12 October 2022

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Solar Flare Impulsiveness and Its Relationship with Ribbon Development and Energy Release

University of Colorado Boulder

NSO National Solar Observatory

LASP

Motivation

Do simulation predictions for the relationship between flare energy release and magnetic field configuration show up in the observations?

How does the geometry of flaring regions on the solar surface relate to the timing of energy release?

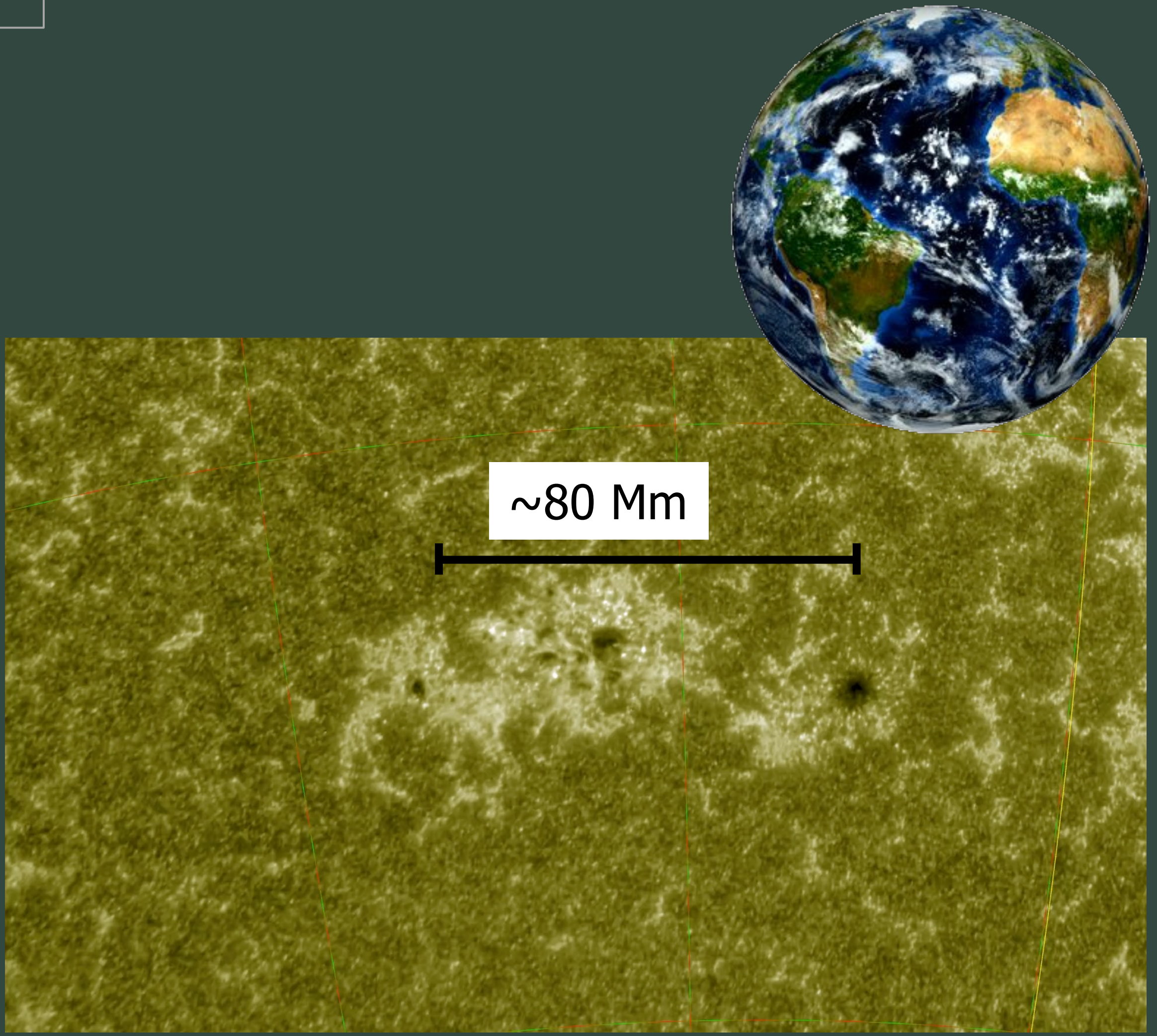
Does impulsiveness, which reflects the energy deposition rate of a solar flare, relate to these quantities?

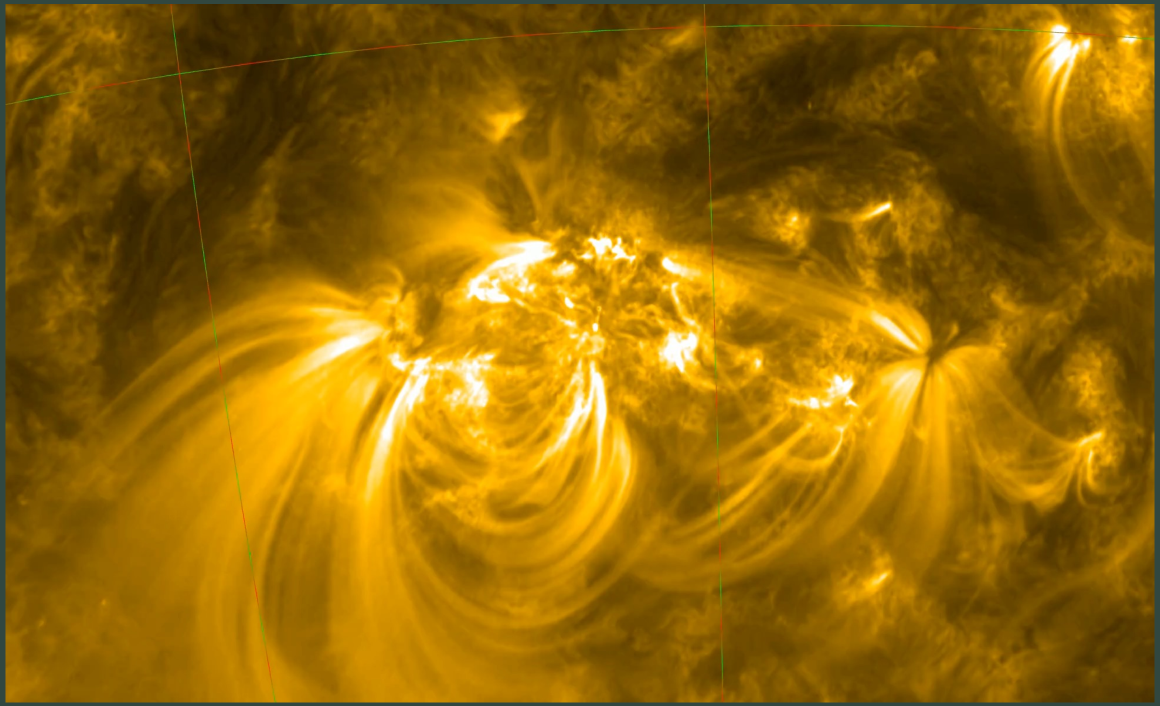
Main science question: ***How does flare impulsiveness relate to he magnetic field configuration and the timing of energy release?***

Outline

1. What is a solar flare, and what in particular do we care about?
2. How did we do what we did?
   a. Instruments and data
   b. Event selection
   c. Ribbon evolution
3. What did we find?
   a. Impulsiveness statistics
   b. Low impulsiveness events
   c. Mid-impulsiveness events
   d. High impulsiveness events
   e. Impulsiveness vs. magnetic shear proxy
4. What else is there to do?

1. Background: Example of observations





Example: 13 October 2013 GOES M1.8 in 1600 Å (left) and 171 Å (right)

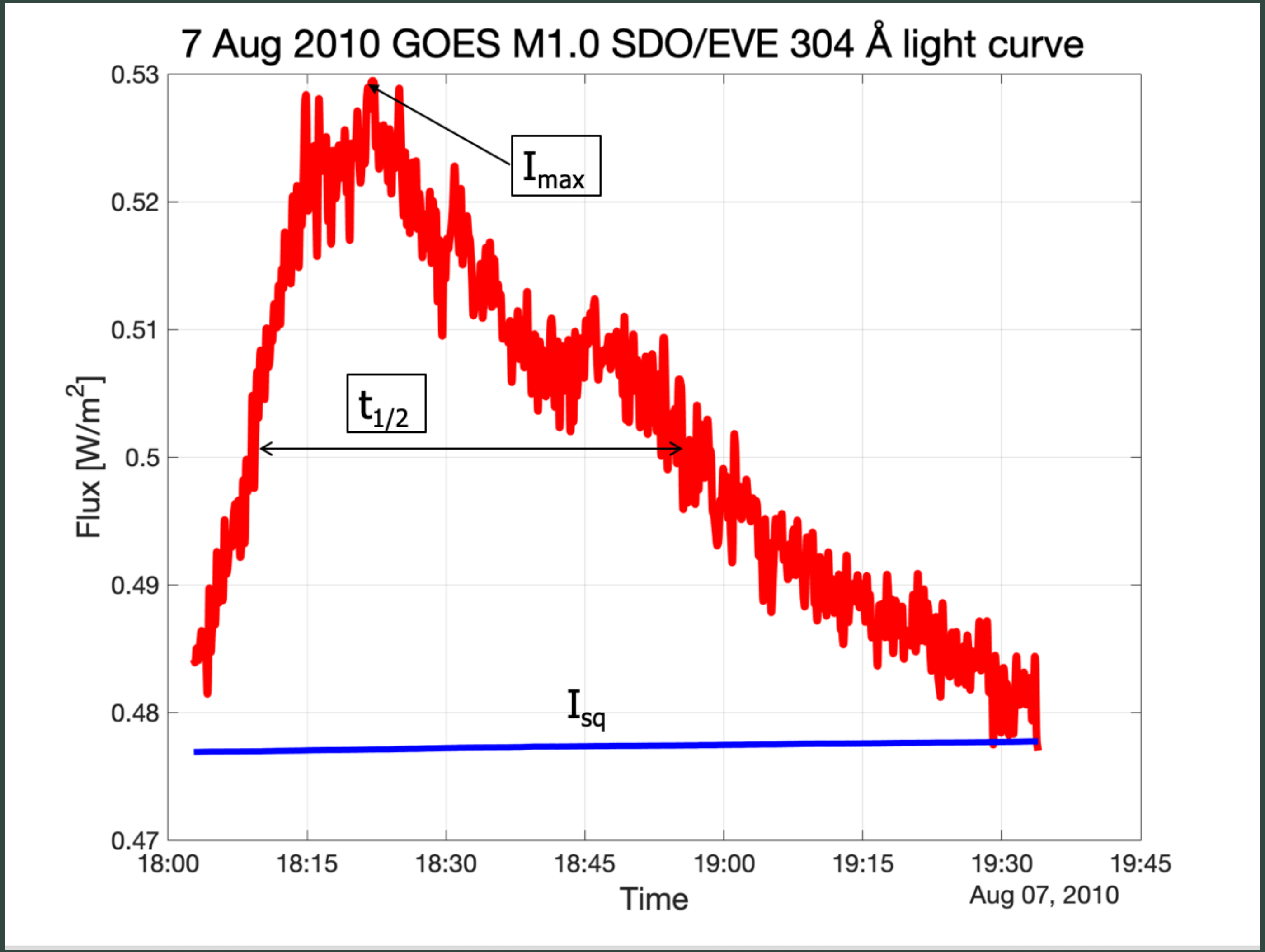
Source: JHelioViewer

1. Background: The Impulsiveness Index

Ratio of peak irradiance to full width at half height in time

$$i = \frac{I_{max}}{t_{1/2}}$$

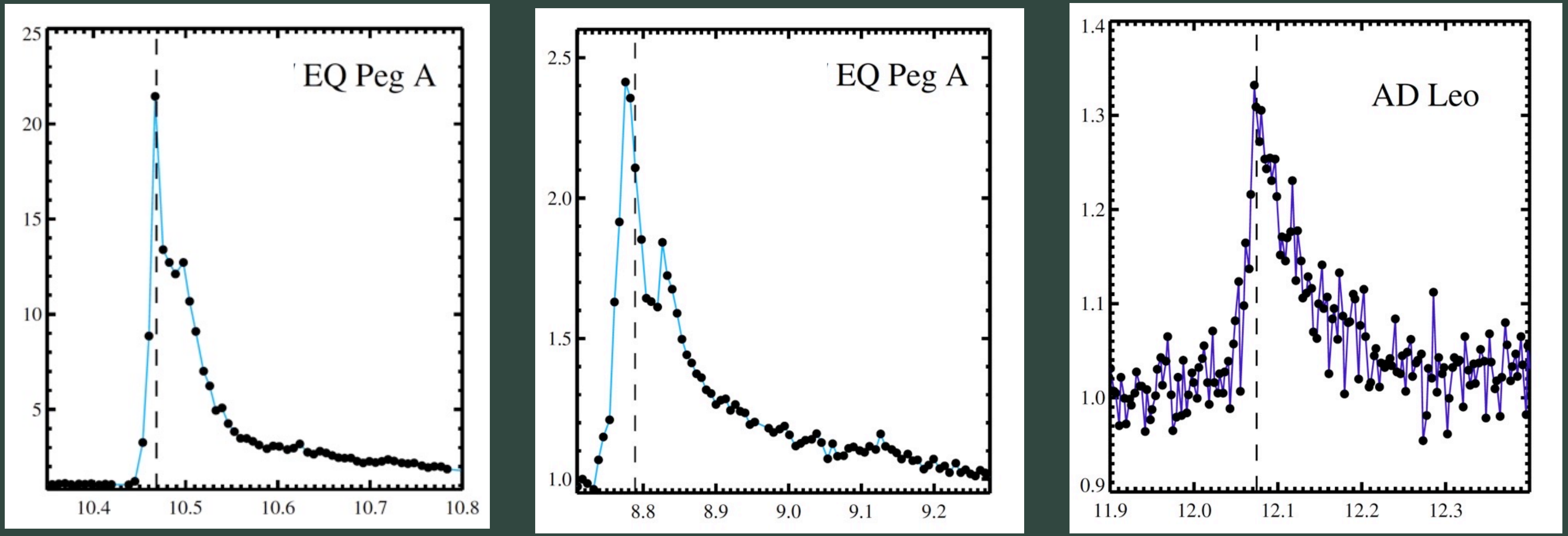
Inspired by Kowalski et al. (2013)



1. Background: Stellar Flare Classification by Impulsiveness

Highly impulsive ***Kinda impulsive*** ***Not very impulsive***

Optical Flux



Time (hours)

Source: Kowalski et al. 2013

Reflects overall light curve evolution rather than just peak intensity; timing of energy release

In stellar flares, higher impulsiveness → lower Balmer jump

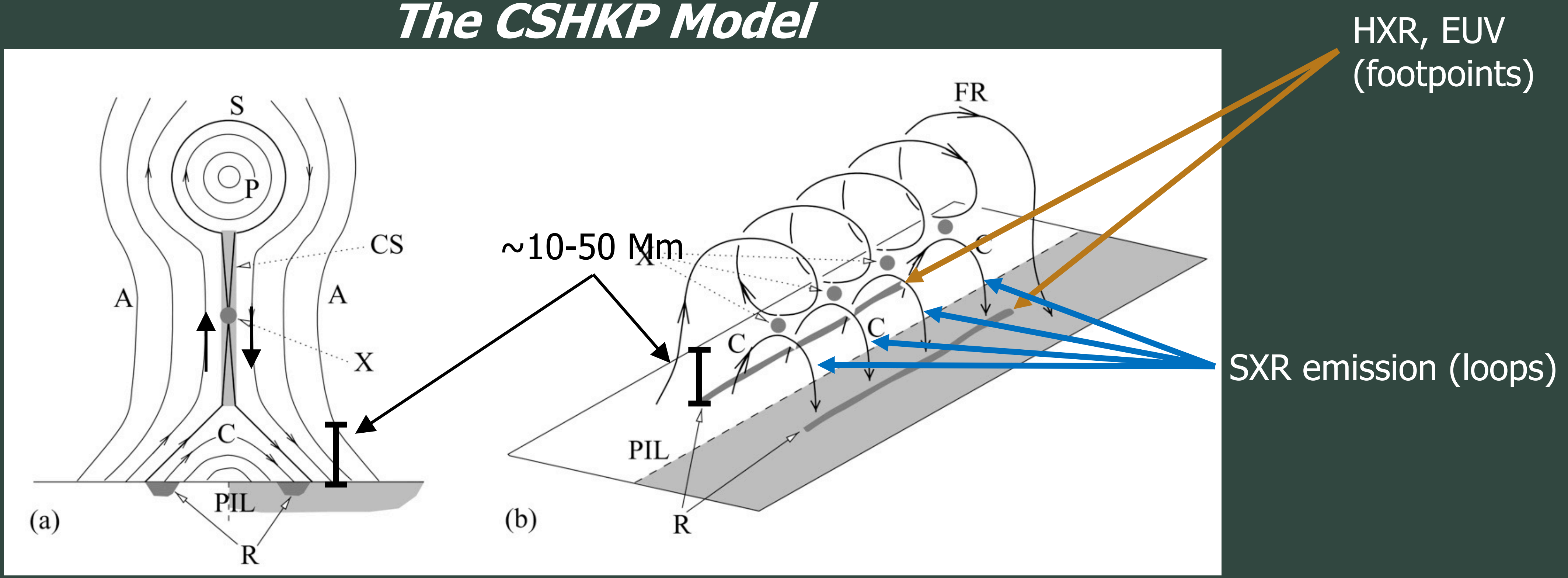
1. Background: Fundamental flare model

Explosive release of energy resulting from magnetic reconnection in the corona

Particle precipitation → HXR, EUV emission: "***Footpoints***"

Chromospheric evaporation → SXR emission near X-point ($T \sim 10^7 K$ in loops)

The CSHKP Model



Source: Longcope et al. (2007)

1. Background: The Third Dimension, and Magnetic Shear

Shear introduced by strength of guide field component of magnetic field

Qiu et al. (2010), Qiu and Cheng (2022), etc.: “strong-to-weak” shear pattern

Evolution of Loop Orientation

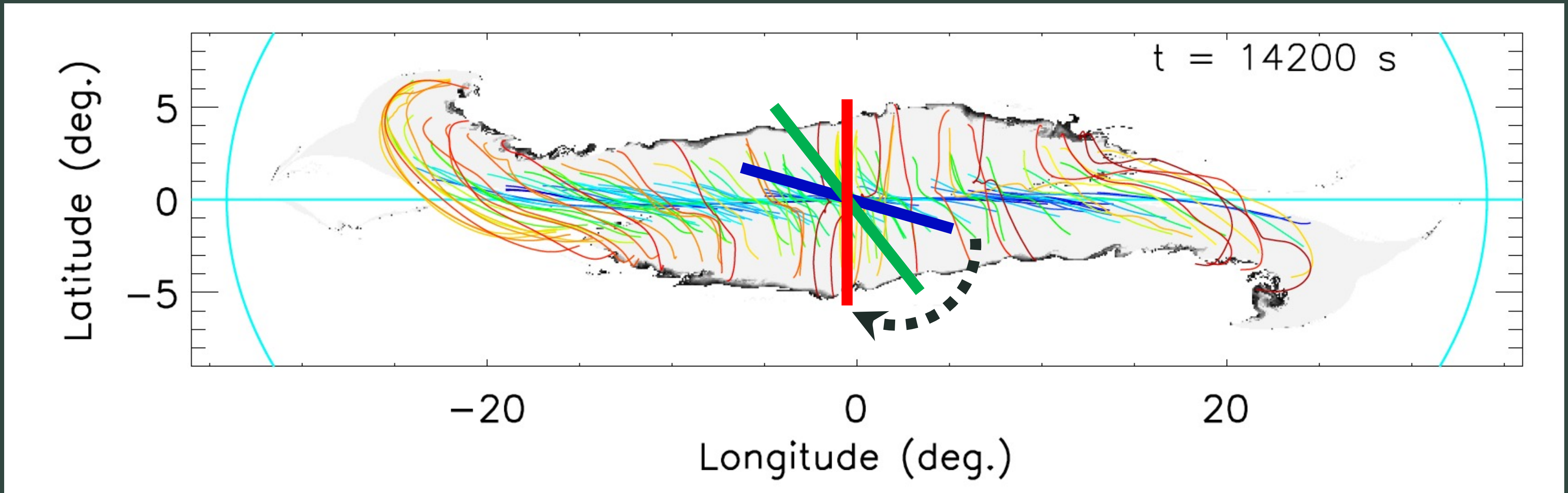


Fig. 4 from Dahlin et al. 2021

$$\frac{\partial \vec{B}}{\partial t} = \nabla\times(\vec{u}\times\vec{B}) + \eta\nabla^2\vec{B}$$

1. Background: Magnetic islands

The diffusion term is important in reconnection due to much smaller length scale ($L \sim 10^3 cm$)

Explaining the speed of reconnection remains a problem

e.g. Tearing instability → "magnetic islands"

Magnetic Islands

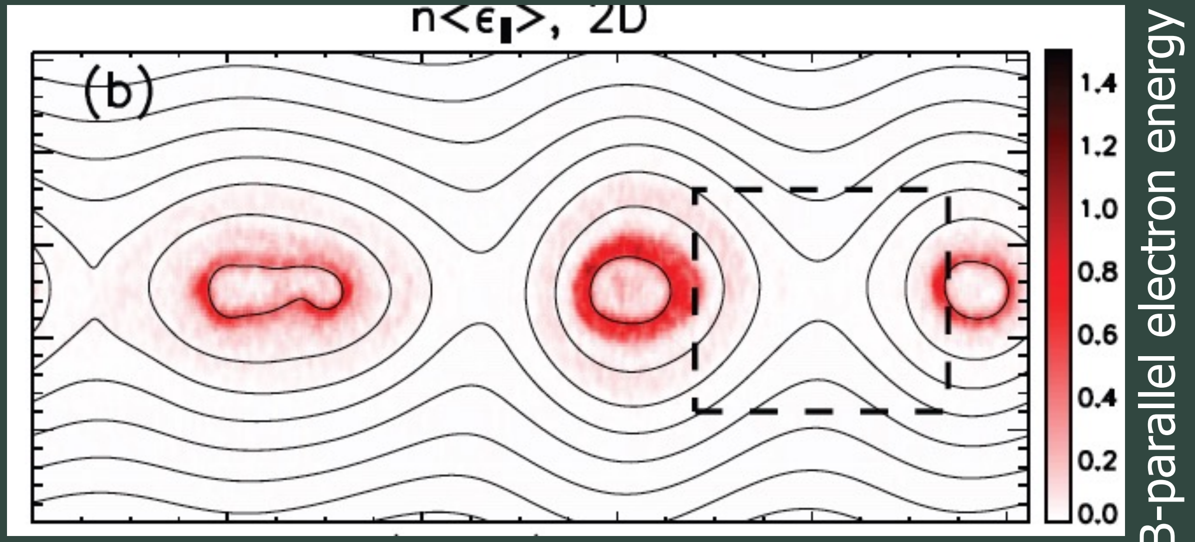


Fig. 8 from Dahlin et al. (2020)

Simple Reconnection Region

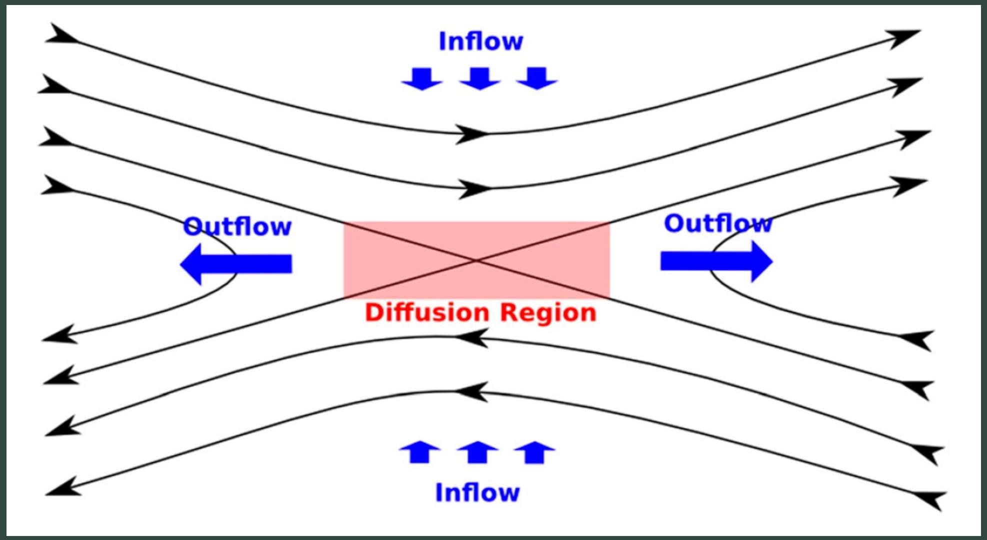
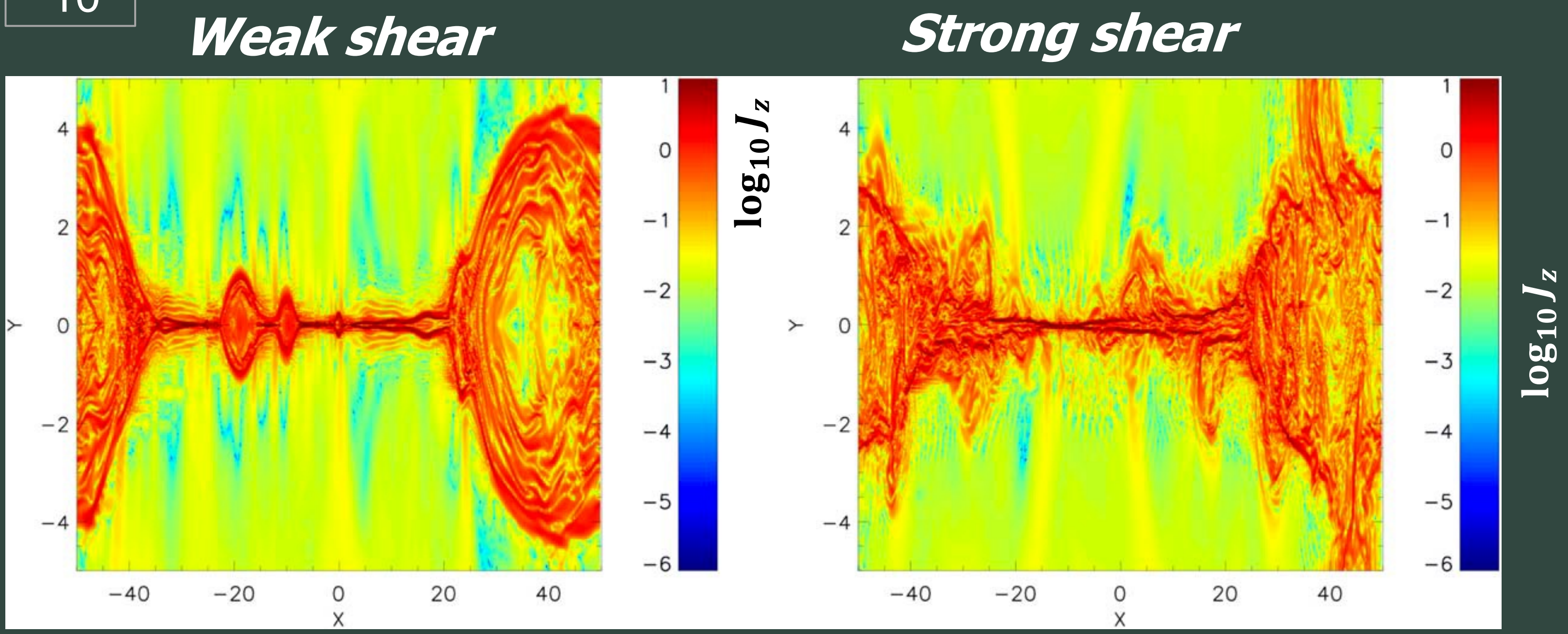
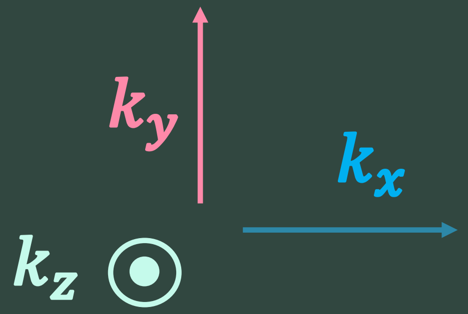


Fig. 1 from Dahlin et al. (2020)



From Daldorff et al. 2022

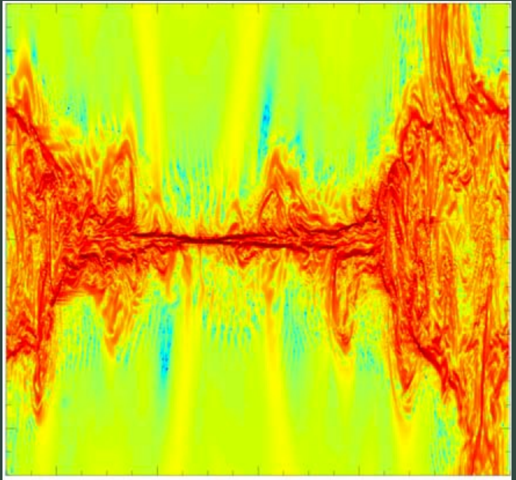
1. Background: The Role of Shear, Explained

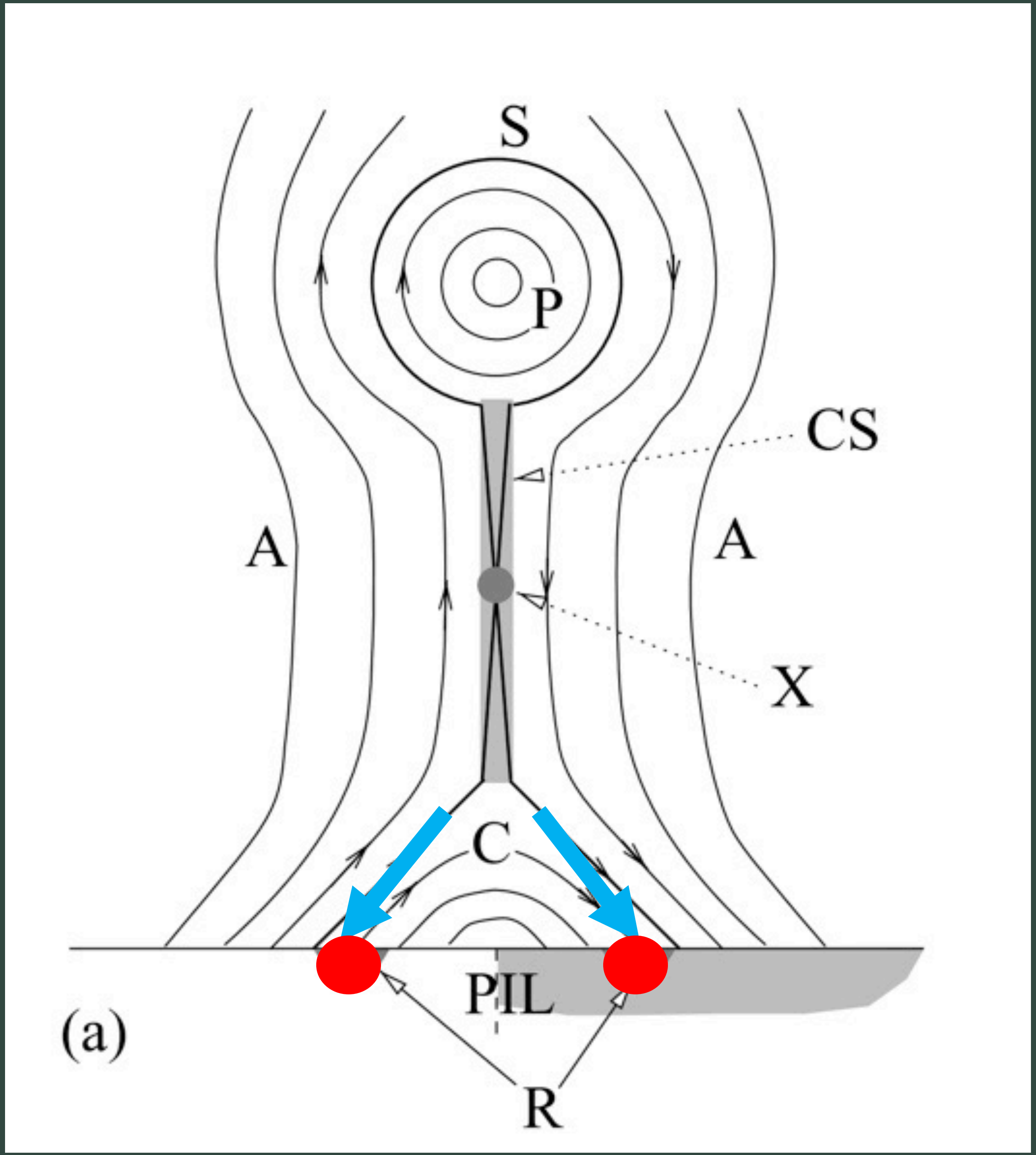


$$V_y(x,y,z) = \sum_{m,l,n} V_0^{mln} \sin\left(k_x - \phi_x^{mln}\right) \sin\left(k_y y - \phi_y^{mln}\right) \sin\left(k_z z - \phi_z^{mln}\right)$$

Tearing instability: Lowers magnetic energy locally (formation of islands); requires resistivity

Guide field → "oblique modes" → more surfaces for tearing instability to grow





Reconnection → Particle Precipitation

1. Background: Importance of magnetic shear

Require mechanism for acceleration of particles in current sheet

Recent findings: three sources of electron energization in a current sheet

$$\frac{d\epsilon}{dt} = qE_{||}v_{||} + \frac{\mu}{\gamma}\left(\frac{\partial \vec{B}}{\partial t} + \vec{u}_E \cdot \nabla \vec{B}\right) + \gamma m_e v_{||}^2 (\vec{u}_E \cdot \vec{\kappa})$$

Amount of ***magnetic shear*** is important to flare development – storage of free energy, timing of particle acceleration

1. Background: Components for electron acceleration

$$qE_{||}v_{||}$$

E-field parallel acceleration

Enhanced by strong shear

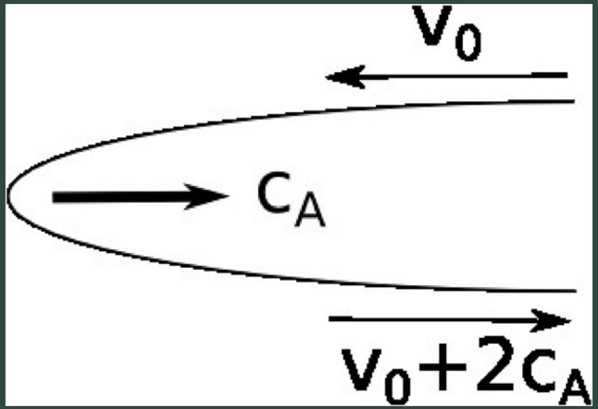
$$\frac{\mu}{\gamma}\left(\frac{\partial \vec{B}}{\partial t} + \vec{u}_E \cdot \nabla \vec{B}\right)$$

Betatron acceleration

$$\gamma m_e v_{||}^2 (\vec{u}_E \cdot \vec{\kappa})$$

Fermi acceleration/reflection via magnetic mirroring

Dahlin 2020



Dahlin et al. (2021) and Daldorff et al. (2022): ***shear suppresses particle precipitation early in flare development***

1. Background: Summary

New classification system: ***impulsiveness, i***

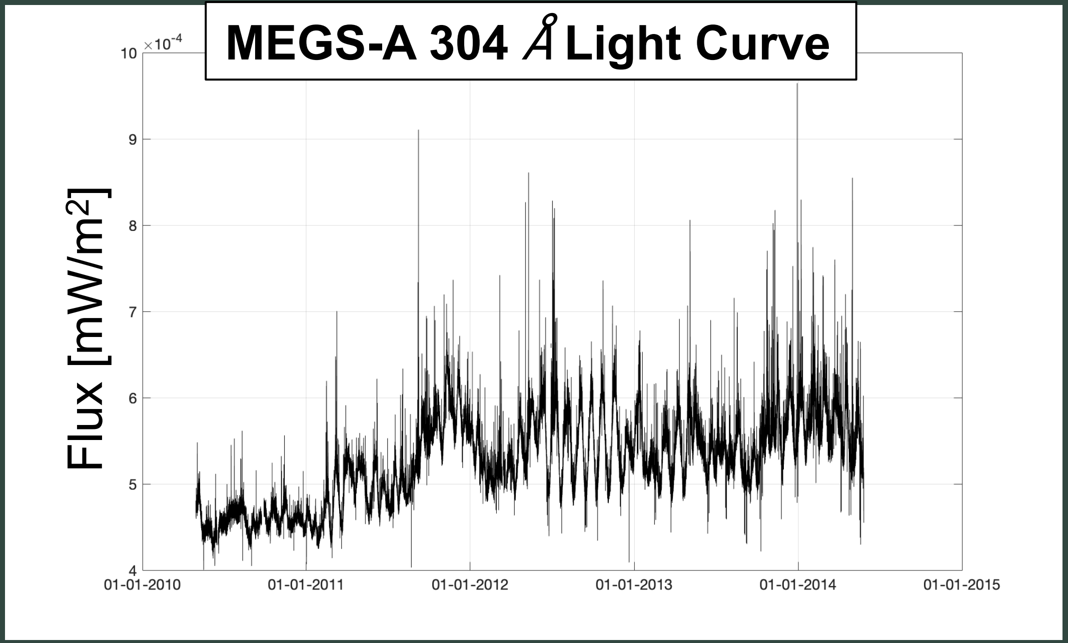
Magnetic reconnection in corona → flare

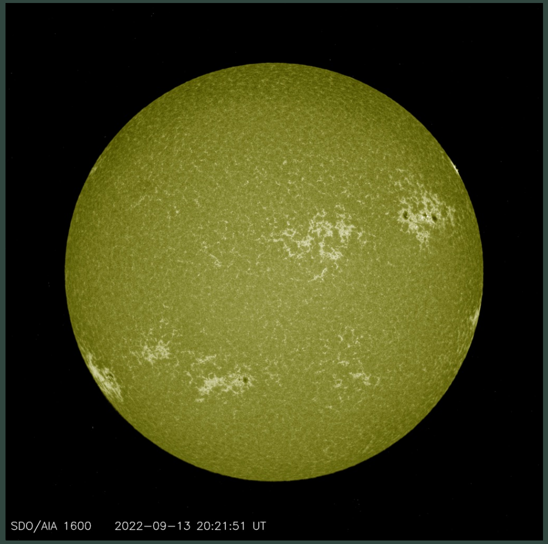
Presence of magnetic shear important to flare development

Do observations support the simulated delay in particle precipitation at strong shear, and is this reflected in the impulsiveness index?

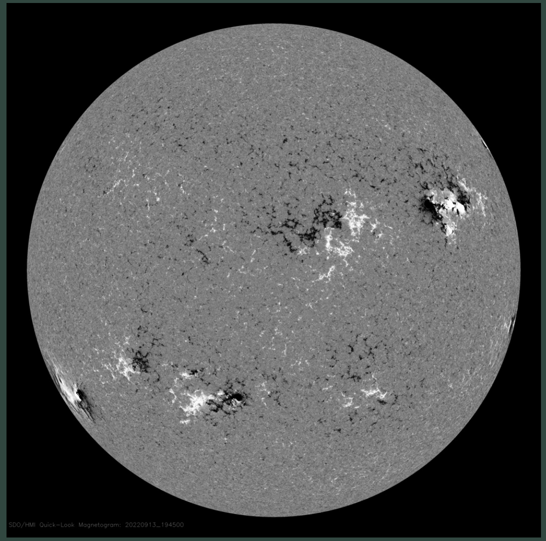
What about the relationship with other flare properties?

2a. Methods: Instruments





SDO/AIA 1600 Å



SDO/HMI Magnetogram

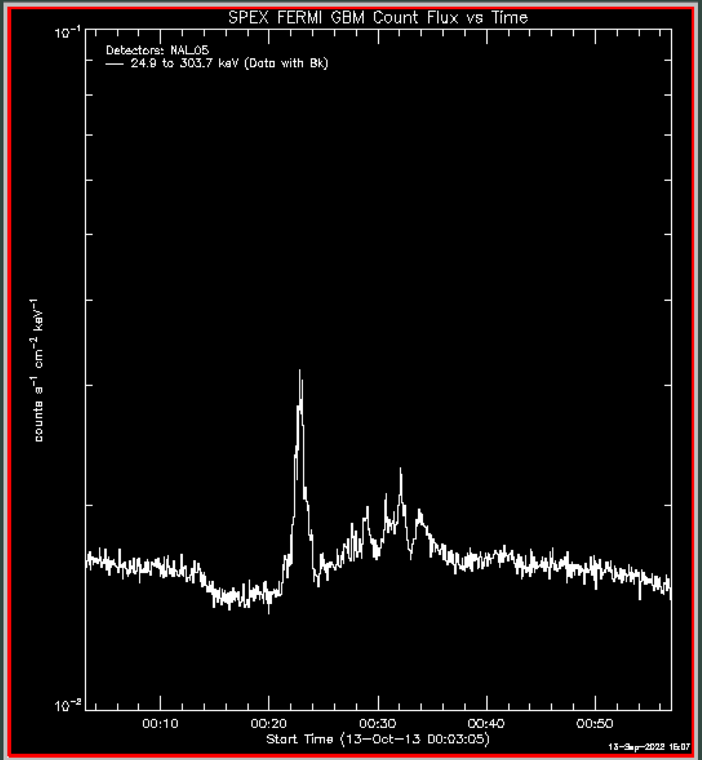
Source: sdo.gsfc.nasa.gov; Accessed 13 Sep 2022

SDO/EVE – 304 Å Sun-as-a-star data, used for impulsiveness development

SDO/AIA – 1600 Å full-disk, used for ribbon evolution; 131 Å full-disk, used to verify coronal loop orientation

SDO/HMI – used to identify magnetic polarity of ribbons

Fermi/GBM – integrated 25-300 keV; particle precipitation



Example of OSPEX, 13 Oct 2013 flare; https://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_explanation.htm

2b. Methods: Event Selection, Light Curve Fitting Algorithm

RibbonDB (Kazachenko et al. 2017) – database of 3137 solar flares between April 2010 and April 2016

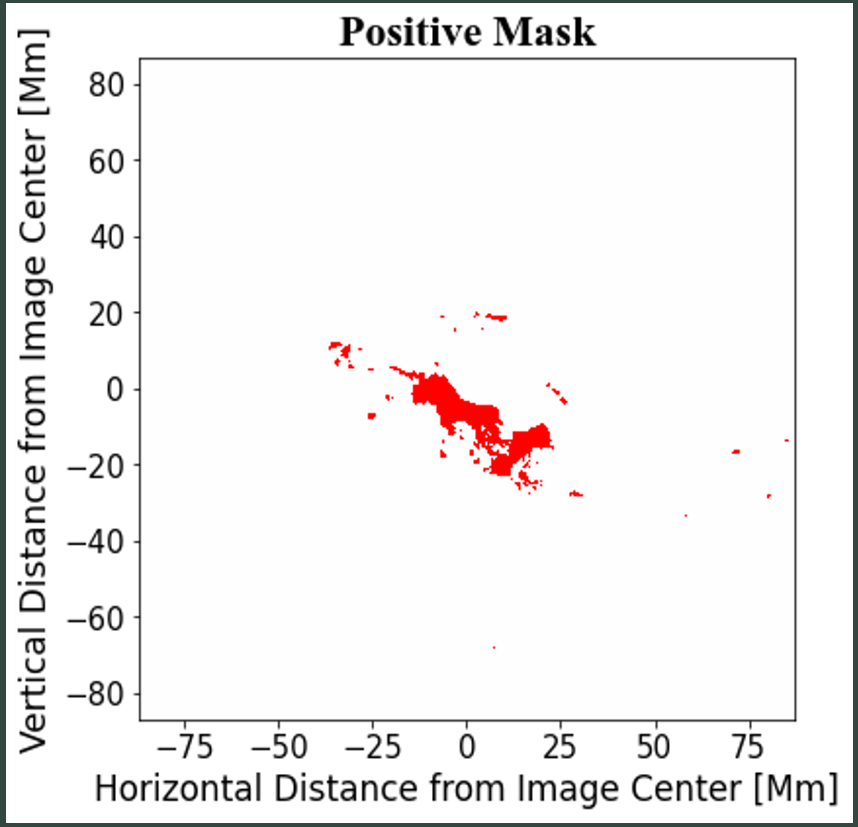
Apply searching algorithm to SDO/EVE 304 Å light curve to identify EUV flare parameters

Model flare rise and decay phase separately

Sample of flares with best S/N is based on fidelity to these models

2c. Methods: Masking Positive and Negative Polarities

$$M_{cut}(x_i, y_i, t_k) = M_{cut}(x_i, y_i, t_{k-1}) \cup N_{cut}(x_i, y_i, t_k)$$



Masks identify pixels such that:

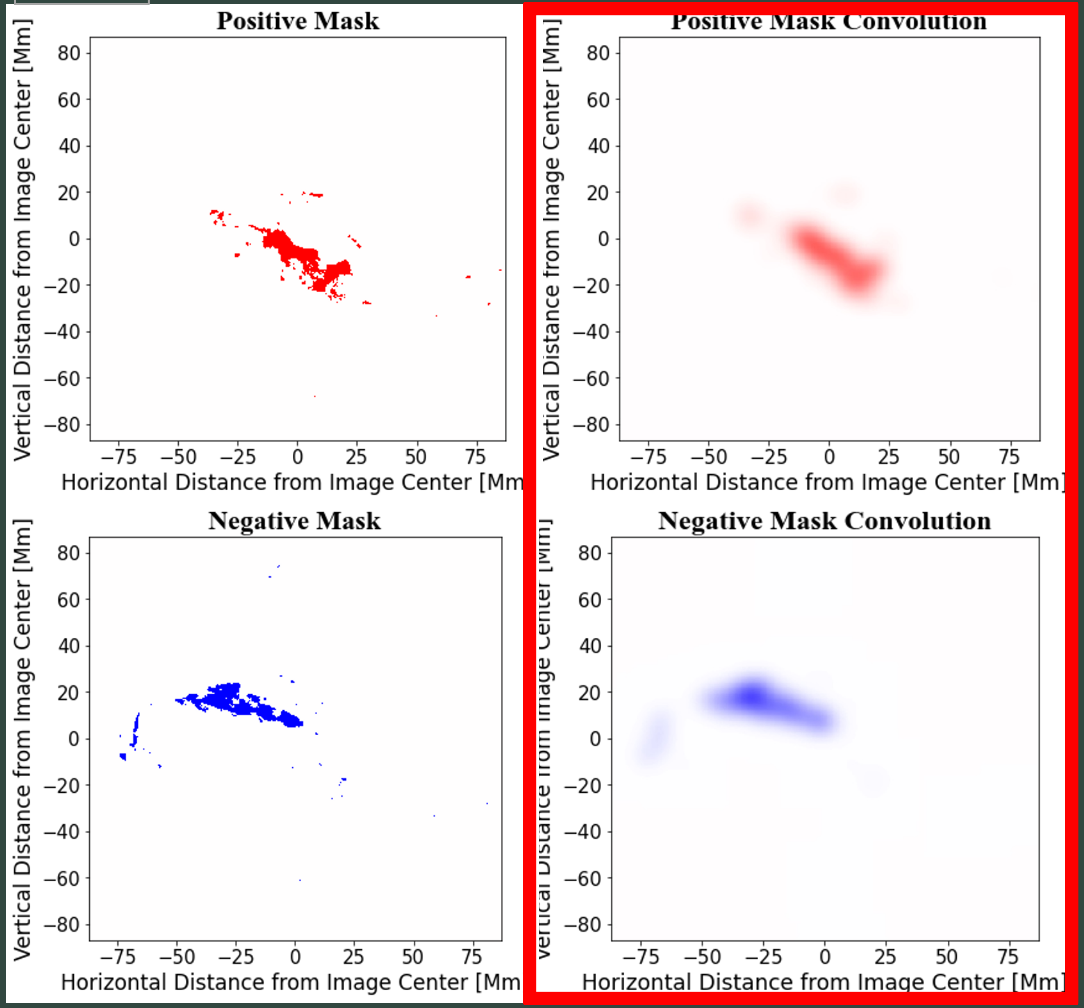
intensity > *c* *median intensity of image

Isolate positive and negative masks with HMI

Left: example of 13 October 2013 flare, positive ribbon mask

Ribbon Masking and Convolution

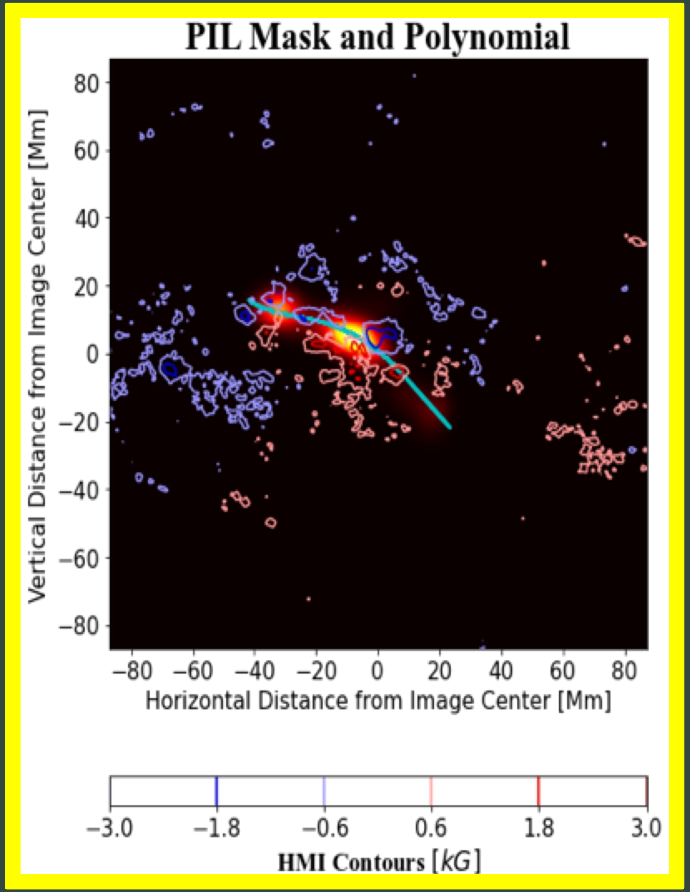
2c. Methods: Ribbon evolution



Inspired by Wang et al. (2021)

Gaussian convolution of masks

Intersection yields PIL mask; fitted polynomial is used as PIL reference

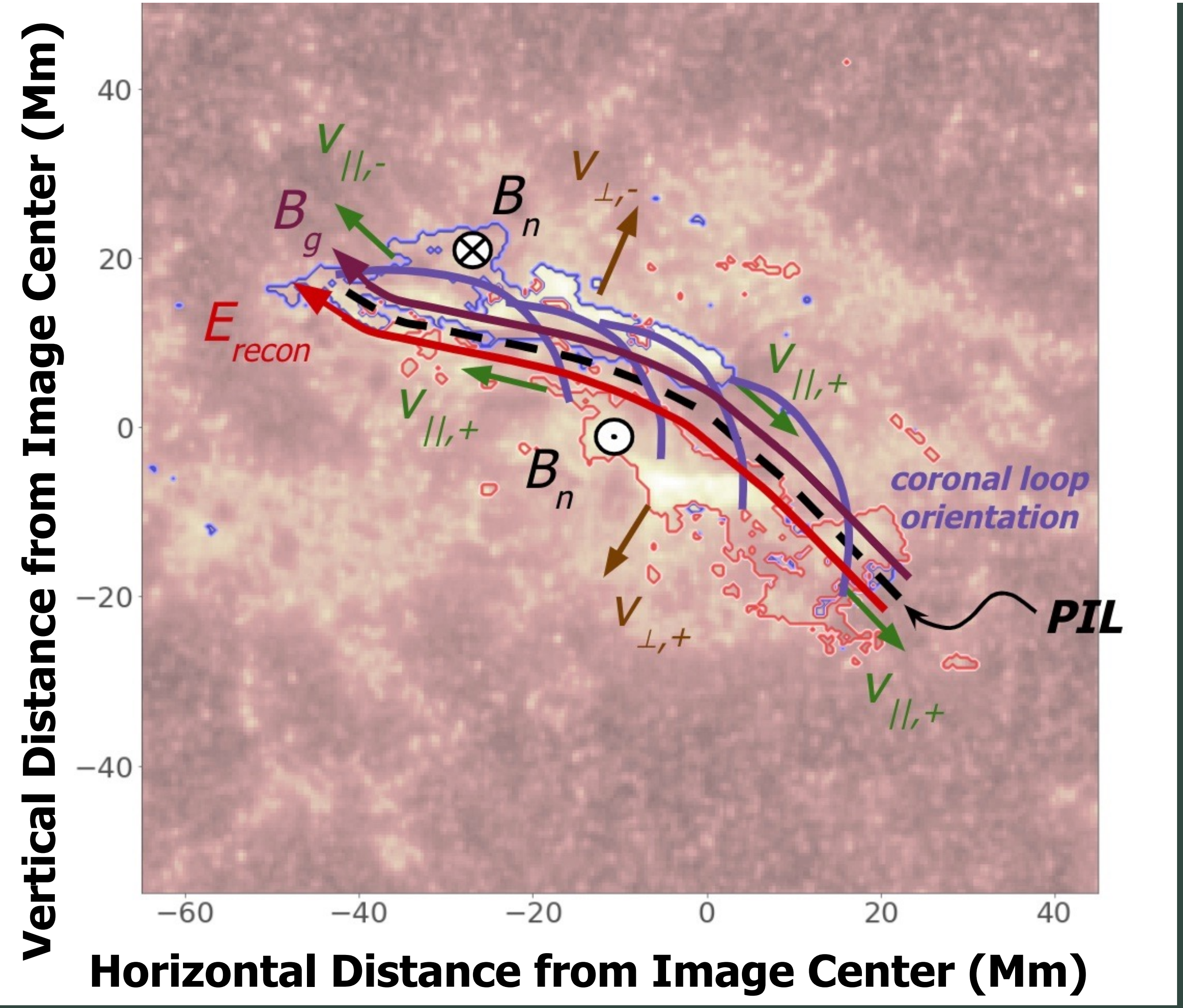


(Left) Sample identification of positive and negative polarity ribbons using SDO/AIA 1600 Å images and HMI magnetograms. (Right) Convolution of ribbon masks with a Gaussian function for use in PIL identification.

Presented at AGU Fall Meeting 2021

2c. Methods: Ribbon evolution

13 Oct 2013; GOES M1.7; $i = -0.97\ \ln(\frac{nW}{m^2 s})$

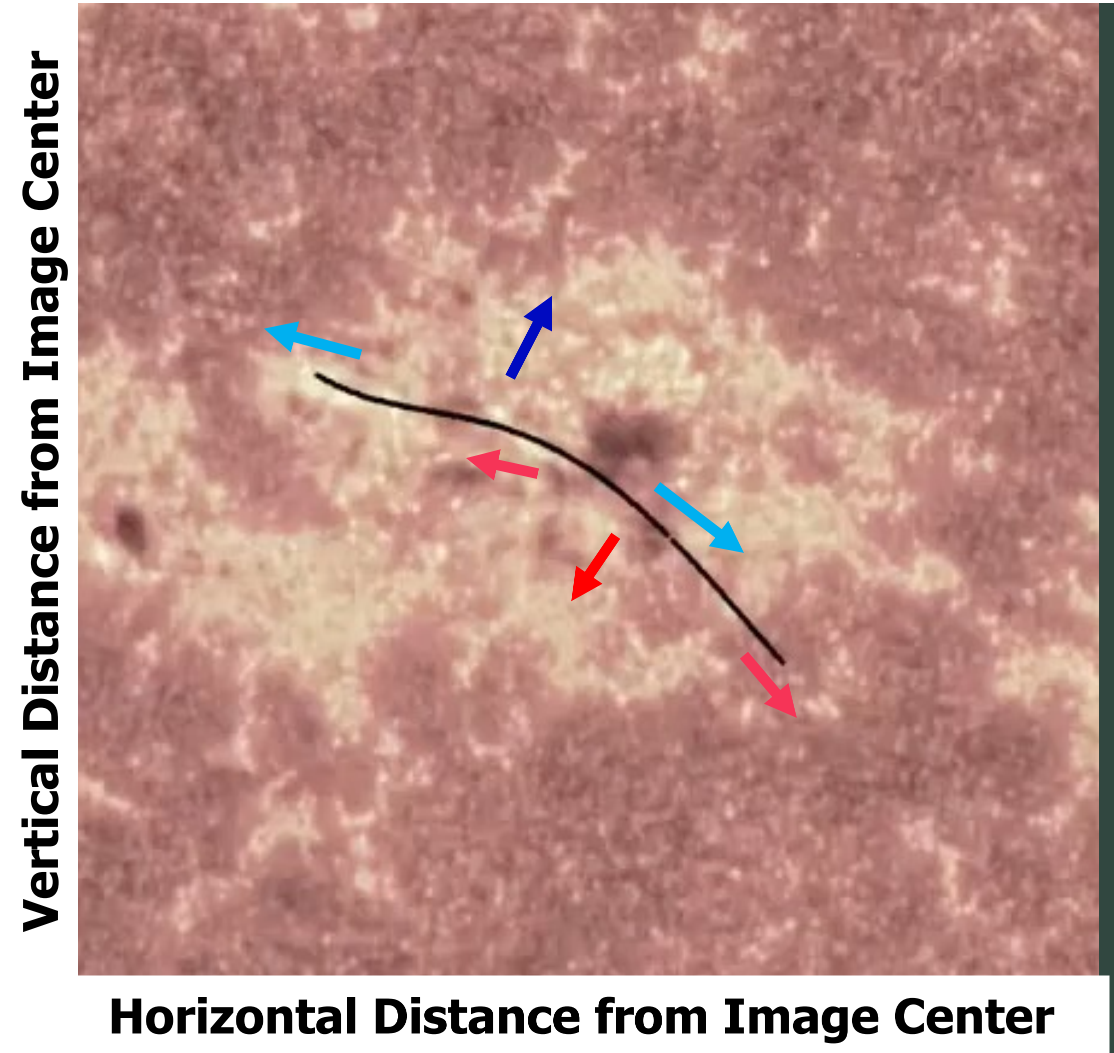


PIL-parallel and **PIL-perpendicular** motion identified for positive and negative polarity ribbons

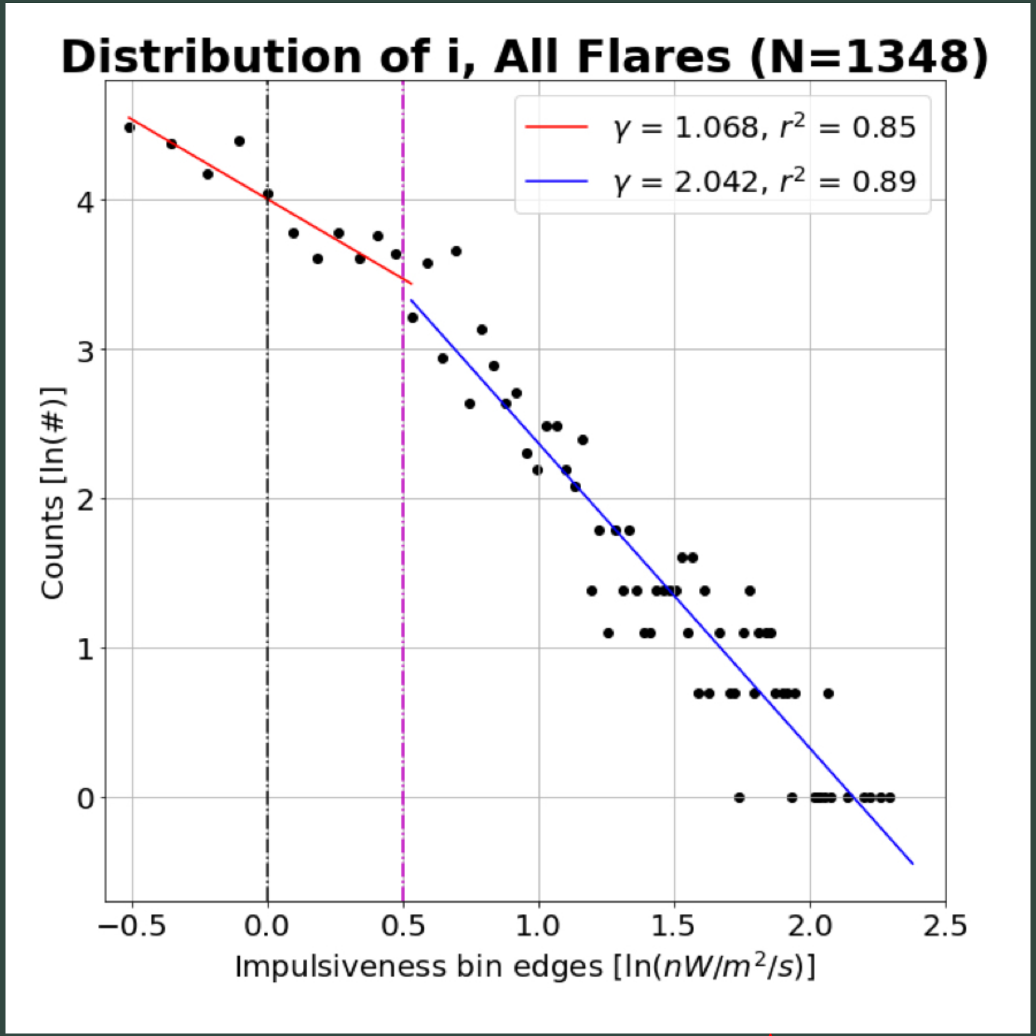
Magnetic shear measured using relative position of ribbons as a proxy for loop orientation

2c. Methods: Decomposition of Ribbon Motion

13 Oct 2013; GOES M1.7; $i = -0.97\ \ln(\frac{nW}{m^2 s})$



3a. Results: Distribution of N=1348 Events



Distribution of impulsiveness, all N=1348 flares: double power law

13 Oct 2013, 15 Oct 2013

20 Nov 2012

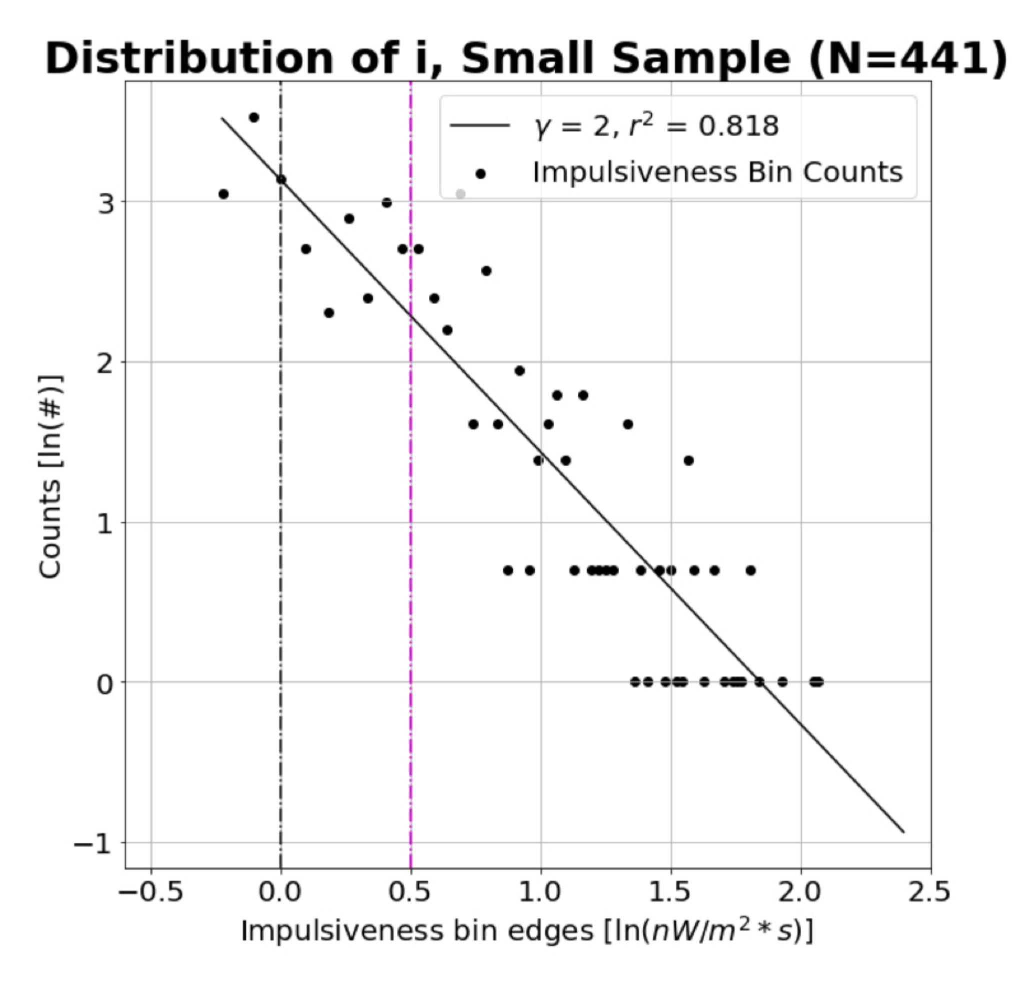
16 May 2013

4 April 2014

15 April 2014

Presented at SPD 2021, AGU Fall Meeting 2021

3a. Results: Distribution of best-performing flares

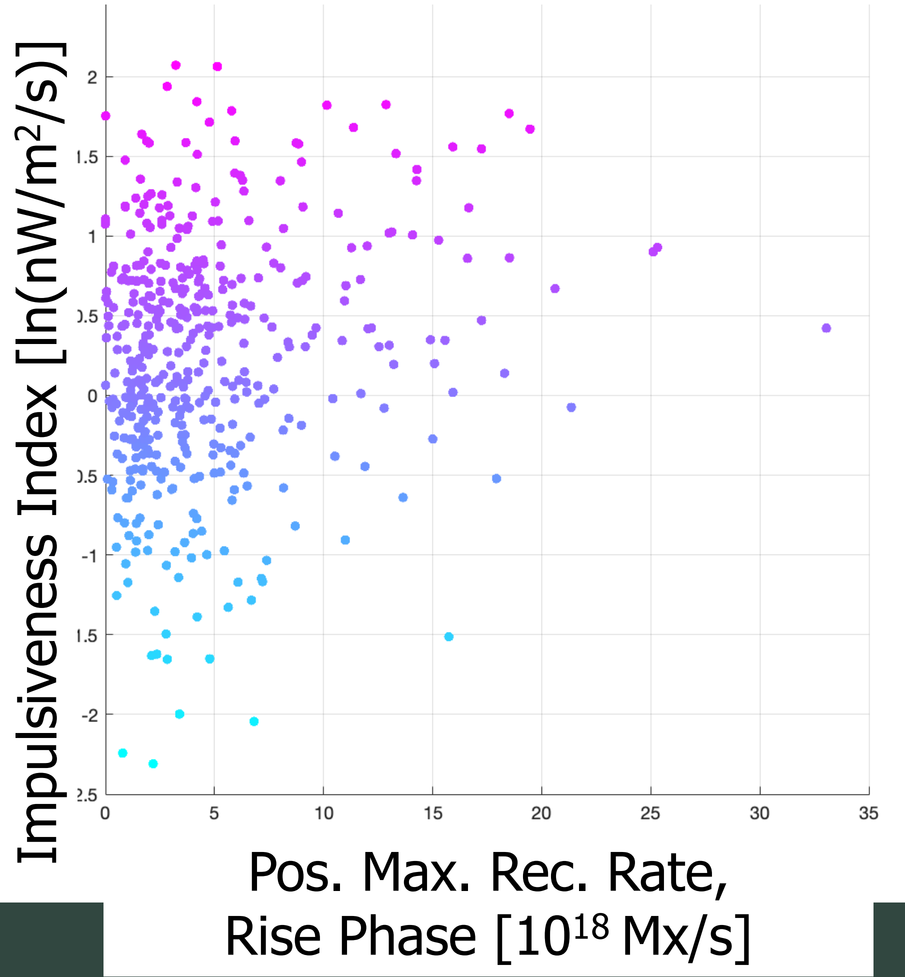


Distribution of only "best 441" flares: single power law

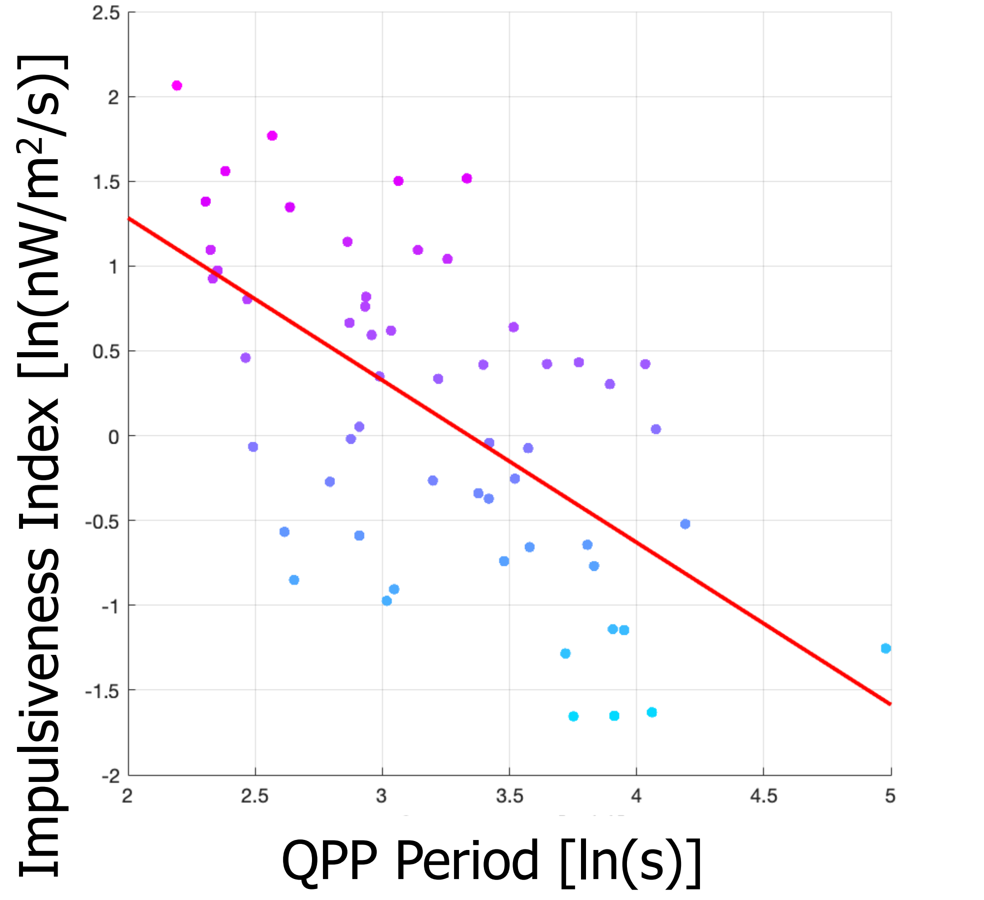
Presented at SPD 2021, AGU Fall Meeting 2021

3a. Results: i and Reconnection Rate, QPP Period

i vs. Rec. Rate, (r^2=0.045)

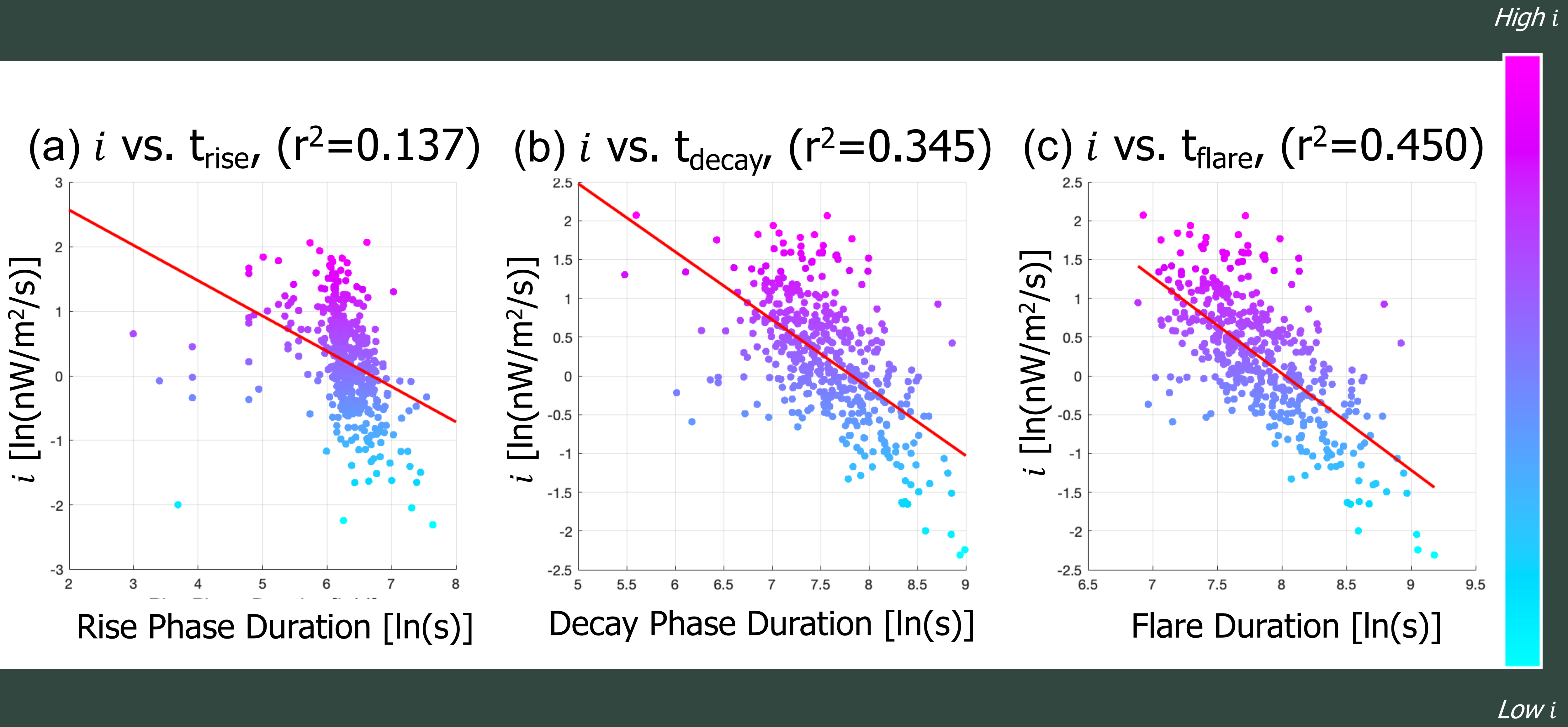


i vs. QPP Period, (r^2=0.372)



Presented at Cool Stars 20.5, SPD 2021, AGU Fall Meeting 2021

3a. Results: i and Flare Duration



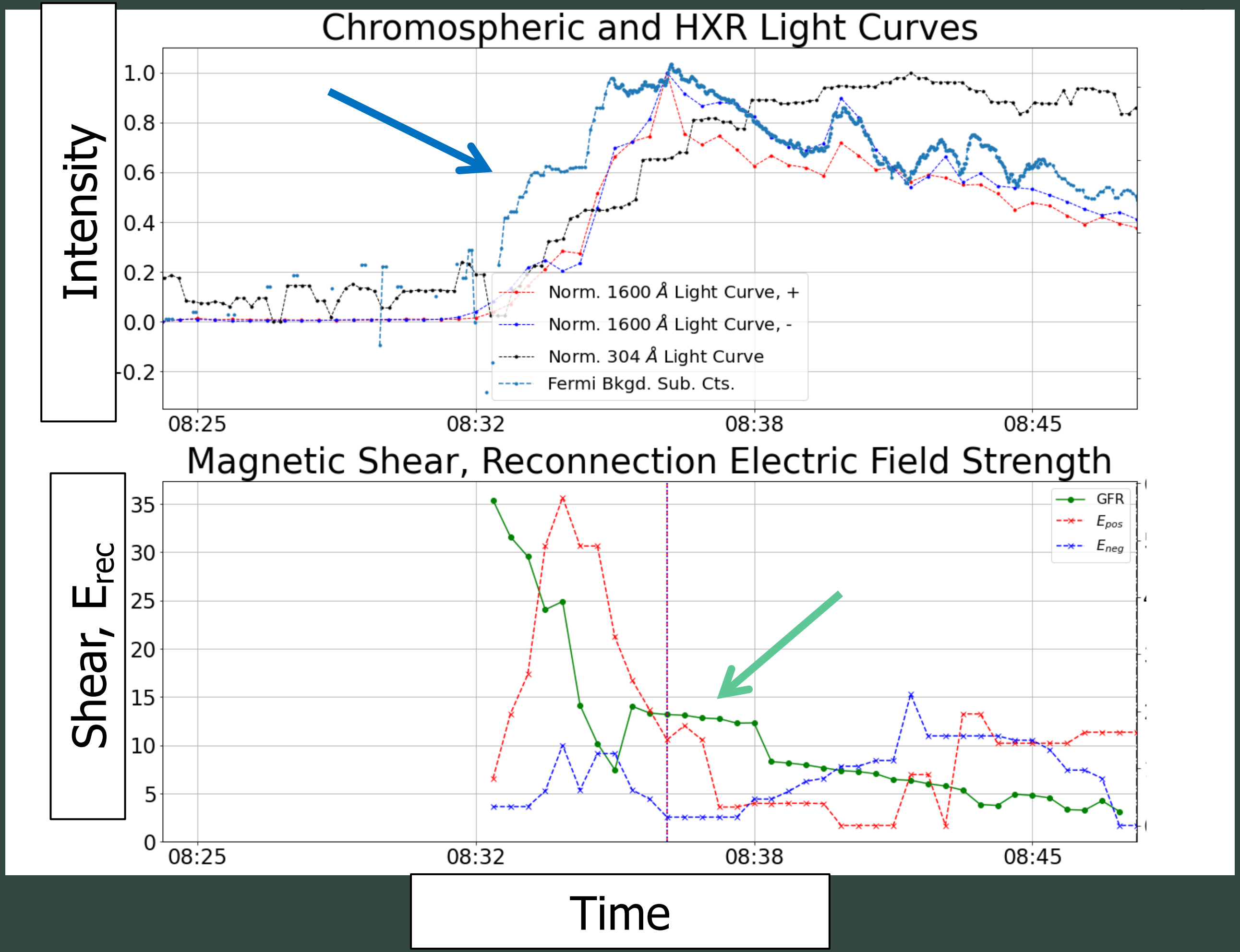
3b. – 3d. Results: Case Studies

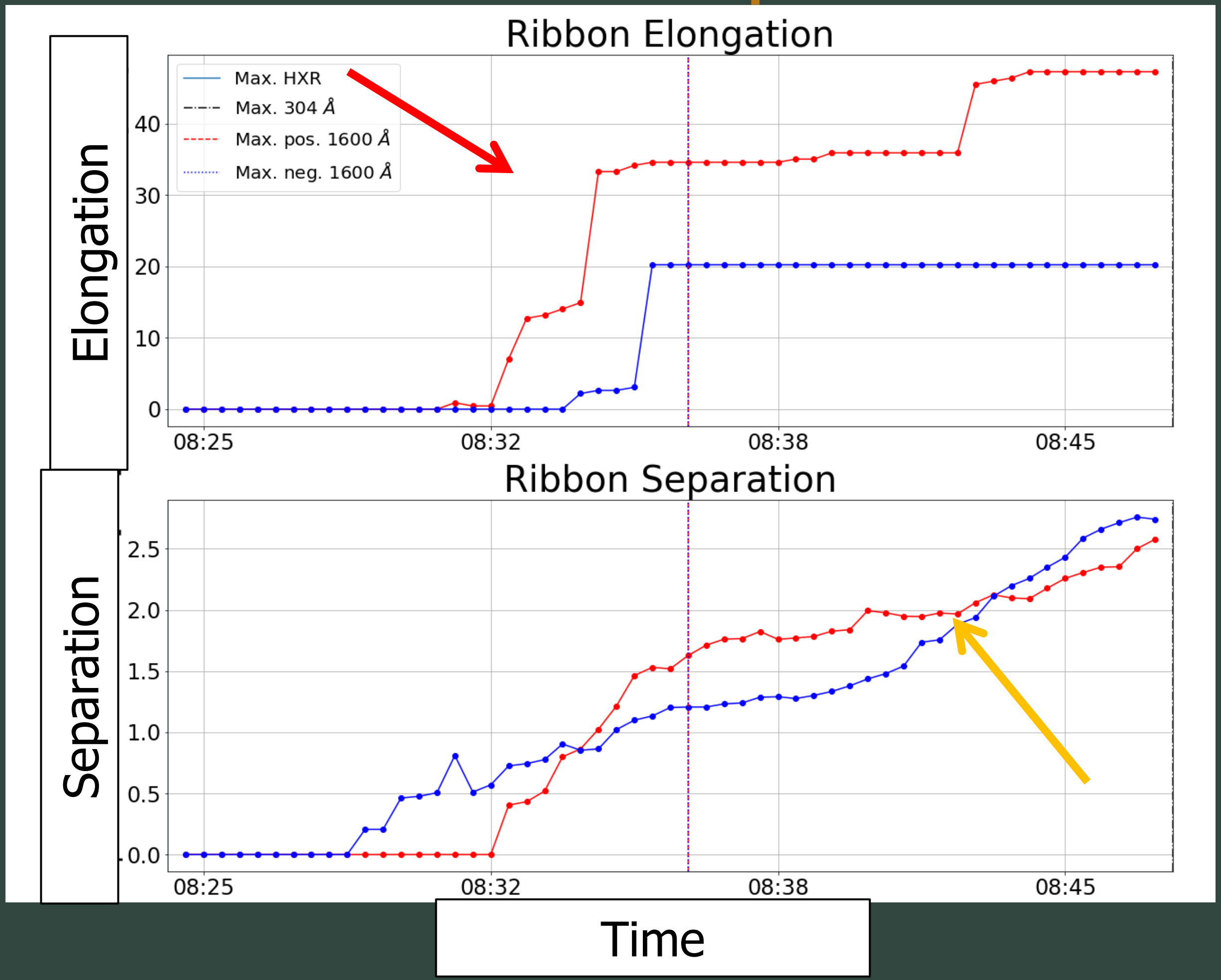
For a selection of six flares (two low impulsiveness, two mid-impulsiveness, two high impulsiveness), we compare the timing of particle precipitation, geometrical ribbon properties (shear, PIL-relative motion), and light curve development.

The goal is to understand how impulsiveness relates to ribbon motion and the timing/magnitude of energy release.

Presented at Cool Stars 21, 2022 SPHERE Workshop and 2022 SPD/TESS meeting

3b. Results: Low impulsiveness





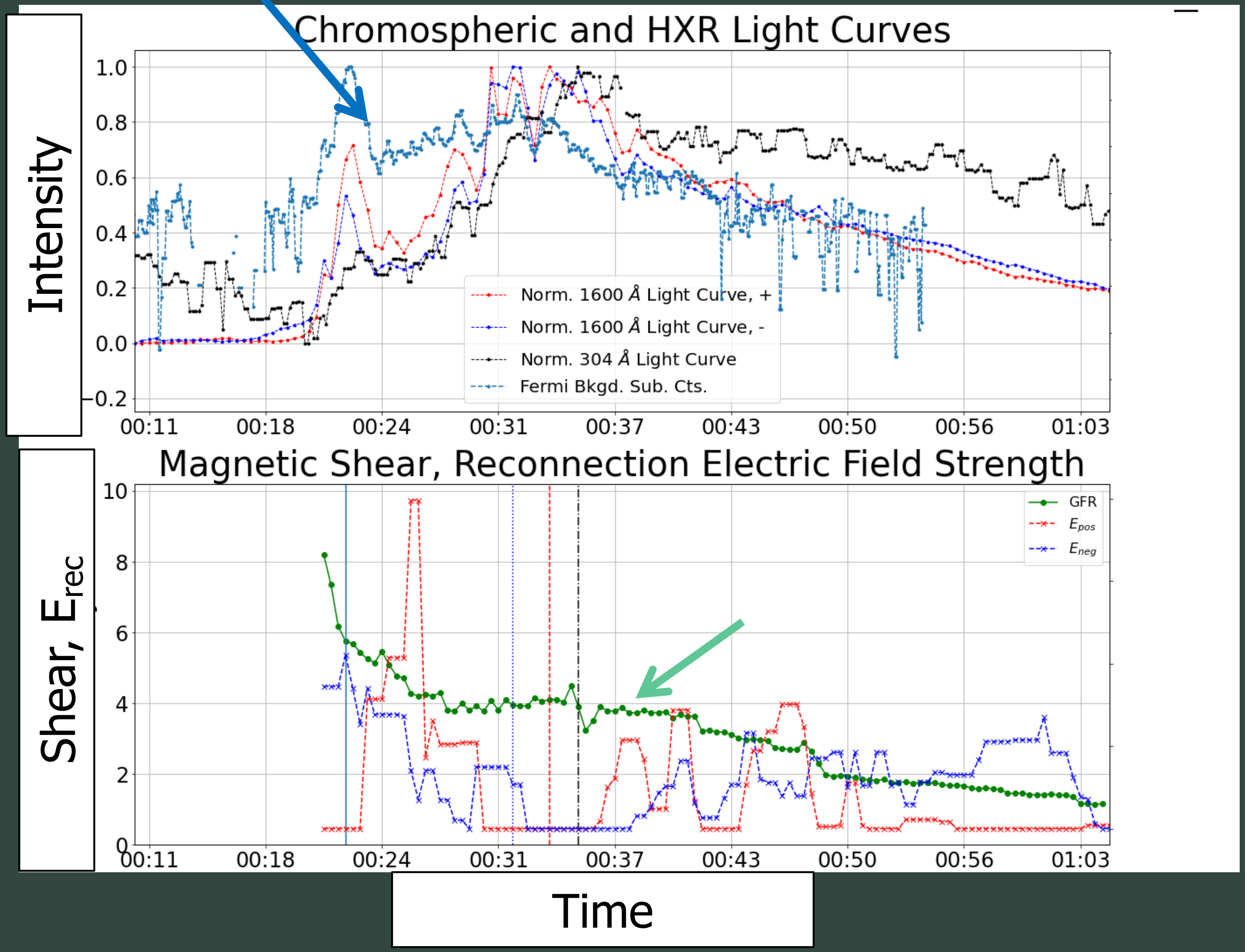
15 Oct 2013, GOES M1.8, $i = -1.00$

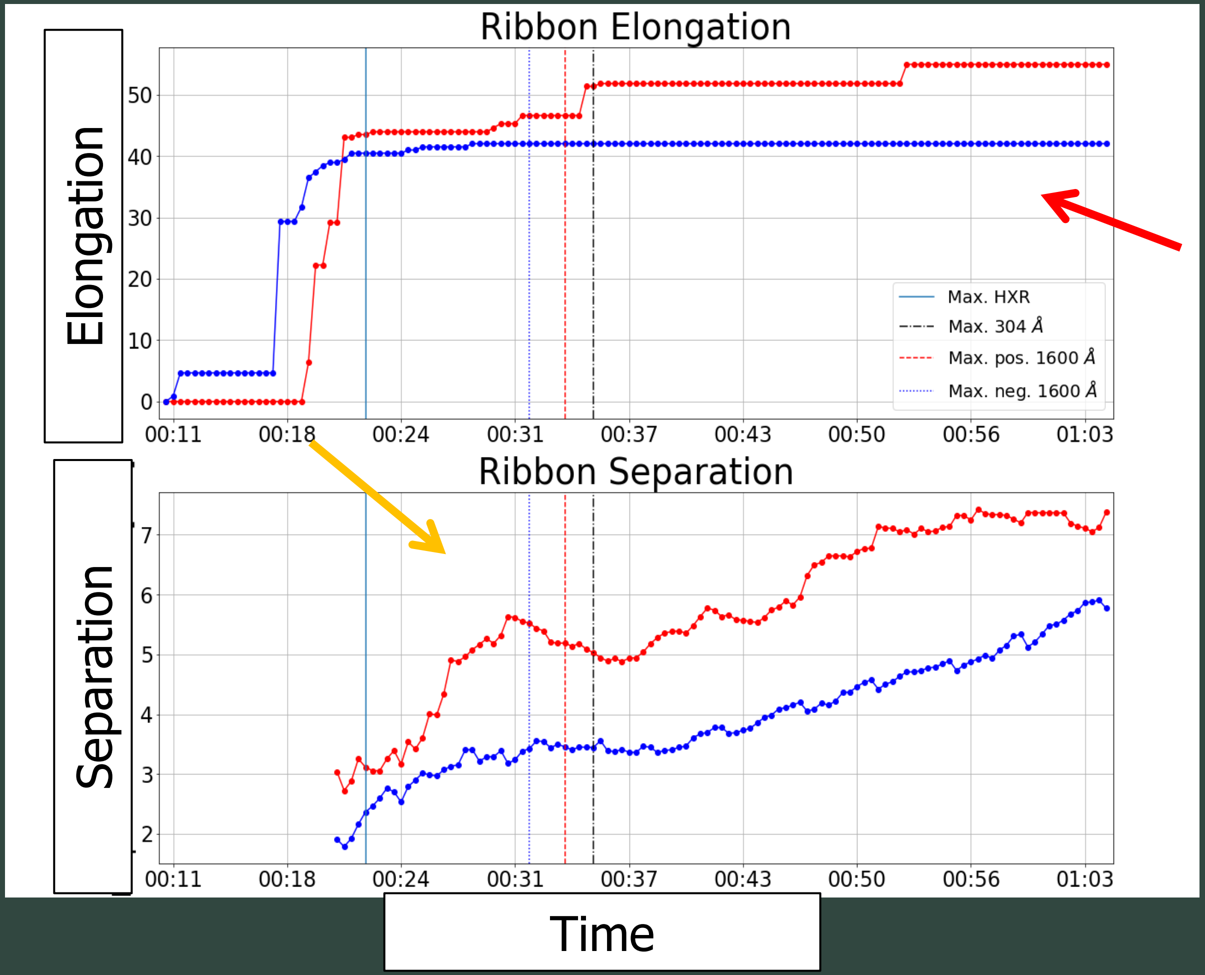
HXR flux rise after decrease in shear; 1600 Å and HXR emission co-temporal, 304 Å extends much longer afterwards

Ribbons elongate during rise phase, separate throughout

<u>75% shear decay time – 12 min</u>

3b. Results: Low impulsiveness





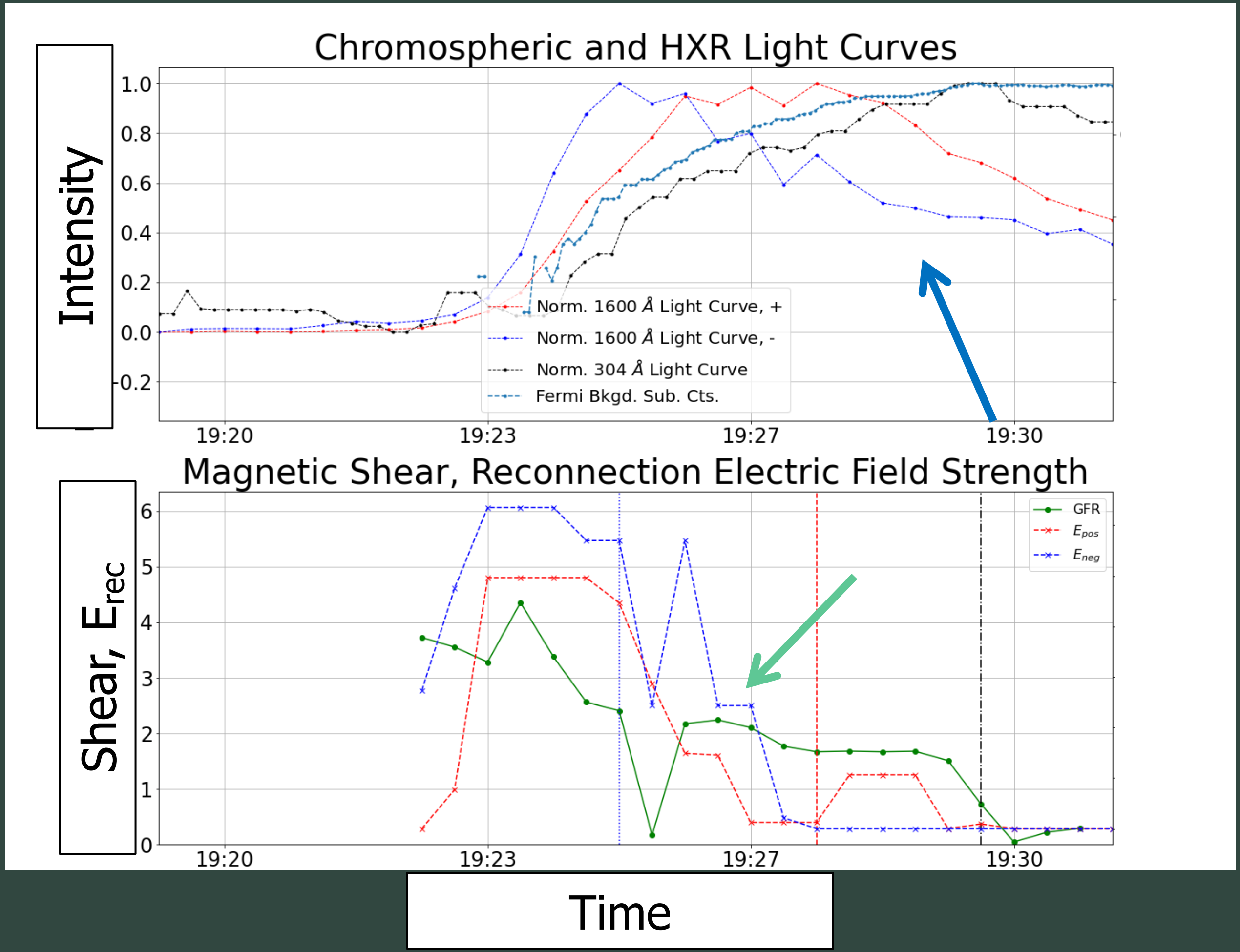
13 Oct 2013, GOES M1.7, $i = -0.97$

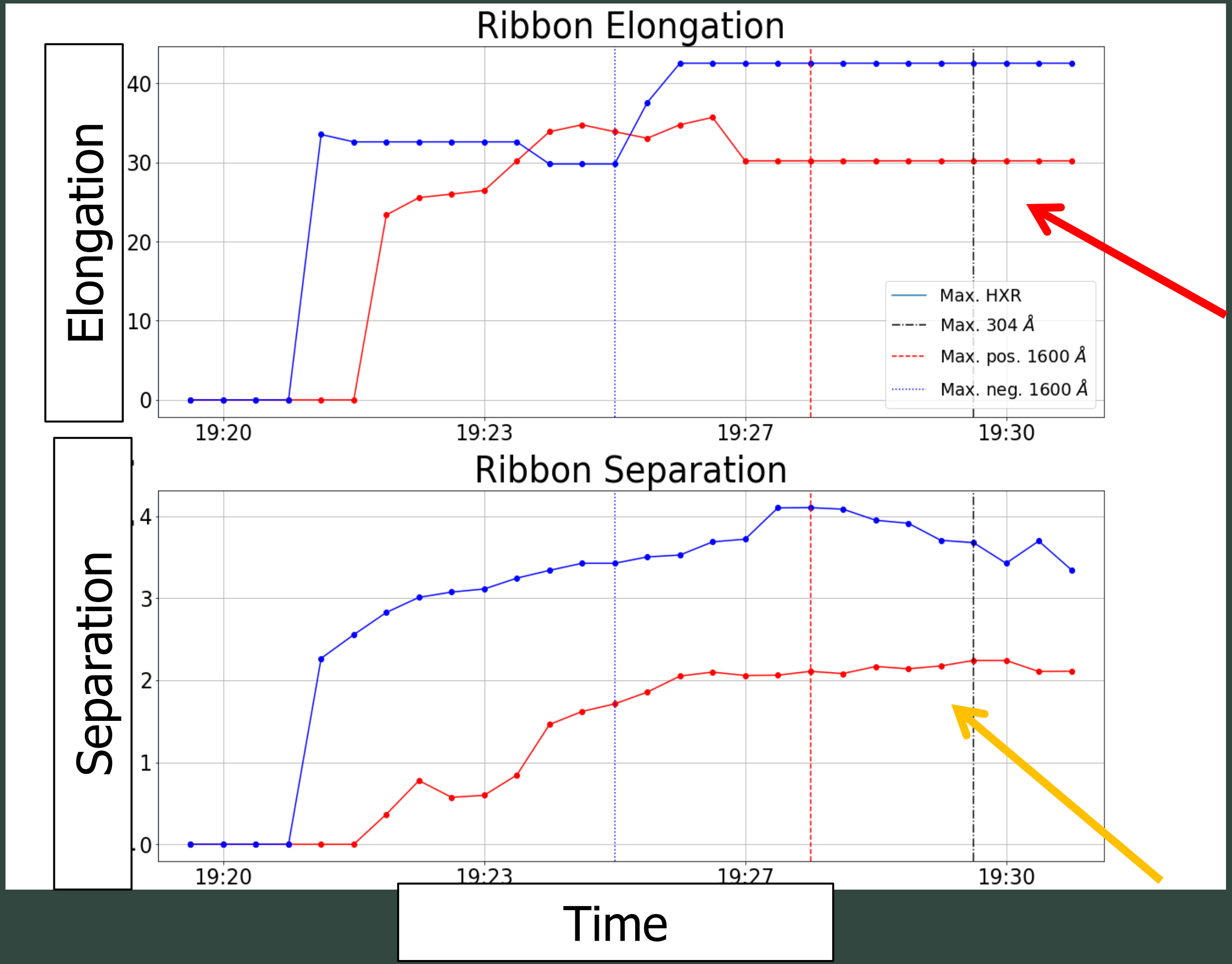
Ribbons elongate during rise phase, separate throughout

HXR flux rise after decrease in shear; 1600 Å emission co-temporal with HXR, 304 Å delayed

75% shear decay time – 14.79 min

3c. Results: Mid-impulsiveness





20 Nov 2012, GOES M1.6, $i = \mathbf{0.0401}$

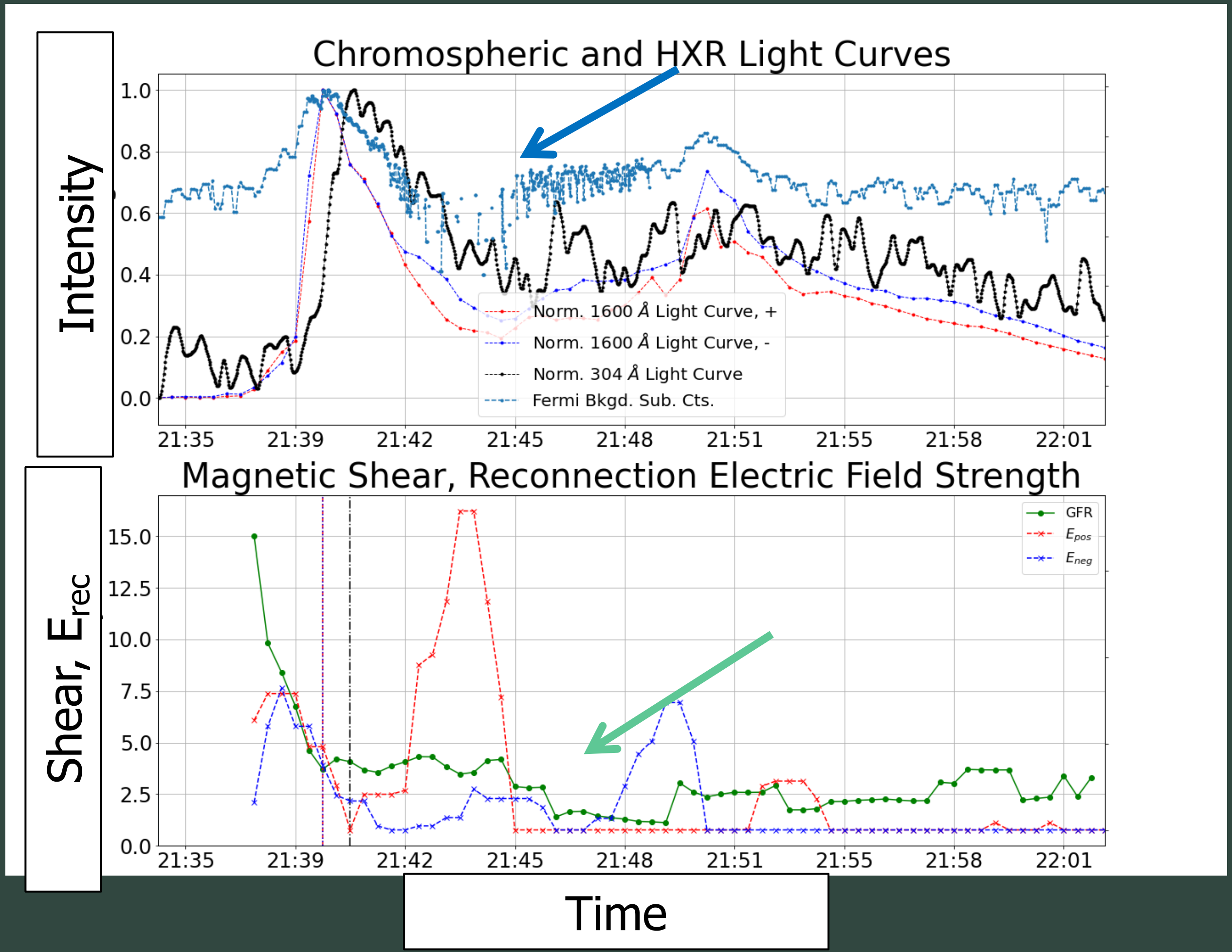
Fermi HXR delayed relative to EUV

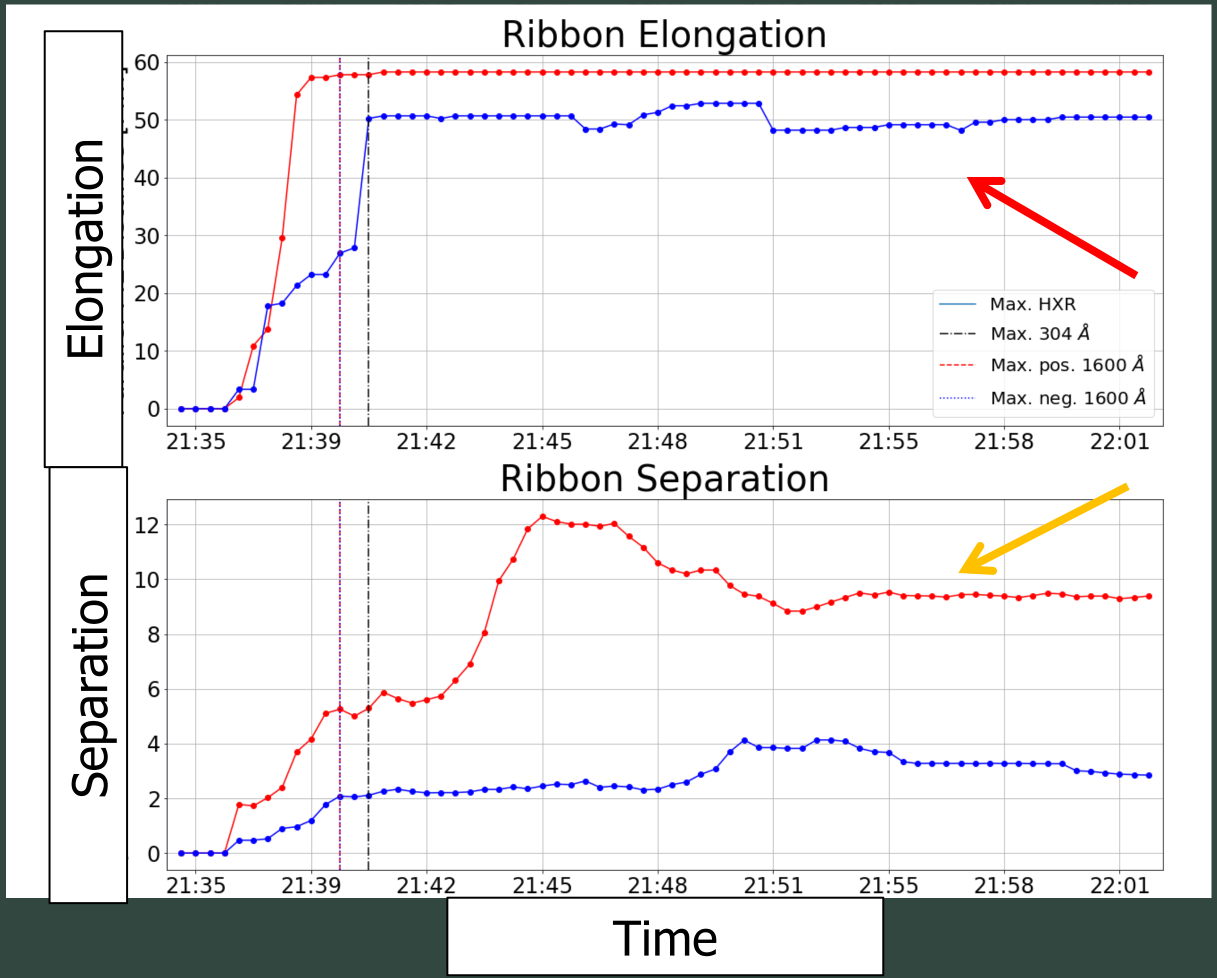
Shear low, constant throughout

Elongation and separation both occur early in rise phase

<u>75% shear decay time – 6.4 min</u>

3c. Results: Mid-impulsiveness





16 May 2013, GOES M1.3, $i = 0.326$

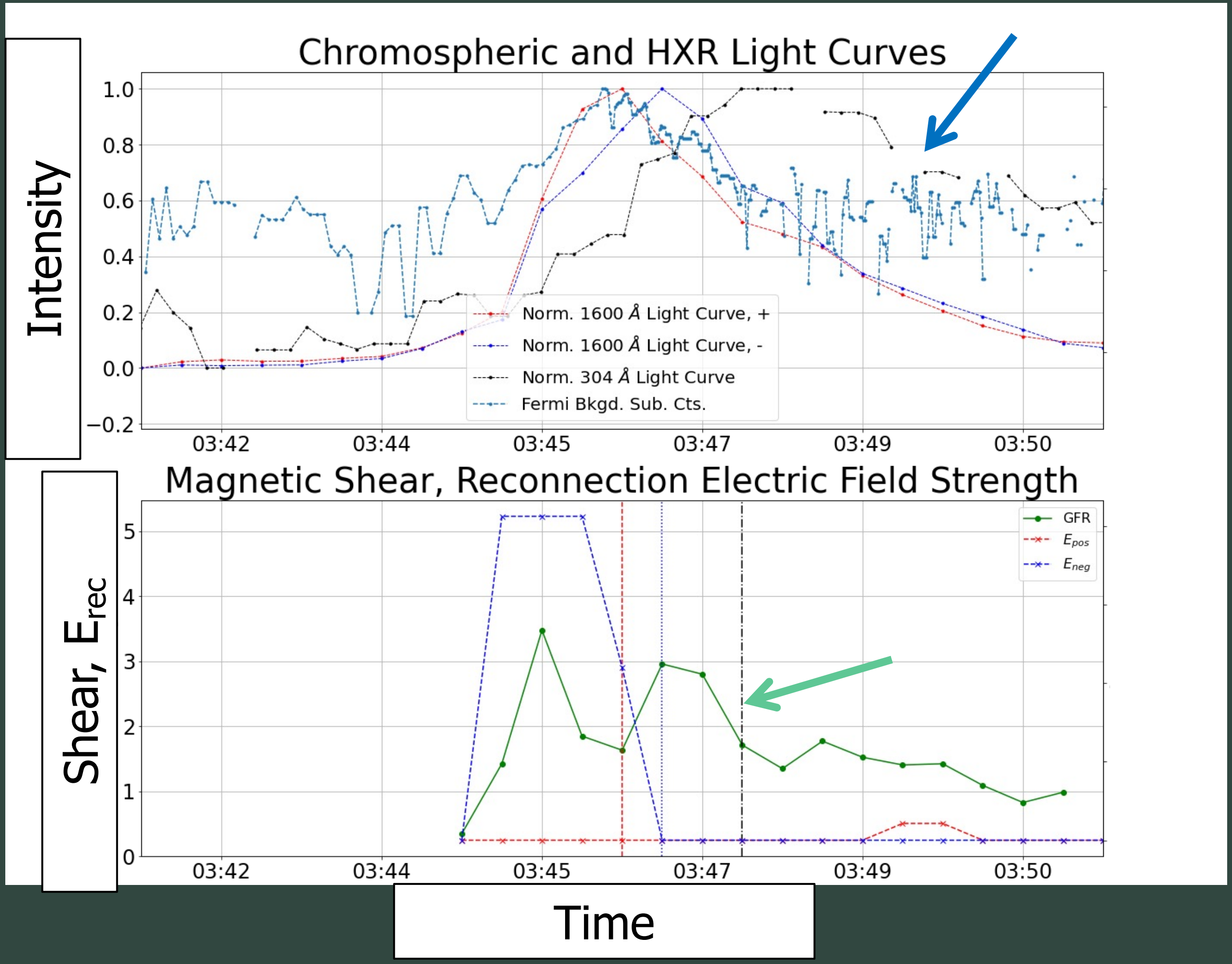
1600 Å and HXR emission co-temporal, 304 Å slightly delayed

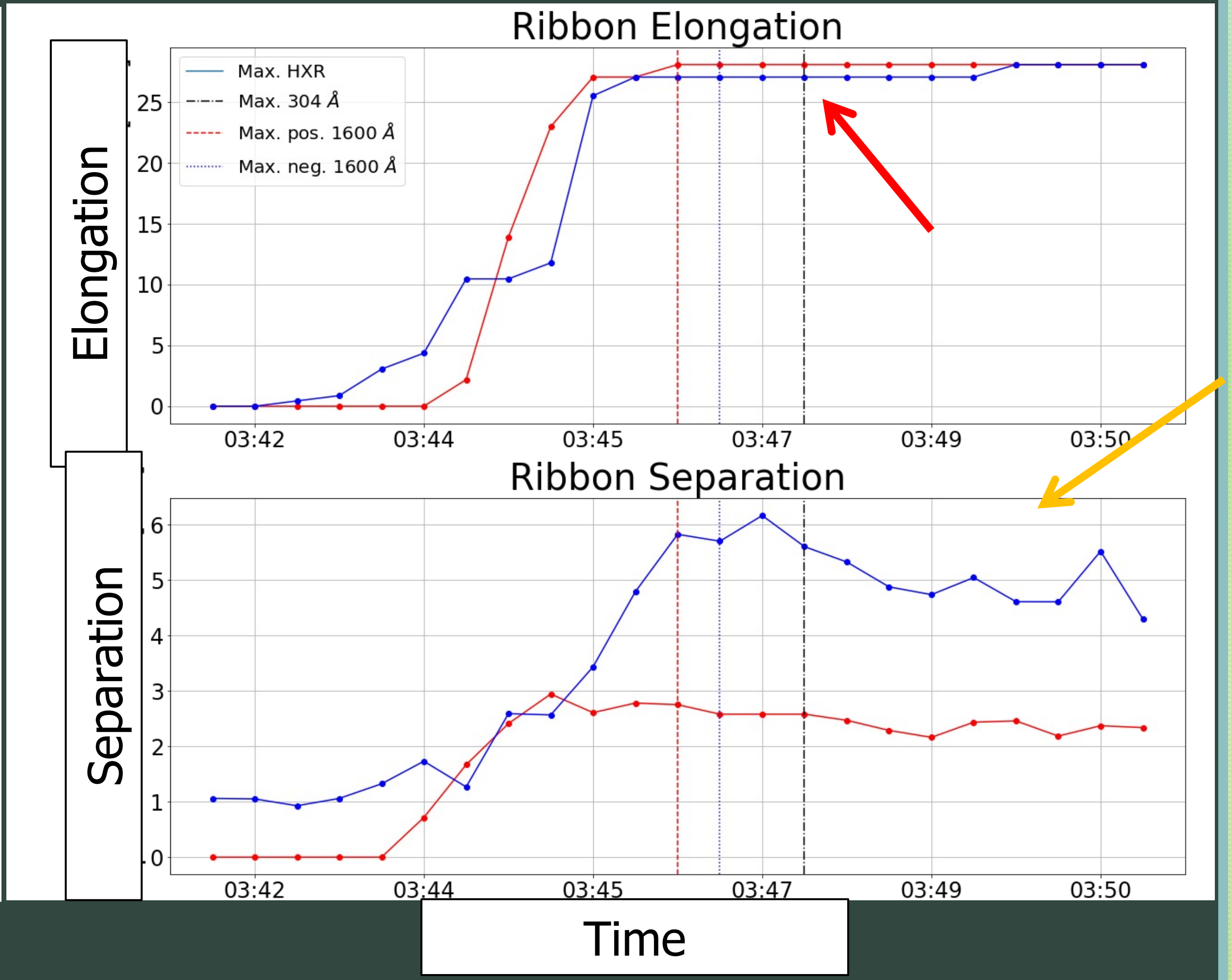
Sharp decrease in shear before rise phase

Ribbon elongation in rise phase, separation extends

75% shear decay time – 1.6 min

3d. Results: High impulsiveness





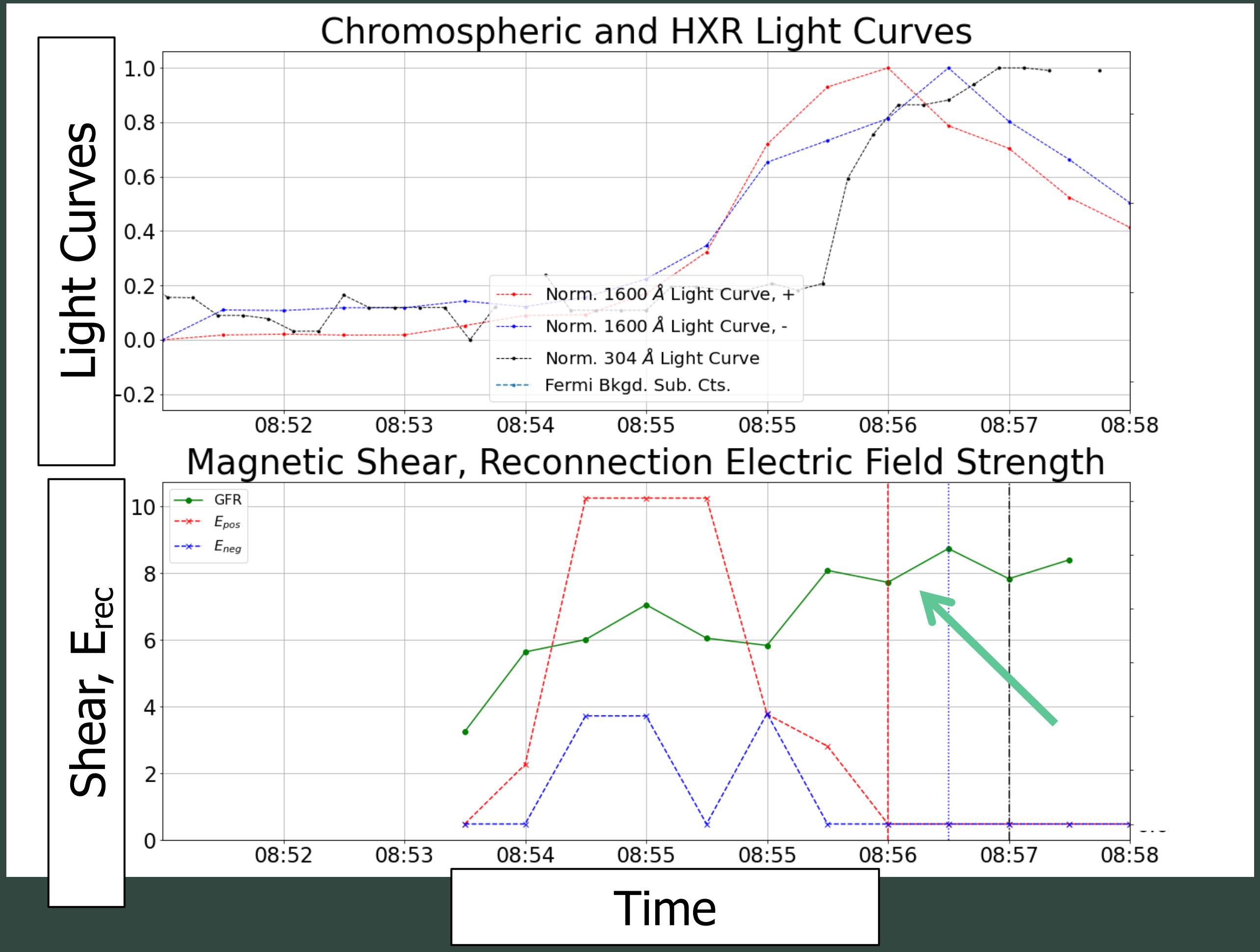
4 April 2014, GOES C3.6, $i = 0.713$

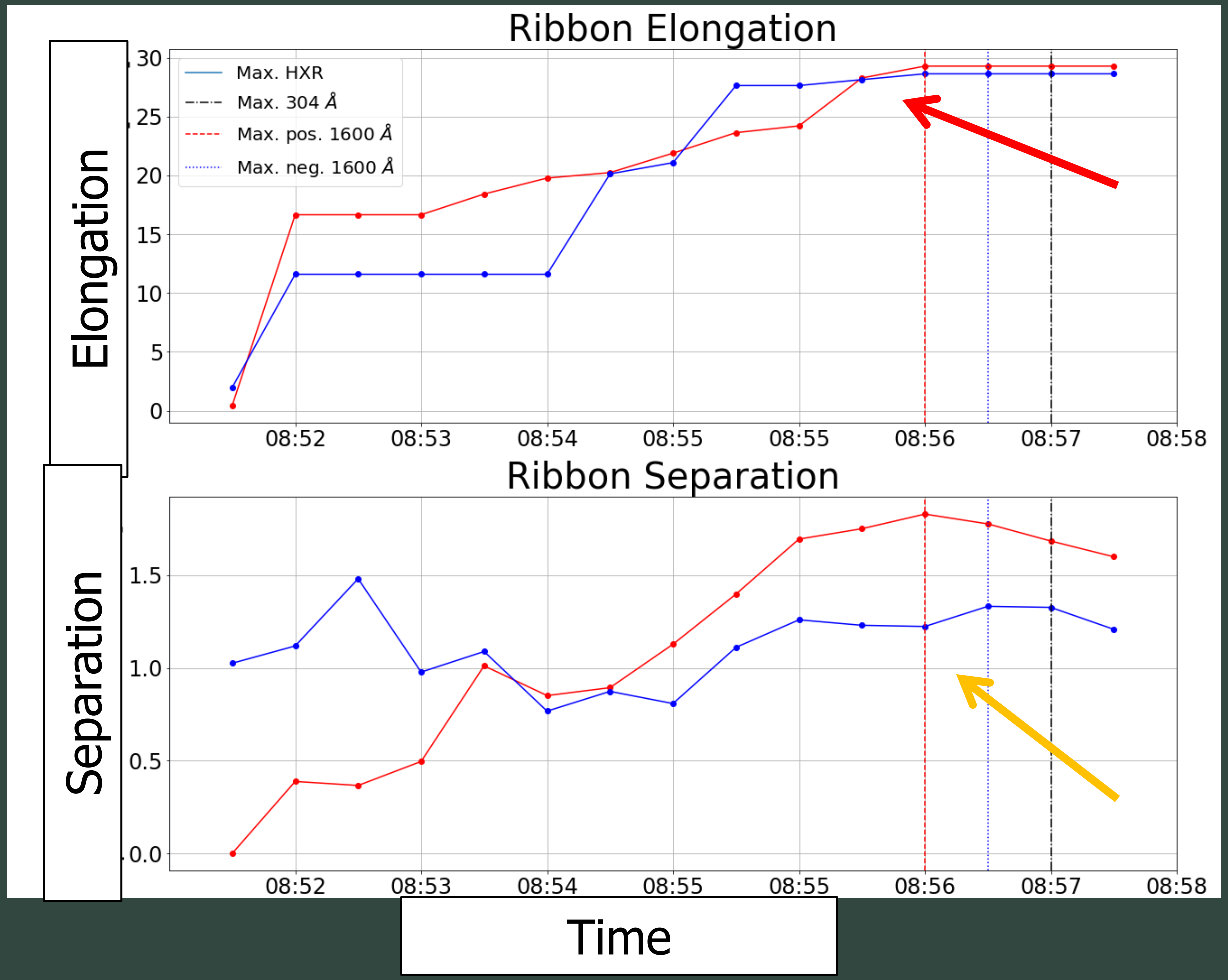
No sharp rise in HXR emission; co-temporal with 1600 Å emission

Constant shear

Ribbon separation and elongation happen during EUV rise

3d. Results: High impulsiveness





15 April 2014, GOES C1.3, $i = 1.75$

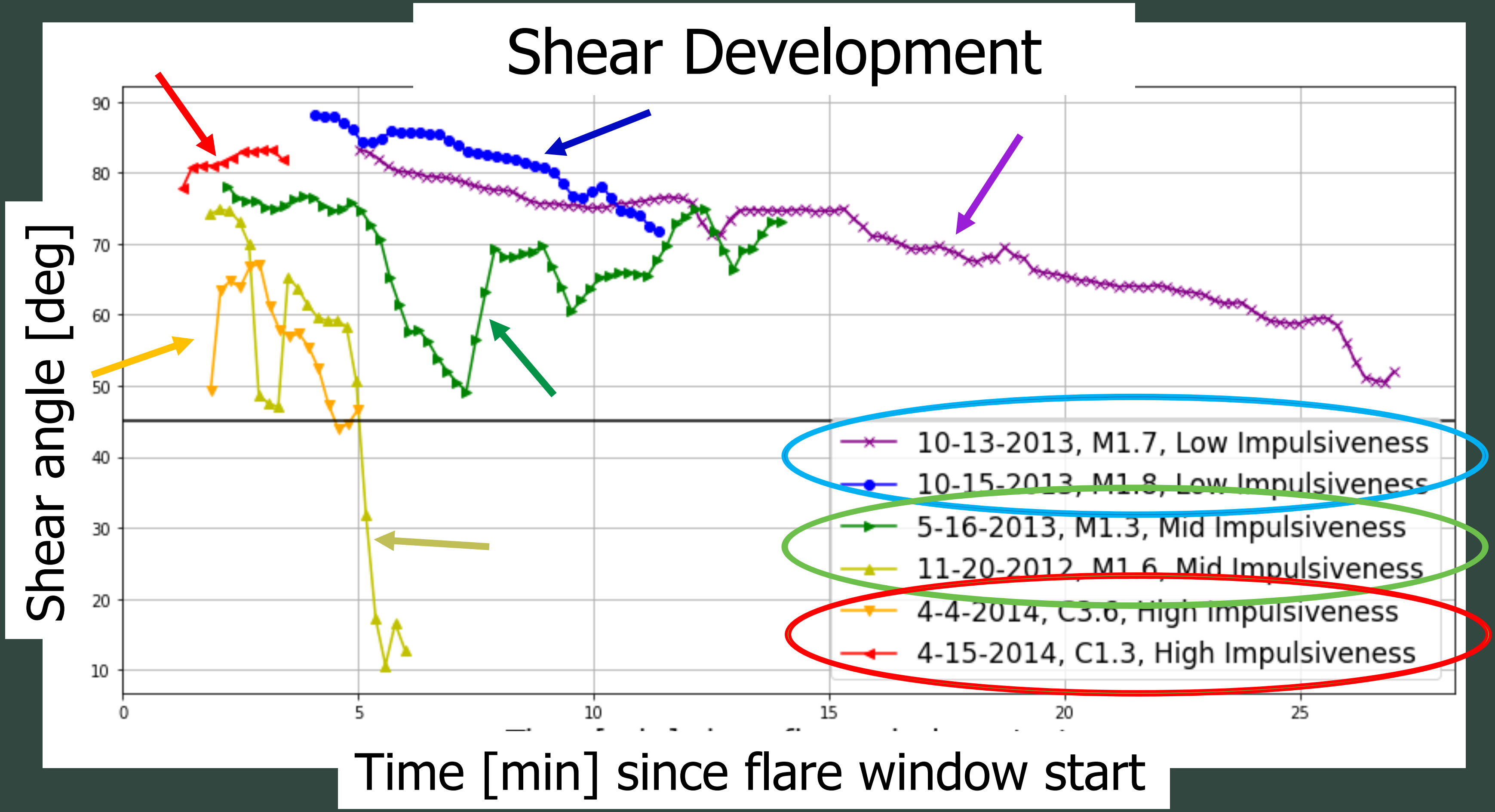
Shear high and constant; no 25-300 keV HXR signature

Ribbon elongation occurs simultaneously as separation

Ribbon separation is slight

Very short flare duration responsible for high impulsiveness?

3e. Results: Comparison of magnetic shear



Presented at Cool Stars 21, 2022 SPHERE Workshop, 2022 SPD/TESS meeting

Impulsiveness inversely proportional to amount of shear in pre-flare configuration and rate of shear decrease

4. Discussion, Summary of Findings

Developed impulsiveness index and applied to flares in the RibbonDB catalog

Analyzed co-temporal spatial development and energetics of six case studies of varying impulsiveness

Validated patterns in ribbon elongation (during rise phase) and separation (throughout flare) for low and mid-impulsiveness flares, with some added complexity in the case of high impulsiveness

Results suggest inverse relationship between impulsiveness and shear, similar to rates and timing of particle precipitation

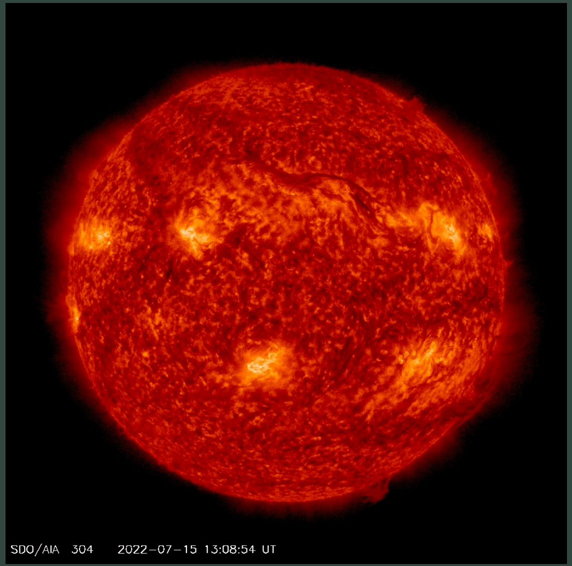
Relationship of impulsiveness with QPP signatures hearkens to discussion of ~1s bursts in stellar light curves (Kowalski et al. 2013, 2016)

4. Relevance and Future work

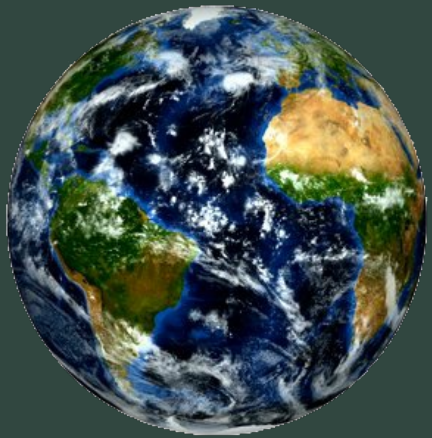
Solar physics: Validation of simulations; comparison to other flare properties; improvement of flare modeling?

Stellar physics: Direct comparison could be made between solar and stellar impulsive events

Life on Earth: Forecasting?



Source: SDO/AIA



Source: NASA

Thanks…

…to the George Ellery Hale Graduate Fellowship…

…to my comprehensive exam committee for their feedback and patience…

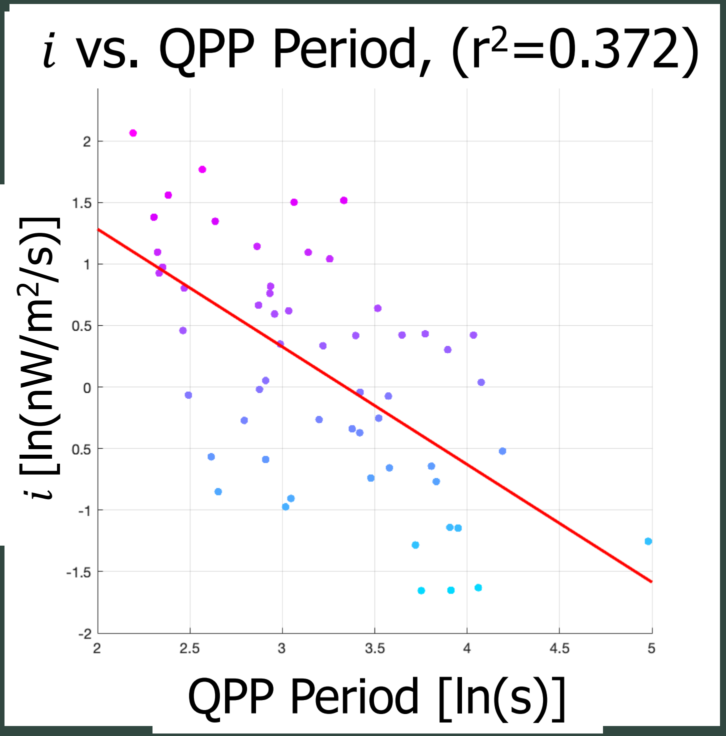
…to Dr. Maria Kazachenko and Dr. Adam Kowalski for over two years and counting of guidance…

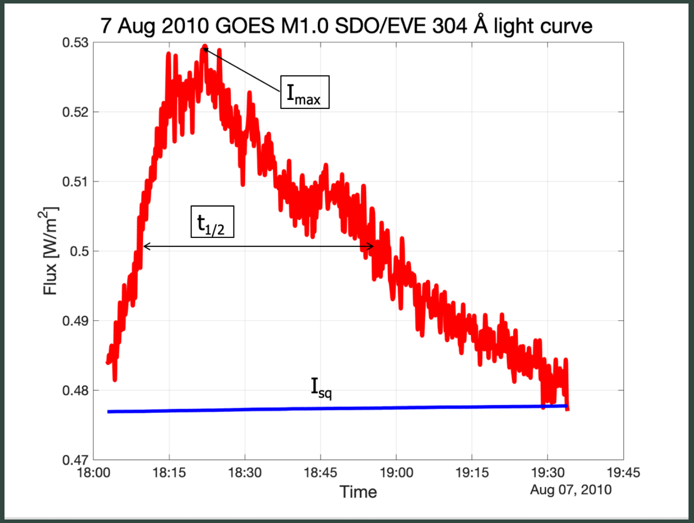
…to the other members of the Kazachenko Research Group (Benoit Tremblay, Andrei Afanasev, Ryan French, Rahul Yadav, Dennis Tillipman, Marcel Corchado-Albelo, and, previously, Kirk Long) for valued input and discussion…

…to the other members of the 3rd year graduate class in APS…

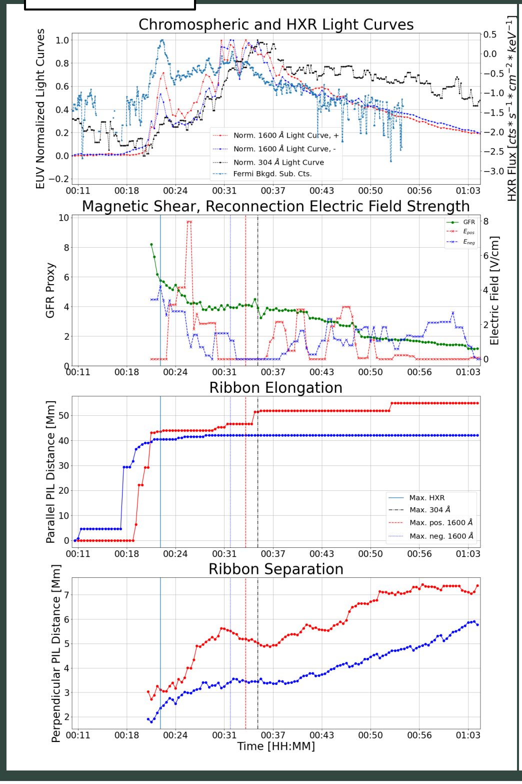
...to my family, a source of constancy as always.

Questions?

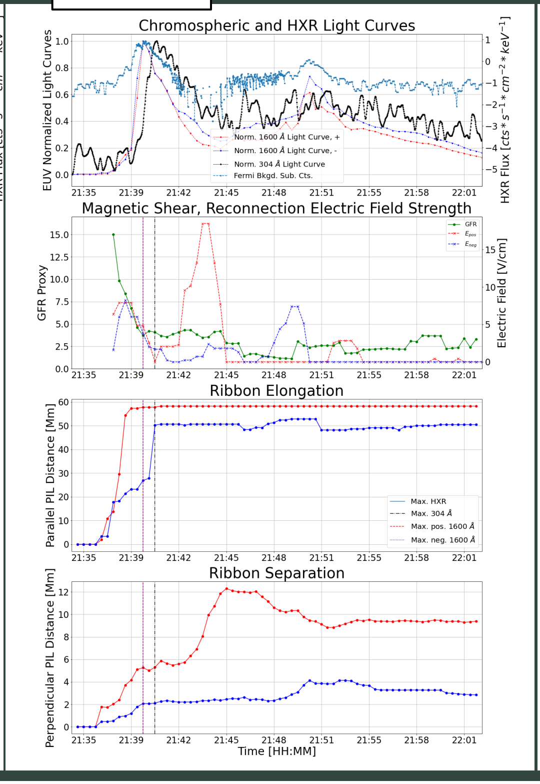




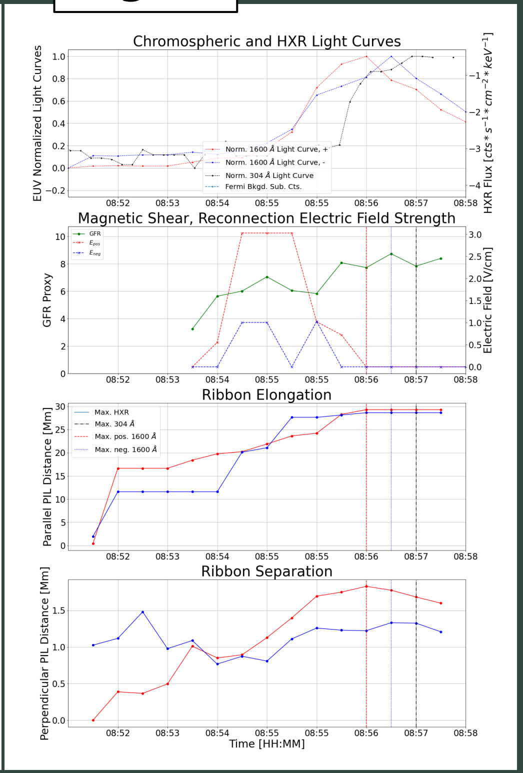
Low i

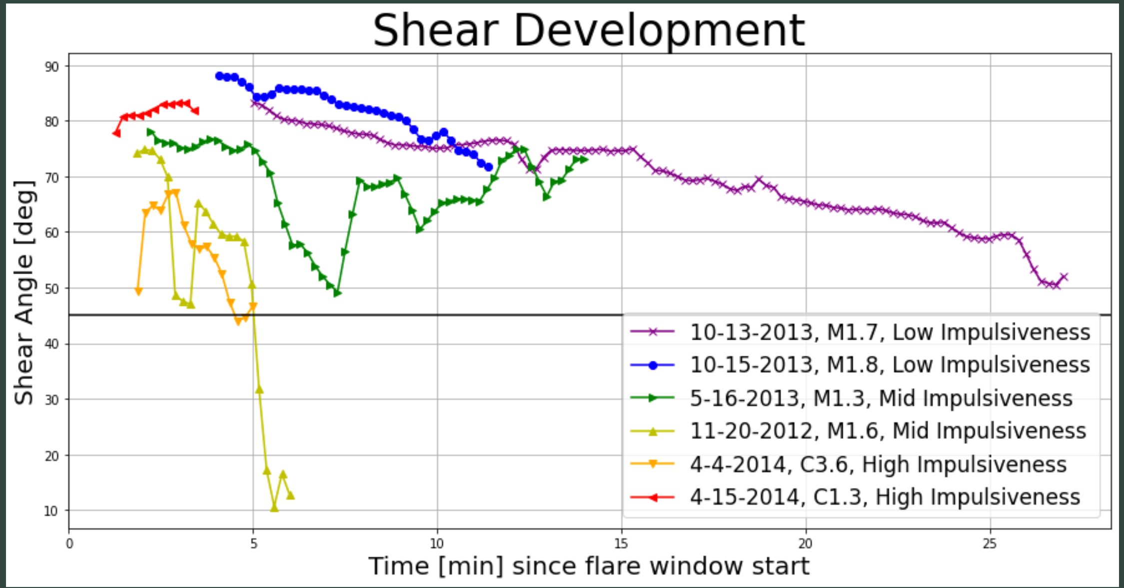


Mid i



High i





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Conceptual/Textual Clarifications, Modifications to Paper

Page 1 – should be thermal conduction *or* particle precipitation – remnant from previous version

Page 2 – 10^8 K - this is misleading, what I mean is that temperatures of these energies correspond to 10^8 K, but it sounds like I'm talking about the ambient plasma, which is not the case. Removed any discussion of temperature, I think it's better left out

Page 3 – Free energy is converted into thermal, kinetic, etc. energy – really I should just list: non-thermal particles, heat conduction, expulsion of plasmoid, etc. etc. ...

Page 4 – would prefer different wording for "free energy is released"

Page 7 – "may classify flares of the same peak X-ray flux together, *independent of* [rather than dependent on] their duration"

Page 12 – "high diffusion reconnecting region" -> "small-scale diffusion region" – the idea is that diffusion becomes important because of the small scale, so I suppose it's high *relative* amounts of diffusion – anyways, I'd like this to have been more clear.

Page 23 – add units (ln(nW/m^2/s)) to the listing of the impulsiveness value

Modification of BJR w.r.t. solar flares in Future Work as well as the Introduction. Although not observed in the quiet Sun, my understanding is that it is more clear in flare spectra – so, maybe, a comparison could actually be made?

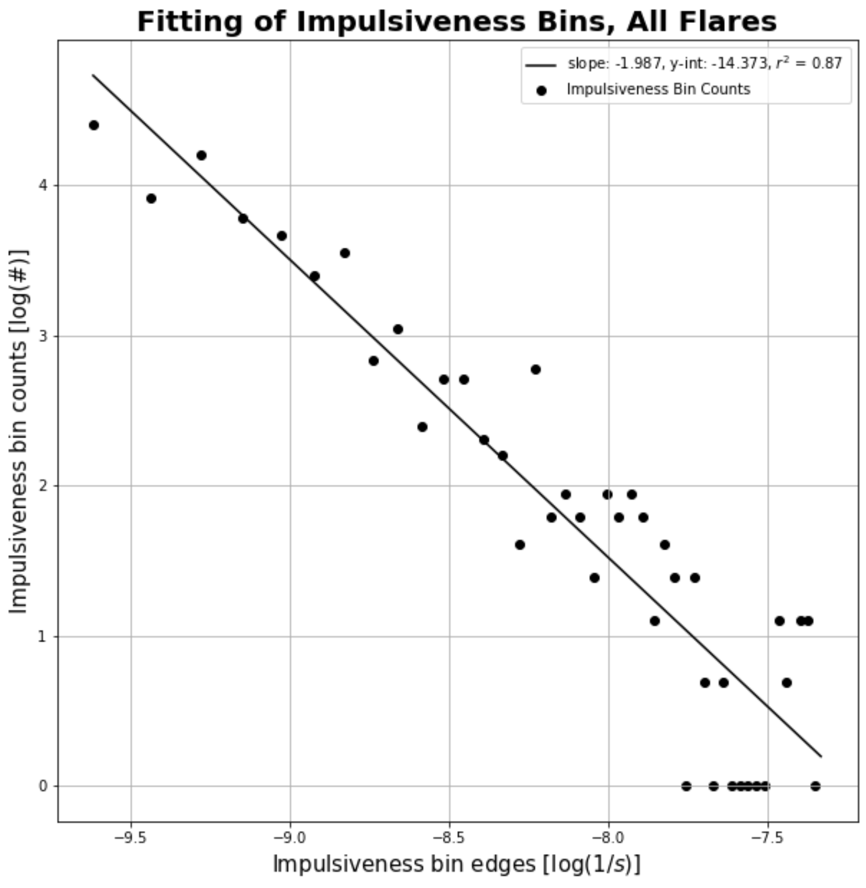
RADYN description – bound free *continuum* rather than *line* (though this may be semantic)

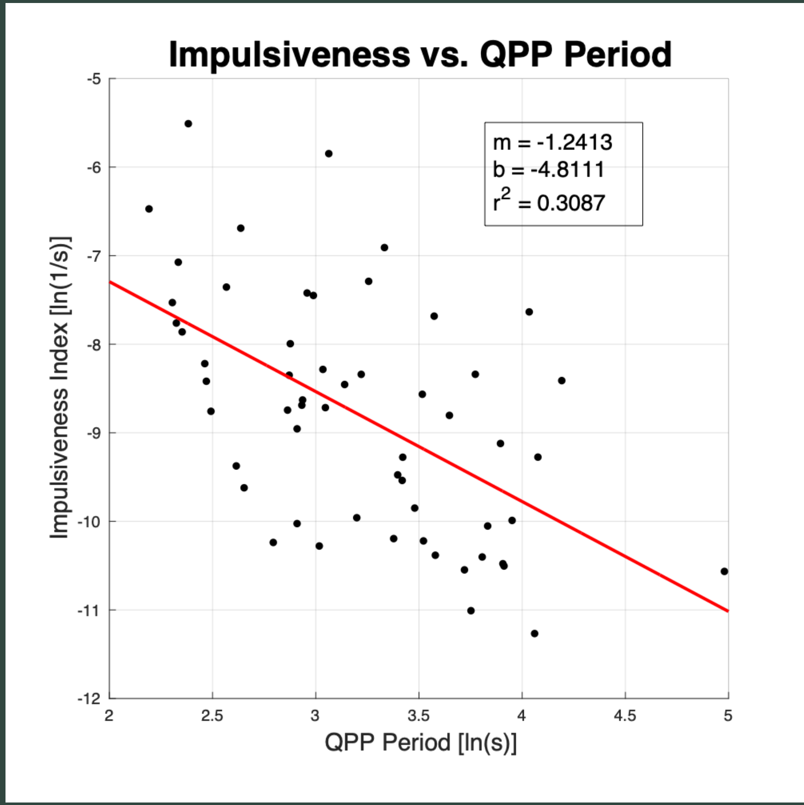
Acknowledgements - Astrophysical and Planetary *Sciences* rather than *Xciences…* I'm pretty sure ☺

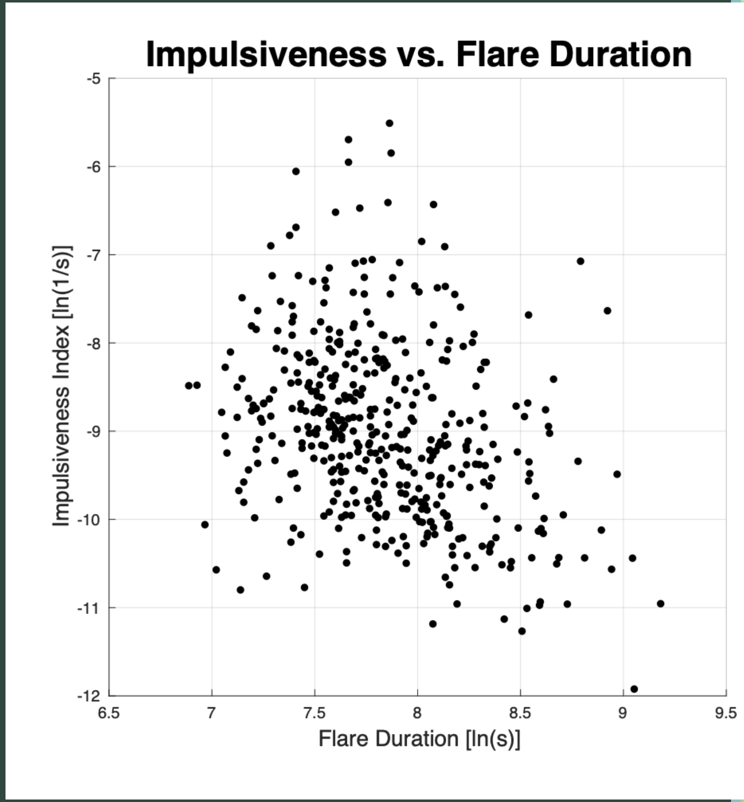
Break in full sample power law is 0.502 nW/m^2/s – the other value was an old version of the model

Finally, less of a correction and more of an improvement: I'd like to add a discussion of DKIST observations of the line-to-continuum ratio Hγ/C4170, which is observable in stars as well as the high-res DKIST observations; opportunity for a comparison to impulsiveness for both datasets.

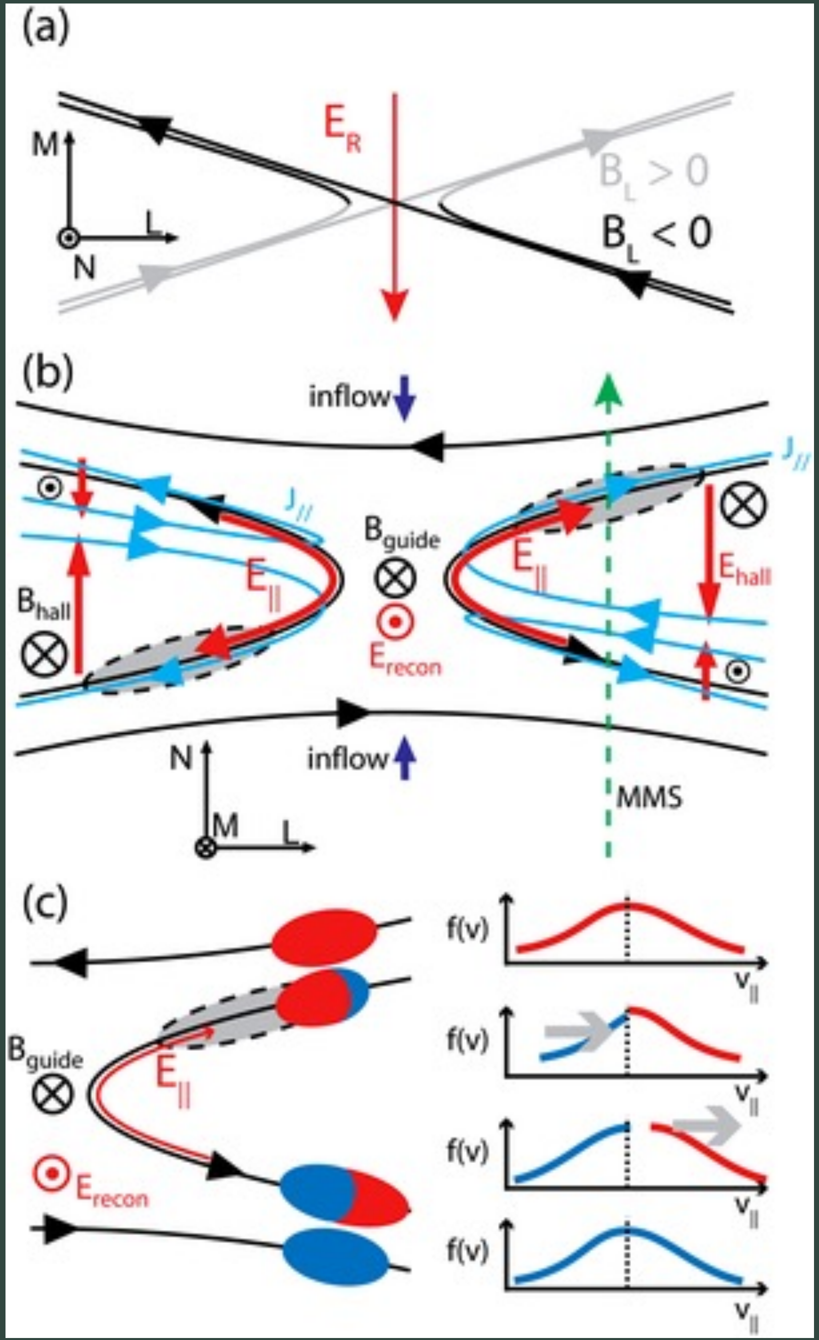
Alternative Impulsiveness (Relative to Quiescence)



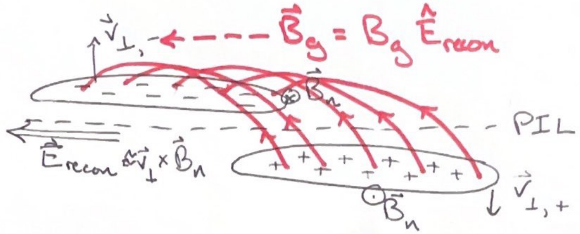




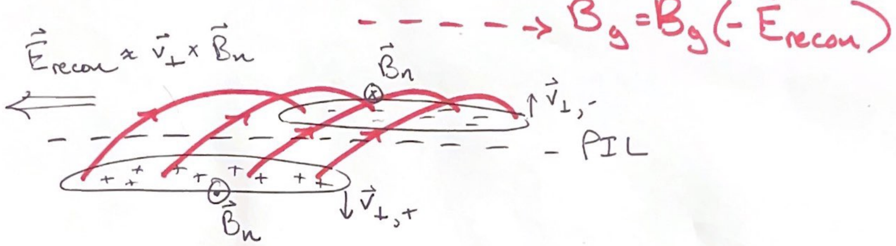
Parallel vs. component reconnection



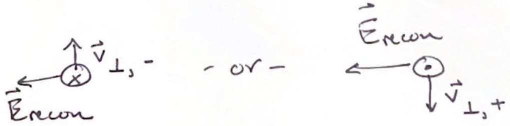
1. $\vec{B}_g \uparrow\uparrow \vec{E}_{recon}$:



2. $\vec{B}_g \downarrow\uparrow \vec{E}_{recon}$:

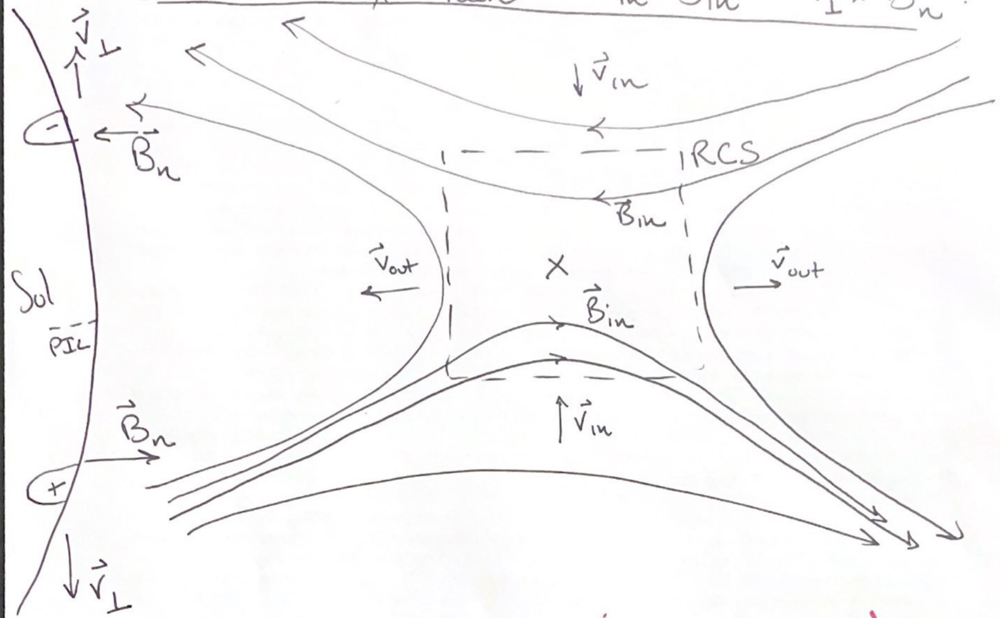


In both cases:

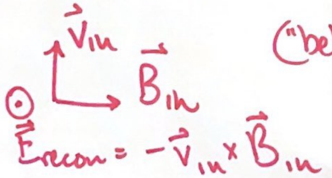


by right-hand rule

Justification for Directionality of $\vec{E}_{recon} = -\vec{v}_{in} \times \vec{B}_{in} \sim \vec{v}_\perp \times \vec{B}_n$:

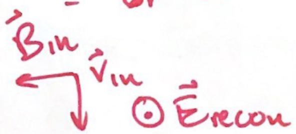


via $\vec{v}_{in}, \vec{B}_{in}$...



("below RCS")

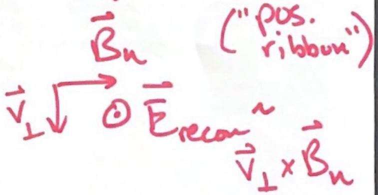
- or -



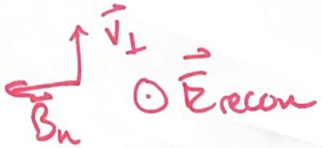
("above RCS")

via $\vec{v}_\perp, \vec{B}_n$...

("pos. ribbon")



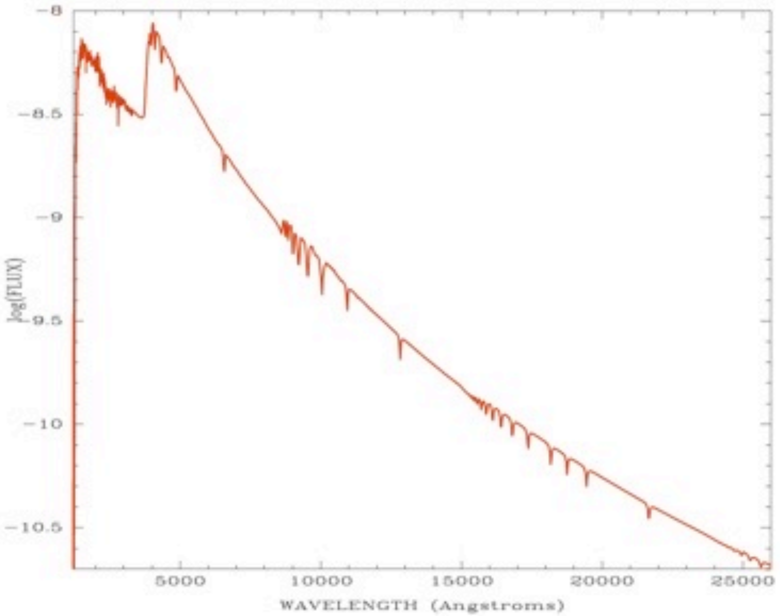
- or -



Stellar continua: the Balmer jump

From the ground we can measure part of Balmer (λ < 3646 A) and Bracket (λ > 8207 A) continua, and complete Paschen continuum (3647 – 8206 A)

Provide information on T, P. Spectrophotometric measurements in UV (hot stars), visible and IR (cool stars)



- ionization changes are reflected in changes in the continuum flux
- for $\lambda > \lambda$(Balmer limit) no n=2 b-f transitions possible → drop in absorption
- → atmosphere is more transparent
- → observed flux comes from deeper hotter layers
- → higher flux BALMER JUMP

Balmer discontinuity (when H^- absorption is negligible T > 9000 K) =

$$\frac{\kappa^{\rm bf}(>3650)}{\kappa^{\rm bf}(<3650)} = \frac{\kappa^{\rm bf}(n=3)+\ldots}{\kappa^{\rm bf}(n=2)+\kappa^{\rm bf}(n=3)+\ldots} \simeq \frac{\kappa^{\rm bf}(n=3)}{\kappa^{\rm bf}(n=2)}$$