Constraining turbulent solar flare acceleration regions by connecting multi-wavelength observations and kinetic modeling

Morgan Stores

Chamberlin (2018)

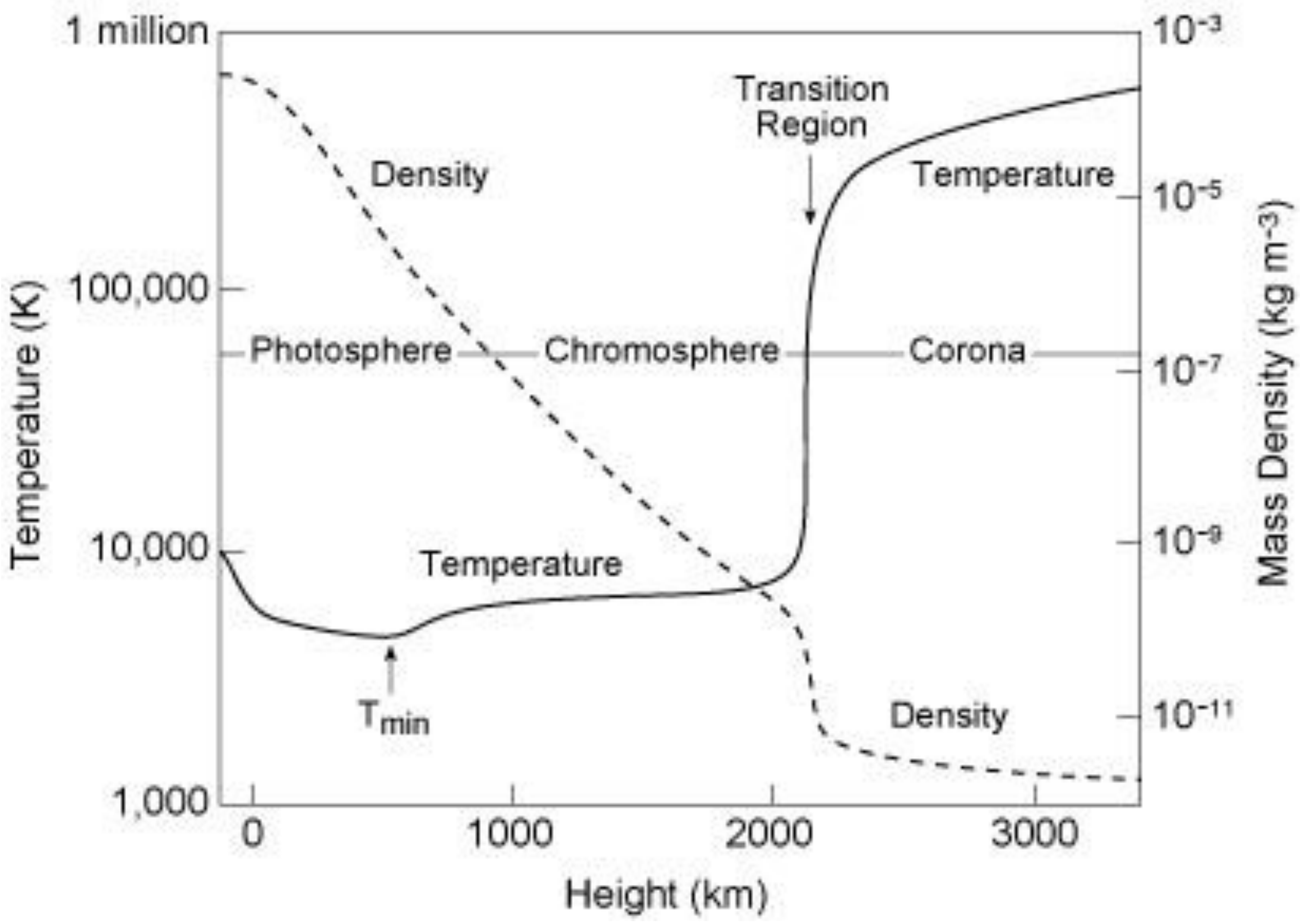
UCAR

University of Minnesota

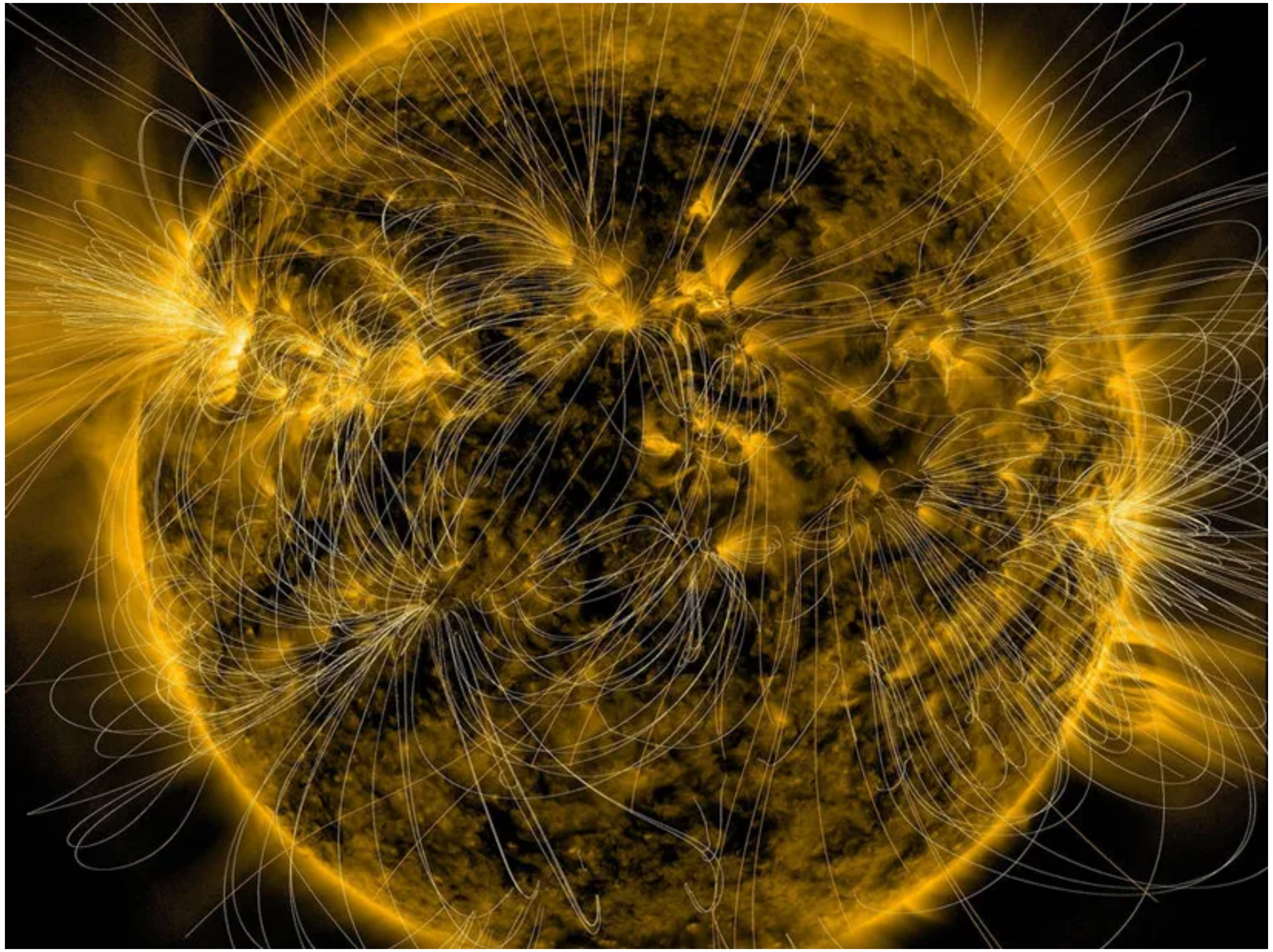
Northumbria University NEWCASTLE

mstores@umn.edu

The Solar Atmosphere



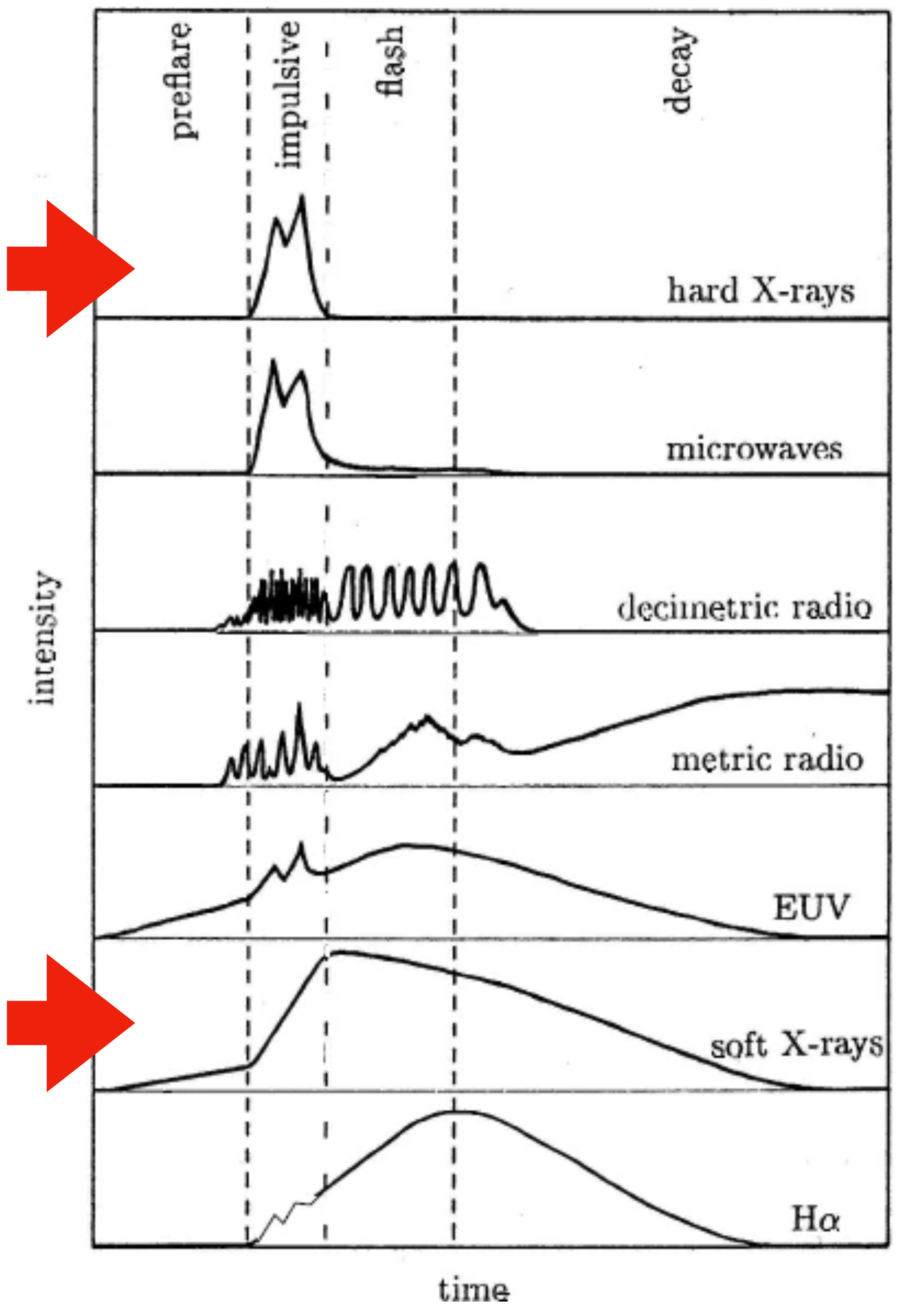
From Priest (2014)



NASA

mstores@umn.edu

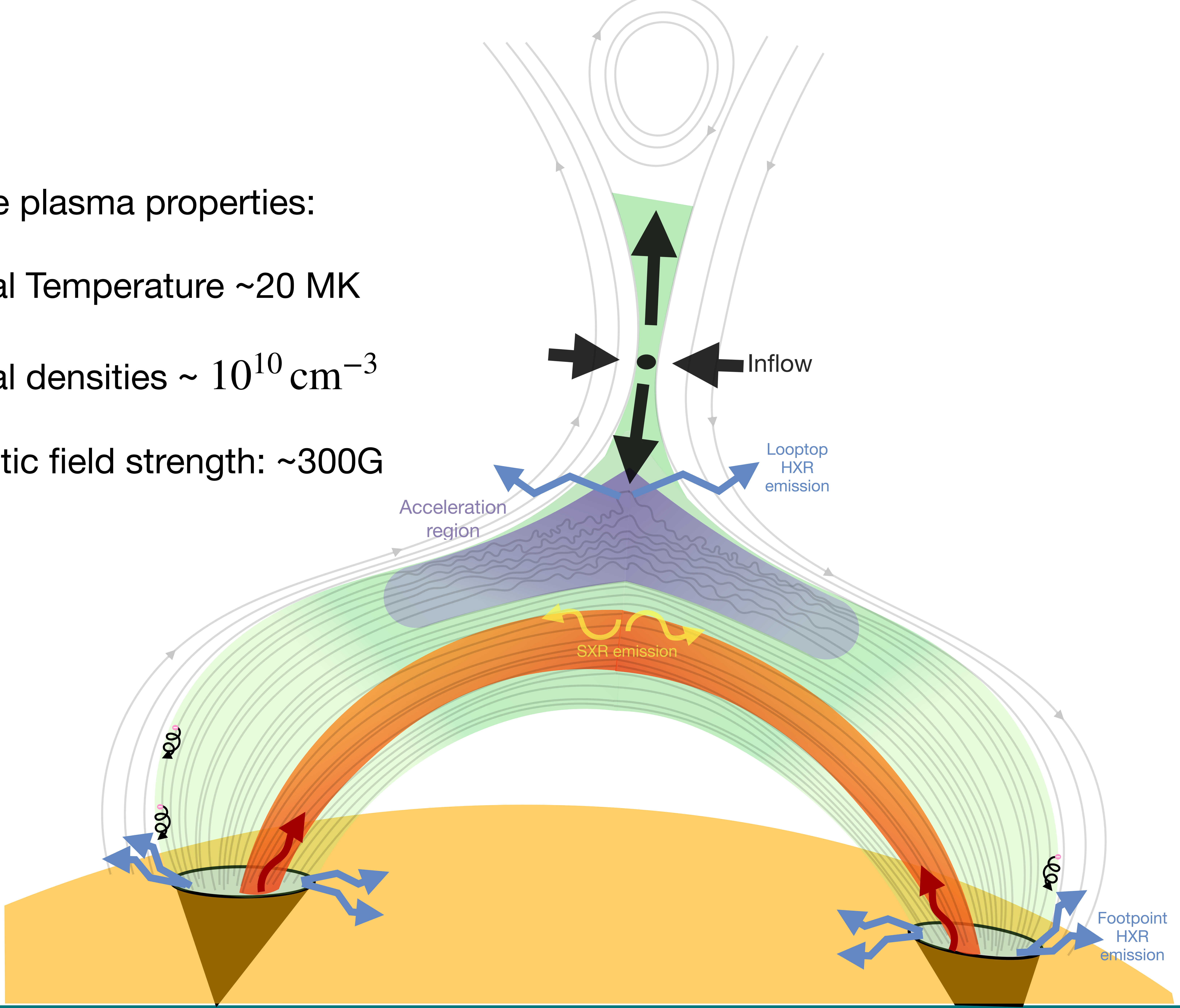
Solar Flares



Benz, A.O. (2002)

Large flare plasma properties:

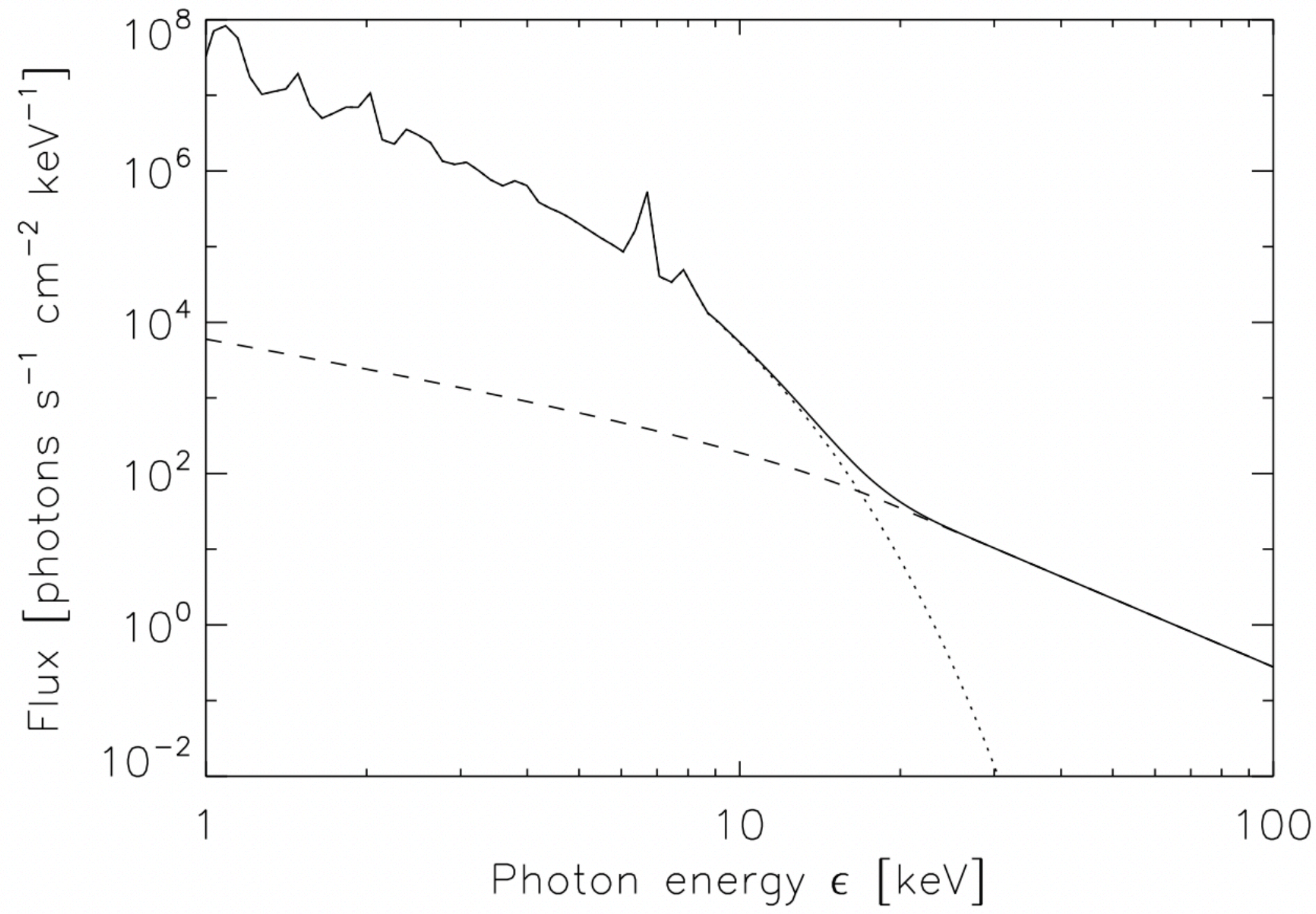
- Coronal Temperature ~20 MK
- Coronal densities ~ $10^{10}\,\mathrm{cm}^{-3}$
- Magnetic field strength: ~300G



mstores@umn.edu

Energy Spectrum

Hollman (2011)



Hard X-ray emission can be described by a power law:

$$I(\epsilon) \propto \epsilon^{-\gamma}$$

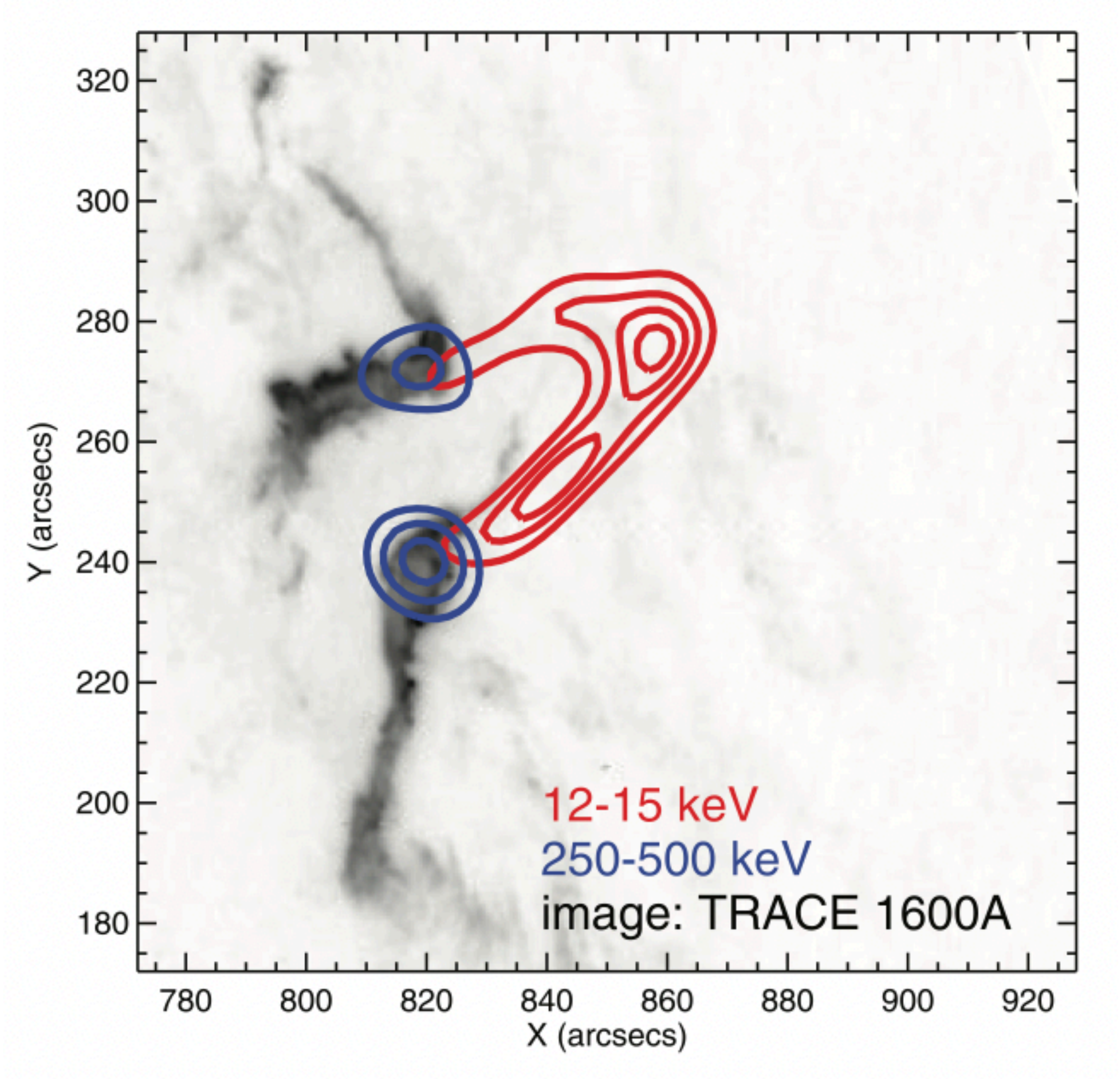
Where γ is the photon spectral index.

The spectral index of the emitting electron distribution:

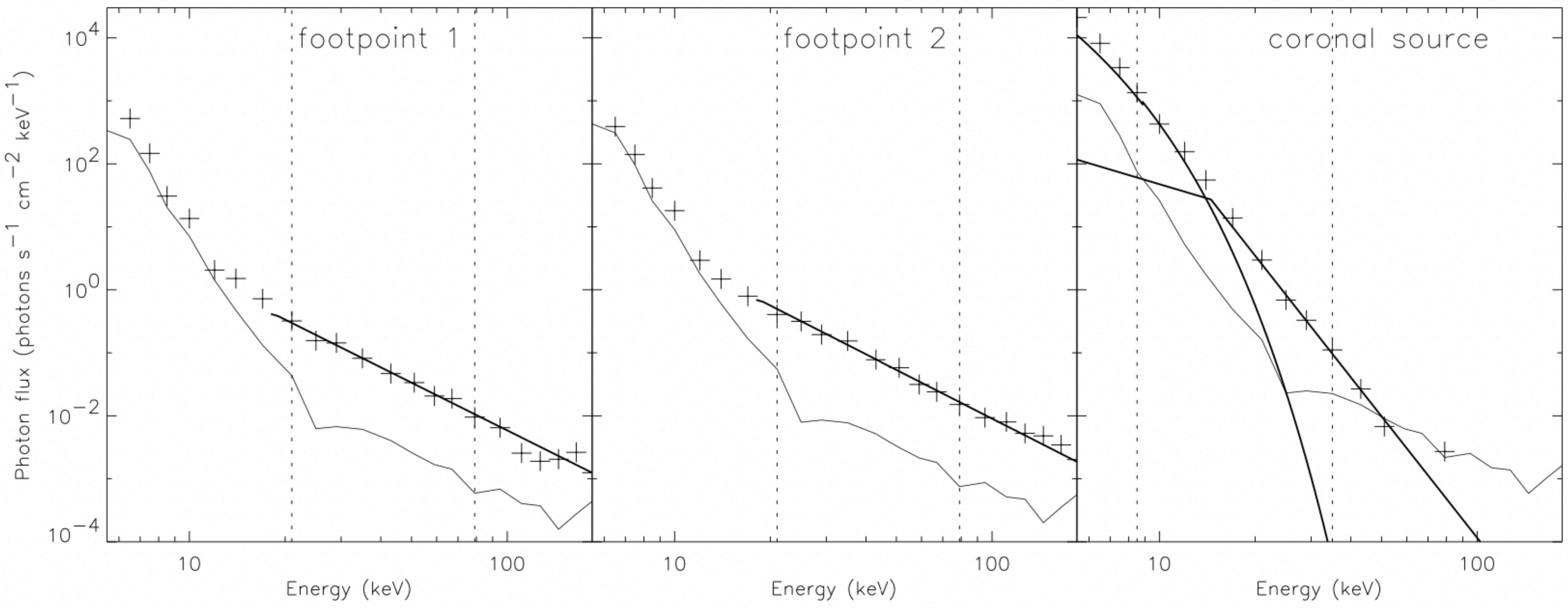
$$\delta_{nVF} \approx \gamma - 1$$

MHD Turbulence

Different X-ray energy spectra in the coronal looptop and chromospheric footpoints - suggesting trapping.



Krucker et al. (2008b)

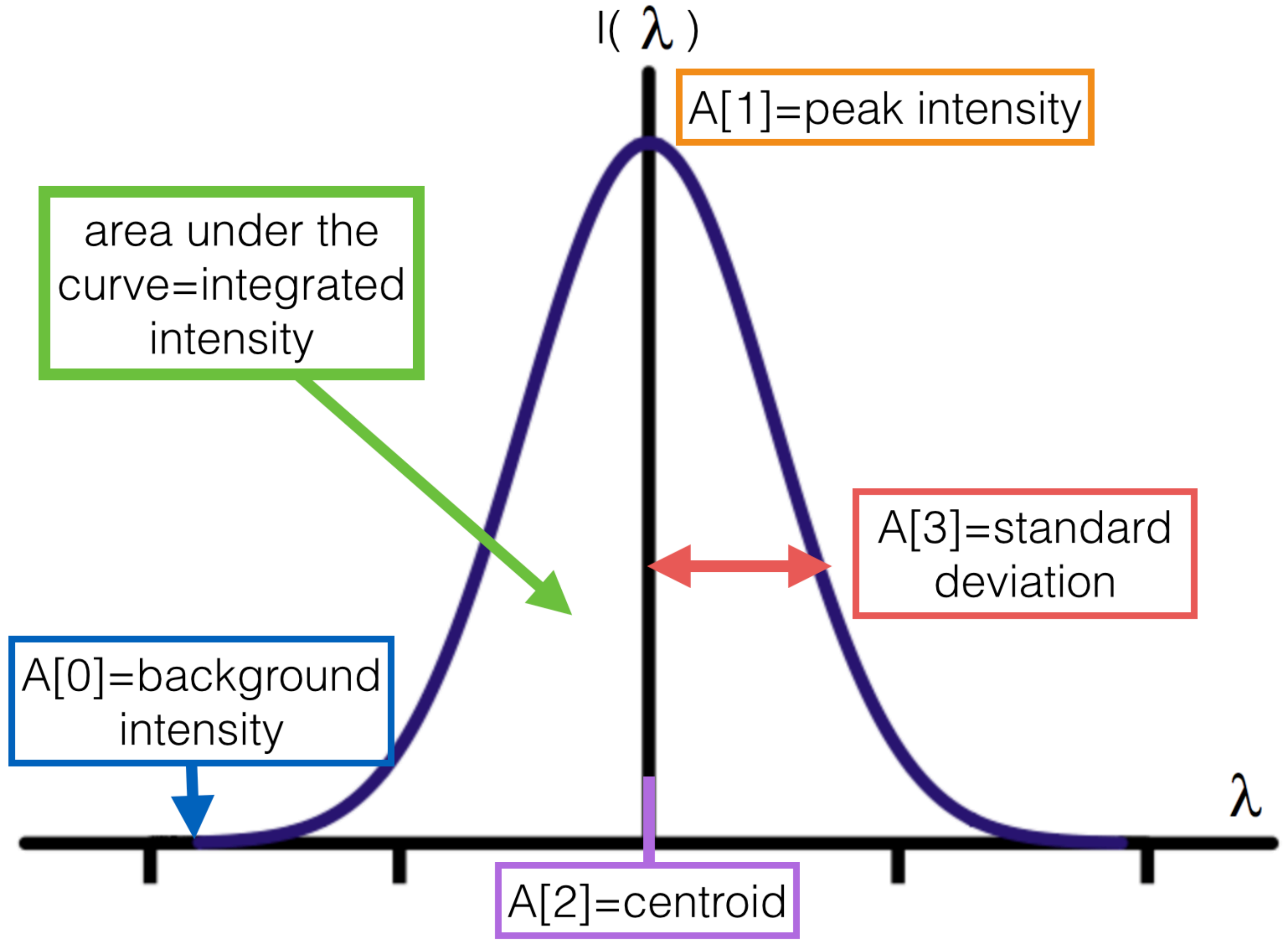


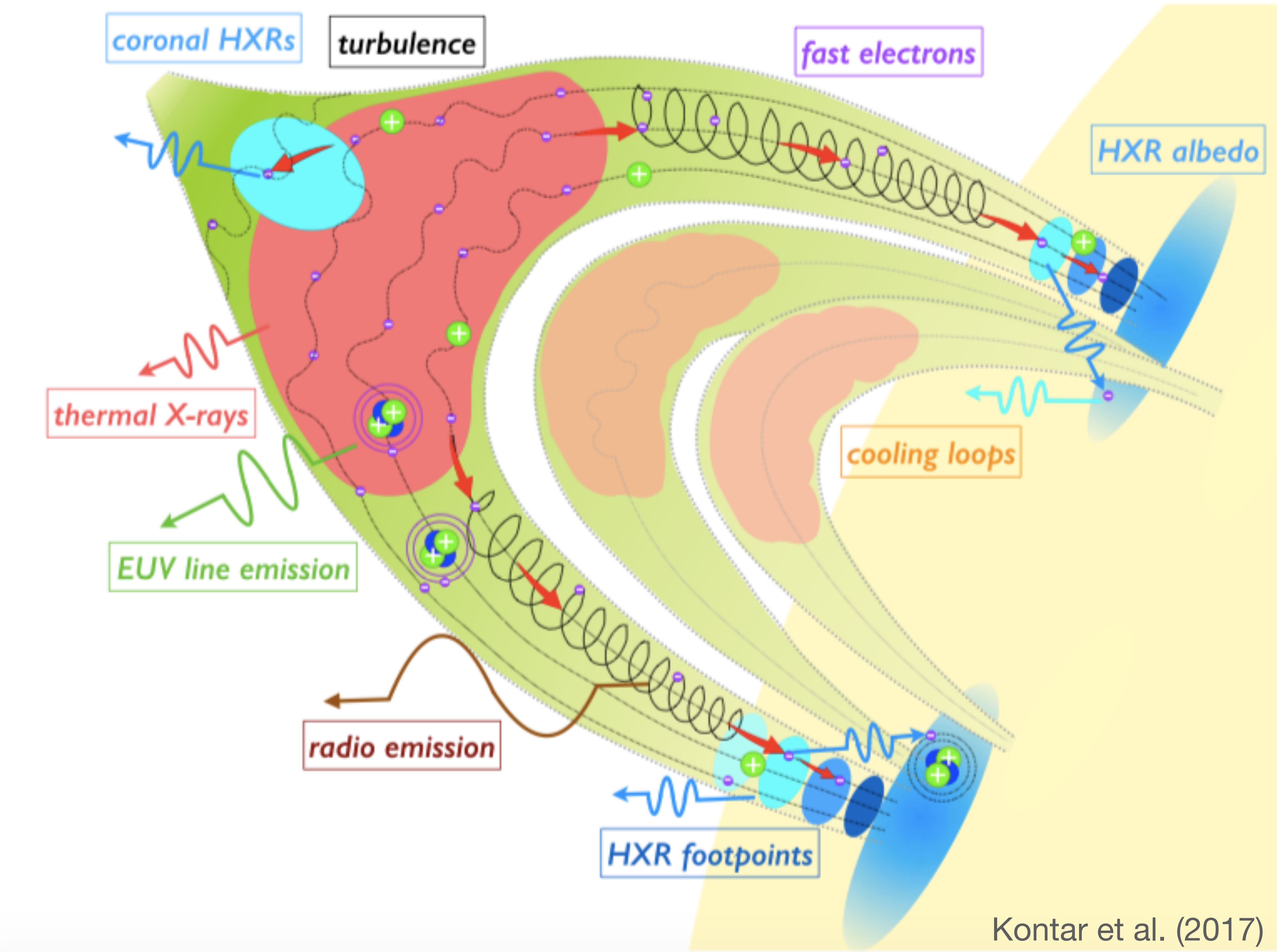
Battaglia & Benz (2007)

mstores@umn.edu

MHD Plasma Turbulence

- MHD plasma turbulence can accelerate particles and cause heating over 10 MK
- During a flare, spectral lines often show line widths in excess of what is expected from random thermal motions alone



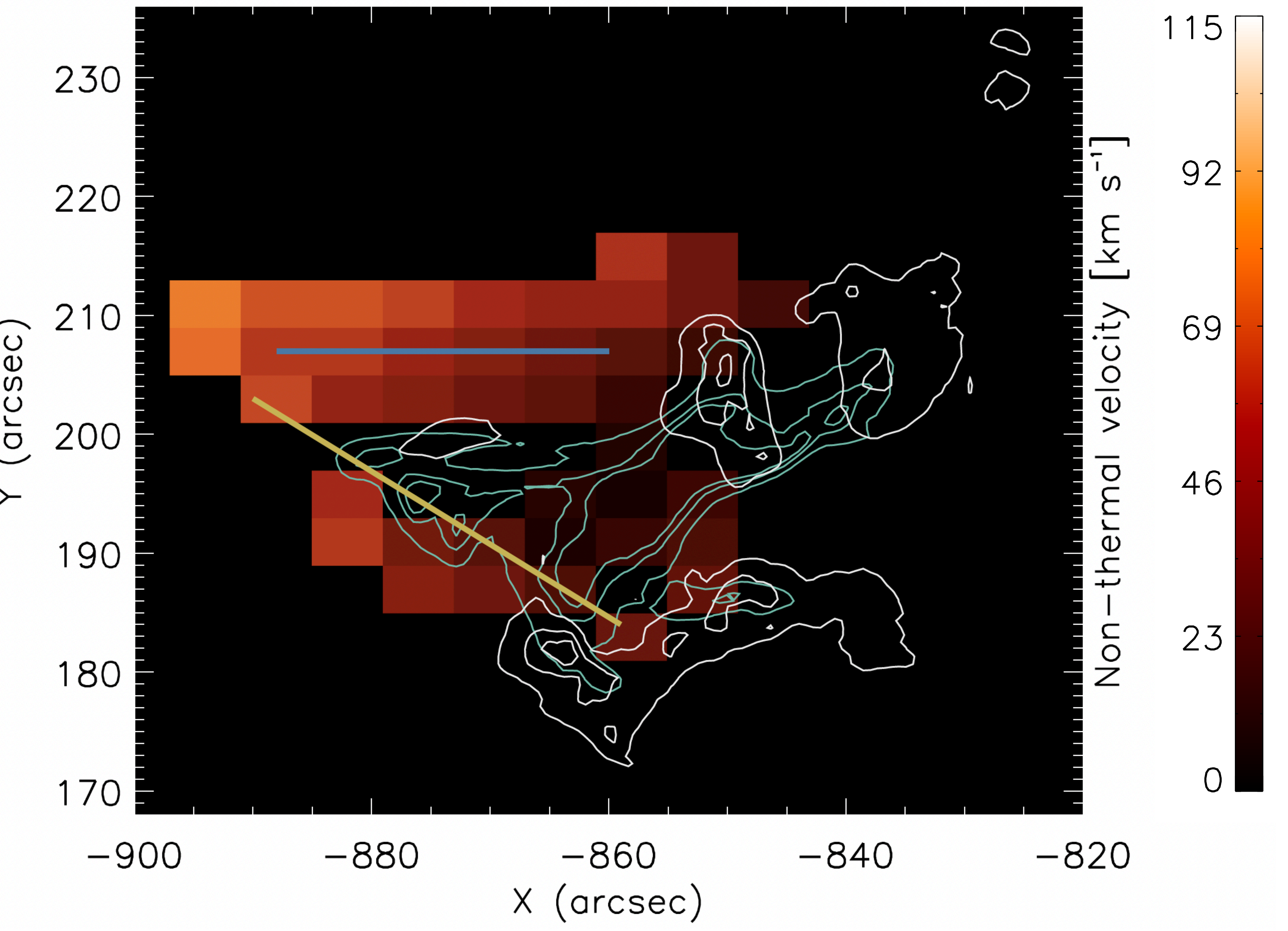


Kontar et al. (2017)

mstores@umn.edu

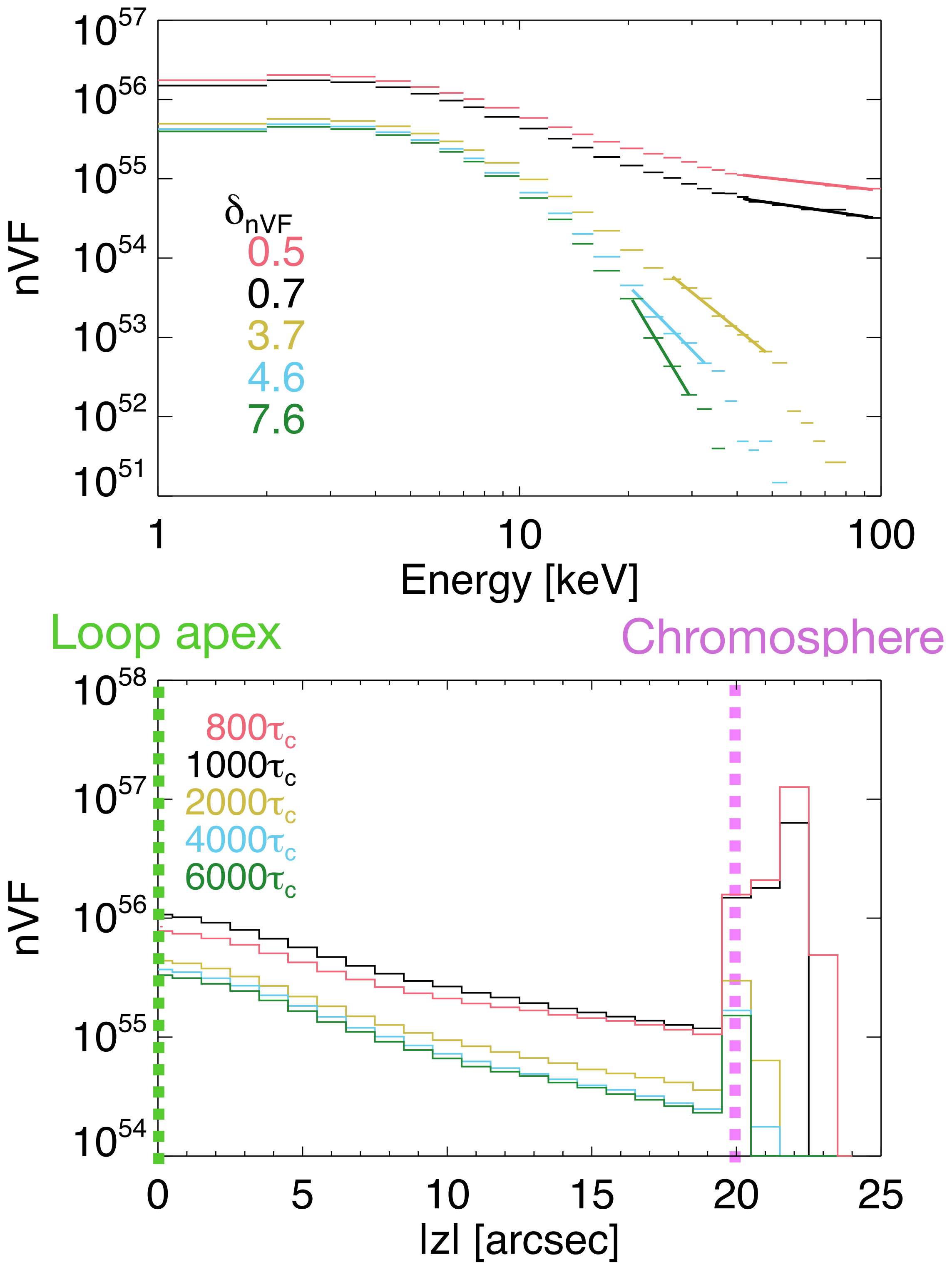
Compare X-ray/EUV observations to simulation outputs to constrain the properties of a turbulent solar flare acceleration region.

X-ray/EUV observations



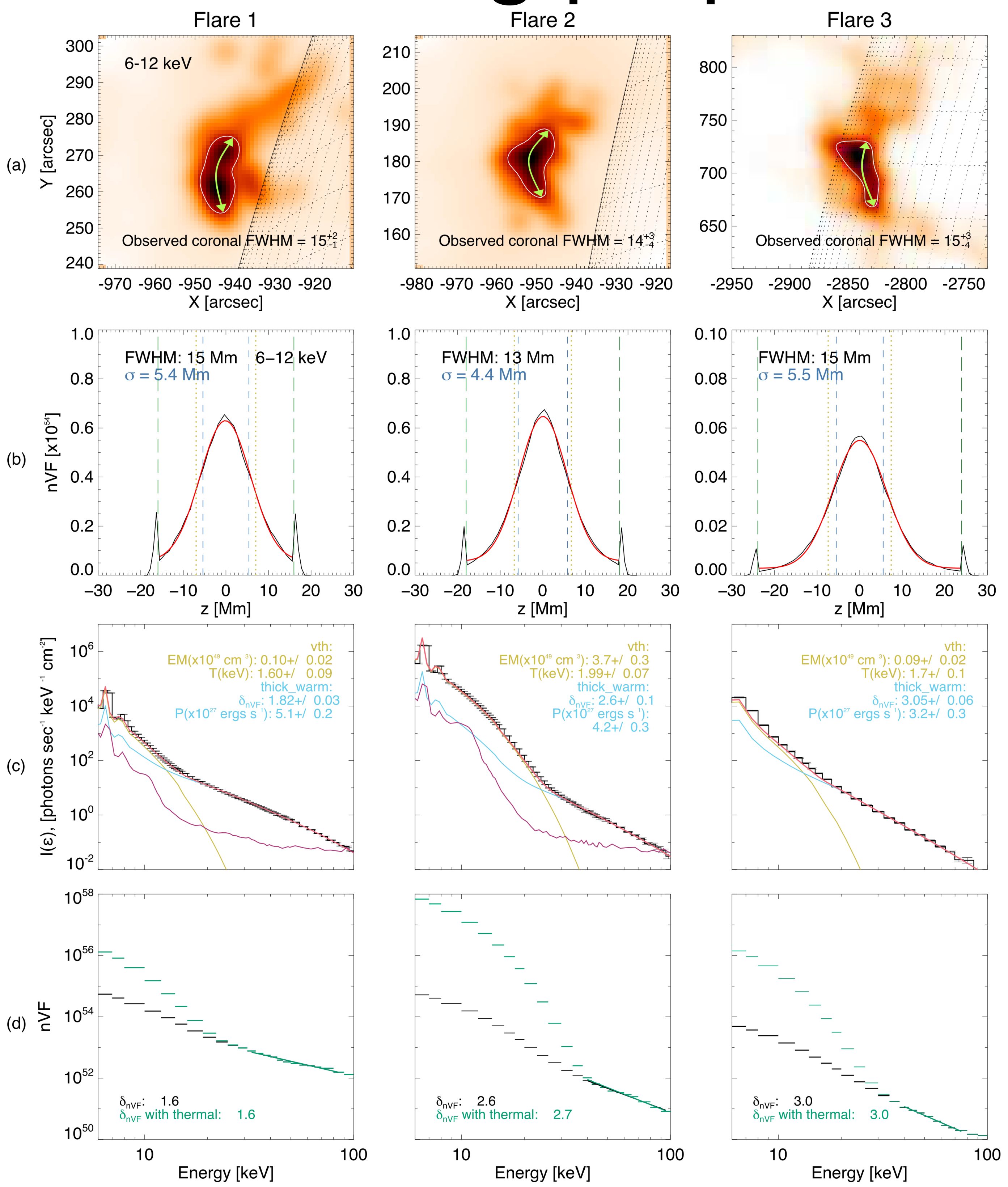
Stores et al. (2021)

Kinetic Modelling



Stores et al. (2023)

Constraining properties



mstores@umn.edu

Kinetic Model

A time-independent Fokker-Planck equation is used to describe the evolution of an electron flux $F(E, z, \mu)$ [electrons cm^{-2} s^{-1} keV^{-1}], which is a function of field-aligned coordinate z [cm], energy E [keV] and cosine of the pitch-angle (β) to the guiding magnetic field $\mu = \cos\beta$.

$$\mu\frac{\partial F}{\partial z} = \underbrace{\sqrt{2m_e^3}\left\{\frac{\partial}{\partial E}\left[E^{3/2}D(v,z)\frac{\partial}{\partial E}\left(\frac{F}{E}\right)\right]\right\}}_{\text{turbulent acceleration}} + \underbrace{\Gamma m_e^2\left\{\frac{\partial}{\partial E}\left[G(u[E])\frac{\partial F}{\partial E} + \frac{G(u[E])}{E}\left(\frac{E}{k_B T} - 1\right)\right]F\right)\right\}}_{\text{collisional energy losses}}$$

$$+\underbrace{\frac{\Gamma m_e^2}{8E^2}\left\{\frac{\partial}{\partial \mu}\left[(1-\mu^2)\left[\mathrm{erf}(u[E]) - G(u[E])\right]\frac{\partial F}{\partial \mu}\right]\right\}}_{\text{collisional pitch-angle scattering}} + \underbrace{\sqrt{\frac{m_e}{2E}}\left\{\frac{\partial}{\partial \mu}\left[D_{\mu\mu}(\mu,z)\frac{\partial F}{\partial \mu}\right]\right\}}_{\text{turbulent scattering}}$$

Stores et al. (2023)

mstores@umn.edu

Constraining turbulent acceleration regions

- Acceleration diffusion coefficient - Stackhouse et al. (2018)

$$D(v, z) = \frac{v_{\mathrm{th}}^2}{\tau_{\mathrm{acc}}}\left(\frac{v}{v_{\mathrm{th}}}\right)^{\alpha} \times \mathrm{H}(z),$$

$\tau_{acc} =$ Acceleration timescale $= A\tau_c$

$H(z) =$ Spatial Function = $\exp\left(-\frac{z^2}{2\sigma}\right)$

$\alpha =$ Velocity Dependence

$\sigma =$ Spatial Extent

mstores@umn.edu

Constraining turbulent acceleration regions

$$D(v,\, z) = \frac{v_{\rm th}^2}{\tau_{\rm acc}} \left(\frac{v}{v_{\rm th}} \right)^{\alpha} \times \mathrm{H}(z),$$

<u>Control simulation</u>

- Spatial Function: Gaussian
- Spatial extent: $\sigma = 3''$
- Velocity dependence: $\alpha = 3$

$\{$

$H(z) =$ Linear, Random

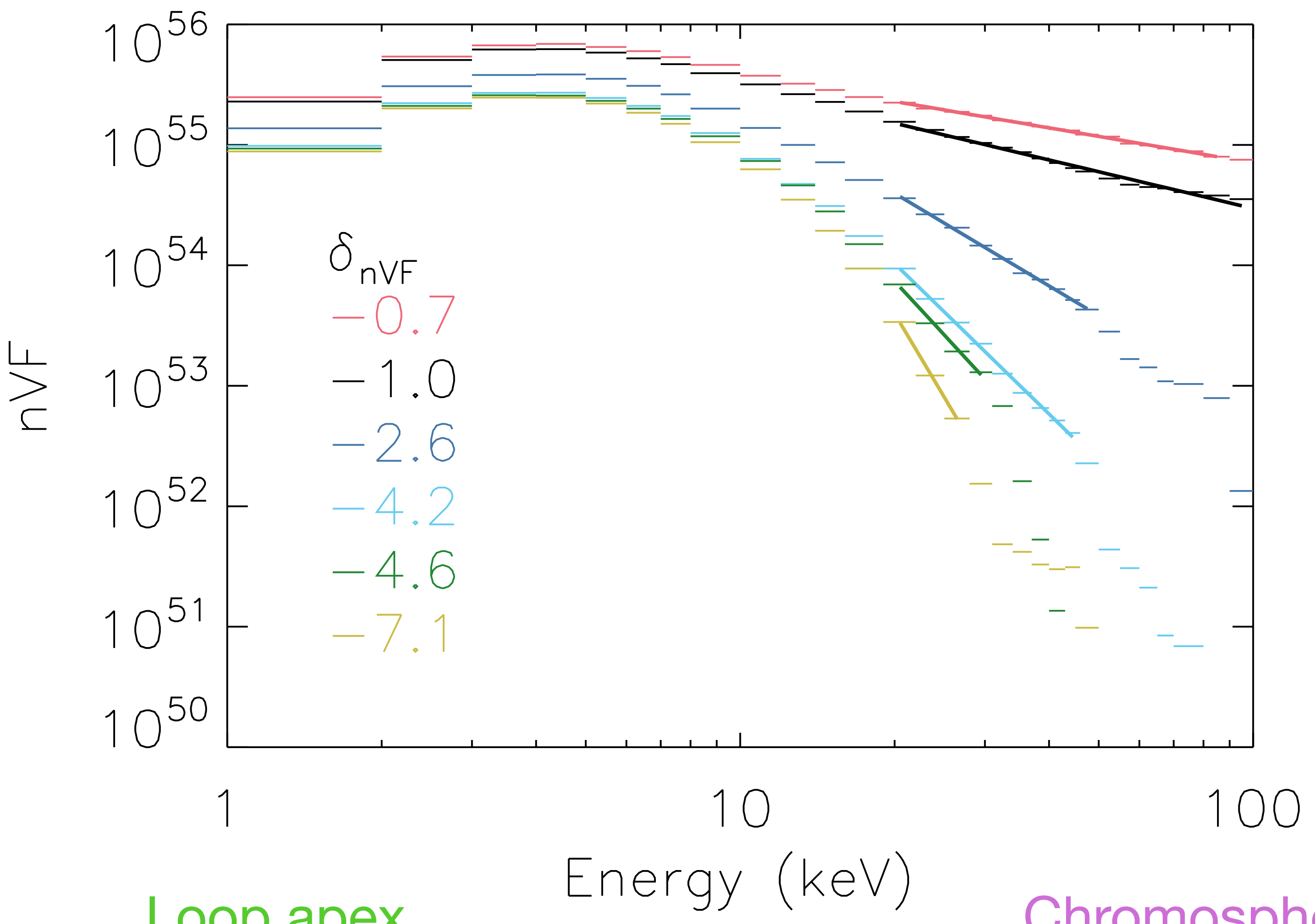
$\sigma = 1'', 7''$

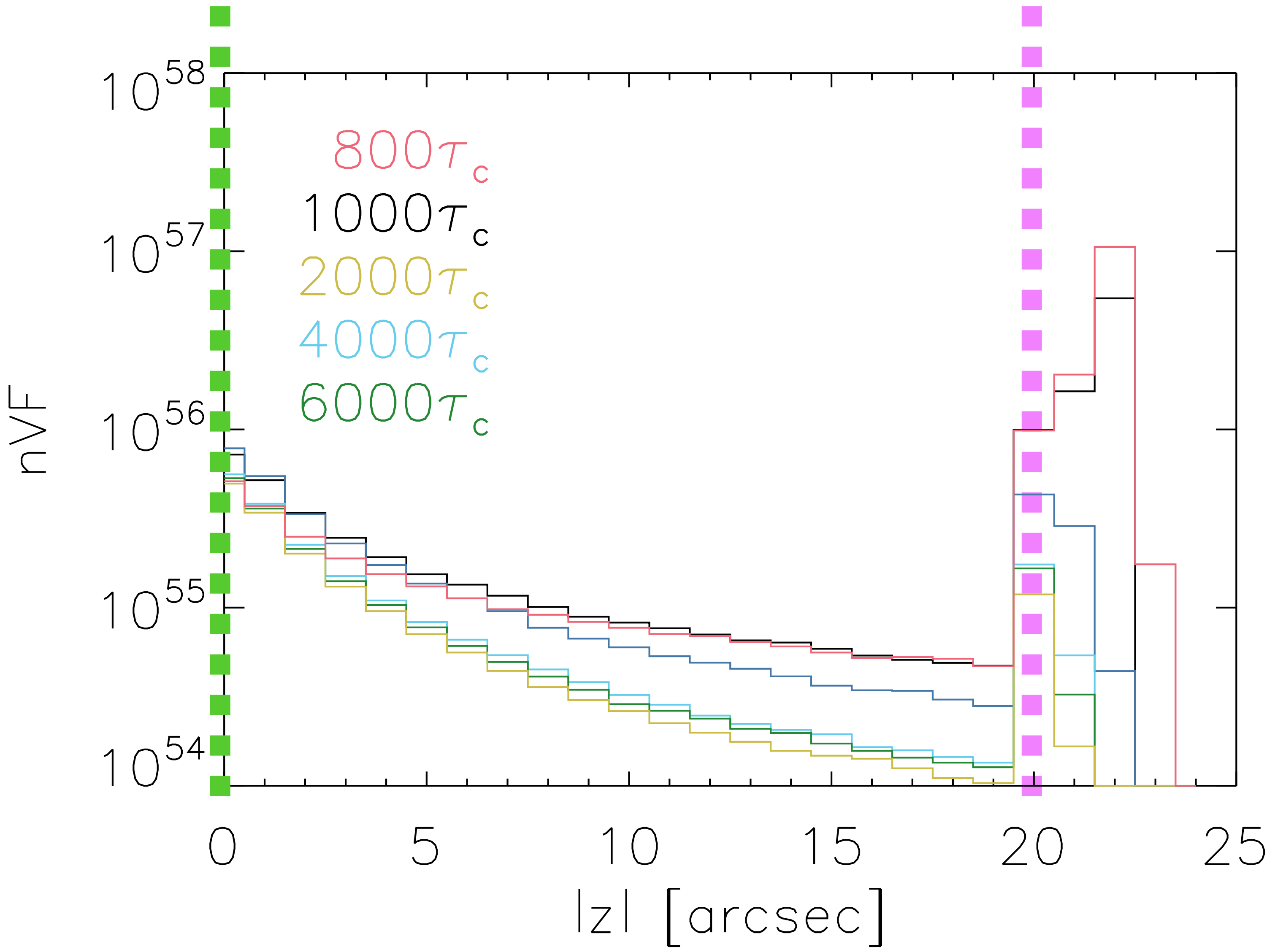
$\alpha = 2, 4$

$$\tau_{acc} = [800{,}1000{,}2000{,}4000{,}6000]\tau_c$$

mstores@umn.edu

Model Outputs





Useful model outputs that can be directly compared to X-ray spectral and imaging diagnostics to constrain the acceleration region properties:

Full flare spectral index

Spectral ratio $\delta_{nVF}^{LT} / \delta_{nVF}^{FP}$

Spectral differences $\delta_{nVF}^{LT} - \delta_{nVF}^{FP}$

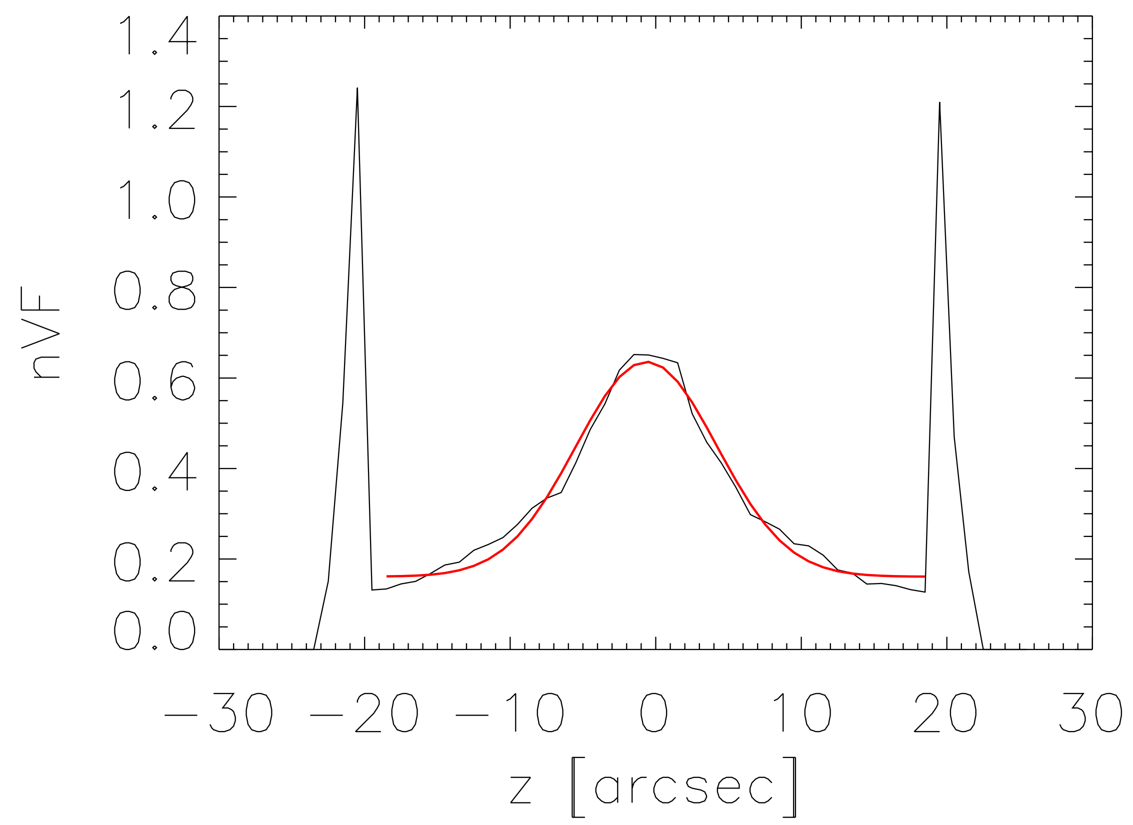
Coronal source FWHM

Electron depth into chromosphere

$$\phi = \frac{nVF(LT)}{nVF(FP)} \qquad \eta = \frac{nVF(E = 6 - 12 \text{ keV})}{nVF(E = 50 - 100 \text{ keV})}$$

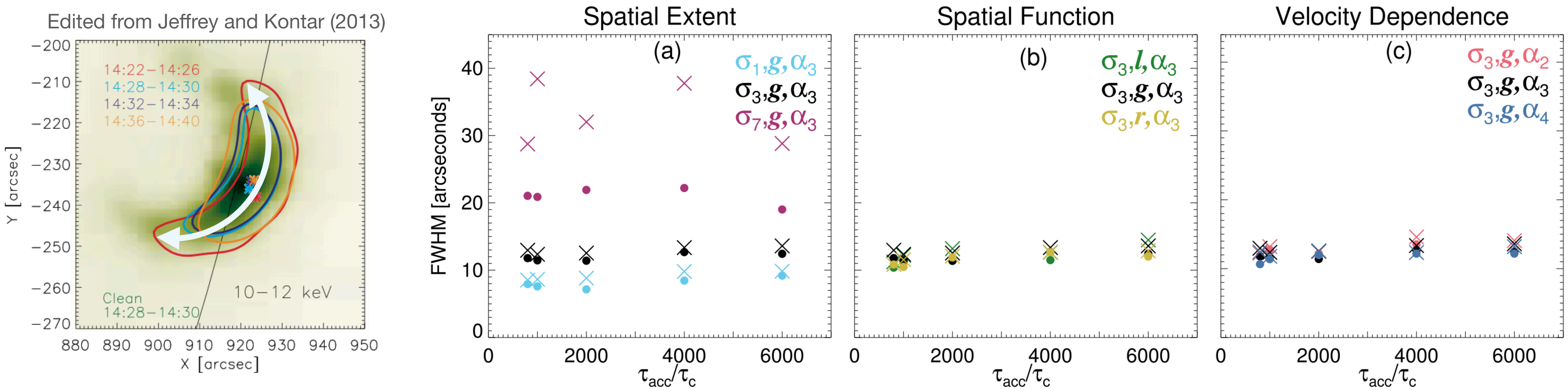
mstores@umn.edu

Coronal Source FWHM



The spatial distribution was fitted with a Gaussian distribution

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\,\Delta z$$

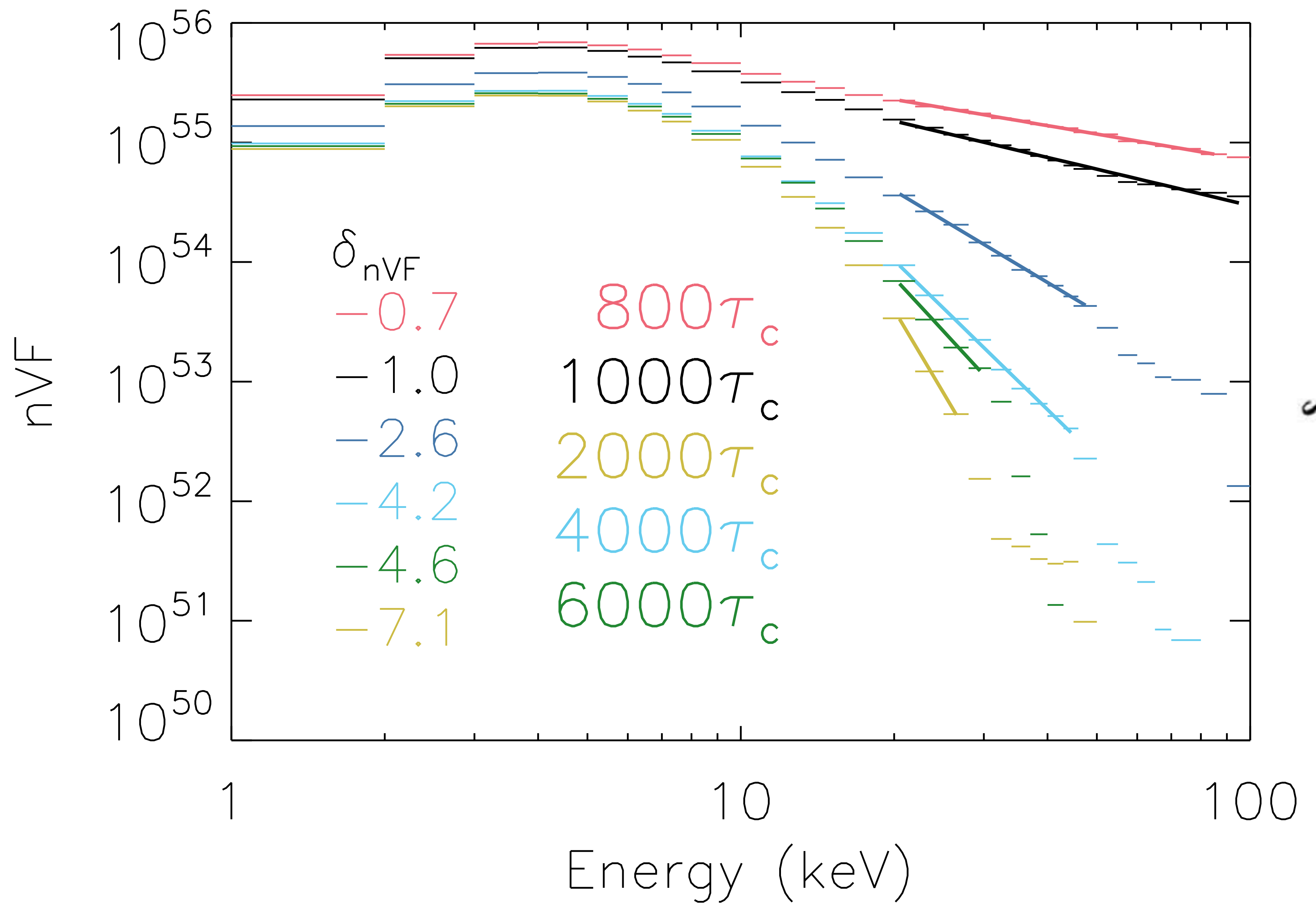


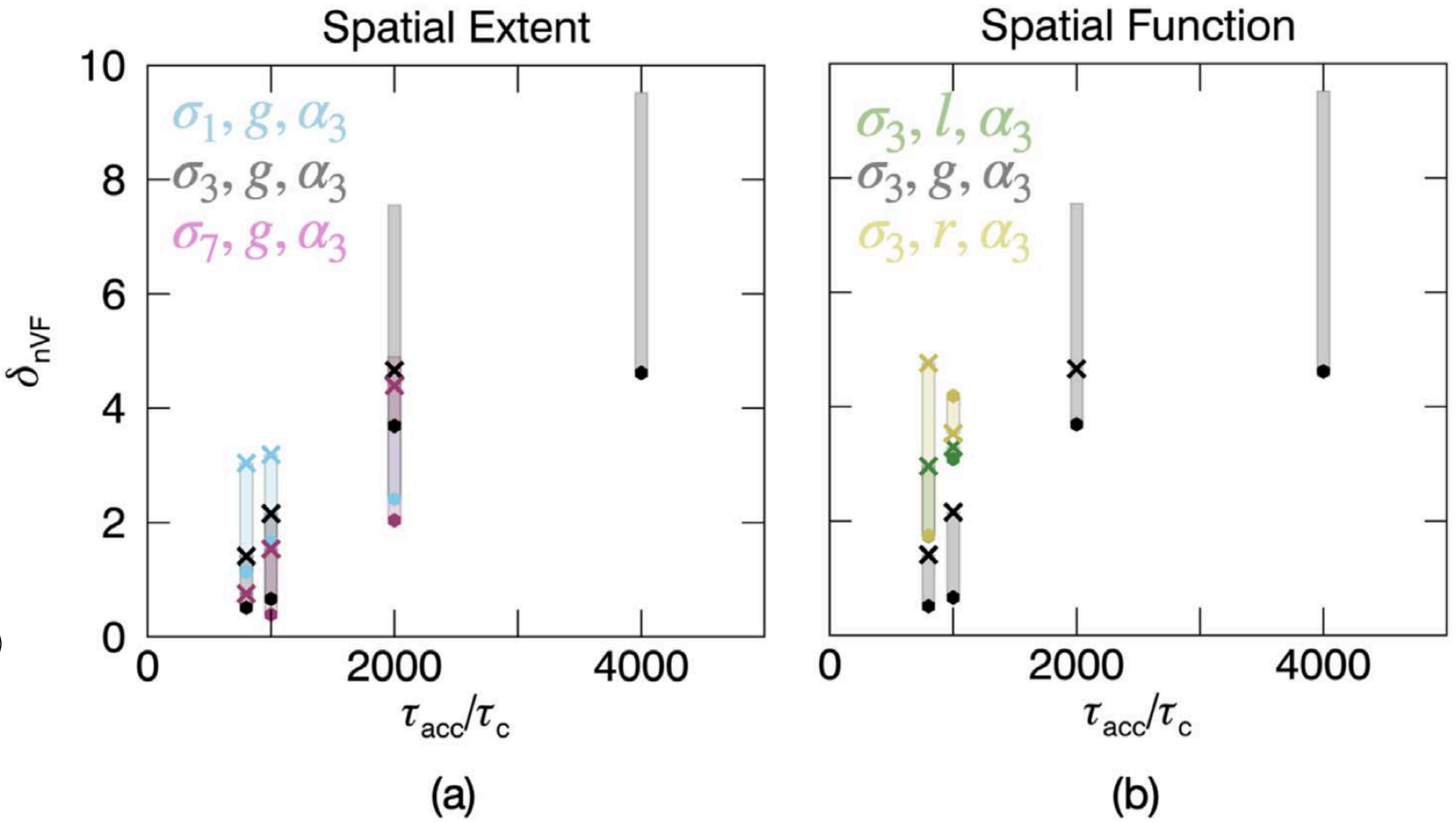
Coronal Source FWHM only changes with the **spatial extent** of the acceleration region.

mstores@umn.edu

Spectral index

The spectral index is determined from the energy spectrum.





Spectral index changes with the **acceleration timescale**.

mstores@umn.edu

Constraining turbulent acceleration regions

- Acceleration diffusion coefficient - Stackhouse et al. (2018)

$$D(v, z) = \frac{v_{\mathrm{th}}^2}{\tau_{\mathrm{acc}}} \left(\frac{v}{v_{\mathrm{th}}} \right)^{\alpha} \times \mathrm{H}(z),$$

$\tau_{acc} =$ Acceleration timescale

$\alpha =$ Velocity Dependence

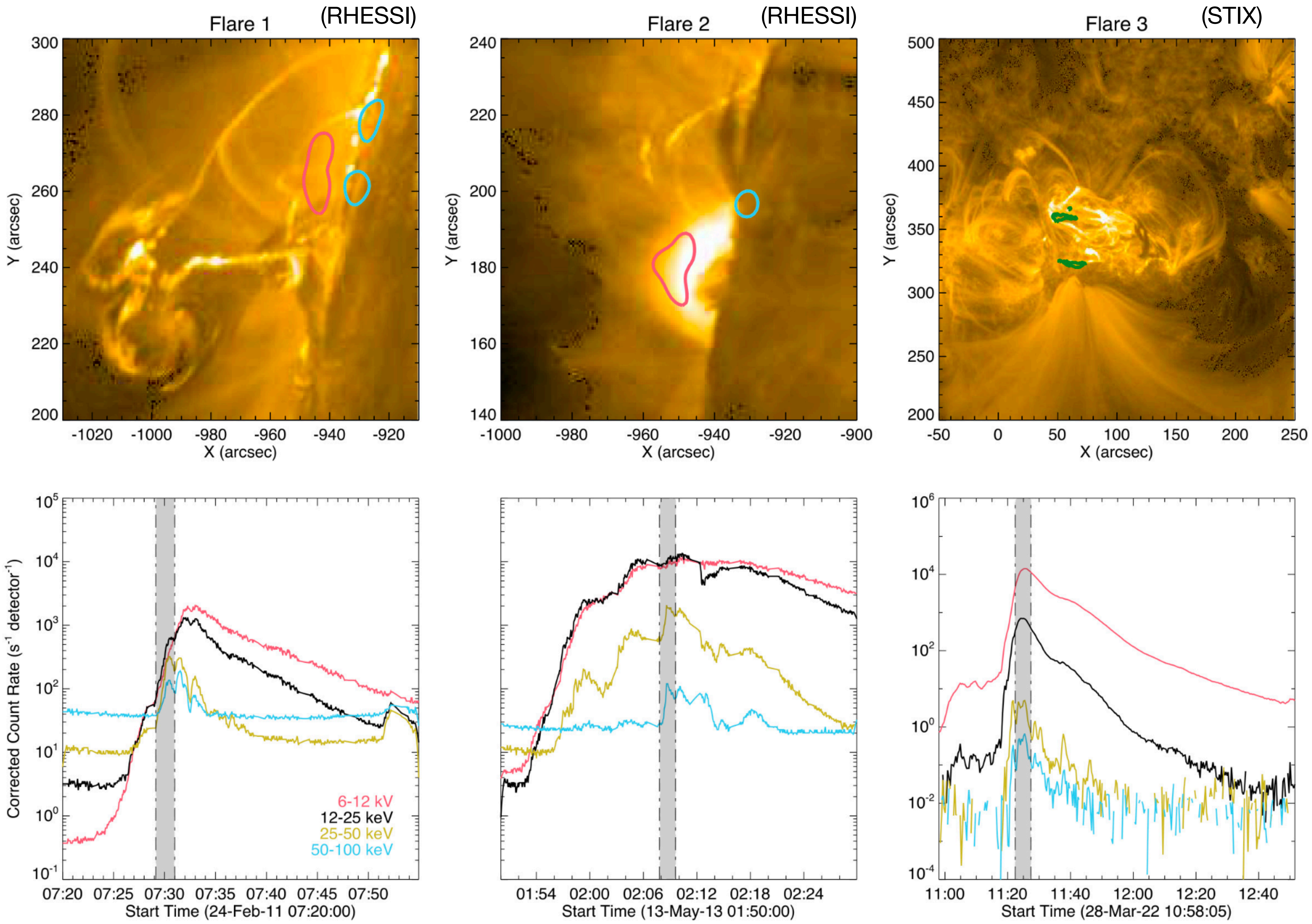
$H(z) =$ Spatial Function

$\sigma =$ Spatial Extent

mstores@umn.edu

X-ray Observations

- Observed by RHESSI or SolO/STIX
- Clear separation between coronal and chromospheric sources
- Found plasma properties and put values into model



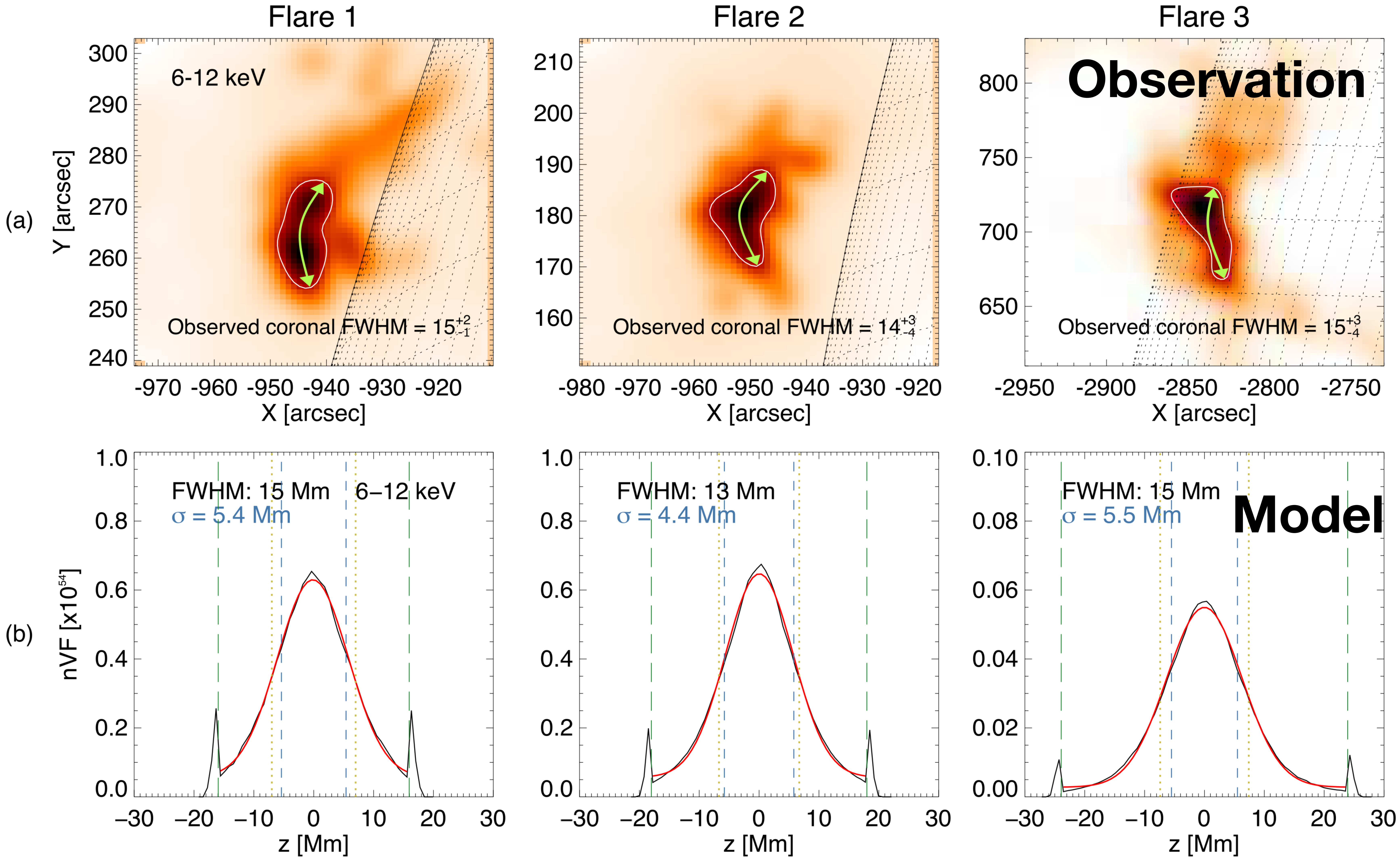
mstores@umn.edu

Constraining the spatial extent of the acceleration region

The spatial extent of the acceleration region can be determined from the coronal source FWHM - Stores (2023)

1. X-ray imaging - coronal source FWHM.
2. Simulation - change spatial extent until coronal source FWHM matches observation.

$$\underline{\sigma \sim 25\,\%\,L}$$



Stores et. al (submitted)

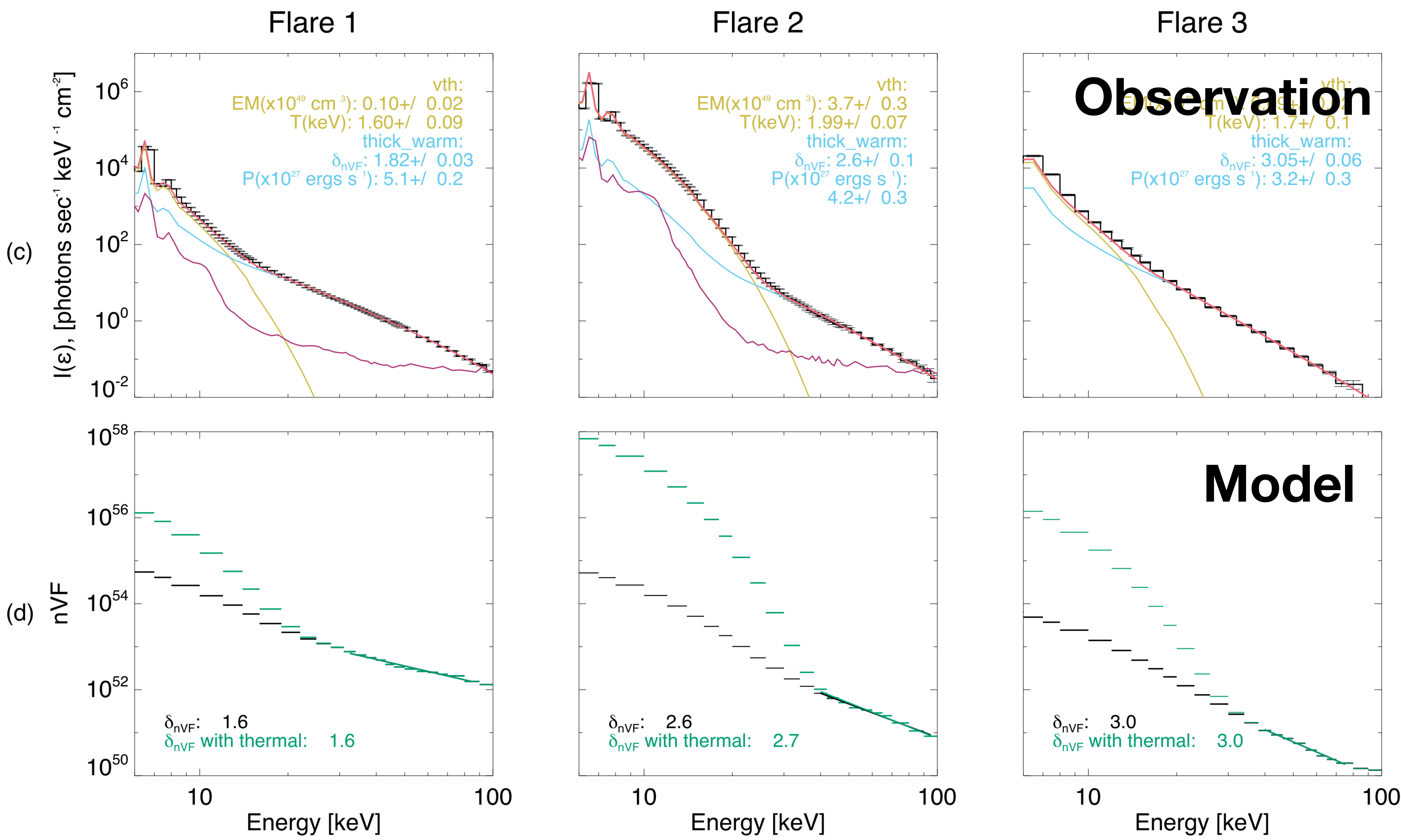
mstores@umn.edu

Constraining the acceleration timescale

The acceleration timescale can be determined from the spectral index. Stores (2023)

1. X-ray spectroscopy - spectral index.
2. Simulation - change acceleration timescale until spectral index matches observation.

$$\tau_{acc} = 7s, 22s, 18.4s$$



mstores@umn.edu

Constraints from X-ray data alone

$$D(v, z) = \frac{v_{\rm th}^2}{\tau_{\rm acc}} \left(\frac{v}{v_{\rm th}} \right)^{\alpha} \times {\rm H}(z),$$

$H(z) =$ Spatial Function

$\tau_{acc} =$ Acceleration timescale

$\sigma =$ Spatial Extent

$\alpha =$ Velocity Dependence

The multiple simulations may produce outputs that match the X-ray observation

	Acceleration Region Properties					Spectral and imaging diagnostics			
	H(z)	Ts	σ [Mm]	α	τ_{acc} [s]	FWHM [Mm]	δ_{nVF}	γ_{FP}	η_{FP}^{Xray}
Flare 1	*l*	No	5.4	3	8.7	14.5	1.9	4.0	11.6
	l	**Yes**	**5.4**	**3**	**7.0**	**14.0**	**1.6**	**3.1**	**6.3**
	r	No	5.4	3	7.8	14.7	1.8	-	48.5
	r	*Yes*	*5.4*	*3*	*9.1*	*13.9*	*1.7*	*2.9*	*5.4*
	g	No	5.4	3	19.5	15.3	1.5	3.0	5.9
	g	*Yes*	*5.4*	*3*	*18.2*	*14.1*	*2.0*	*2.9*	*5.8*

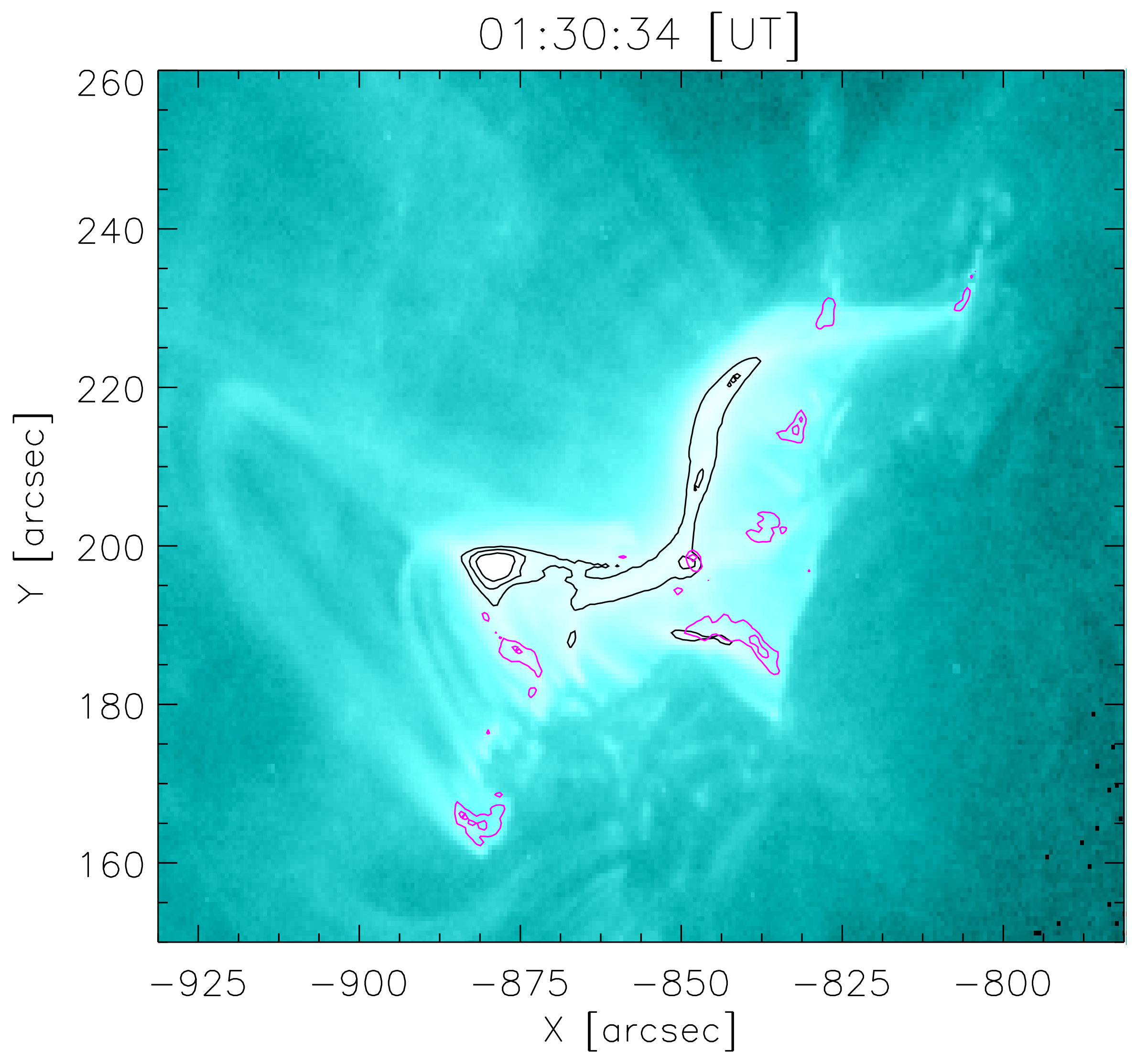
mstores@umn.edu

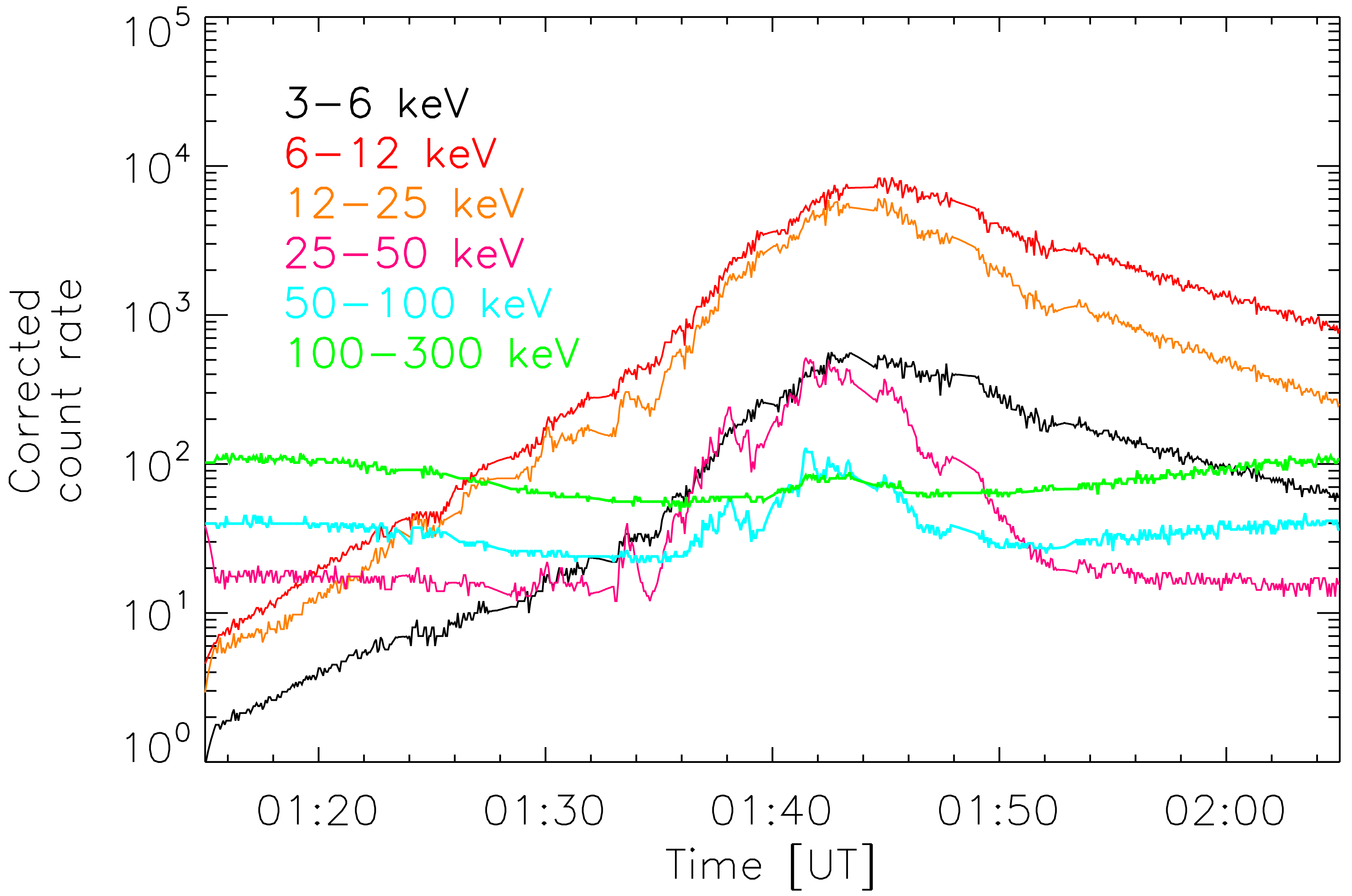
Spatial distribution of Turbulence

- EUV Imaging Spectrometer (EIS) onboard Hinode
- HXR emission, rises and peaks at approximately 01:34:00 UT and 01:42:00 UT respectively.

Table 1 EIS spectral data

Ion	λ(Å)	log *T* (K)
Fe XXIV	255.1136	7.2
Fe XVI	262.9760	6.8
Fe XXIII	263.7657	7.2





5 EIS observation times

Stores et al. (2021)

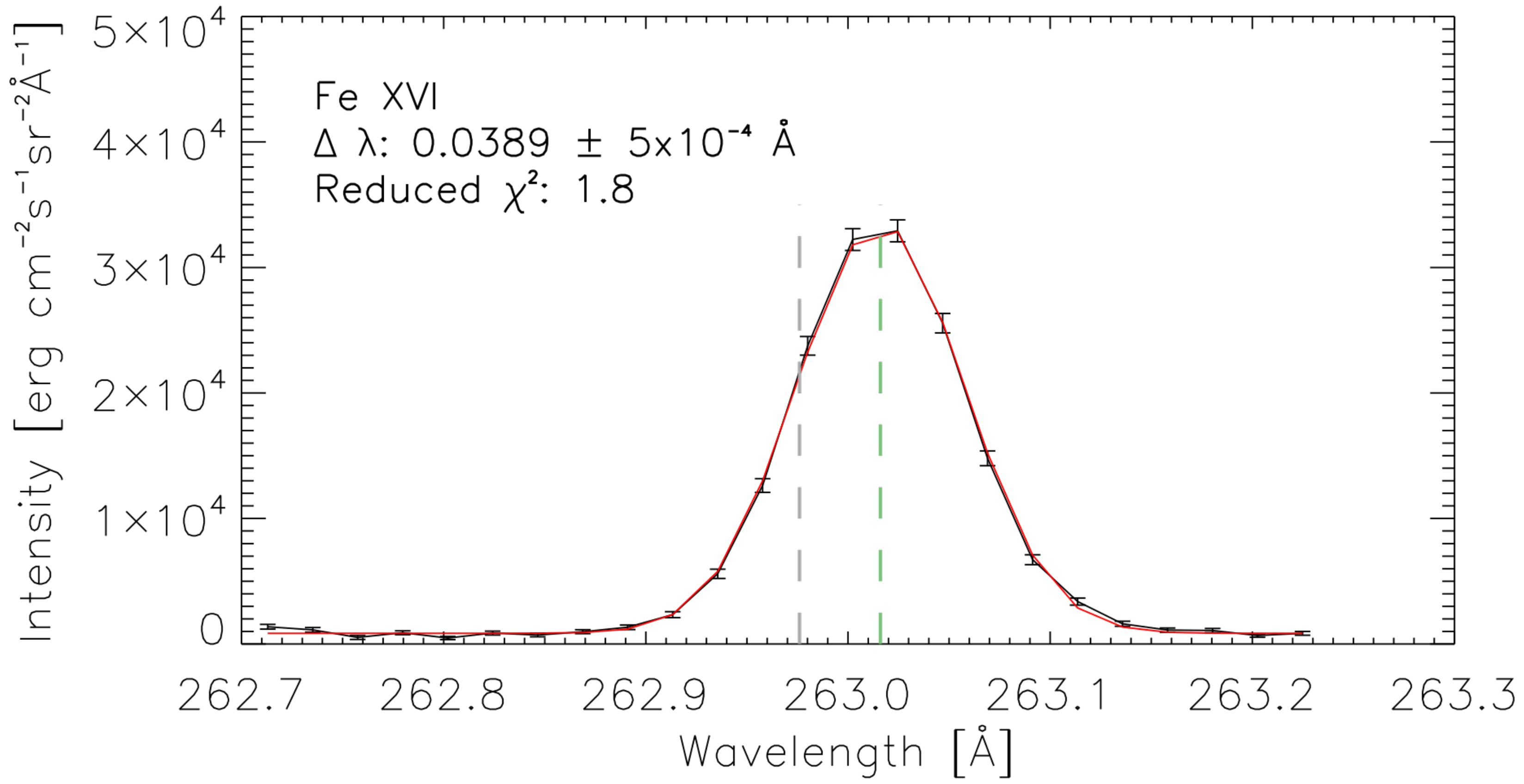
mstores@umn.edu

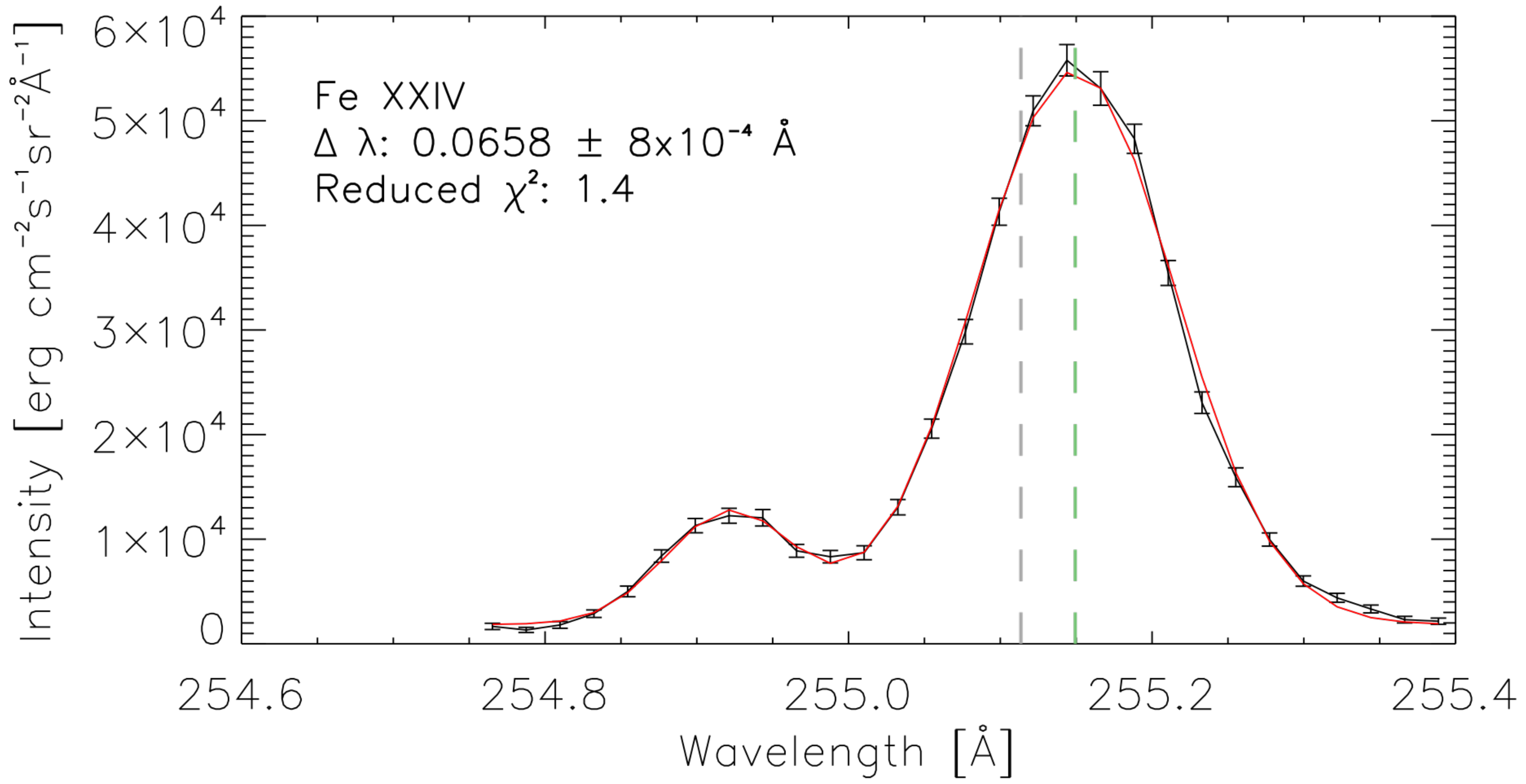
Gaussian Fitting

All studied lines with intensity I(λ) are fitted with the following Gaussian function,

$$I(\lambda) = I_B + I_0 \exp\left(- \frac{(\lambda - \lambda_0)^2}{2\Delta\lambda^2} \right)$$

I_B - Background intensity
I_0 - Peak intensity
λ - wavelength
λ_0 - measured centroid position
$\Delta\lambda$ - line broadening



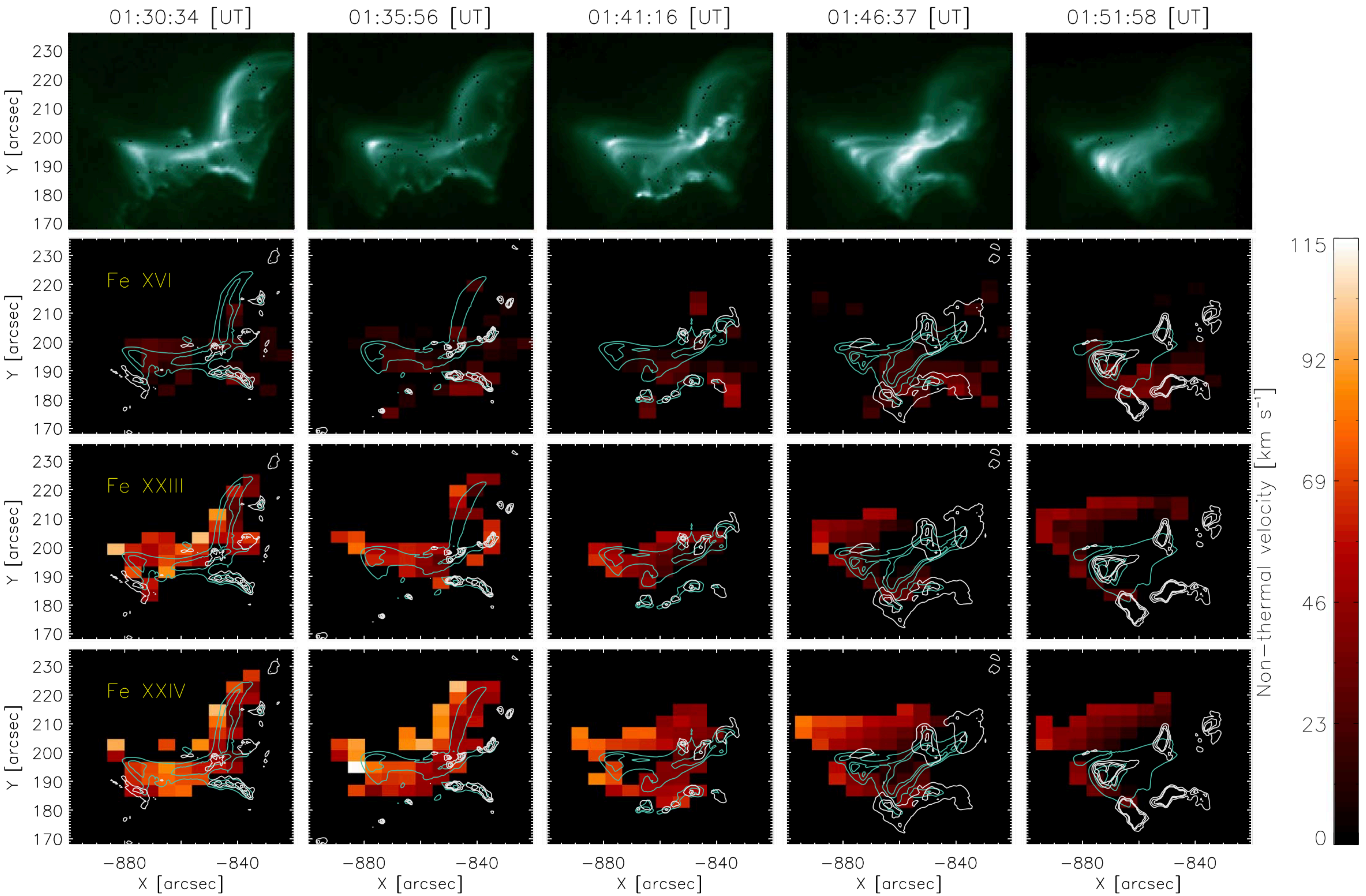


Then to get the non-thermal velocity of the plasma motions:

$$\text{FWHM} = 2\sqrt{2\ln 2}\,\Delta\lambda$$

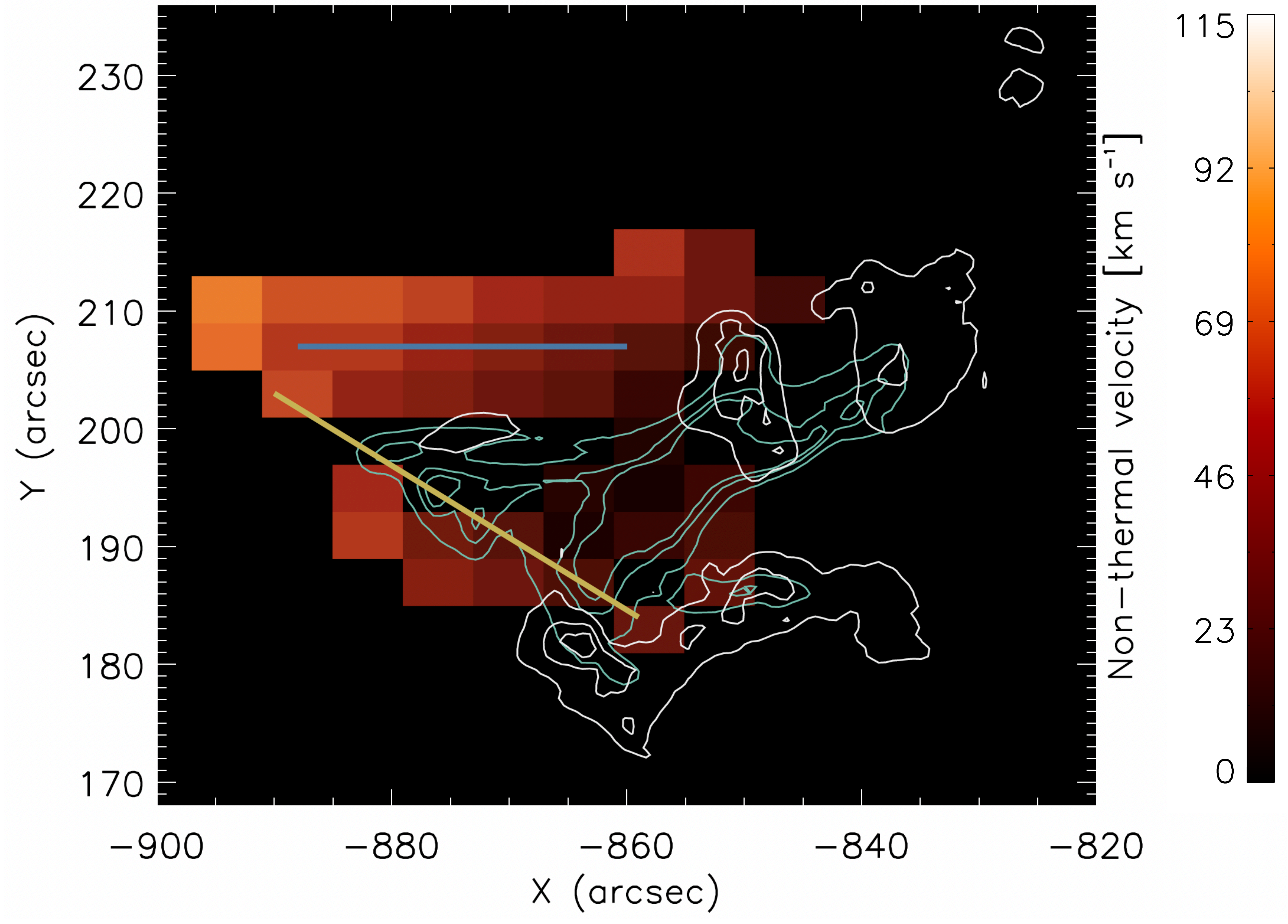
$$\text{FWHM} = \sqrt{4\ln 2 \left(\frac{\lambda_0}{c}\right)^2 \left(\frac{2k_B T_i}{m} + v_{nth}^2\right) + \text{FWHM}_I^2}$$

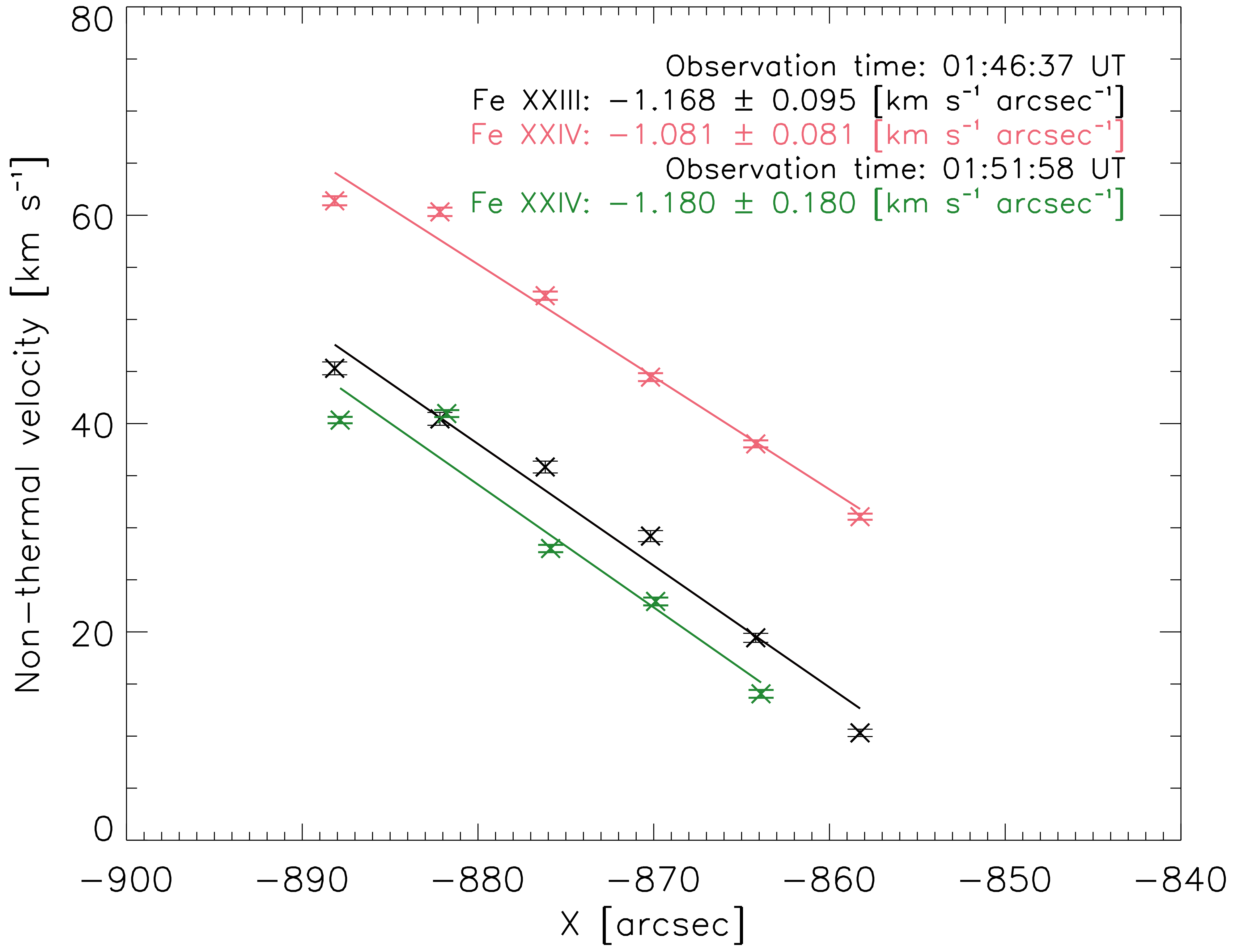
mstores@umn.edu



mstores@umn.edu

Spatial Distribution of Turbulence



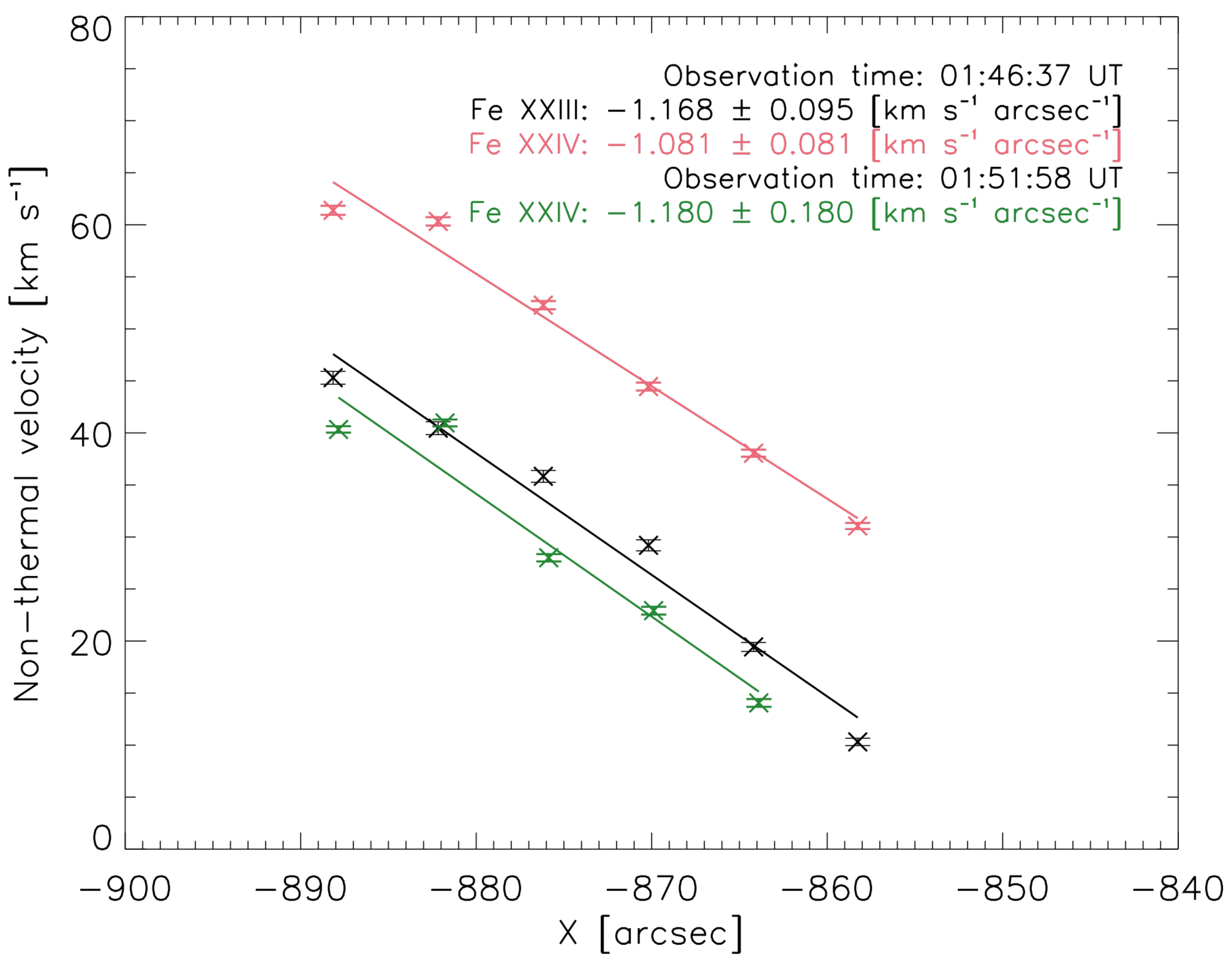


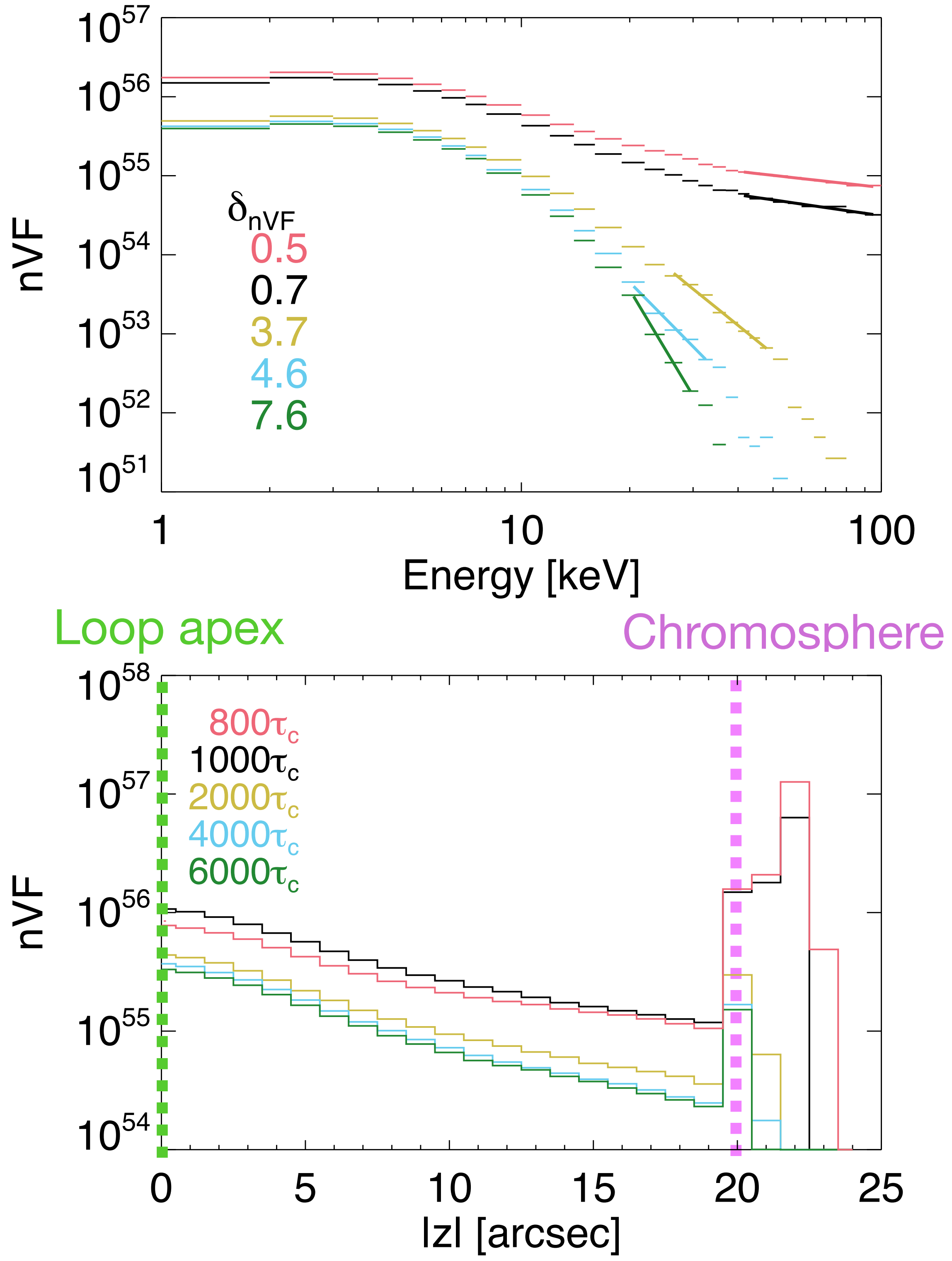
- At 01:51:58 UT, v_{nth} for Fe XXIV is ~20-25 kms^{-1} lower than at 01:46:67 UT
- The decrease in v_{nth} is approximately linear

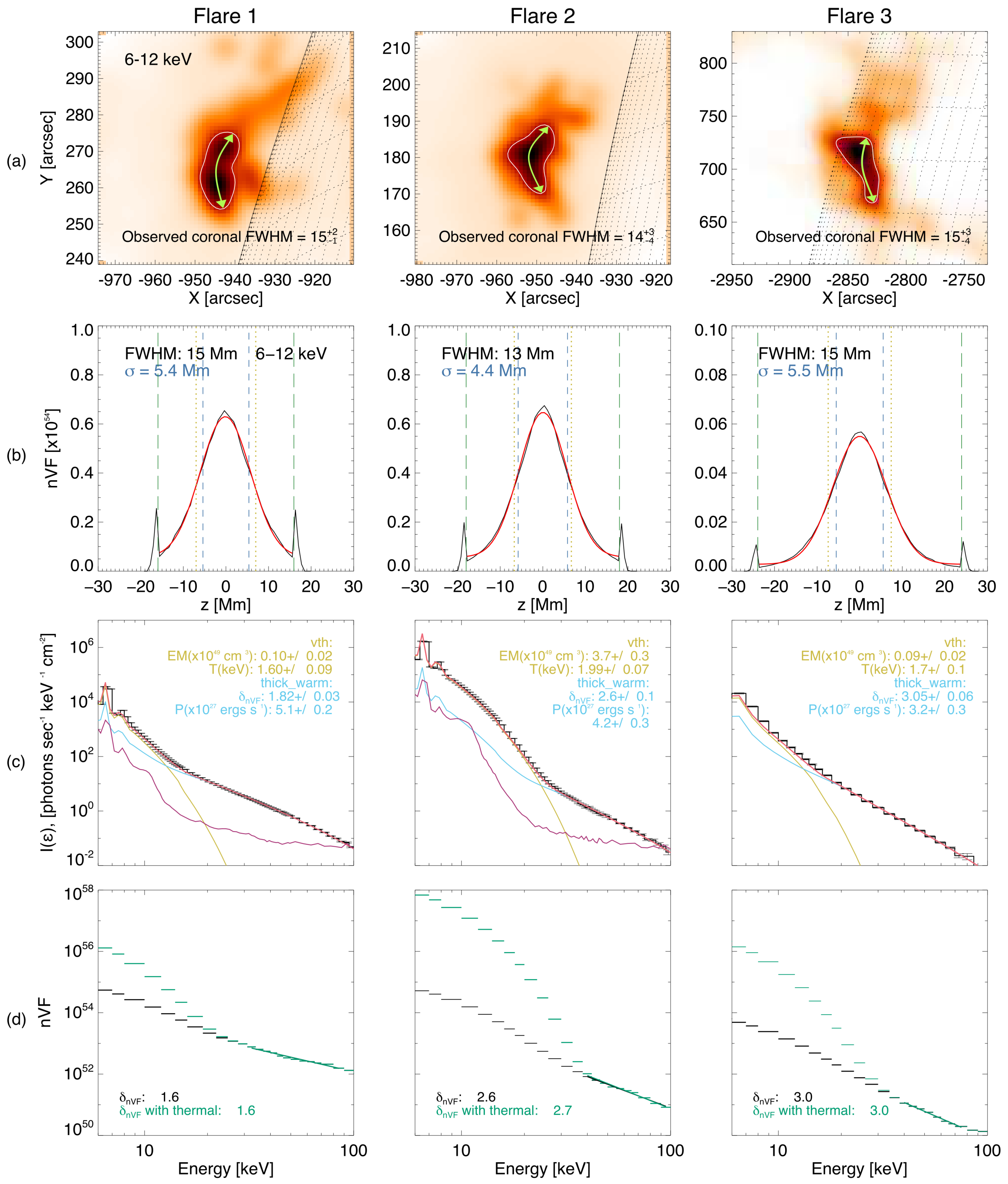
mstores@umn.edu

Conclusion

Using a combination of observations and modelling, we begin to determine how a spatially varying distribution of turbulence, in an extended acceleration region in the corona, determines the properties of flare-accelerated electrons and our determination of these properties.







Suggestions welcome:

A large (X or M class) off limb flare observed by Hinode and RHESSI or Solar Orbiter/STIX?

mstores@umn.edu