University of Glasgow

Science & Technology Facilities Council

Detecting non-Gaussian (E)UV spectral lines: signatures of ion acceleration and/or turbulence?

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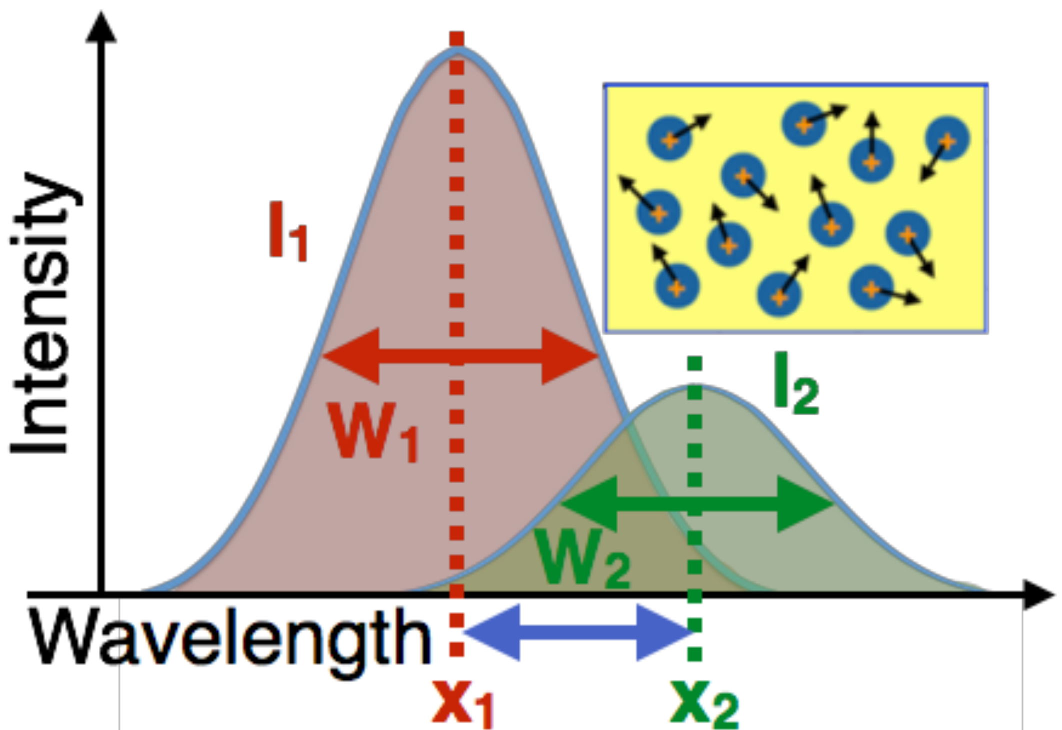
EUV line spectroscopy at the Sun

- **EUV line spectroscopy** is a vital tool for determining the properties of solar flare plasma which are usually found from Gaussian fitting and the first three moments:



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

1st moment=Centroid position
(plasma mass motion)

2nd moment=Variance (broadening)
(temperature, excess=turbulence etc.)

Total line broadening W:

$$w = \sqrt{w_{th}^2 + w_{inst}^2 + \xi^2}$$

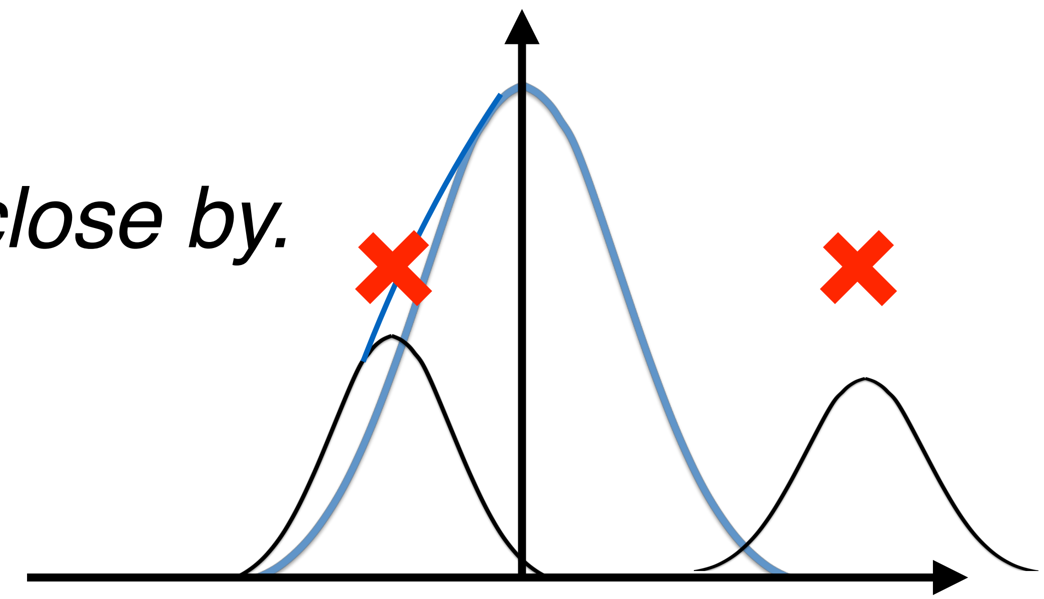
thermal — *instrument* — *excess*

- **For *optically thin* MK solar flare lines, the ion Doppler velocities (thermal and "non-thermal") will determine the line broadening.**

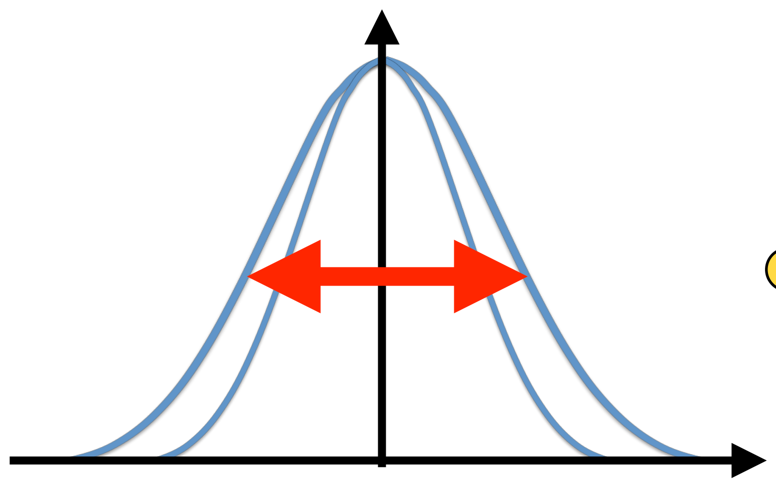
For solar flare lines, the distribution of ion and/or turbulent plasma velocities will also determine *the overall line shape*.

Looking for non-Gaussian spectral line shapes

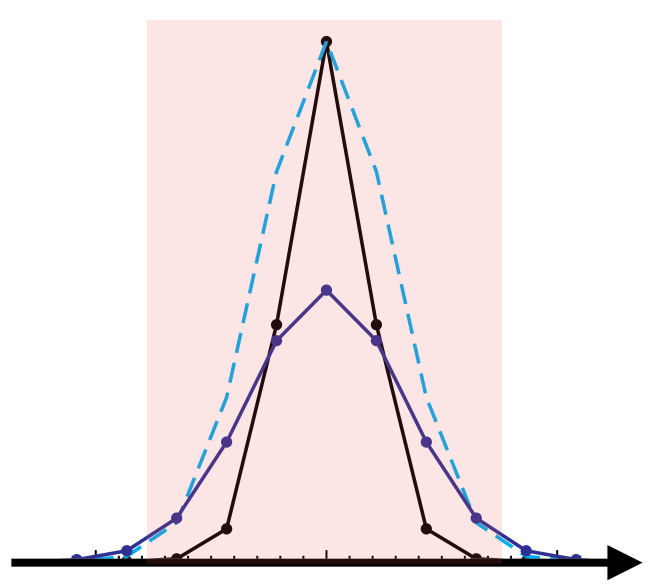
Line profile analysis is usually difficult! We have to account for…



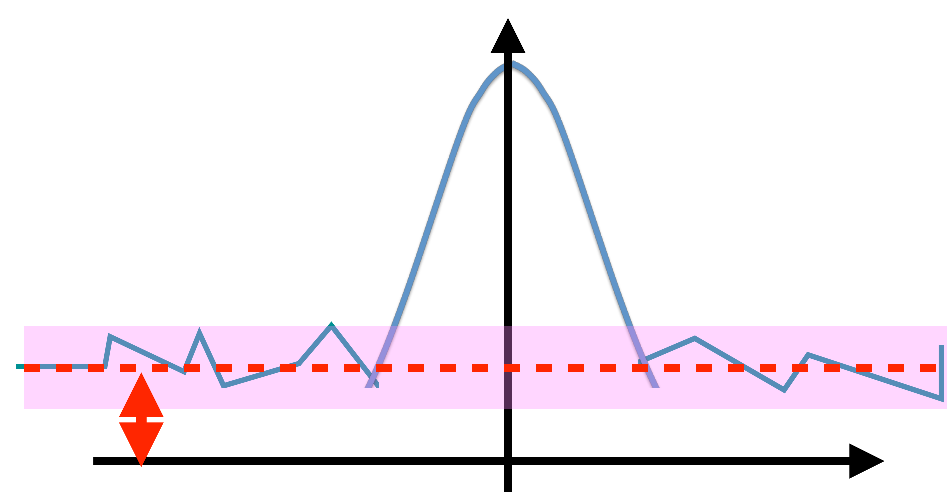
- *Blended lines, or other lines located close by.*
- *Moving components, line skewness.*



- *The (Gaussian?) instrumental broadening.*



- *Fitted wavelength range, spectral resolution.*



- *Noise, background level.*

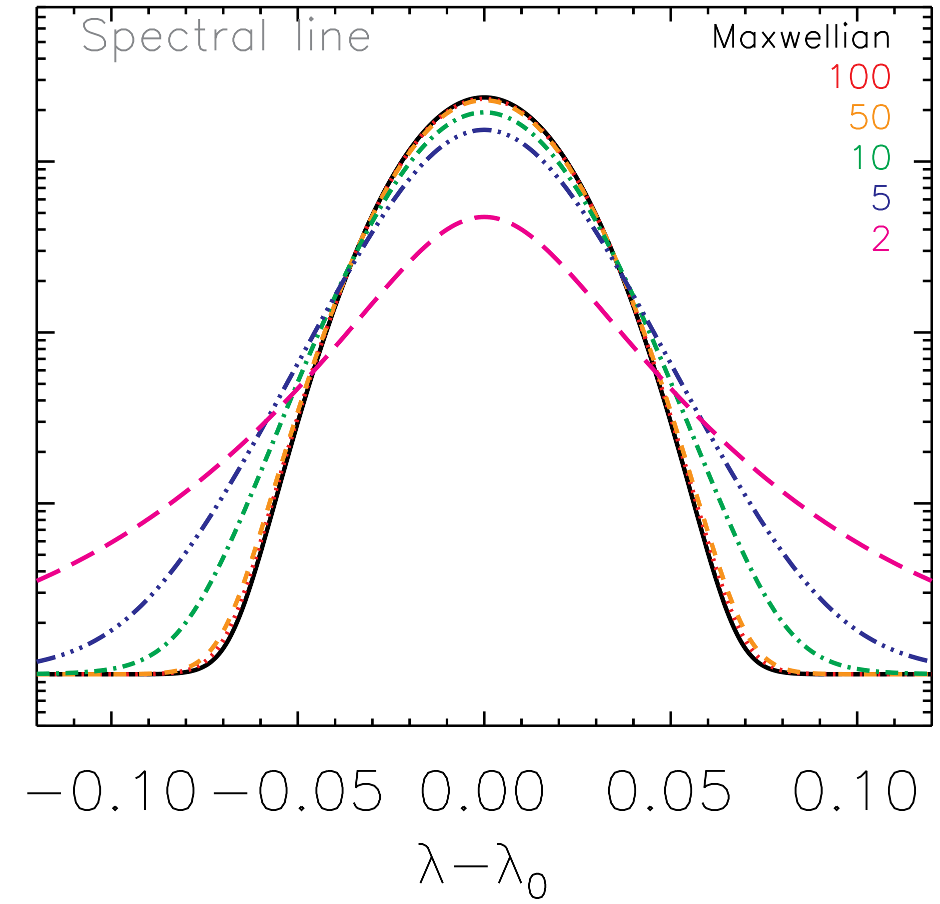
Non-Gaussian spectral line fitting

How do we detect the presence of non-Gaussian spectral lines?

- **Kappa line profile** (generalised Lorentzian).

  (from a kappa velocity distribution)

$$I(\lambda) = A_\lambda \left(1 + \frac{(\lambda - \lambda_0)^2}{\kappa 2\sigma_\kappa^2}\right)^{-\kappa+1}$$



- Gaussian as $\kappa \longrightarrow$ infinity (or ~> 20).
- *Good approx. for any non-Gaussian shape.*
- We must account for the instrument profile (e.g. EIS).

One method: fit a convolved kappa (physical)-Gaussian (instrumental):

Gaussian (instrumental) — **Kappa** (physical)

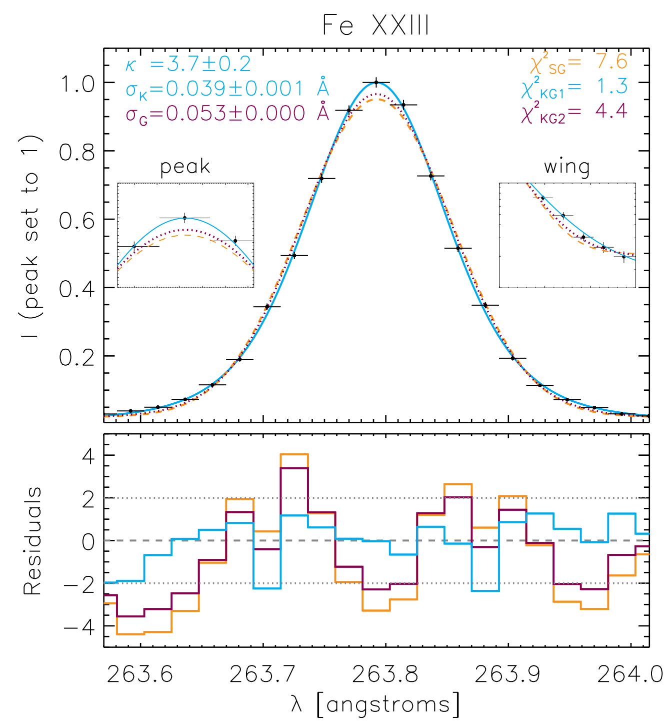
$$\mathcal{W}(\lambda) = \mathcal{G}(\lambda) * \mathcal{K}(\lambda) = A[0] + A[1] \times \sum_{\lambda'} \exp\left(-\frac{(\lambda' - A[2])^2}{2\sigma_I^2}\right) \left(1 + \frac{(\lambda - \lambda' - A[2])^2}{2A[3]^2 A[4]}\right)^{-A[4]+1}$$

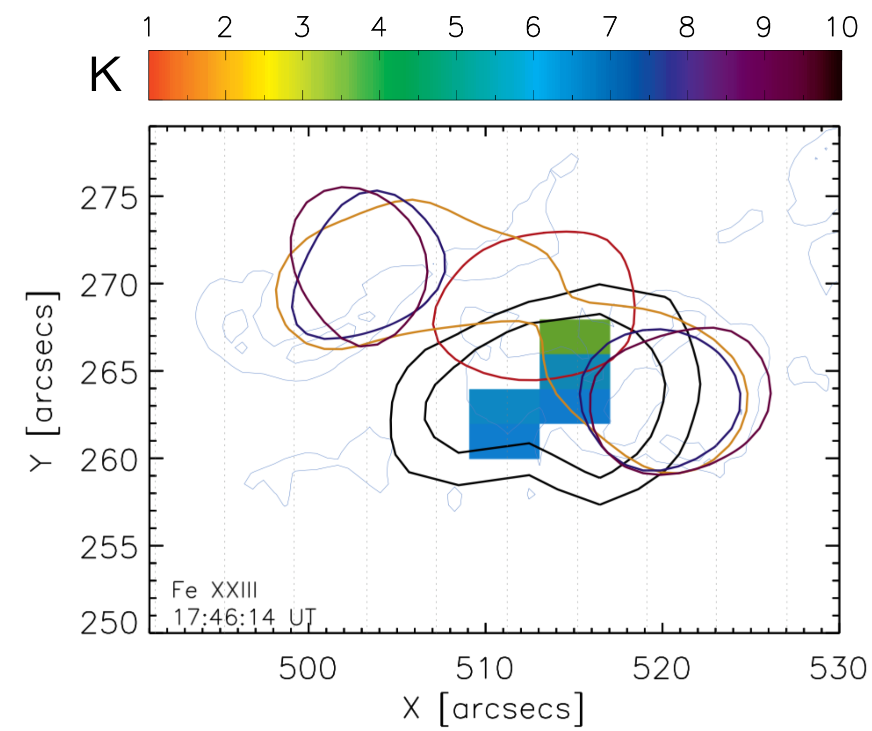
Observations of non-Gaussian spectral lines

- In different solar structures, several spectroscopic studies with Hinode EIS and IRIS have already inferred non-Gaussian spectral lines.

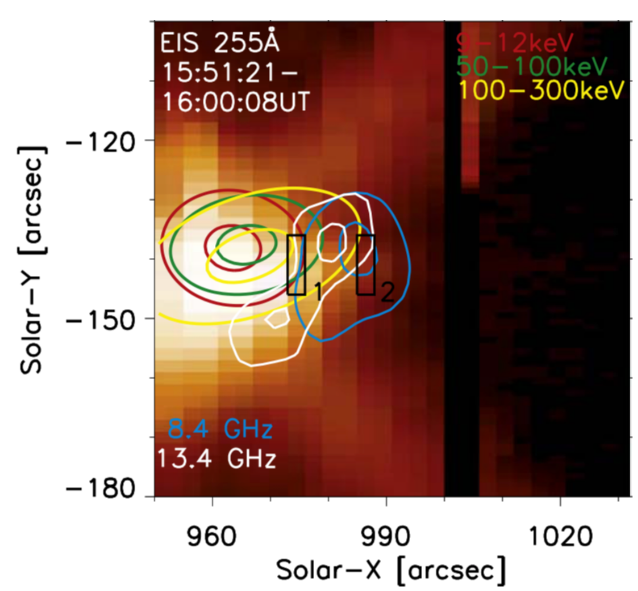
    - **In solar flares:**

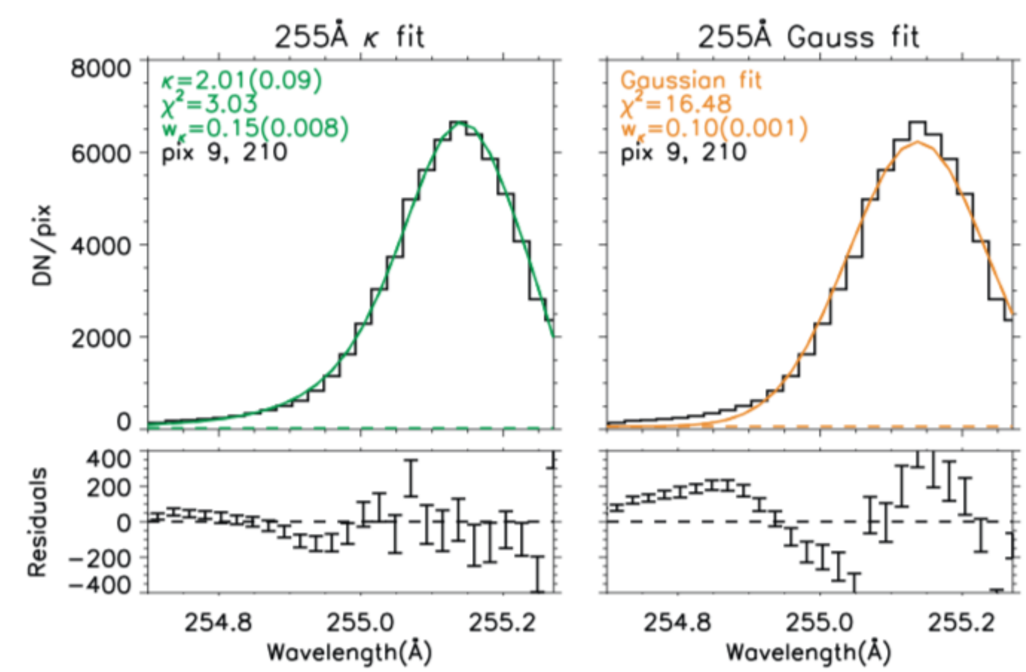
Jeffrey et al. (2016, 2017) *found non-Gaussian spectral lines in different regions of two* ***solar flares*** *using EIS, and from different temperature lines (Fe XXIII, Fe XVI).*





Polito et al. (2018) *found non-Gaussian spectral lines in the hot coronal loop top of one* ***solar flare*** *(Fe XXIV).*





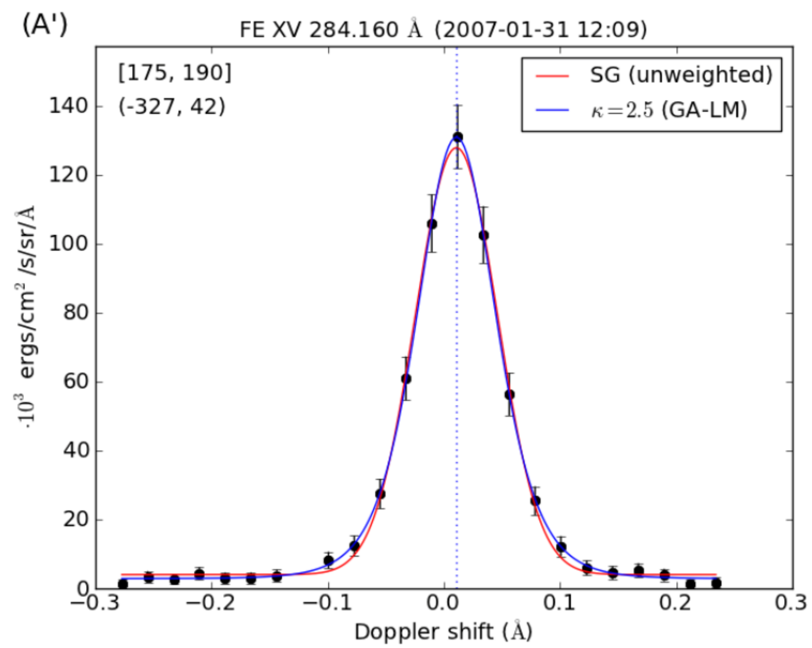
Observations of non-Gaussian spectral lines

- In different solar structures, several spectroscopic studies with EIS and IRIS have already inferred non-Gaussian spectral lines.

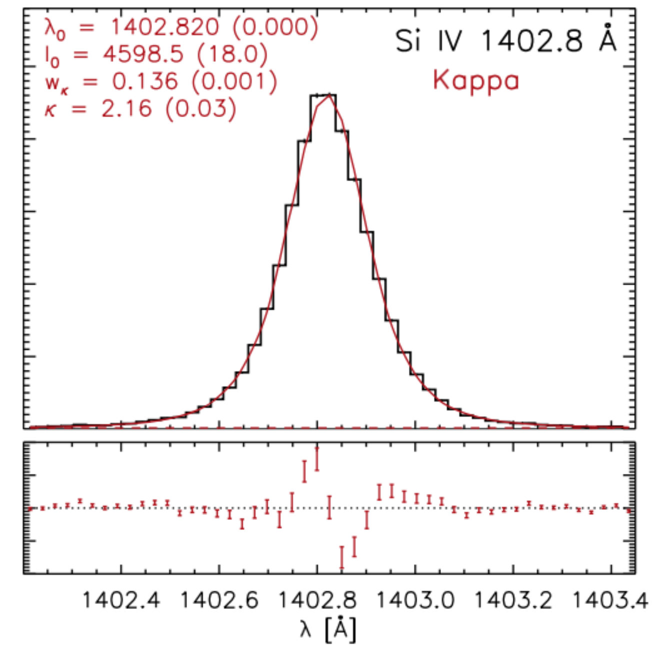
  - **In active regions:**

    Lee et al. (2013) *found evidence of non-Gaussian lines in the* ***corona (active regions)*** *using EIS.*

    Dudík et al. (2017) *used IRIS to detect non-Gaussian lines in the* ***transition region (active regions)****.*



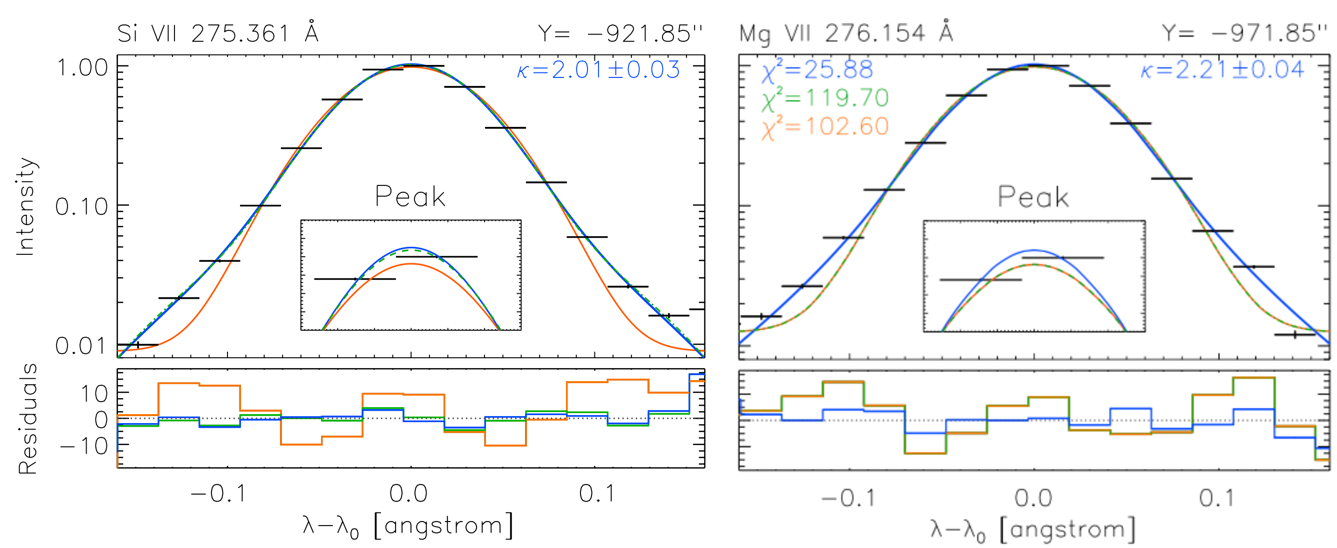
Lee et al. (2013)



Dudík et al. (2017)

  - **In coronal holes/fast solar wind:**

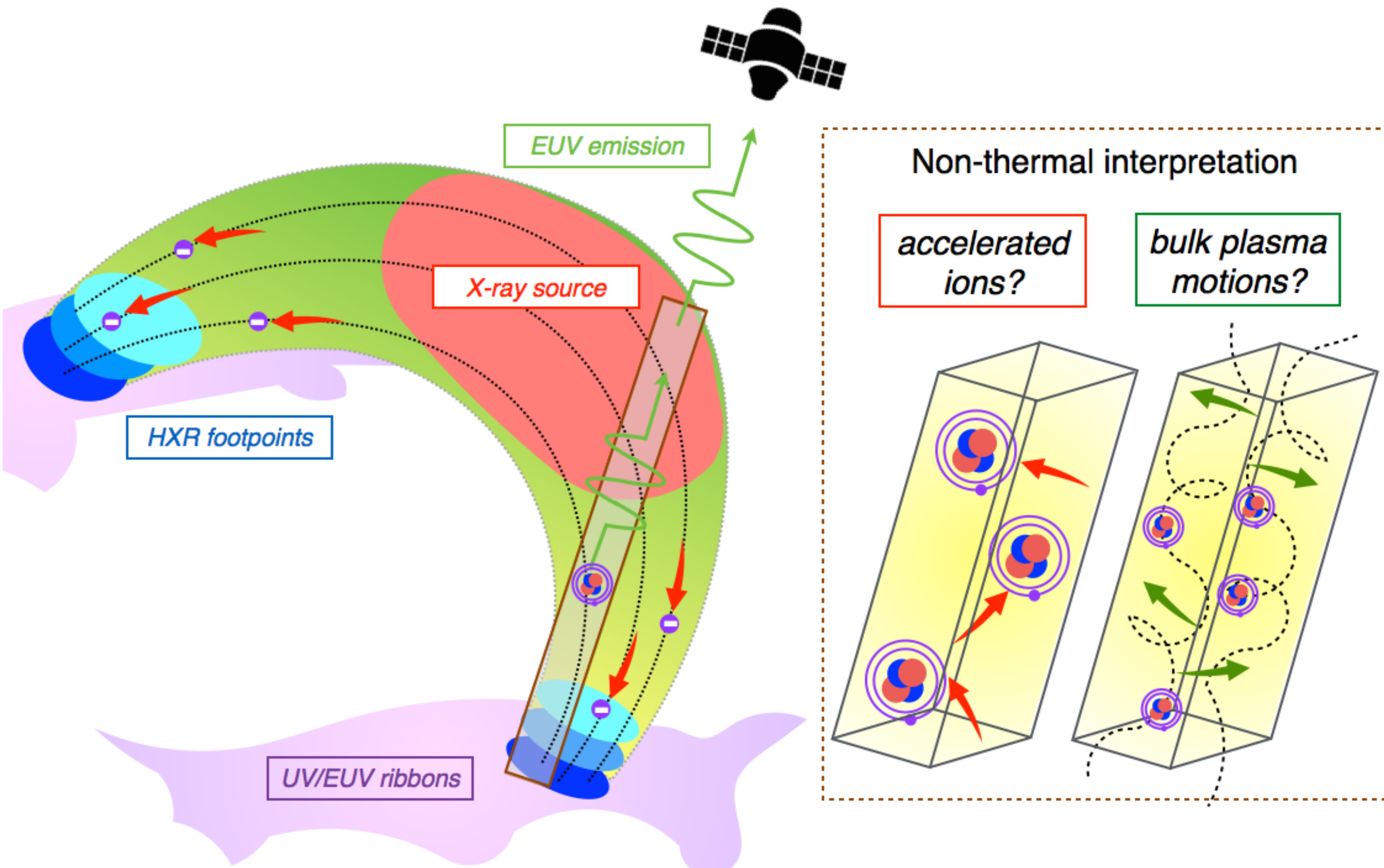
    Jeffrey et al. (2018) *found non-Gaussian lines in a* ***polar coronal hole close to the base of the fast solar wind*** *using* Hinode EIS.



Causes of non-Gaussian spectral lines?

- Could the presence of non-Gaussian spectral lines in flares be due to:

1. Solar flare-accelerated ions? or **2. Non-Gaussian turbulence?**



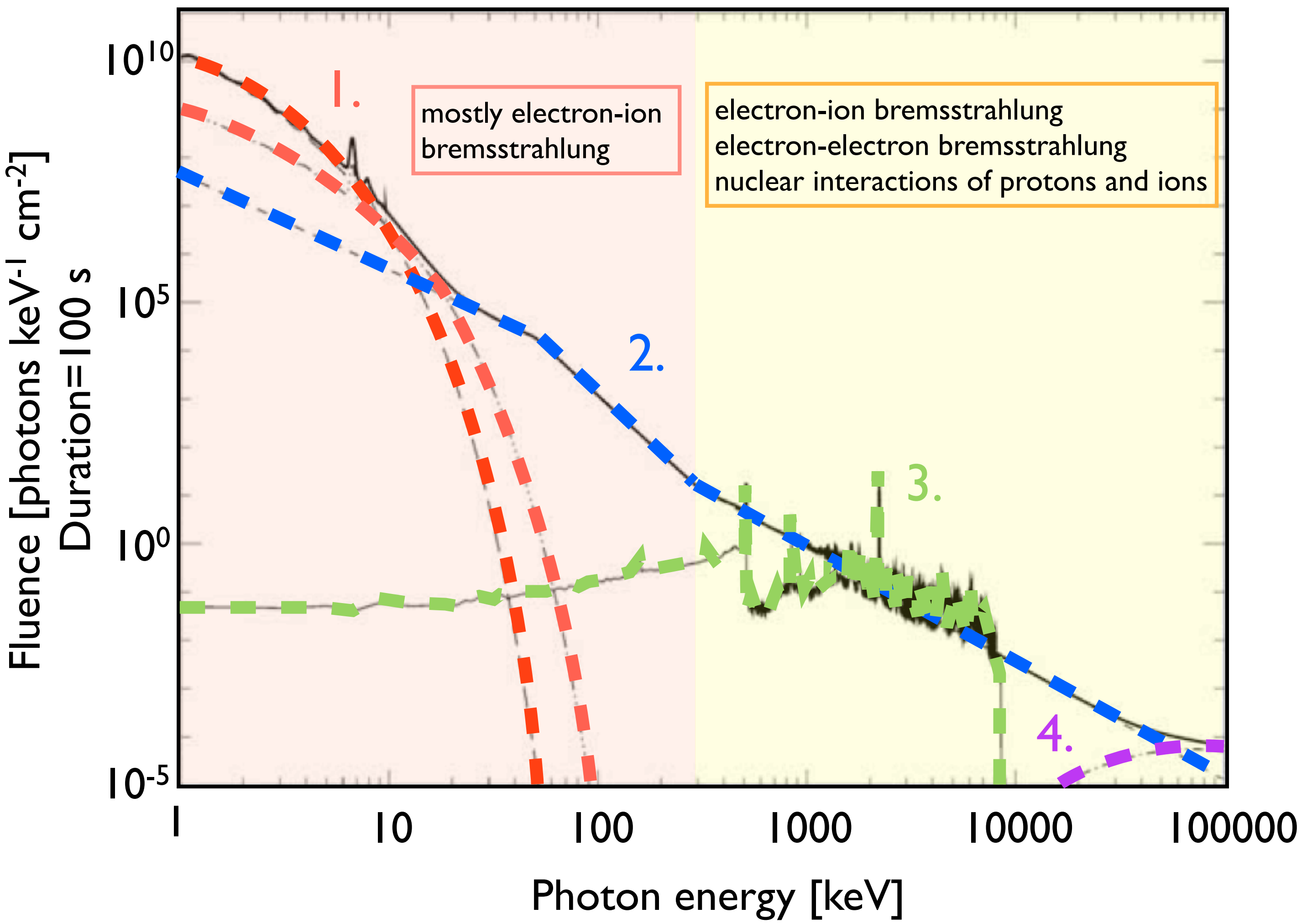
Causes of non-Gaussian spectral lines?

- Could the presence of non-Gaussian spectral lines be due to:

  Solar flare-accelerated ions?

- We know about non-thermal electrons from bremsstrahlung X-rays BUT we hardly ever see any detectable MeV ion gamma-ray line emission - *only a small minority of flares show detectable emission e.g. 23-July-2002*.

- Could we detect the presence of low-energy (< MeV) accelerated ions?



- Generally, we know nothing about the ions, especially any low-energy < MeV ions.

i. Help to constrain the properties or even the type(s) of acceleration???

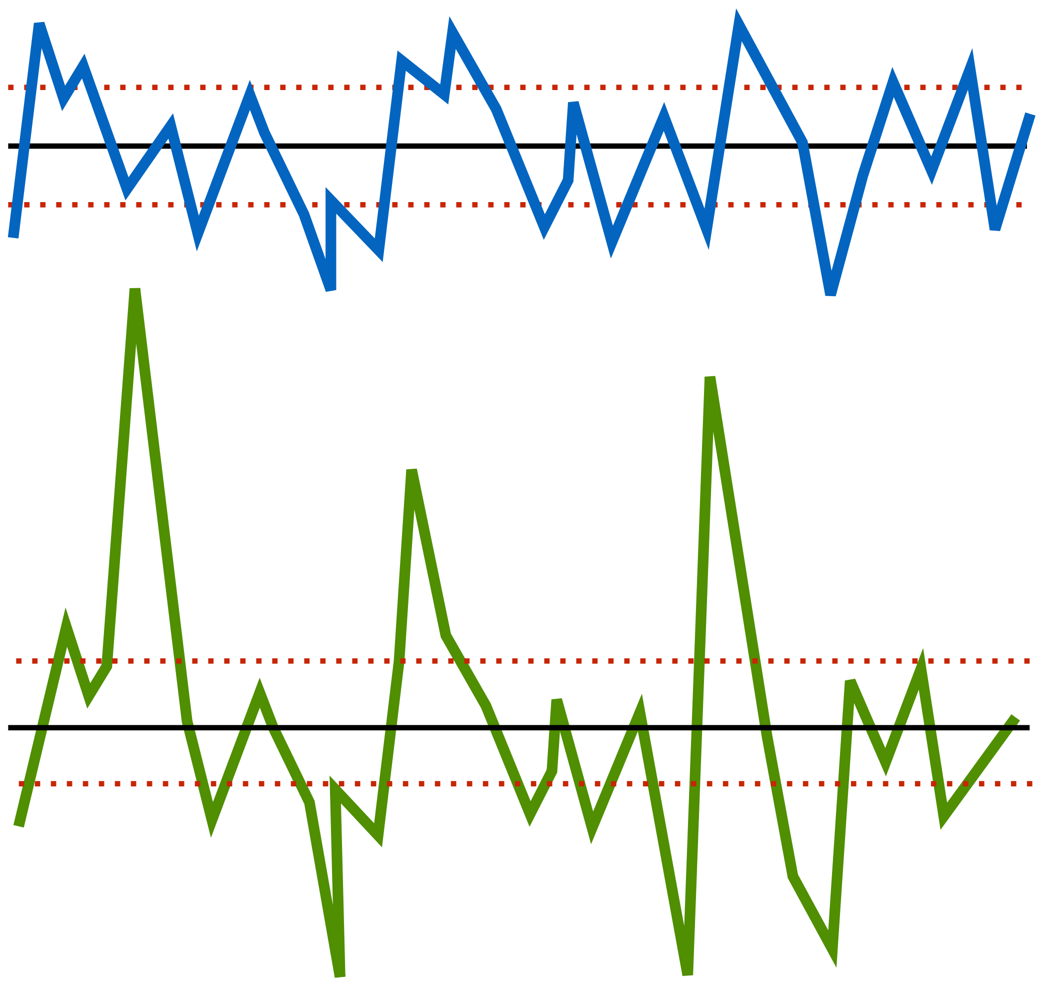
ii. Low-energy non-thermal ions - energy content???

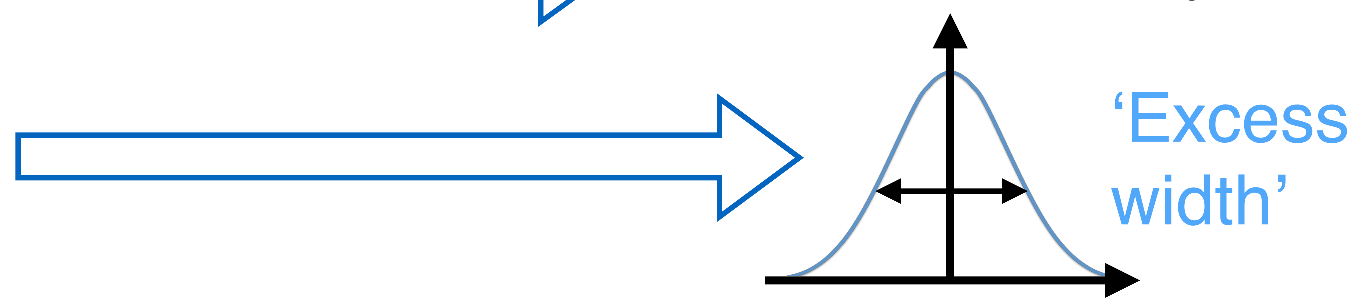
Causes of non-Gaussian spectral lines?

- Could the presence of non-Gaussian spectral lines be due to:

Non-Gaussian turbulence

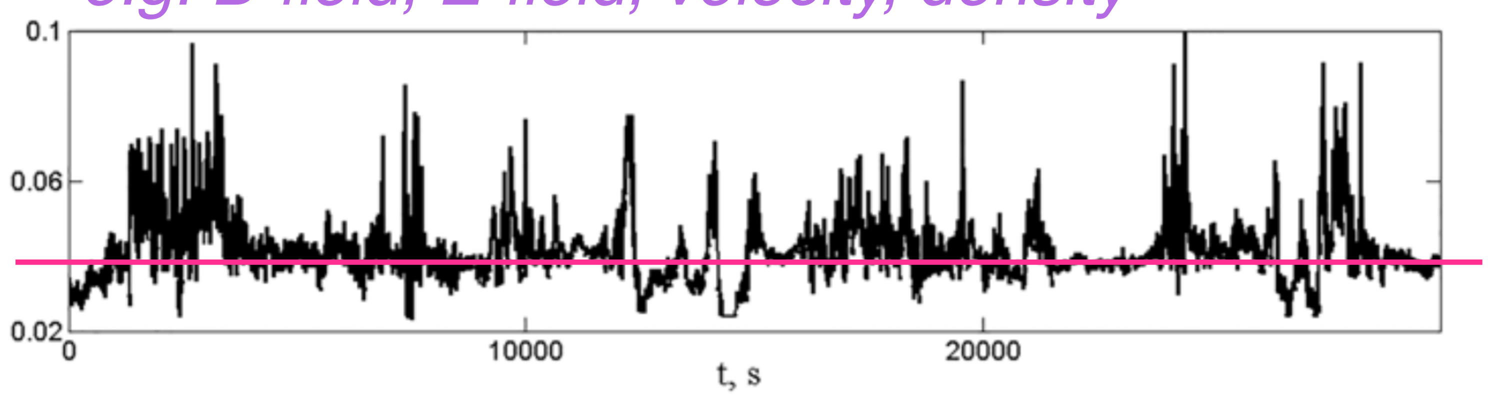
Stochastic turbulence with **Brownian** motion ⇨ Gaussian velocity PDF





- **Large, sporadic motions** around the mean lead to non-Gaussian velocity PDFs.
- Non-Gaussian turbulence is seen in different forms in space plasmas.

e.g. B-field, E-field, velocity, density



i. Diagnostic of spatial non-uniformity of energy transfer across scales?

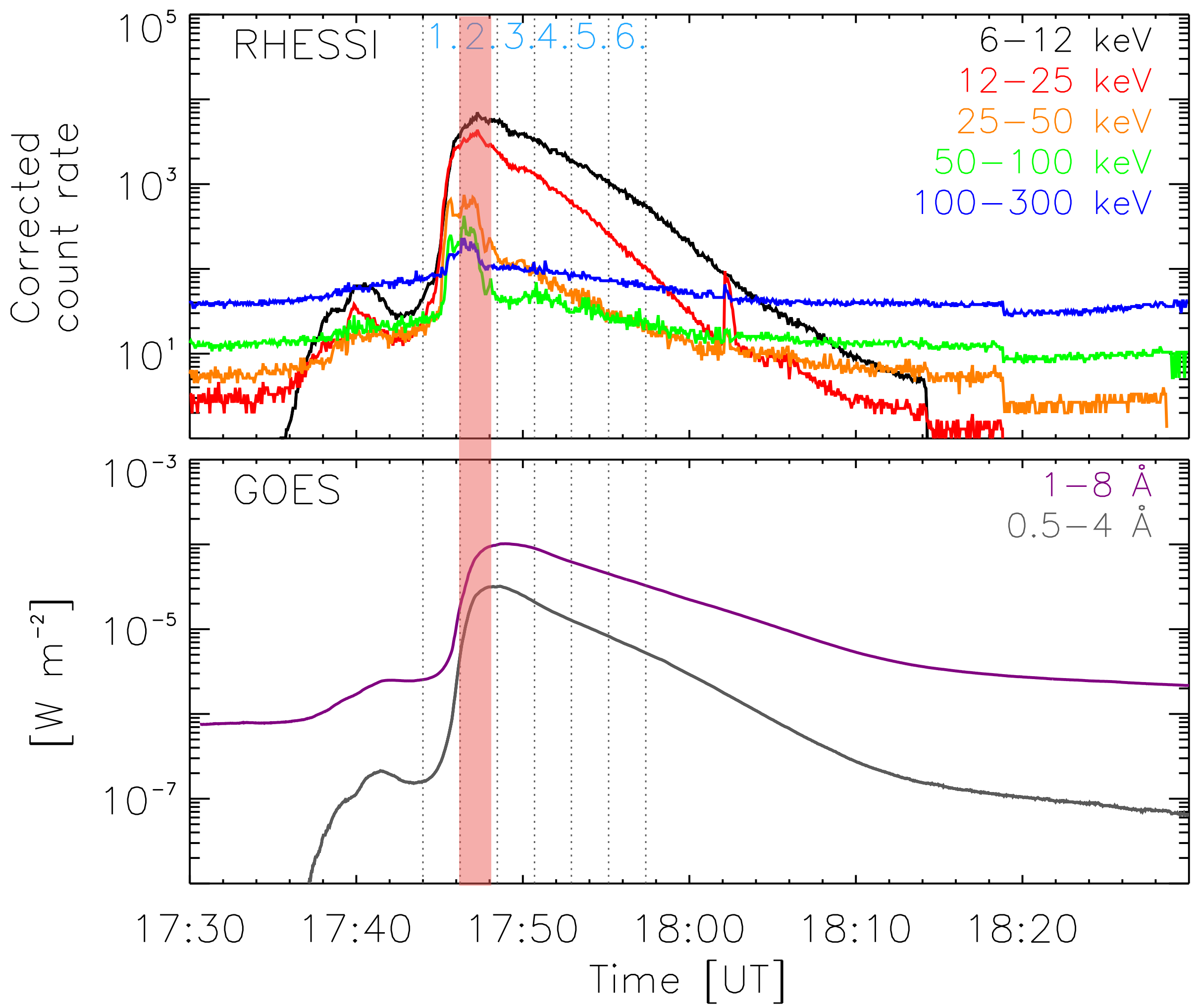
ii. Does this e.g. change rates of particle acceleration in different regions?

Non-Gaussian spectral lines in flares

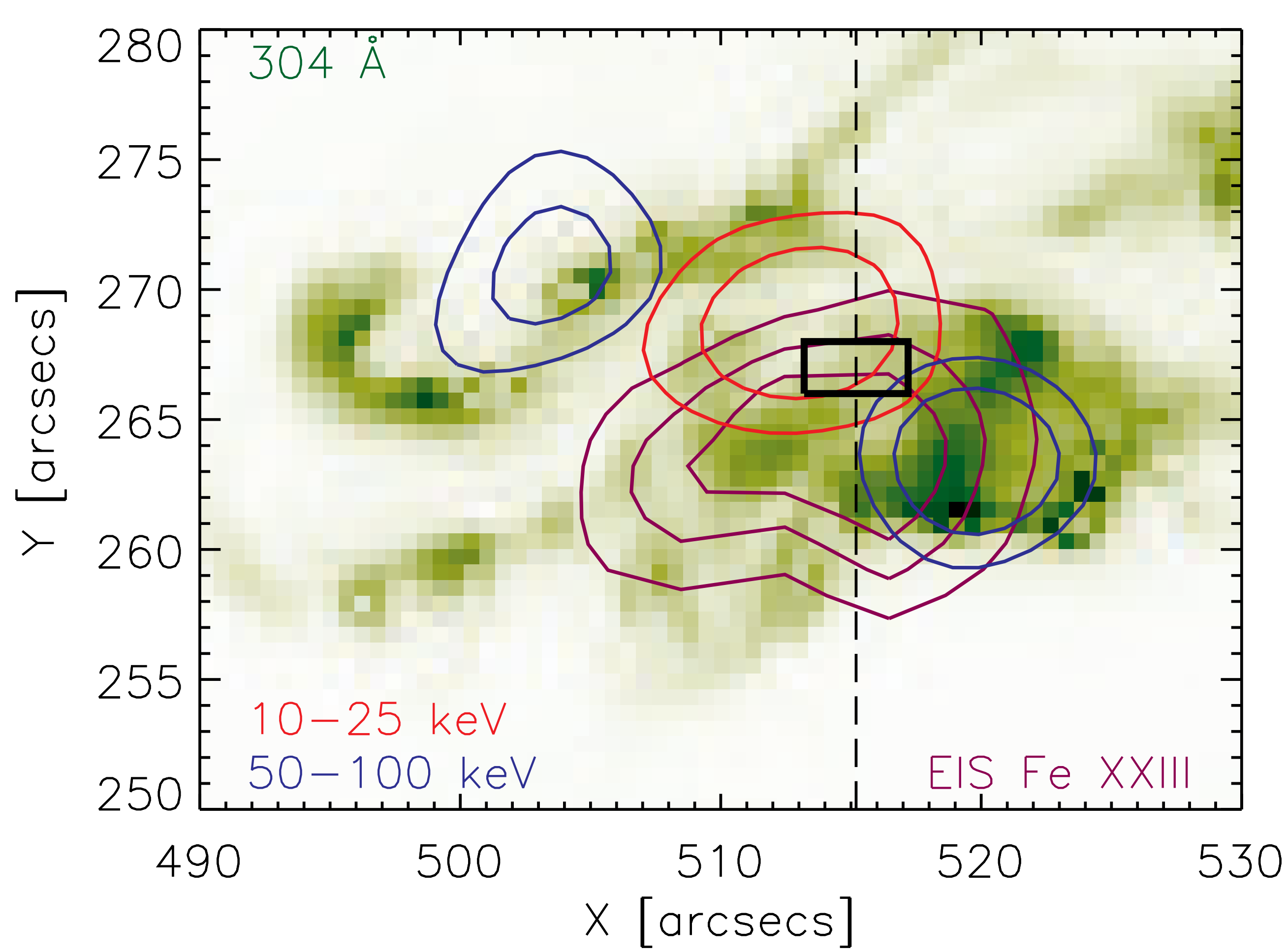
Flare example: X-class, 29th March 2014 17:44 UT

- ***Why?*** This flare was chosen as it has two ***strong***, ***unblended*** and ***different temperature*** lines (**Fe XVI** and **Fe XXIII**) suitable for a line profile analysis.

RHESSI/GOES light curves



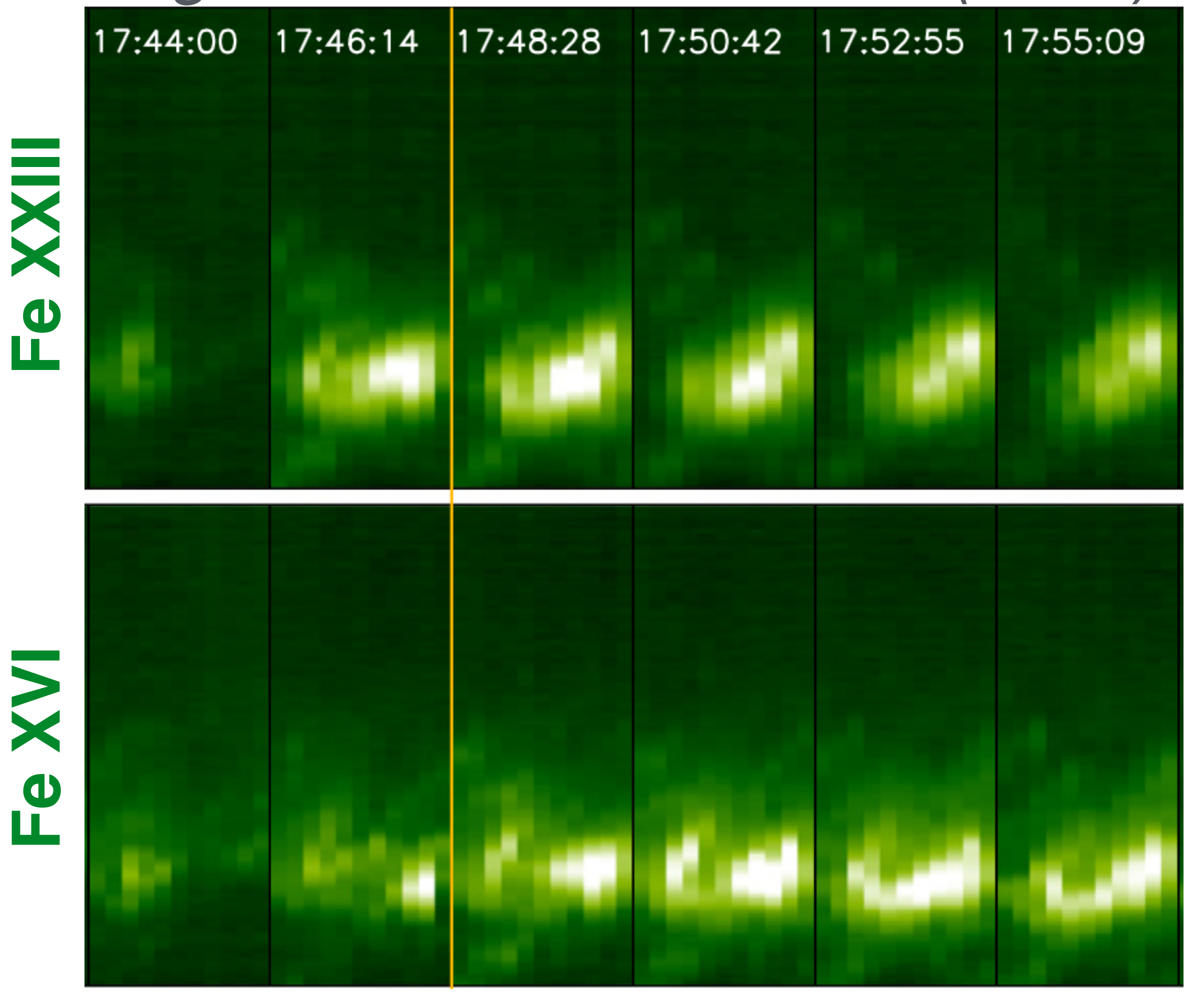
The flare at the X-ray peak



Non-Gaussian spectral lines in flares

- Six EIS rasters covering the rise, peak and decay of the flare.
- Fast raster mode (2 min 14 seconds) and the slit moves every 12 seconds).
- The observation uses the 1$''$ slit with X binning=3$''$.99 and Y binning=1$''$.

Figure taken from Li et al. (2015)



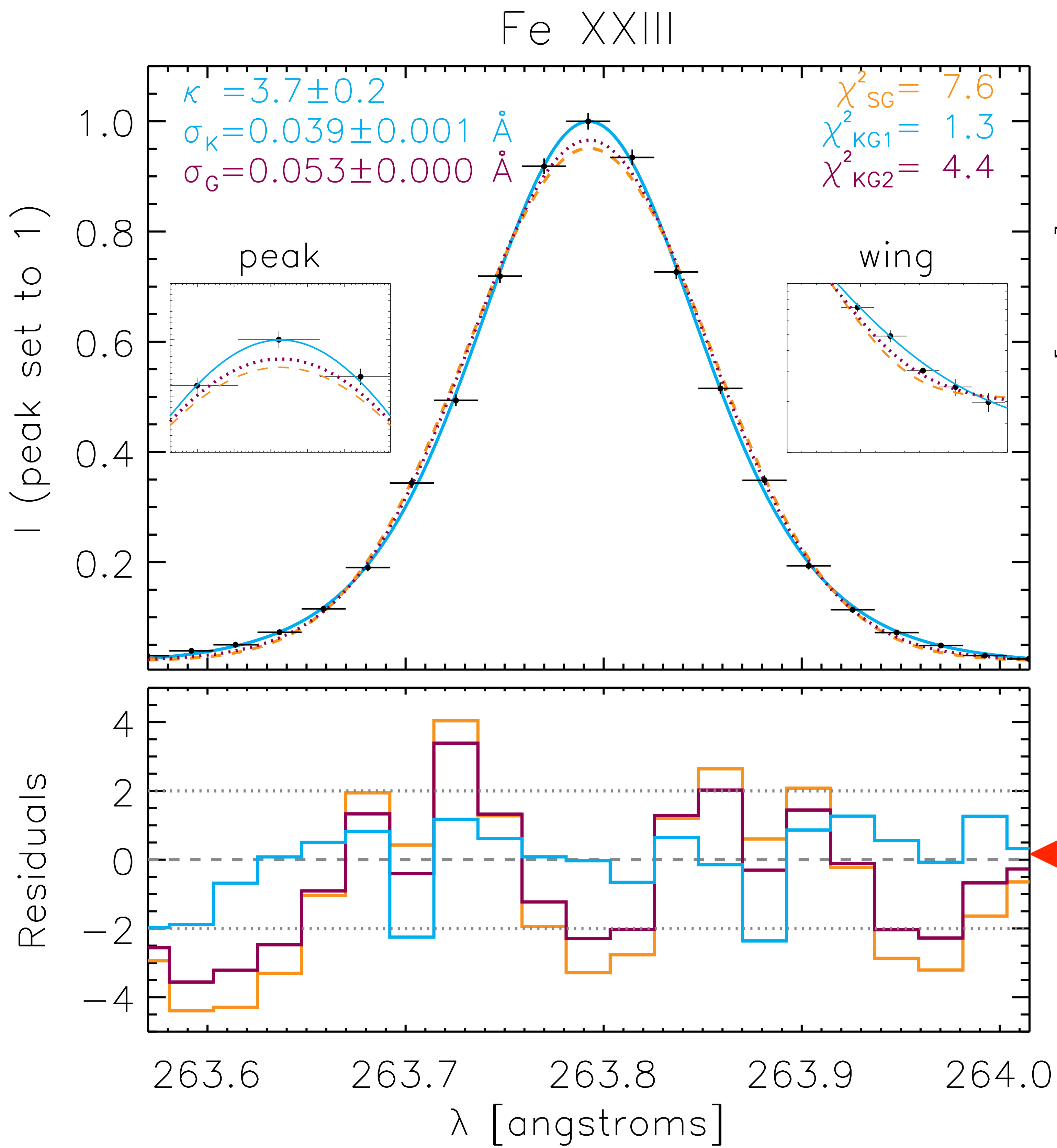
Available wavelength windows

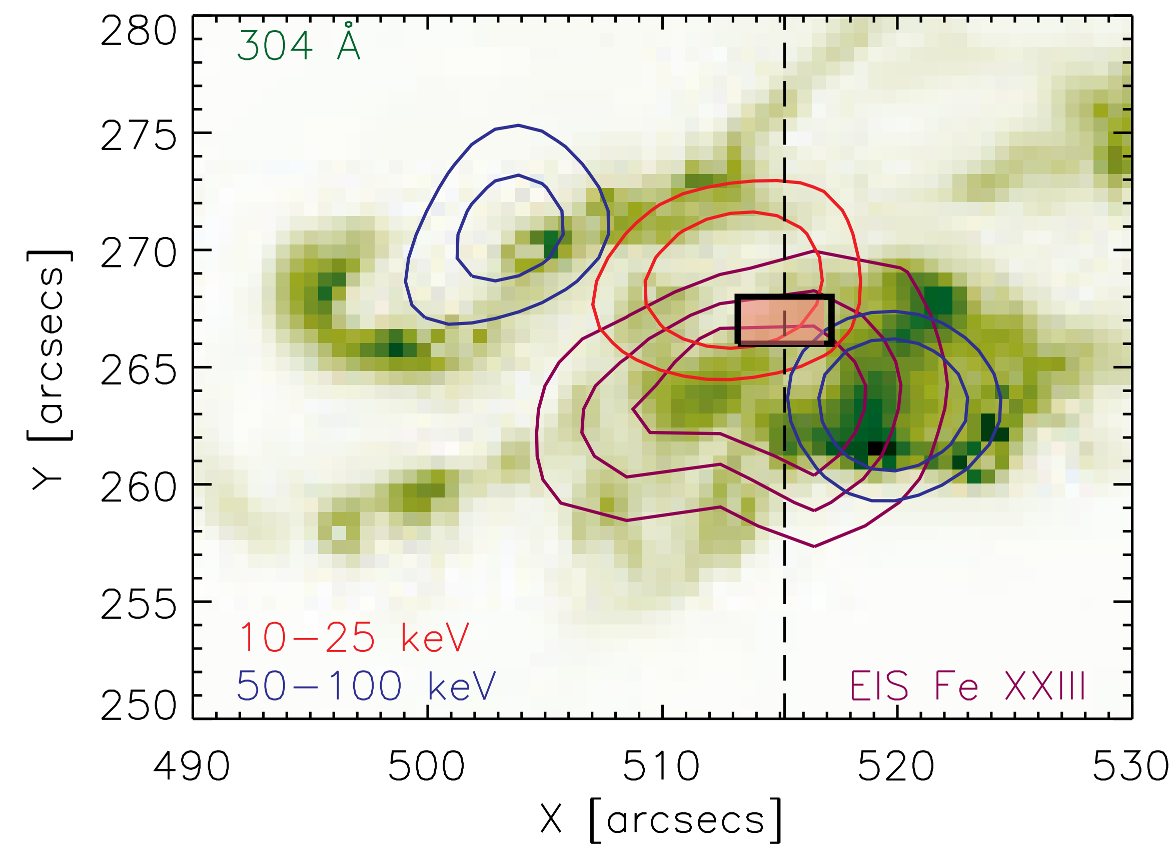
Line	Minimum wvl.	Maximum wvl.
Ca XV	181.64	182.15
Ca XV	182.60	183.11
Fe XII	186.39	187.08
Fe XII	192.14	192.65
Ar XIV	194.15	194.84
He II	256.01	256.52
Fe XXIII	262.69	264.09
Fe XVII	268.81	269.68

- The EIS Gaussian instrumental broadening is 0.059 Å.
- The EIS data in the Y direction is binned into 2$''$ bins (from 1$''$).

Non-Gaussian spectral lines in flares

- Flare observation of Fe XXIII, formed at T~15-16 MK (flare peak).

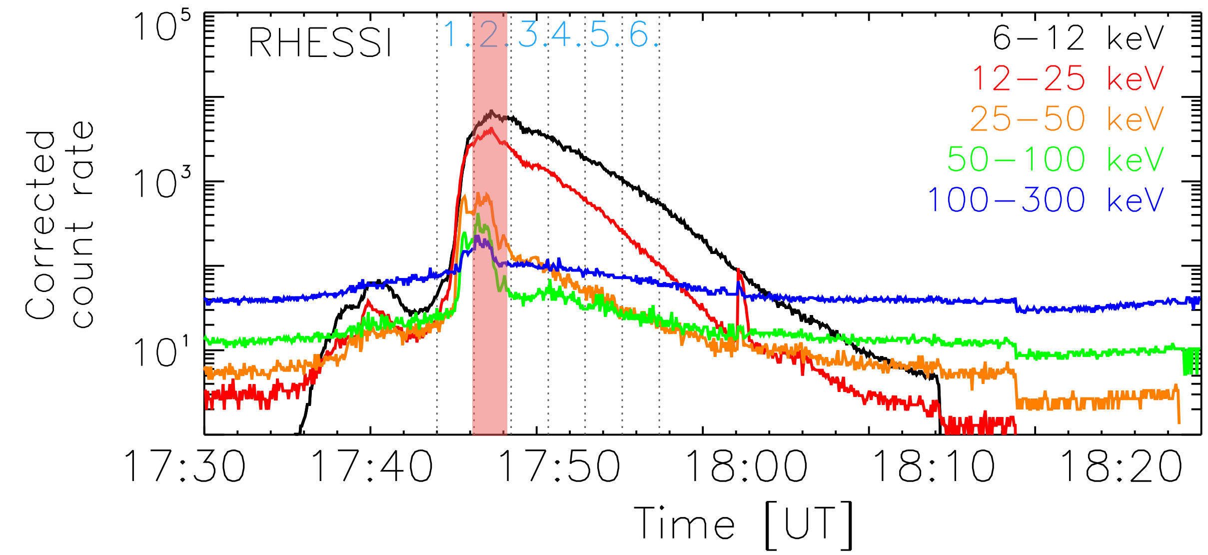




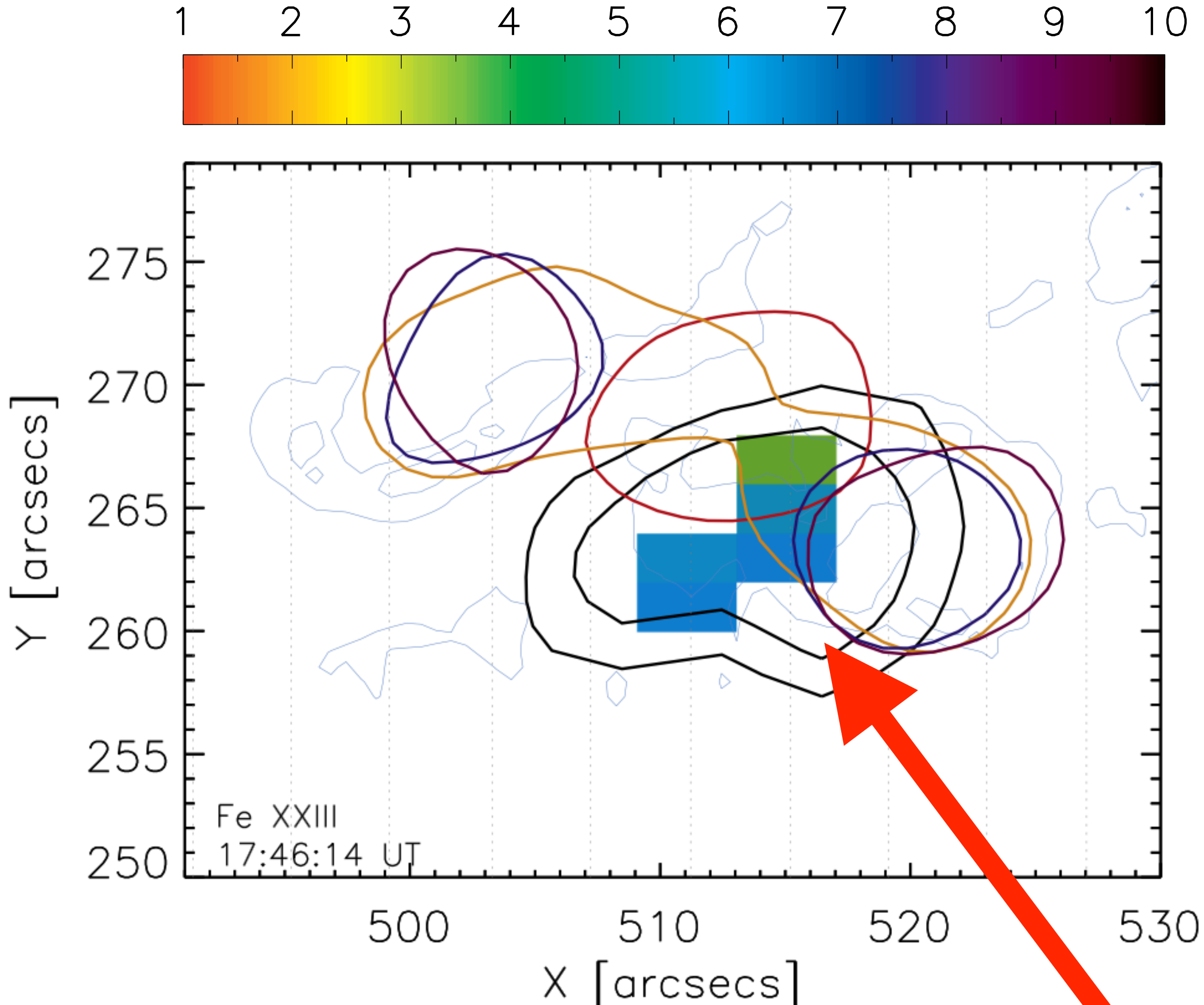
We can see from the residuals that the kappa-Gaussian **(blue)** is a better model

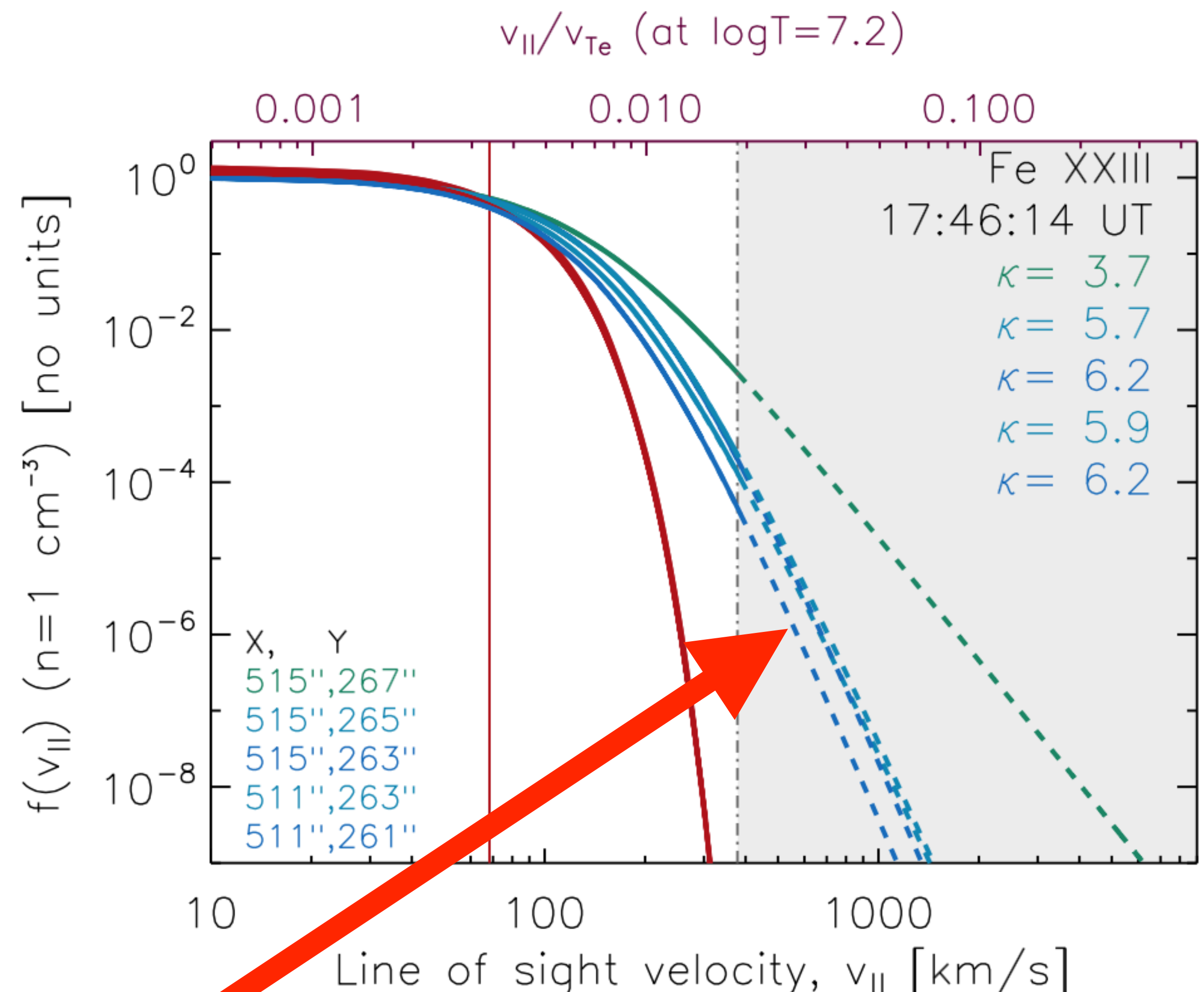
Non-Gaussian spectral lines in flares

- Flare observation:
  Fe XXIII (T~15-16 MK)



Kappa index map

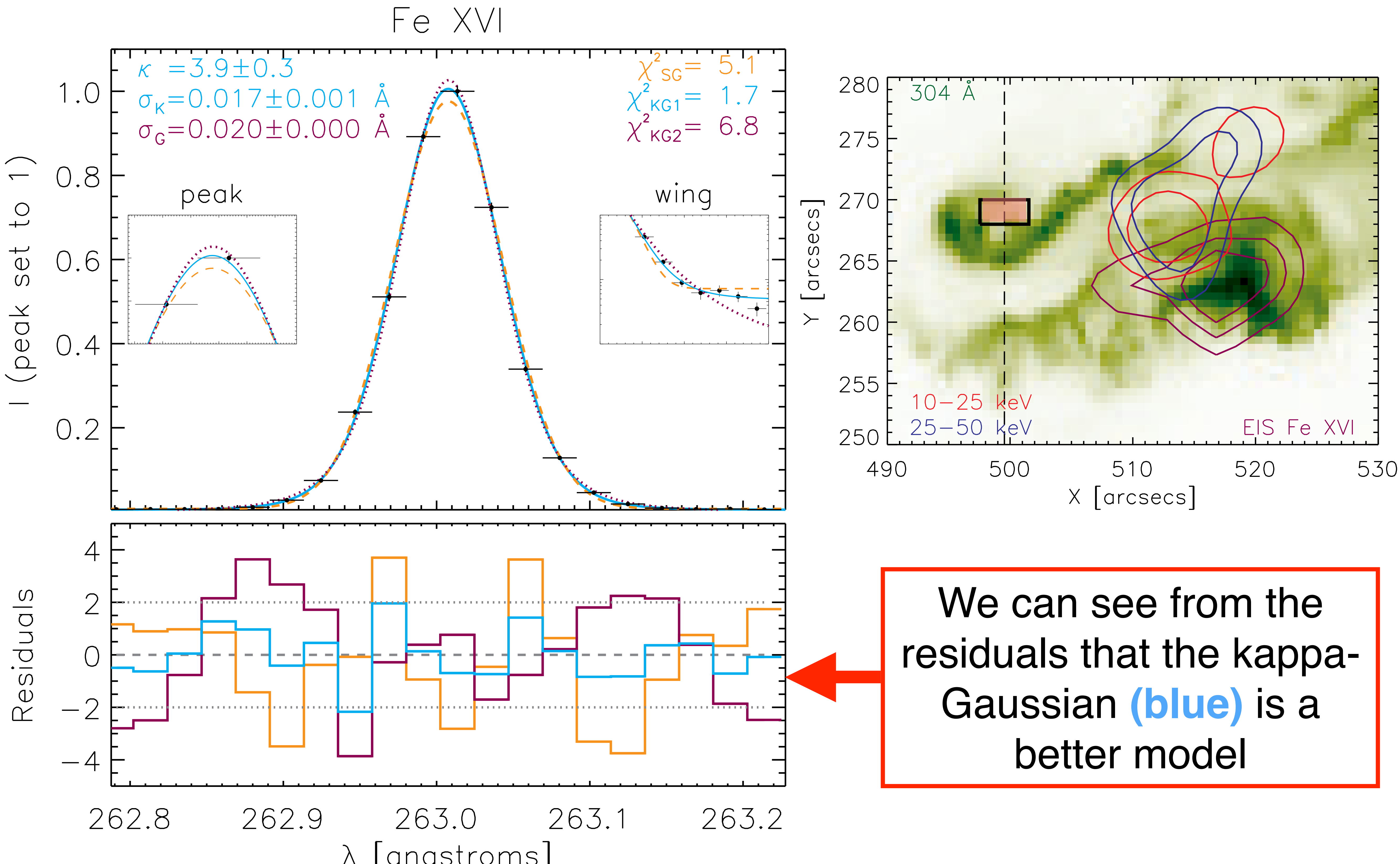




Line shape → Gaussian further from the X-ray coronal source?

Non-Gaussian spectral lines in flares

- Flare observation of Fe XVI, formed at T~1-2 MK (after the peak).



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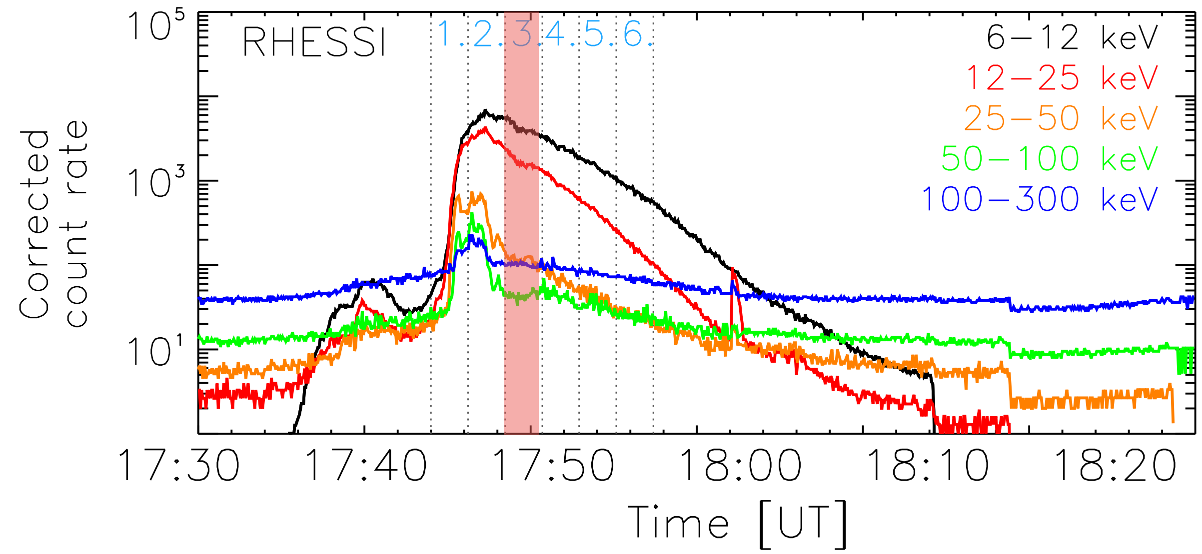
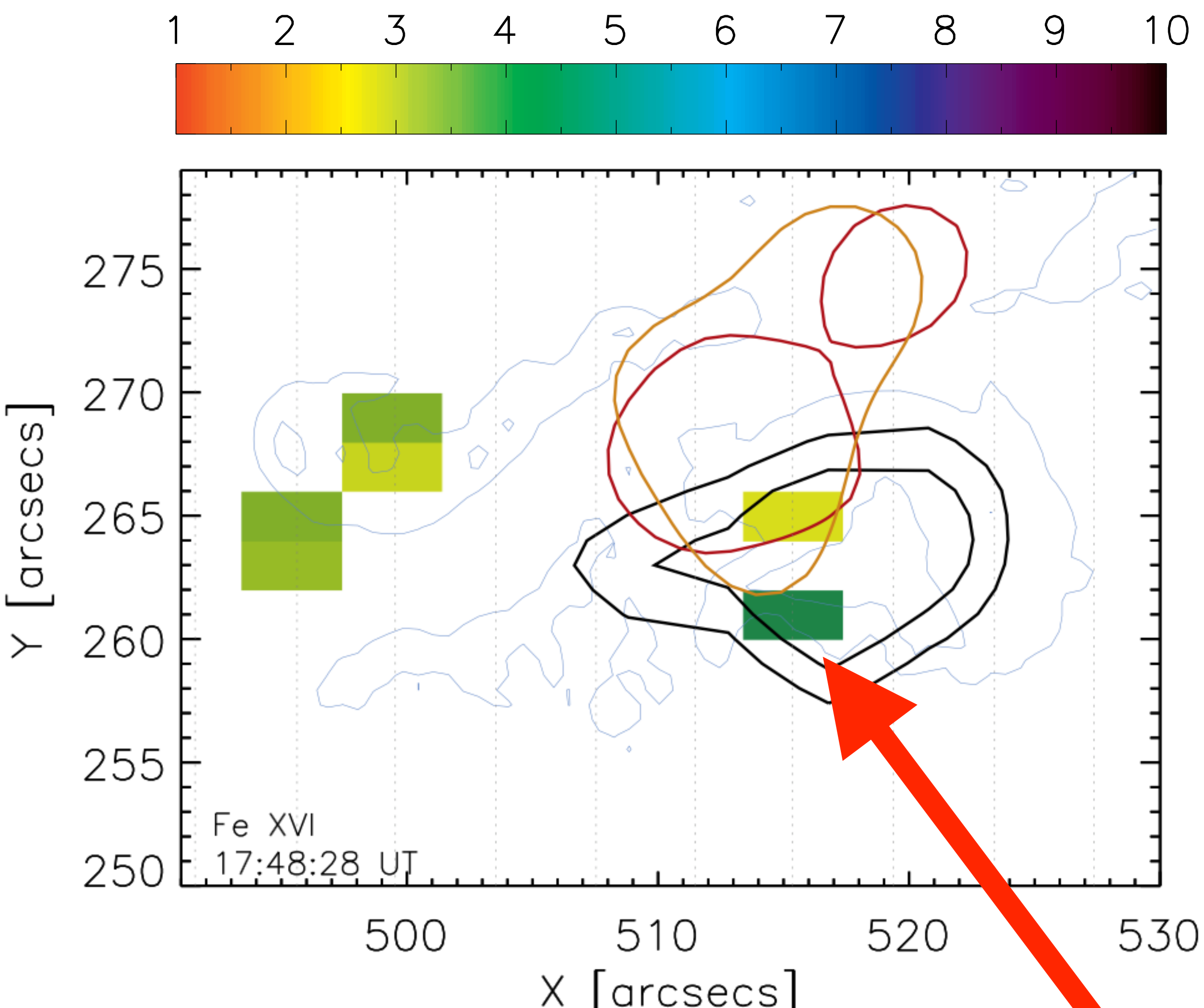
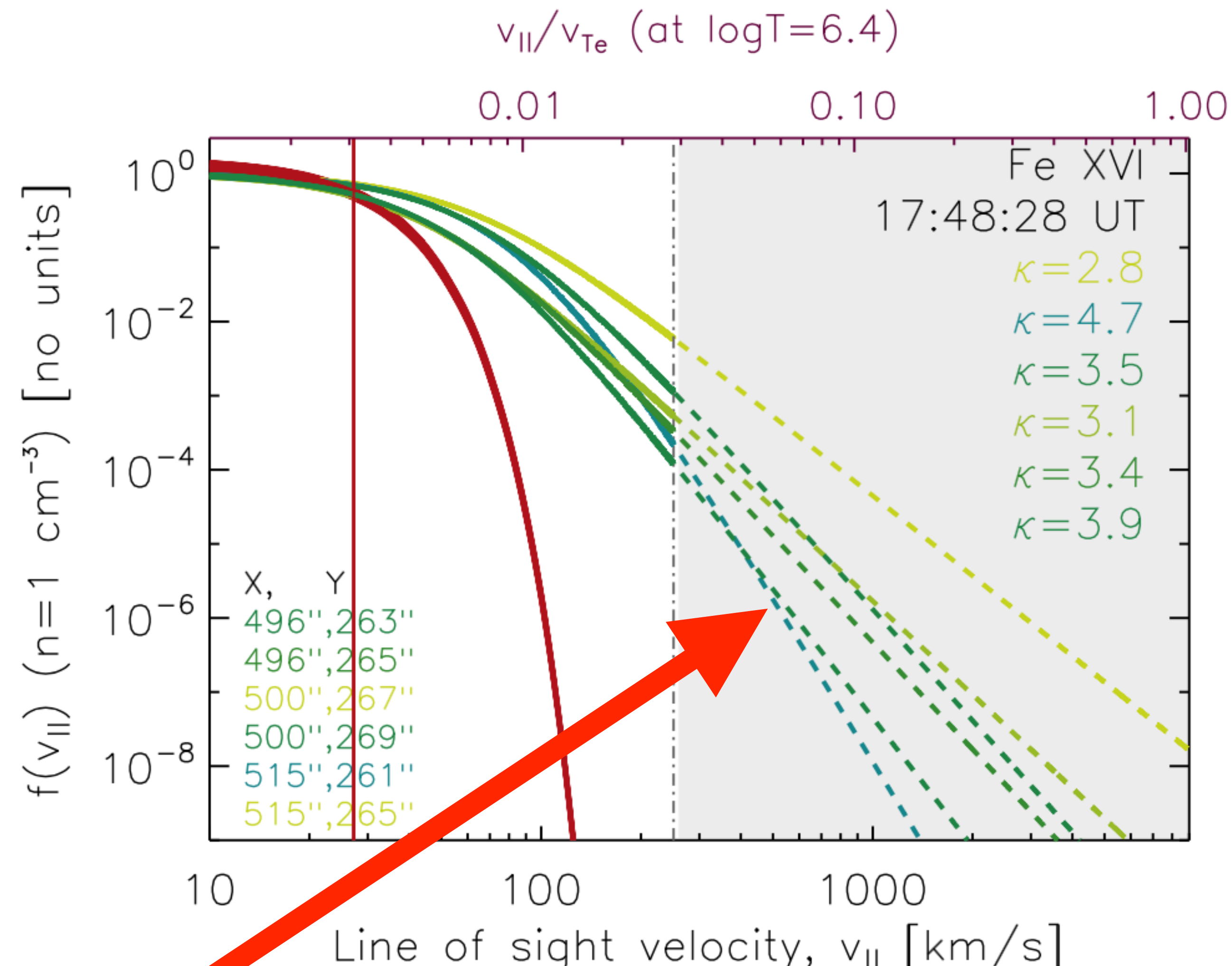
Non-Gaussian spectral lines in flares

- Flare observation:
  Fe XVI (1-2 MK)



Kappa index map

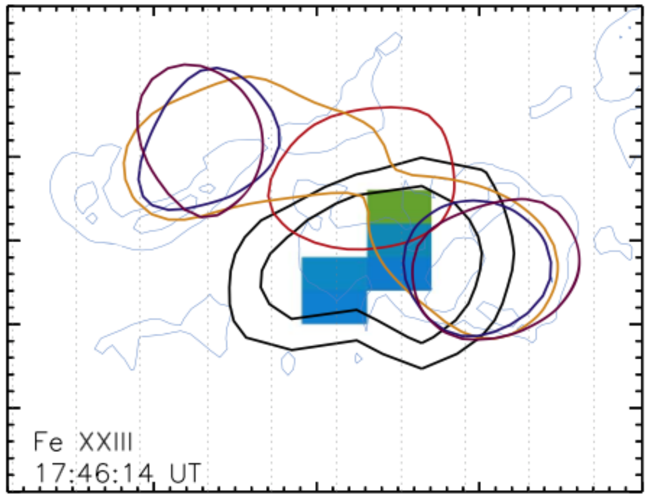




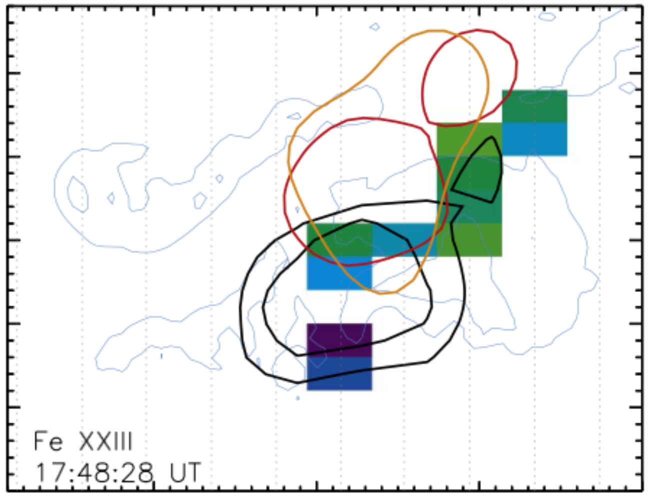
Fe XVI tends to have smaller kappa indices than Fe XXIII.

The main results of the line profile study

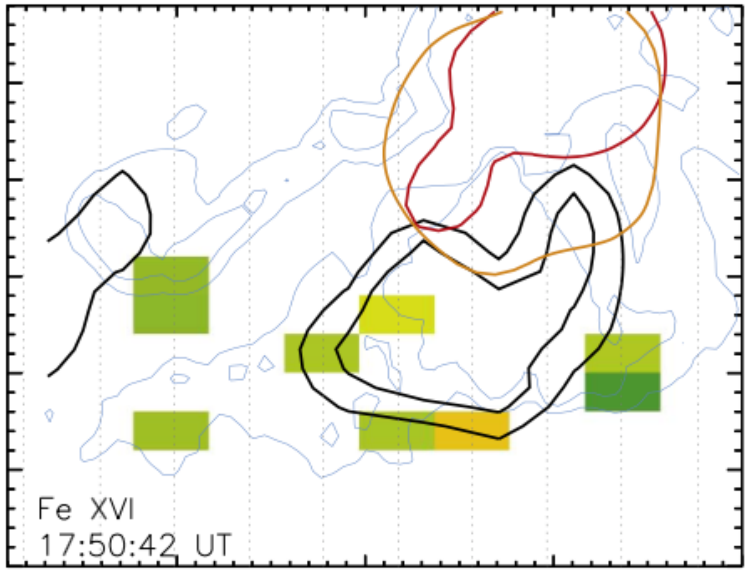
- *Non-Gaussian lines consistent with kappa distributions were found during the flare (in the loop-top, HXR footpoints and ribbons).*



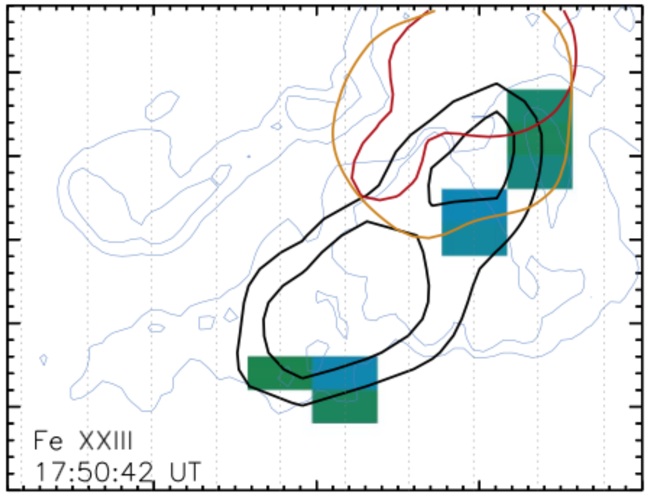
- *Fe XXIII kappa profiles are situated closer to the coronal source. They move with the coronal source over time with smaller values of κ index closer to the X-ray coronal sources early in the flare.*



- *Fe XVI kappa profiles are situated further from the coronal source and often in regions where HXR sources were previously observed.*



- *The Fe XVI κ index values are smaller than Fe XXIII values and not so systematic in terms of position and value.*

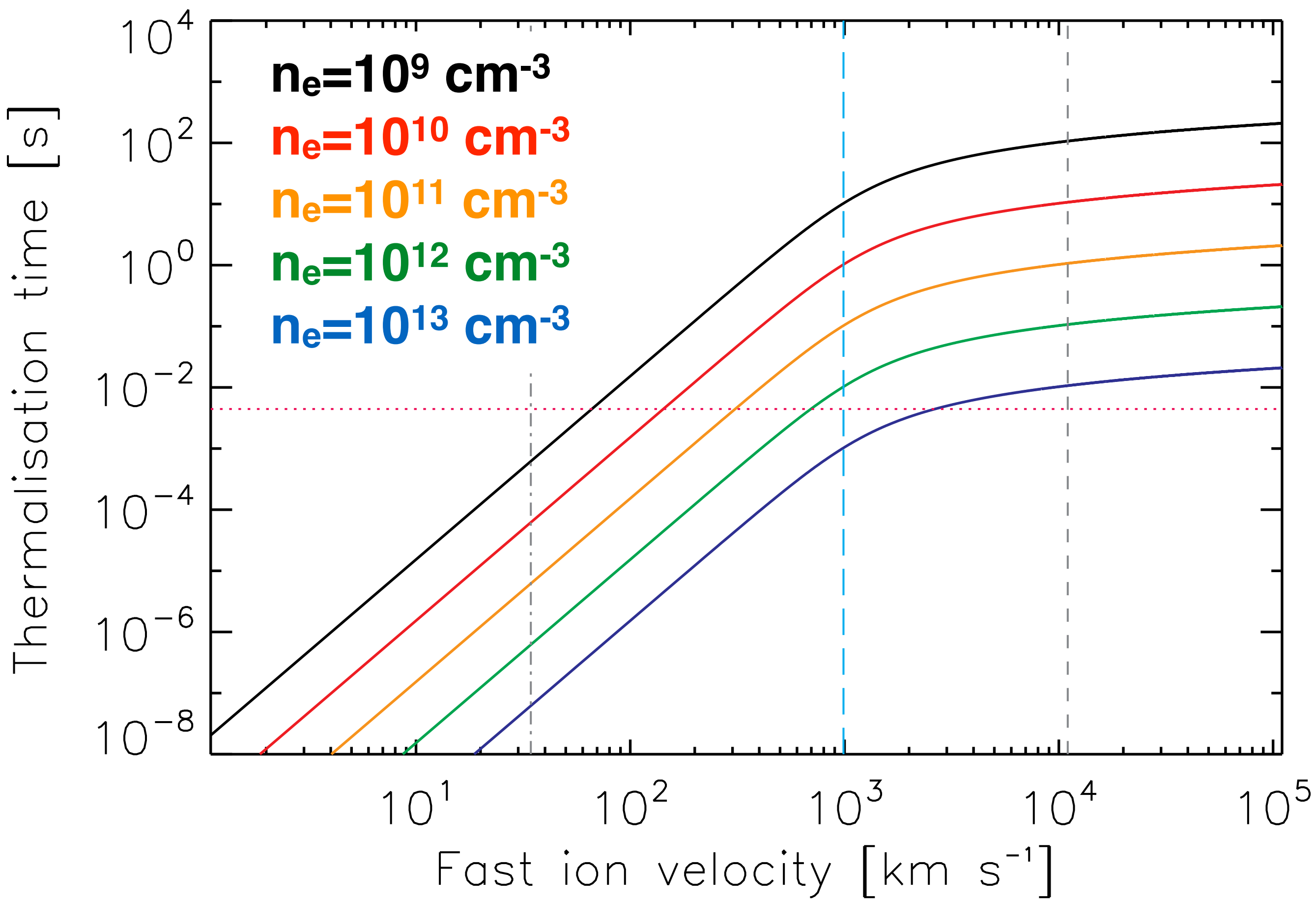


Causes of non-Gaussian lines: accelerated ions?

Could the observations be due to low-energy (< MeV) accelerated ions? What about high flare densities, collisions?

- We examine Fe XVI ions interacting in an electron-**proton** plasma.

Ion thermalisation time:



$$\tau_f \simeq \frac{\tau_S}{3} \ln \left[1 + \left(\frac{\epsilon}{\epsilon_c} \right)^{3/2} \right]$$

Number density:	$n_p = 10^{10}$ cm^{-3}
Ion velocity:	200 km/s
Thermalisation time:	$\tau_f \sim 0.01$ s
Thermalisation length:	$L_F = <<1''$

Ions would have to be accelerated locally, i.e. where we see the EUV line emission!

- The κ index is the ratio of **acceleration time t_{acc}** to the **collisional time t_c**:

Acceleration timescale: $\kappa = \Gamma_c / 2D_0 = \tau_{acc}/2\tau_c$ → $\tau_{acc} = 2 \times \tau_c \kappa <= 0.1$ s

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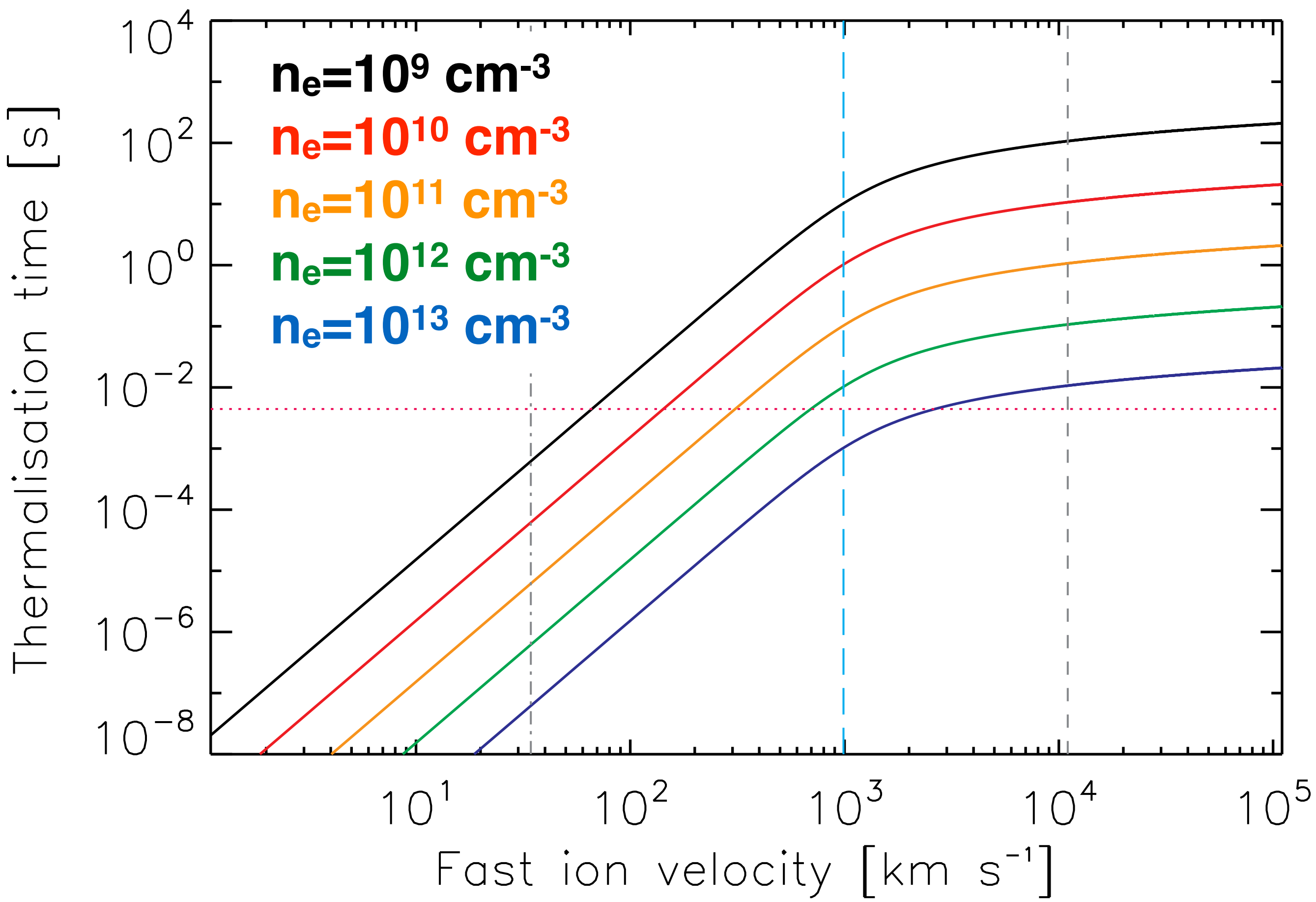

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Thermalisation time: $\tau_f \sim 0.01$ s

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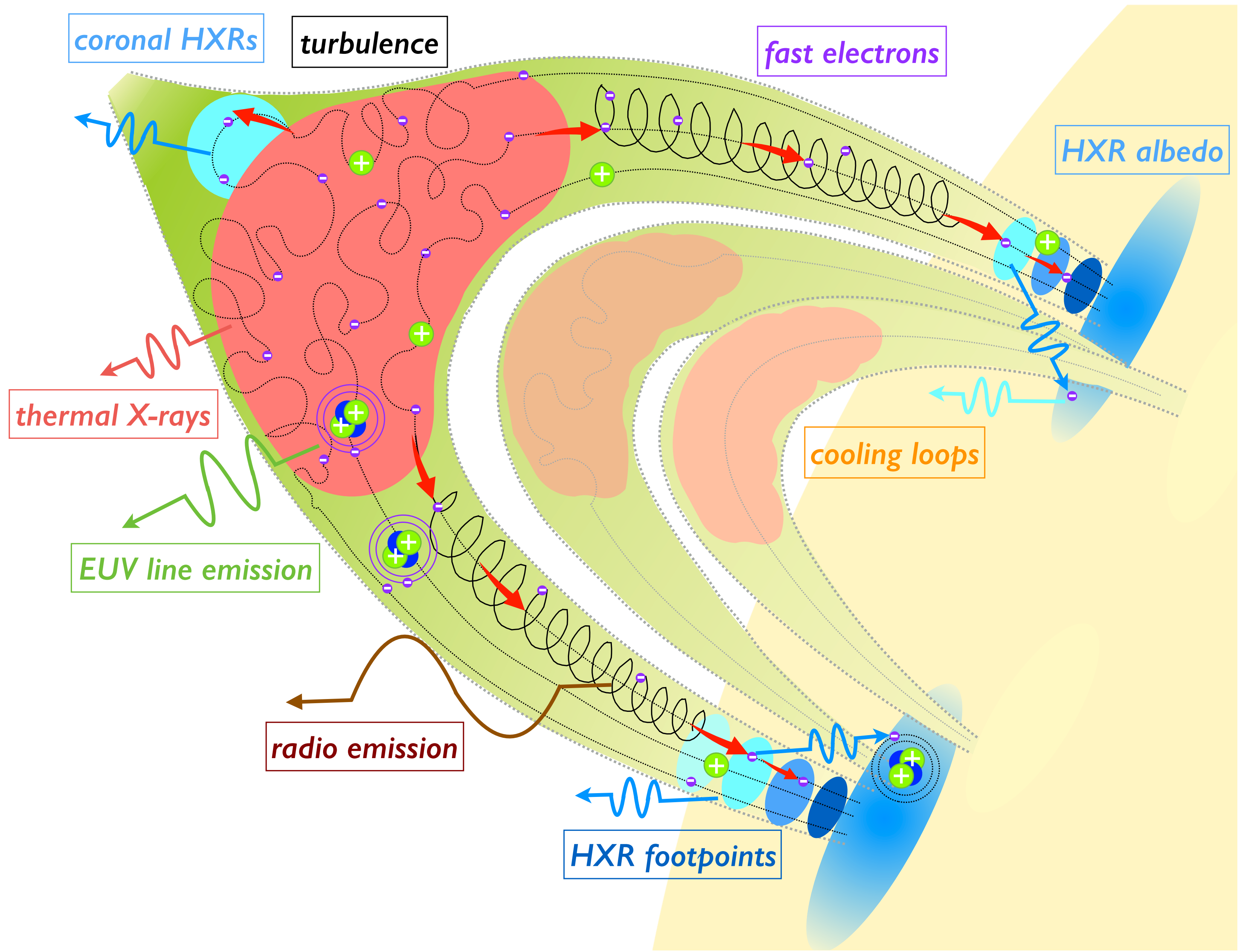
Ions would have to be accelerated locally, i.e. where we see the EUV line emission!

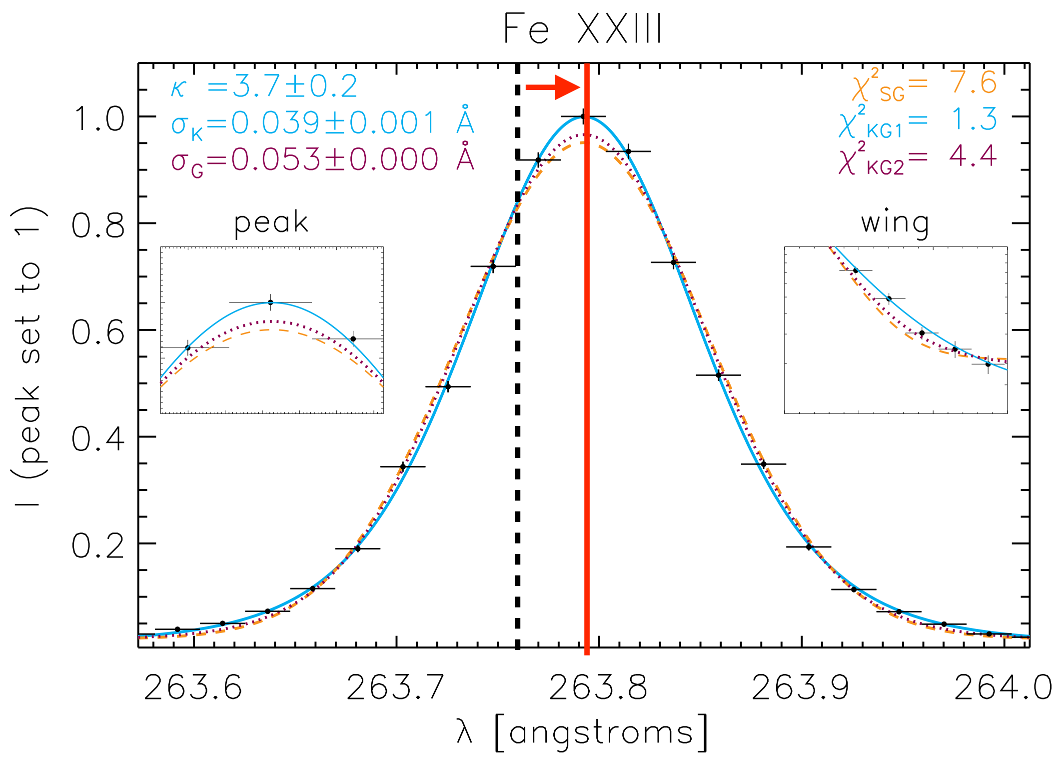
This suggests that we are observing another diagnostic of turbulence (alongside "non-thermal" broadening) in flares?

Causes of non-Gaussian lines: turbulence?

*Could the observations be due to plasma turbulence (and non-Brownian plasma motions during the flare)? **Extra diagnostic alongside broadening**?*

- Fe XVI/Fe XXIII lines are red-shifted ⟶ small down flows +10-40 km/s.



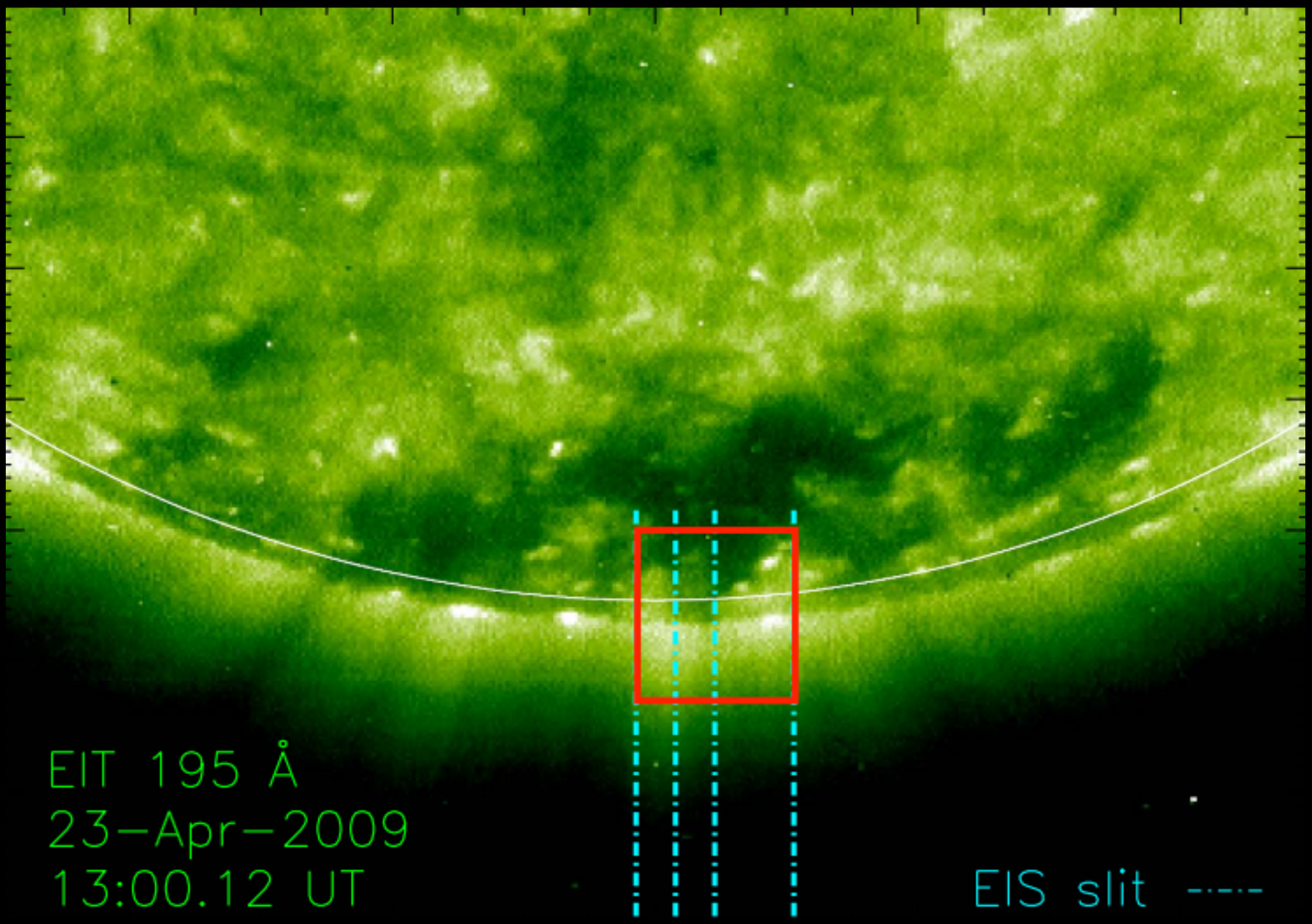


- *Plasma down flows leading to turbulence???*

Non-Gaussian spectral lines in coronal holes

- We analysed Hinode EIS EUV spectral data from the polar coronal hole on 23rd April 2009 *(Hahn et al. (2012), Hahn & Savin (2013a))*.

SOHO EIT 195 Å image of the coronal hole



- The EIS 2′′ slit locations for four separate 30-minute observations are combined.
- The data preparation and averaging have been previously described in *Hahn et al. (2012)* and *Hahn & Savin (2013a)*.
- Full EIS wavelength observation.

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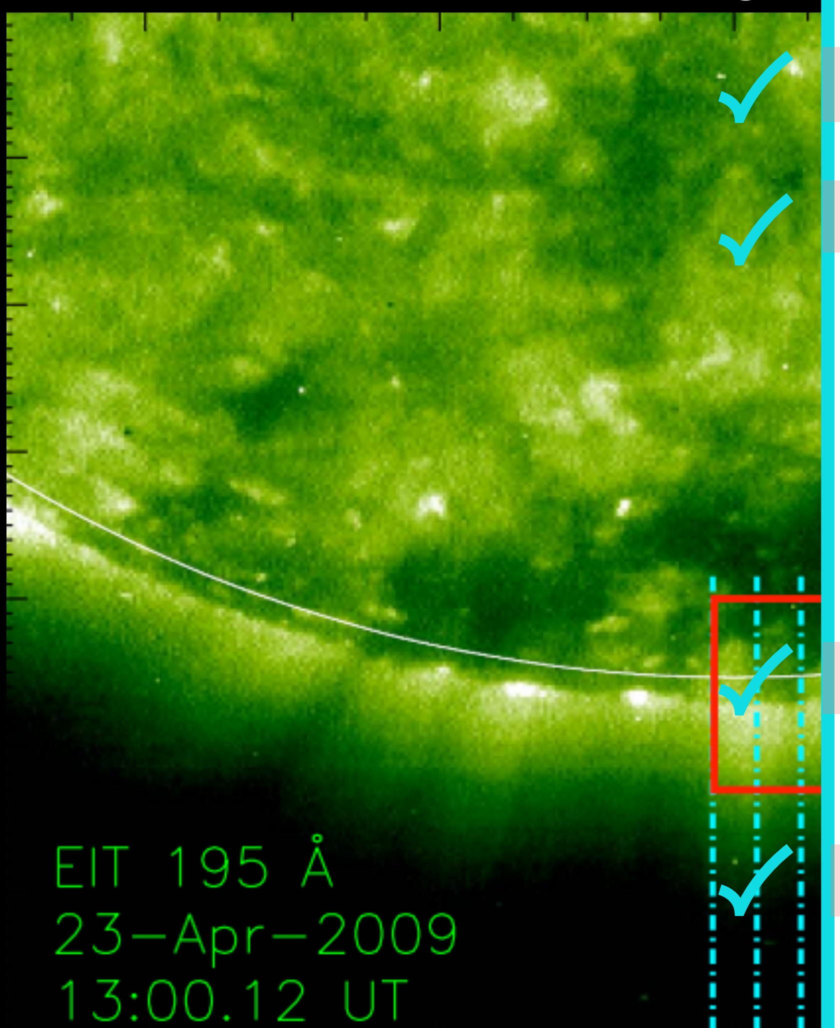


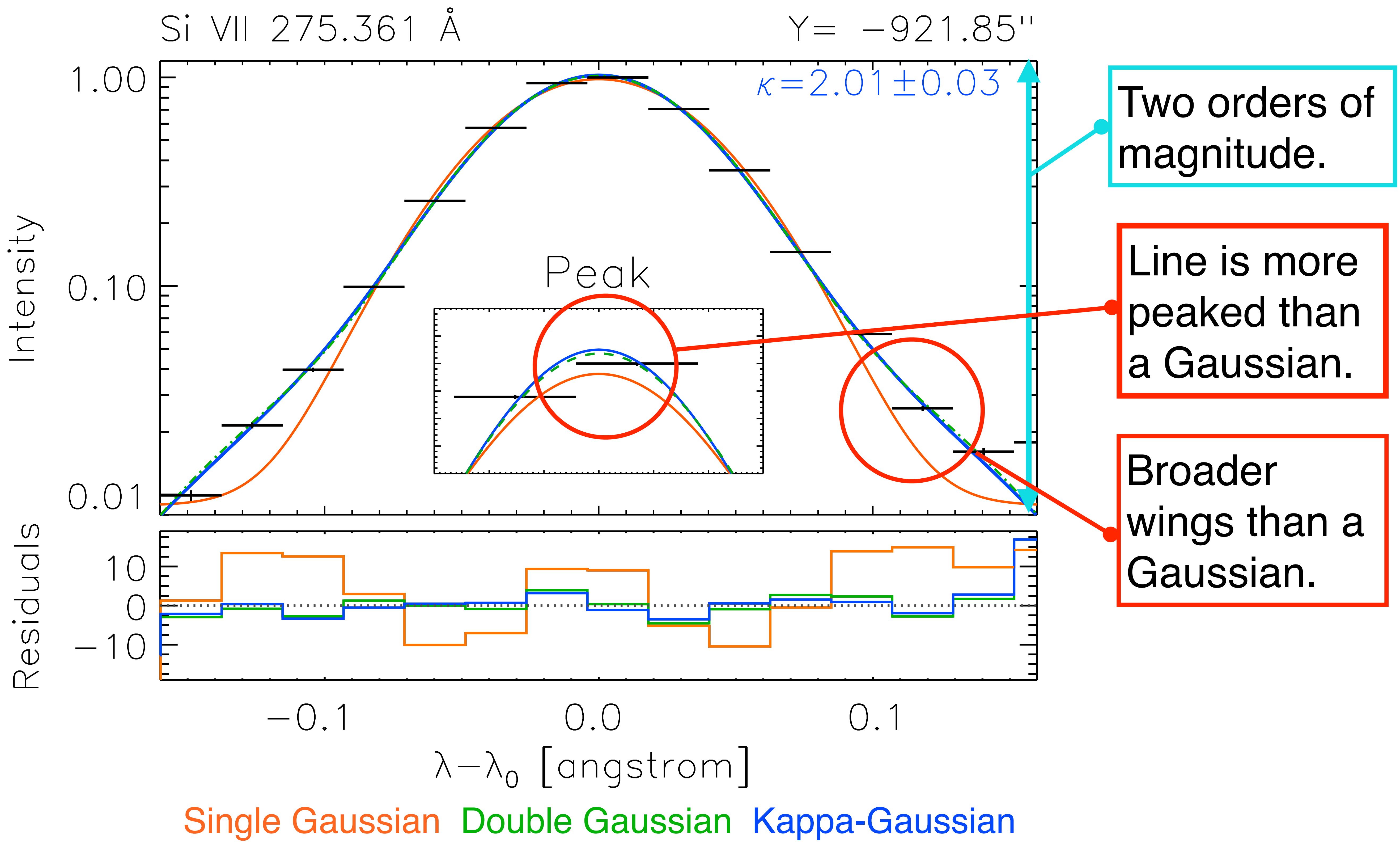
O VI	183.937
O VI	184.118
Mg VII	276.154
Si VII	272.648
Si VII	275.361
Si VII	275.676
Si X	258.374
Si X	261.057
Si X	271.992
Si X	277.264
S X	264.231
Fe VIII	185.213
Fe VIII	186.599
Fe VIII	194.661
Fe IX	188.497
Fe IX	189.941
Fe IX	197.862
Fe X	184.537
Fe X	190.037
Fe X	193.715
Fe X	{257.259, 257.263}
Fe XI	180.401
Fe XI	188.217
Fe XI	188.299

- The EIS 2″ slit locations for four separate 30-minute observations are combined.
- The data preparation and averaging have been previously described in *Hahn et al. (2012)* and *Hahn & Savin (2013a)*.
- Full EIS wavelength observation.

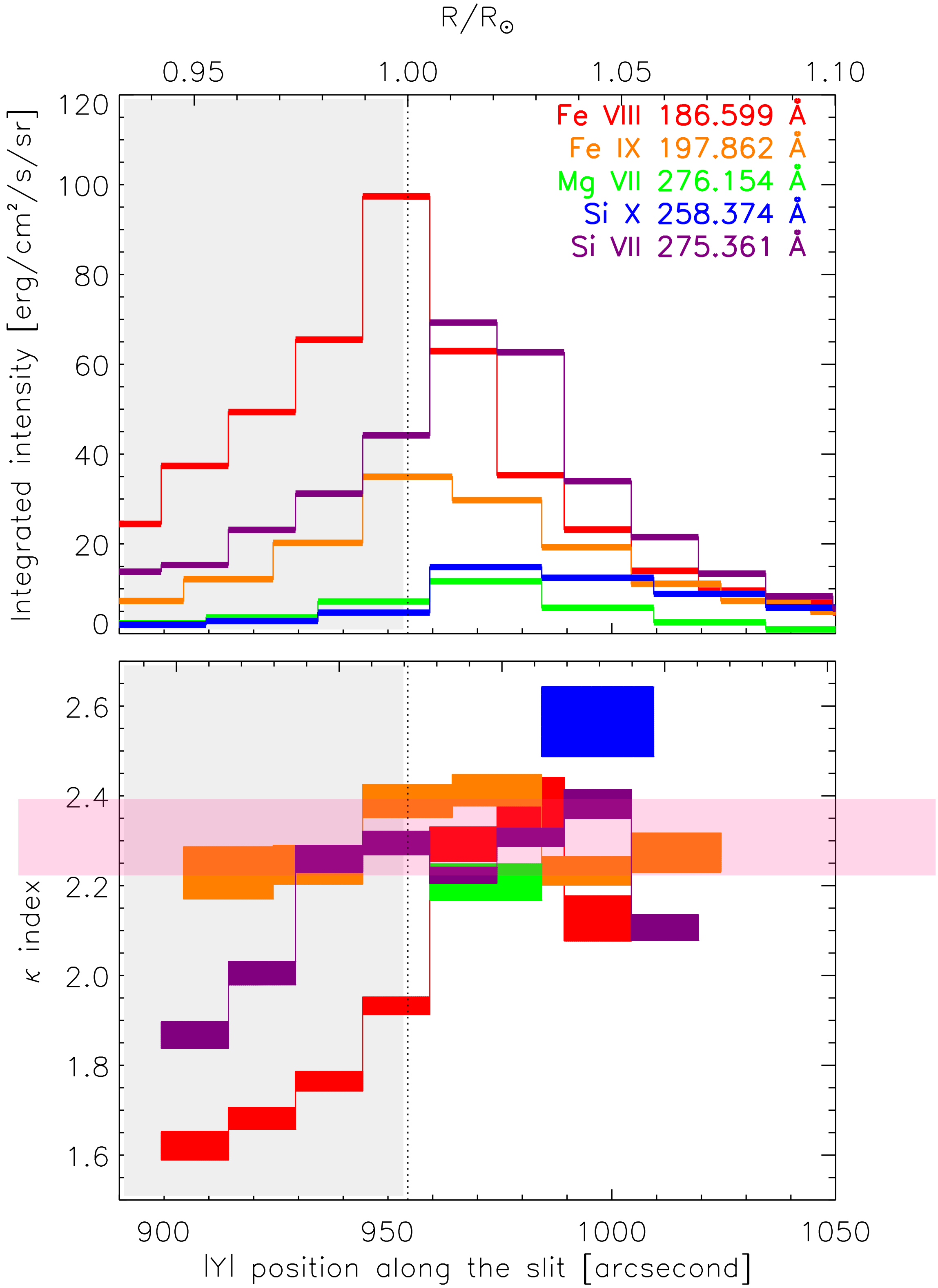
We focus on unblended spectral lines suitable for the study.

Results - some examples

- A kappa-Gaussian function is a much better fit to the non-Gaussian line shape! Wings are easier to see than for the flare case!



Coronal hole data: full results



- We find **non-Gaussian line profiles low in a coronal hole**, which are better represented by kappa distributions with κ<2.6.
- The inferred value of **κ increases moving radially outward until the observations reach the solar limb**, as can be seen for both Si VII and Fe VIII before ≈1 solar radii.
- Above this altitude, Si VII **κ remains approximately constant at values of κ≈2.1–2.3**. The other lines have similar κ values.

To the best of our knowledge, this is the first time that ion VDFs in the fast solar wind has been probed so close to its source region.

Again…fluid motions or ion motions or both?

Ion	Wavelength (Å)	$\log T$	Q/M	No. of Altitudes	Full κ Range	Off-limb κ Range	Off-limb $\langle\kappa\rangle$
Fe VIII	186.599	5.7	0.14	7	1.6–2.3	1.9–2.3	2.1
Si VII	275.361	5.8	0.25	8	1.8–2.4	2.1–2.4	2.3
Mg VII	276.154	5.8	0.29	1	2.1	2.1	2.2
Fe IX	197.862	6.0	0.16	6	2.0–2.3	2.2–2.4	2.3
Si X	258.374	6.2	0.36	1	2.6	2.6	2.6

- Fluid motions might be expected to affect all ions in the same way, but the **ion VDFs may differ due to heating that depends on M or Q/M**

  - *Similar techniques have been used to separate thermal from non-thermal broadening in spectral lines (Tu et al. 1998; Landi & Cranmer 2009; Hahn & Savin 2013a, 2013b).*

- Alternatively, processes such as the **cascade of MHD waves** toward smaller scales might be expected to produce more **efficient ion acceleration, and hence lower κ indices, for ions with lower cyclotron frequencies** $\Omega_{c,i}$, since $\Omega_{c,i}=(Q/M)\ \Omega_{c,p}$.

- At low altitudes, the **Doppler motions are observed perpendicular to the magnetic field**, which could be suggestive of, e.g., **Alfvénic fluctuations**. Evidence of Alfvén wave dissipation via non-thermal broadening was presented in Hahn & Savin (2013a).

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Summary

- Non-Gaussian spectral lines have been found in **flares**, **active regions**, and in the **fast solar wind/coronal holes**.

- In flares, non-Gaussian spectral lines were found in hot (Fe XXIII) and cooler lines (Fe XVI).

- The cause of these non-Gaussian line profiles may be:

  (a) **non-Maxwellian ion VDFs** at the base of fast solar wind**,**
  (b) fluid motions such as **non-Gaussian turbulent fluctuations** or **non-uniform wave motions**, or
  (c) some **combination of both**.

- Following-on from *flare observations*, we looked for non-Gaussian spectral lines low in the fast solar wind, and **report the detection of non-Gaussian EUV spectral line shapes at the base of the fast solar wind (<1.1 R_{sun})**.

  - The findings are a timely precursor to future observations with the ***Parker Solar Probe*** *which will study ion VDFs in situ as close as ≈8.5 R_{sun}, and hence help to test whether non-Gaussian VDFs are indeed formed very close to the Sun.*

Future?

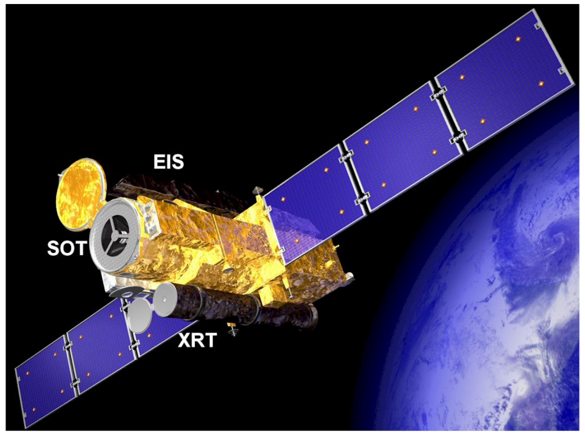
- **Future studies:**

1. **Hinode EIS**, **IRIS** studying different layers of the atmosphere.

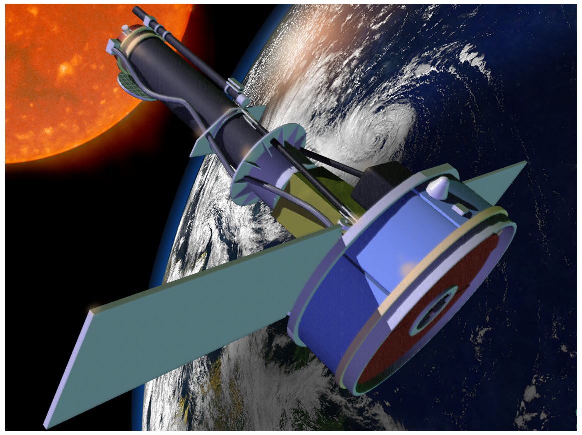
2. **DKIST Cryogenic Near Infrared Spectropolarimeter (Cryo-NIRSP)** and **Diffraction Limited Near Infrared Spectropolarimeter (DL-NIRSP)** will be able to collect spectra from infrared lines in the corona ($\lambda \approx 5000$– 50,000 A). Broad temperature range for coronal holes, quiet Sun regions, and active regions. Colleagues at Columbia University are hoping to study such lines. **Good for coronal holes.**

3. **Solar Orbiter/SPICE** alongside **SolarOrbiter (& PSP)** in-situ instruments. **Good for coronal holes and flares?**

Hinode EIS



IRIS



DKIST

Solar Orbiter