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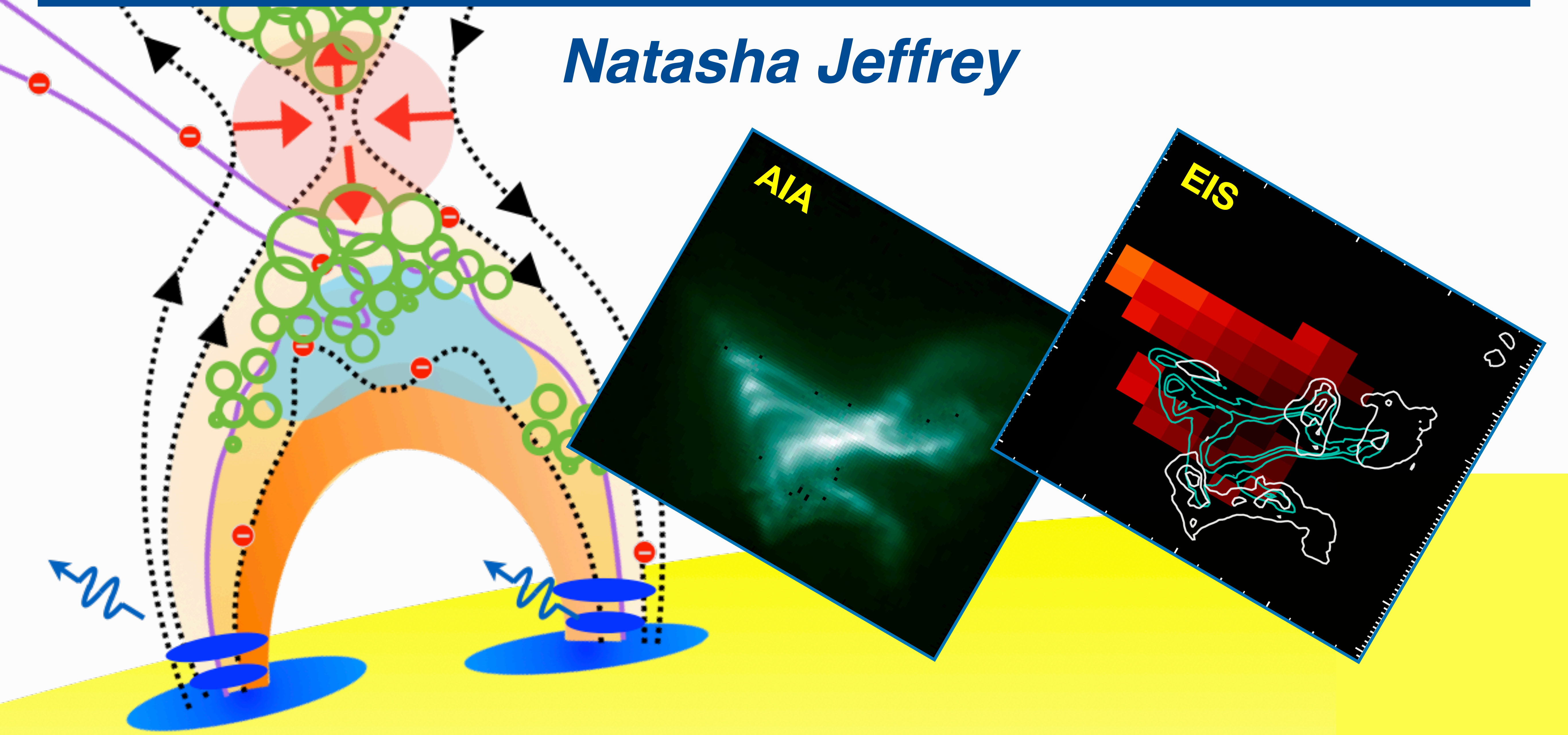
The role of turbulence in solar flares; a very brief observational overview.

Natasha Jeffrey



16th ESPM September 2021

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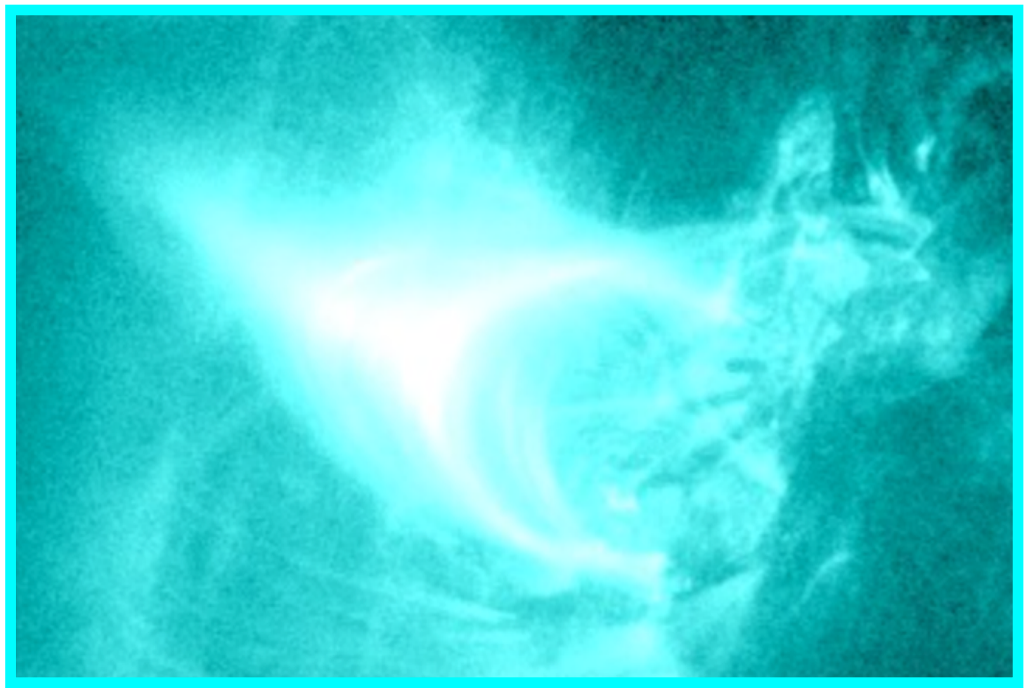
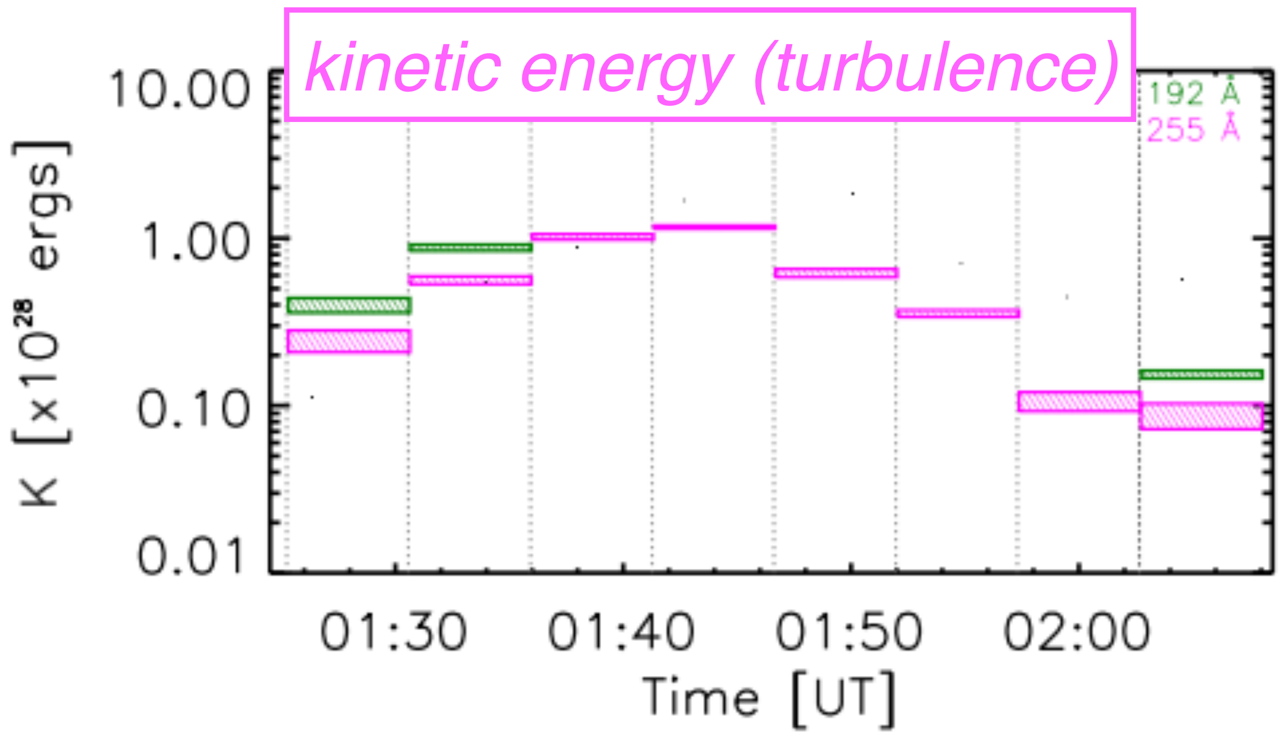
Solar flare turbulence: background

A substantial fraction of the magnetic energy goes into non-thermal electrons.

e.g., **Emslie et al. 2012, Warmuth & Mann 2016, Aschwanden et al. 2017.**





- **Turbulence** is an important mechanism for the transfer of magnetic energy e.g. **Larosa & Moore 1993, Petrosian 2012, Vlahos et al. 2016.**
- **Turbulence** may dissipate energy over multiple fragmented regions during the flare e.g. **Vlahos et al. 2016, Gordovskyy et al. 2016.**
- **Energy is transferred** from large scales (~size of a solar flare loop 10^9 cm) to small scales (particle level).

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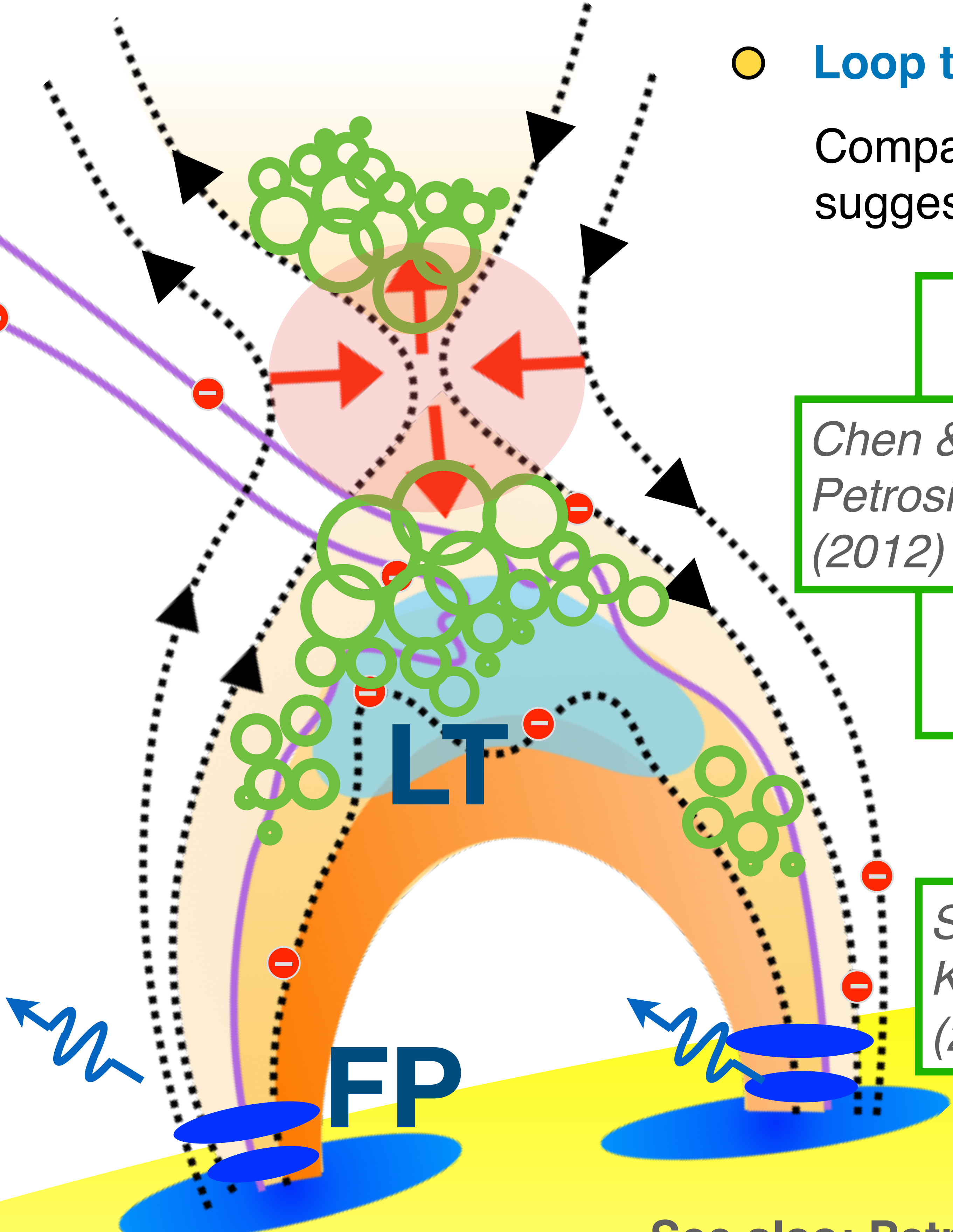
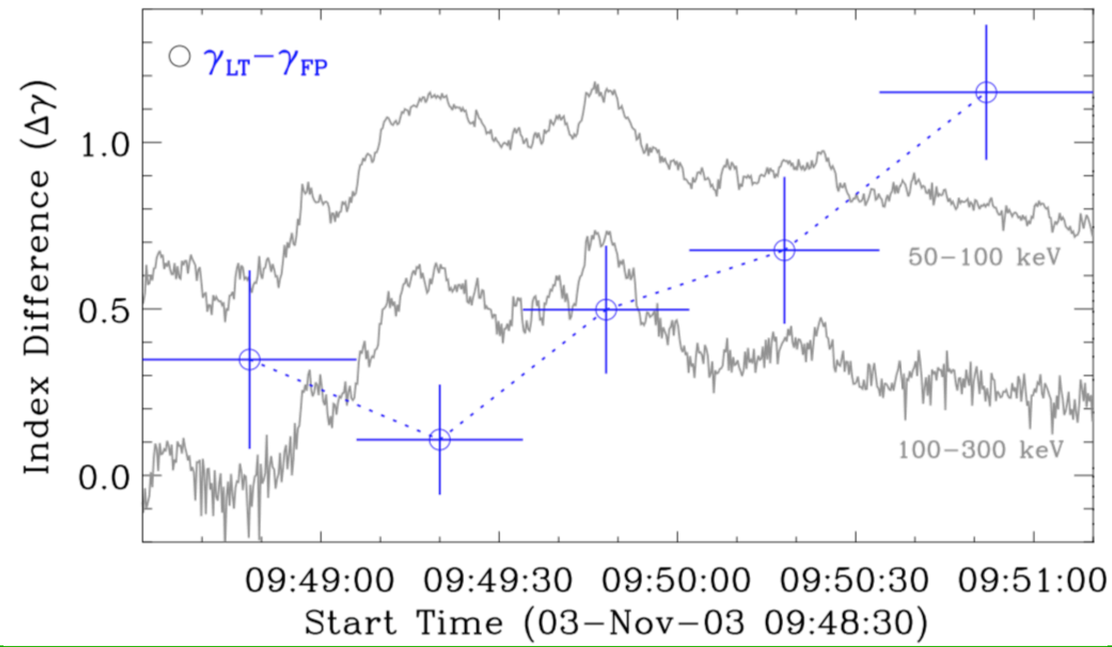
Evidence for turbulence in solar flares?



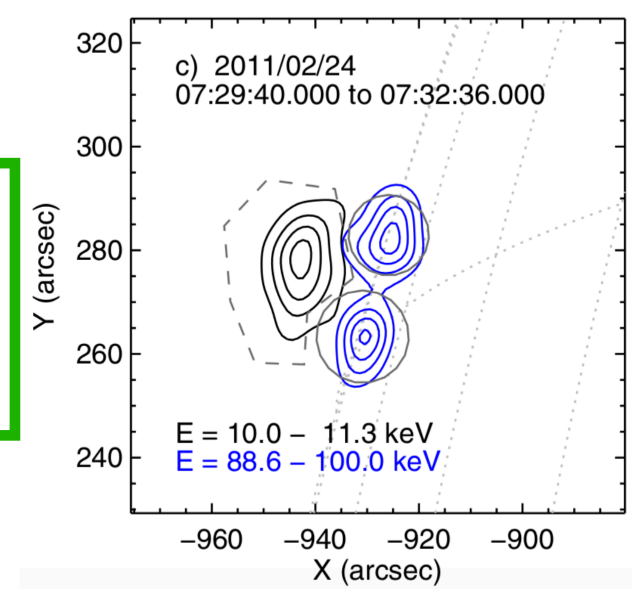
- **Loop top/footpoint parameter differences/ratios**

Comparing electron properties in the LT and at FPs suggests **'coronal trapping'** in some flares.

Chen & Petrosian (2012)



Simões & Kontar (2013)

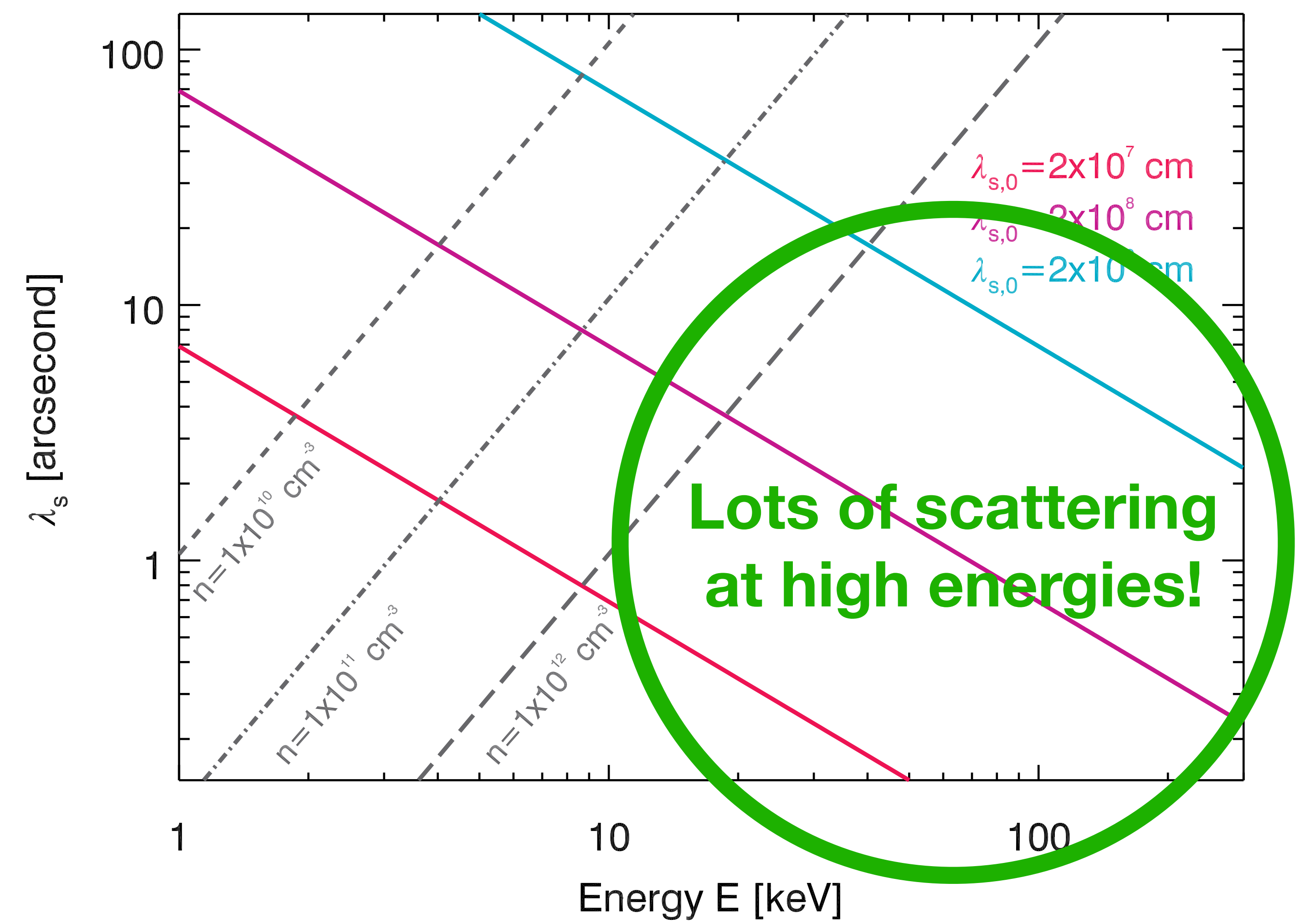


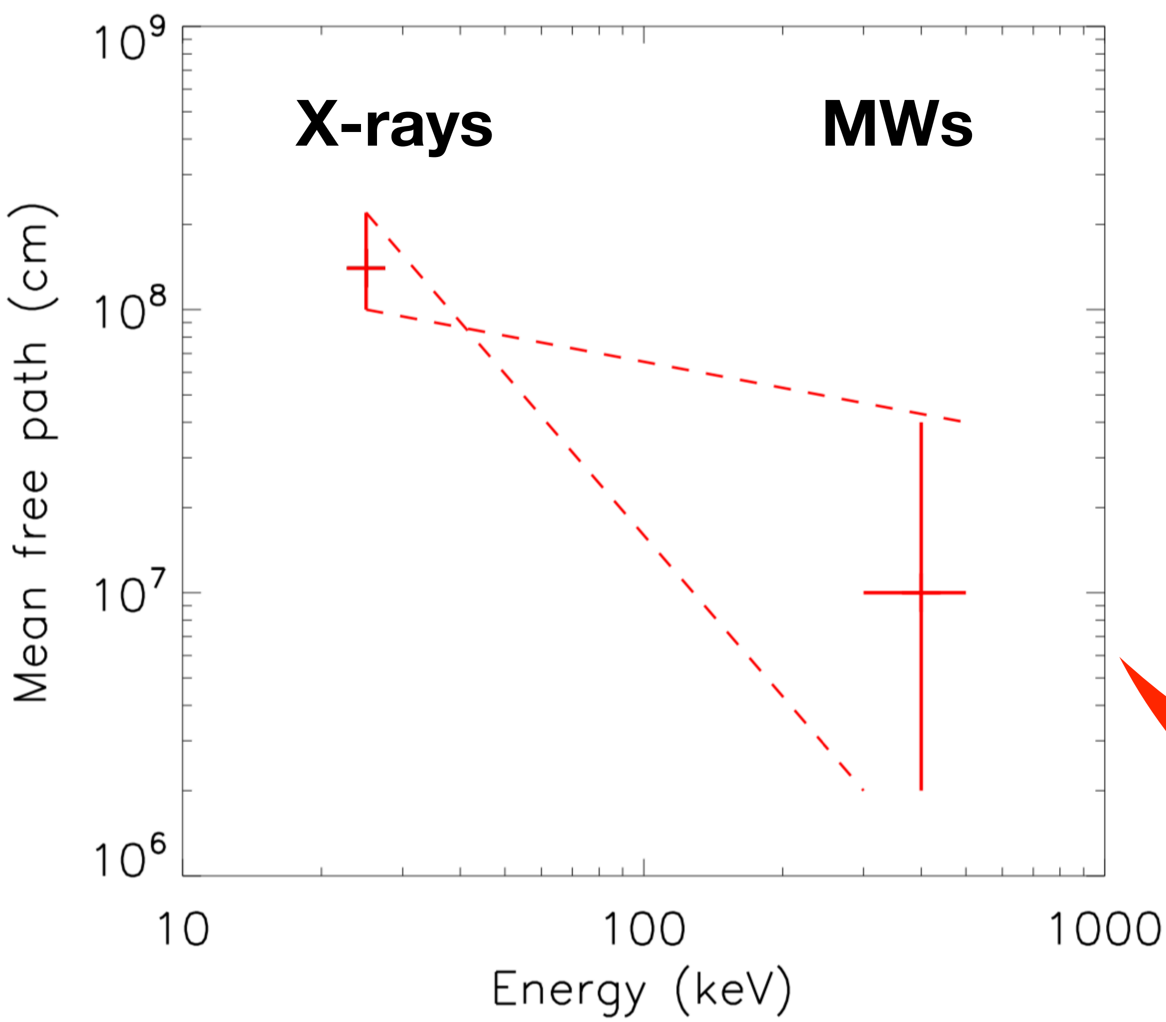
$$\frac{\dot{N}_{LT}}{\dot{N}_{FP}} > 1$$

See also: Petrosian et al. (2002), Battaglia & Benz (2006)

Solar flare turbulence: scattering

- **Turbulent scattering** can lead to diffusive transport of electrons and trap them in the corona **e.g. Schlickeiser 1989, Bian et al. 2011, Kontar et al. 2014.**

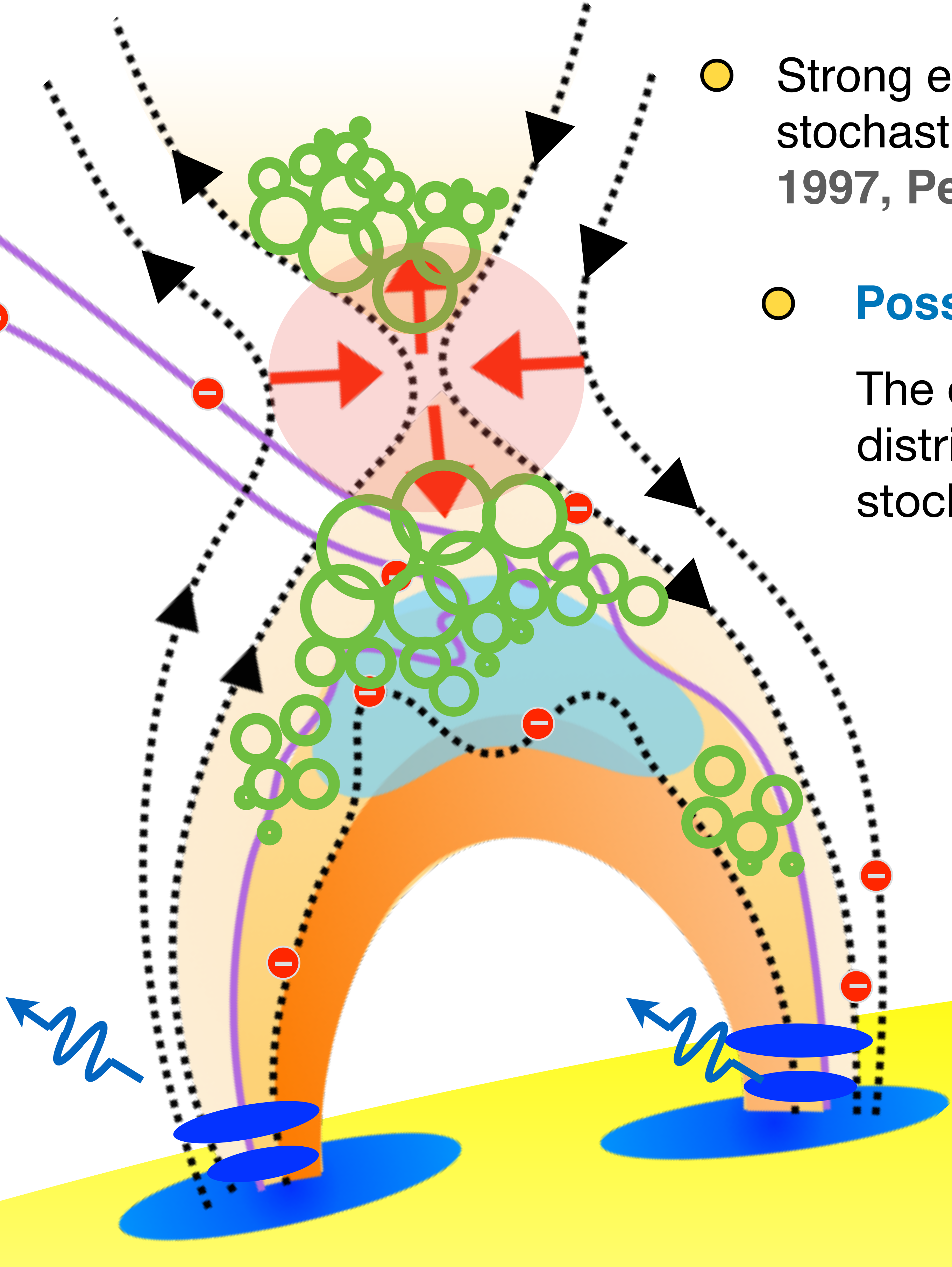




- **Musset et al. (2018)** demonstrated the presence of scattering from combined X-ray and microwave observations.

$$\lambda_s \simeq 2 \times 10^8 [\mathrm{cm}] \left(\frac{25[\mathrm{keV}]}{E} \right).$$

Evidence for turbulence in solar flares?

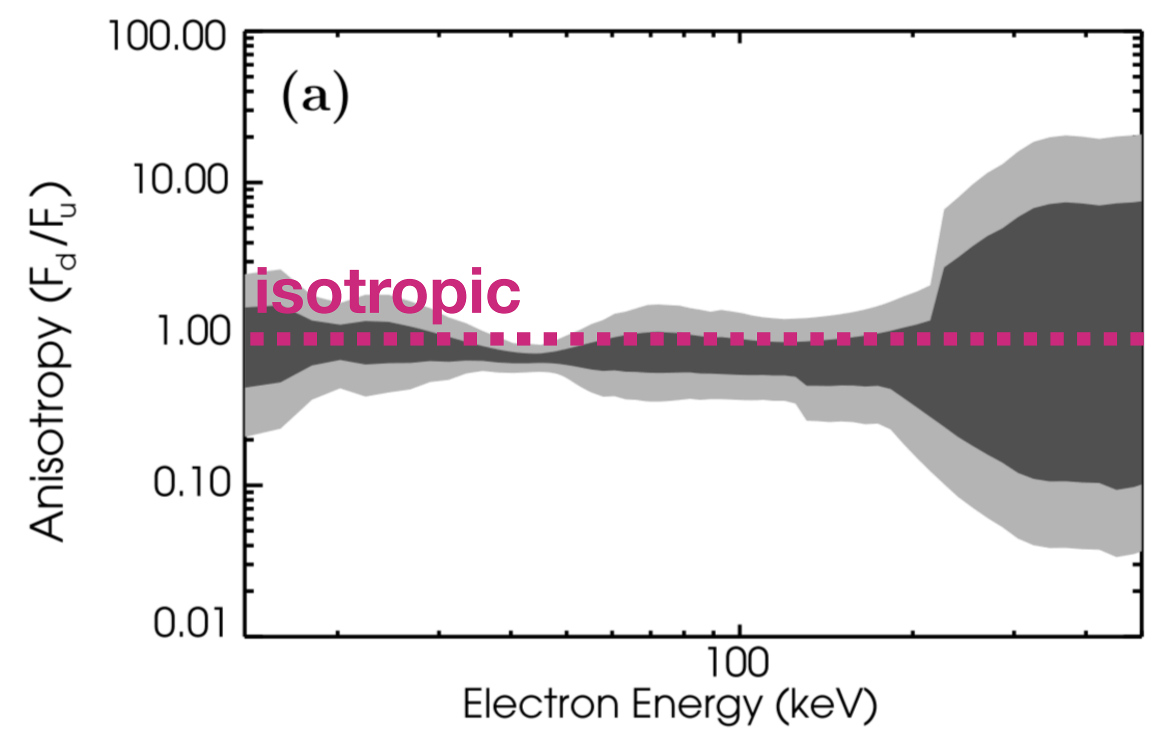


- Strong electron scattering is required for efficient stochastic acceleration (**Sturrock 1966, Miller et al 1997, Petrosian & Donaghy 1999, Bian et al 2012**).

- **Possible isotropy?**

  The detection of close to isotropic electron distributions from X-ray albedo could suggest a stochastic acceleration mechanism.

Dickson & Kontar 2013



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Turbulence from line broadening

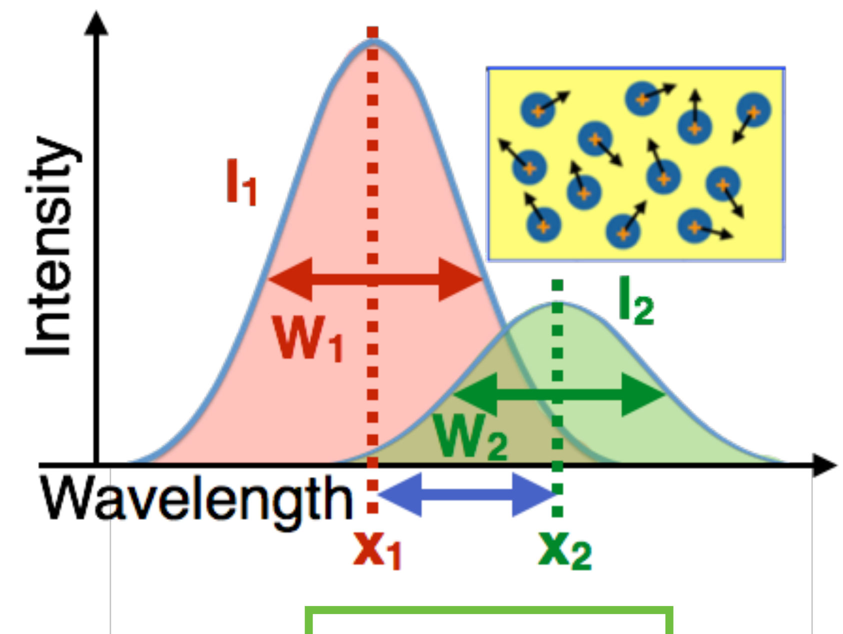
Turbulence can be inferred spectroscopically using line broadening.

- The properties of the plasma are found by determining the first three moments:

Zero moment=Integrated intensity
(ion abundance, electron density)

First moment=Centroid position
(plasma mass motion)

Second moment=Variance (broadening)
(temperature, turbulence)



Optically thin flare lines: **ion and plasma velocities determine *width and shape*.**

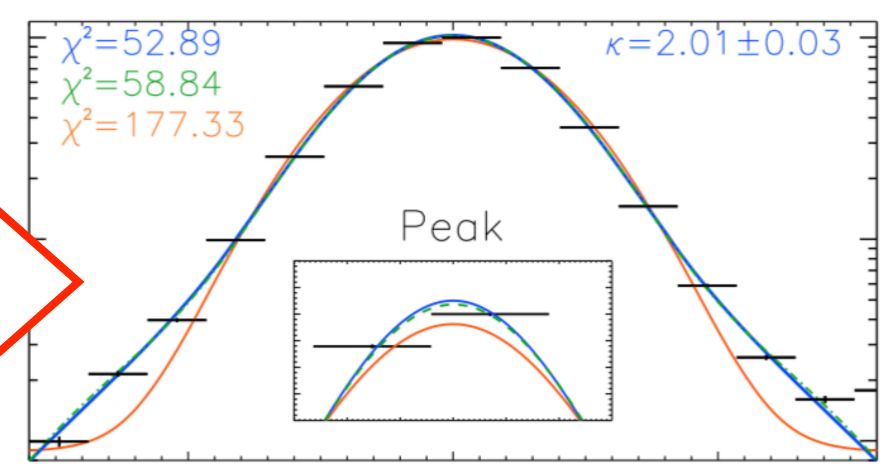
The **non-thermal velocity** is attributed to **plasma turbulence**.

instrument

$$v = \sqrt{v_{\rm th}^2 + v_{\rm inst}^2 + v_{\rm nth}^2}$$

thermal *non-thermal*

- Turbulence might produce **non-Gaussian line shapes** e.g., **Jeffrey et al. 2016, 2017, 2018, Dudik et al. 2017, Polito et al 2018**.



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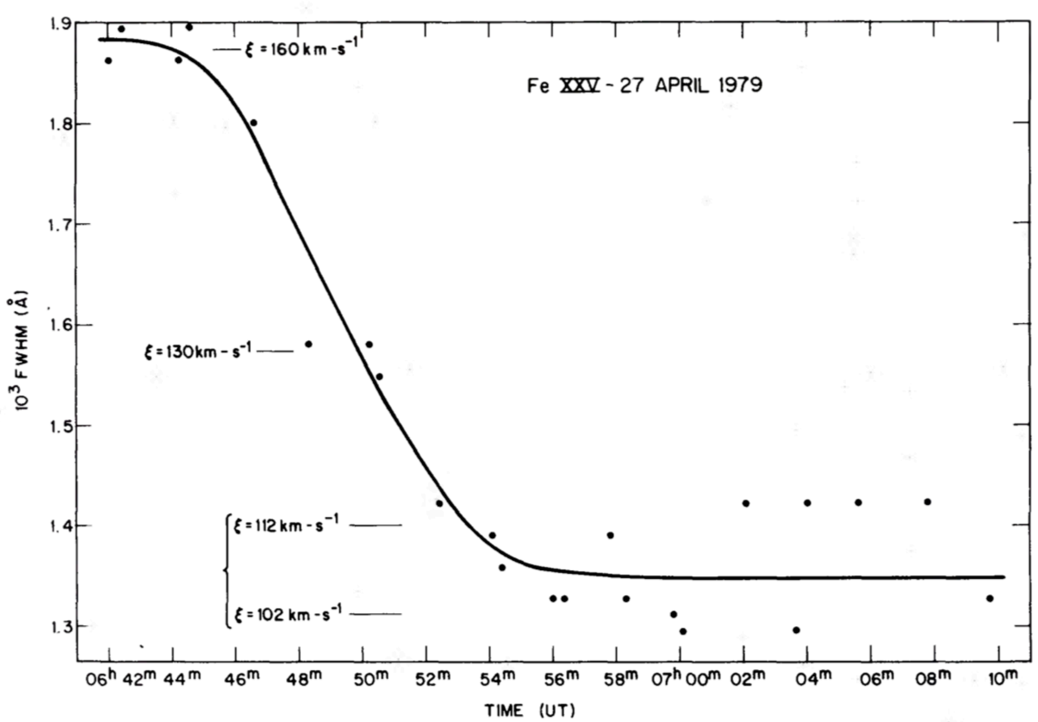
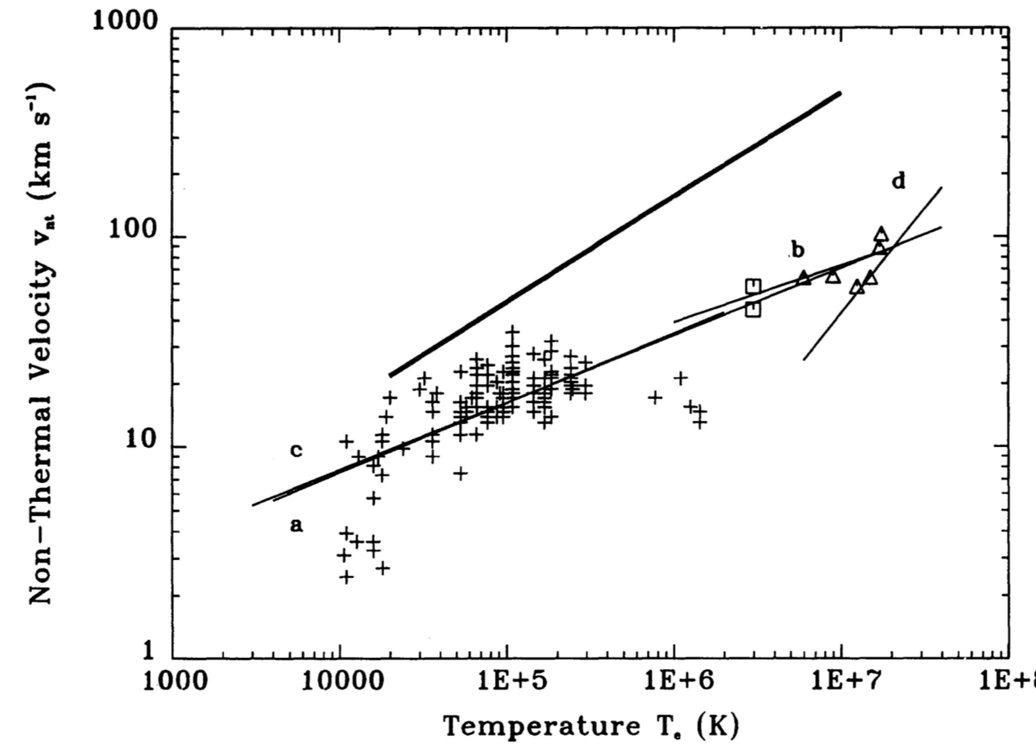
Solar flare turbulence: observations

- ***Early spatially integrated results:***

Doschek et al. 1980

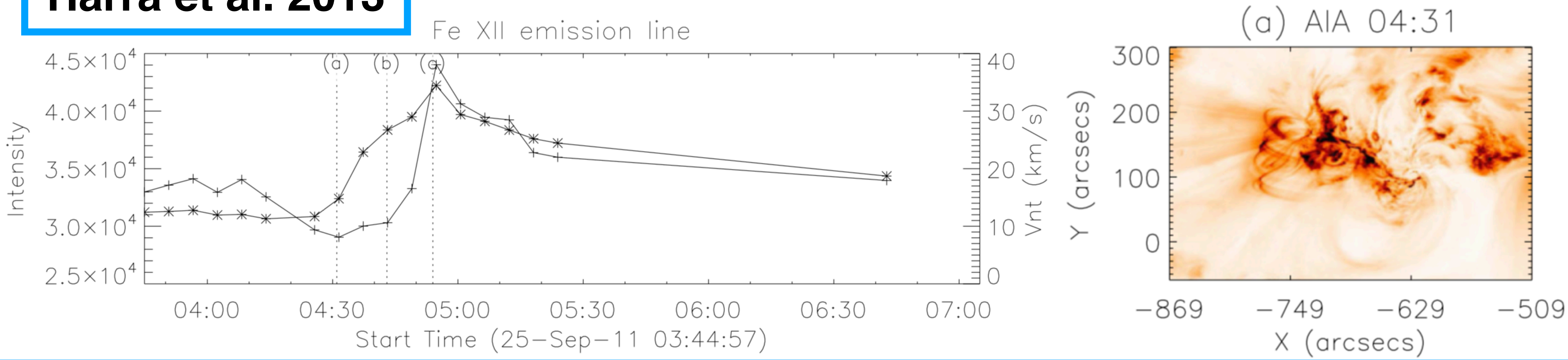


Antonucci & Dodero 1995



- ***Spatially resolved observations with Hinode EIS: flaring active regions***

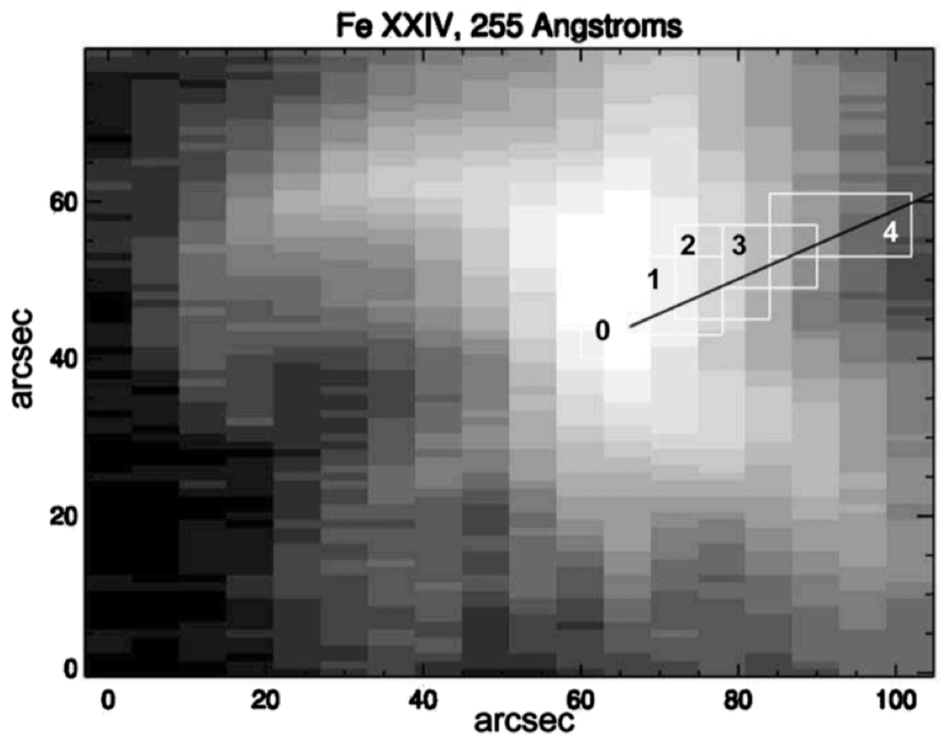
Harra et al. 2013

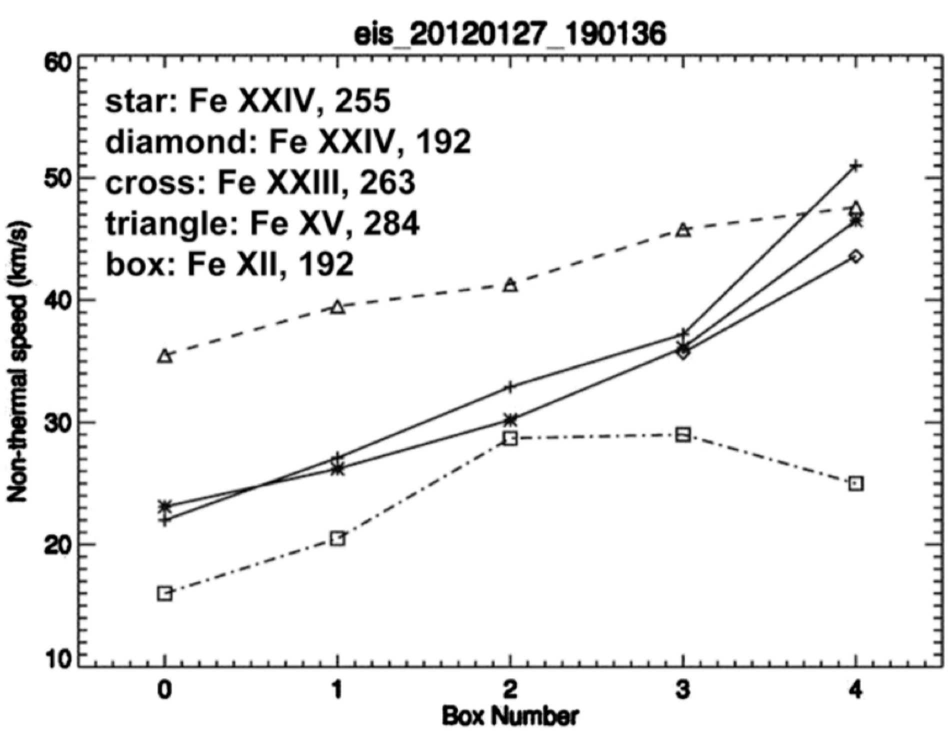


Solar flare turbulence: observations

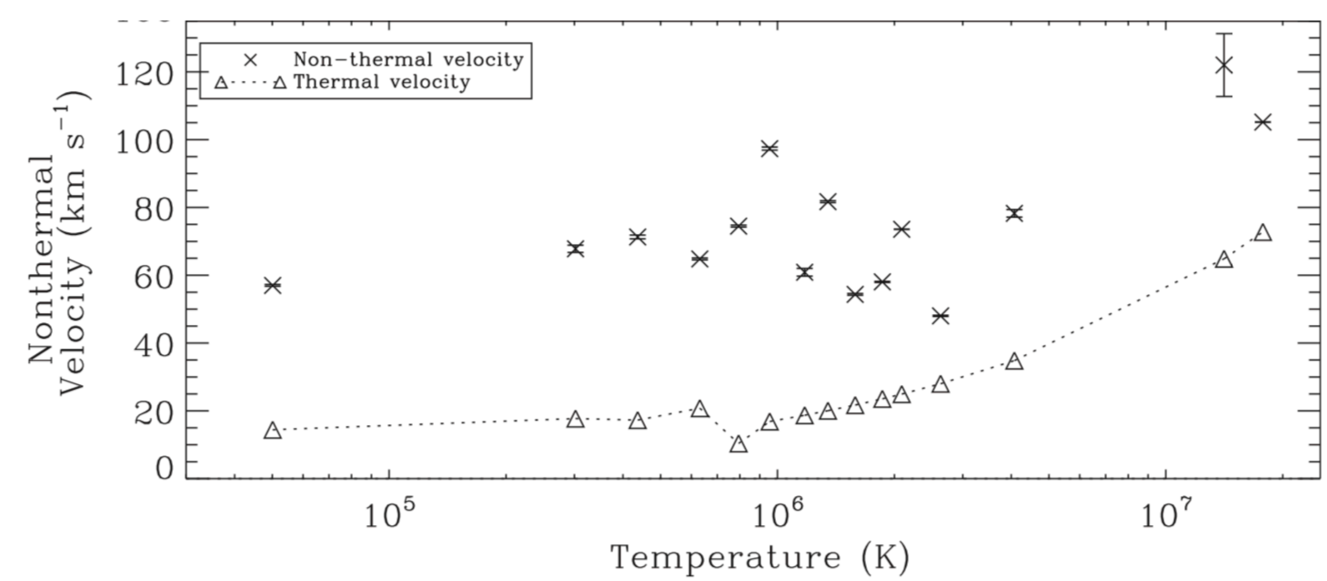
- ***Spatially resolved observations with Hinode EIS and IRIS: flares/brightenings***

Doschek et al. 2014

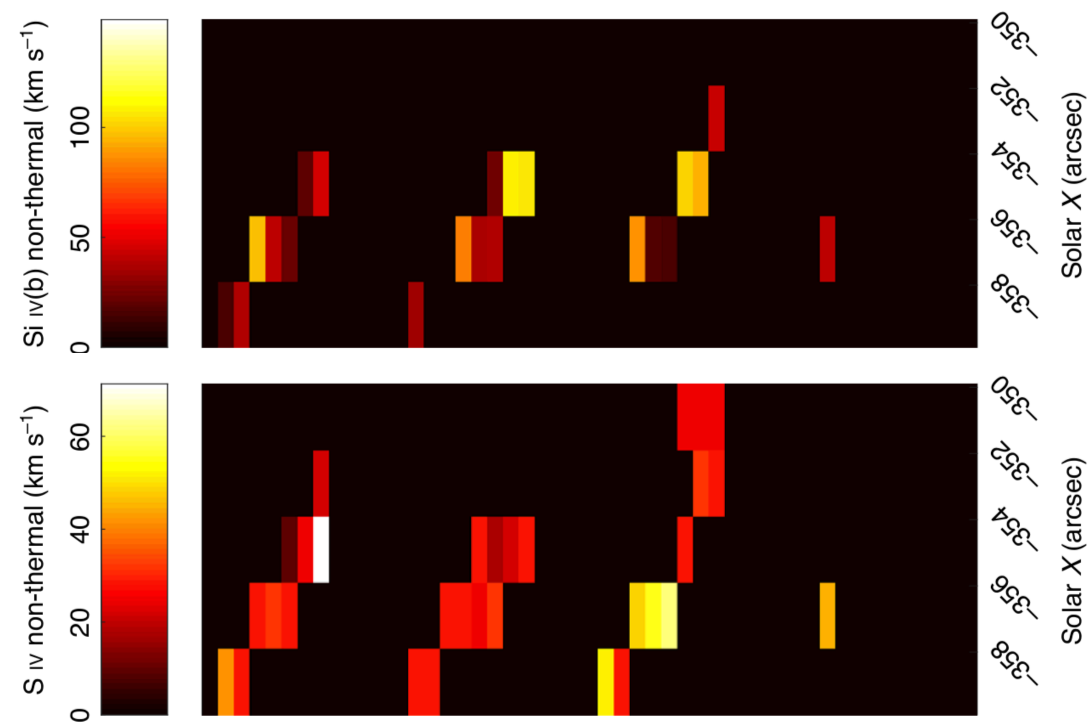




Milligan 2011



Bahauddin et al. 2021



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Solar flare turbulence: observations

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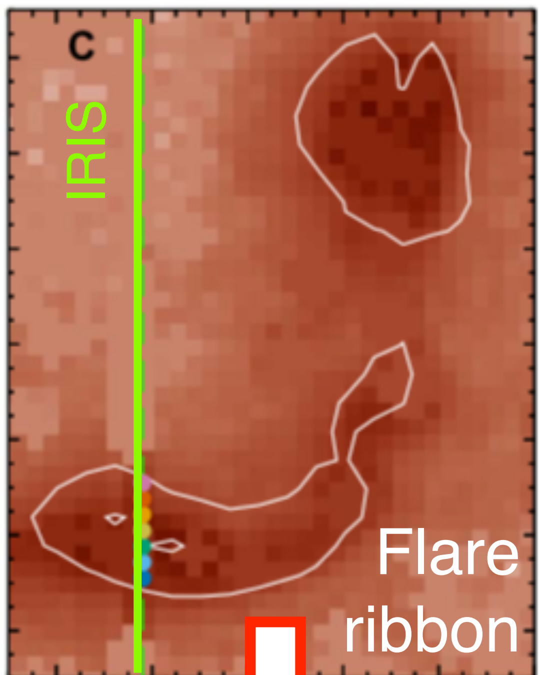
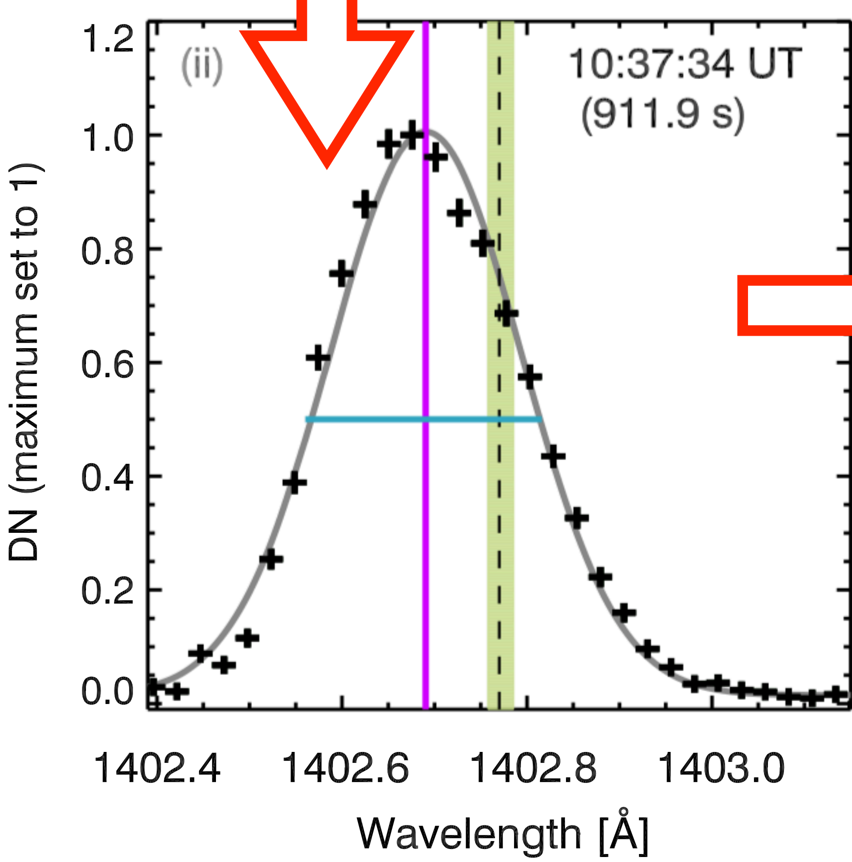
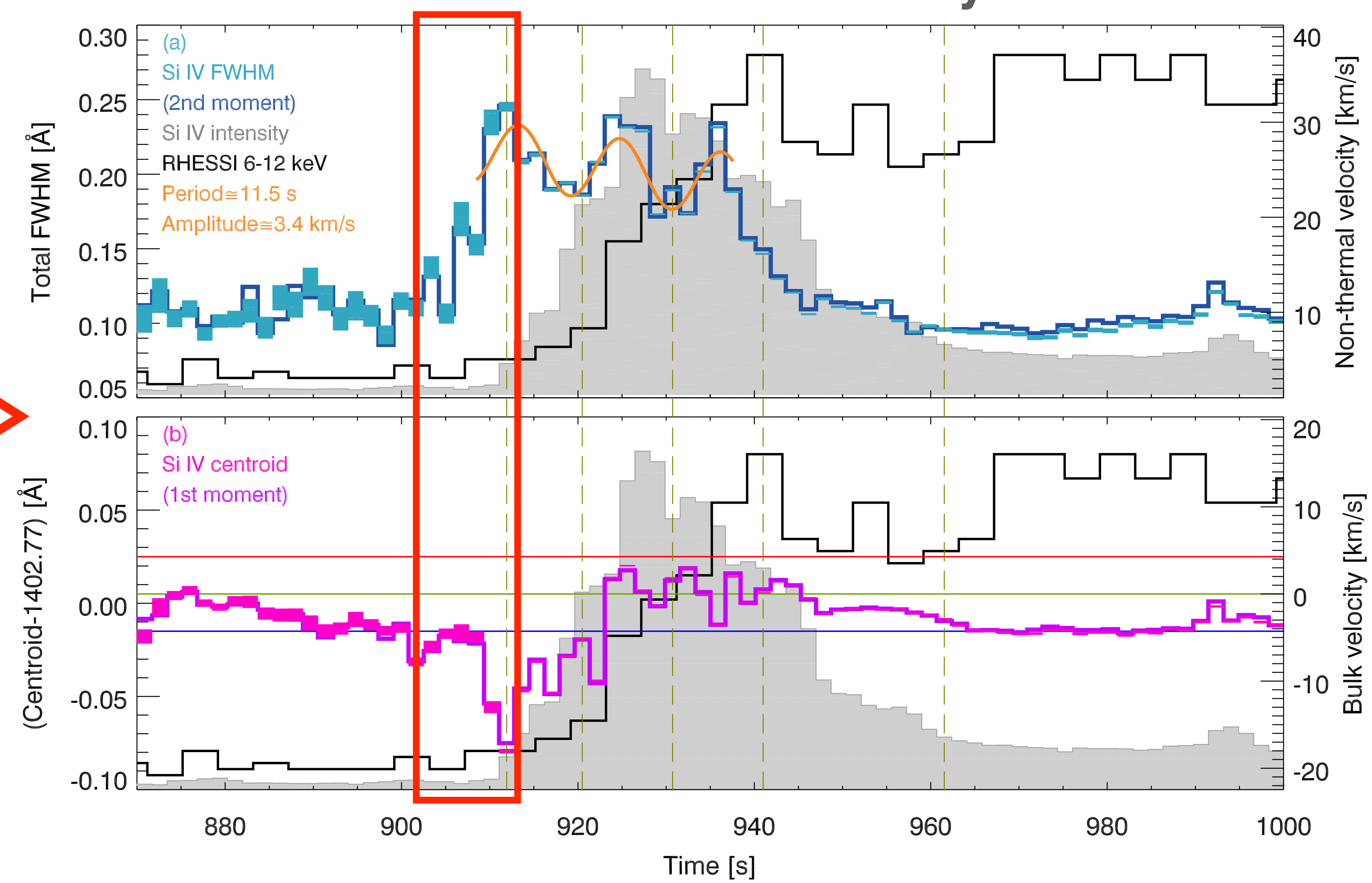


- **IRIS** provides low atmosphere (TR/chromosphere) spectroscopy at time resolutions as low as <2 s.
- One observation (of Si IV 1402.77 Å), **sit-and-stare** with **<2 s cadence** suggests turbulence in the transition region at the start of a flare?



Jeffrey et al. 2018



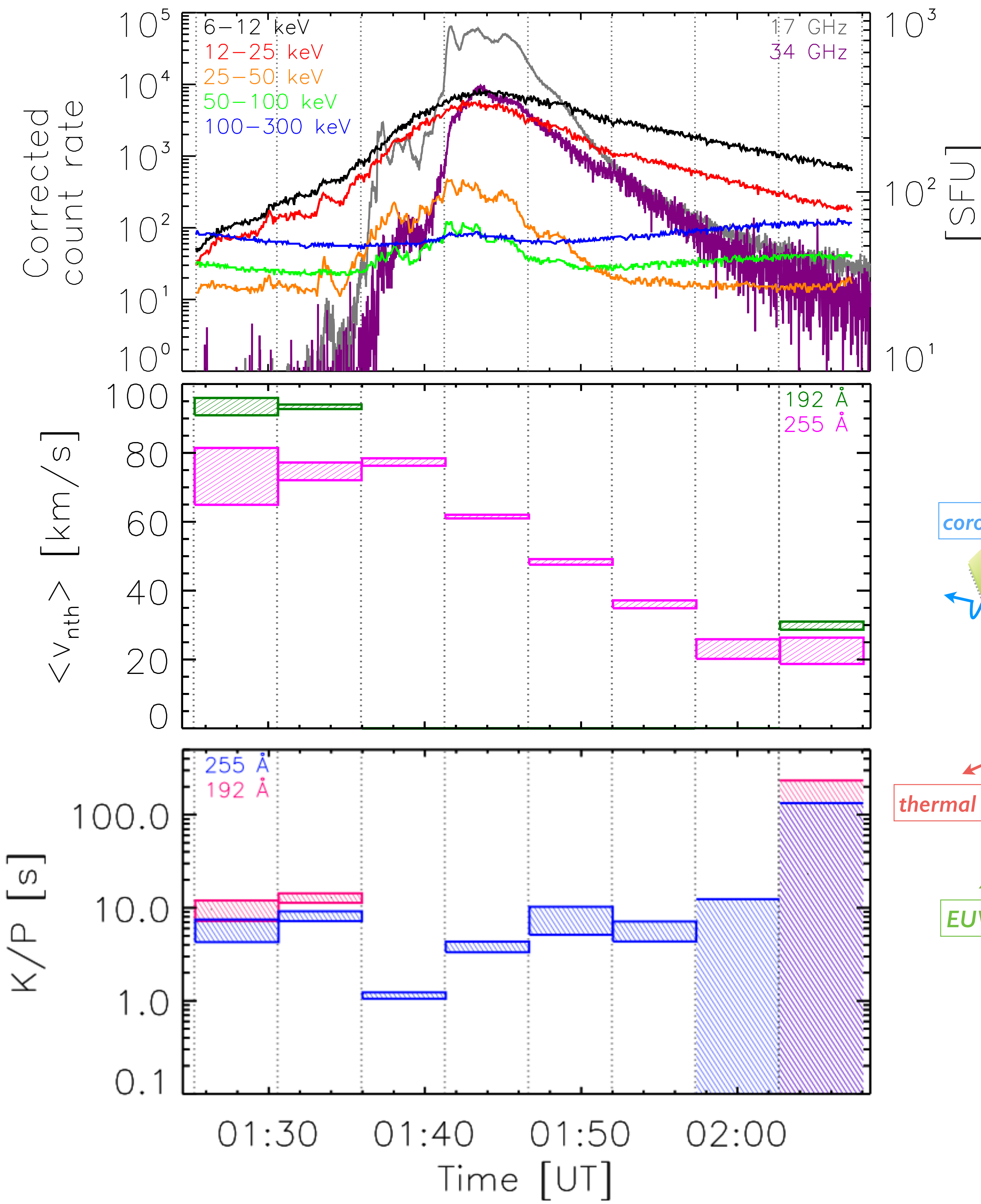
Solar flare turbulence: observations

Turbulence plays a vital role in the transfer of energy from magnetic fields.

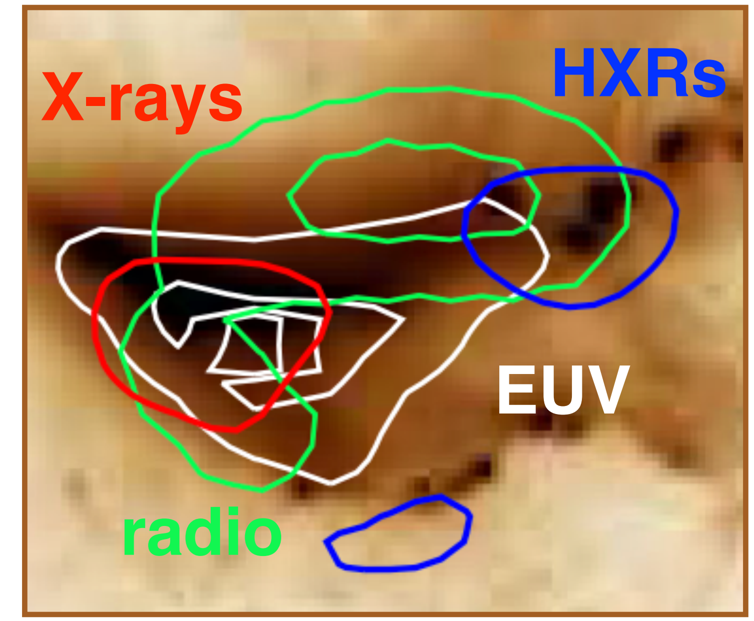
Flare Light curves

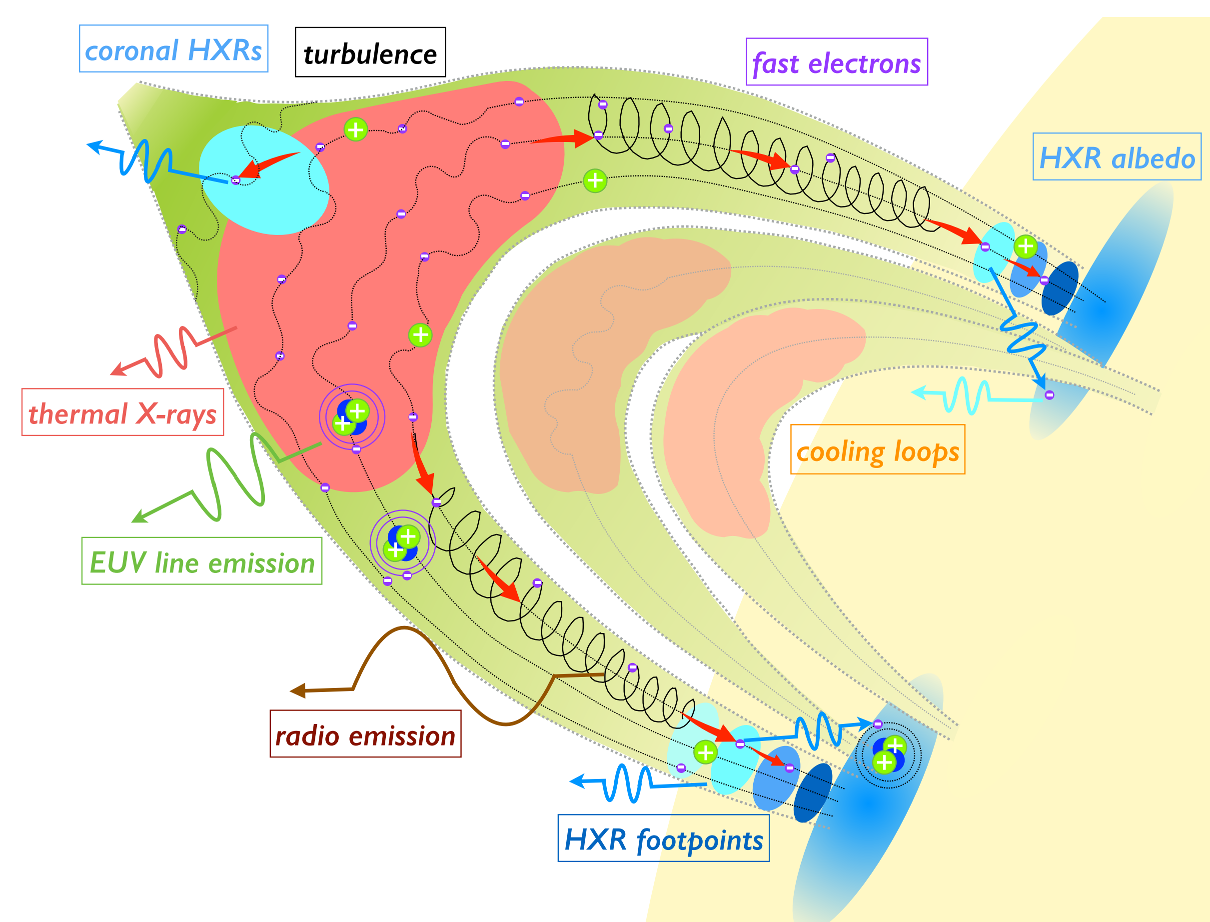
Non-thermal velocity (turbulence)

Turbulent dissipation time



Kontar et al. 2017





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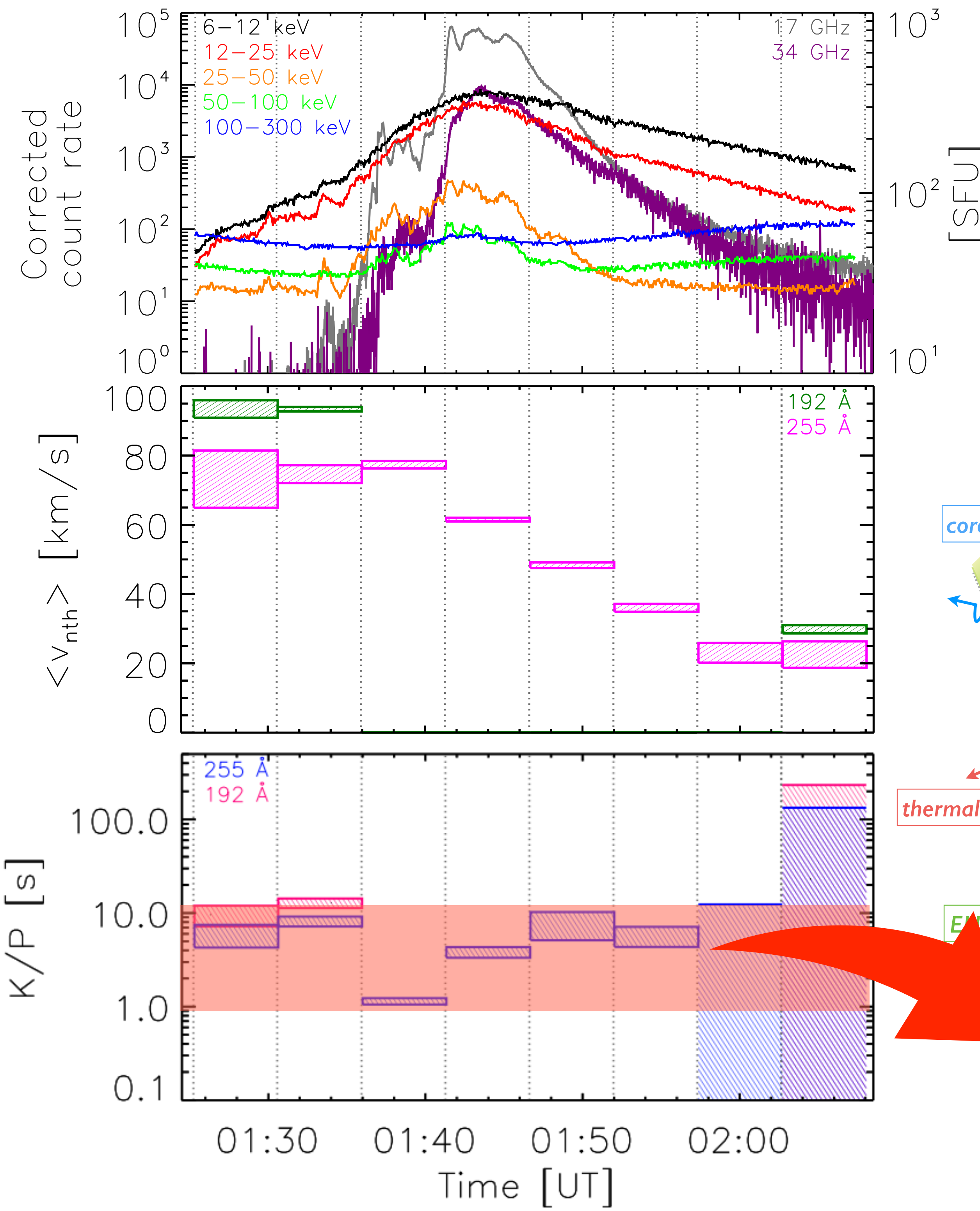
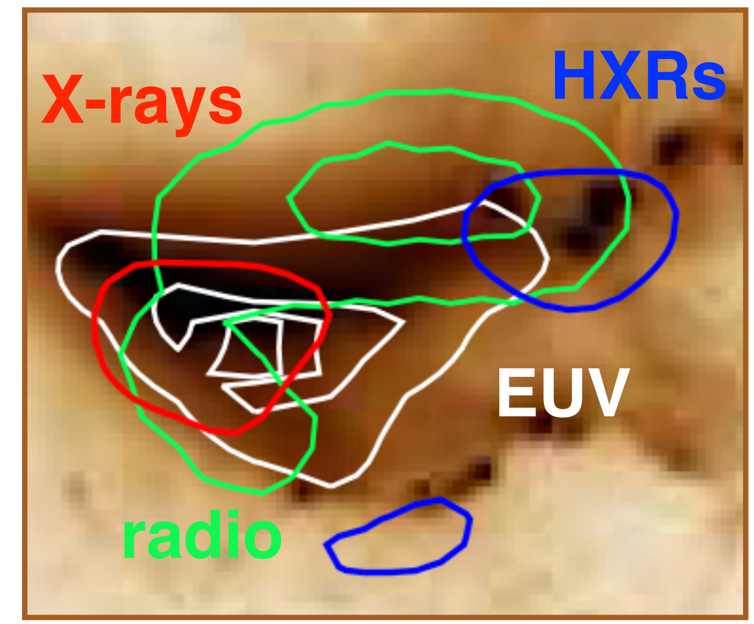
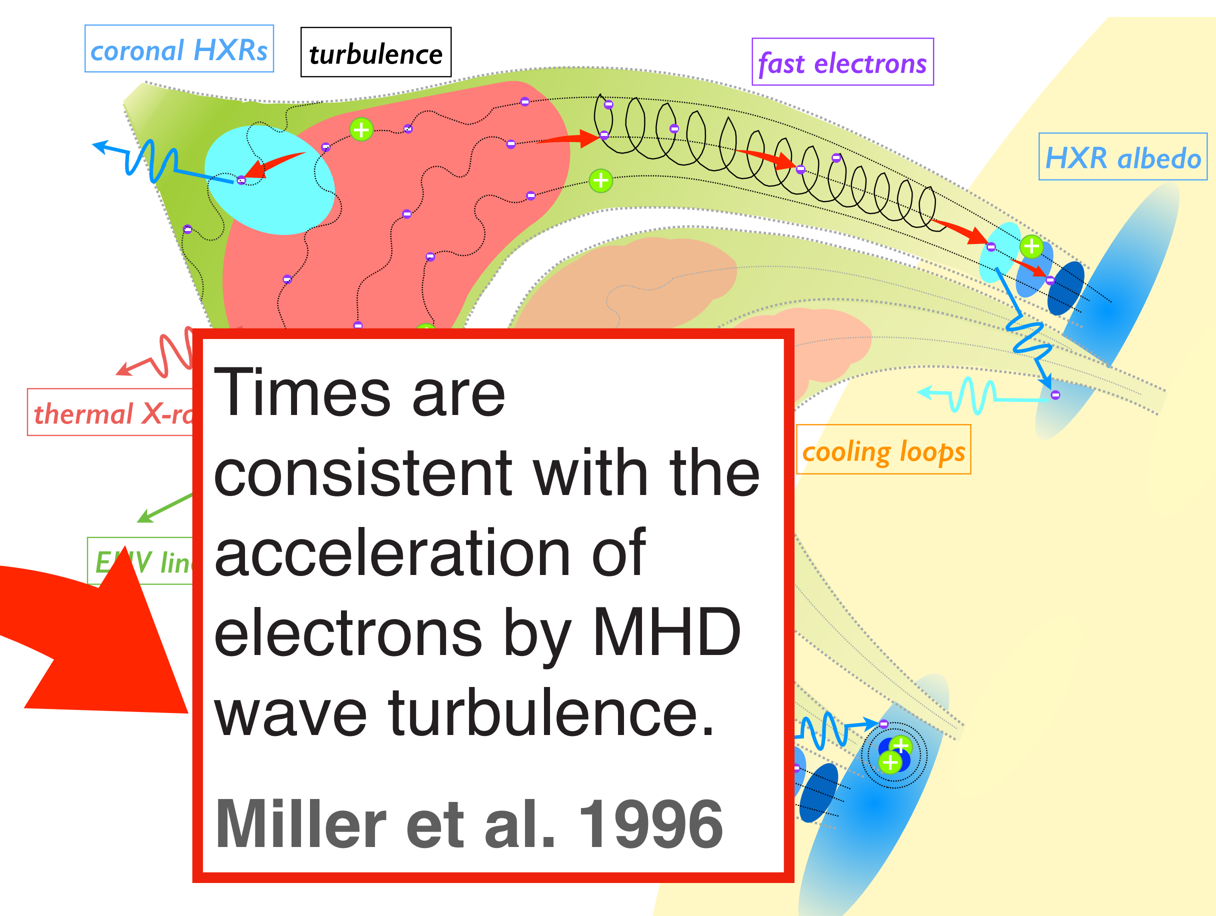


Kontar et al. 2017





Times are consistent with the acceleration of electrons by MHD wave turbulence.

Miller et al. 1996

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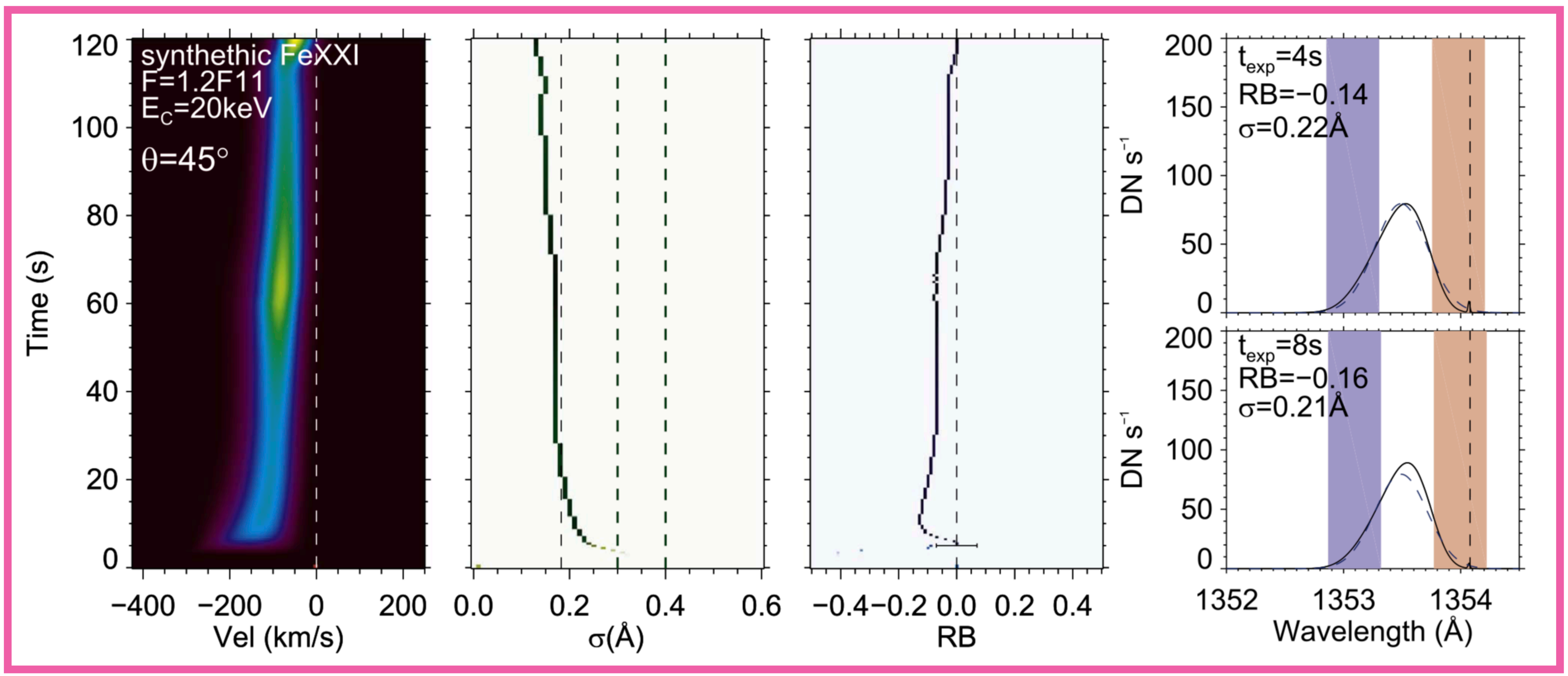
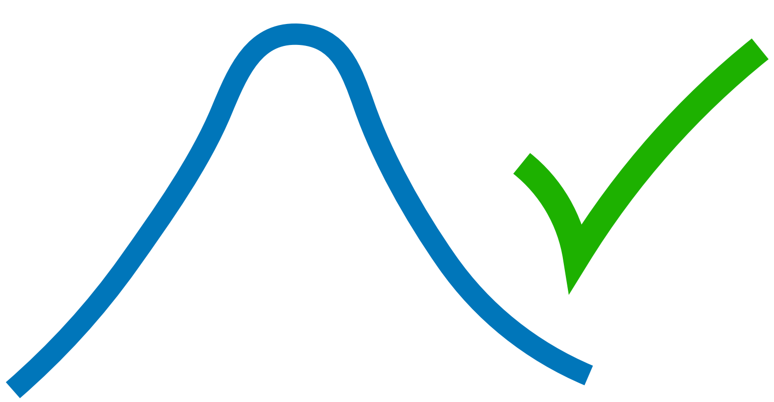
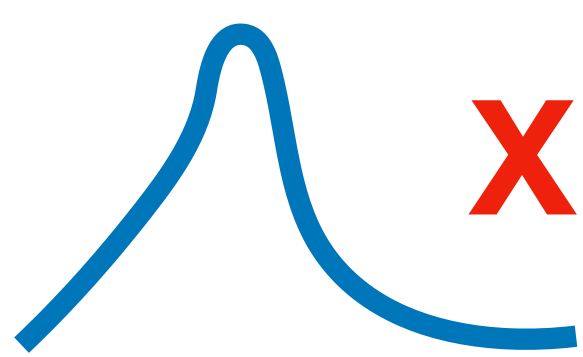
Turbulence or unresolved flows???

- Turbulence OR superposition of unresolved plasma flows along the line of sight?
- **Polito et al. 2019** suggest that it is difficult to reconcile symmetrical broadened lines with flows (flows are more likely to produce asymmetrical broadened lines).





More likely random plasma motions - Turbulence?



More likely superposition of unresolved, independent flows?

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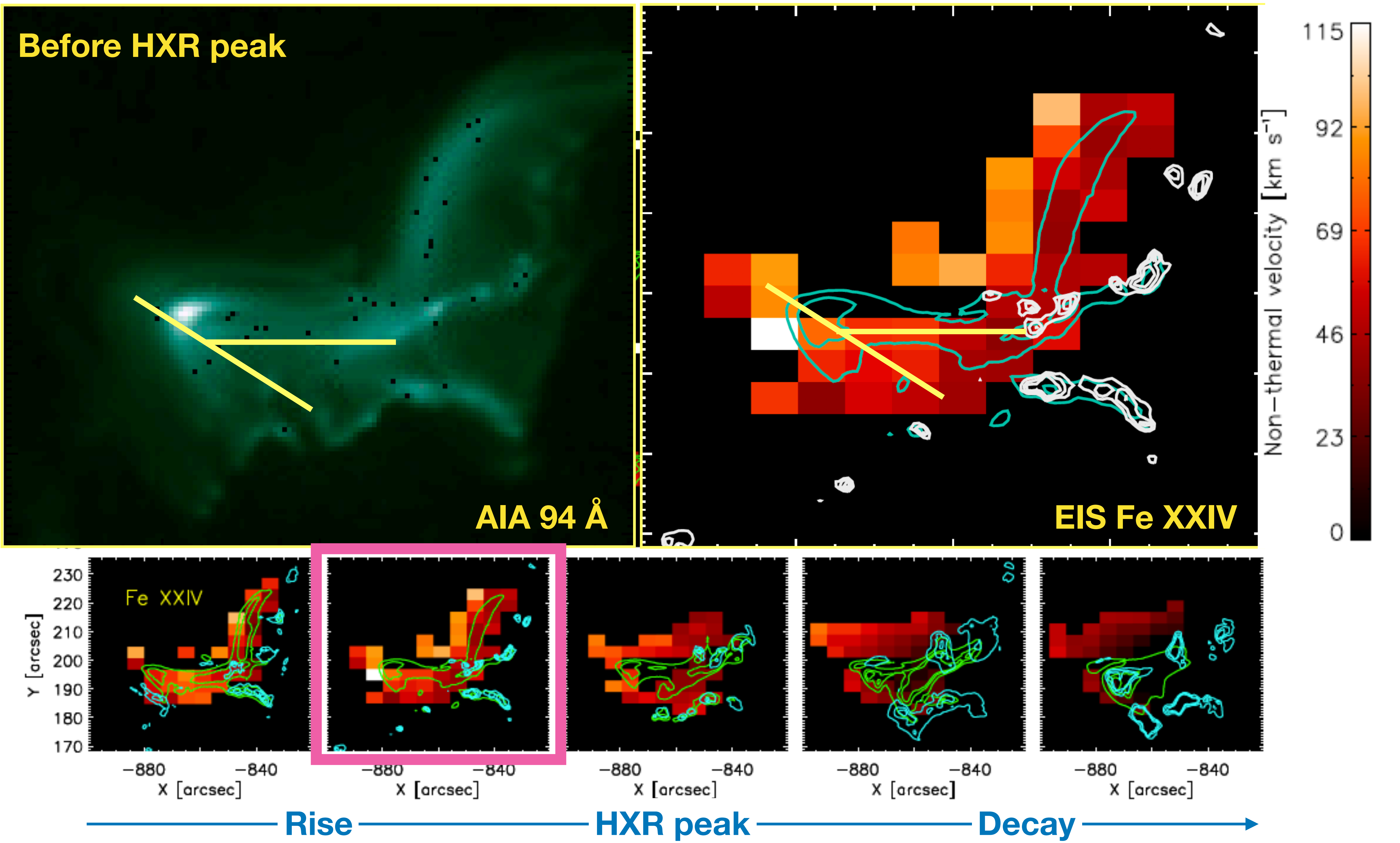
Spatial changes in turbulence

- **Stores et al. (2021, under review)** provides a detailed study of turbulence in space.



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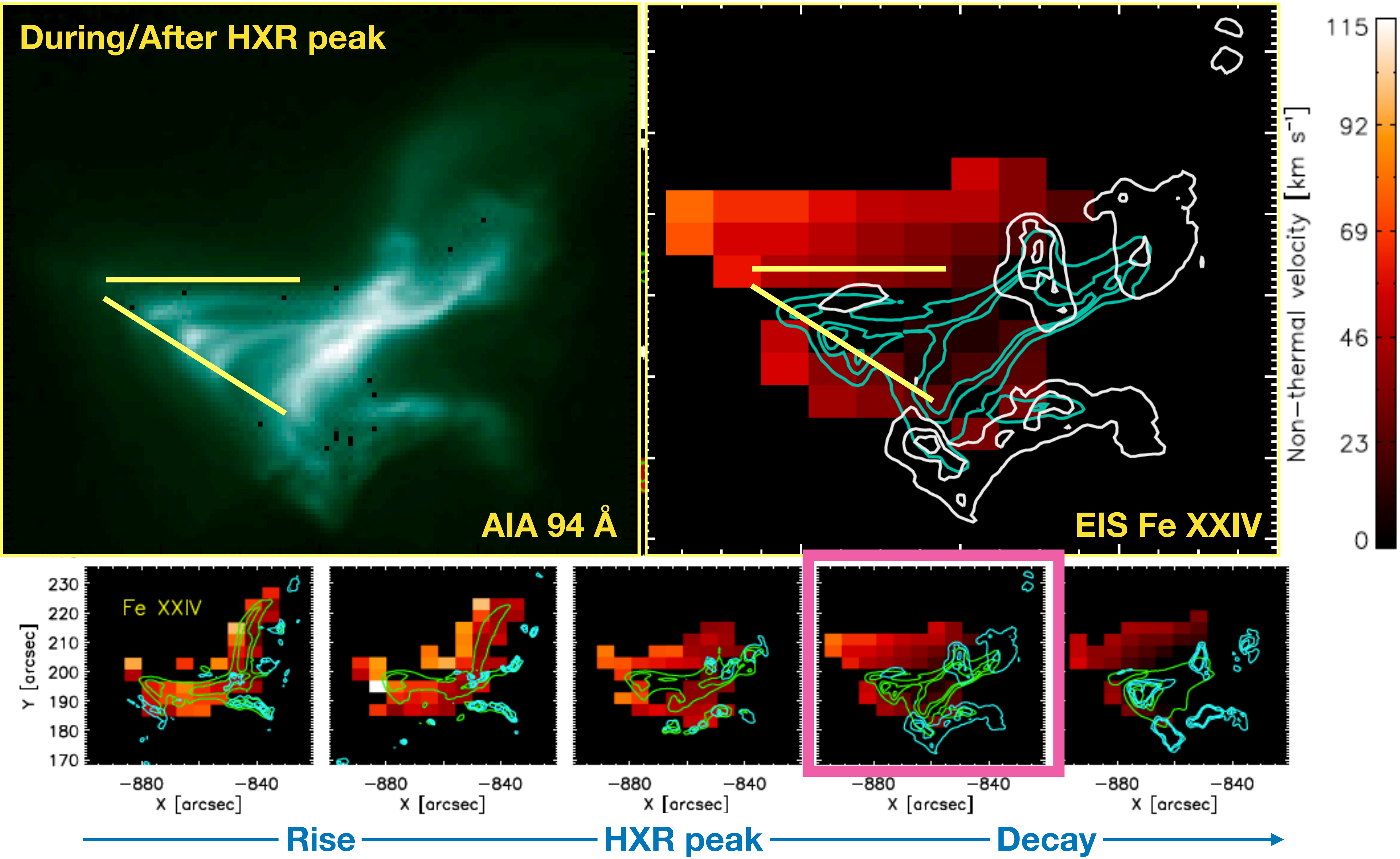
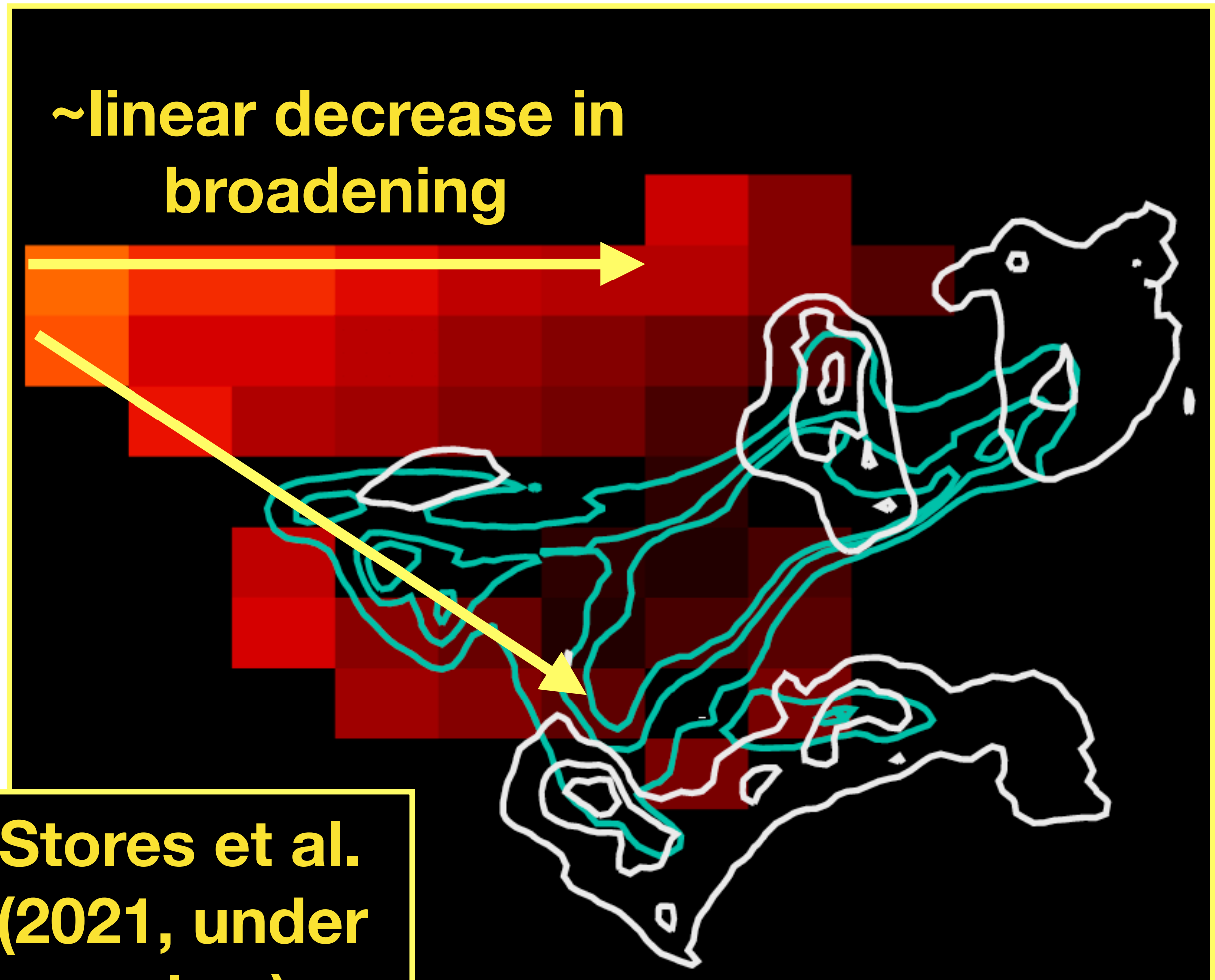


Spatial changes in turbulence

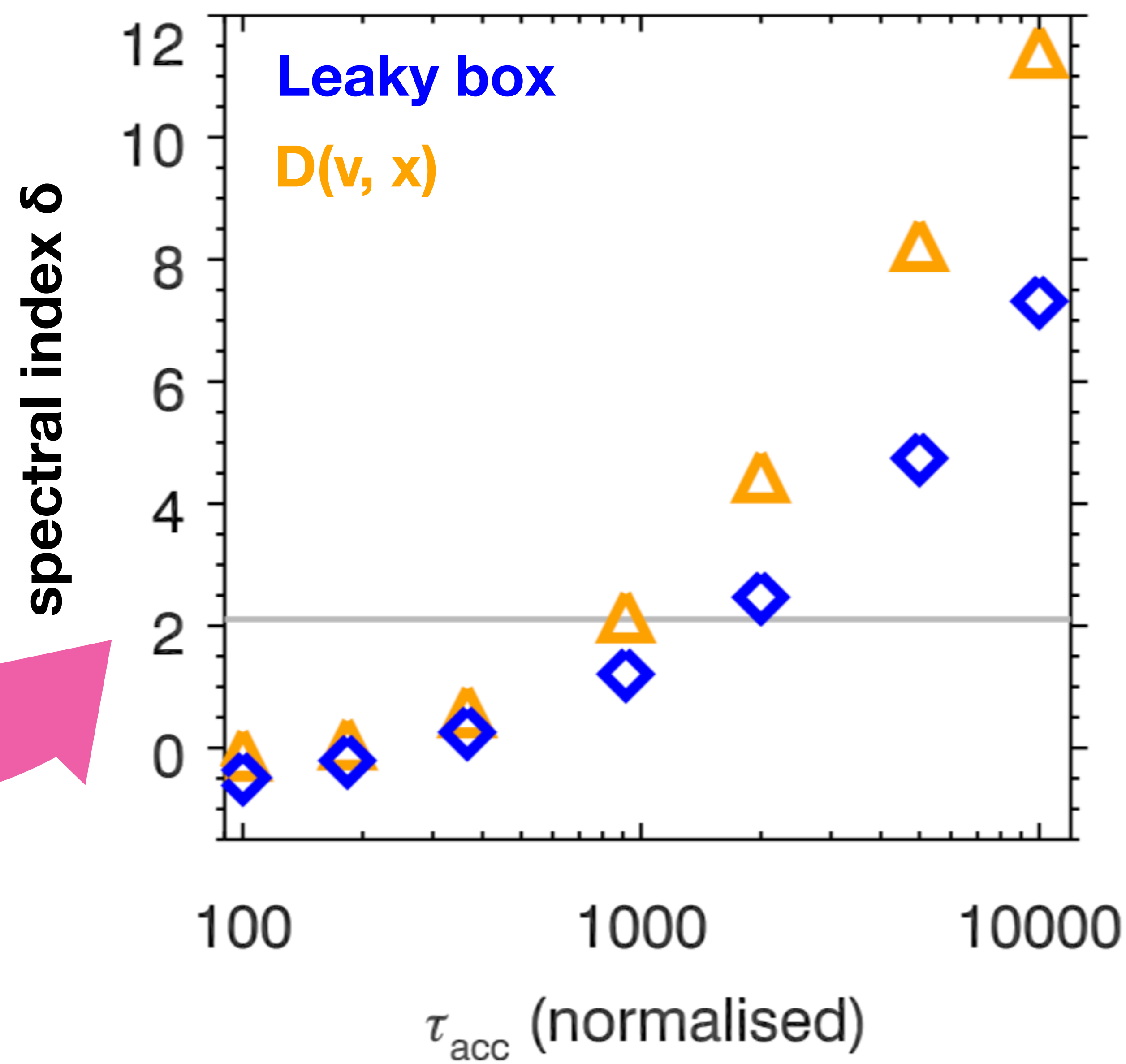


Stores et al. (2021, under review)

- Many turbulent acceleration models in the past has used a ‘leaky box’ type model (e.g., **Chen & Petrosian 2013**, **Bian et al. 2014**) where the spatial distribution of turbulence in the flare is not taken into account.

- **Stackhouse & Kontar 2018** - used a spatially distributed acceleration model

$$D(v, x) = \frac{v_{\rm te}^2}{\tau_{\rm acc}}\left(\frac{v}{v_{\rm te}}\right)^{\alpha} \underline{e^{-x^2/2\sigma^2}}$$



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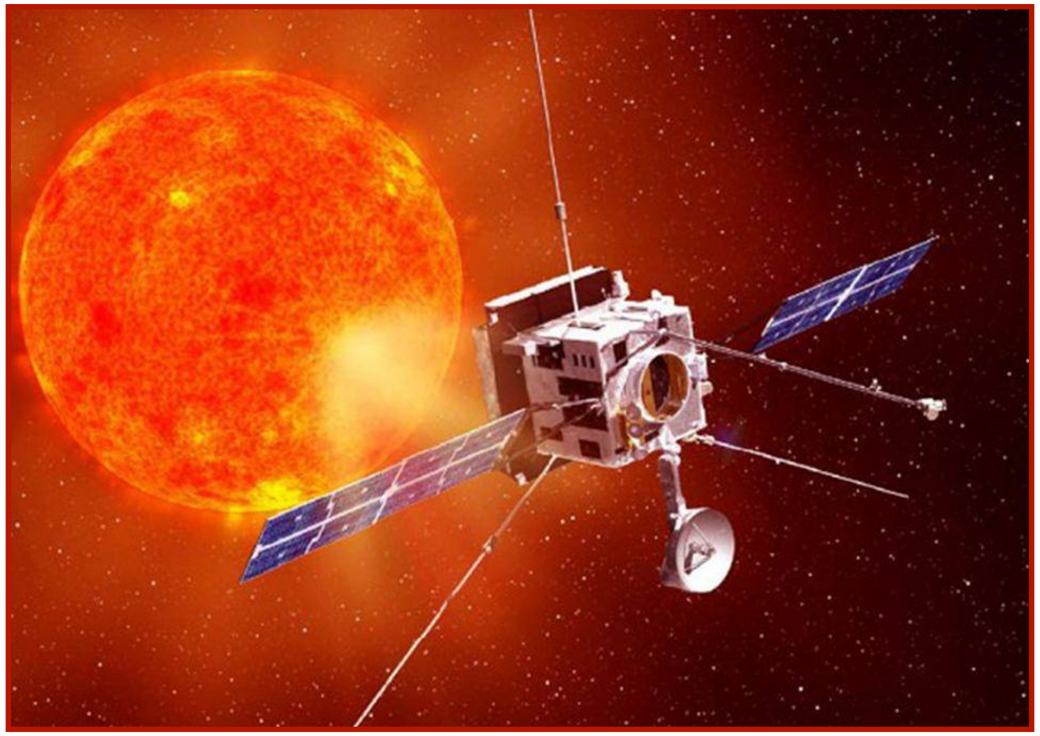
Summary and Future Work

Multiple observations suggest that turbulence generated by magnetic reconnection plays a vital role in both the acceleration and transport of flare energetic electrons.

- Turbulence is often discussed as a localised phenomena occurring in the corona but many spatially resolved observations show it is present in many flare regions.
- Observationally driven studies taking into account spatial changes in turbulence are an important next step for determining the true role of turbulence in solar flare particle acceleration and transport and for constraining properties.



- **STIX (Krucker et al. 2020) onboard Solar Orbiter will observe solar flare X-rays between 4 and 150 keV.**
- **Upcoming stereoscopic observations with STIX and LEO missions (ASO-S/HXI and Aditya/HEL1OS) will help to measure electron anisotropy - will be interesting if strong directivity is detected!**