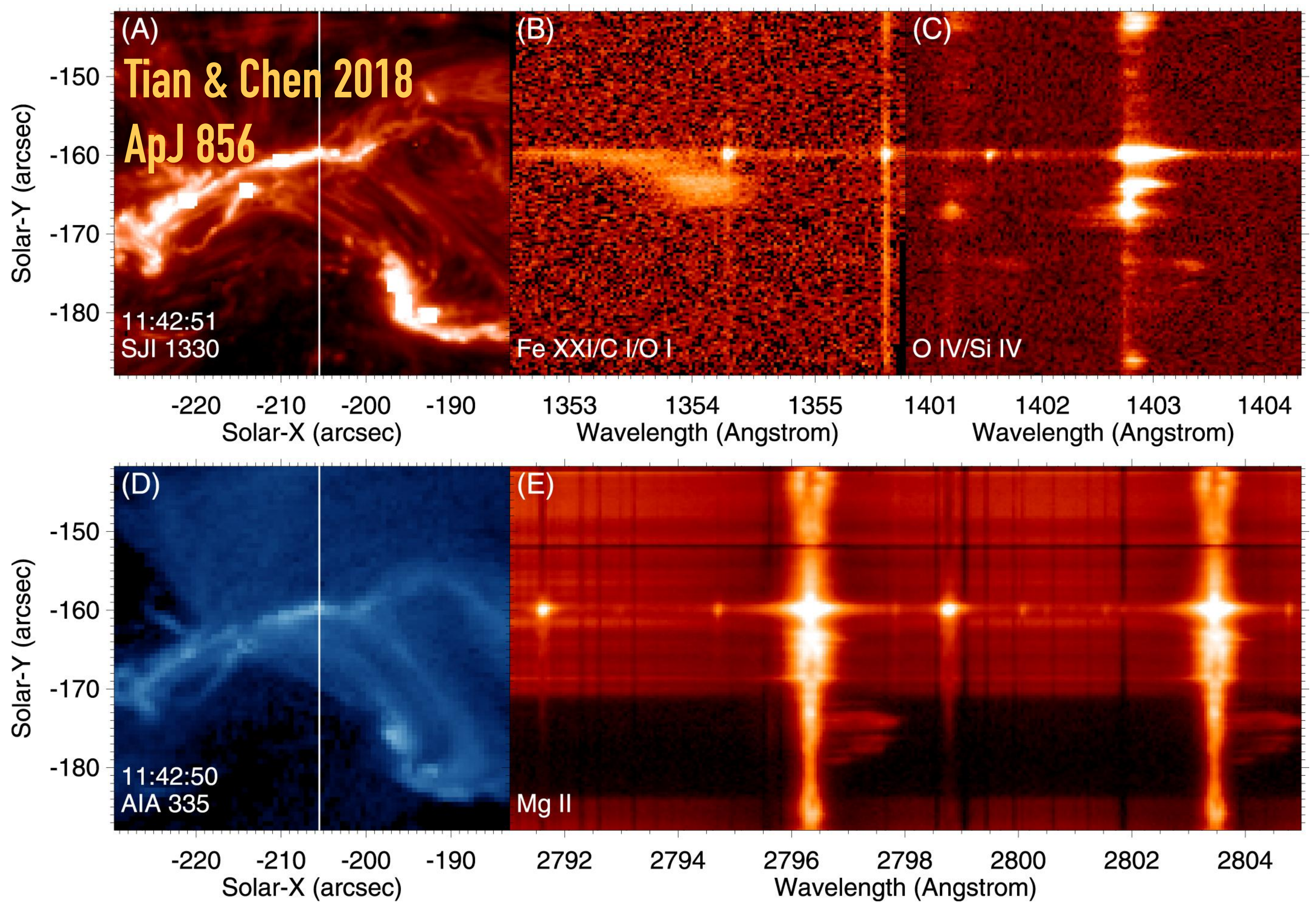
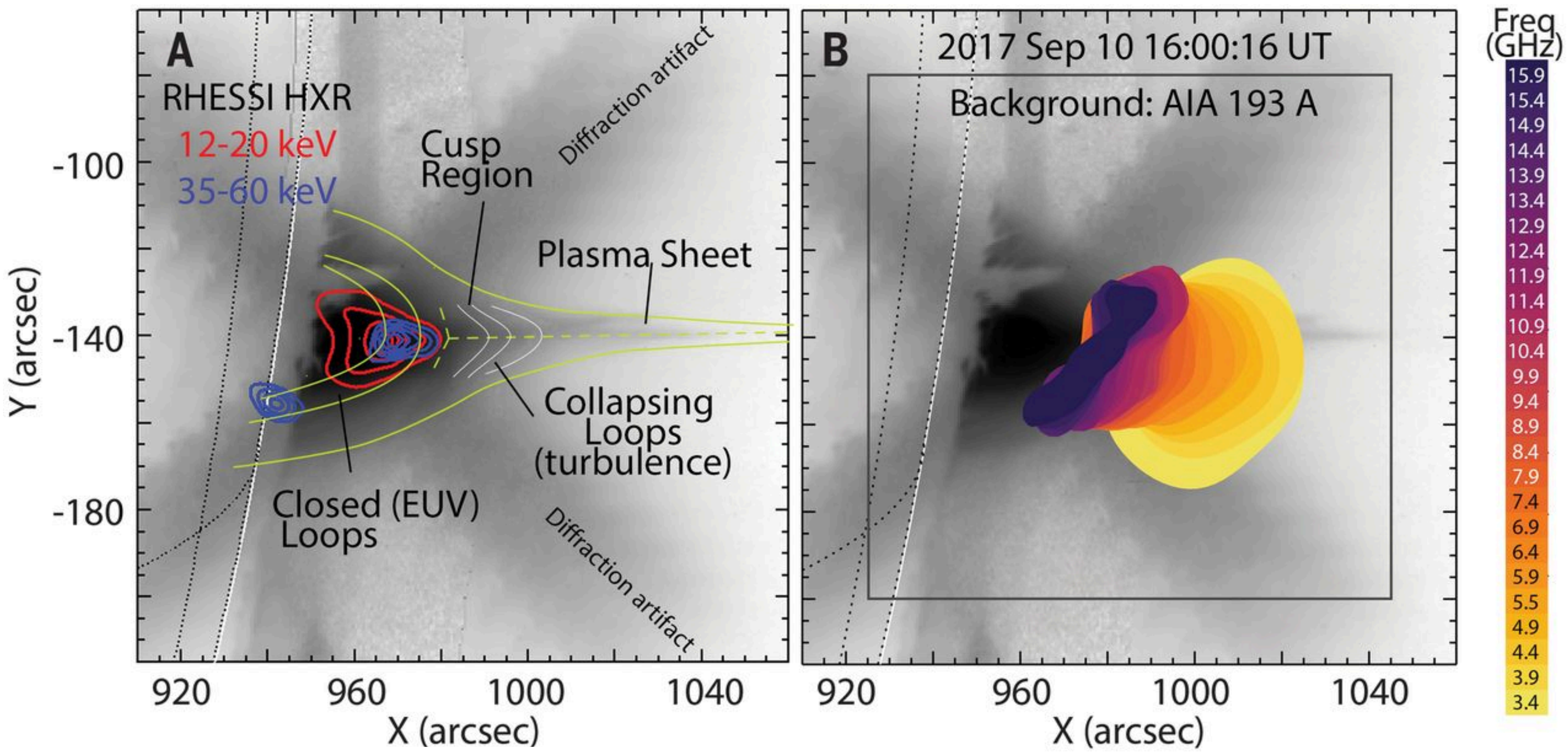


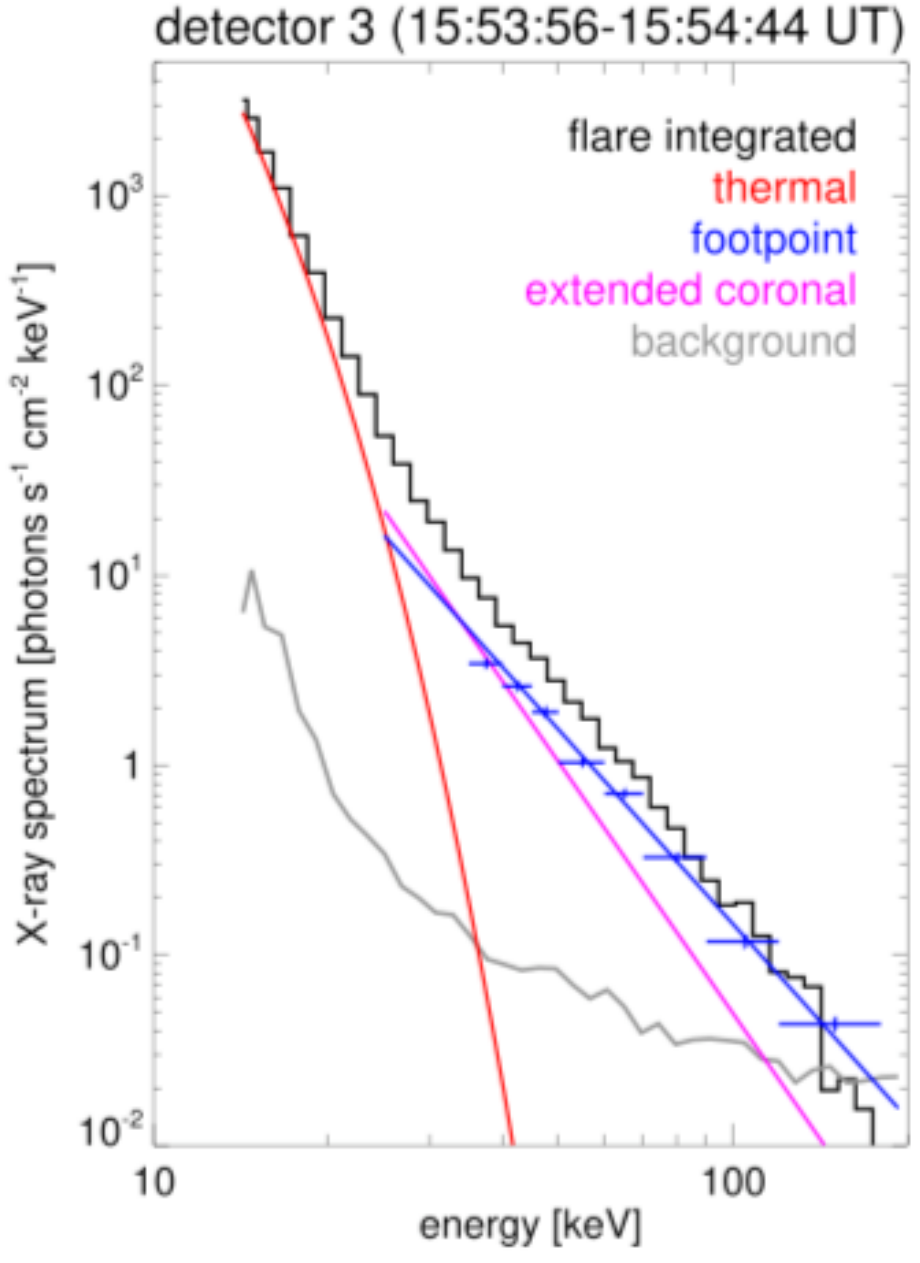


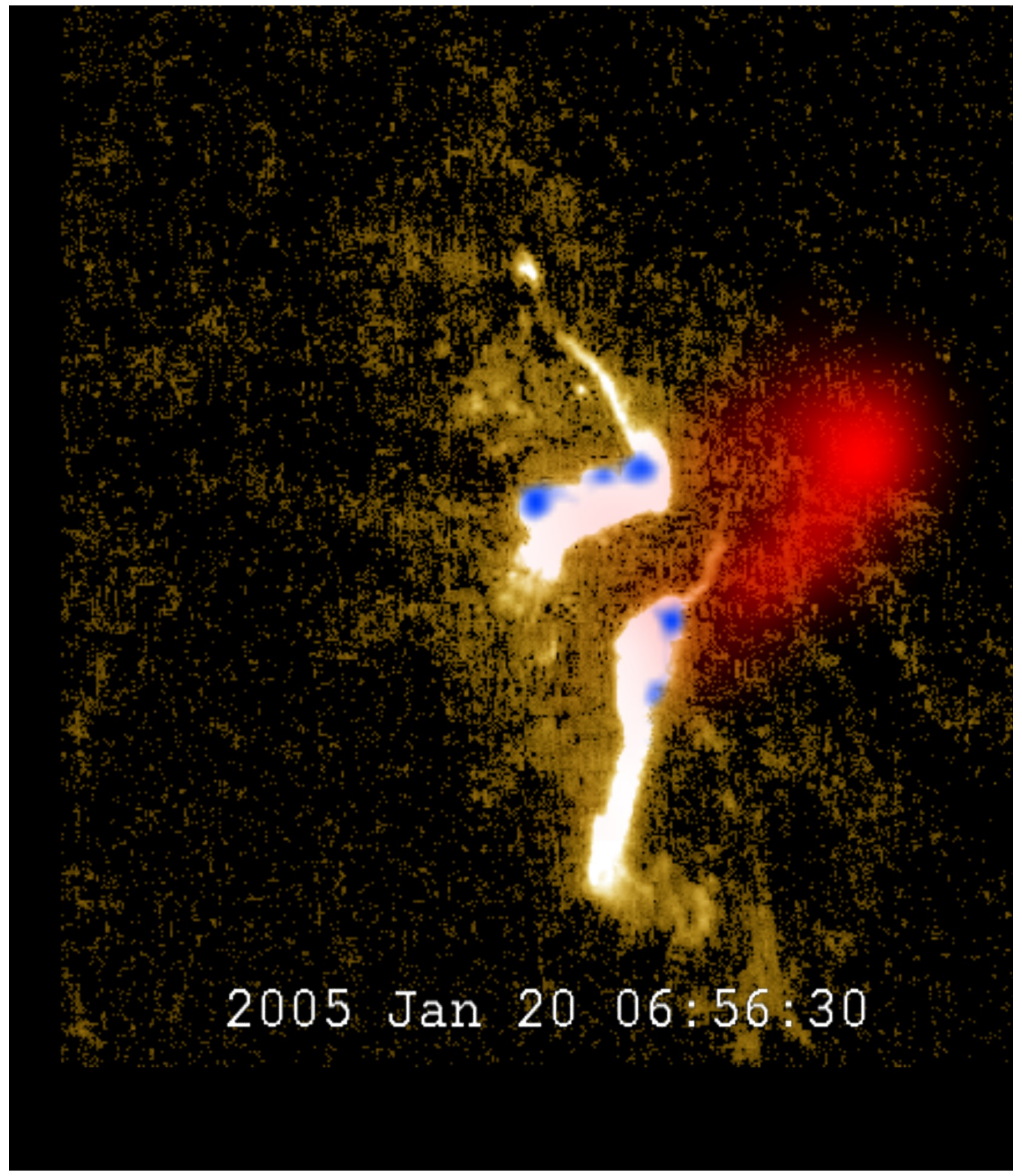




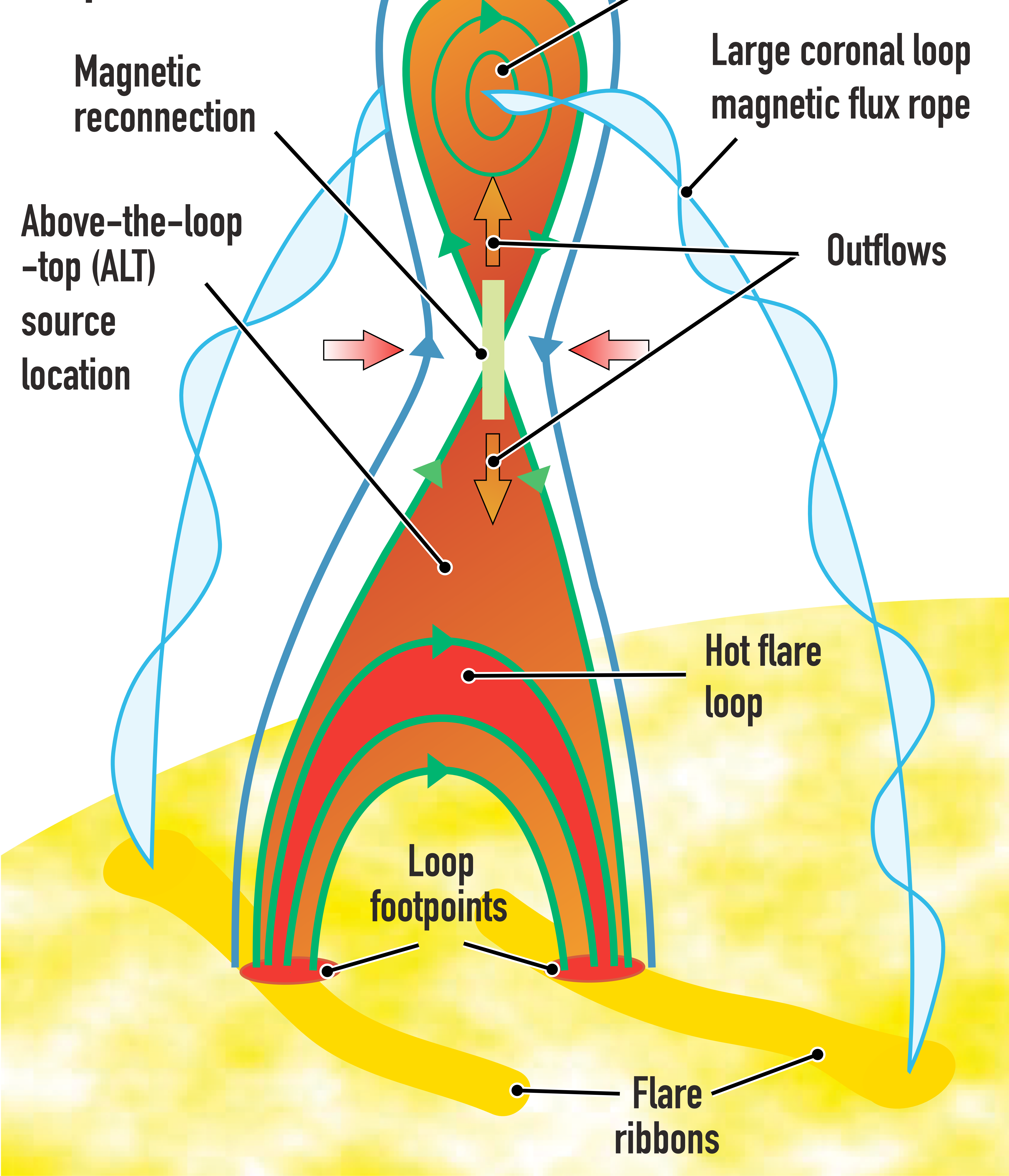
Example Solar Eruptive Event

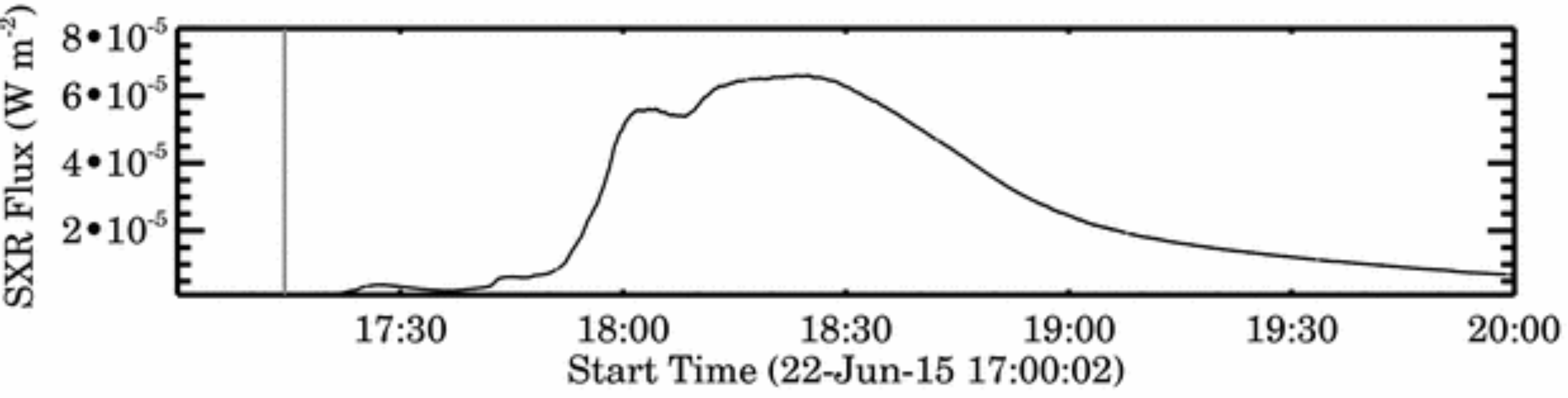


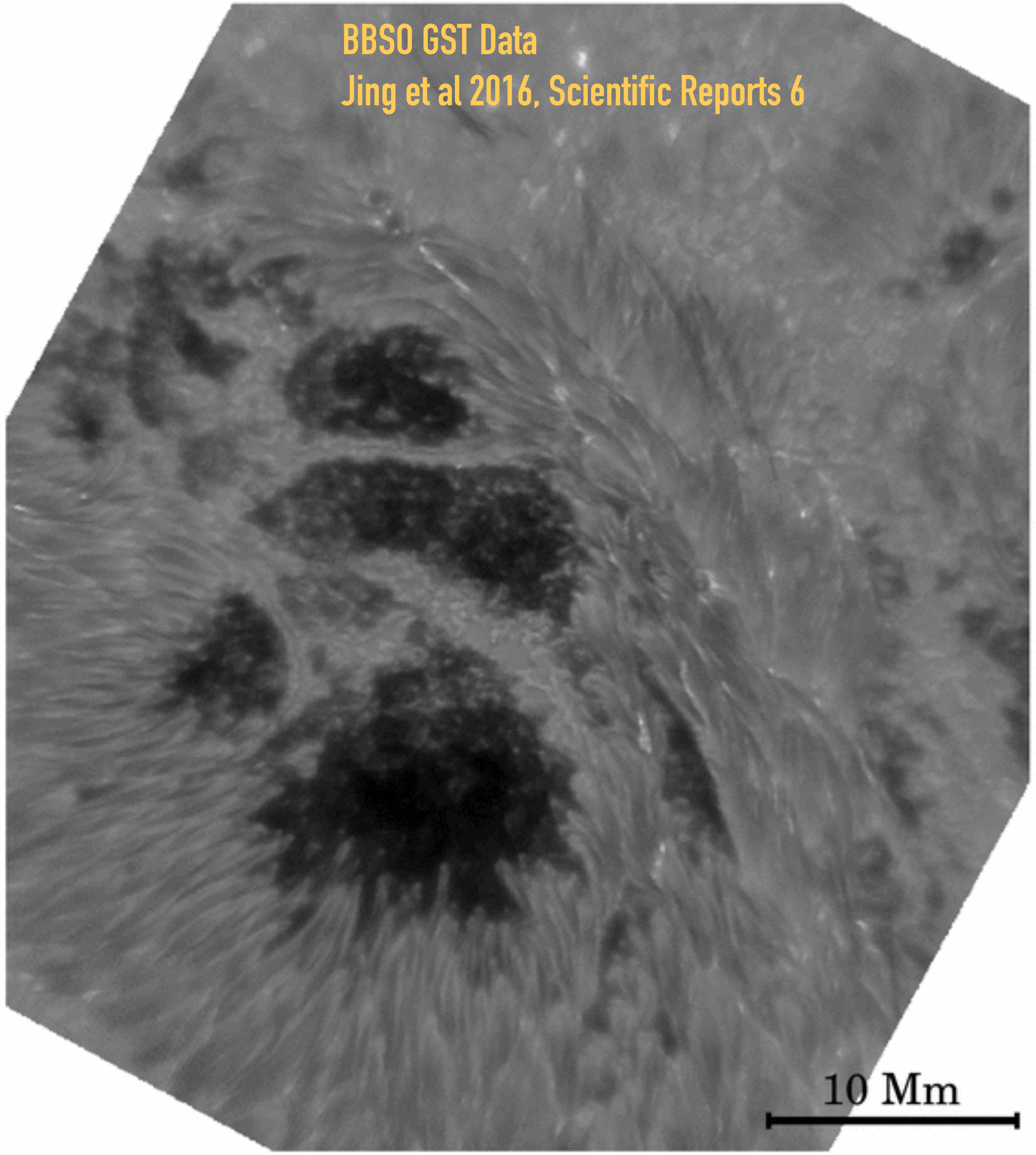




X-ray obs can be used to derive non-thermal electron distributions, which are then used to drive flare models.



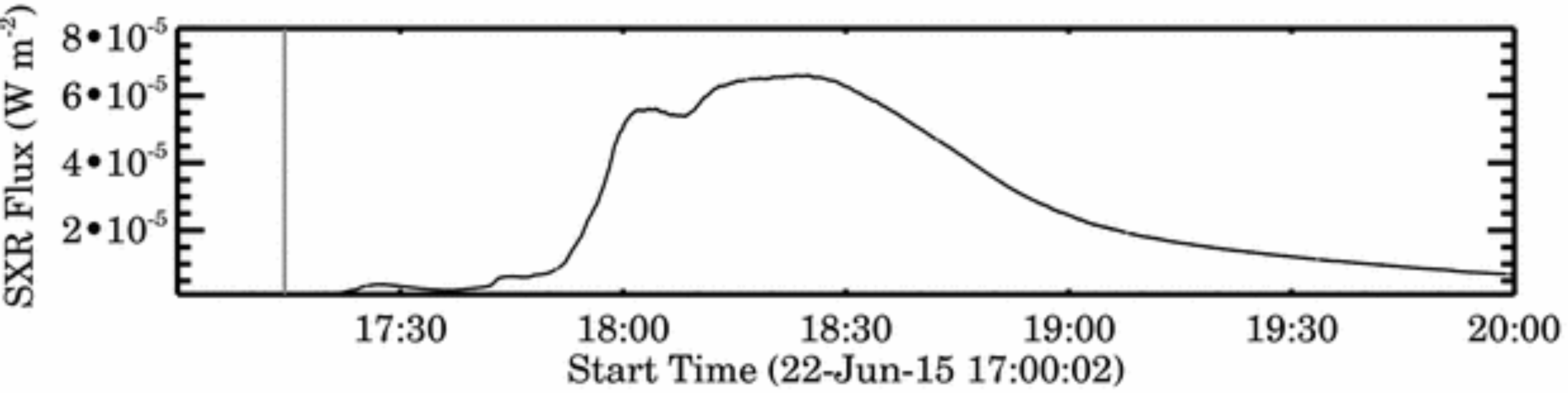


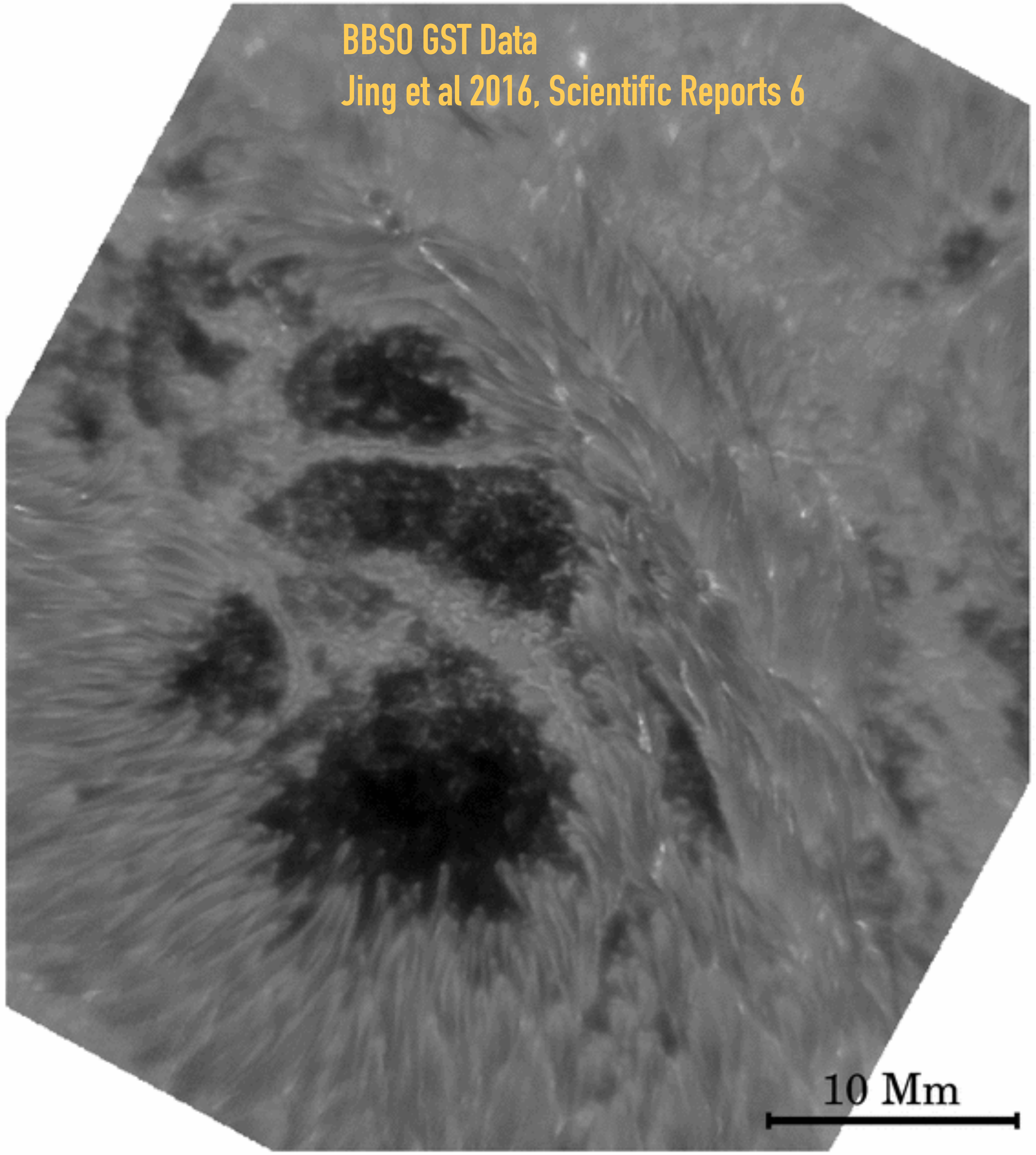


With the fortune of increasingly high quality data comes the need for state-of-the-art numerical models to both:

1) help extract and interpret what information observations contain;
2) determine if theory stands up to the stubborn reality of observations.

Field-aligned loop models (1D) of solar flares allow us to study the detailed physics and complex feedback between the radiation and hydrodynamics at the high spatial and temporal resolution demanded during flares.



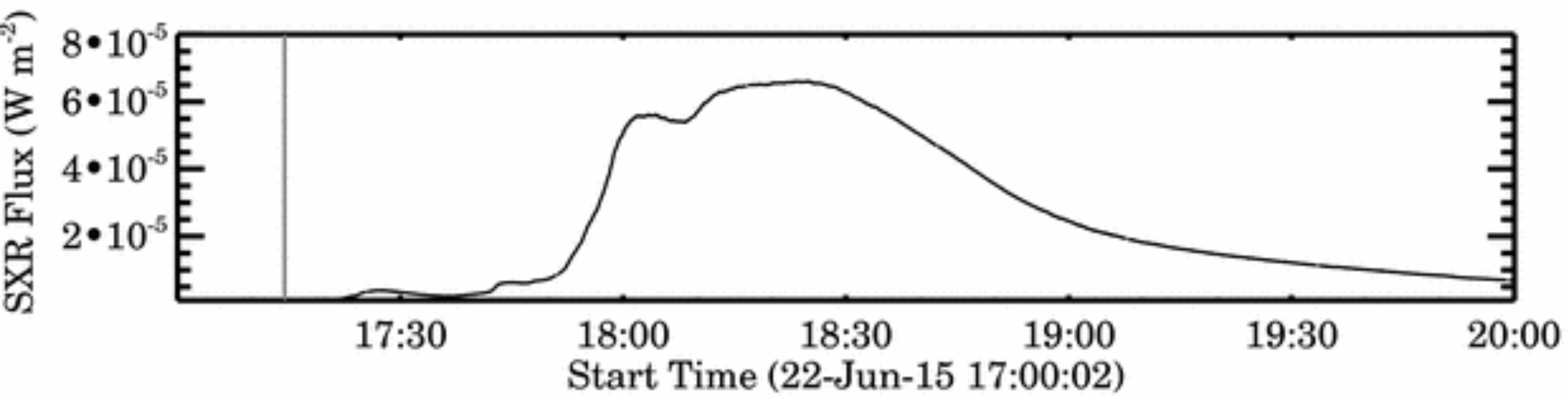


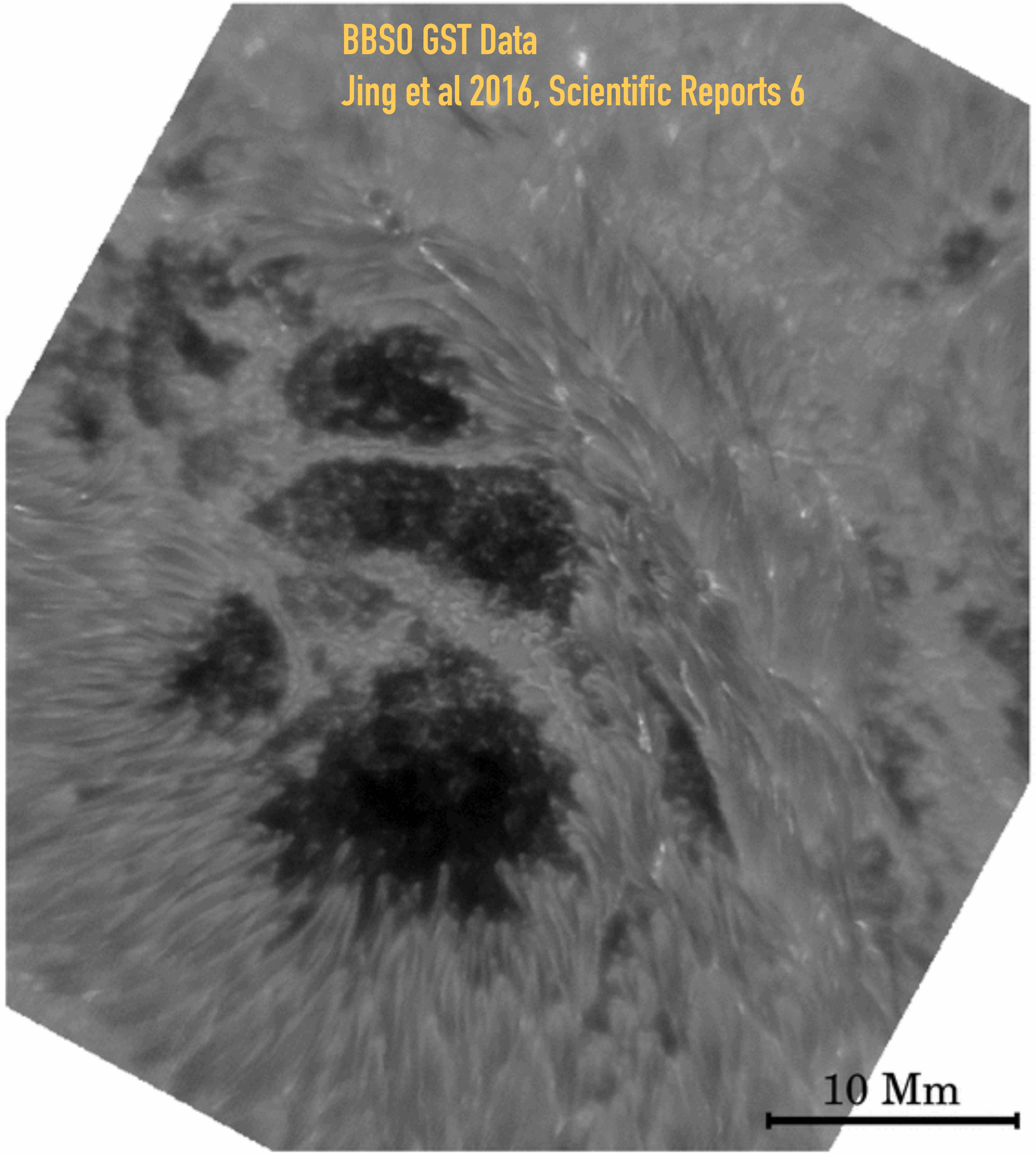
– Highlight just a few recent(-ish) results.**

– Discuss where models are currently not consistent with observations, and potential future directions.

– Present what I and some colleagues think is feasible way forward to make progress towards an end-to-end model of solar eruptions.

** Sorry if I don't cover your particular study or favorite result… I do likely cover them in a recent review article though!





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REVIEW article

Front. Astron. Space Sci., 21 December 2022
Sec. Stellar and Solar Physics
Volume 9 - 2022 |
https://doi.org/10.3389/fspas.2022.1060856

This article is part of the Research Topic
Flare Observations in the IRIS Era: What Have We Learned, and What's Next?
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Interrogating solar flare loop models with IRIS observations 1: Overview of the models, and mass flows

REVIEW article

Front. Astron. Space Sci., 06 January 2023
Sec. Stellar and Solar Physics
Volume 9 - 2022 |
https://doi.org/10.3389/fspas.2022.1060862

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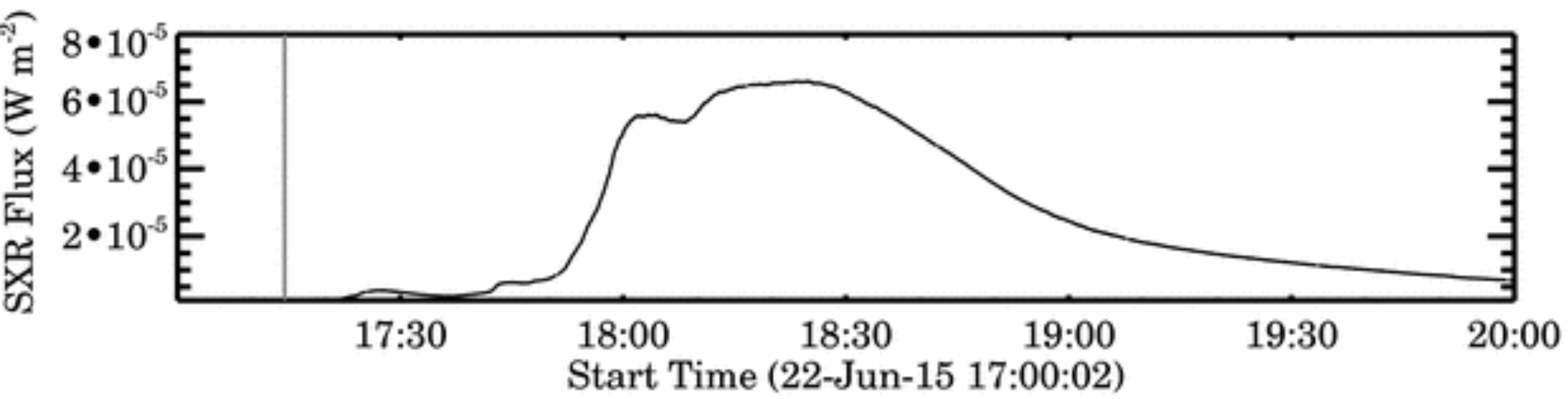

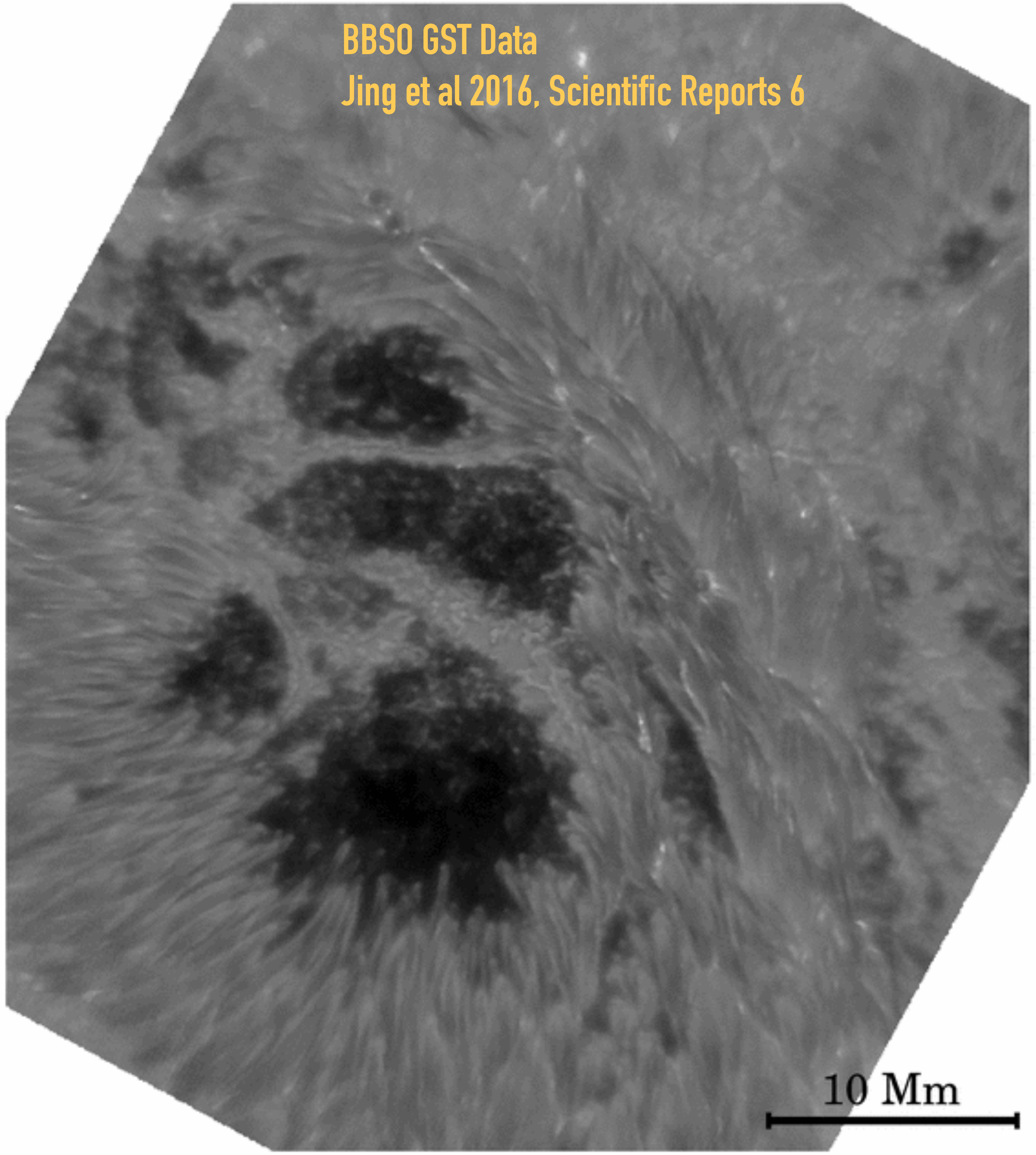

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NEXT-GENERATION COMPREHENSIVE DATA-DRIVEN MODELS OF SOLAR ERUPTIVE EVENTS

A white paper in response to the **Solar and Space Physics (Heliophysics) Decadal Survey**

Principal Author

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https://www.nationalacademies.org/our-work/decadal-survey-for-solar-and-space-physics-heliophysics-2024-2033

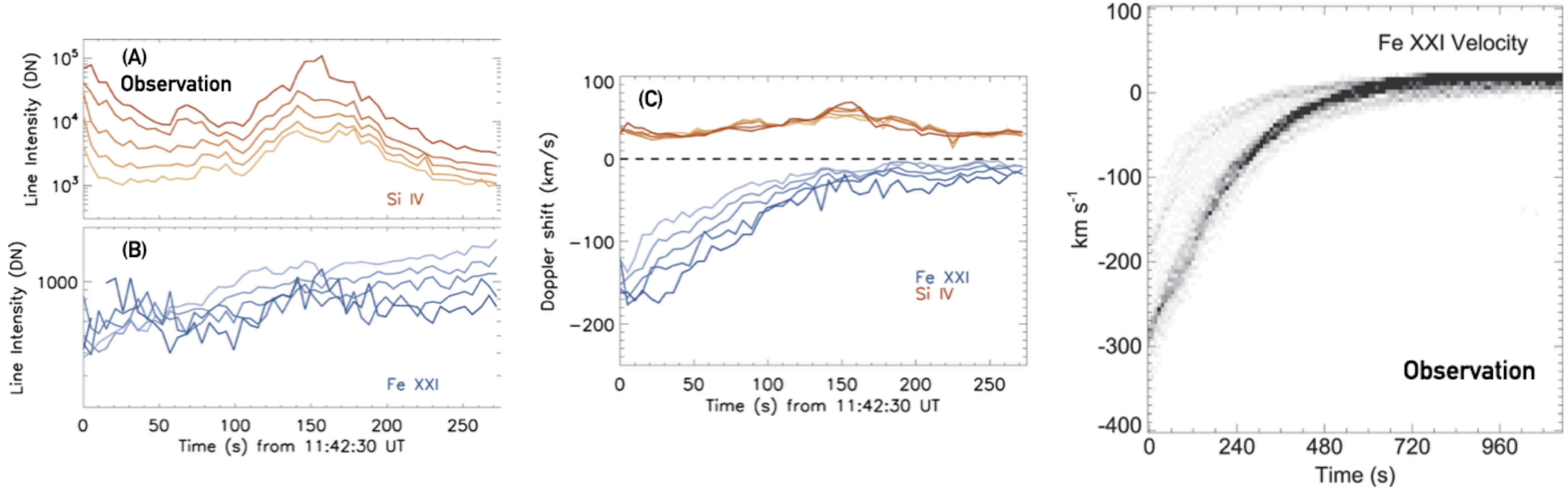
Code	Key Features	Geometry	Heating	Chromosphere	References
Flarix (RHD)	Accurate chromosphere and radiative transfer; test particle code to calculate heating (incl return currents, non-thermal collisions).	Half loop, fixed but optimised grid.	Electron beam (test particle code); Conduction	Full NLTE for H, Ca II (and sometimes Mg II)	Kasparova et al 2009; Varady et al 2010; Heinzel et al. 2016
RADYN (RHD)	Accurate chromosphere and radiative transfer; well developed flare physics (incl return currents, non-thermal collisions)	Half loop, adaptive grid with fixed # points to resolve where needed.	Particle beam (Fokker-Planck, both electron and ions); Alfvénic waves (approximated); Conduction (incl. suppression)	Full NLTE, non-equilibrium, for H, He I, He II, Ca II (and sometimes Mg II)	Carlsson & Stein 1995, 1997, 2002; Allred et al. 2005, 2015, 2020, 2022; Kerr et al 2016
HYDRAD (HD)	Non-equilibrium ionization for minor species; flexible geometry; two fluid plasma	Full loop, full AMR, magnetic field expansion.	Electron Beam (Hawley & Fisher 1994); Alfvénic waves; Conduction	Approximation to NLTE for H (Sollum); Carlsson & Leenaarts radiative losses	Bradshaw & Cargill 2013; Reep et al. 2019

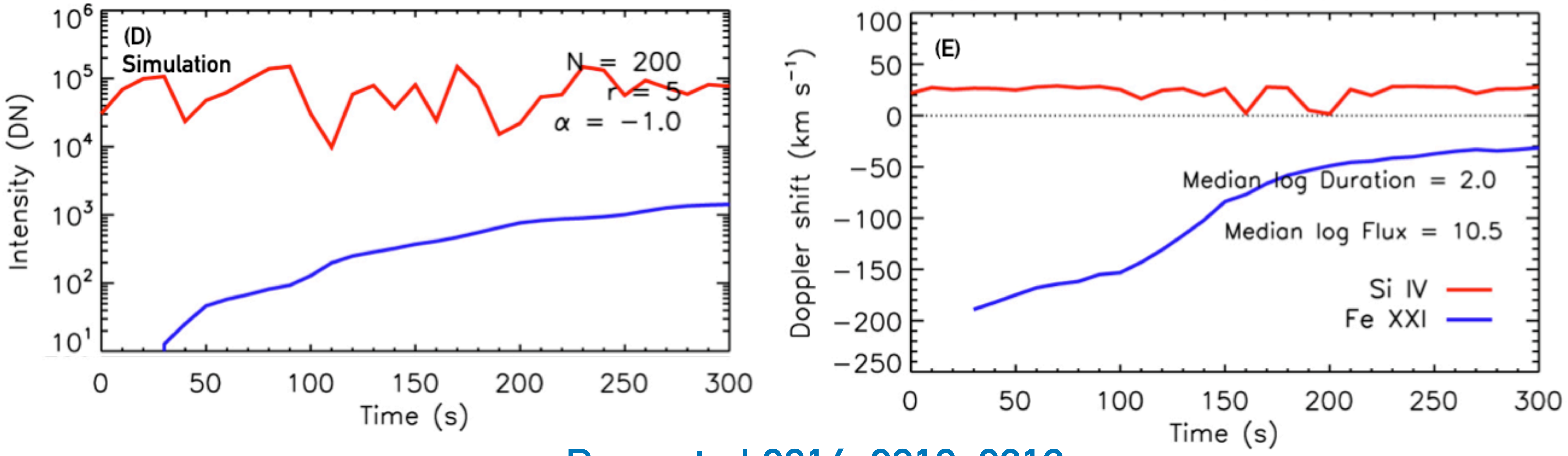
Some Recent Successes (IRIS)

MASS FLOWS IN SOLAR FLARES: LONG DURATION UPFLOWS

- Chromospheric evaporation (upflows) persist for 100s, **but** loop models predict the cessation of flows soon after we stop injecting energy.
- Multi-threaded modelling has proved successful – ~100 loops per IRIS pixel (<0.01”), variable injection onto each loop for up to tens of seconds (or longer).
- However, total duration into each pixel still needs to be several minutes.

Graham & Cauzzi 2015



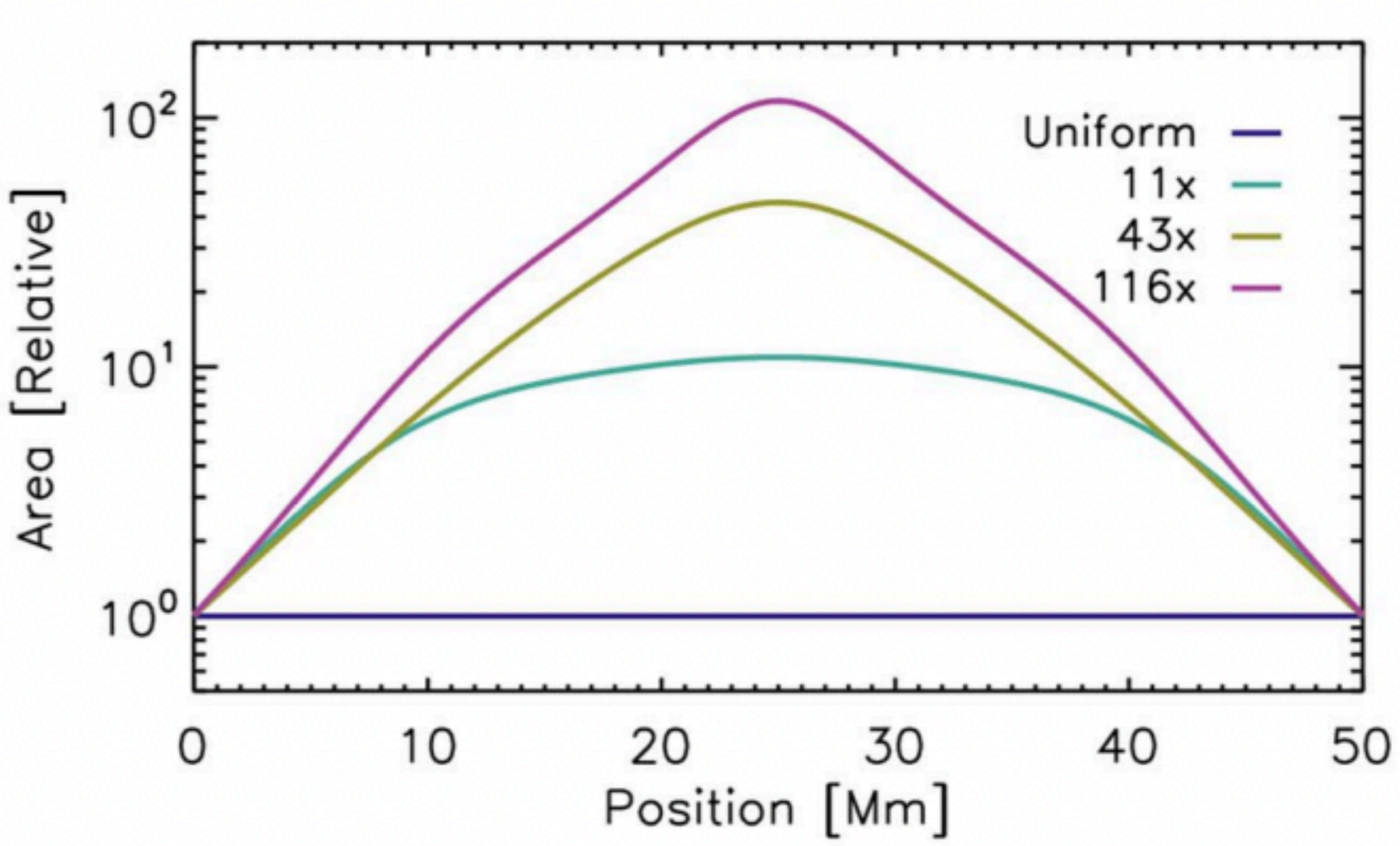


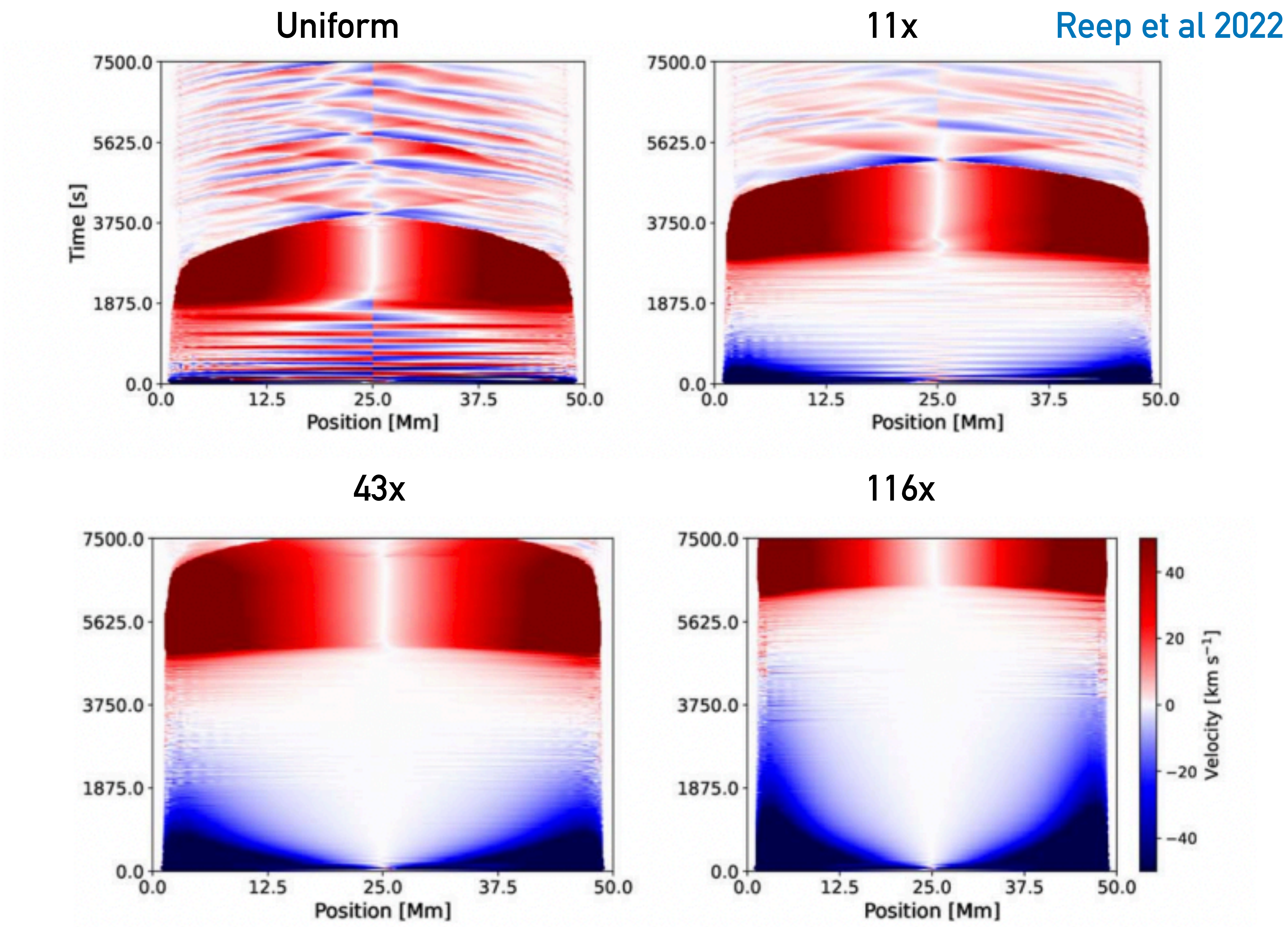
Reep et al 2016, 2018, 2019.

MASS FLOWS IN SOLAR FLARES: LONG DURATION UPFLOWS

- Chromospheric evaporation (upflows) persist for 100s, **but** loop models predict the cessation of flows soon after we stop injecting energy.

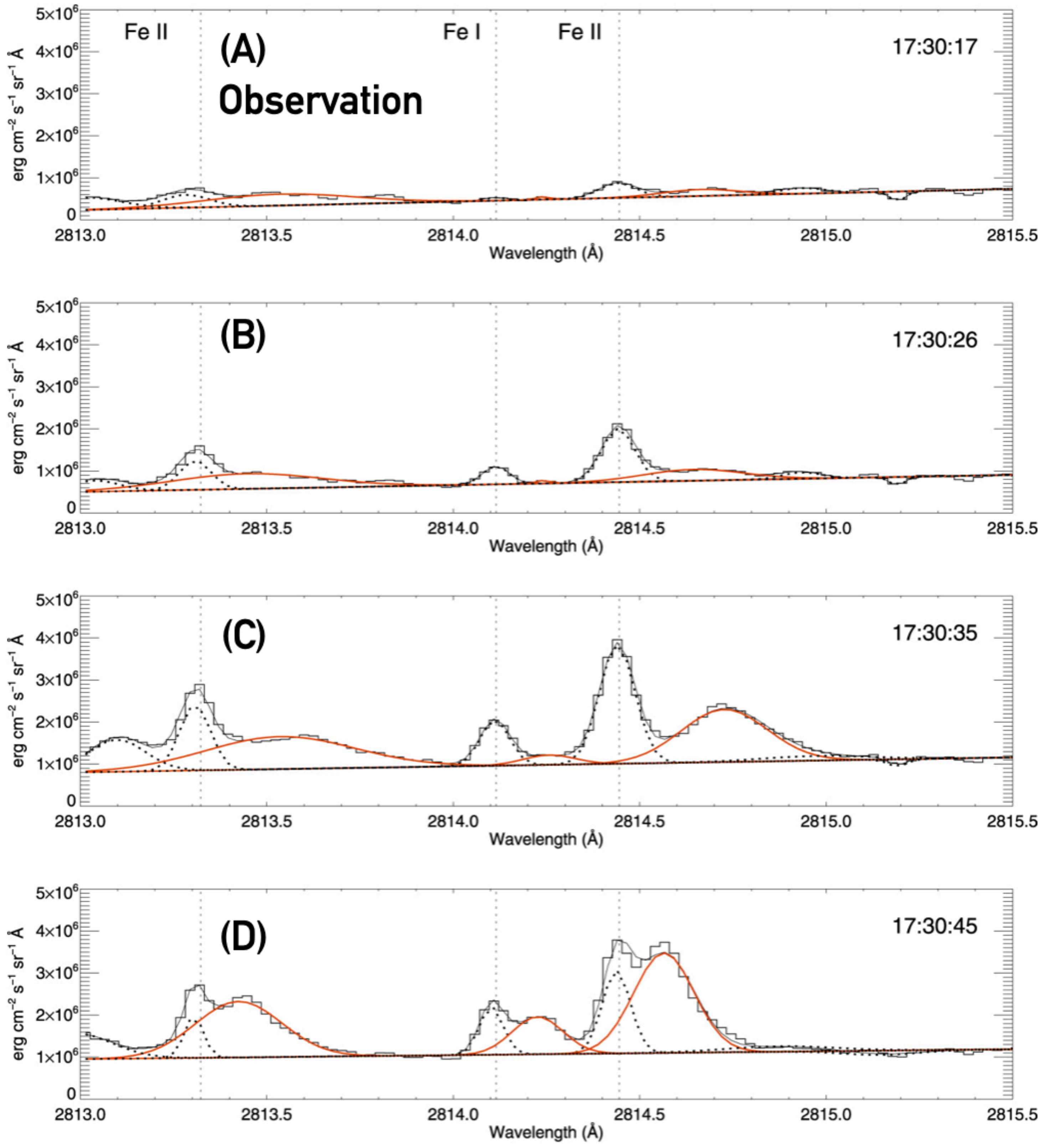
- One other potential solution is to include area expansion along the loop.



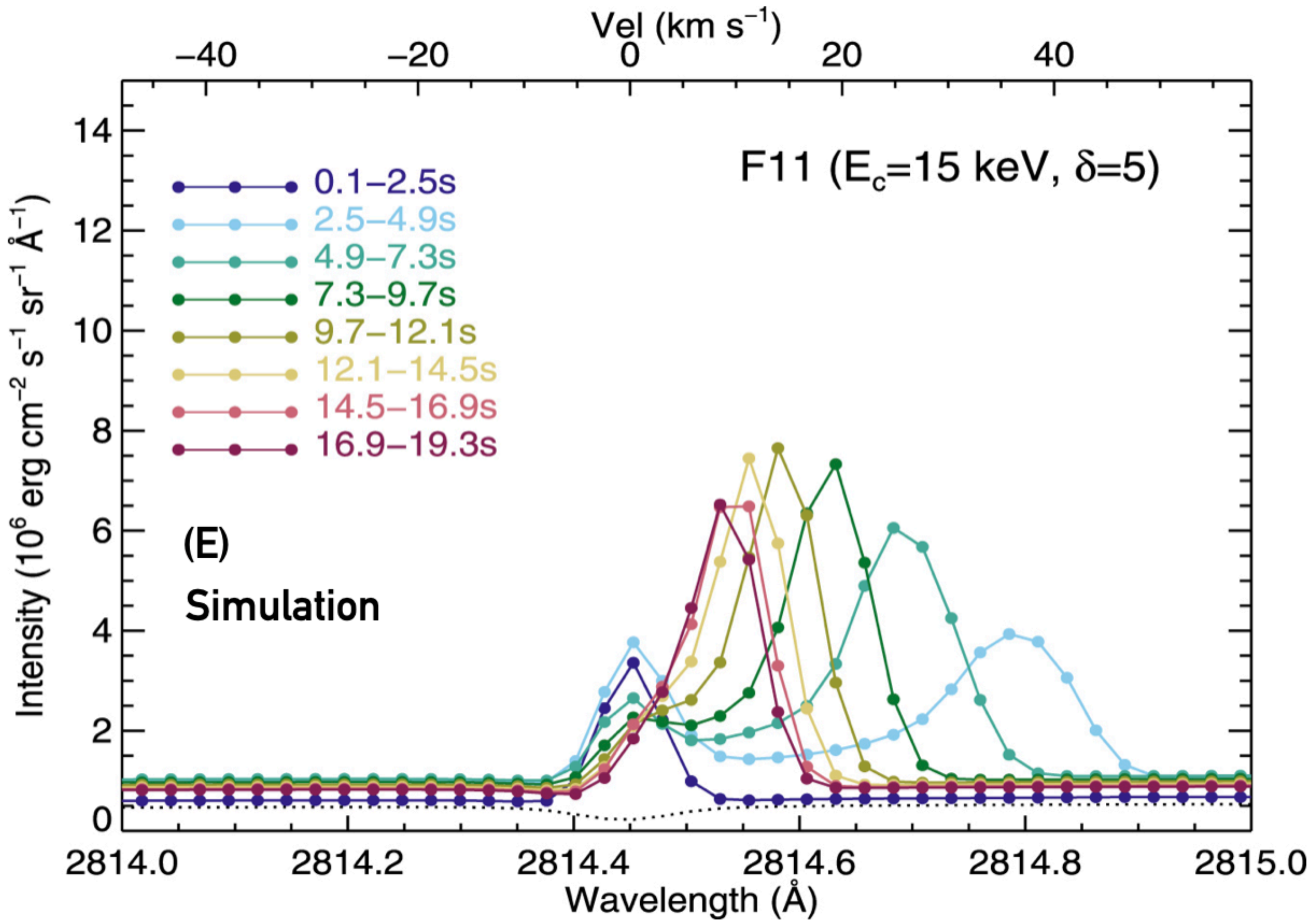


MASS FLOWS IN SOLAR FLARES: RED WING ASYMMETRIES

- Curiously, however, chromospheric condensations can be reasonably well produced by models and do not seem to require repeated energy injection into the loop.
- A RADYN model of an IRIS flare reproduced the red-wing component behavior.
- Only a slightly shorter timescale, and it is likely their condensation was too dense.

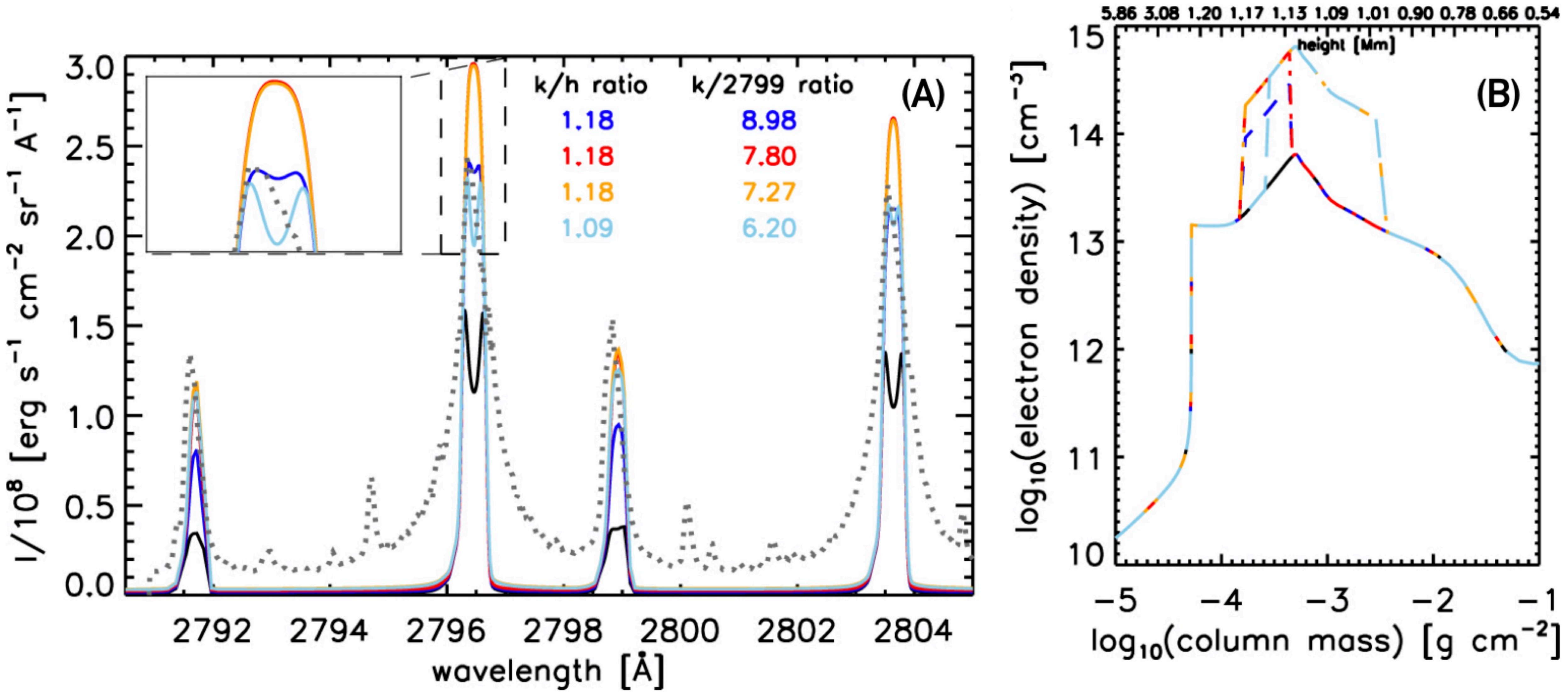


Graham et al 2020

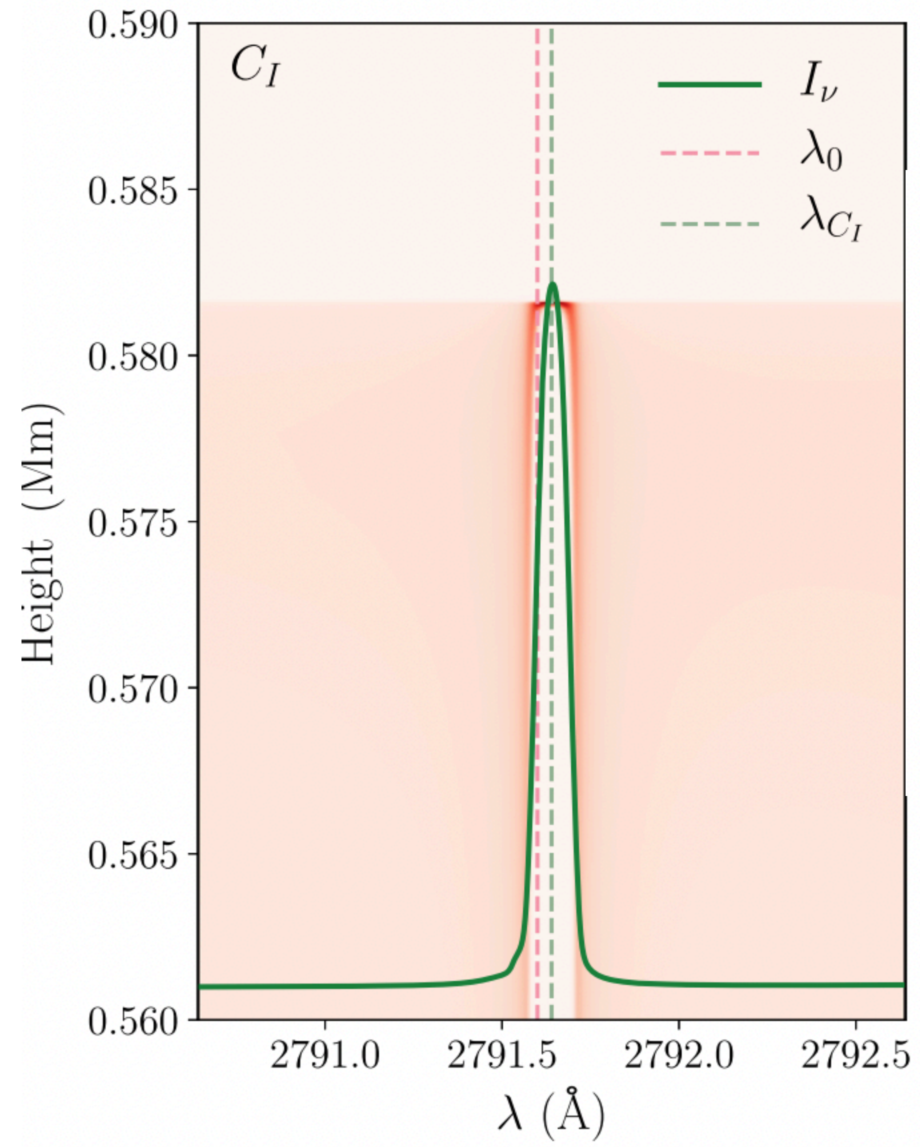


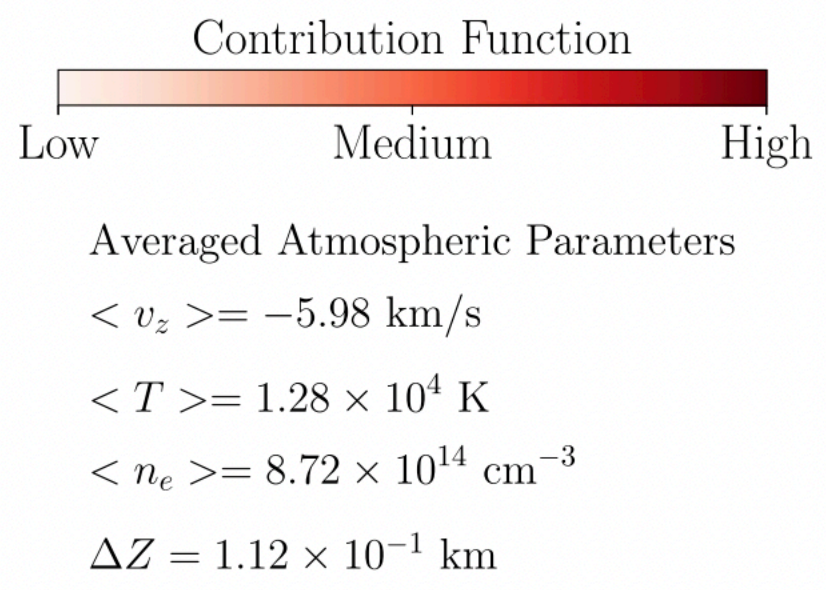
SINGLE PEAKED MG II PROFILES — INDICATES HIGH CHROMOSPHERIC DENSITY

- Mg II flare profiles are *(almost)* always single peaked, but most models have some level of central reversal.
- Parametric study by Rubio da Costa & Kleint (2017) indicated that a very large electron density was required in the upper chromosphere to achieve this: $n_e > \sim 5 \times 10^{14}$ cm^{-3}
- Zhu et al 2019, using a high injected energy flux, produced this ‘naturally’ in a flare simulation, which required a very large injected energy flux $F = 5 \times 10^{11}$ erg s^{-1} cm^{-2}
- Mg II core formed over a vanishingly narrow region in the upper chromosphere, only a few tens of meters thick!



Rubio da Costa & Kleint 2017



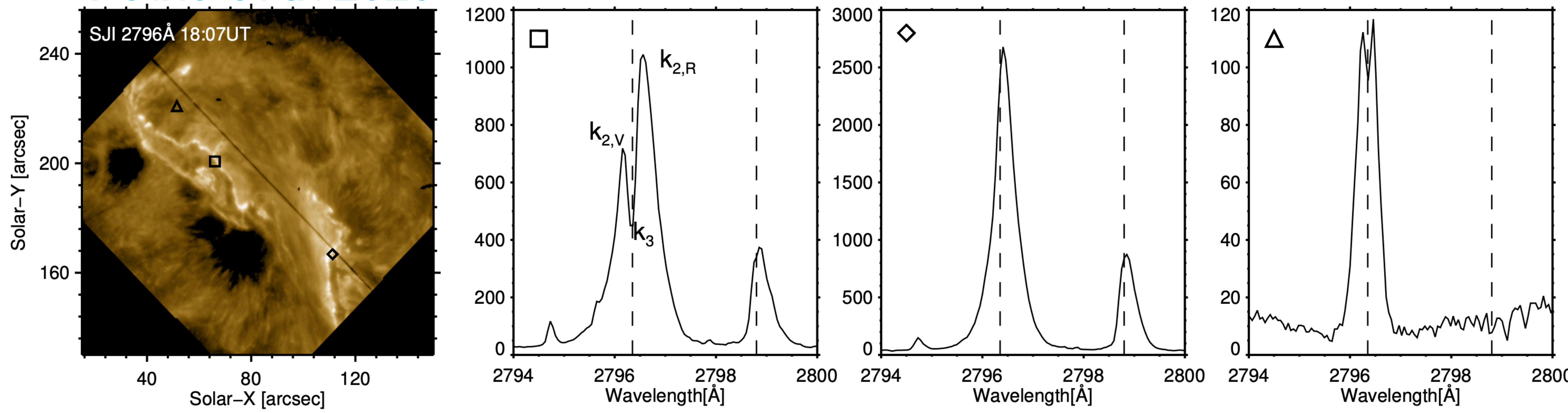


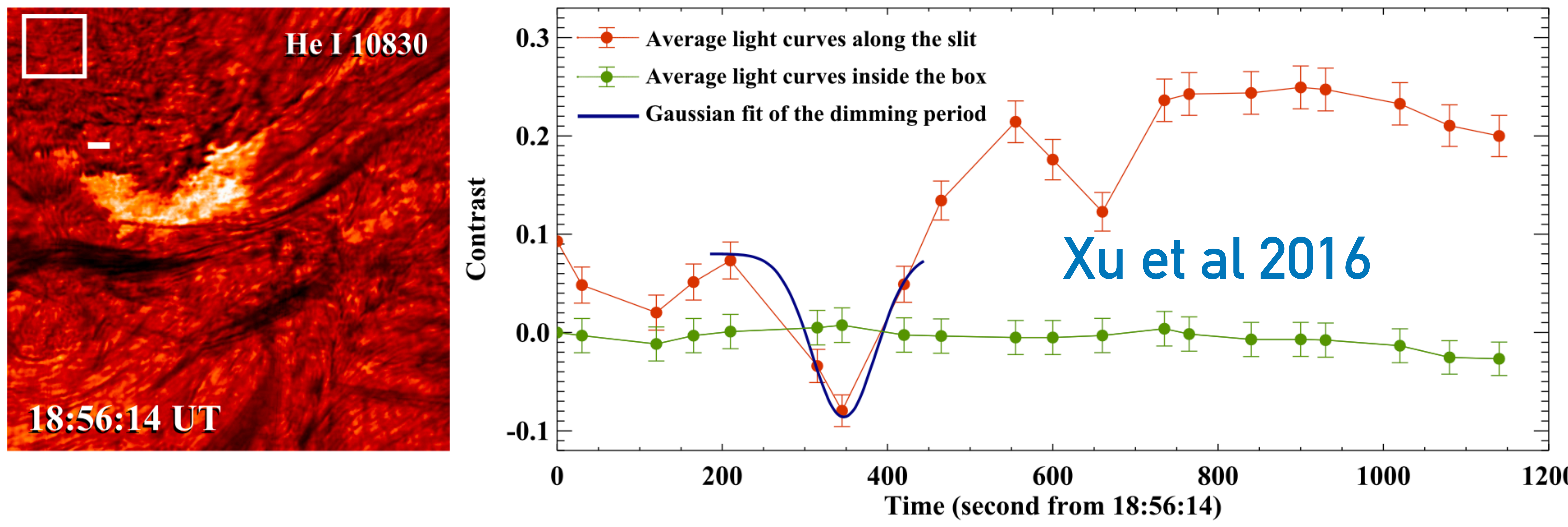
Zhu, Kowalski et al 2019

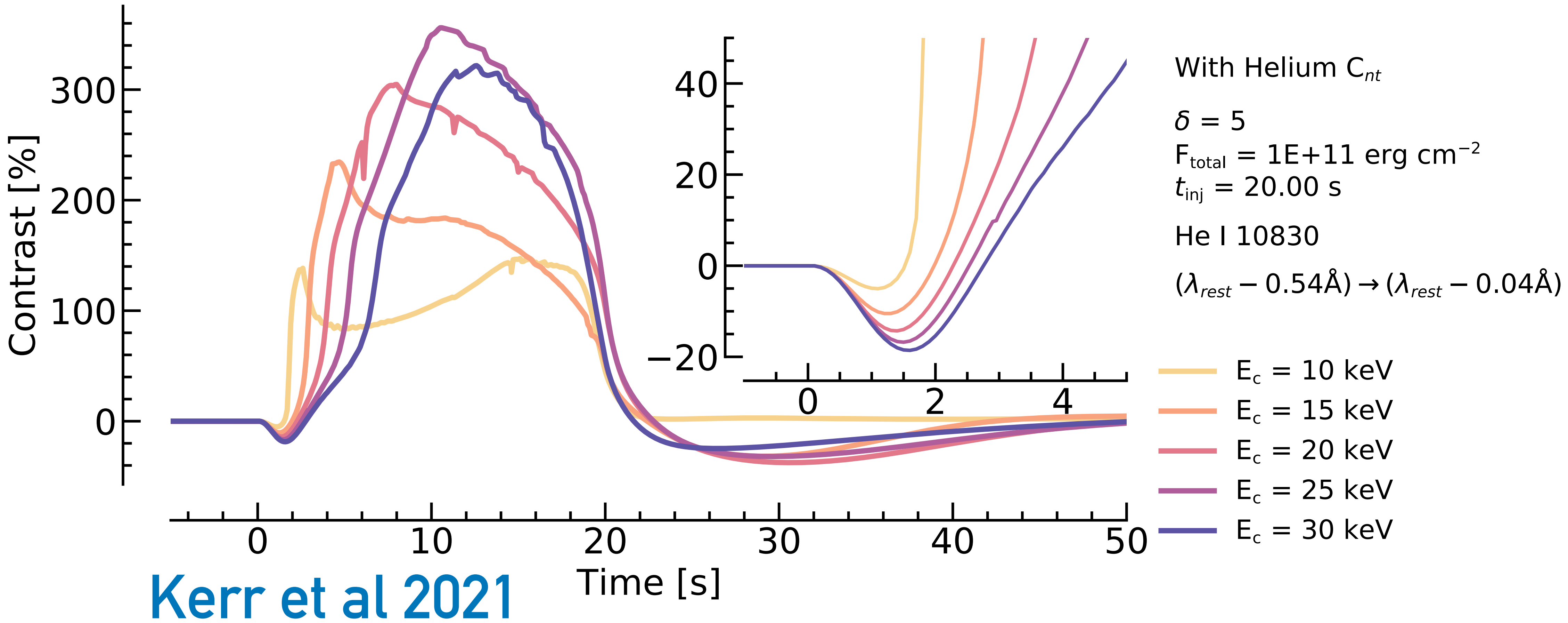
RIBBON FRONTS

- At the leading edge of flare ribbons we have seen:
  - He I 10830 dimmed for up to several hundred seconds before brightening (Xu et al 2016);
  - Mg II exhibited deep central reversals, were slightly blueshifted, and extremely broad (Xu et al 2016, Panos et al 2018,2021ab).
  - That NUV/FUV intensities took several tens of seconds and up to 2 minutes to reach peak after activation (Naus et al 2022).
- RADYN modelling (Kerr et al 2021, Polito et al 2022, Kerr et al 2023 *in prep*) has gone some way to explaining these features: ribbon fronts require a very weak flux of non-thermal electrons compared to the main ribbons that produce the brighter emission. **Could suggest up to 2-3 minutes of 'pre-heating' by a weak flux of electrons in some locations.**
- Ribbon fronts have T< 20kK, $n_e < 5\times10^{12}\ cm^{-3}$, and are undergoing gentle evaporation.

Polito et al 2023







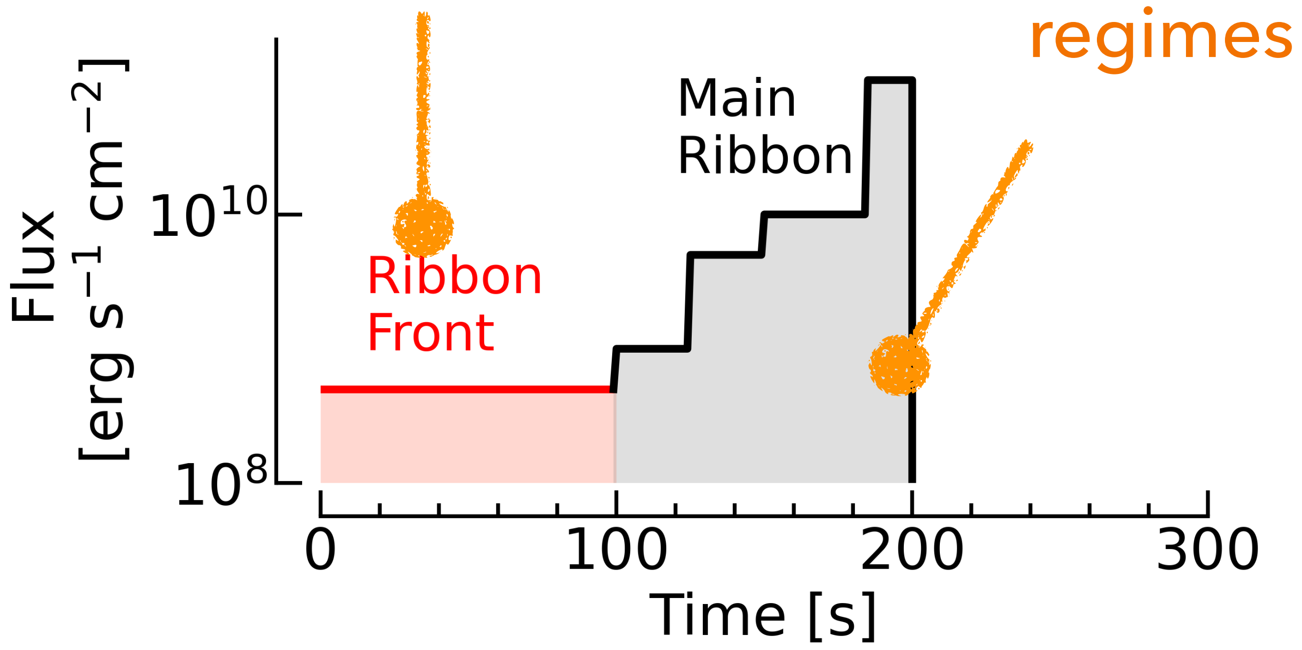
Kerr et al 2021

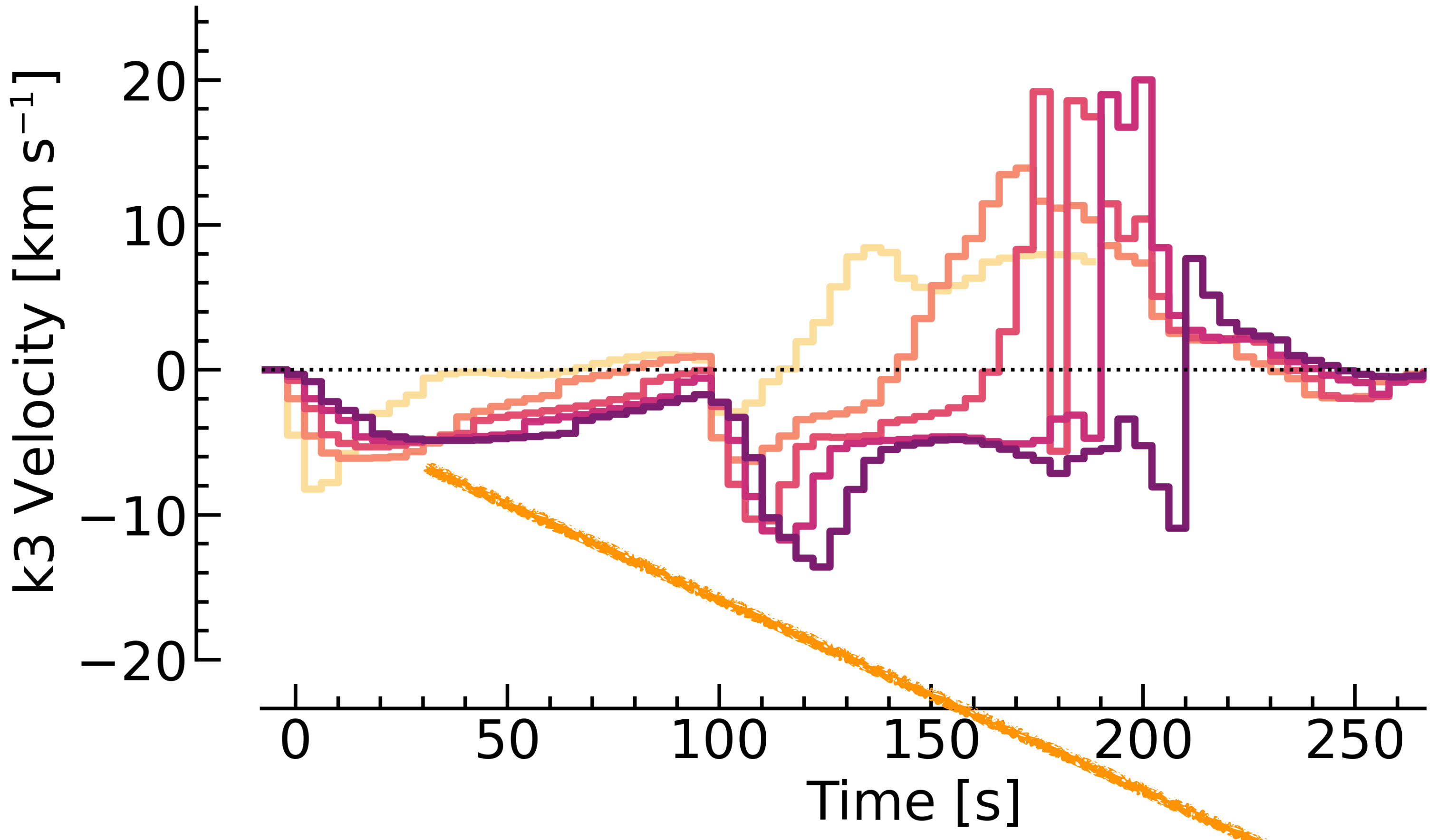
RIBBON FRONTS

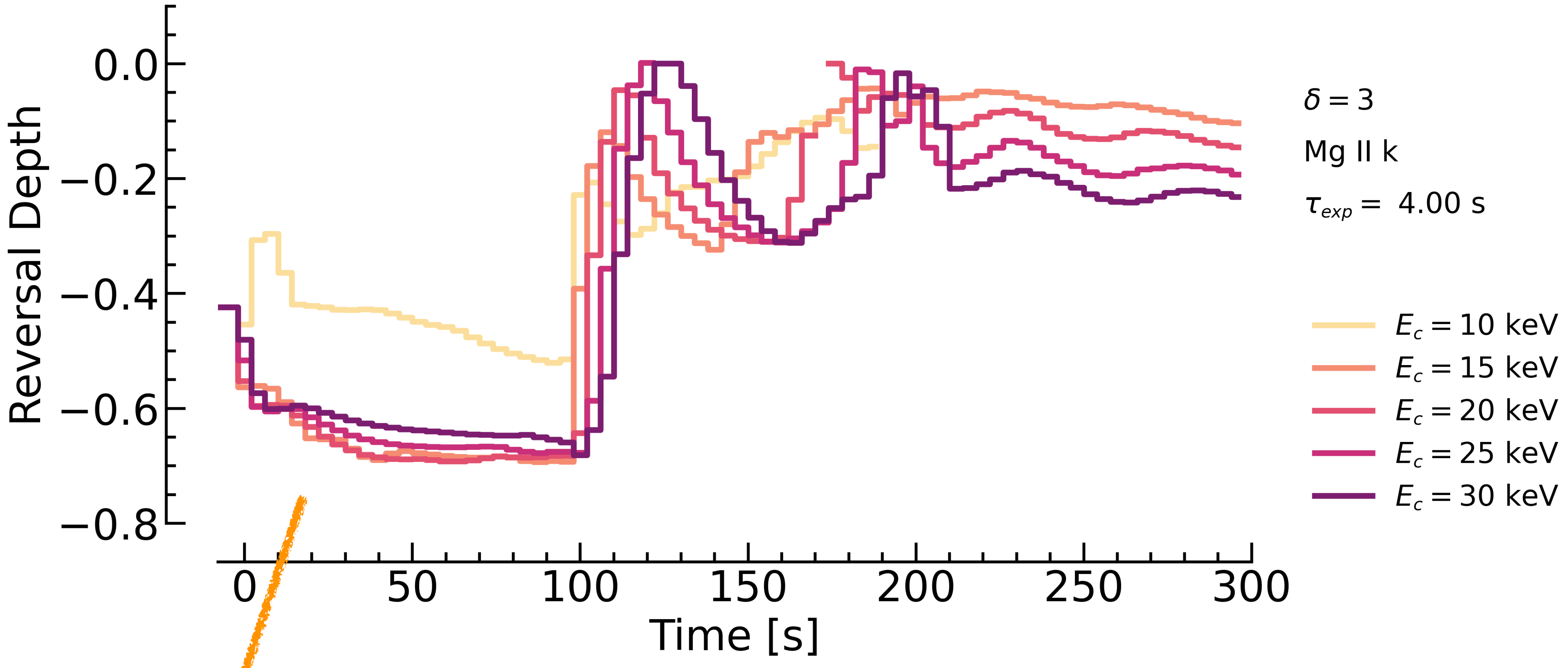
Kerr et al 2023 (in prep)

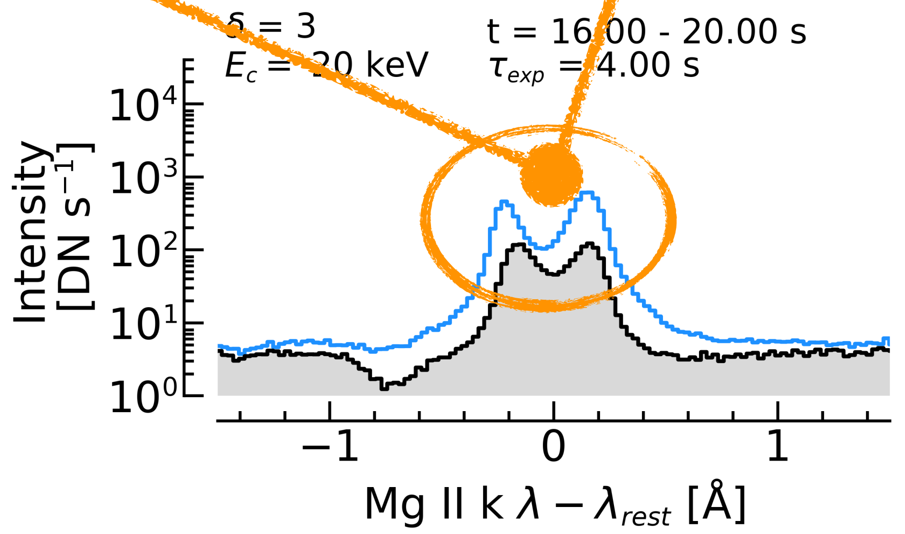
Time based on ribbon front lifetime

Ad-hoc to experiment with different regimes

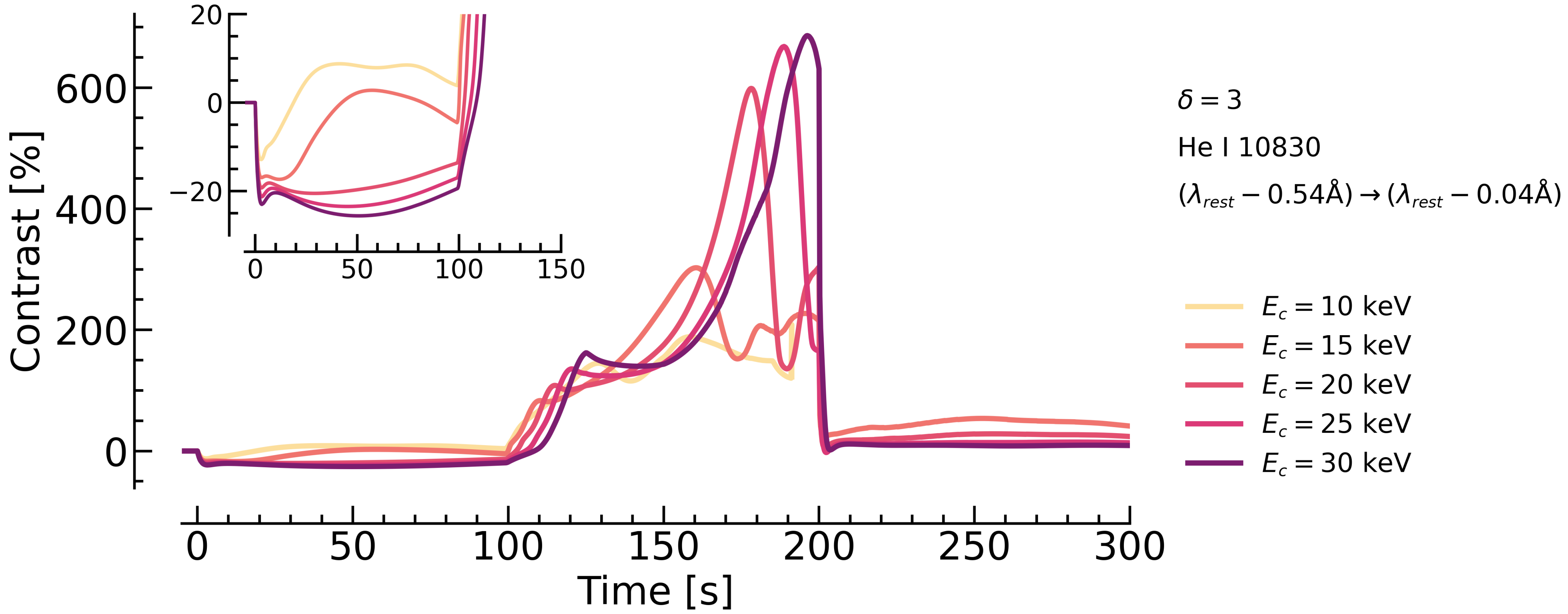


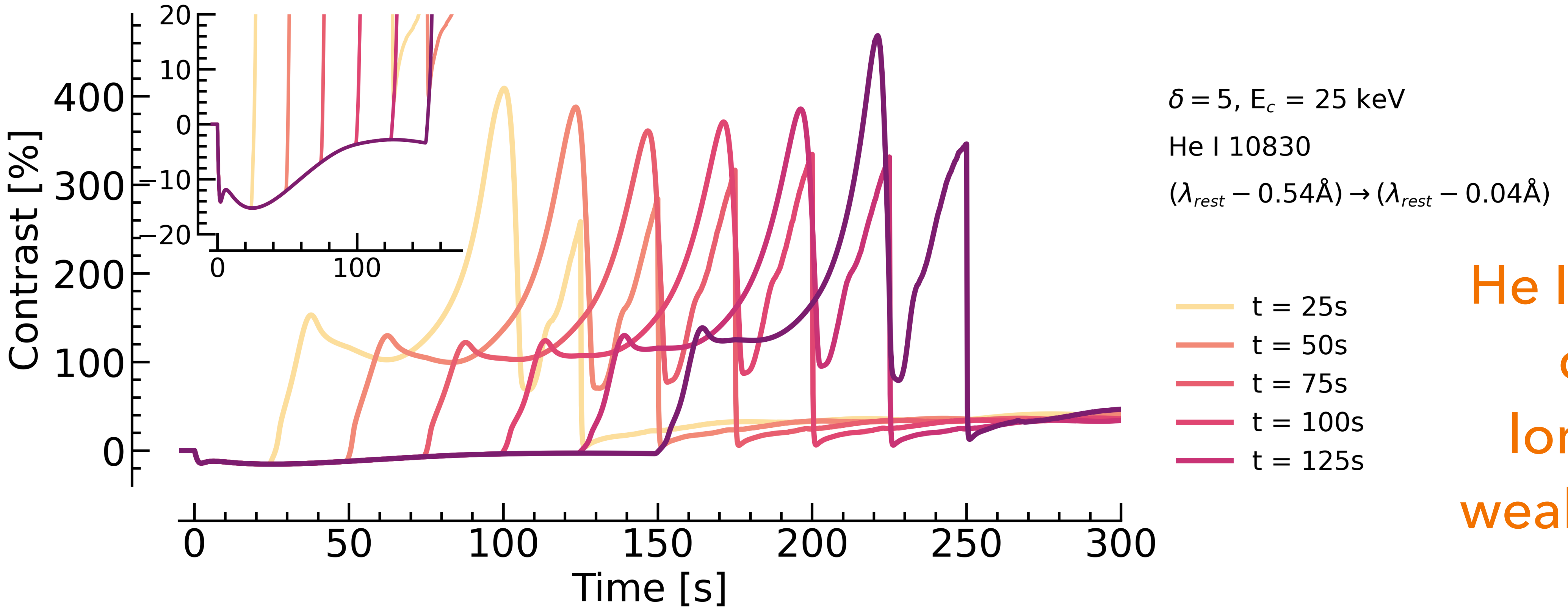






Reversal has deepened and is slightly blue shifted



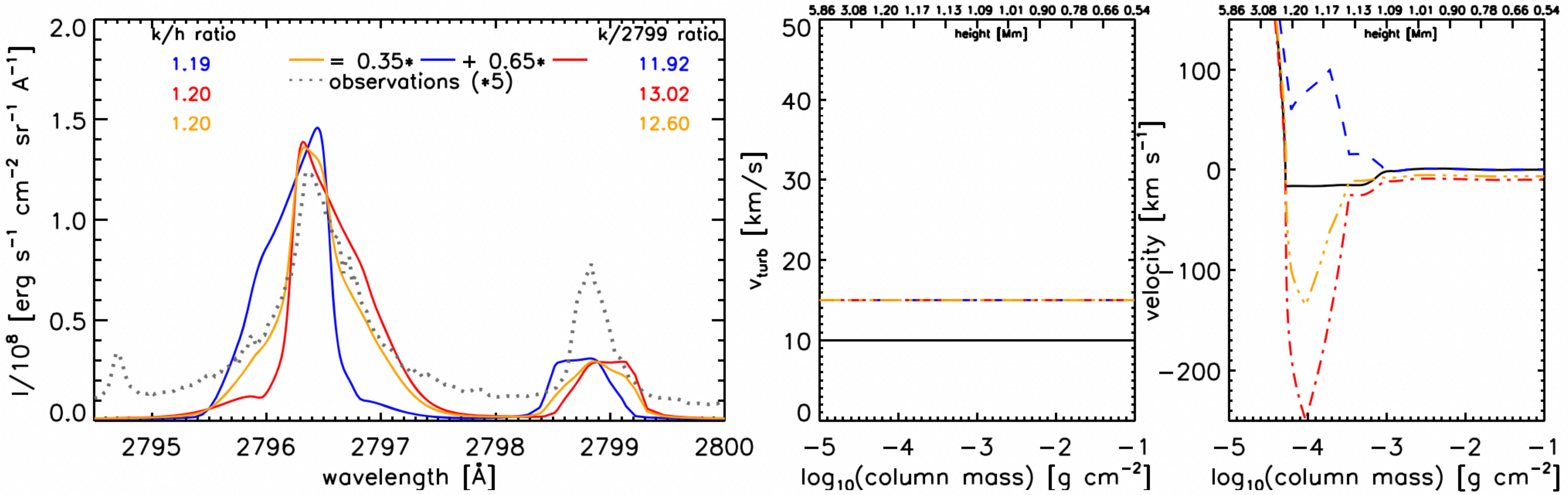


He I 10830Å remains dimmer for as long as we inject a weak flux of electrons

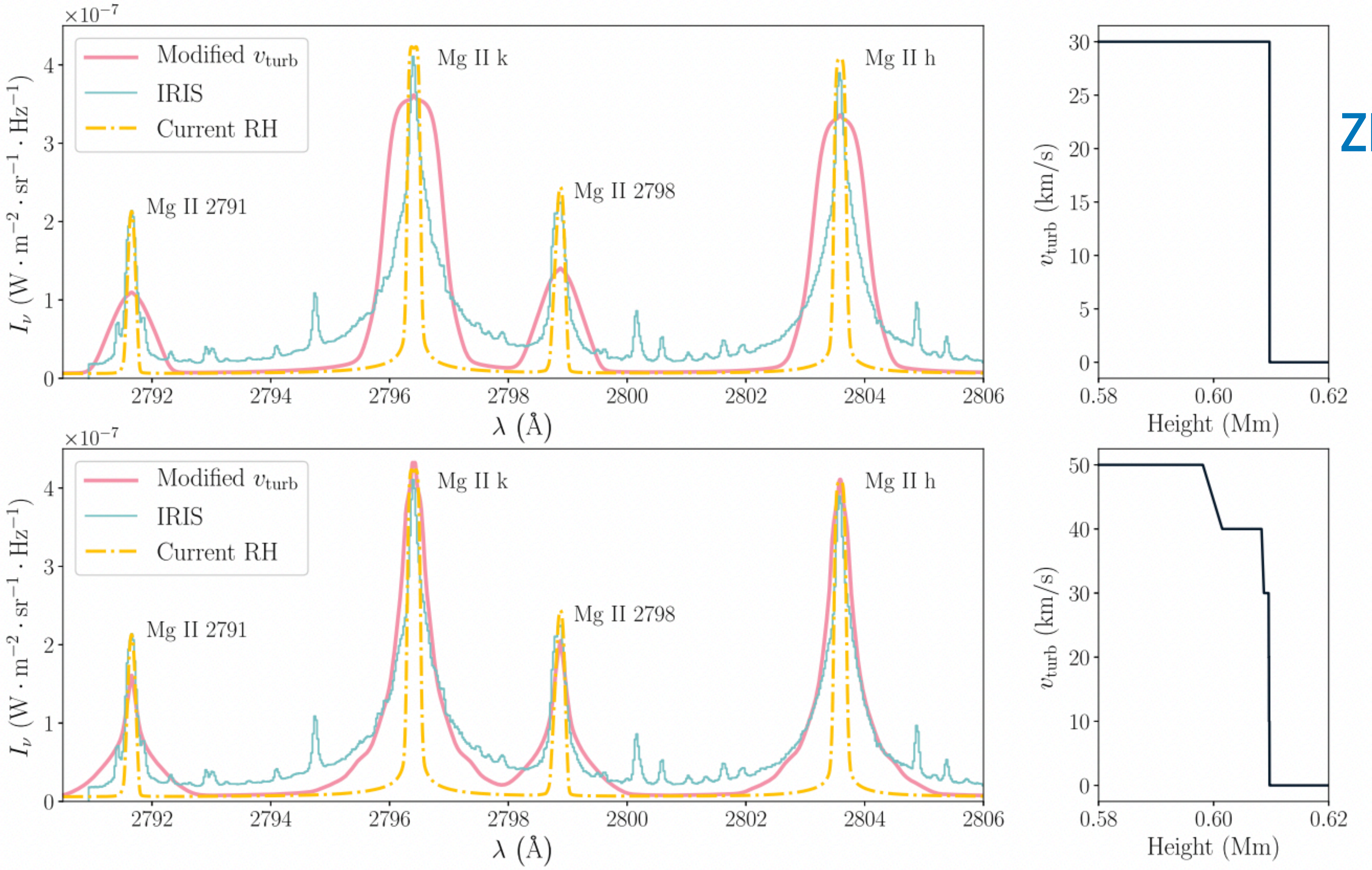
Some persistent problems

LINE WIDTHS! – CHROMOSPHERIC LINES (MG II)

Rubio da Costa & Kleint 2017



- Chromospheric and transition region lines are much broader than observed.
- Suggestions include:
  - Extreme bi-directional flows (any evidence?)
  - Large amounts of micro-turbulent broadening (up to 30-50 km/s). However, observations suggest this is unlikely.

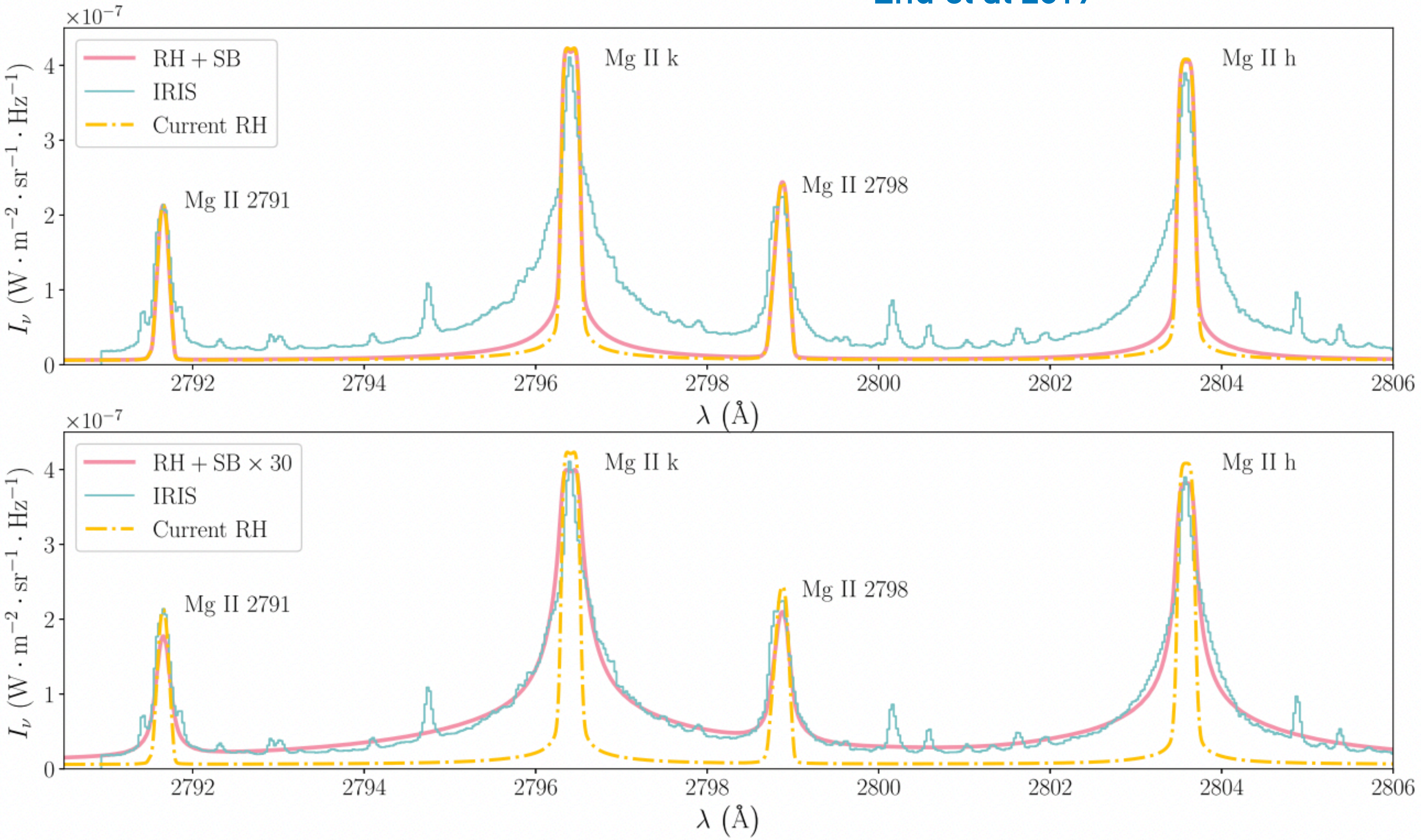


Zhu et al 2019

LINE WIDTHS! – CHROMOSPHERIC LINES (MG II)

- Improved the treatment of Stark broadening for Mg II, using the STARK-B database broadens the lines but still not enough – another factor of 30x was needed.
- One possibility is that we are not heating the lower atmosphere sufficiently.

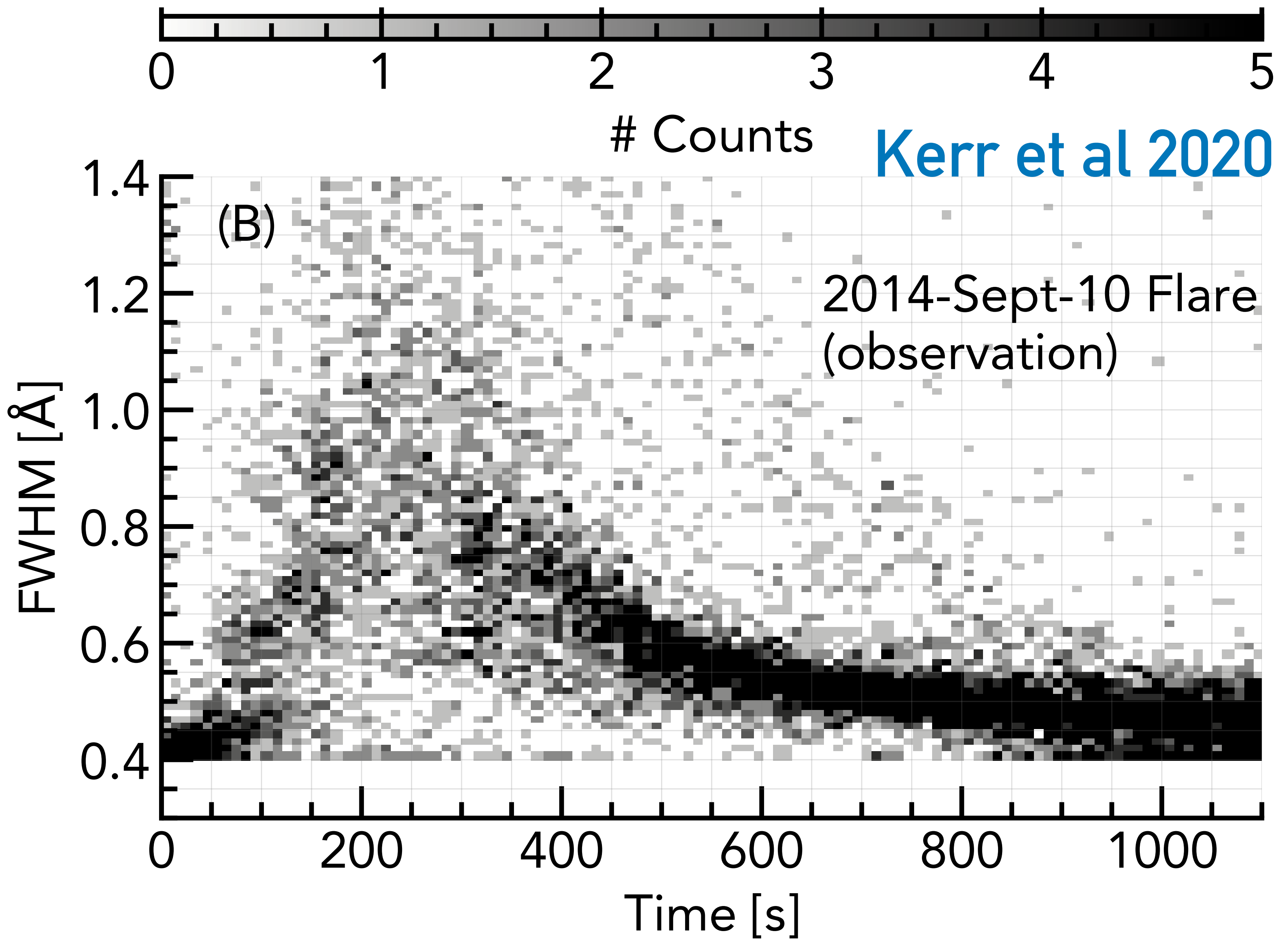
Zhu et al 2019



** See also Kowalski et al 2022 for improved treatment of H Stark broadening in RADYN, achieving much better model-data consistency

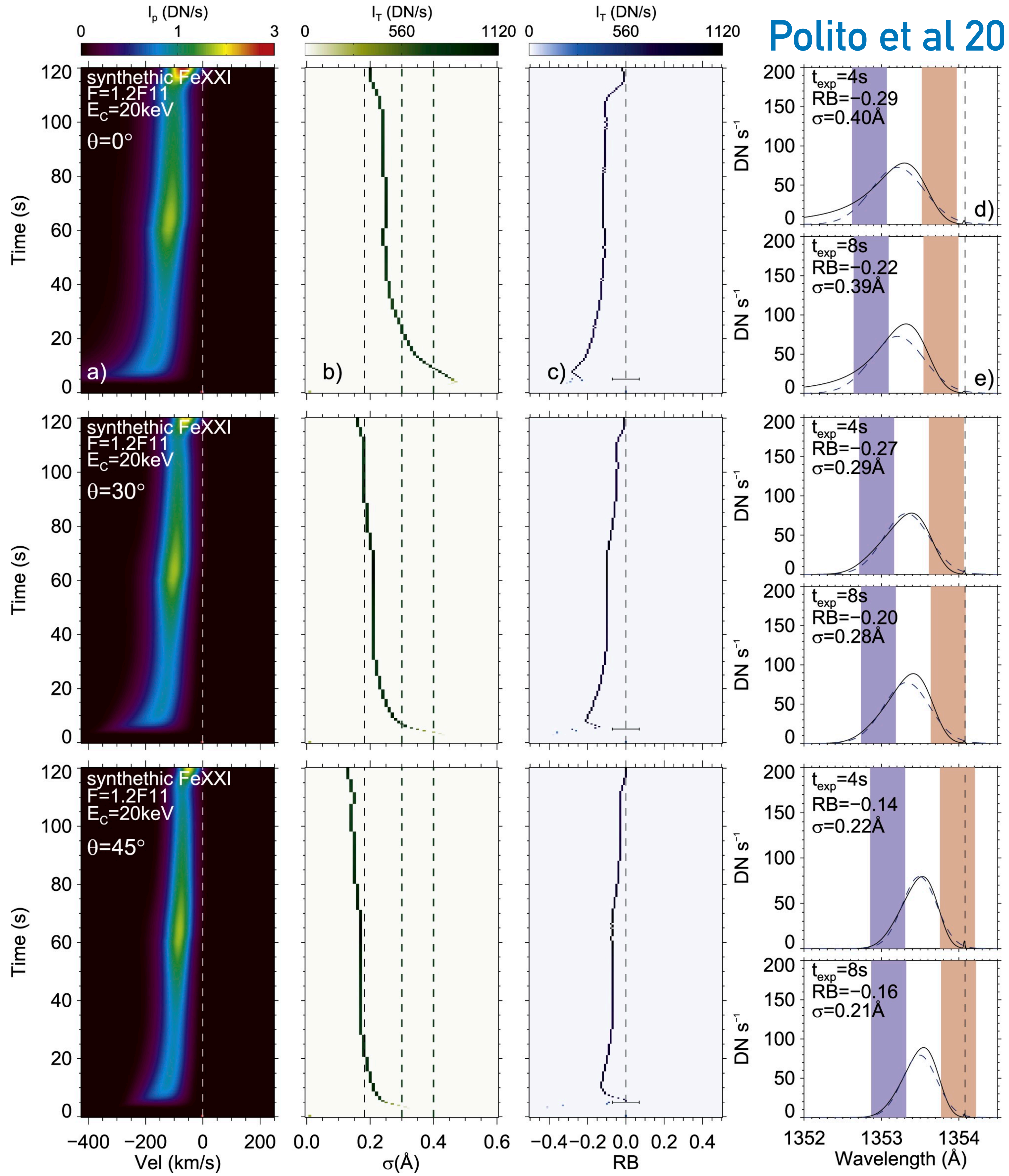
LINE WIDTHS! – FE XXI

- Line widths of coronal species, e.g Fe XXI aren't much better.
- Modelling suggests that superposition of loops is not the answer to the Fe XXI line broadening observed by IRIS.



Kerr et al 2020

Polito et al 2019



Re: MHD turbulence, see also Ashfield & Longcope, 2023 (and their poster!) and Wenzhi Ruan's talk this afternoon.

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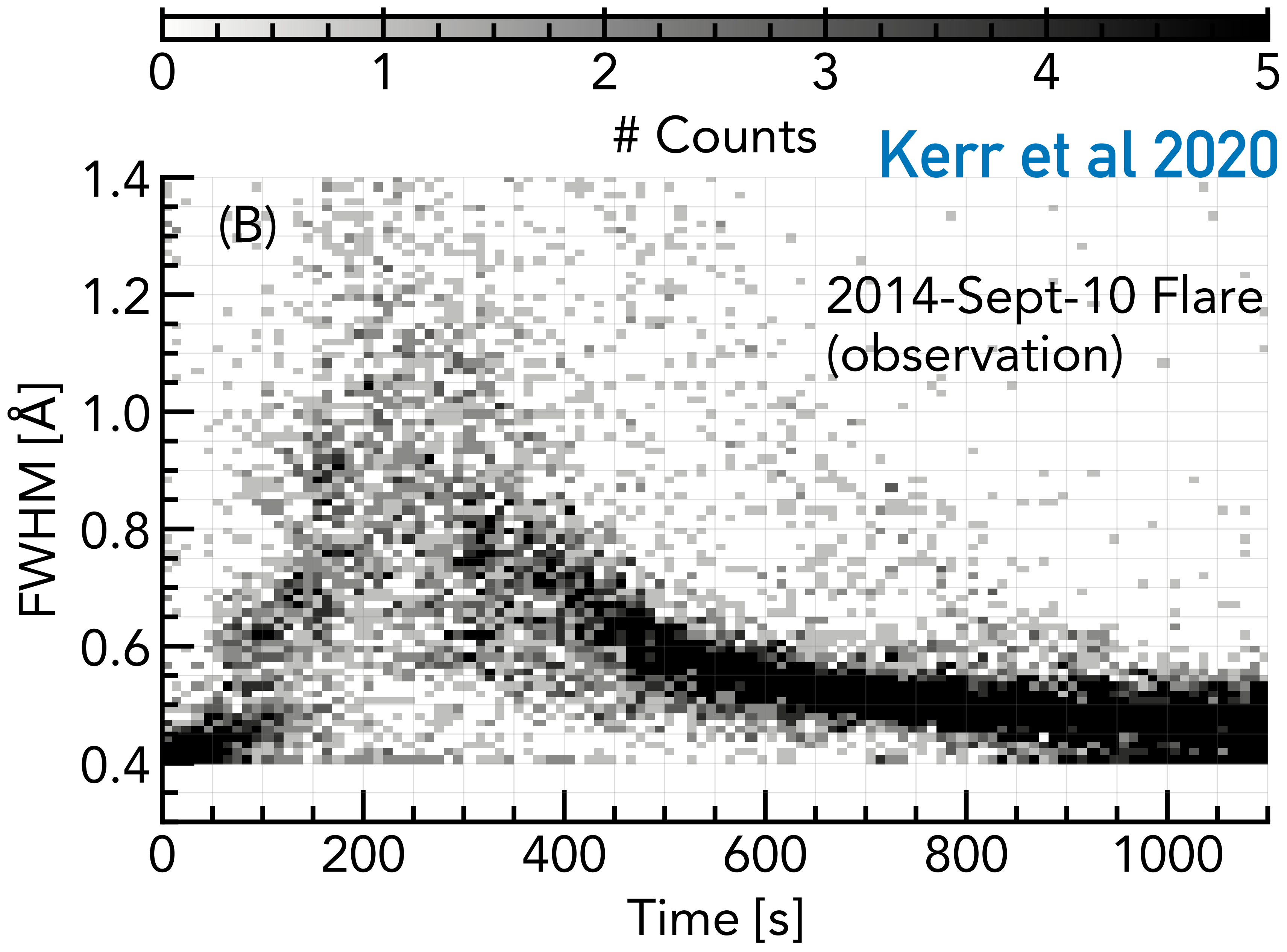

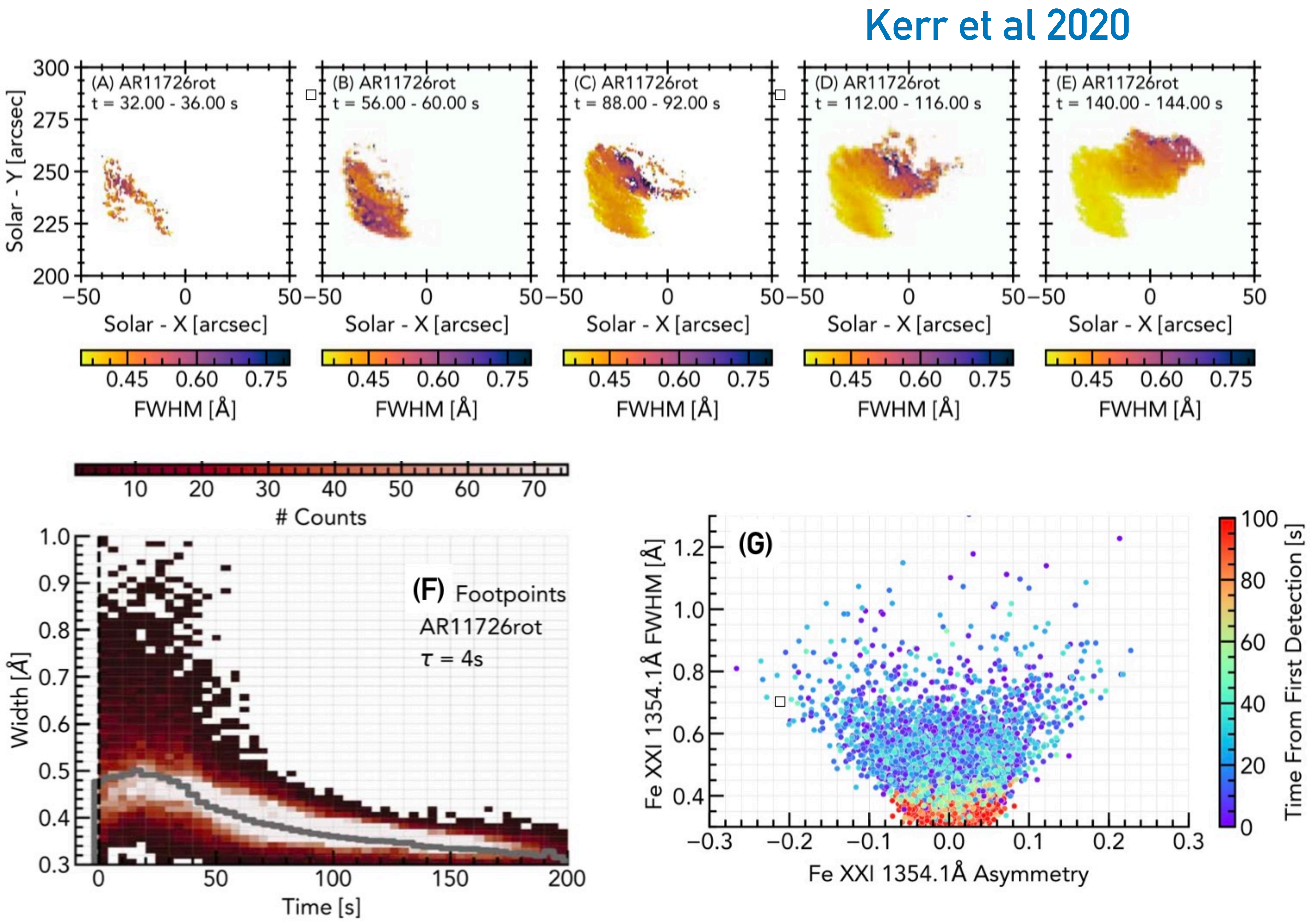

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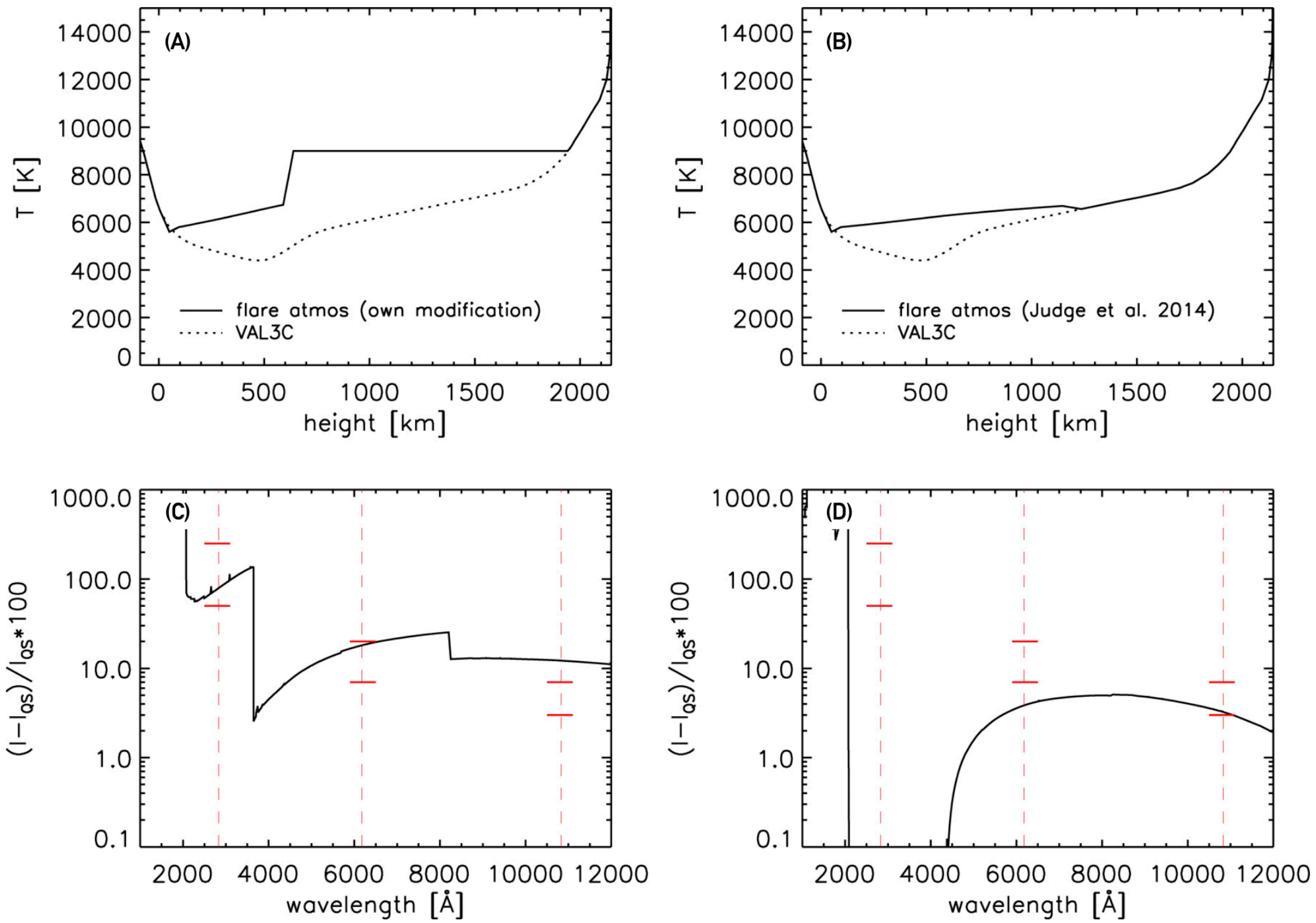
DEEP HEATING: WHITE LIGHT FLARES

- Evidence from continuum observations of the optical and NUV that there could be emission coming from deep layers.
- Emission mechanisms behind white light flares are ambiguous, with some observations consistent with upper photospheric heating and others with mid-upper chromosphere (models predict primarily upper chromospheric).
- Fe II - to - NUV continuum also suggests heating at high column mass.
- How do we heat deeper than models currently predict? – missing energy transport ingredients.

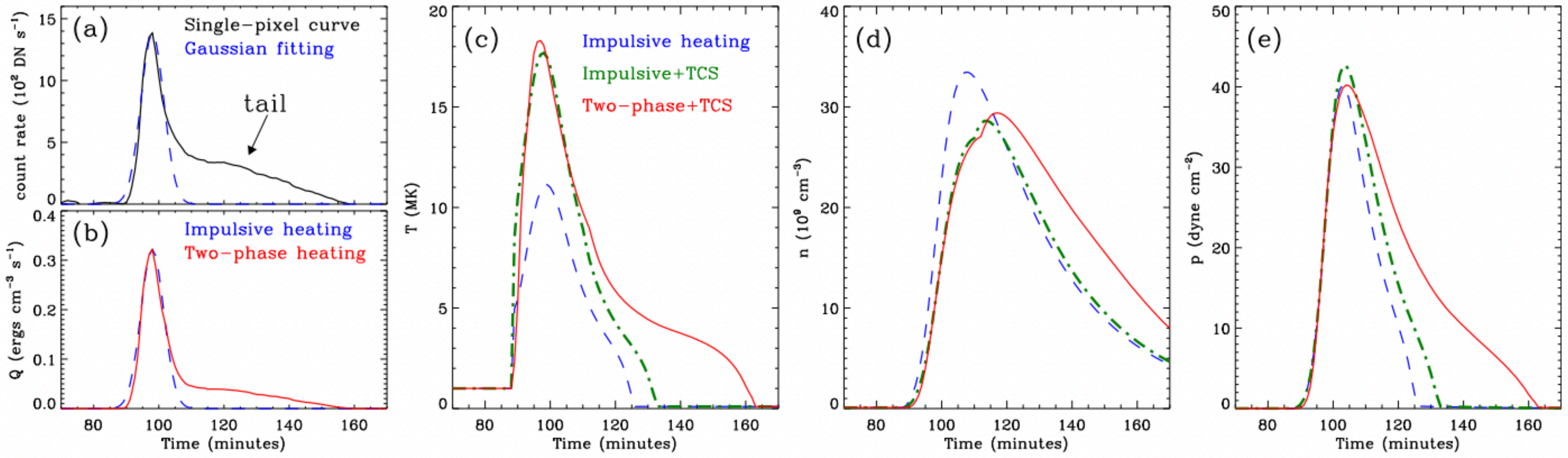
Kleint et al 2016

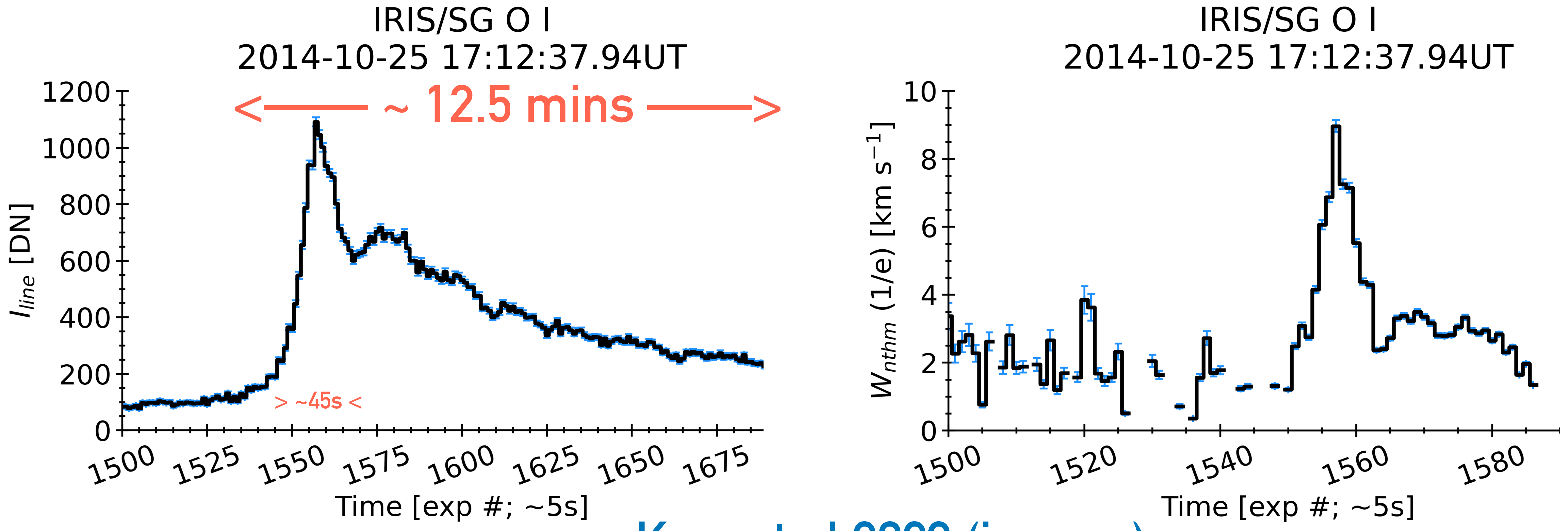


DURATION OF THE FLARE GRADUAL PHASE

- Both the global and local gradual phase predicted by loop models are far too short.
- Observations of the decay in individual flare footpoints in the chromosphere suggest that after the initial rapid decay (~ one minute?) there is an extended period of up to several minutes (sometimes longer!).
- Models show that as soon as energy injection ceases the atmosphere cools catastrophically and that line intensities plummet.
- Two schools of thought: (1) continued energy injection through the gradual phase (with magnitudes rivaling the impulsive phase) or (2) thermal conduction is suppressed.

Zhu et al 2018

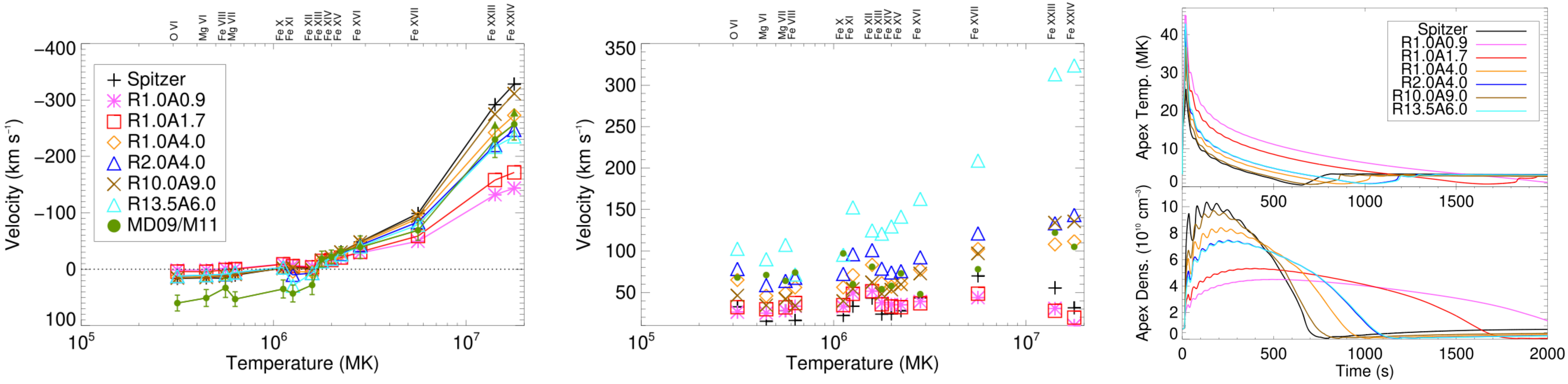




Kerr et al 2023 (in prep)

DURATION OF THE FLARE GRADUAL PHASE

- Allred et al 2022 included suppression of thermal conduction when modelling the flare from Milligan and Dennis (2009), using the theory of Emslie & Bian 2018.
- Cooling times were extended dramatically, magnitude of flows were reduced, AND the non-thermal widths were more consistent with observations (calculated using the turbulent mean free path that causes the conduction suppression).



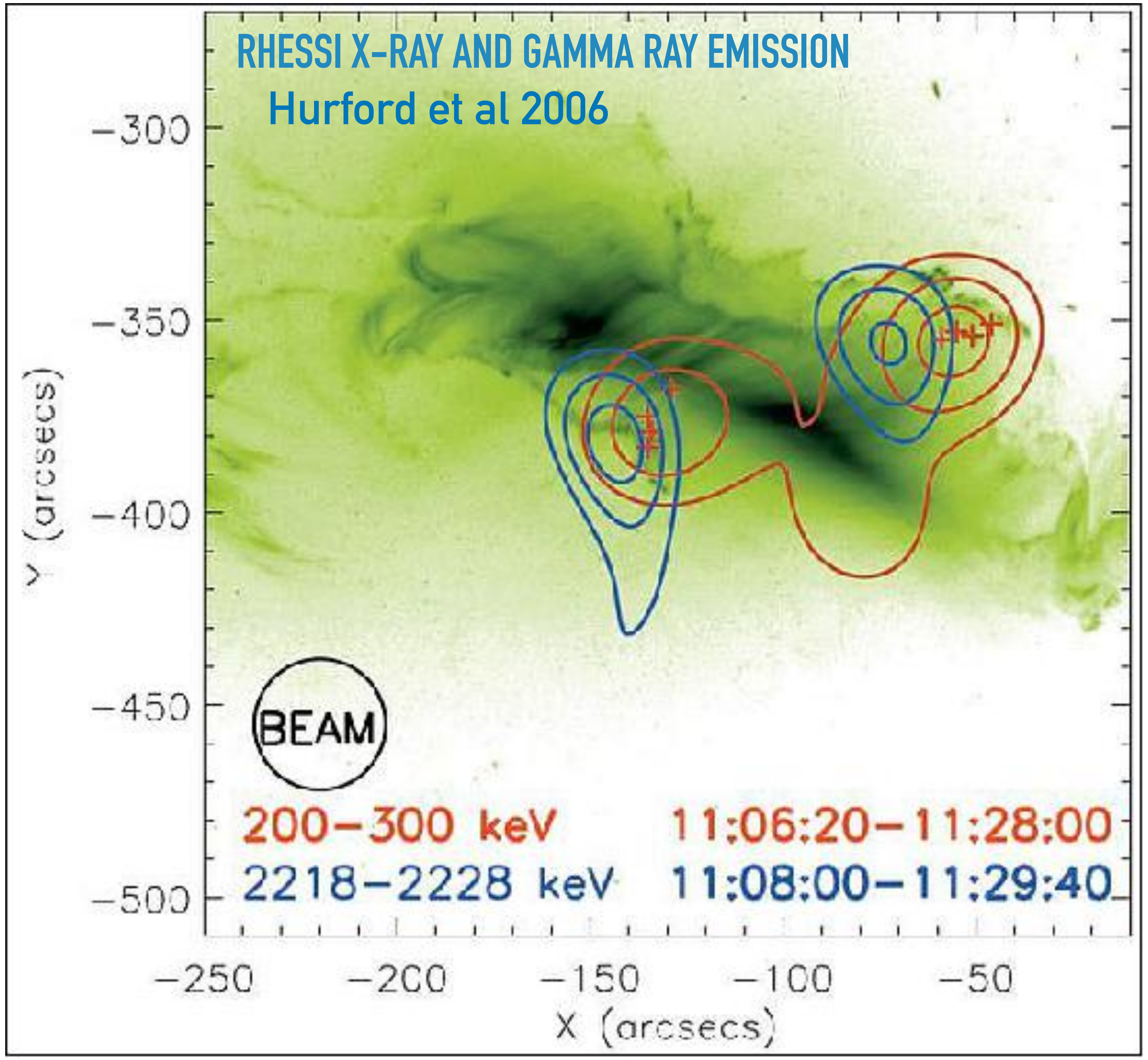
Allred et al 2022

Re: MHD turbulence, see also Ashfield & Longcope, 2023 (and their poster!) and Wenzhi Ruan's talk this afternoon.

Future Directions

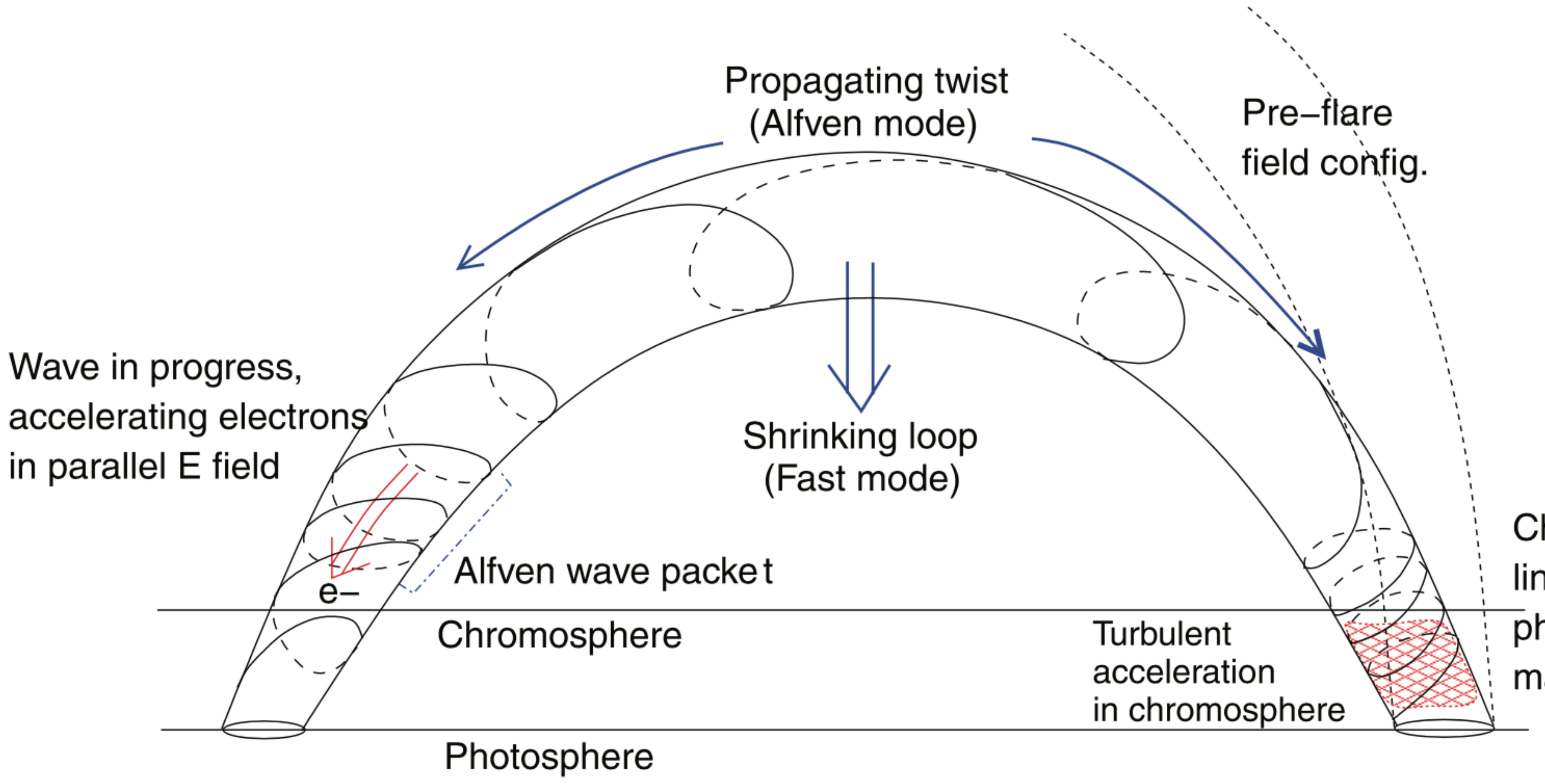
PROTON BEAMS IN SOLAR FLARES

- Very likely that protons are accelerated in flares too.
- They may even carry a substantial fraction (potentially equal to that of electrons!) of the energy released in a flare 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!
- RADYN+FP now has the ability to model these and we have started those investigations… see Kerr et al 2023 ApJ for the first of those.

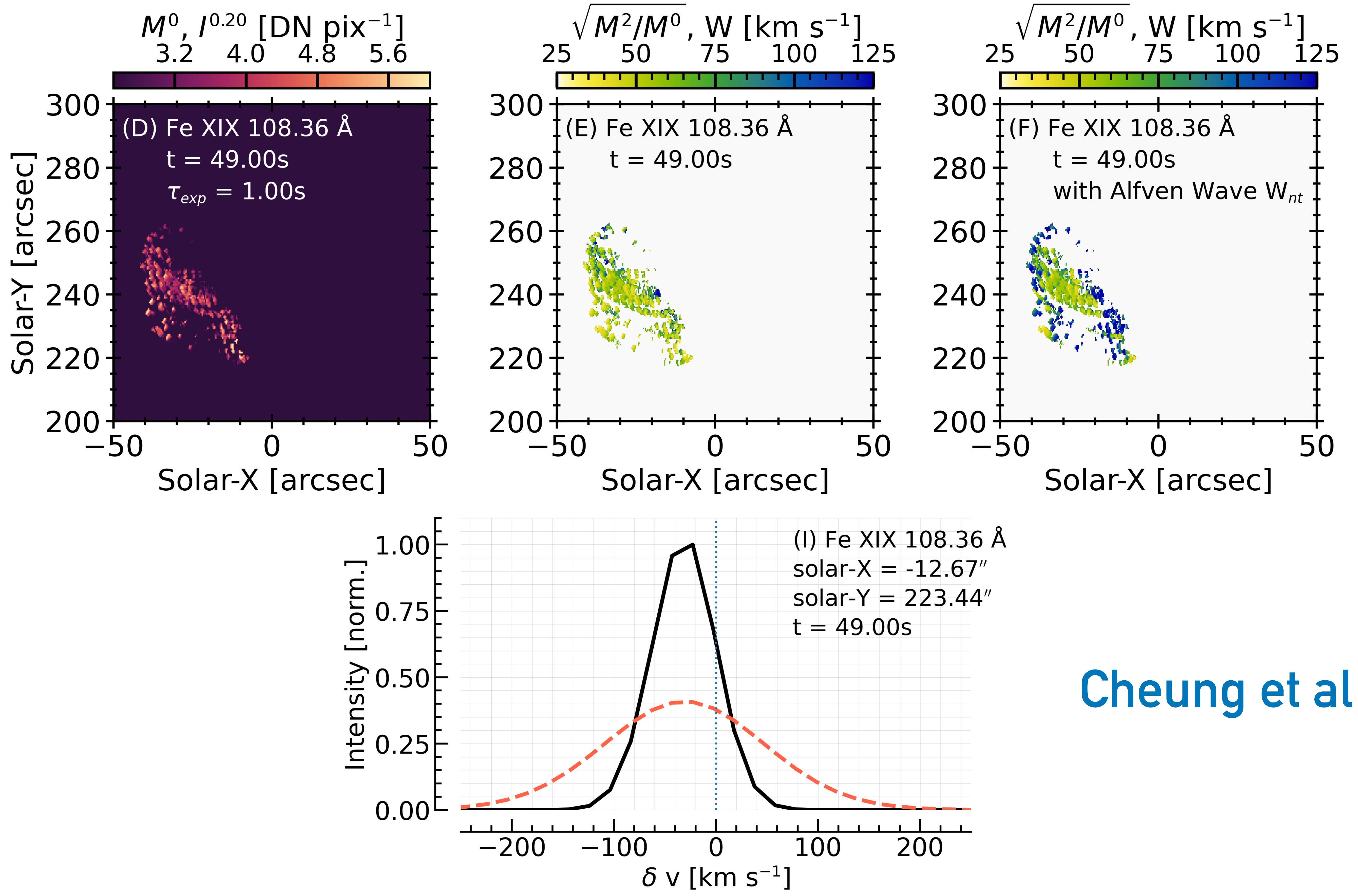


ALFVEN WAVES IN SOLAR FLARES

- Flares are fundamentally a large scale magnetic disturbance, so it is very reasonable to expect that MHD waves are produced, and logical to study their role in energy transport.
- There has been interest in energy transport mechanisms 'beyond the standard model' for some time, but this was recently renewed by Fletcher & Hudson (2008).
- Dissipation of Alfvén waves has been suggested as either an alternative, or complementary mechanism to deliver energy from the coronal release site to the chromosphere: Reep et al 2016, 2018; Kerr et al 2016.



Fletcher & Hudson, 2008



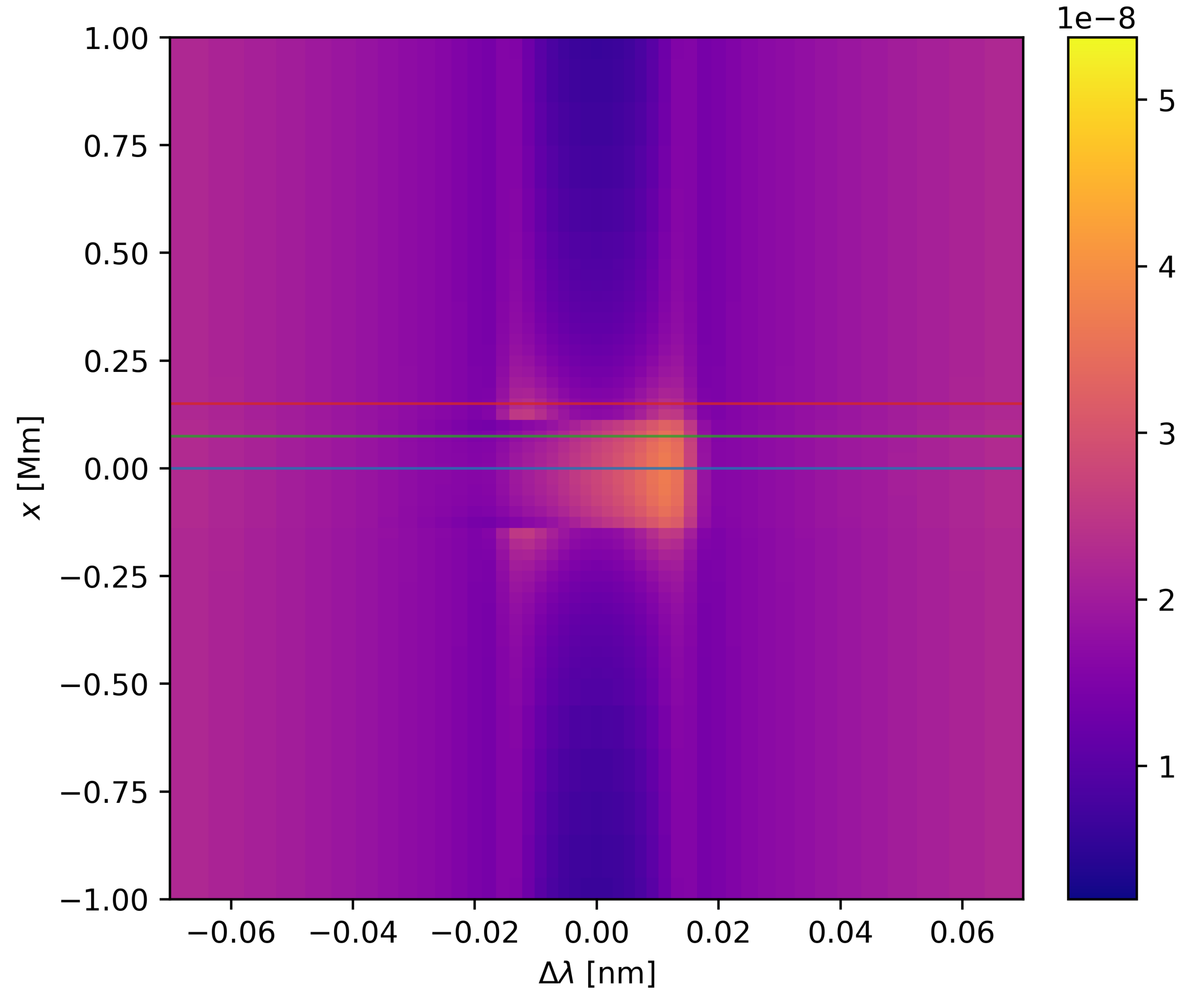
Cheung et al 2022

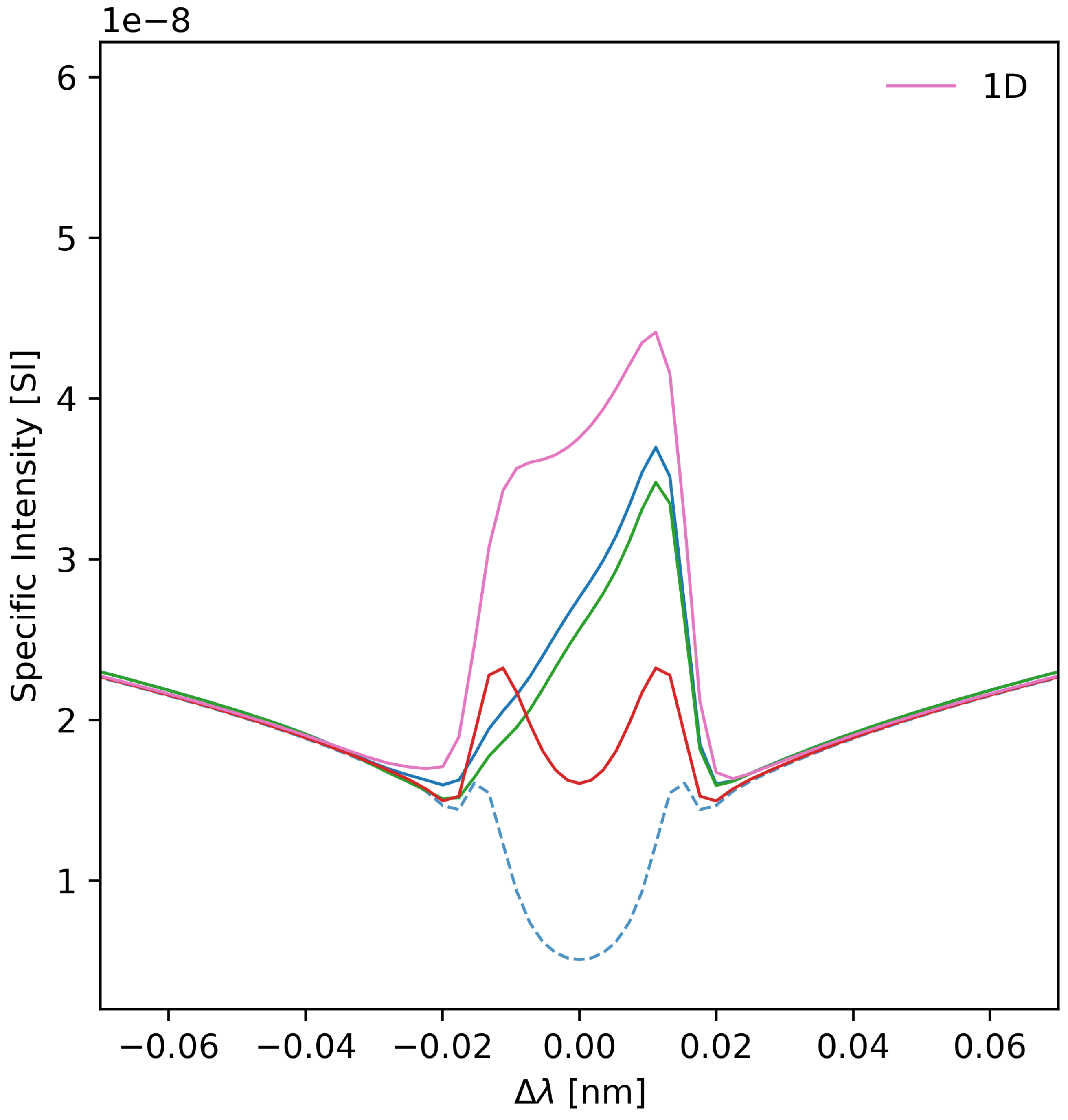
Re: MHD turbulence, see also Ashfield & Longcope, 2023 (and their poster!) and Wenzhi Ruan's talk this afternoon.

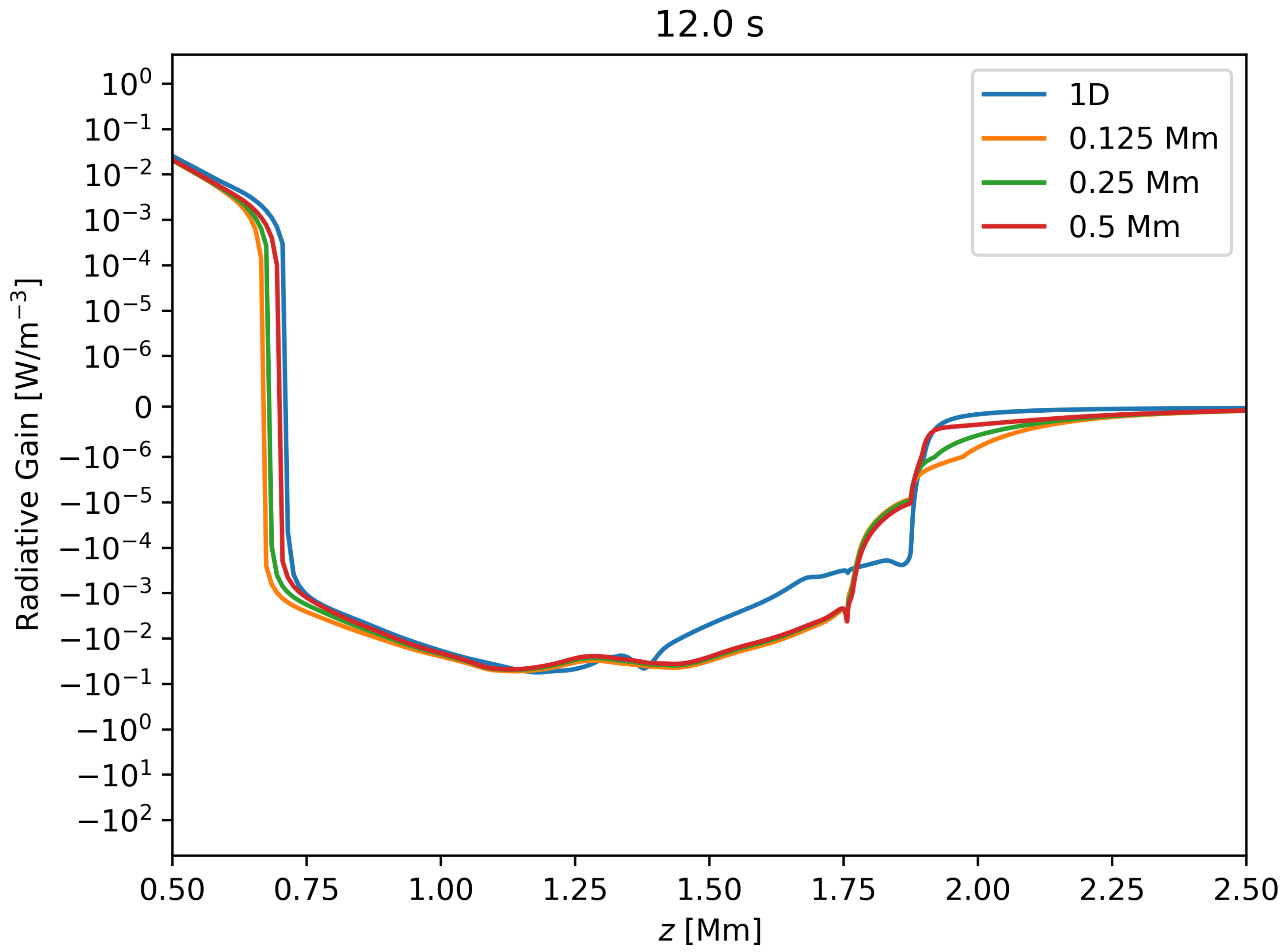
MULTI-D RT

- Implant a kernel of RADYN flare atmosphere of width *k* in a 2D periodic volume and solve for time-dependent NLTE populations by "replaying" the thermodynamic evolution of the RADYN model.

  Osborne & Fletcher 2022







Ca II 8542 Å
k = 250 km
t = 12 s
F9 flat deposition for 10s
δ = 5, E_c = 20 keV

TOWARDS A COMPREHENSIVE SOLAR ERUPTIVE EVENT MODEL FRAMEWORK

Upcoming game-changing observations demand new ways of thinking about flare modelling.

DKIST ~ now!

EUVST ~2027

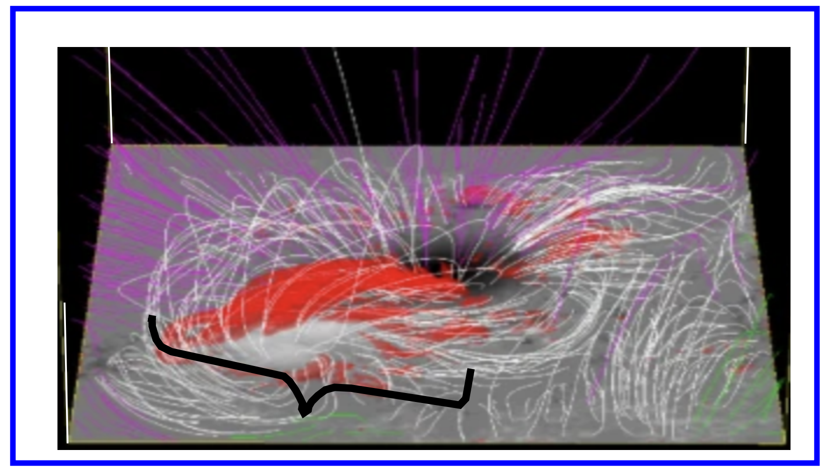
MUSE ~2027

Allred et al NASEM 2023 Decadal Survey white paper

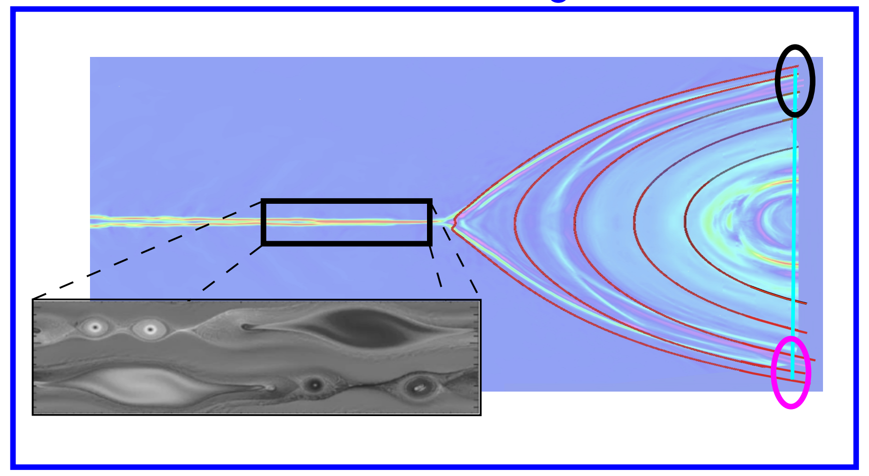
(See also Ruan et al 2020 for a hybrid model)

Magnetic Build-up Energy Release → Acceleration Direct Heating → Propagation Along Loop Secondary Heating → Forward model NLTE Radiative (Magneto-) hydrodynamics

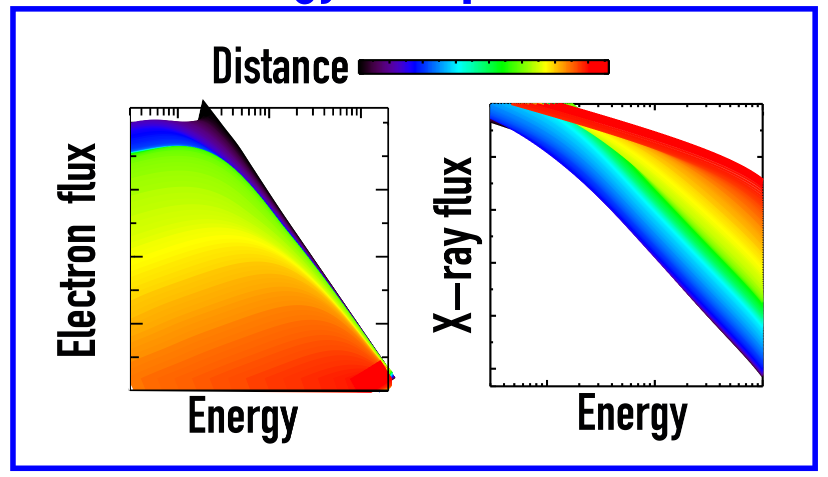
Magnetic topology & reconnection



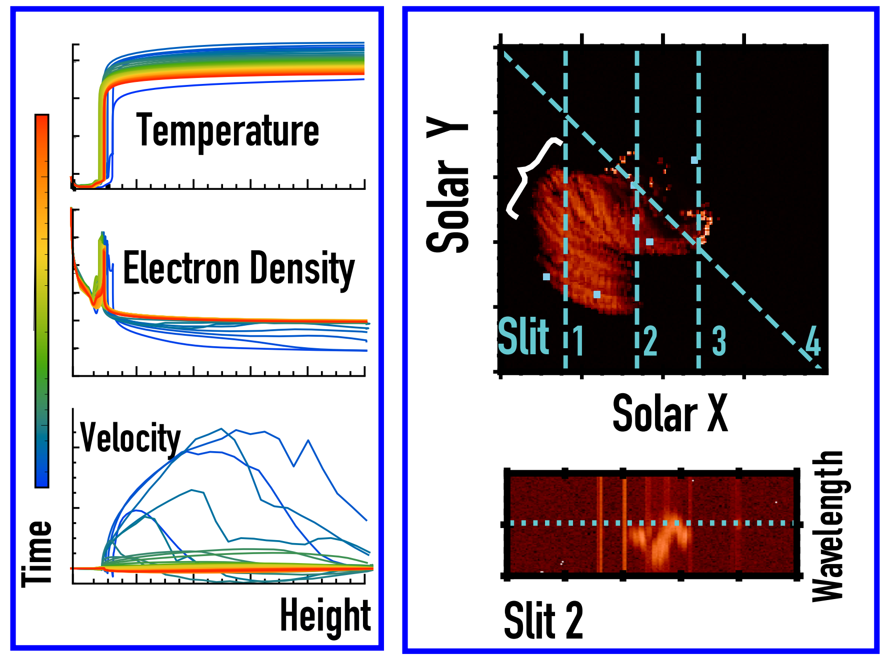
Particle acceleration, wave generation in-situ heating



Nonthermal particle transport Energy dissipation

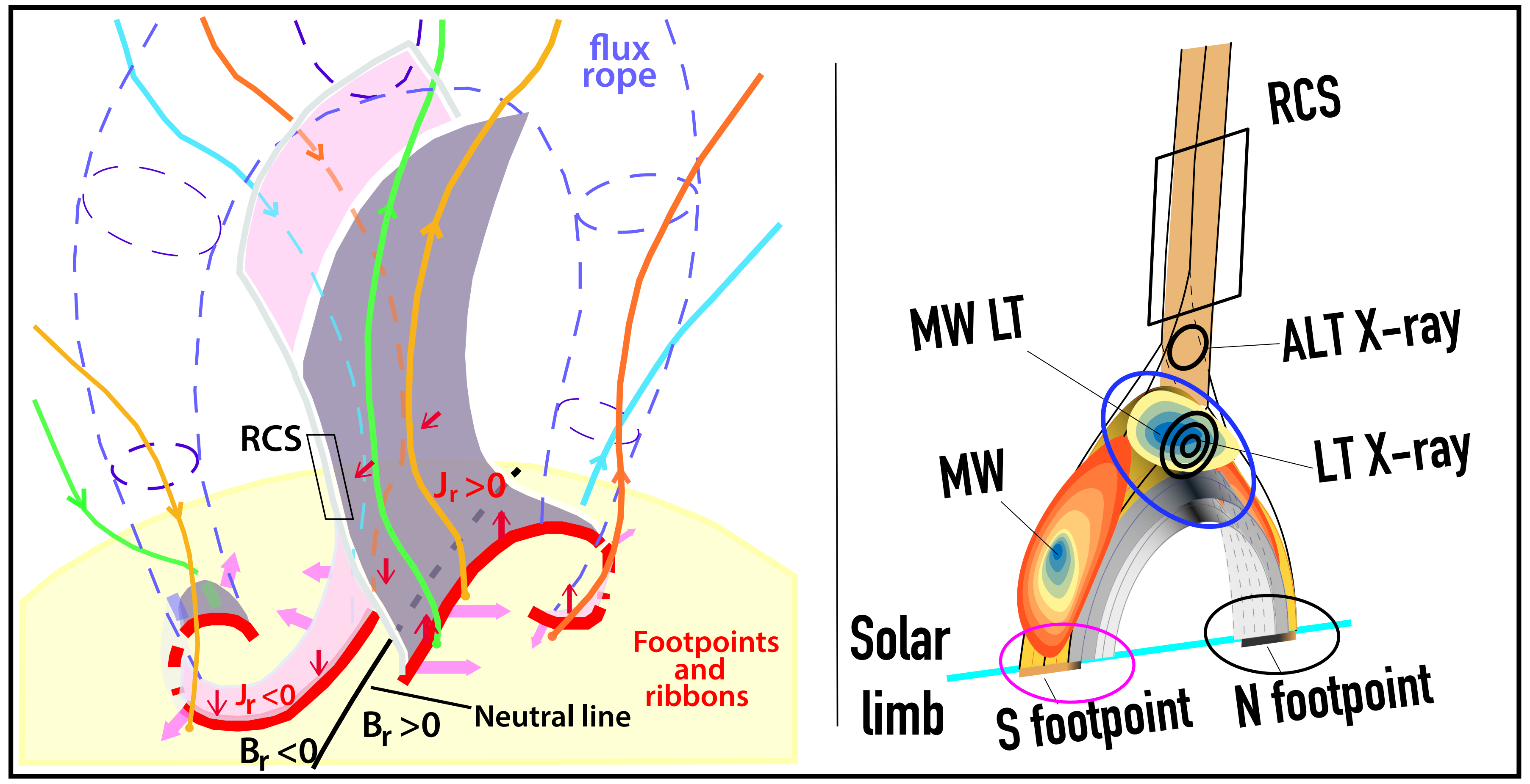


Radiative & hydrodynamic response

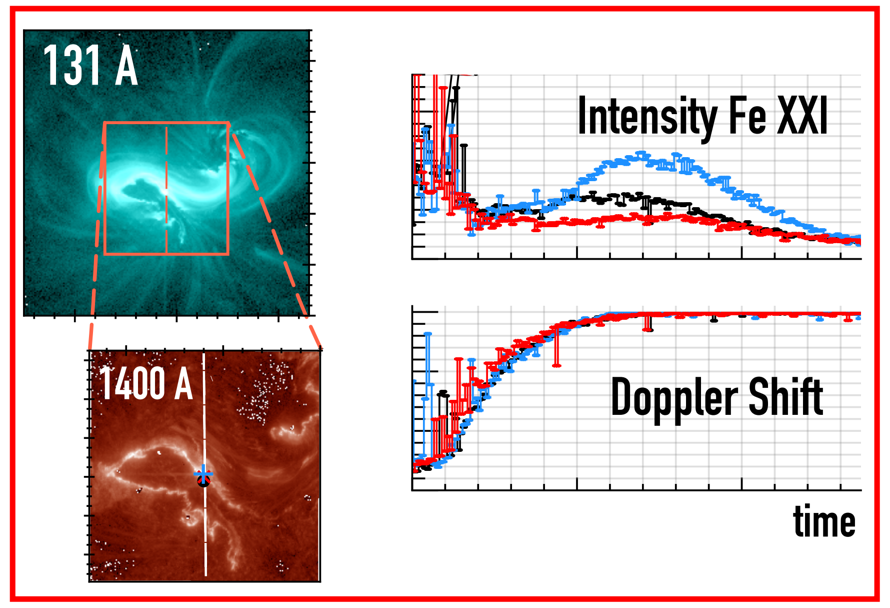


Arcade
Footpoint (FtPt)
Looptop (LT)

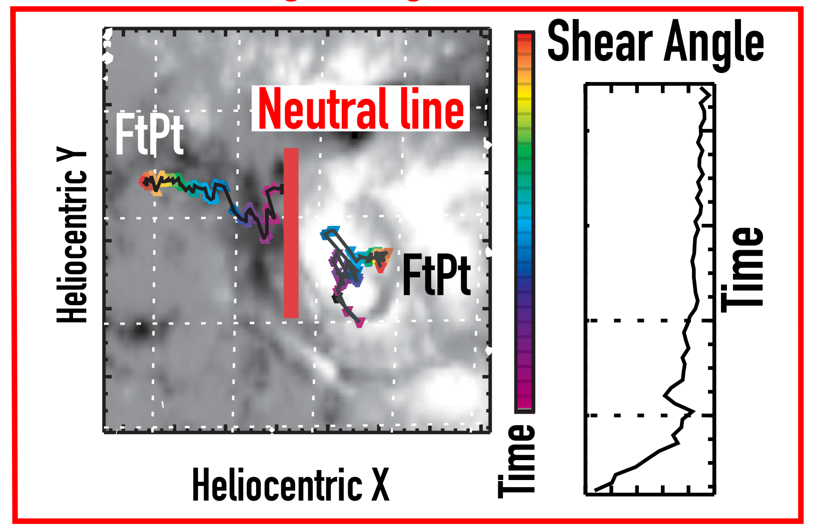
MW Microwave
ALT Above-the-looptop
RCS Reconnecting current sheet
CS Coronal source



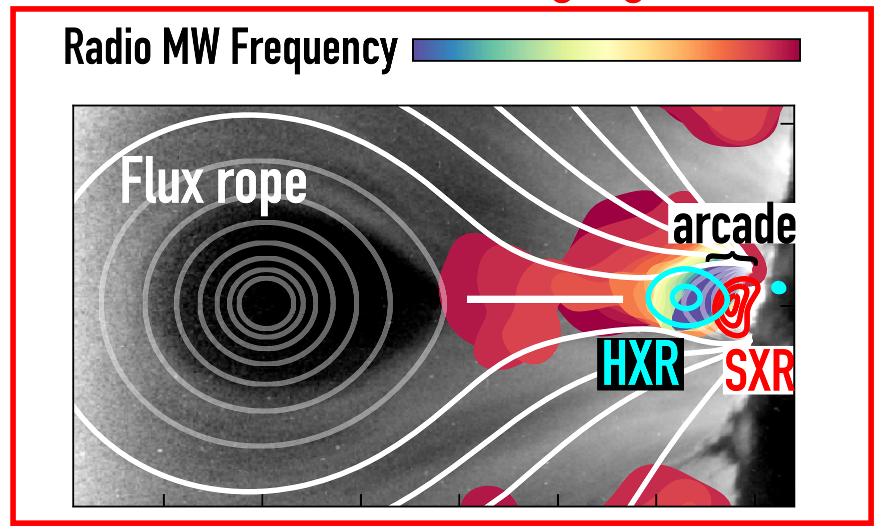
EUV/UV imaging spectroscopy



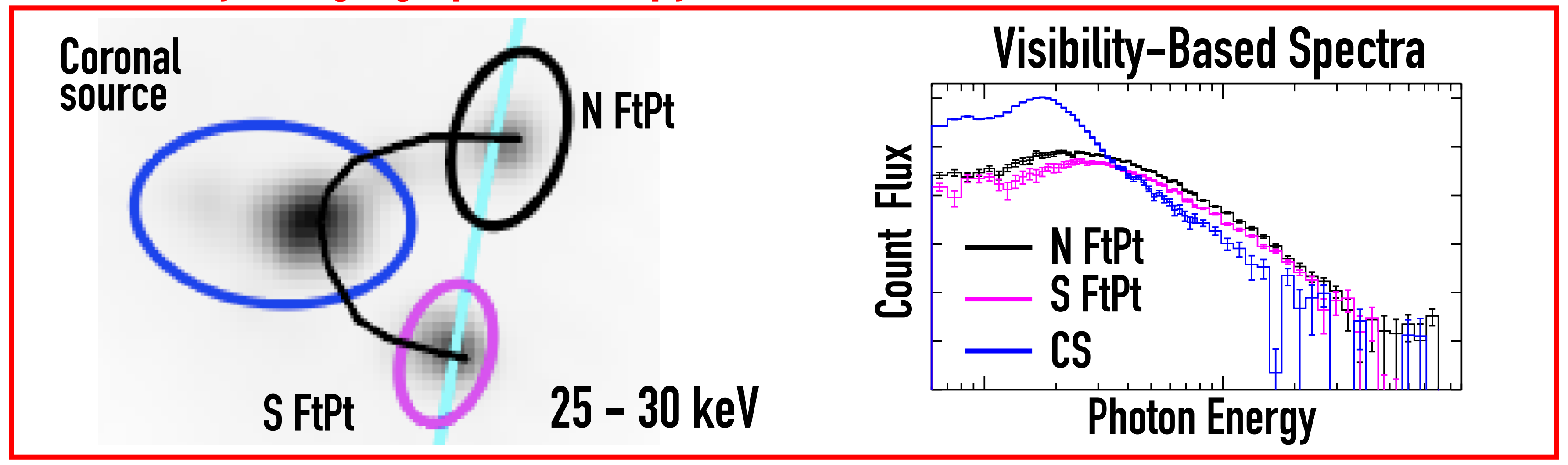
HXR and magnetograms



HXR, SXR, MW, EUV imaging



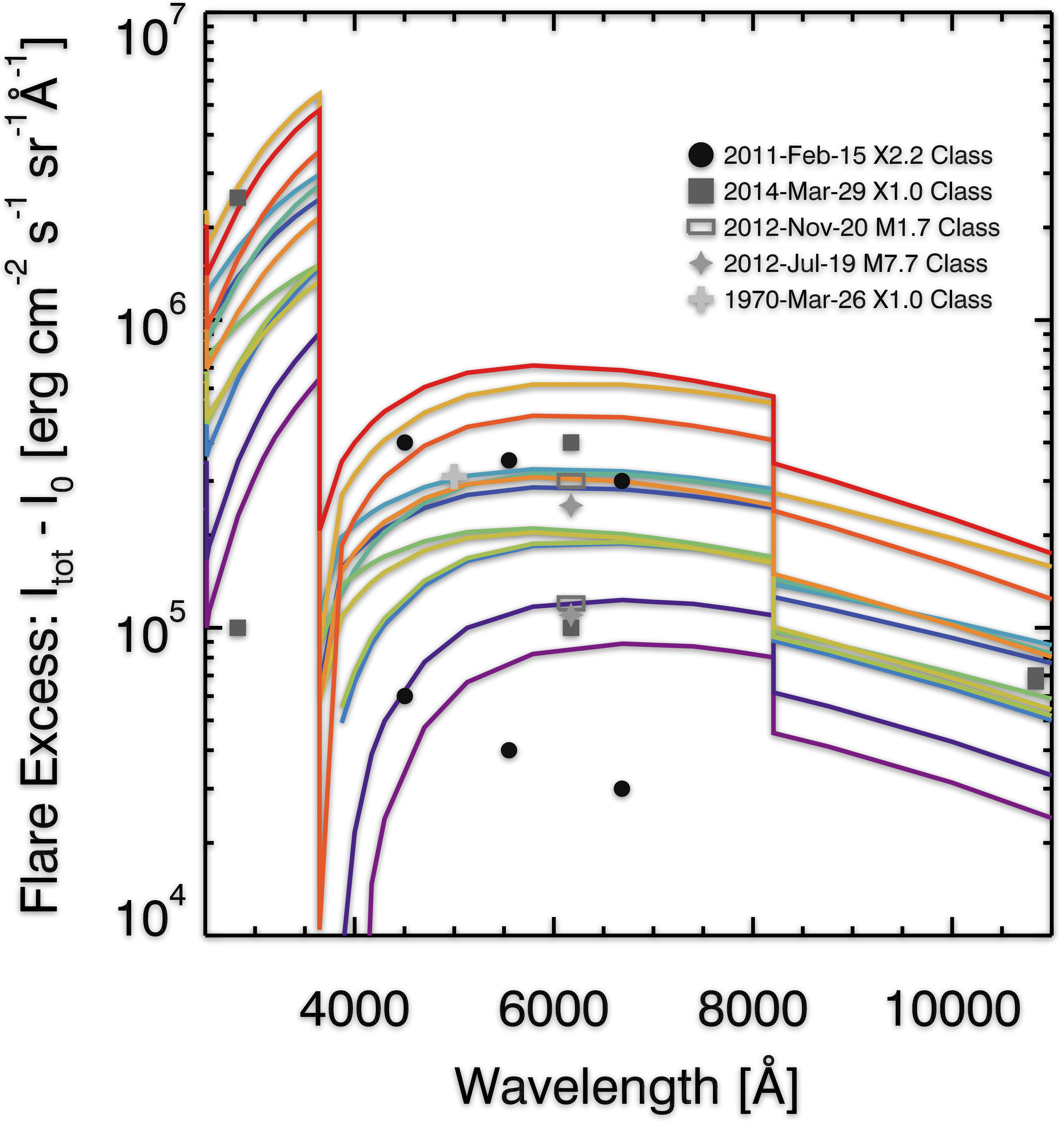
Hard X-ray imaging spectroscopy



Backup slides for Hugh

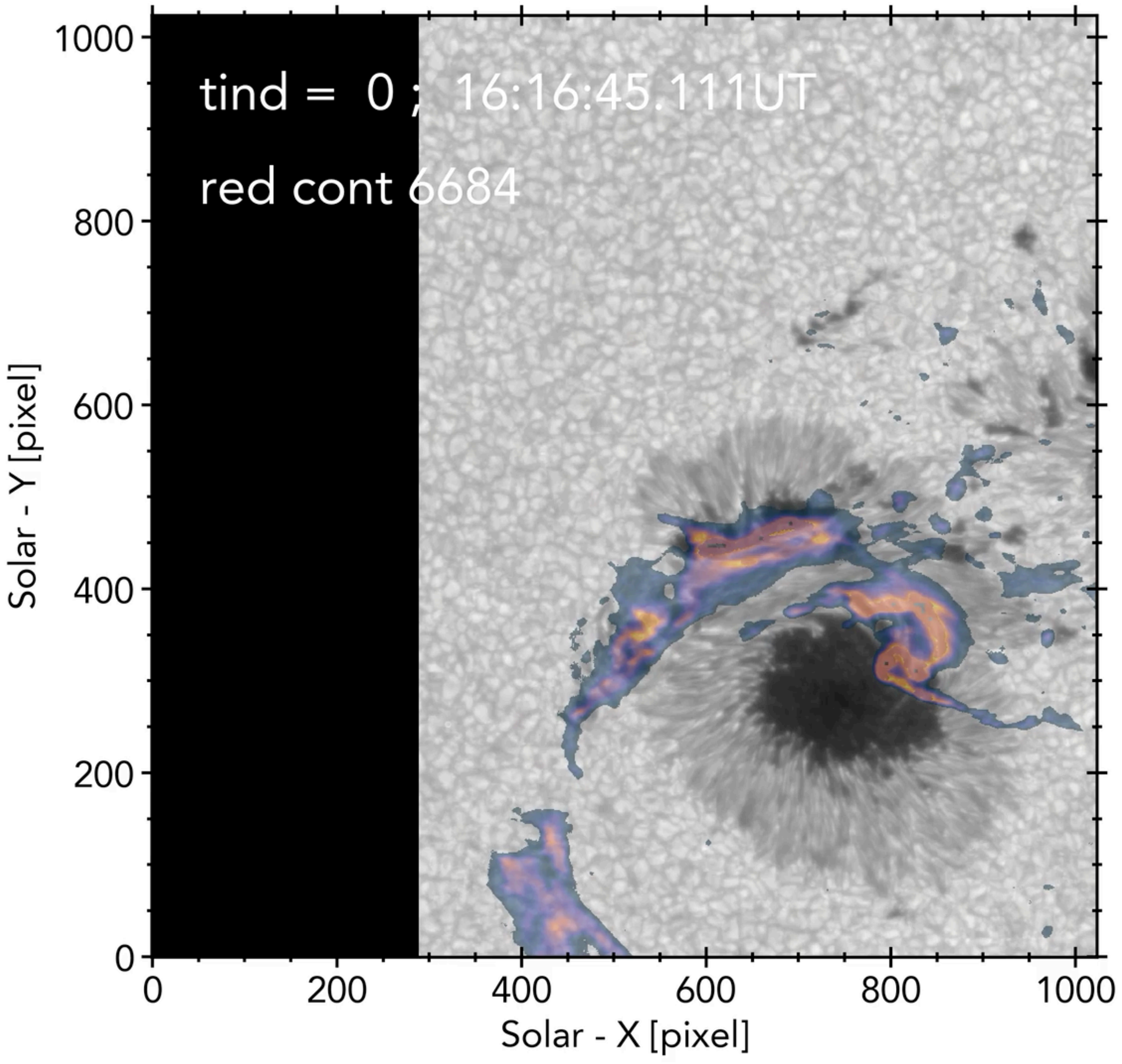
WLF FORMATION IN RHD MODELS

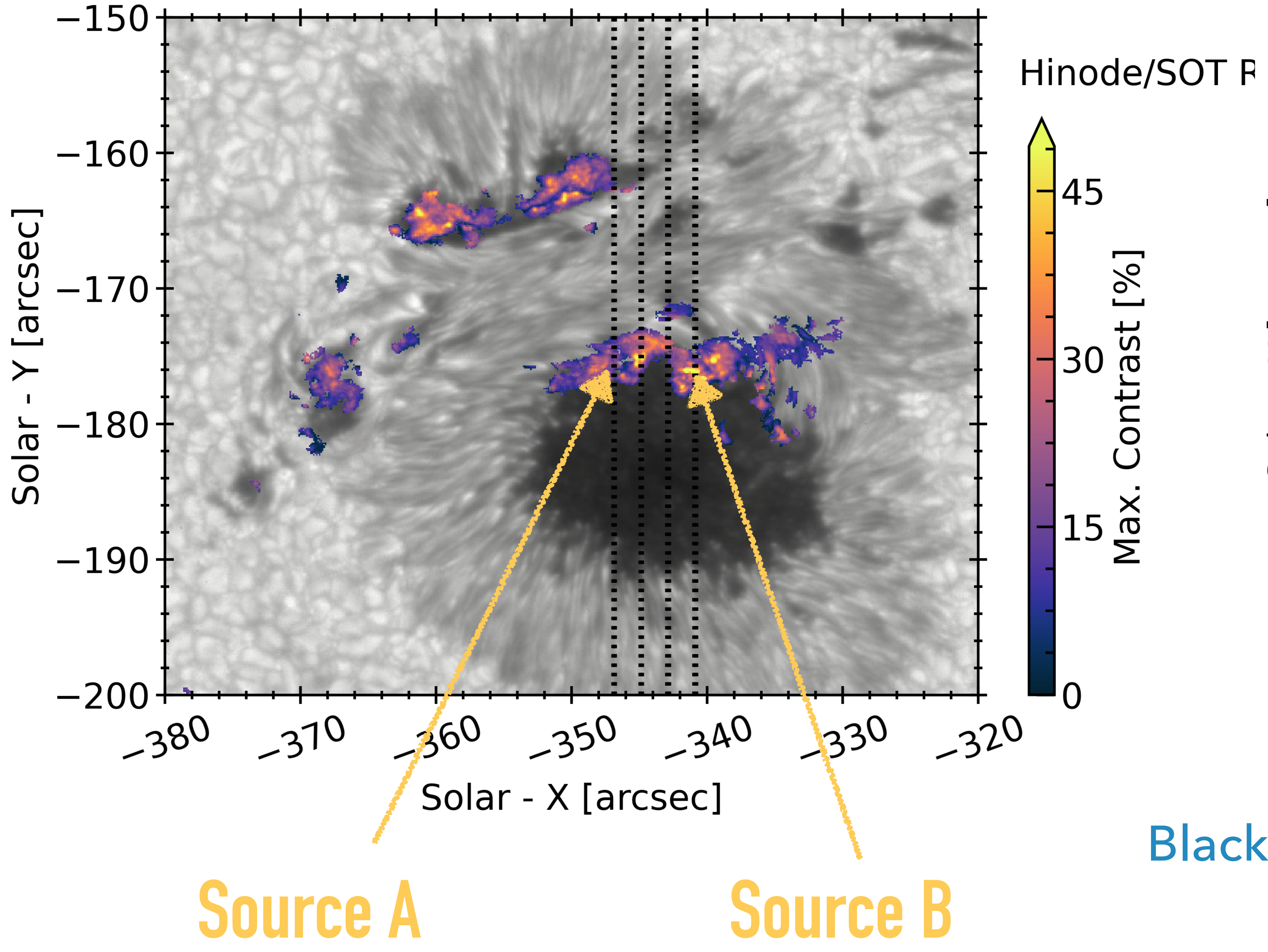
- Radiation hydrodynamics (RHD) flare modelling suggests that in strong flares the Balmer jump is always present.
- Synthetic WLFs are the result, primarily, of optically thin hydrogen recombination radiation produced in the mid-upper flaring chromosphere.
- Plasma properties in the emitting volume are typically T~8-15kK and n_e ~10^{12-14} cm^{-3}
- Width (vertical extent) of the emitting region varies from a few dozen to several hundred km.
- **How well do observations agree with this?**

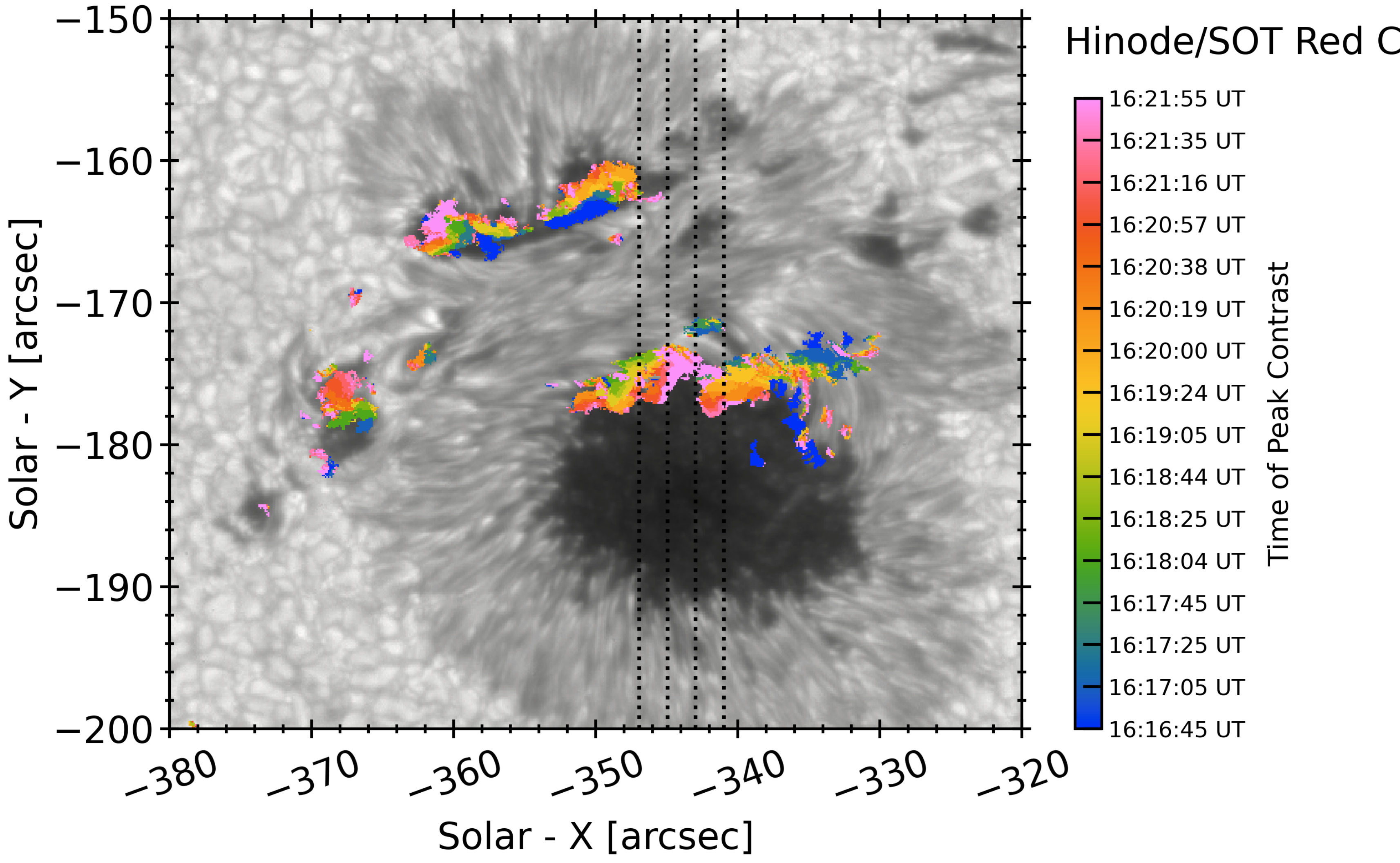


WLF OBSERVATIONS: HINODE/SOT OPTICAL IMAGES

- Three passbands: red (6684Å), green (5550Å), blue (4504Å).
- Running difference of those images was used to identify the most likely WLF sources.
- Those sources were used as seeds in a region growing algorithm to identify weaker sources.



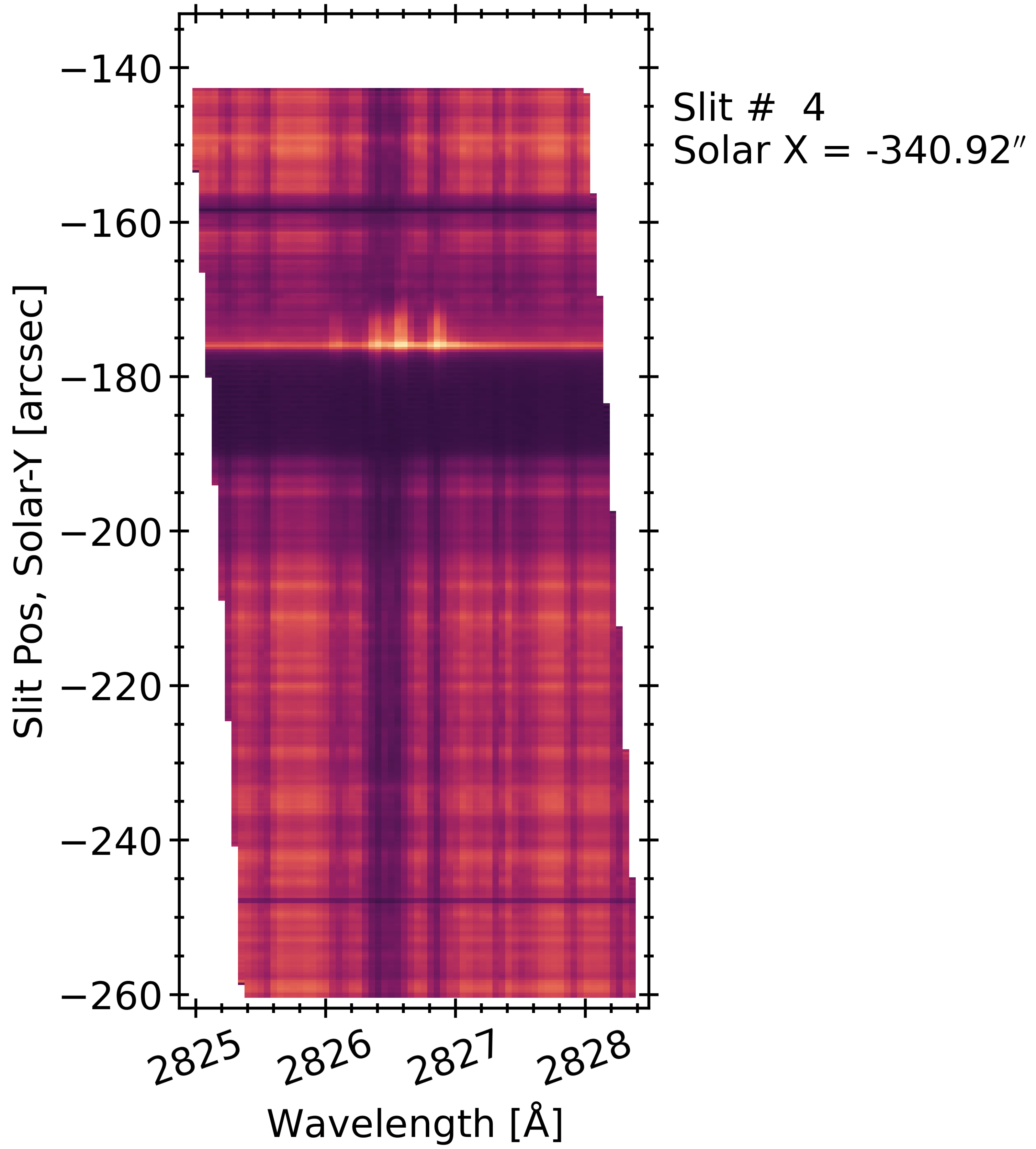


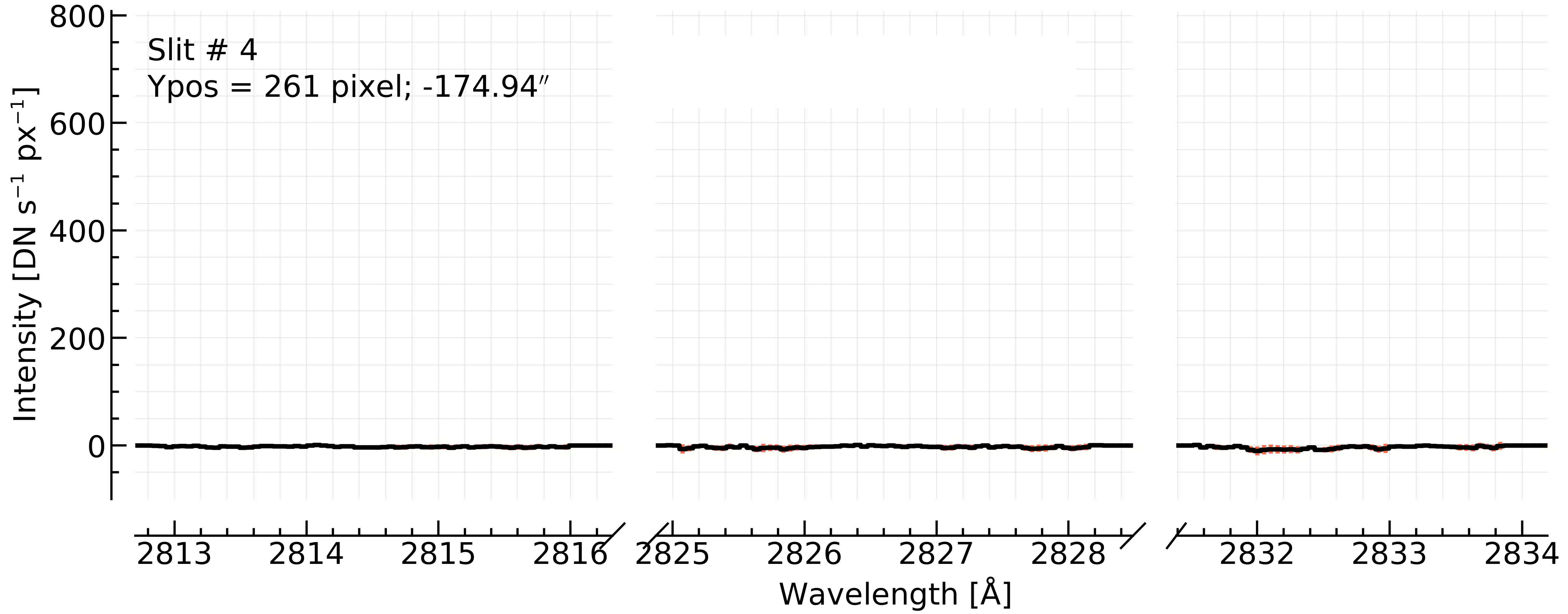


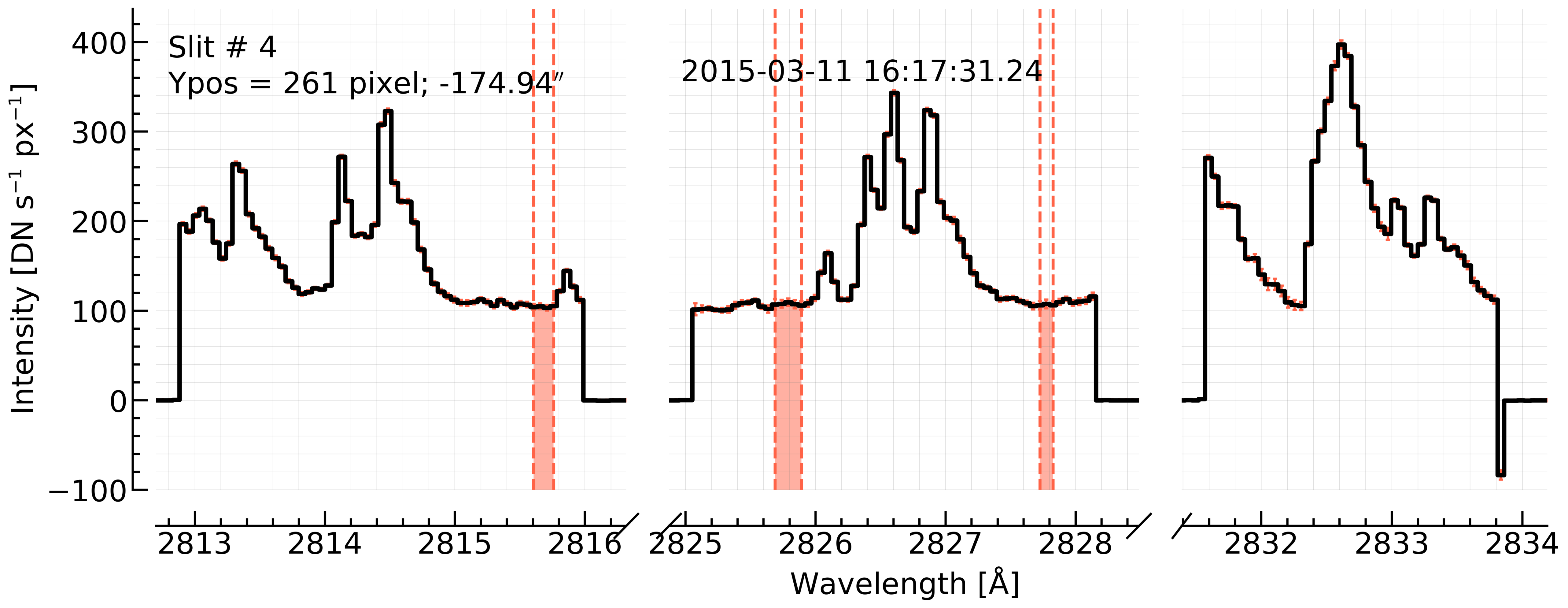
Black dashed lines are the locations of the IRIS slit.

WLF OBSERVATIONS: IRIS NEAR-UV SPECTRA

- IRIS NUV spectra, allows us to extract line free portions to measure the continuum enhancement near 2826Å.

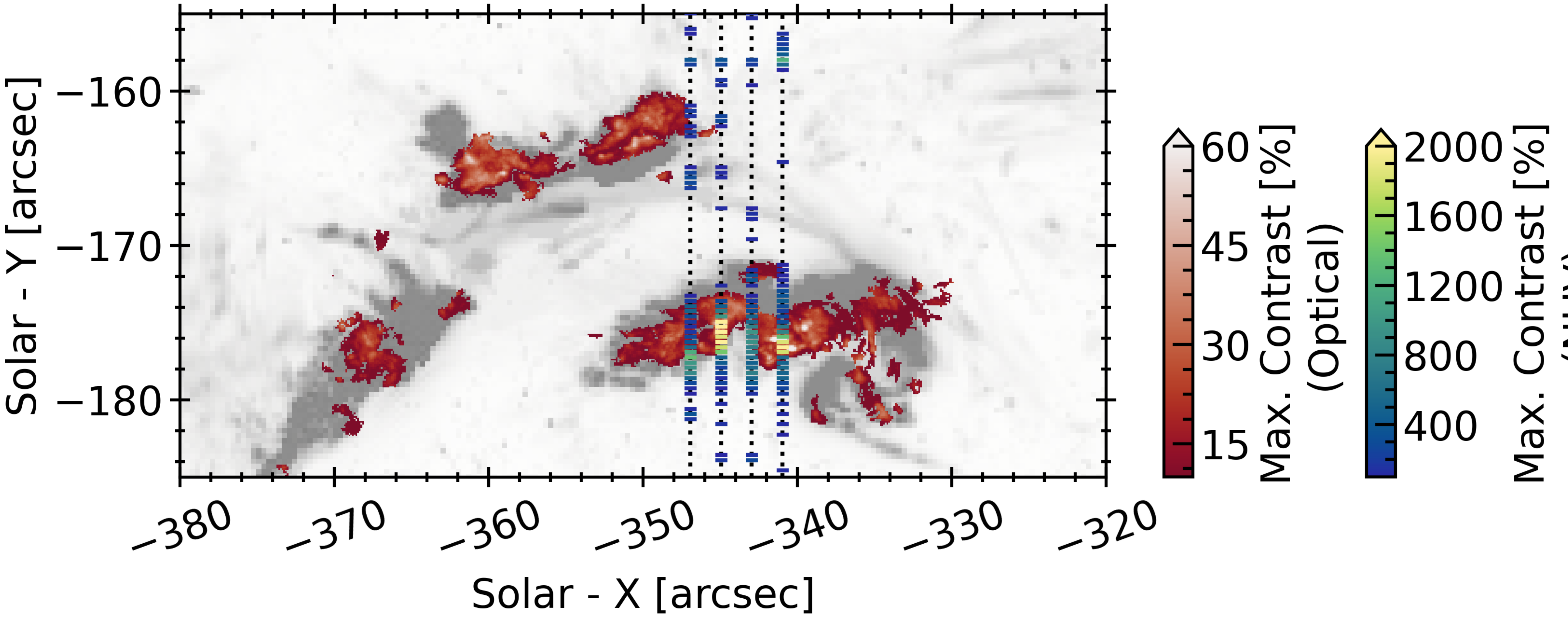






WLF OBSERVATIONS: COMBINING NUV + OPTICAL

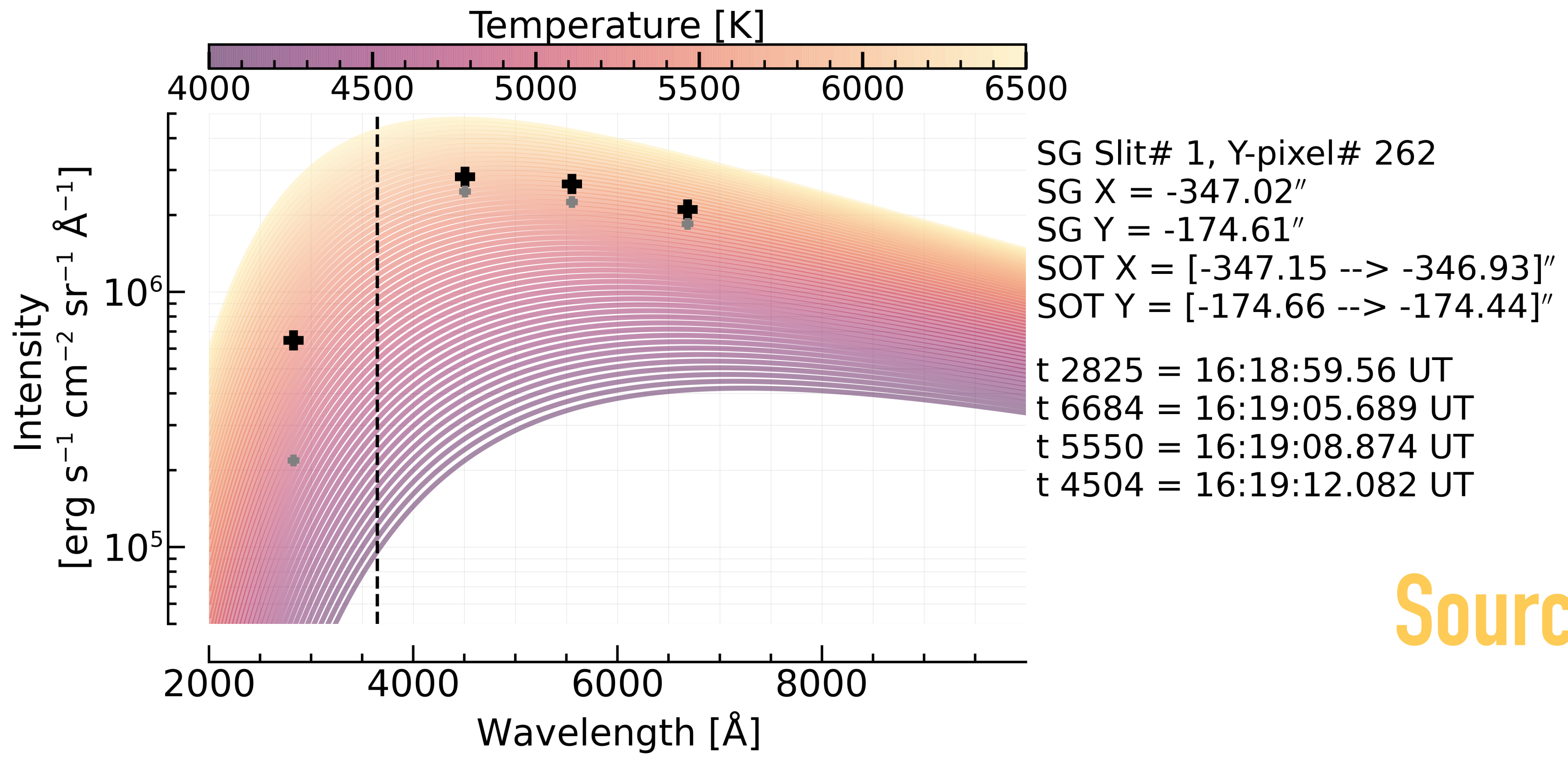
- Optical continuum enhancements and NUV continuum enhancements are largely co-spatial, but there are NUV sources with no optical counterpart.
- NUV contrast is very much larger than optical (it's hard to outshine the optical photosphere).



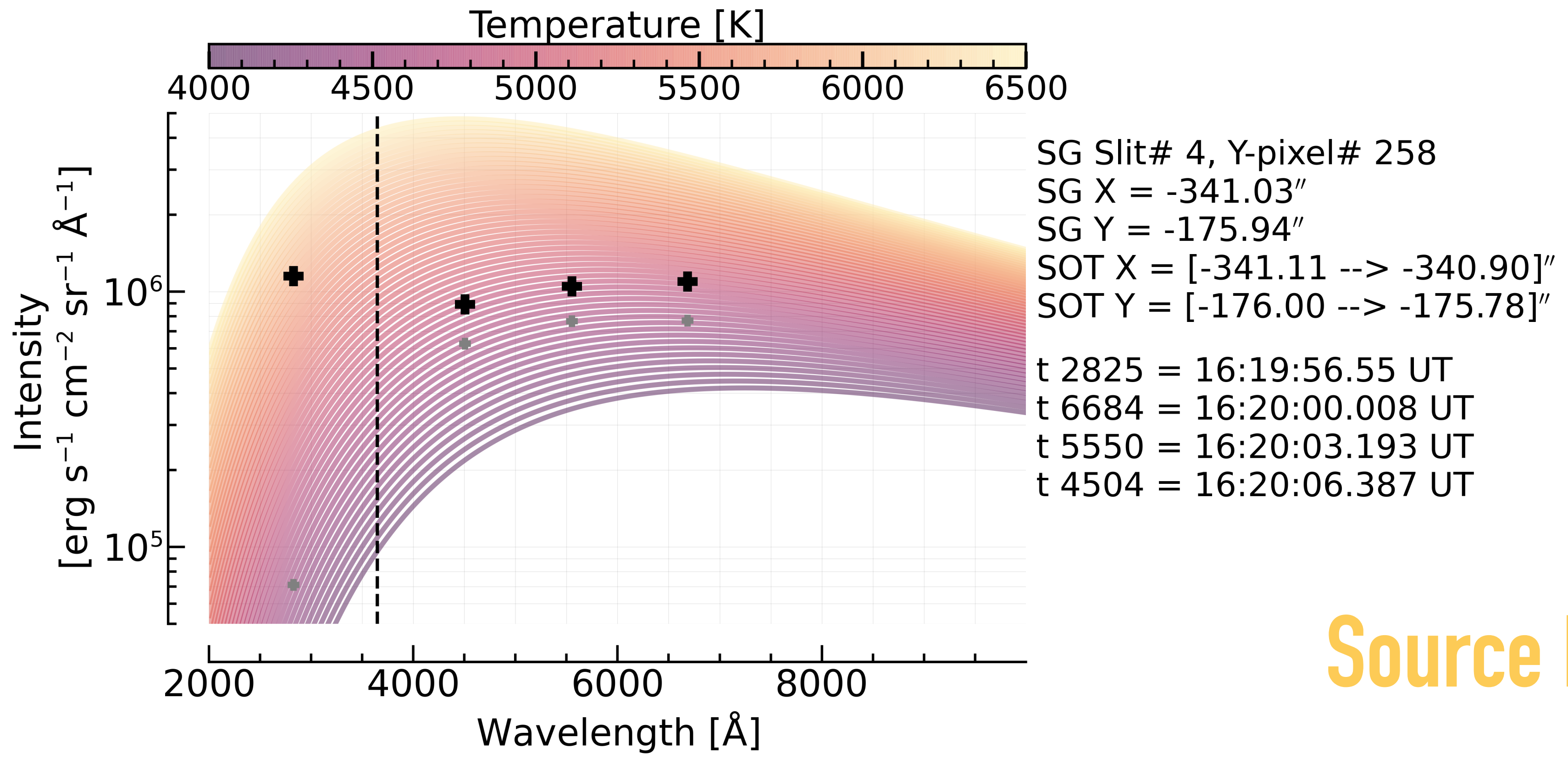
WLF OBSERVATIONS: COMBINING NUV + OPTICAL

- The shape of the spectra varies in different sources.
- Assuming that NUV is recombination Balmer radiation means we can estimate the Paschen emission for different temperatures.
- There is a large excess of optical emission – Paschen recombination can't explain it all.

Our models don't predict this – are we missing heating deep in the atmosphere?



Source A



Source B