GRAHAM S. KERR (CUA / NASA GSFC)

FLARE MODELS & THE OBSERVATIONS THAT DRIVE THEM

Validating and constraining next-generation models with next-generation observations

OVERVIEW

- Run through of the different types of flare numerical models (spectral inversions, loop models, rMHD).

- Brief introduction to where we want flare numerical models to go in the next decade.

- Some examples of observations that can validate and constrain models (cherry-picked and by no means exhaustive).

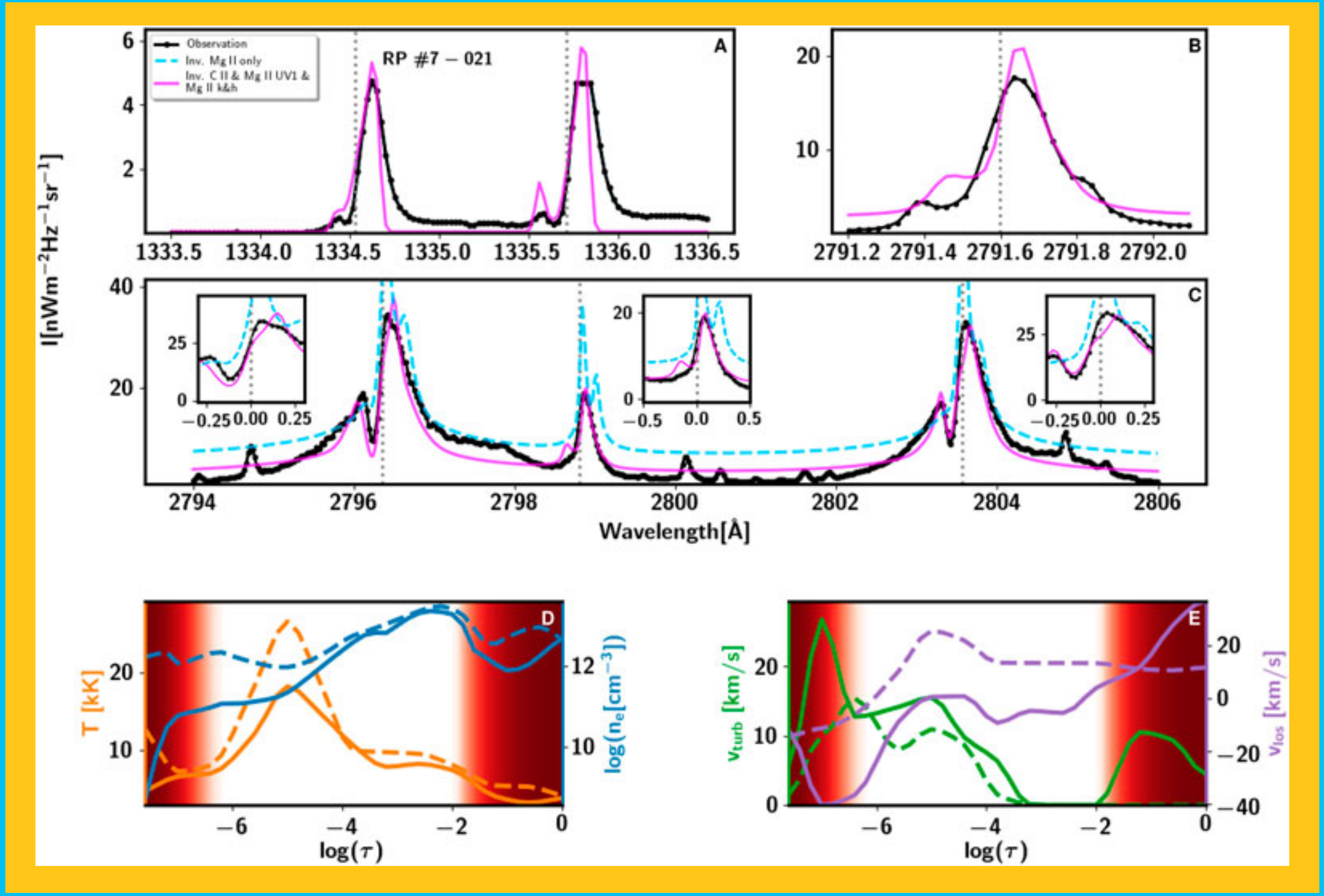
The main takeaway should be that modellers and observers should be working hand-in-glove (worked very well for IRIS, and for helping MUSE get selected).

… this talk is biased towards the flare part of Solar Eruptive Events. CMEs and SEPs could use their own talk!

SPECTRAL INVERSIONS

- Find a best-fit model atmosphere that can 'reproduce' observed spectra.
- Modern codes like STiC (de la Cruz Rodriguez et al 2019) solve the multi-level and multi-species NLTE problem.
- Difficult in flares which are by their nature dynamic (e.o.s. in those codes often demands hydrostatic equilibrium)… but recently we have had successes.
- Doesn't tell us *how* the atmosphere reached the required stratification.

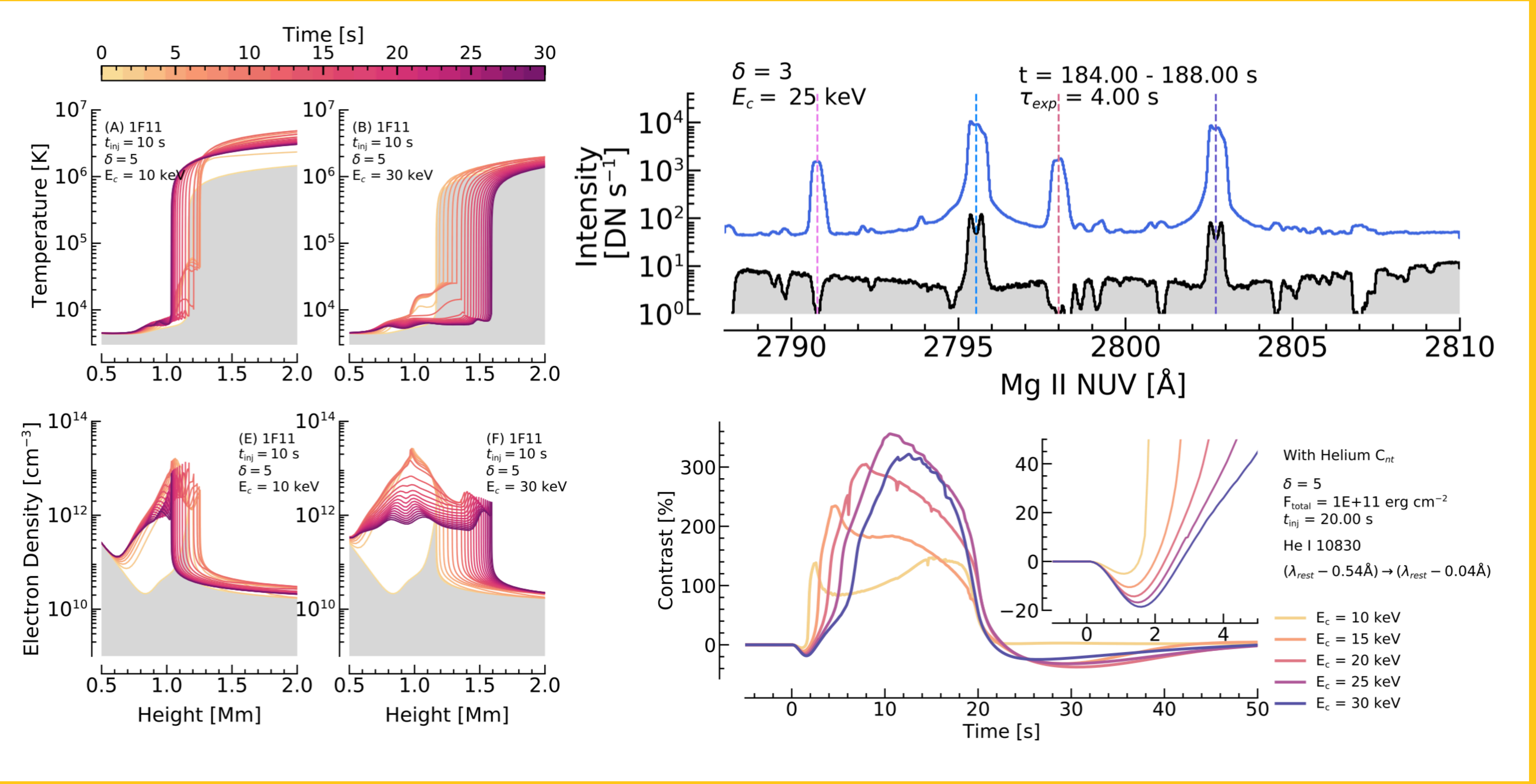
Sainz Dalda & de Pontieu (2023)

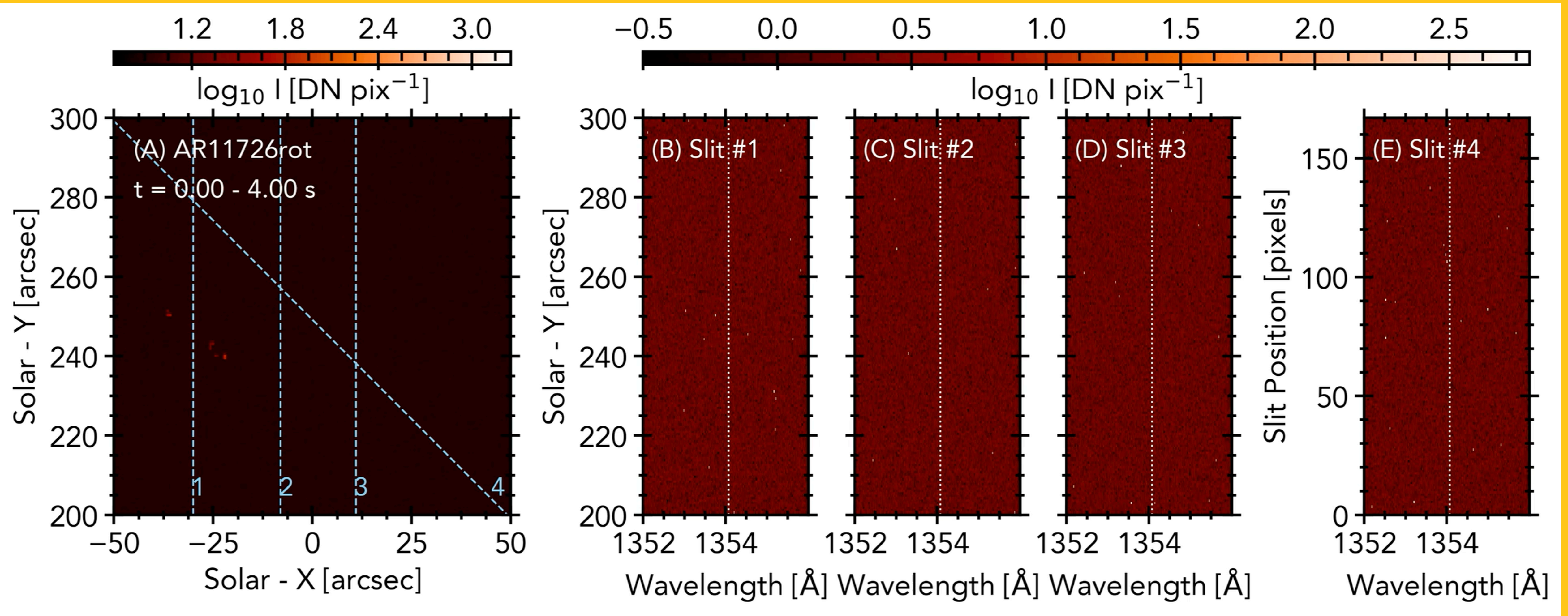


LOOP MODELS

- Field-aligned (1D) models that solve hydrodynamic response of atmosphere, including RT and nonthermal particle transport/ thermalisation.
- Varying degrees of complexity (e.g. NLTE chromospheres, multi-species fluid etc.,).
- Allows very small spatial scales where necessary (sub-metre!) and can explore physical processes in great detail.
- Flare energy is injected and dissipated in parameterised fashion, useful for running large, controlled experiments.
- Normally no magnetic fields!

Kerr, Polito, Xu & Allred (in prep)



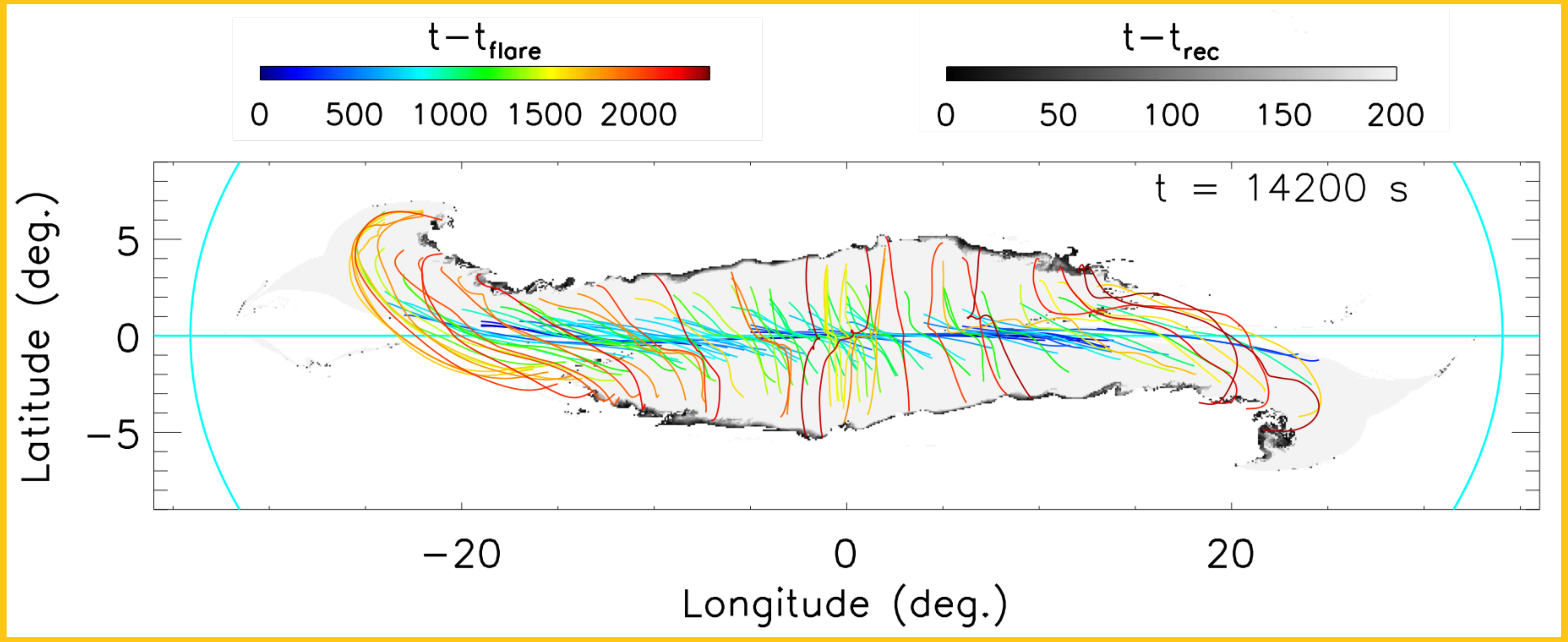


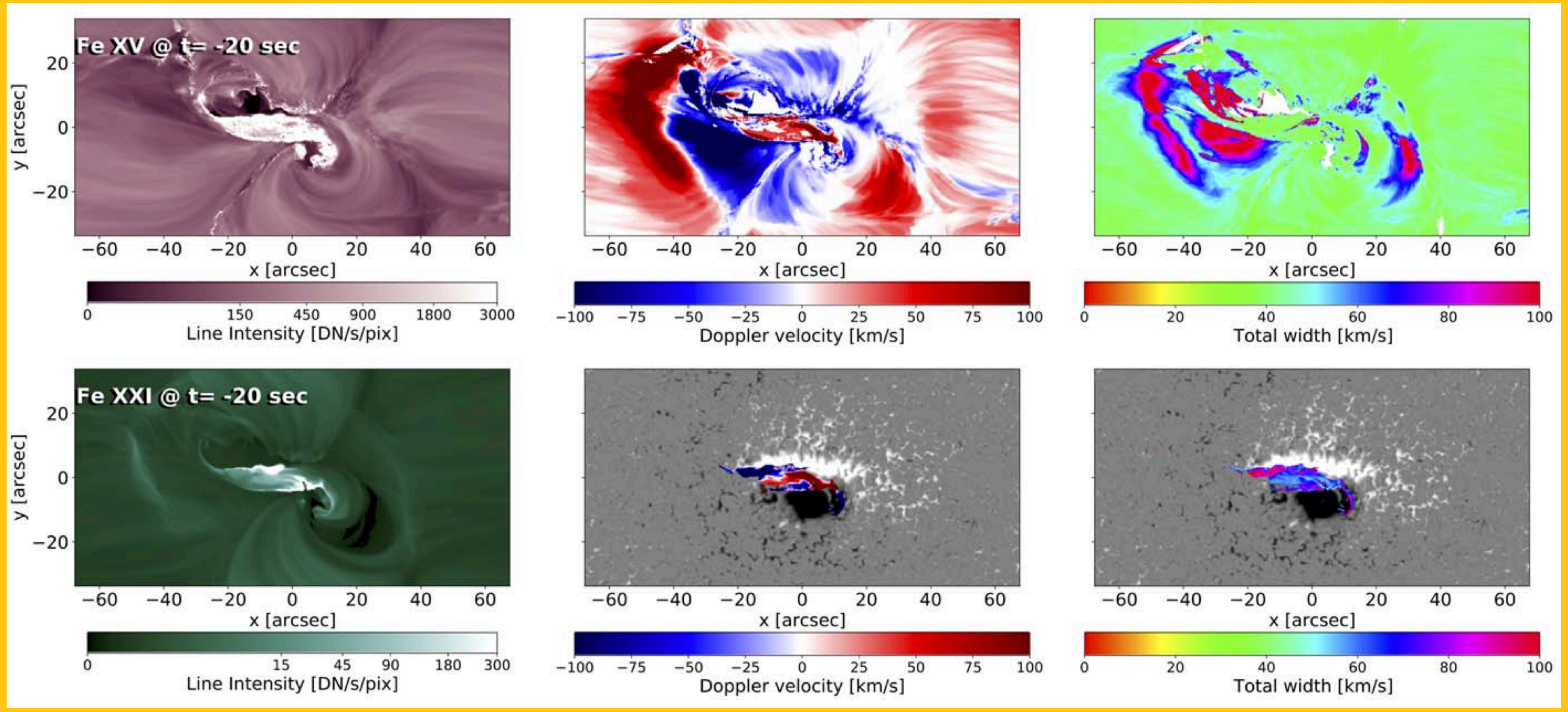
Kerr, Allred & Polito (2020)

(r)MHD MODELS

- Allows the influence of the magnetic field to be modelled, including energy build up and release following reconnection.
- Large scale features and the dynamics of the loops themselves can be modelled.
- Can explore how various flare features (incl. current sheet dynamics, flux rope eruptions, MHD instabilities and pre-cursors) appear in observations.
- More difficult to ‘control’ the energy release and generally miss the effects of non-thermal particles.

Dahlin, Antiochos, Qiu & Devore (2022)





Cheung, Martínez-Sykora & MUSE Science Team (2022)

THERE ARE NO SELF-CONSISTENT, *COMPREHENSIVE* FLARE NUMERICAL MODELS ...

... BUT WE ARE GETTING CLOSER, AND NEW OBSERVATIONS ARE REQUIRED FOR BOTH CONSTRAINING INITIAL CONDITIONS AND VALIDATION.

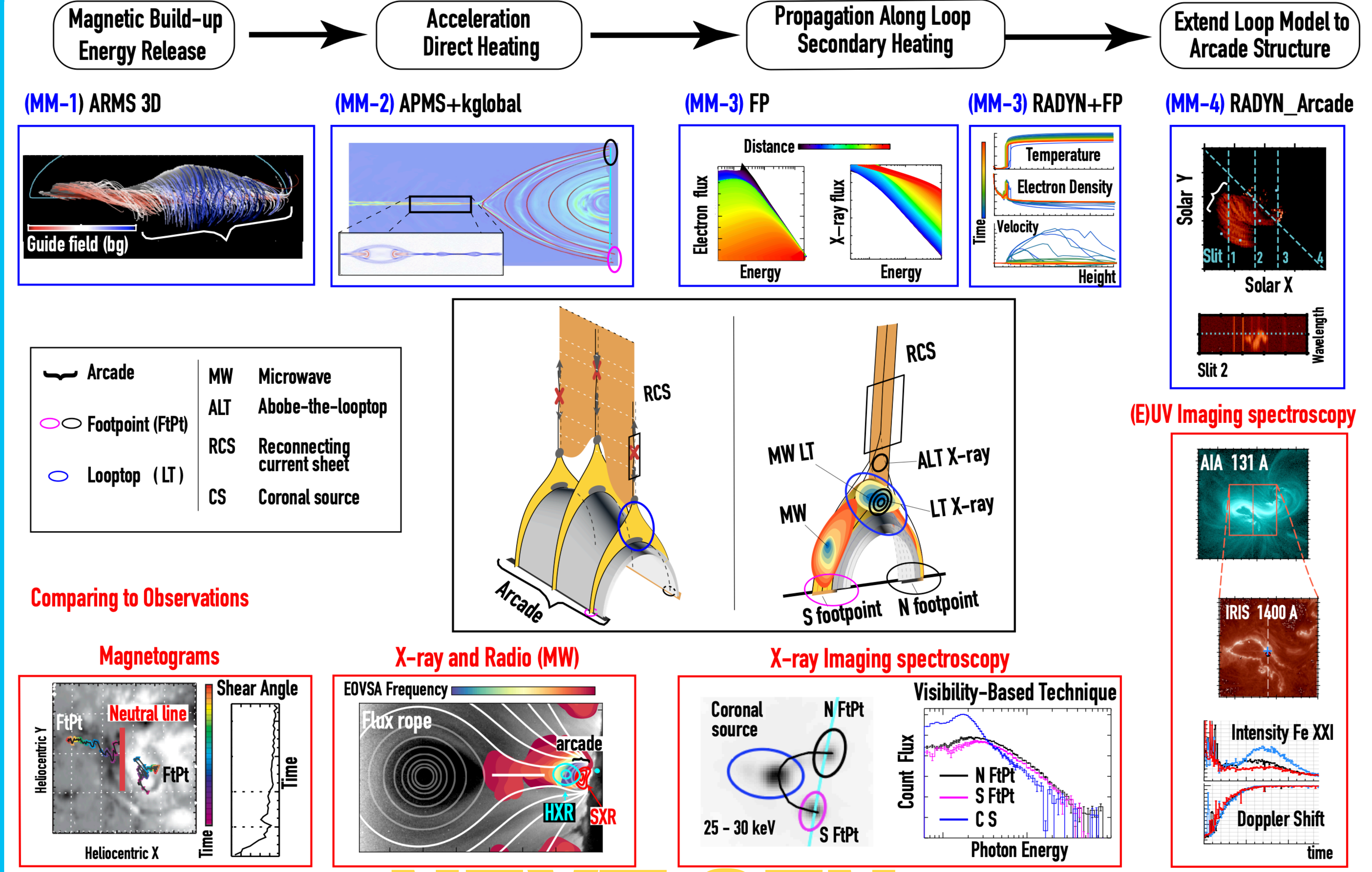
End-to-End Flare Modelling Framework

Each link in the chain feeds into the next, with outputs being inputs to the next step.

This attempts to bridge the gap across the vastly different scales required to model flares — from MHD to kinetic.

First iteration being worked on by a NASA GSFC, UMd, and NASA MSFC collaboration (PI Allred).

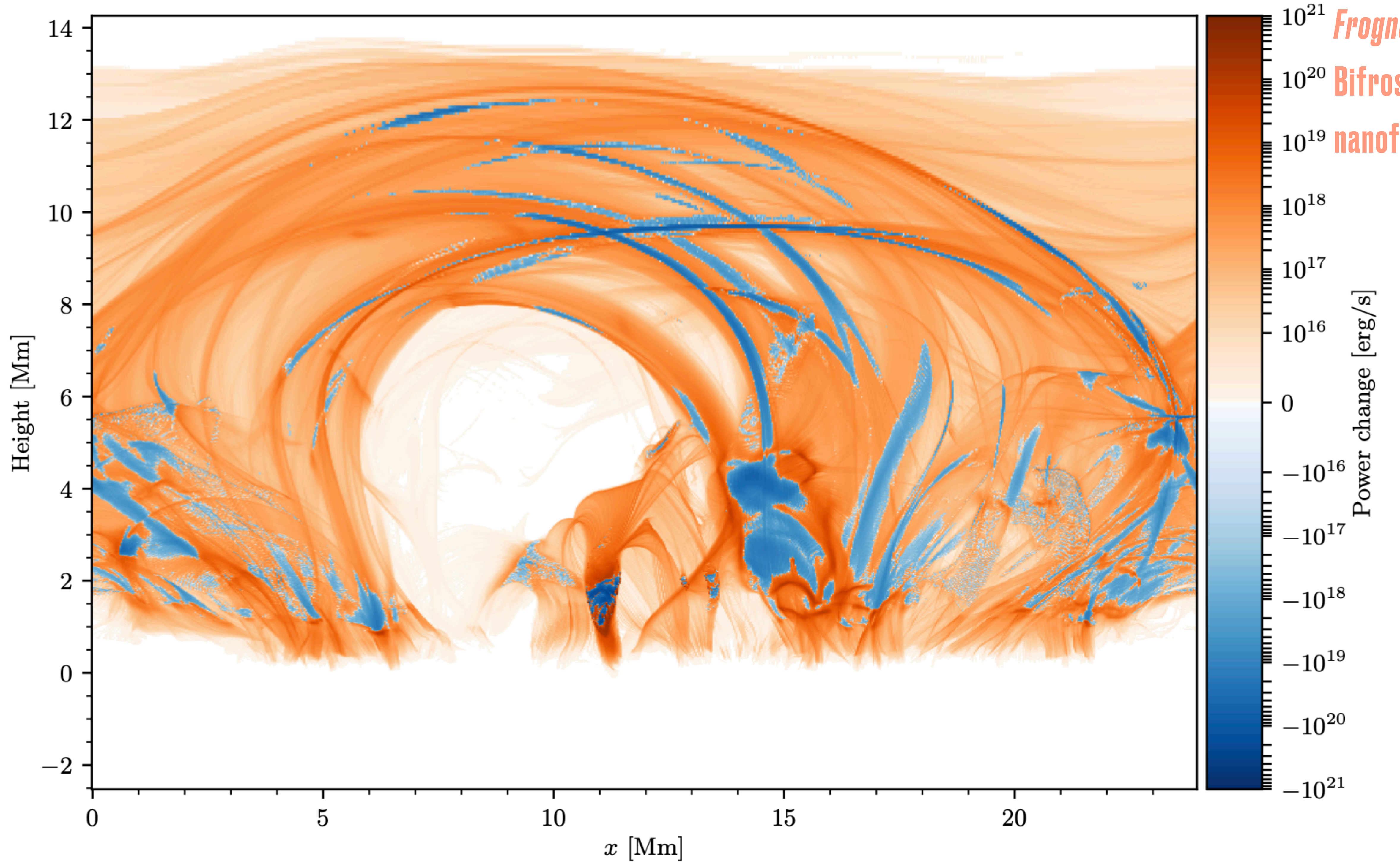
In the current framework, links go one way, without feedback back up the chain.

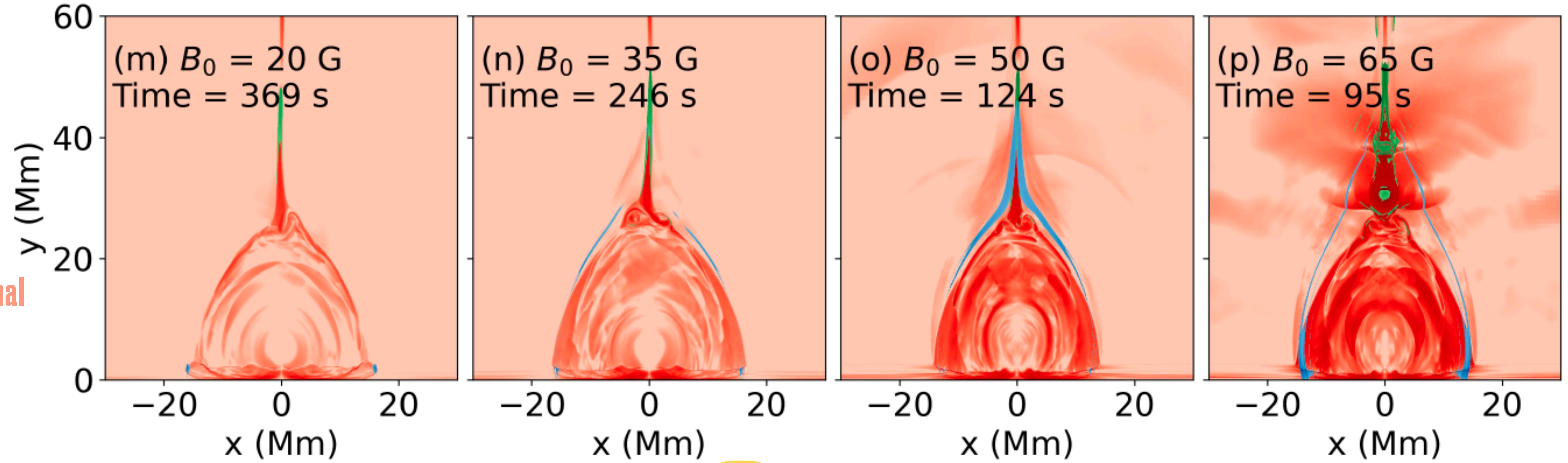


Allred et al BAAS 2023 (Decadal Survey white paper)

NEXT-GEN (EX1)

MHD Models w/ Energetic Particles





NEXT-GEN (EX 2)

MHD models, e.g. Bifrost and AMRVAC, where energetic particles are injected at reconnection sites which can then carry energy elsewhere.

Some elements need parameterised, for example how much of the released magnetic energy does the nonthermal particle distribution carry, what is the low-energy cutoff etc.,

Currently (r)MHD models cannot model the chromosphere with the spatial resolution required and with approximated RT.

STRATIFIED MAGNETIC FIELDS

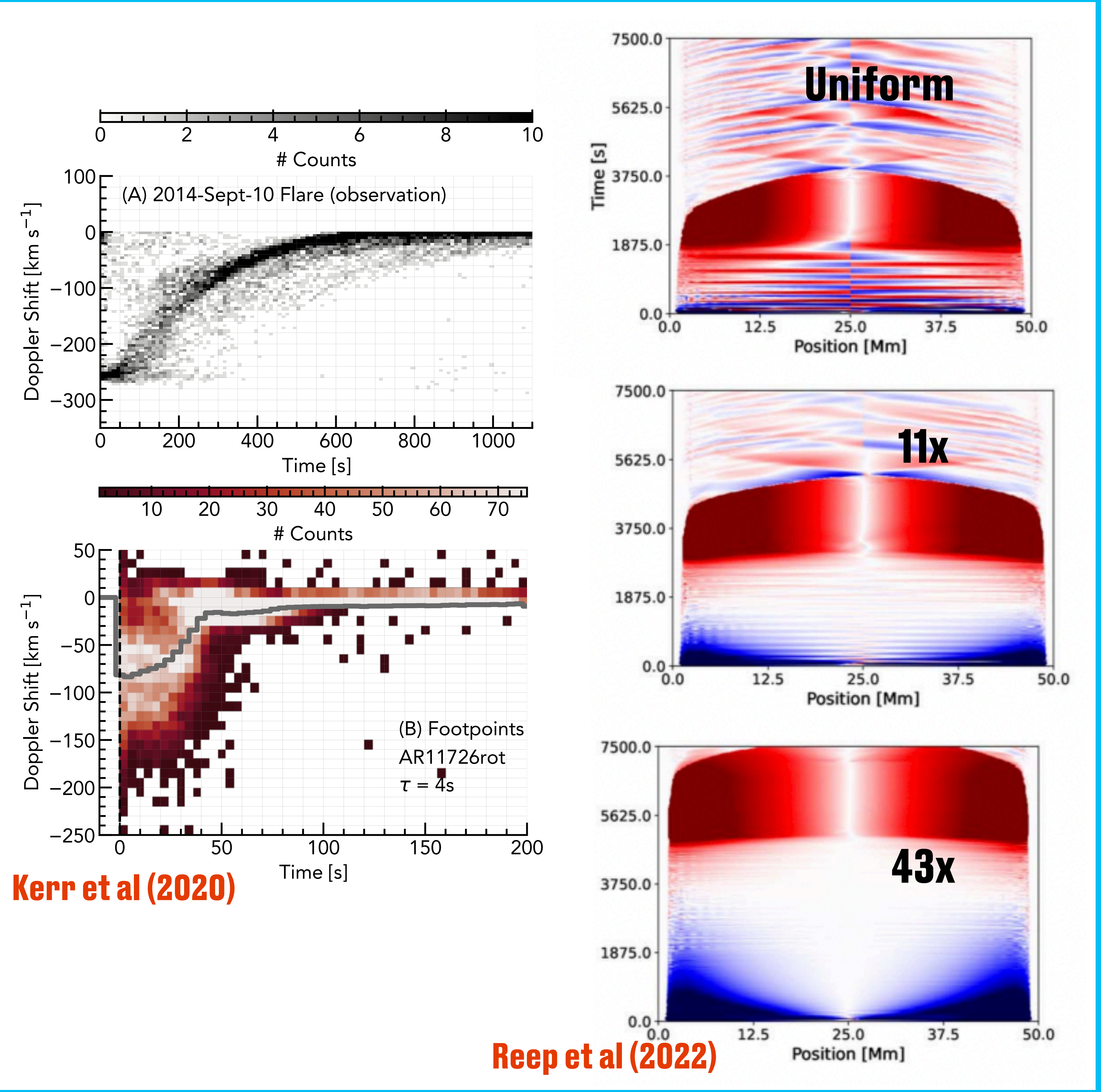
OBSERVATIONAL WISH #1

MODELLED DOPPLER FLOWS SUBSIDE TOO FAST

Once energy injection stops flows are quenched, decreasing up to an order of magnitude too fast.

Multi-threaded modelling could help, but recent work also suggests area expansion of the loop could also be an answer.

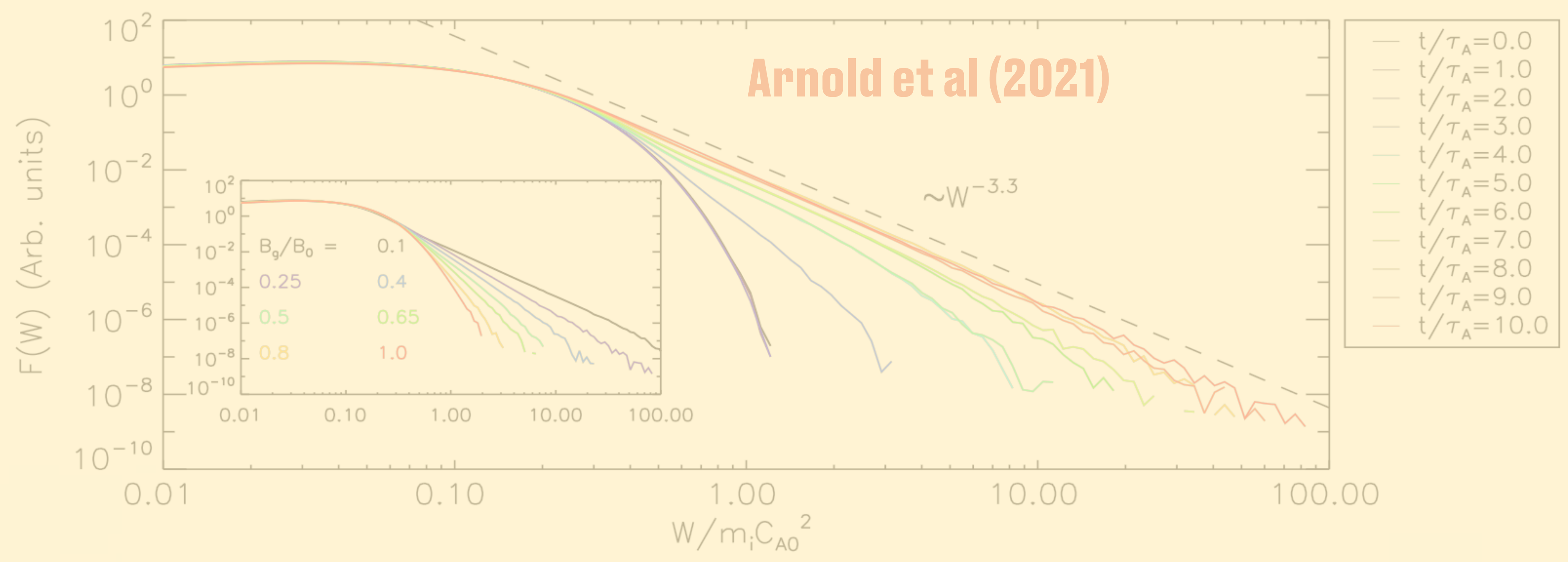
Need magnetic field information to constrain expansion.



GUIDE FIELD SEEMS TO PLAY A ROLE IN PARTICLE ACCELERATION

In particle acceleration models that produce nonthermal electron distributions with power-law tails over many energy decades, the strength of the guide field (magnetic shear) plays an important role.

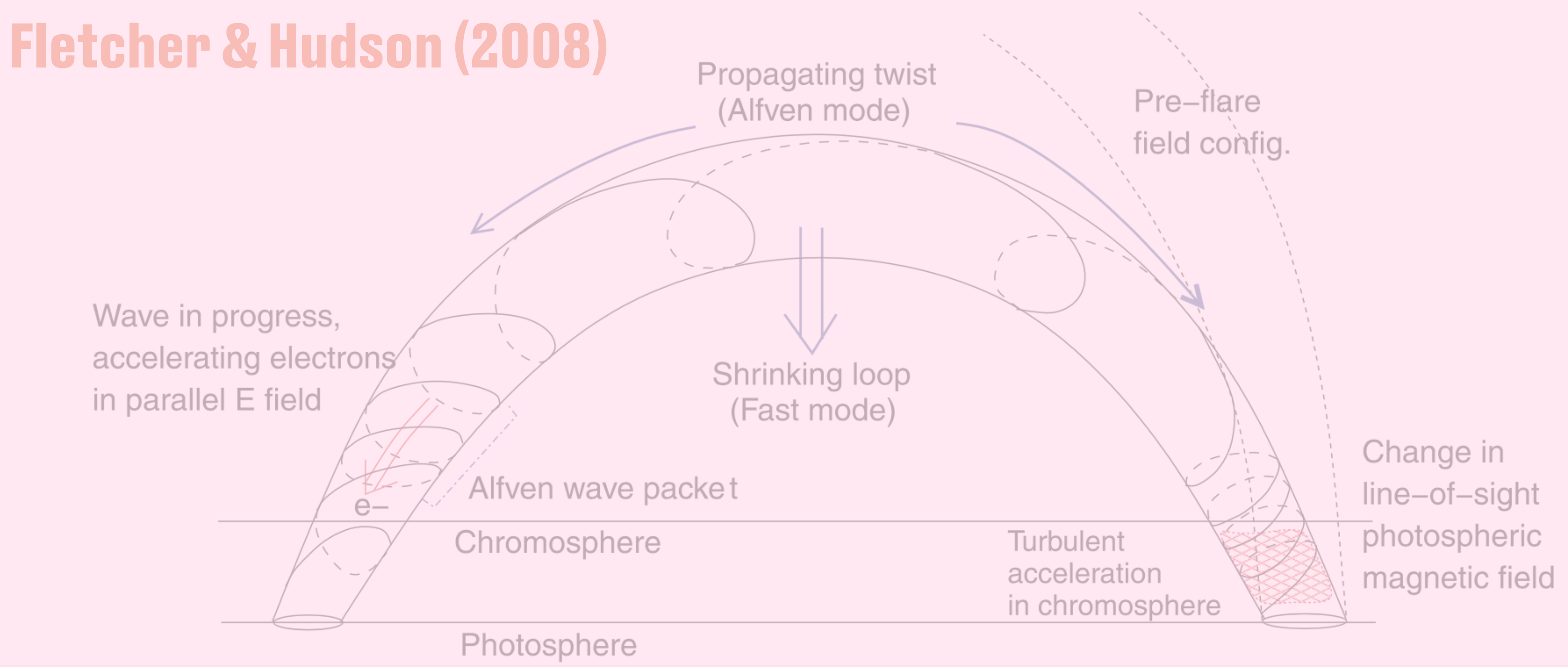
Observations of the Sun's coronal magnetic field are important in developing data-driven models of flares with particle acceleration.



DO ALFVÉN WAVES PLAY A ROLE IN FLARE ENERGY TRANSPORT?

Alfvén waves are undoubtedly produced, but do they play a role in transporting flare energy, or even accelerating particles?

Various efforts are underway to explore this, but we need knowledge of the magnetic field to help estimate Alfvén speeds and Poynting fluxes.



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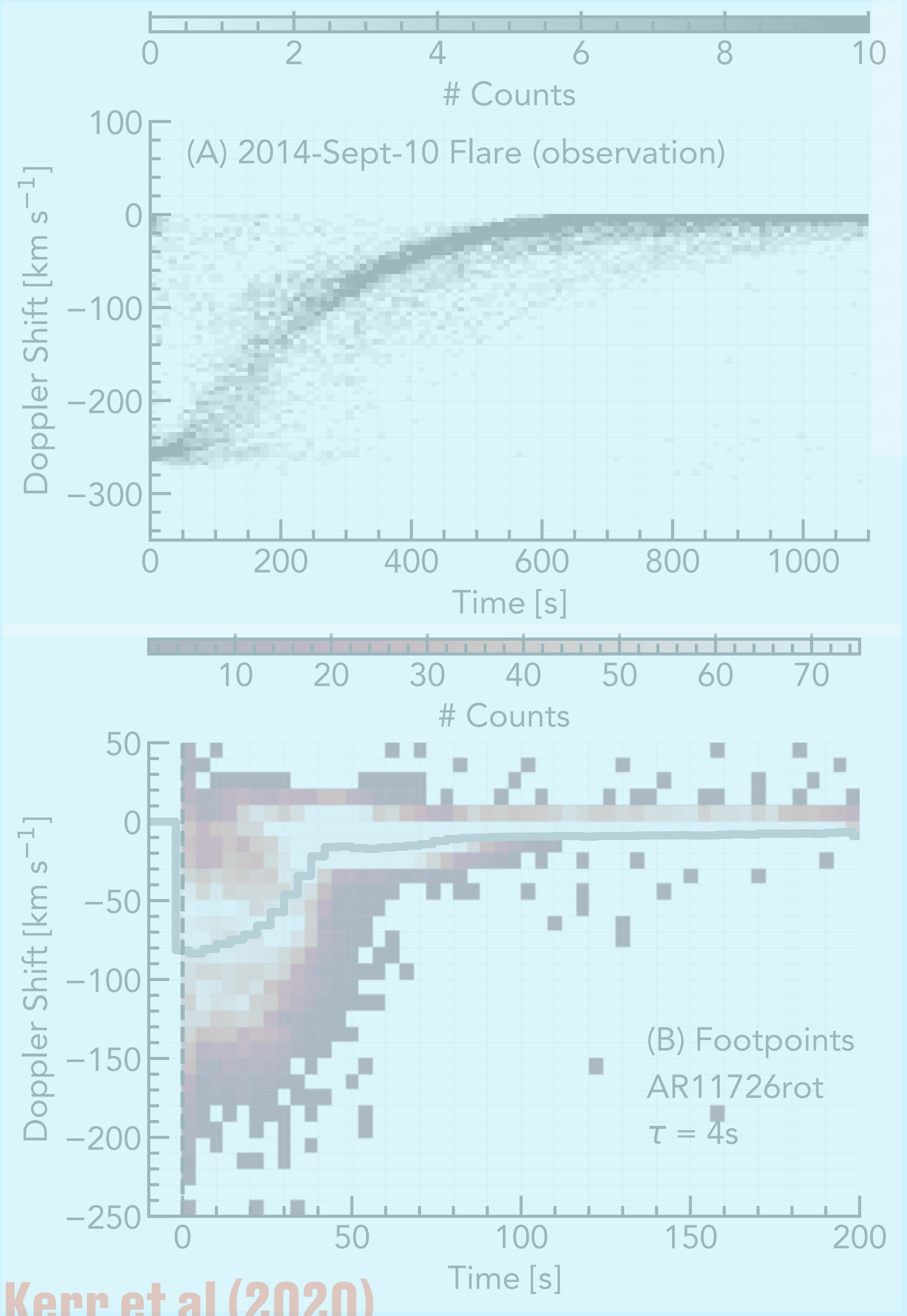
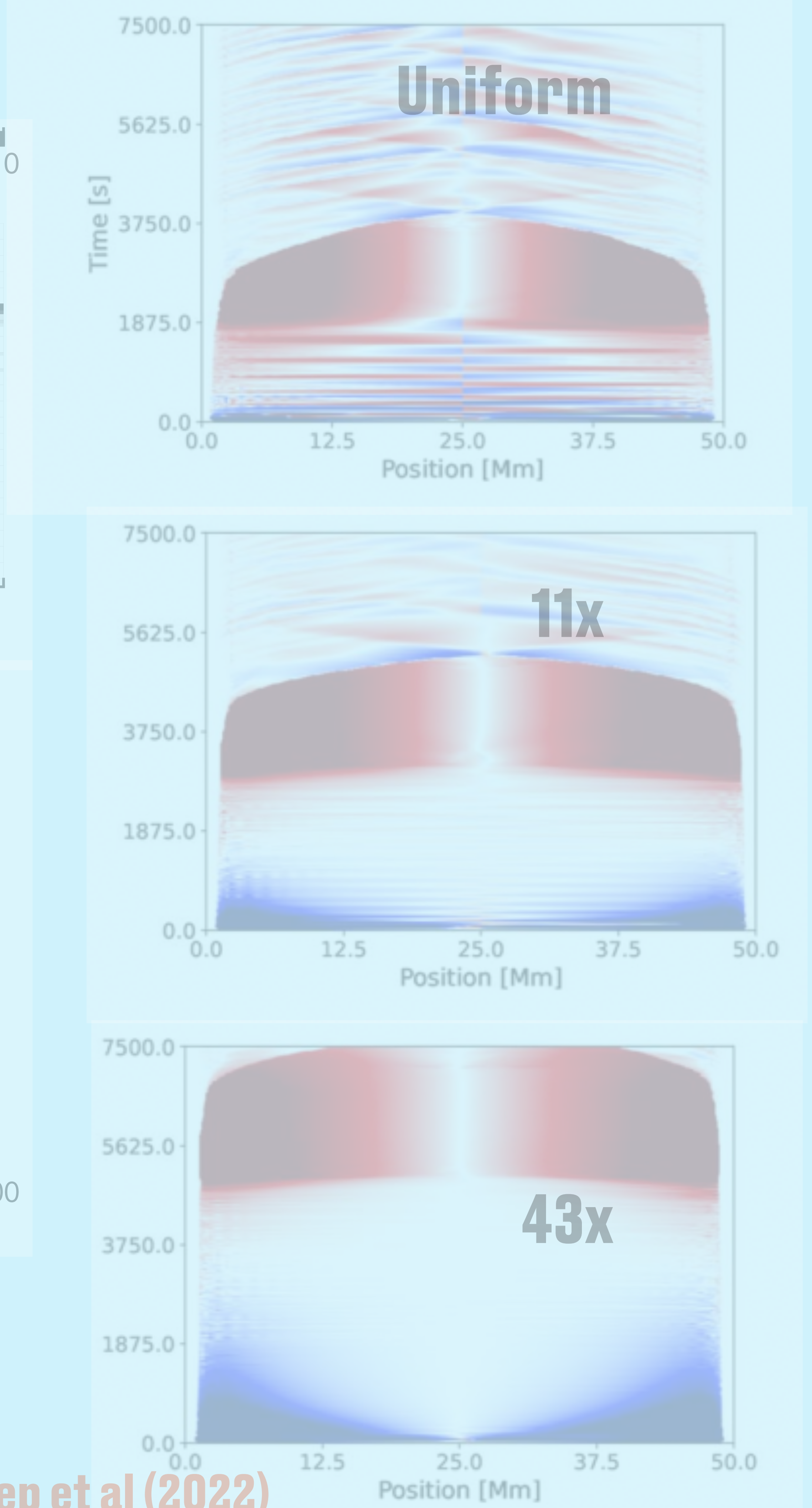


Kerr et al (2020)



Reep et al (2022)

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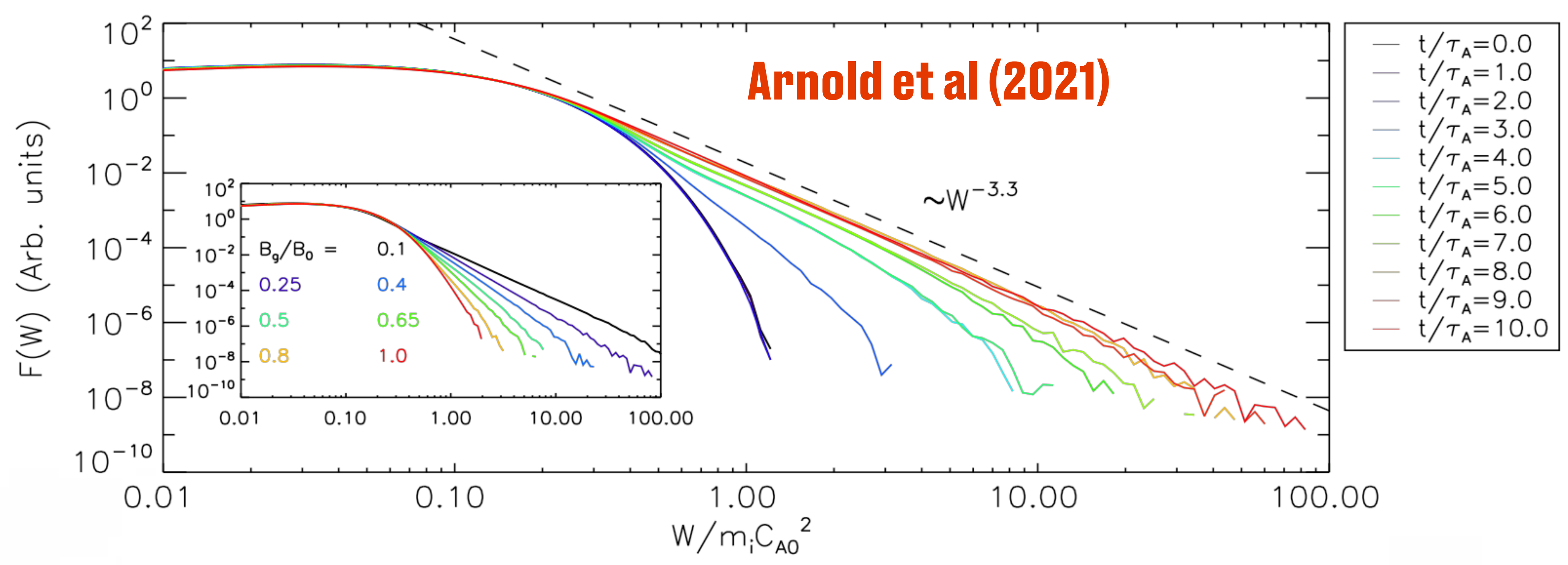

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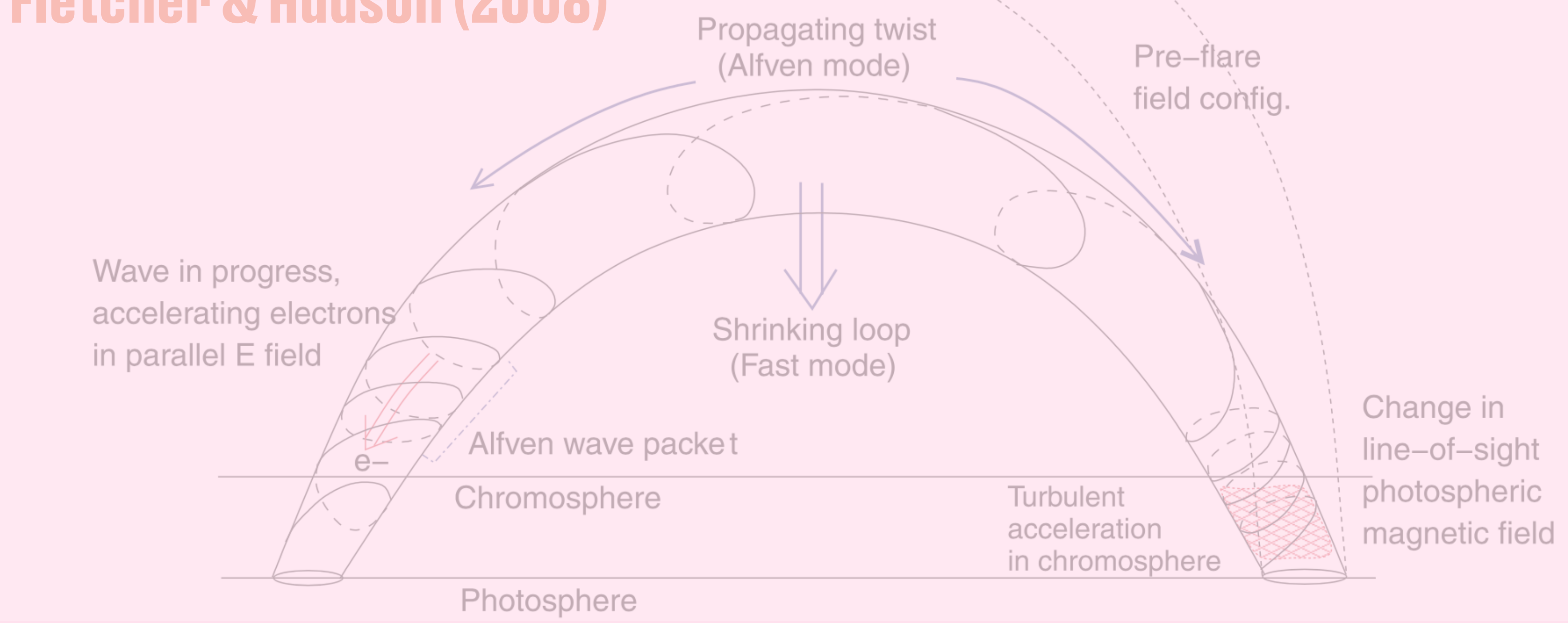
Fletcher & Hudson (2008)



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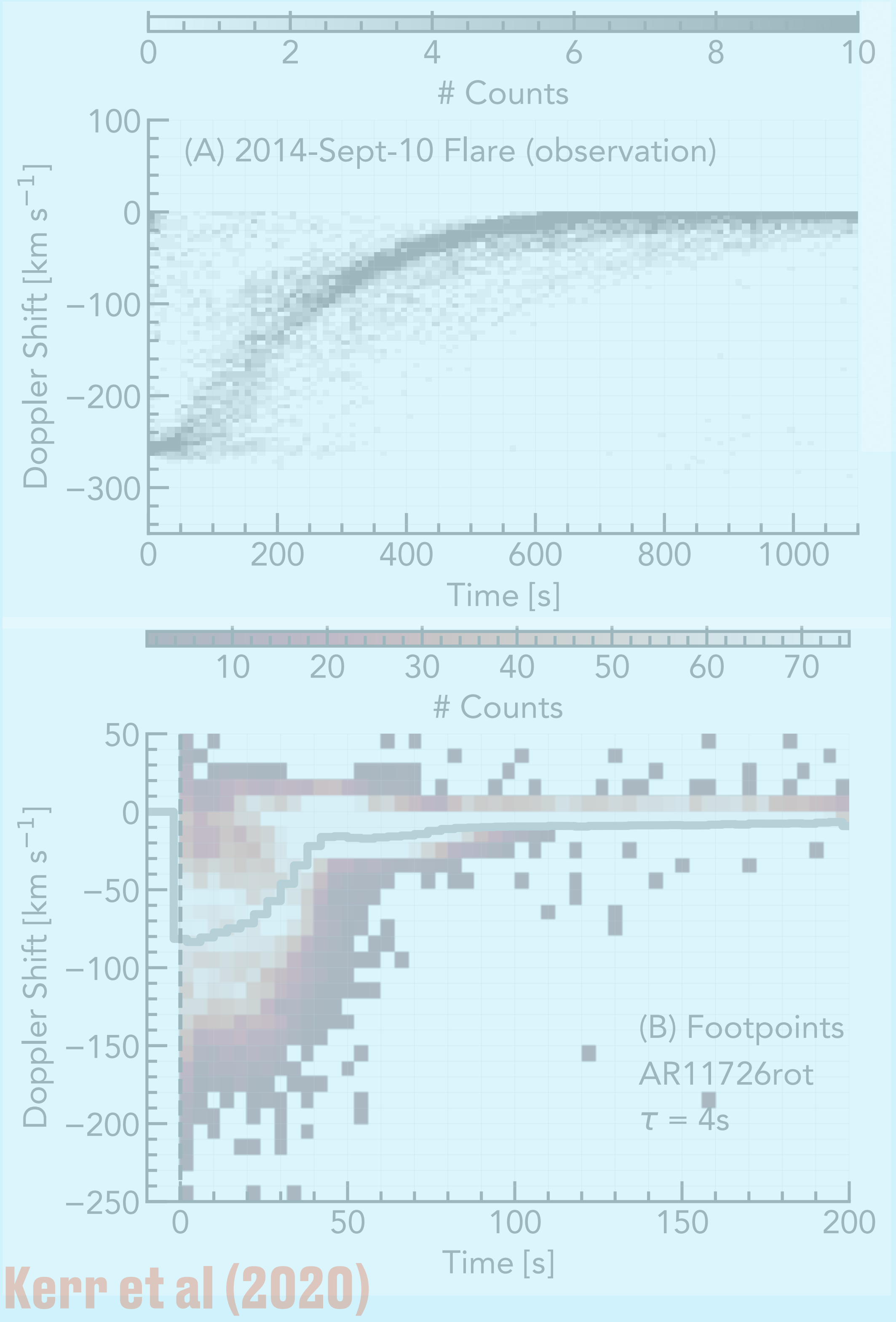

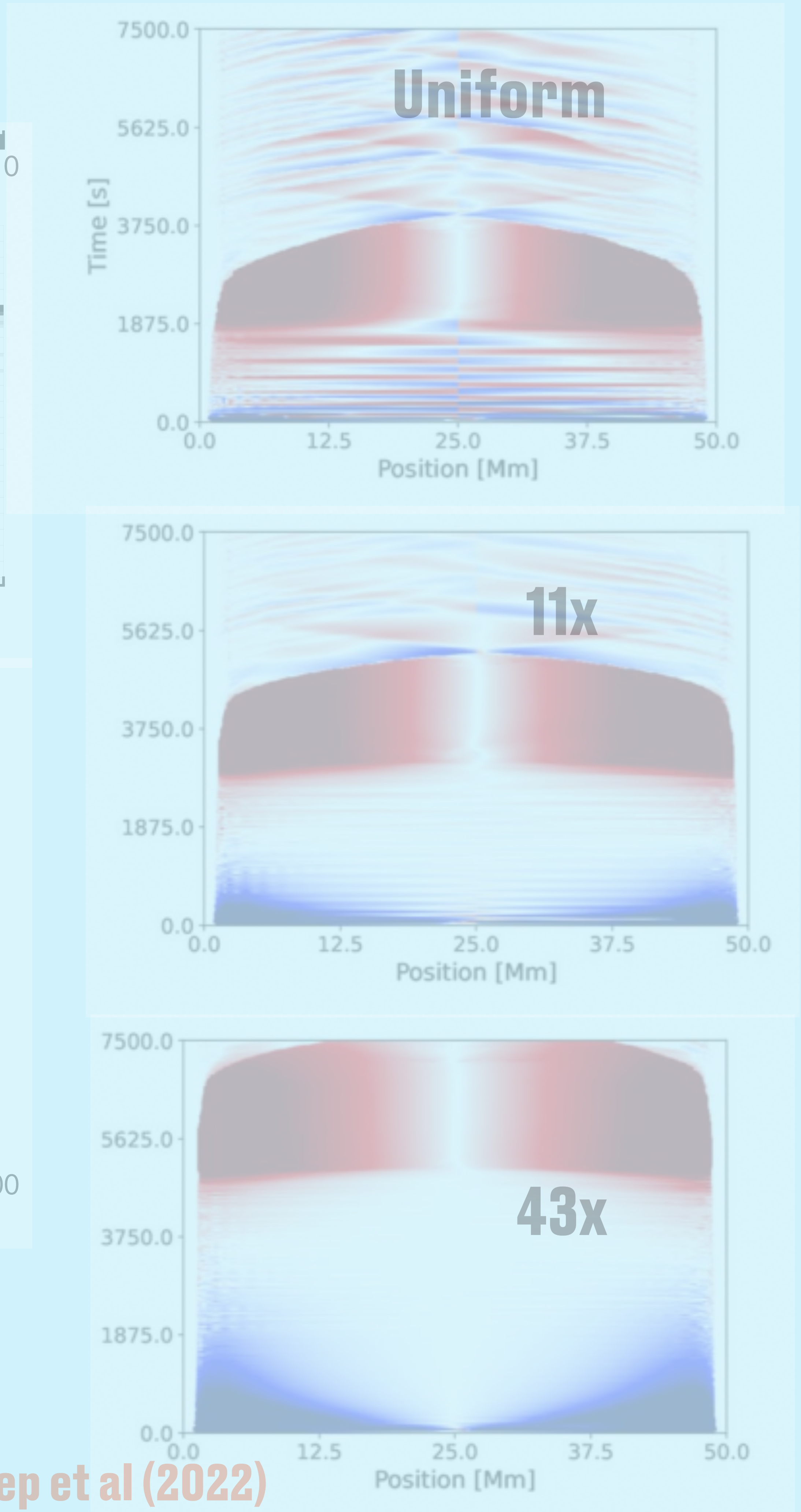

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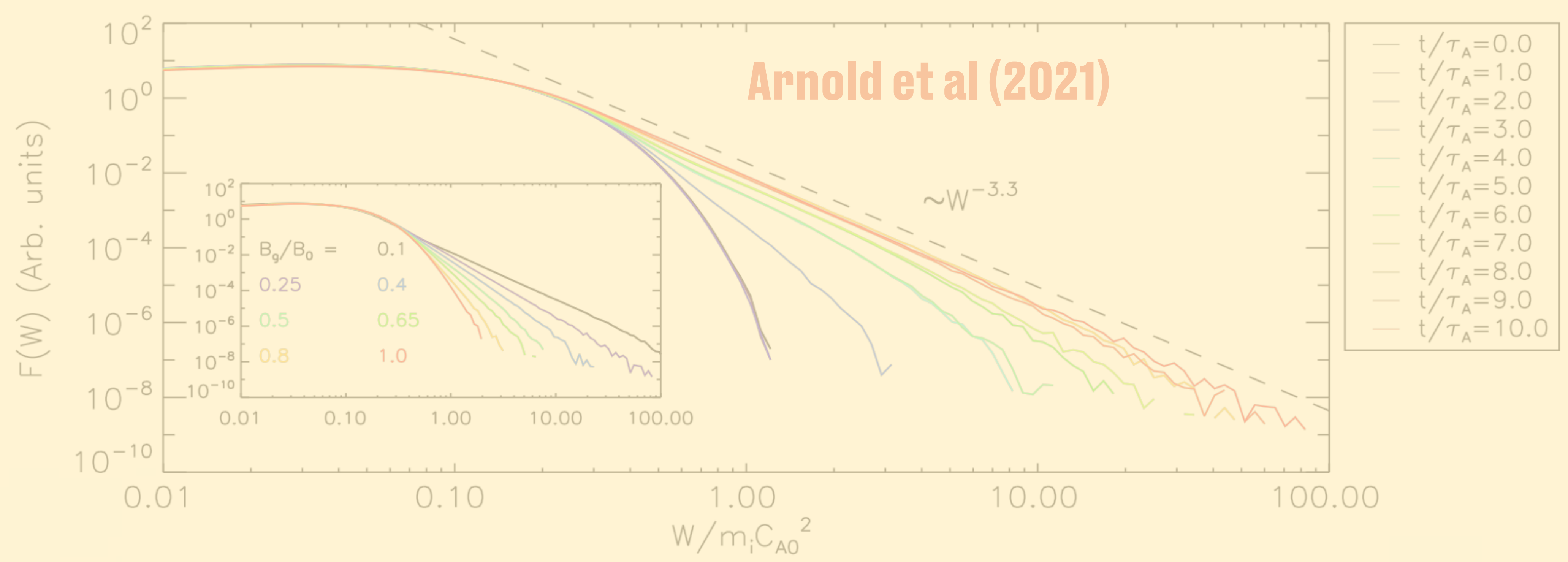

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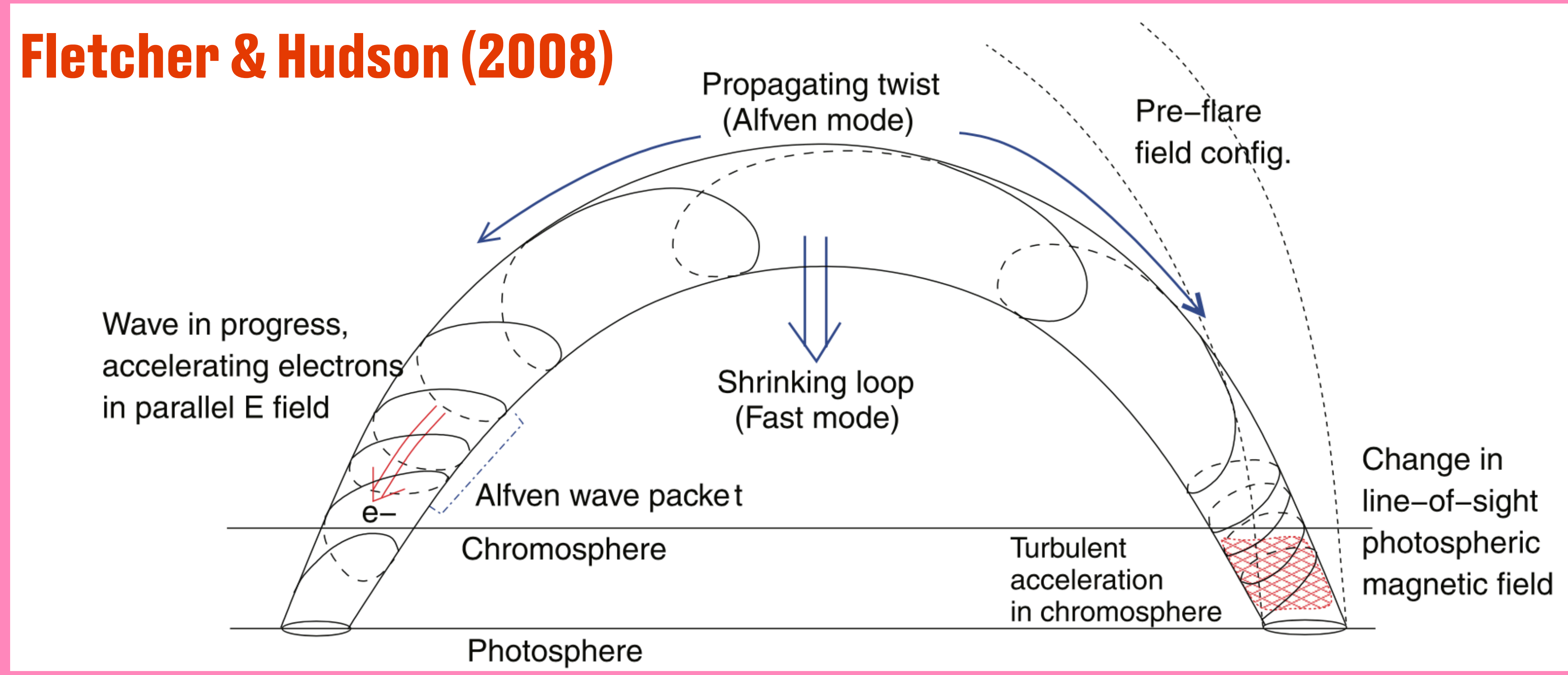


ENERGY CONTENT & DISTRIBUTION OF NONTHERMAL IONS

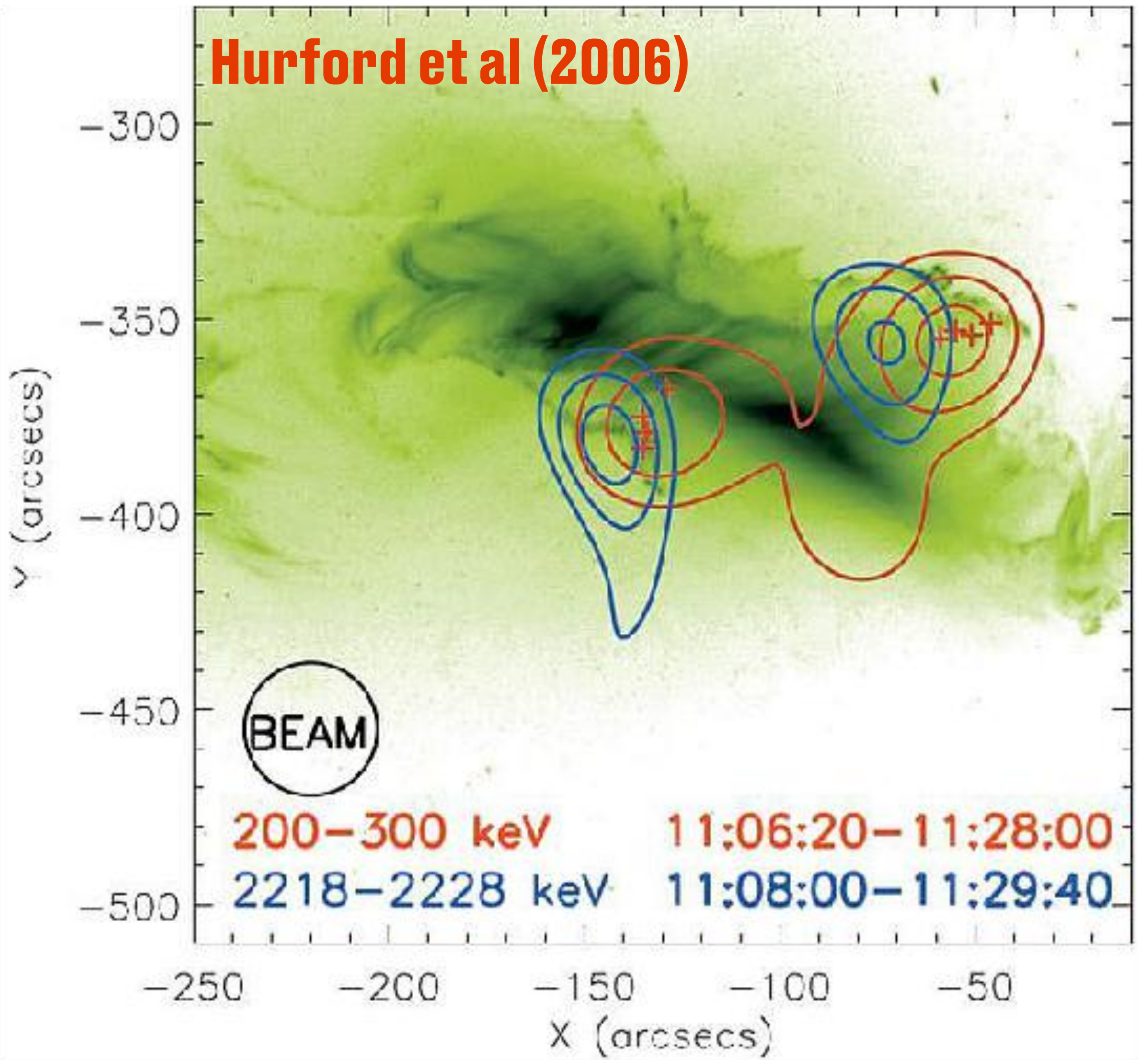
OBSERVATIONAL WISH #2

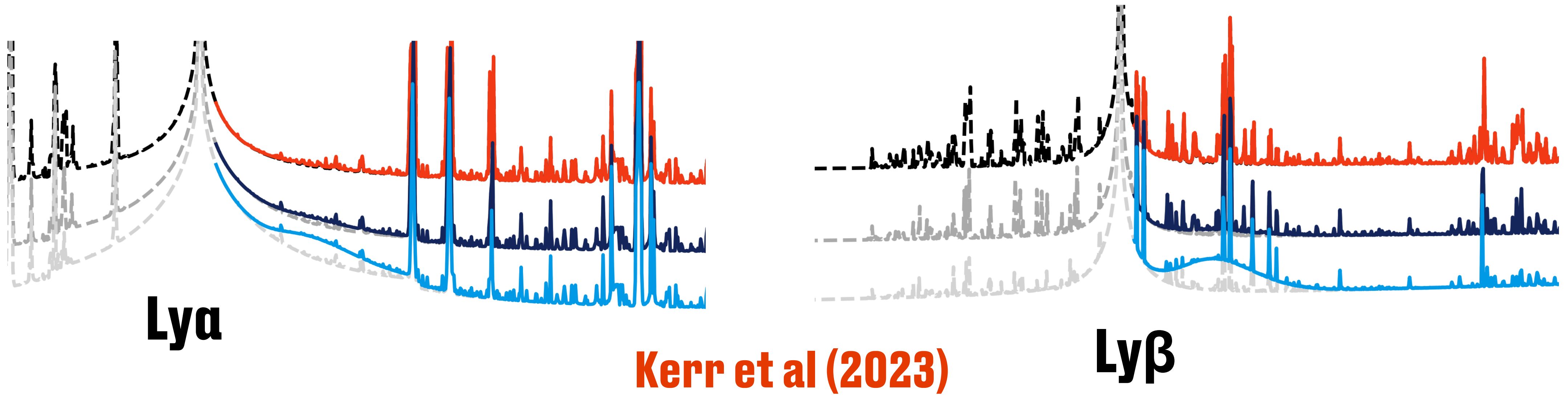
HOW MUCH FLARE ENERGY IS CARRIED BY NONTHERMAL IONS?

Some studies suggest they may carry energy comparable to nonthermal electrons.

We are potentially not considering a significant fraction of the flare energy budget transported to the lower atmosphere!

Having information regarding both the energy content, and also the distribution functions are essential to correctly model the lower atmosphere's response and to validate particle acceleration models.

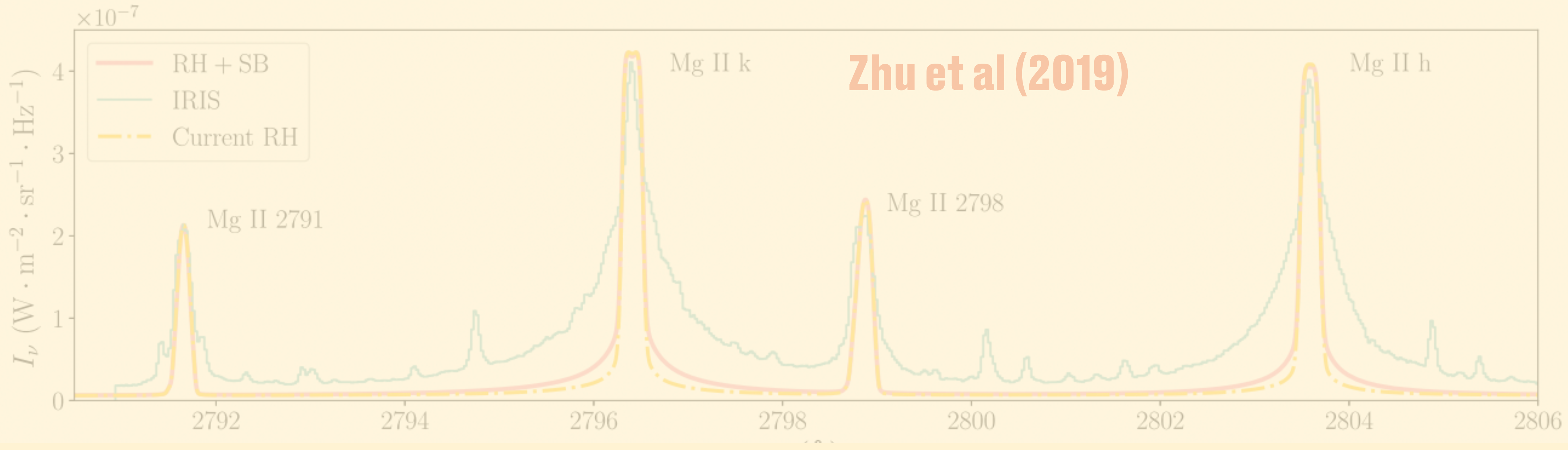


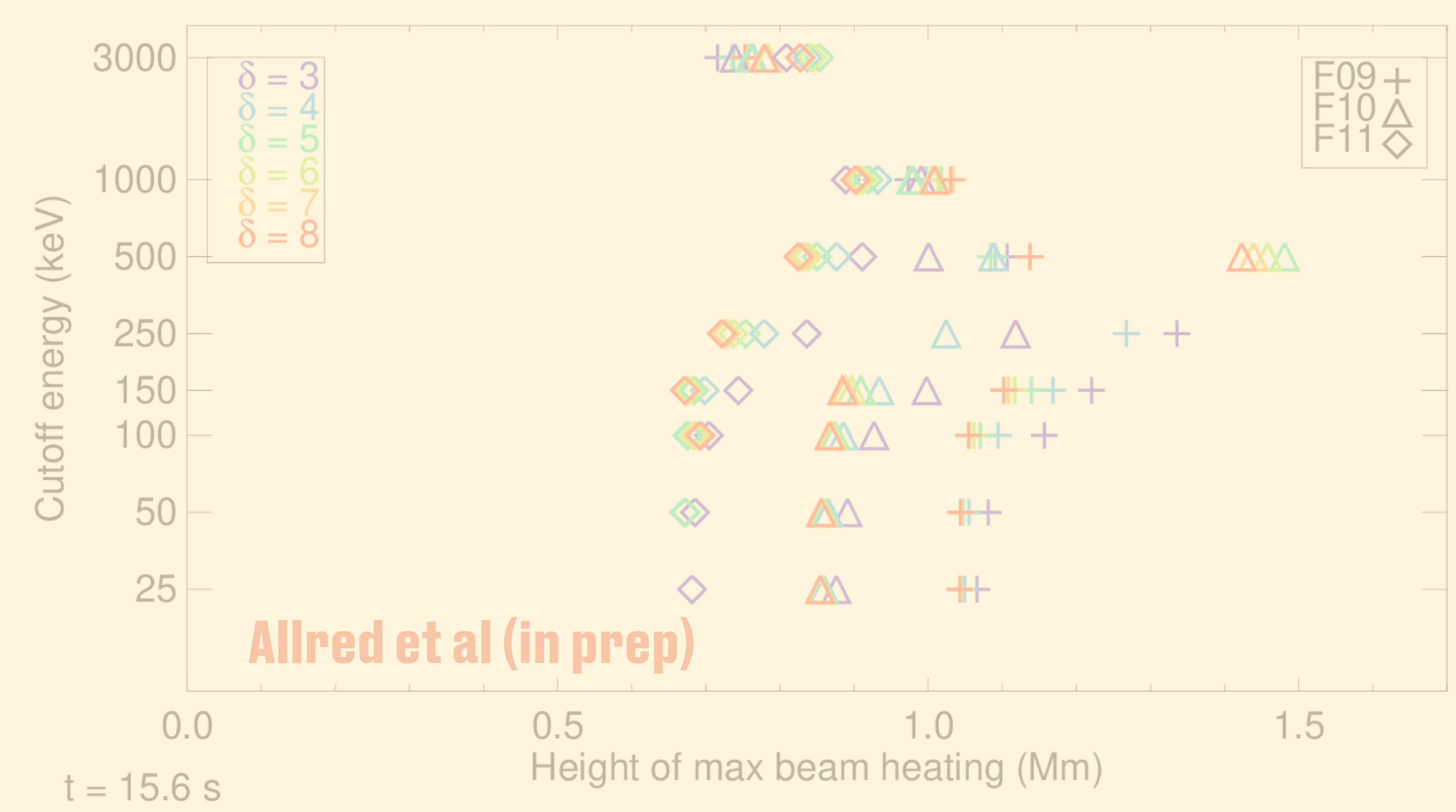


DO WE NEED HEATING DEEPER THAN CURRENTLY PREDICTED BY ELECTRON-BEAM ONLY MODELS?

Various strands of evidence (strong temperature-minimum response, wider-than-predicted wings of chromospheric lines, and the white light continuum response) suggest that we could need heating deeper in the chromosphere than currently predicted.

Proton beams can carry energy deeper into the Sun's atmosphere than nonthermal electrons... **but the distribution injected to our models is unconstrained**!





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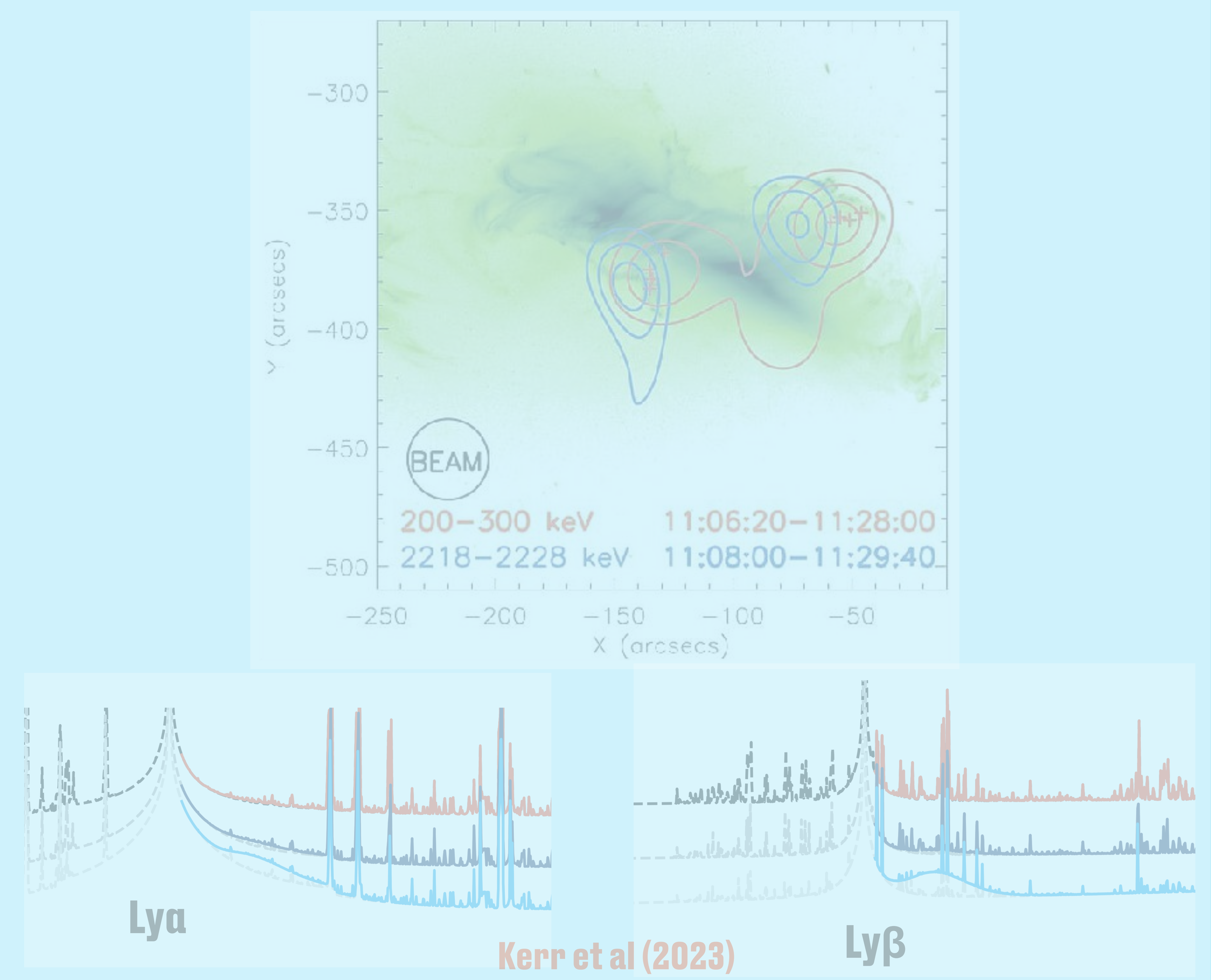

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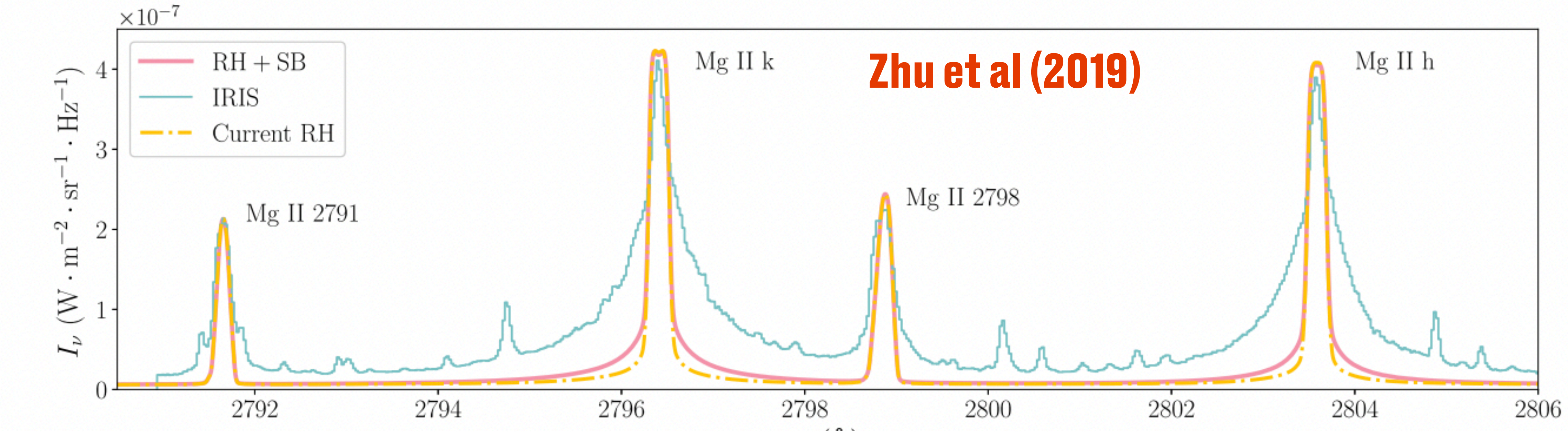
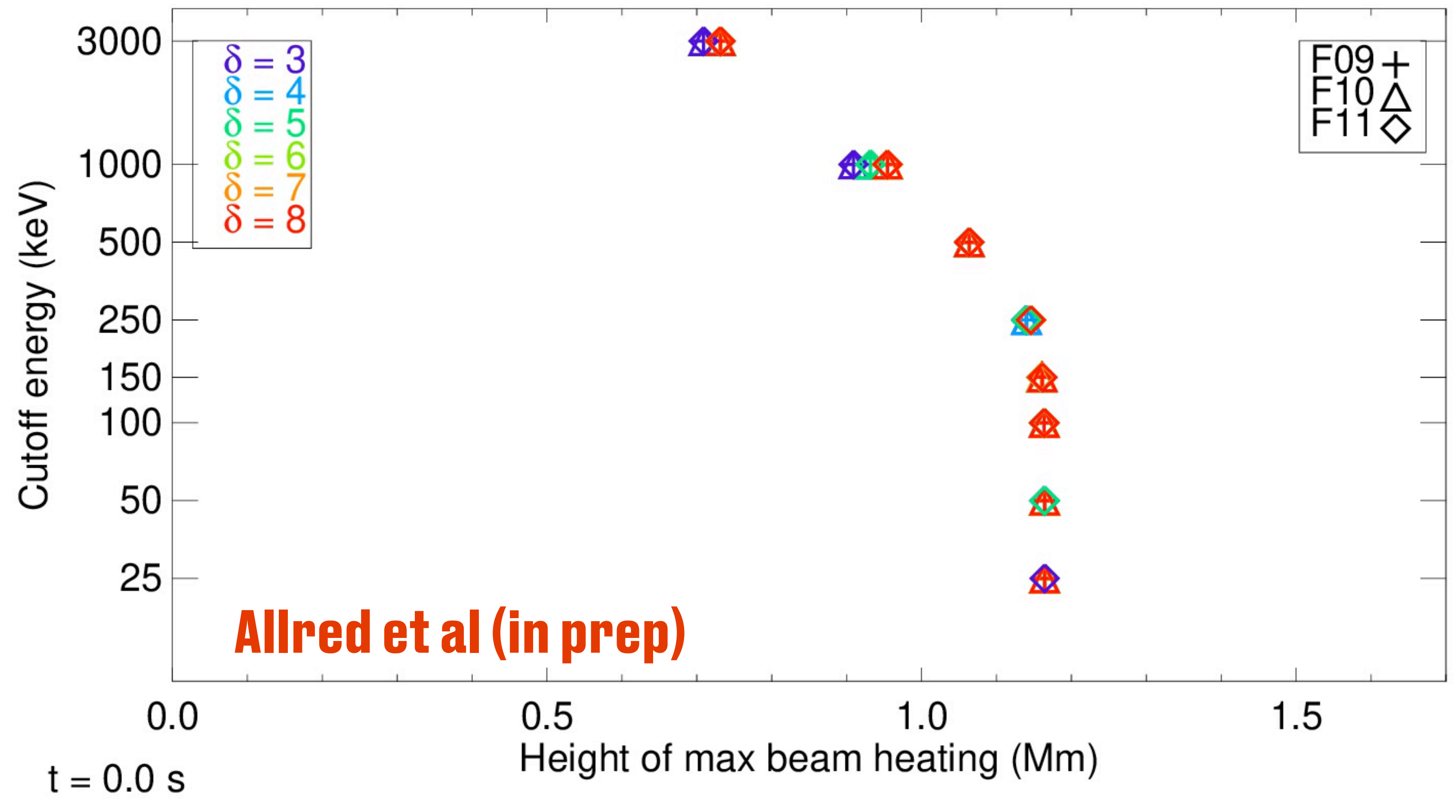




TURBULENCE SCALES THROUGHOUT THE ATMOSPHERE

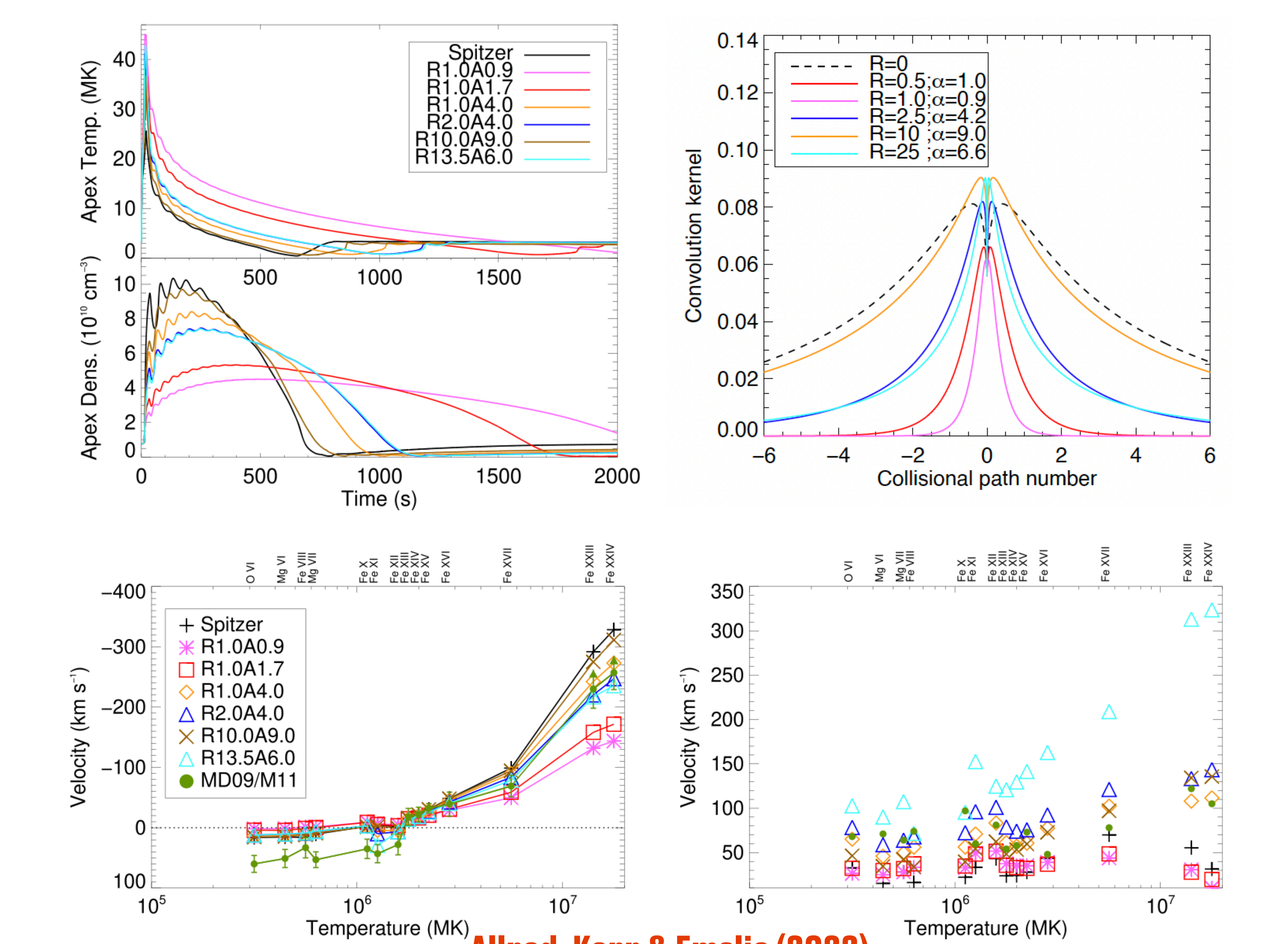
OBSERVATIONAL WISH #3

THE FLARE GRADUAL PHASE IS MUCH LONGER THAN PREDICTED

Suppression of thermal conduction can lengthen the predicted gradual phase to be more in-line with observations.

However parameters of the turbulent mean free path length and the velocity dependence are very unconstrained.

Knowledge of turbulence throughout the flare atmosphere is essential to understand if suppression of conduction can fix most of the problem or if we need additional energy injection in the post-impulsive phase of flares.



Allred, Kerr & Emslie (2022)

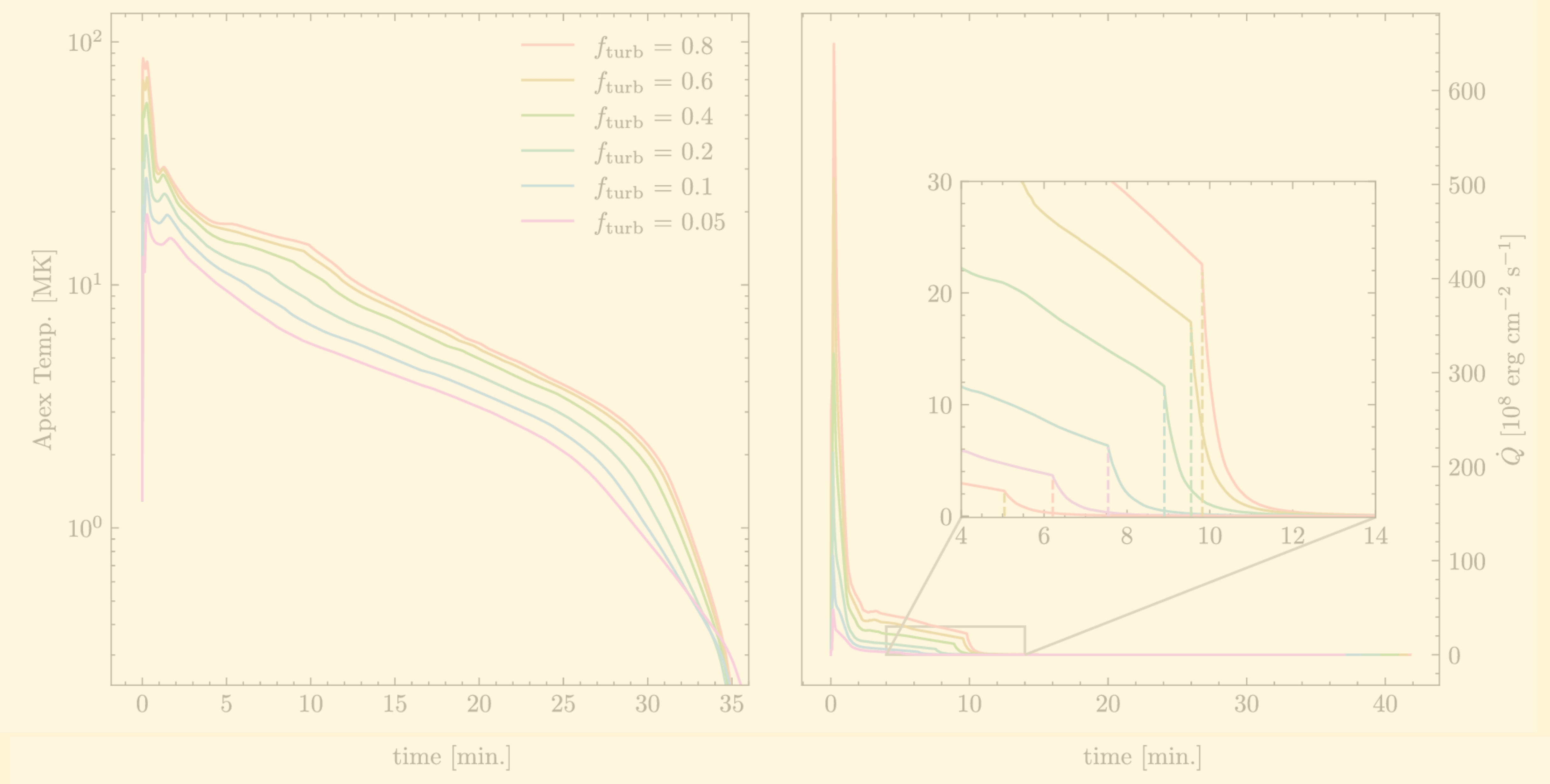
CAN TURBULENCE ACTIVELY *HEAT* DURING THE GRADUAL PHASE

Models of retracting magnetic loops experiencing drag have shown that MHD turbulence develops due to counter-propagating Alfvén waves (**Ashfield & Longcope, 2023**).

Heating of the flare loops and footpoints result, which could account for gradual phase heating.

To test this we need observations of the coronal magnetic field, un-saturated high cadence EUV loops, and measures of turbulence (e.g. line broadening at multiple temperatures).

Ashfield & Longcope (2023)



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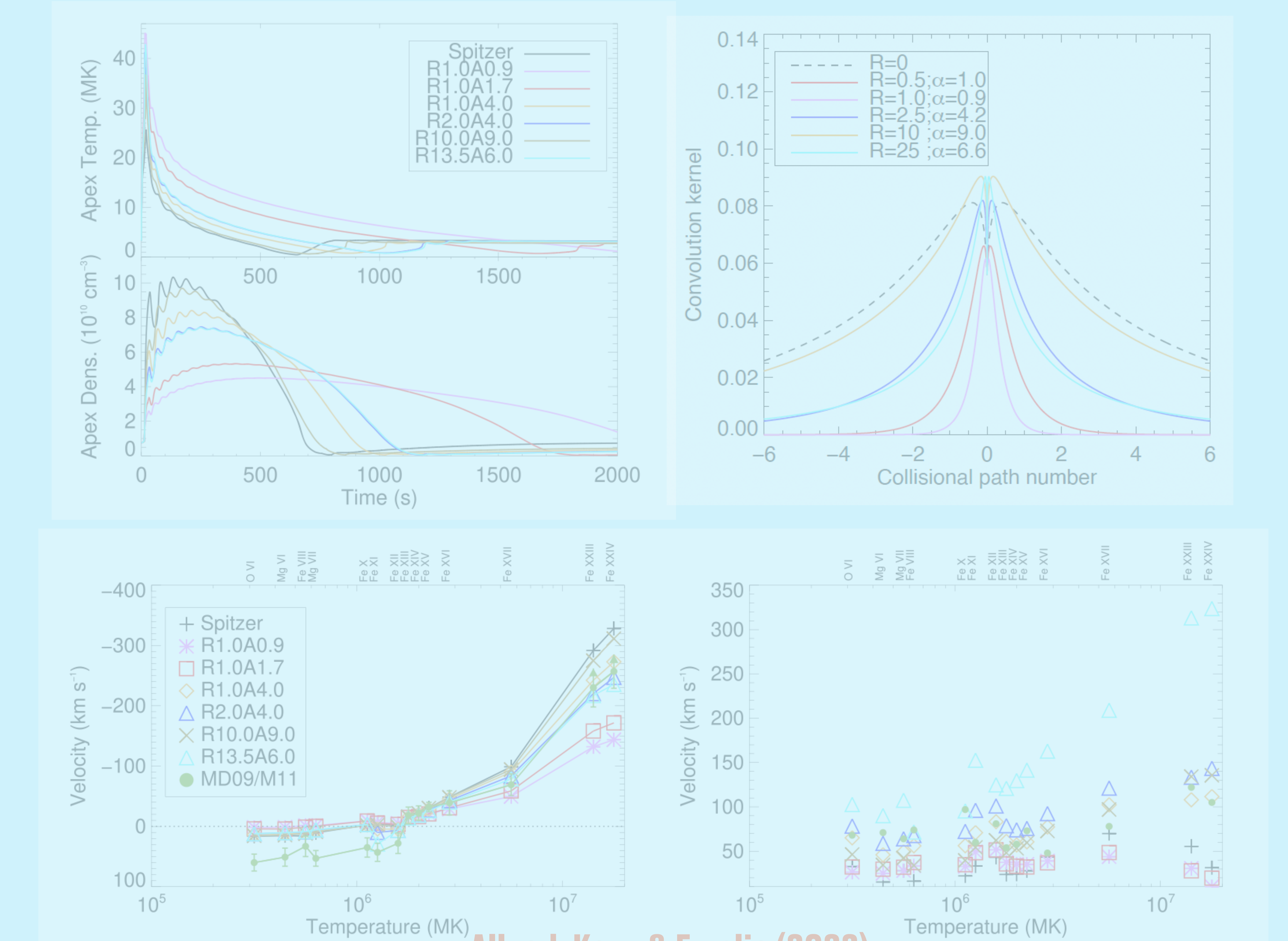

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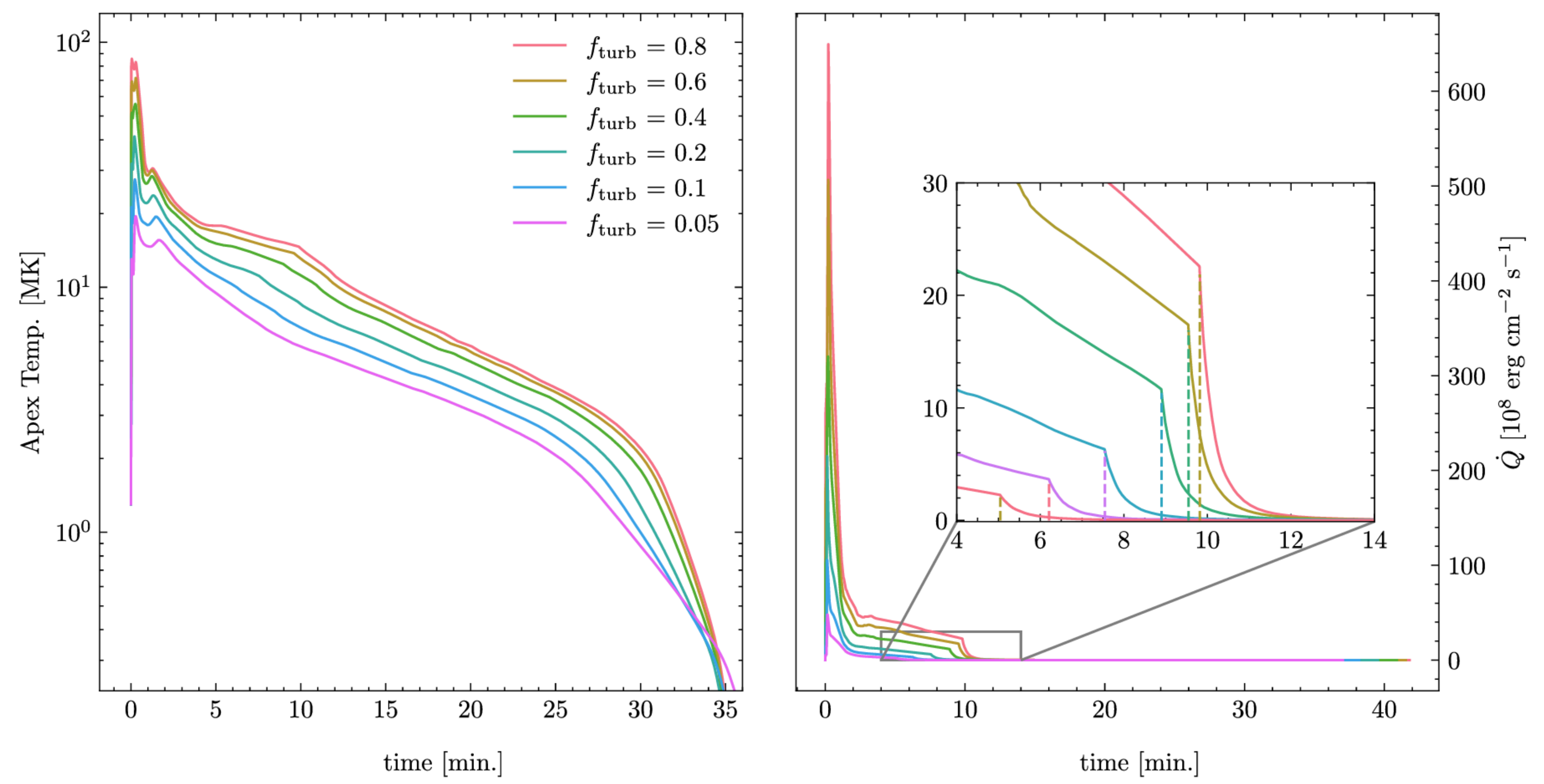

SUMMARY

Different types of solar flare (eruptive event) numerical modelling target different aspects of the flare problem: spectral inversions; loop models with parameterised heating; multi-D (r)MHD models

Next-Gen models will bridge the orders of magnitude spatial scales at which physical processes operate in flares: end-to-end framework, with linked models; (r)MHD with parameterised nonthermal electrons

Observations are required to validate and constrain. If validation fails, we tinker, add physics, and invariably need additional constraints.

Some observations that (I personally think) are needed to constrain models: stratified magnetic fields (area expansion, MHD wave parameters, energy build up, guide field), properties of flare accelerated ions (are we missing a significant portion of flare energy?) & measures of turbulence (suppression of thermal conduction)... I have a long list of others!