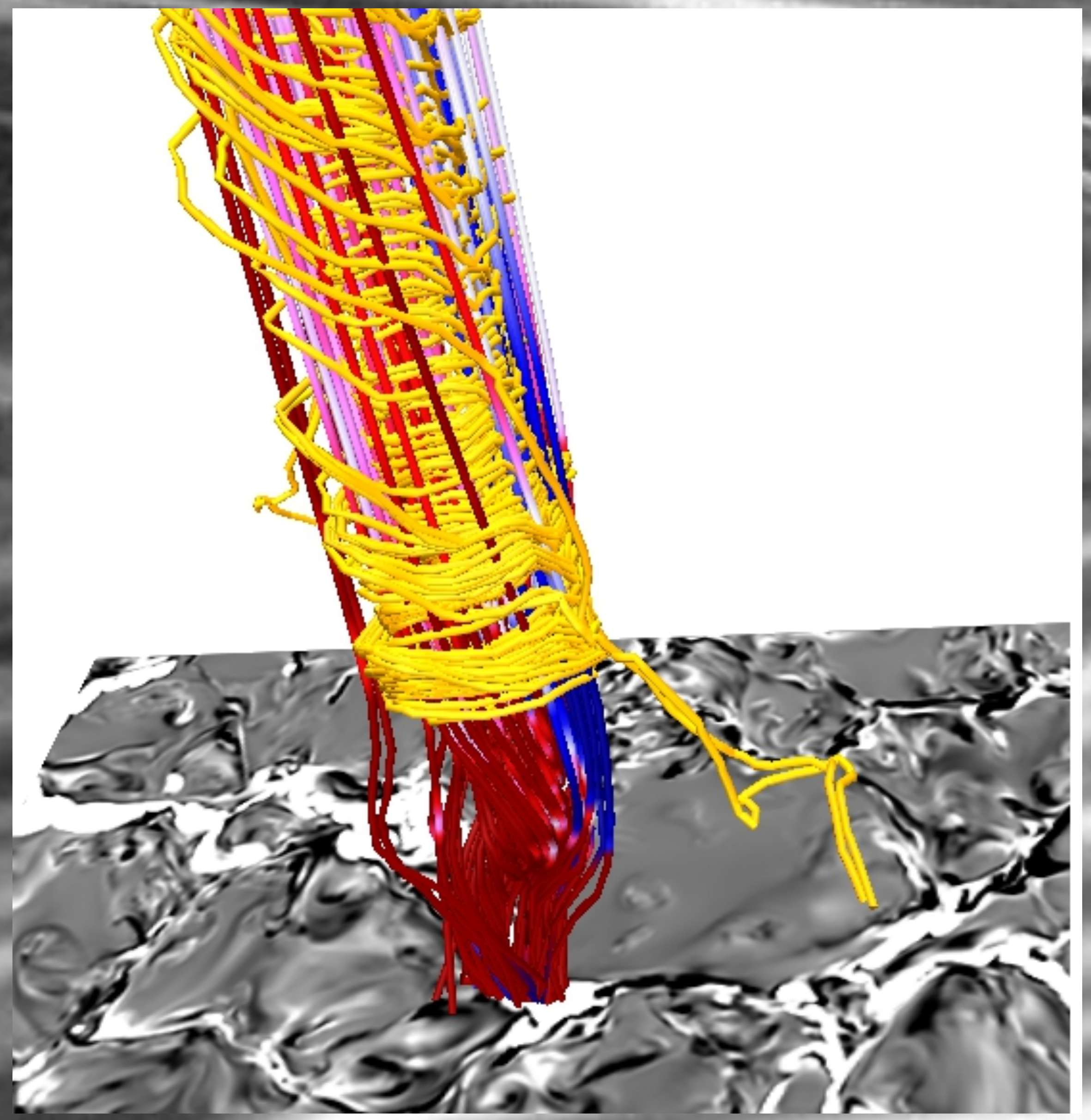
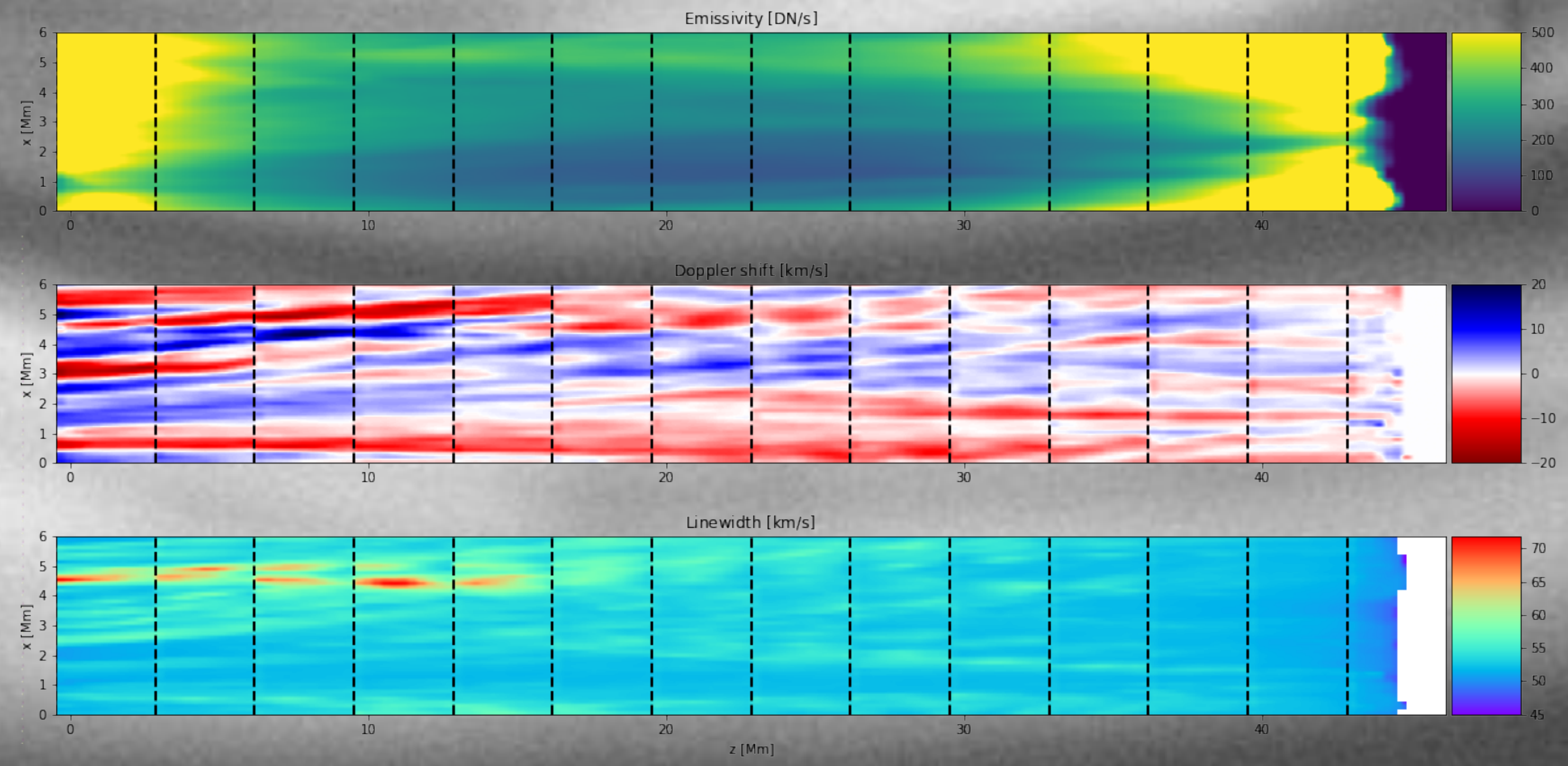
Cosima Breu
NASA Goddard, 03/08/2023



Broadening of coronal lines in a 3D MHD loop model

Raster Scan



University of
St Andrews

Motivation

"We see how we may determine their [the star's] forms, their distances, their bulk, their motions, but we can never know anything of their chemical or mineralogical structure."

Auguste Comte (1798-1857)

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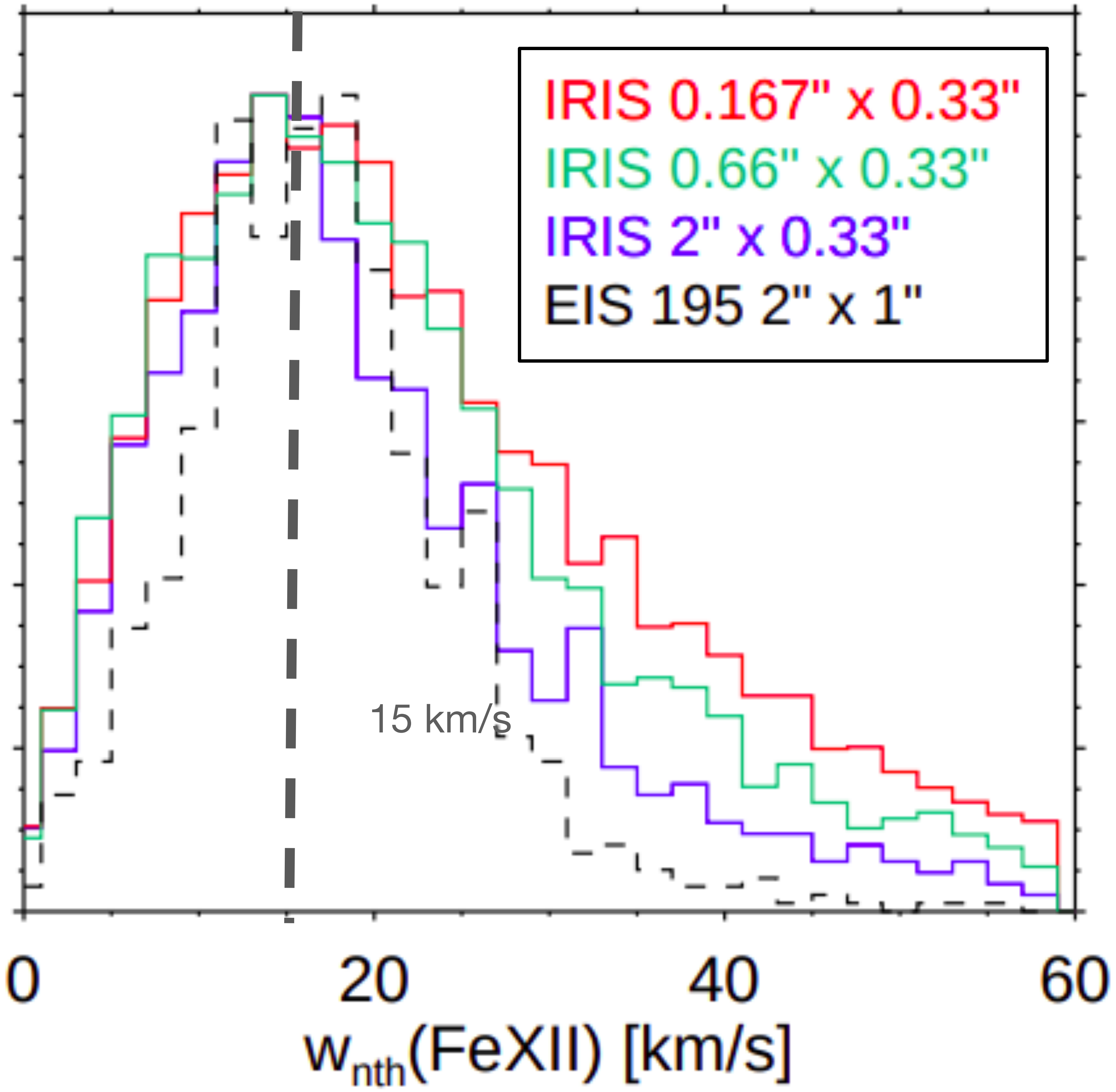
Auguste Comte (1798-1857)

- Unresolved motions at subsonic speeds within spatial resolution element of the instrument and along line-of-sight -> Non-thermal line broadening
- Candidates: Turbulence, quasi-periodic upflows, shocks, Waves
- Typical observed non-thermal broadening at temperatures above 1 MK: 15-20 km/s
- Approximately independent of instrument resolution
- Underestimated in most numerical simulations (except e.g. Pontin et al. 2020)
- Do simulations reproduce observed spectra?

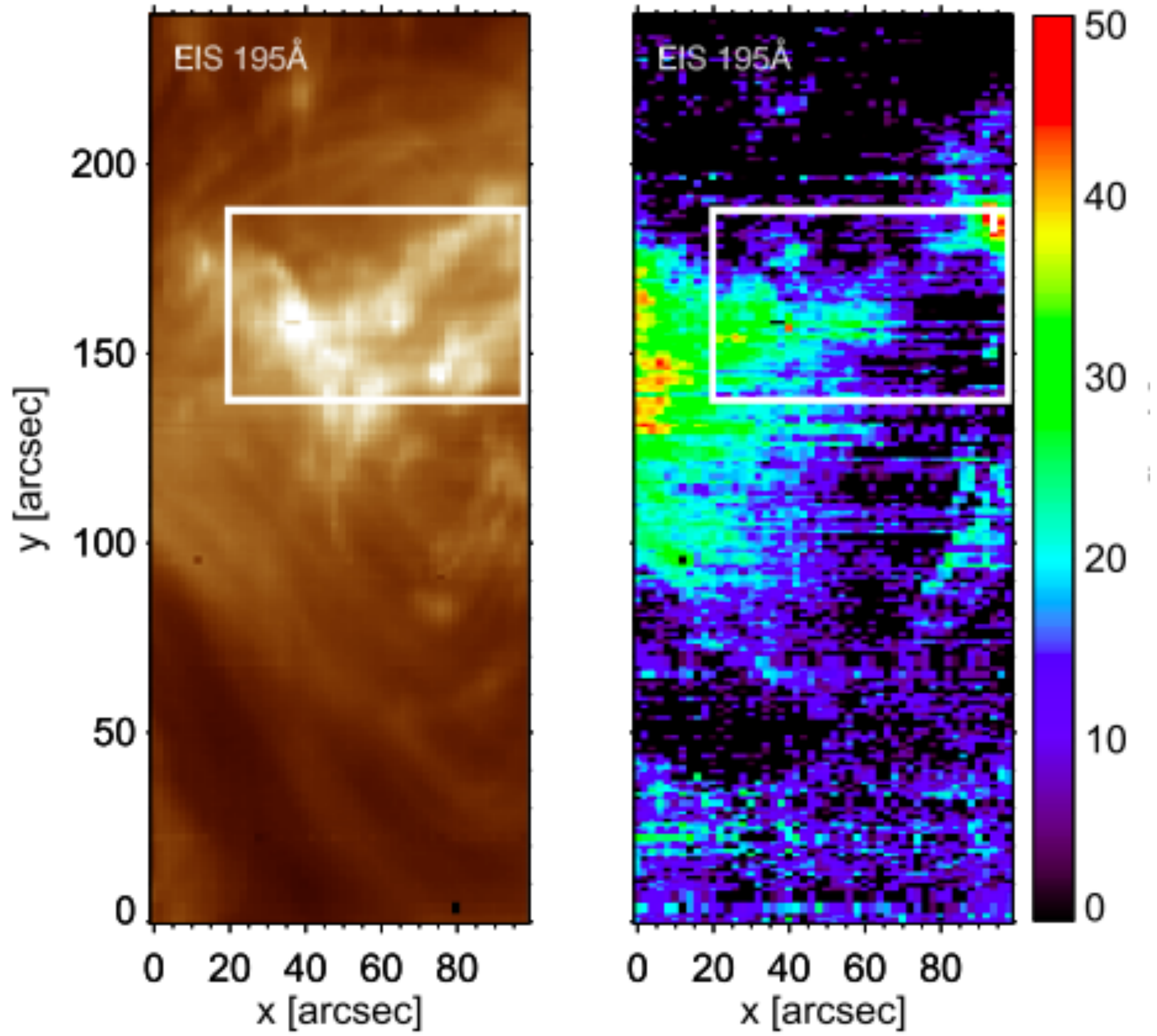
Observed nonthermal line widths

Observation of an active region



Testa et al. 2016

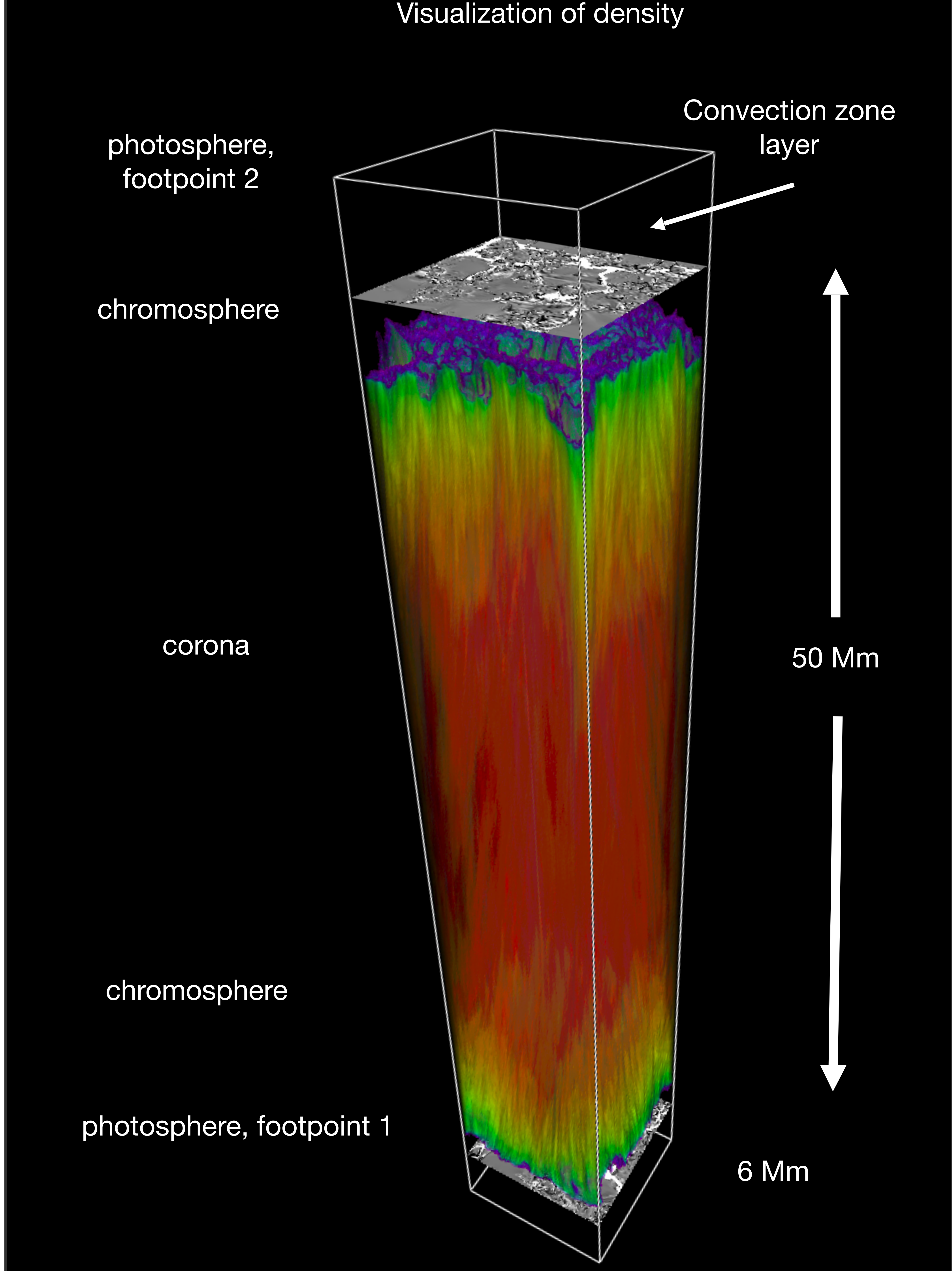
- Typical observed nonthermal linewidths: 15-30 km/s



Numerical Setup

Straightened loop model including magnetoconvection at the footpoints at the photosphere and below (and gravitational stratification)

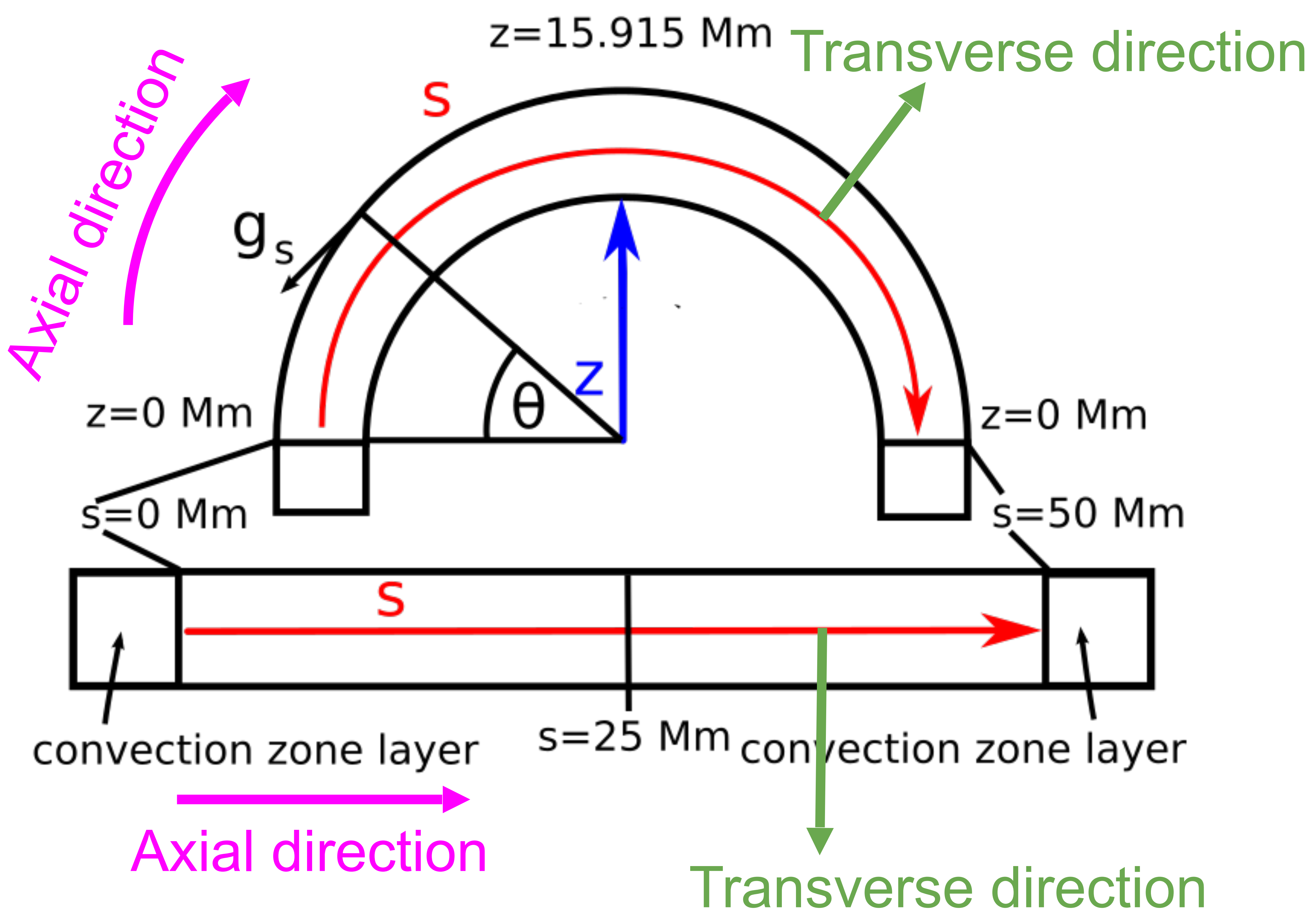
3D resistive MHD simulation
MURaM code (Voegler 2005, Rempel 2014, Rempel 2017)
Computational box: 6x6x57 Mm (grid:500x500x5000)
High resolution: Δx=Δy=60-12 km



The loop model

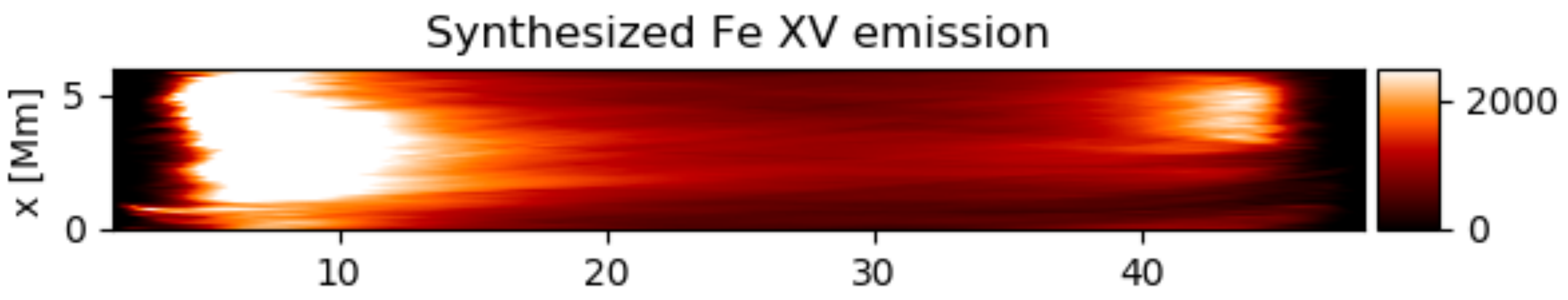
- Gravitational stratification
- Spitzer heat conduction parallel to the magnetic field
- Optically thick radiative losses in the photosphere and chromosphere
- Optically thin radiative losses in the corona

Model described in Breu et al. 2022



Nonthermal linewidths

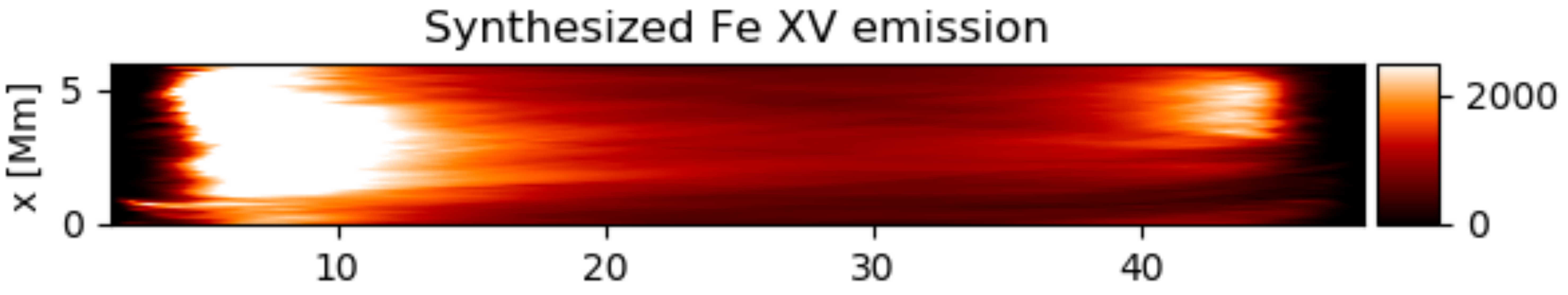
Fe XV 284 Å



- Compute emissivity at each gridpoint (assuming ionization eq.)

Nonthermal linewidths

Fe XV 284 Å



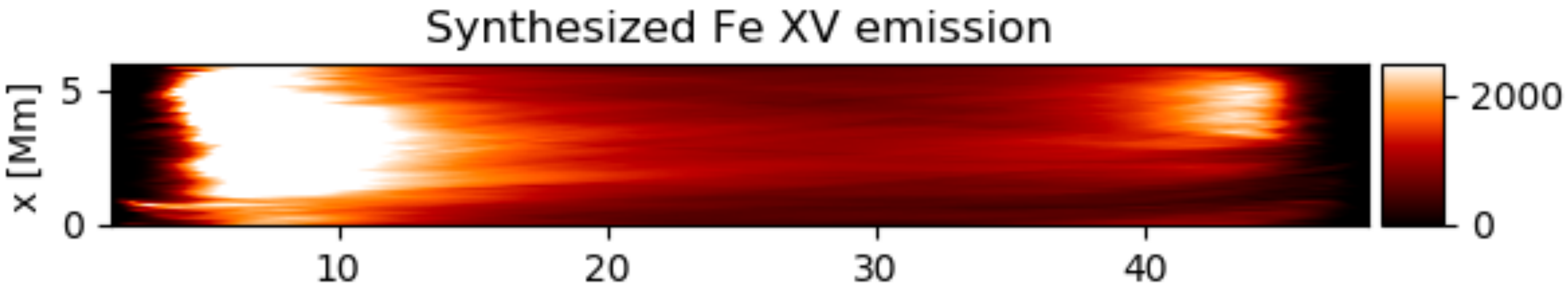
- Compute emissivity at each gridpoint (assuming ionization eq.)

- Reproduce stranded loop appearance

Nonthermal linewidths

- Compute emissivity at each gridpoint (assuming ionization eq.)
- At each gridpoint: Gaussian profile (width given by thermal width) shifted according to LOS velocity
- Integrate along LOS

Fe XV 284 Å



Nonthermal linewidths

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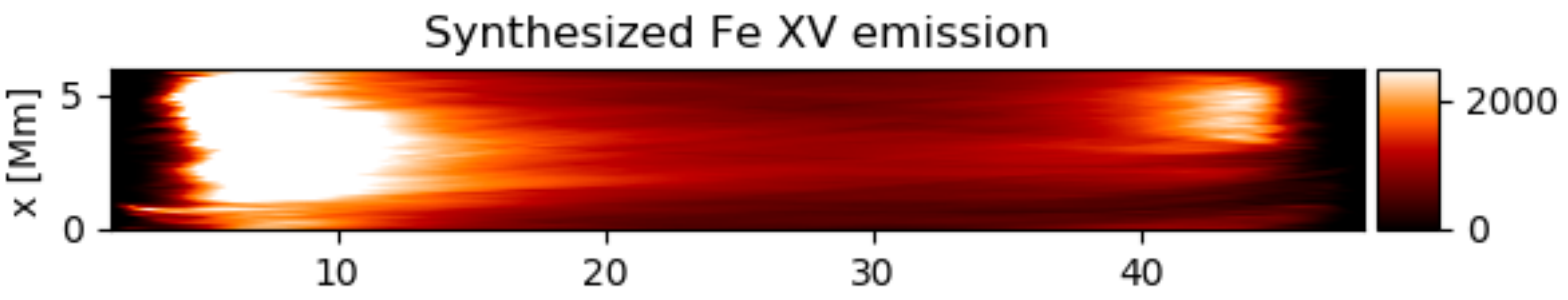

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$$I(v) = \frac{\varepsilon}{\sqrt{\pi}\, w_{\mathrm{th}}} \exp\left(-\frac{(v - v_0)^2}{{w_{\mathrm{th}}}^2}\right)$$

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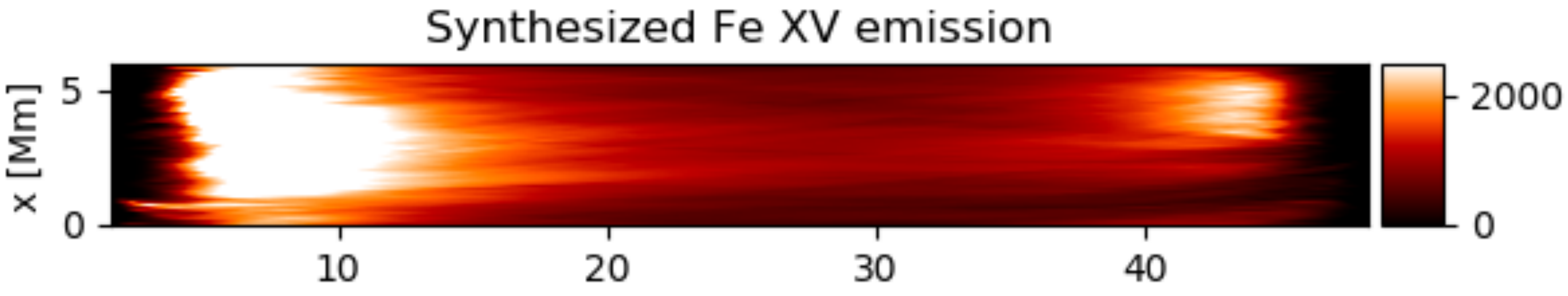

$$I(v) = \frac{\varepsilon}{\sqrt{\pi}\, w_{\text{th}}} \exp\left(-\frac{(v - v_0)^2}{\text{w}_{\text{th}}{}^2}\right)$$

$$I_v^{\text{synth}} = \int_{\text{line of sight}} I_v \, dl$$

Nonthermal linewidths

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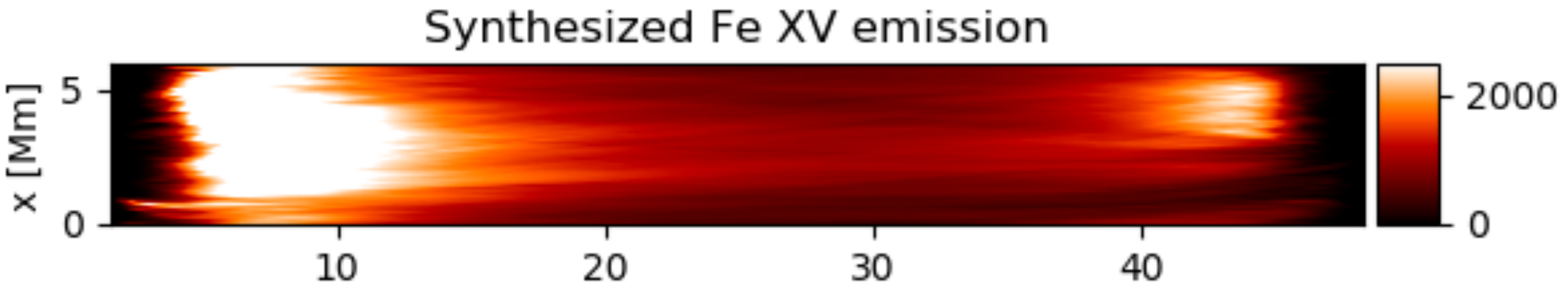


$$I^{\text{synth}} = \int I_\nu^{\text{synth}} dv,$$

$$v^{\text{synth}} = \frac{1}{I^{\text{synth}}} \int v I_\nu^{\text{synth}} dv,$$

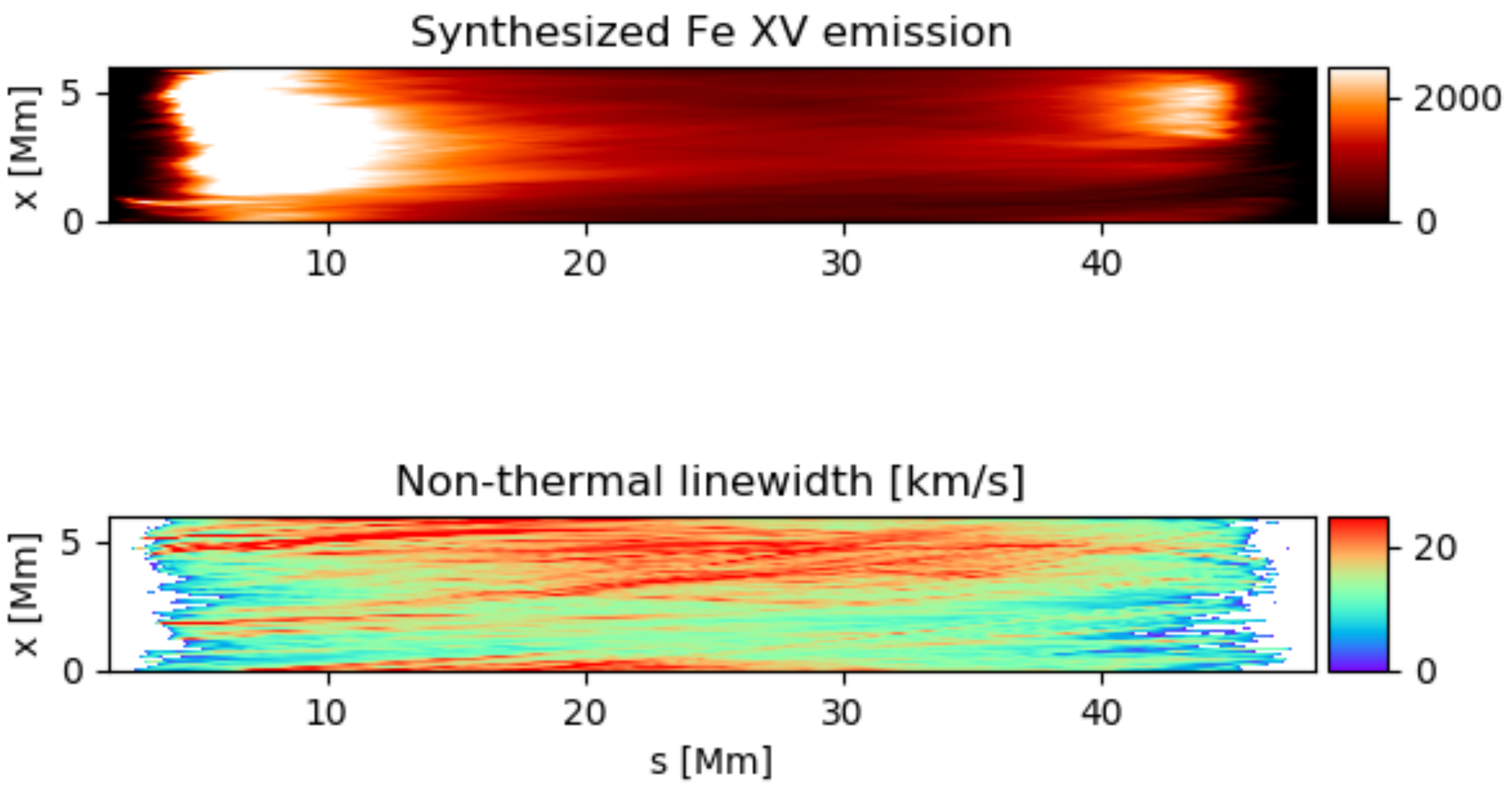
$$w^{\text{synth}} = \left(\frac{2 \int (v - v^{\text{Synth}})^2 I_\nu^{\text{synth}} dv}{I^{\text{synth}}} \right)^{1/2}$$

Nonthermal linewidths

- Compute second moment of the line profile
- Compute non-thermal linewidth assuming the plasma is at line formation temperature

$$w_{\text{int}}^{\text{synth}} = \left(w_{\text{synth}}^{2} - \frac{2k_{\text{B}}T_{\text{line}}}{m_i} \right)^{1/2}$$

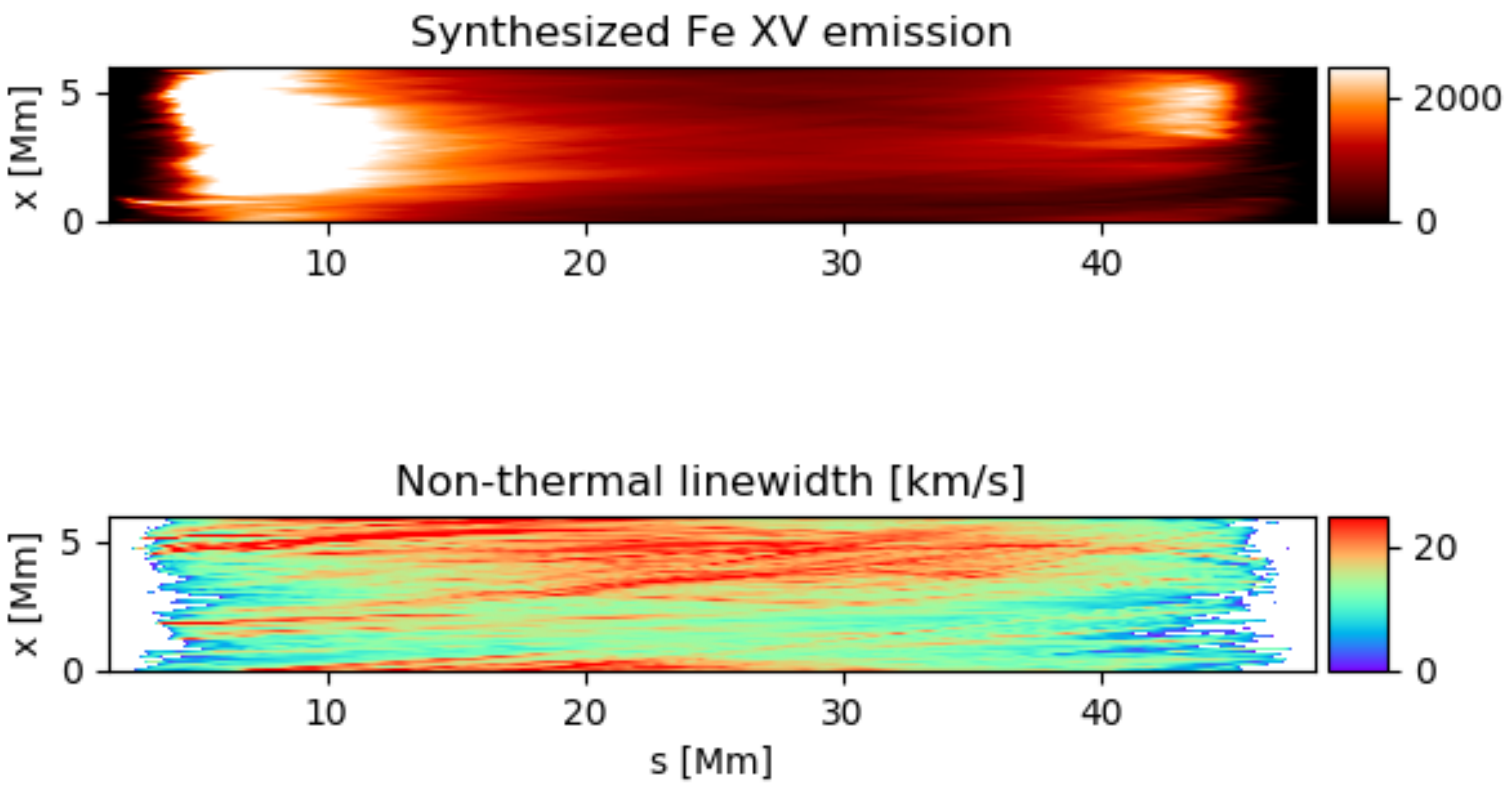
Fe XV 284 Å



Nonthermal linewidths

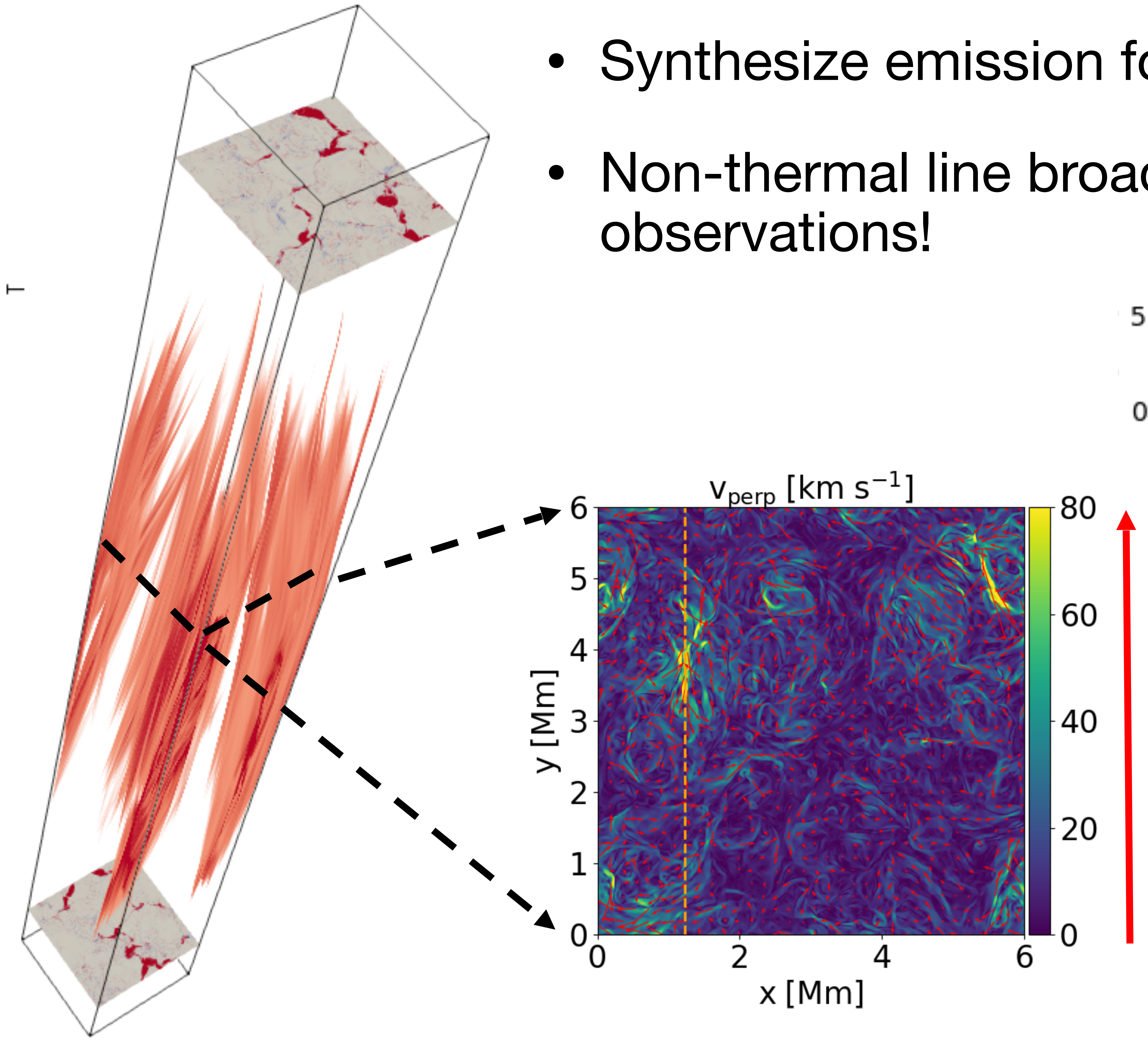
- Compute second moment of the line profile
- Compute non-thermal linewidth assuming the plasma is at line formation temperature
- Fine structure in nonthermal linewidth

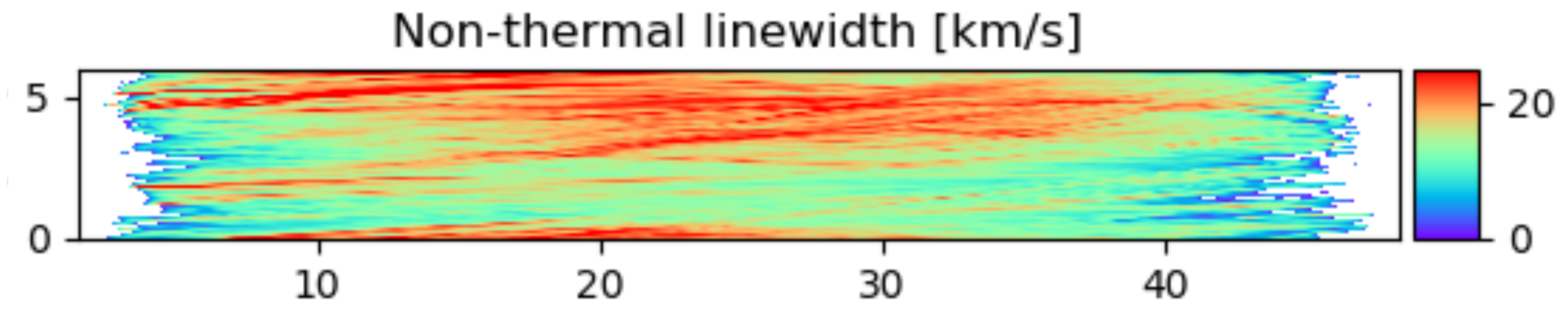
Fe XV 284 Å



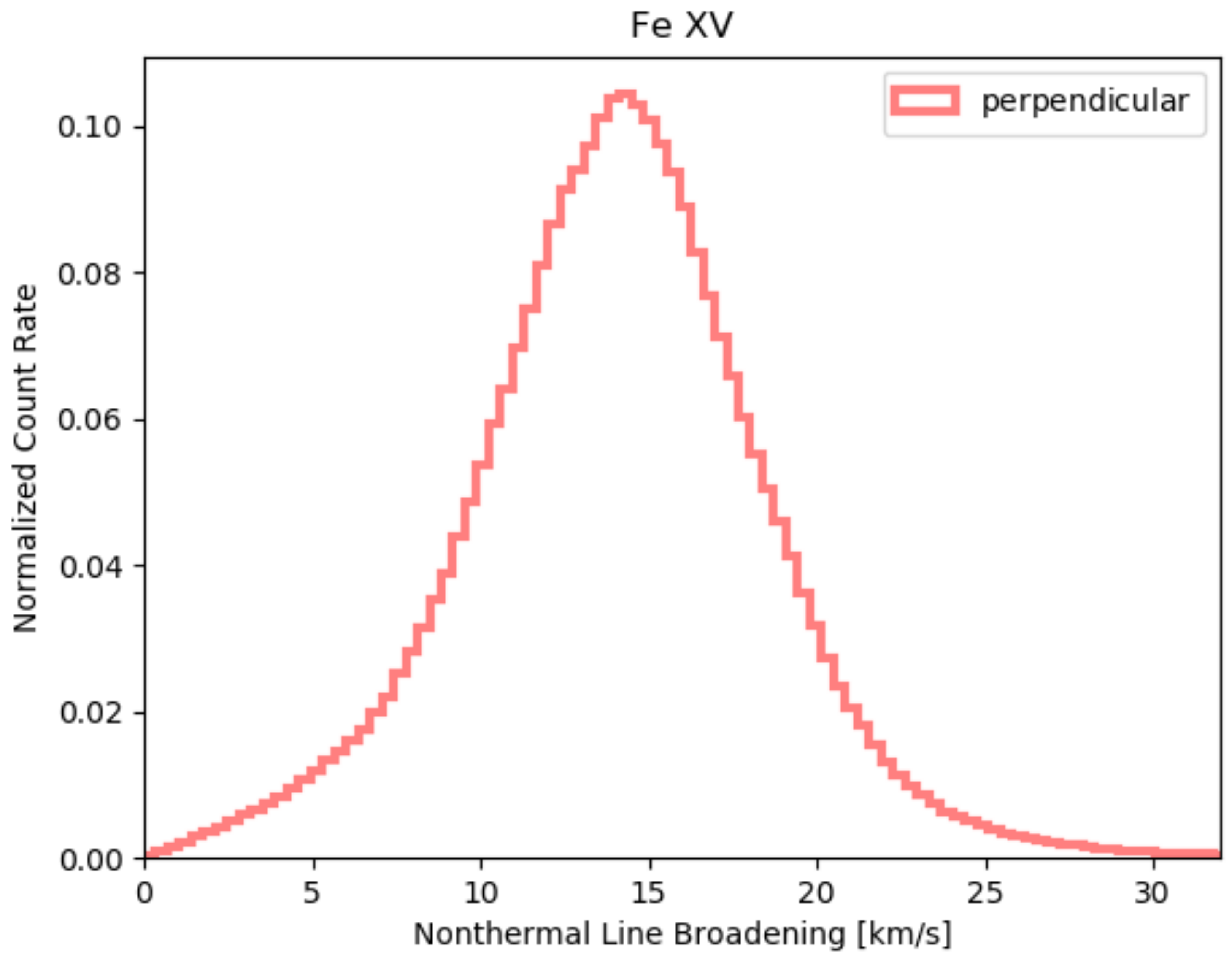
Nonthermal linewidths

- Synthesize emission for Fe XV (~2 MK)
- Non-thermal line broadening of up to 30 km/s consistent with observations!

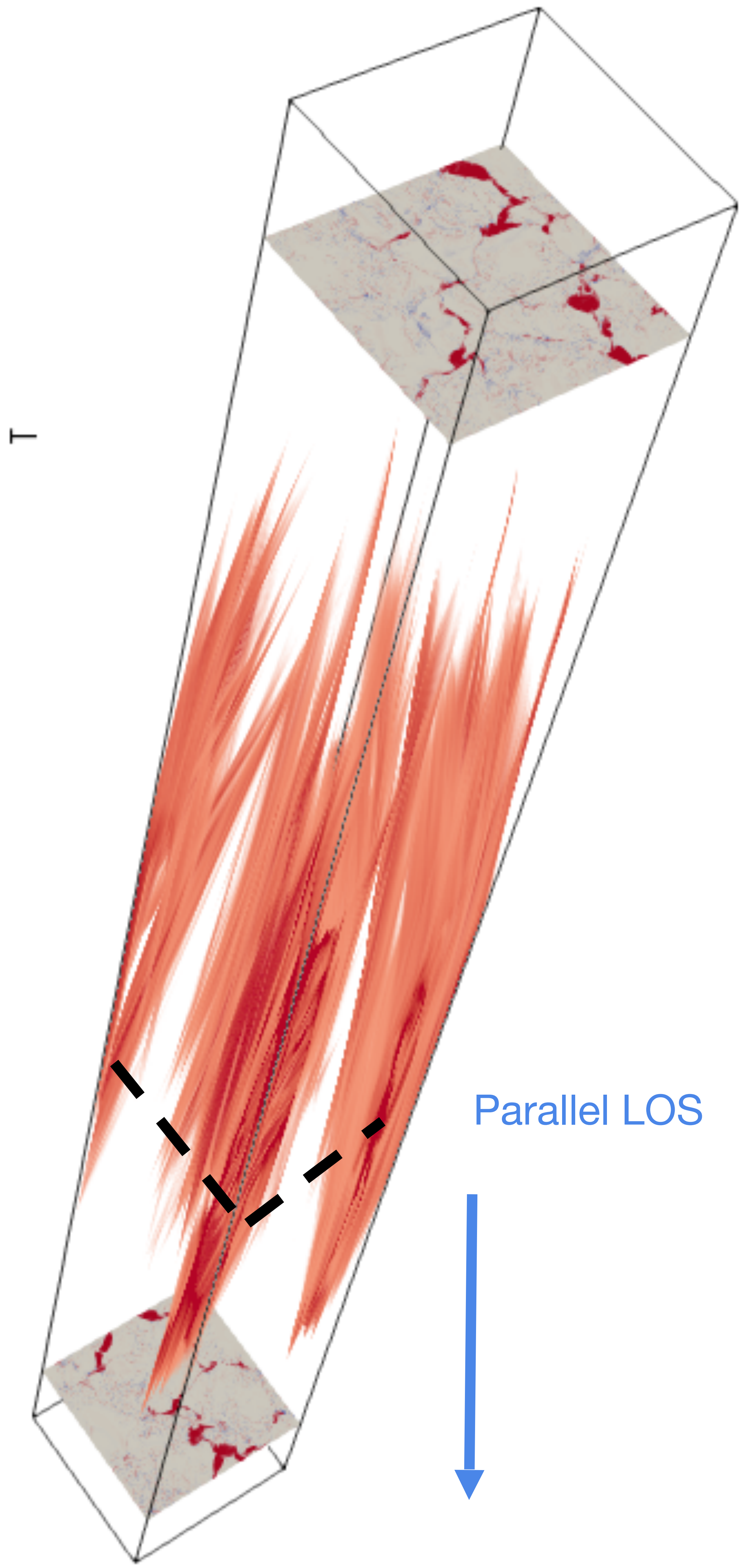




Perpendicular LOS



Nonthermal linewidths



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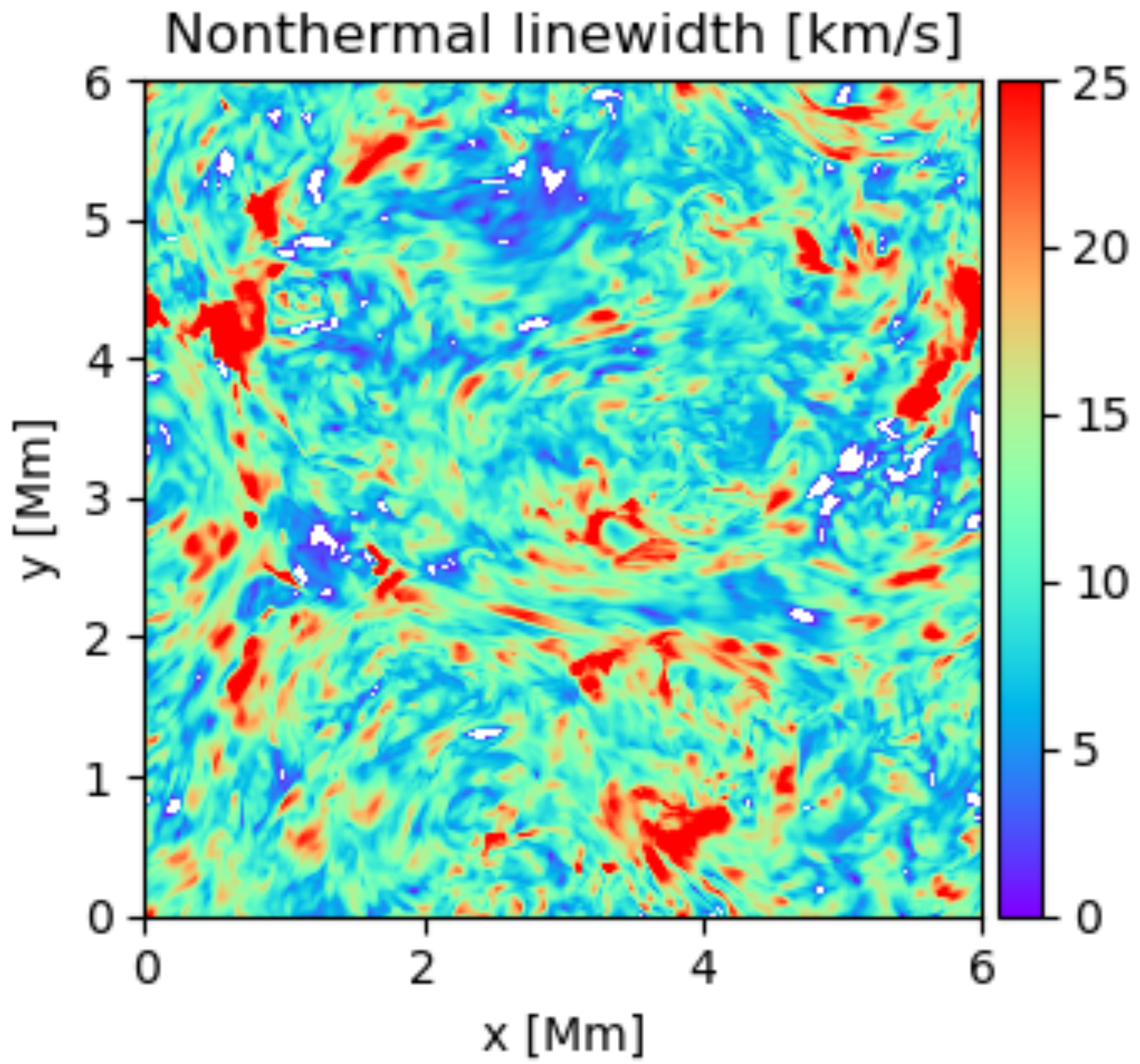
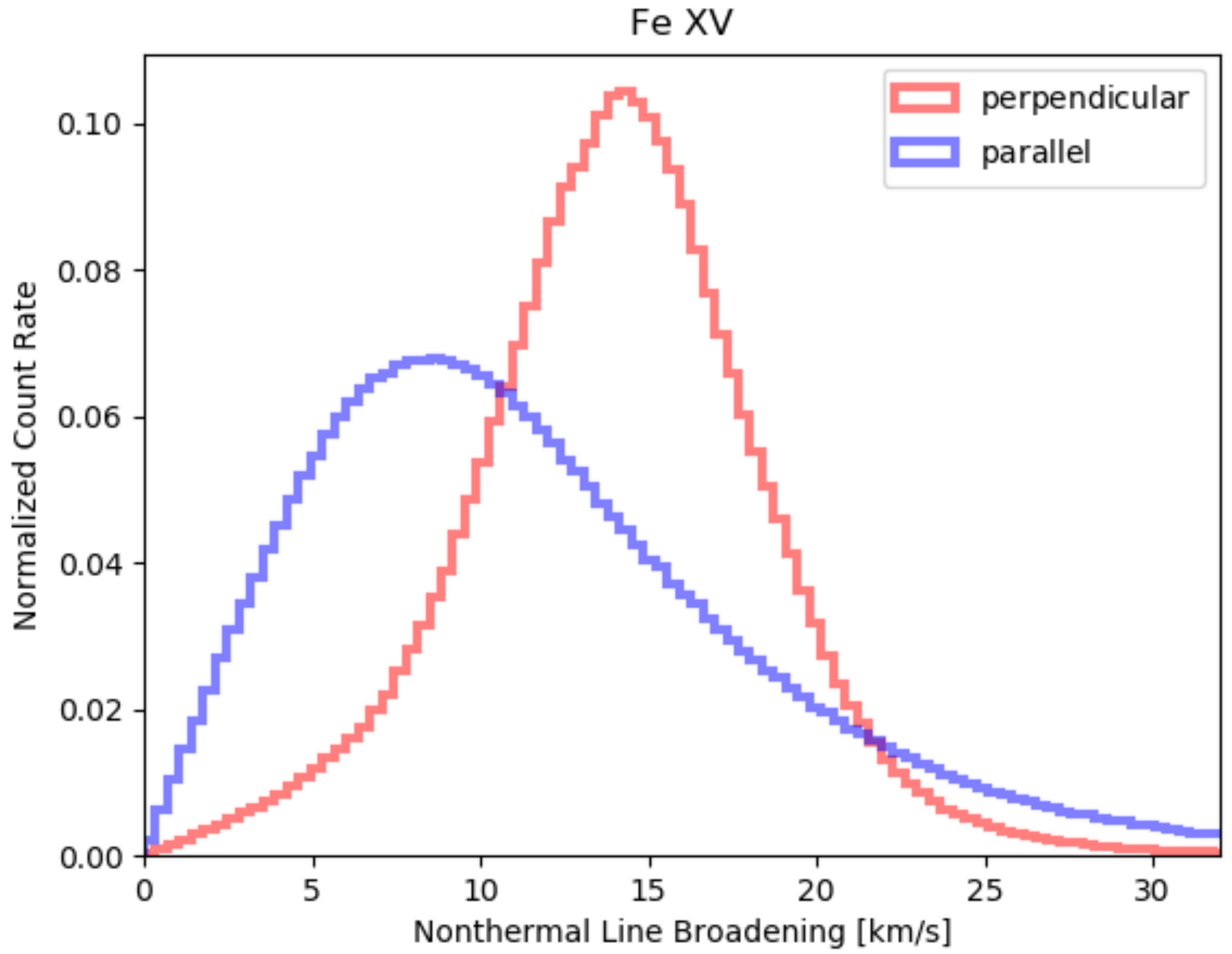
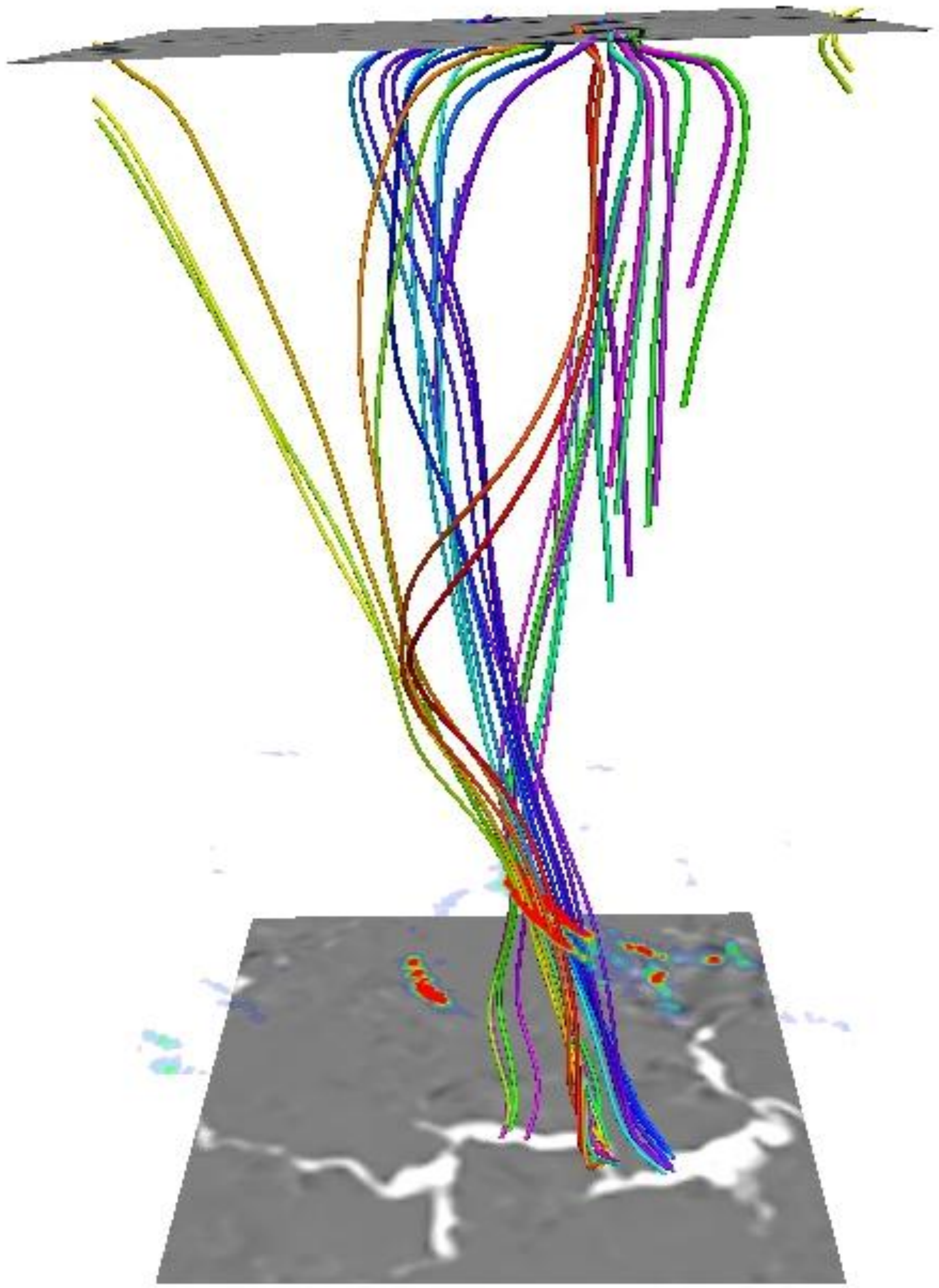
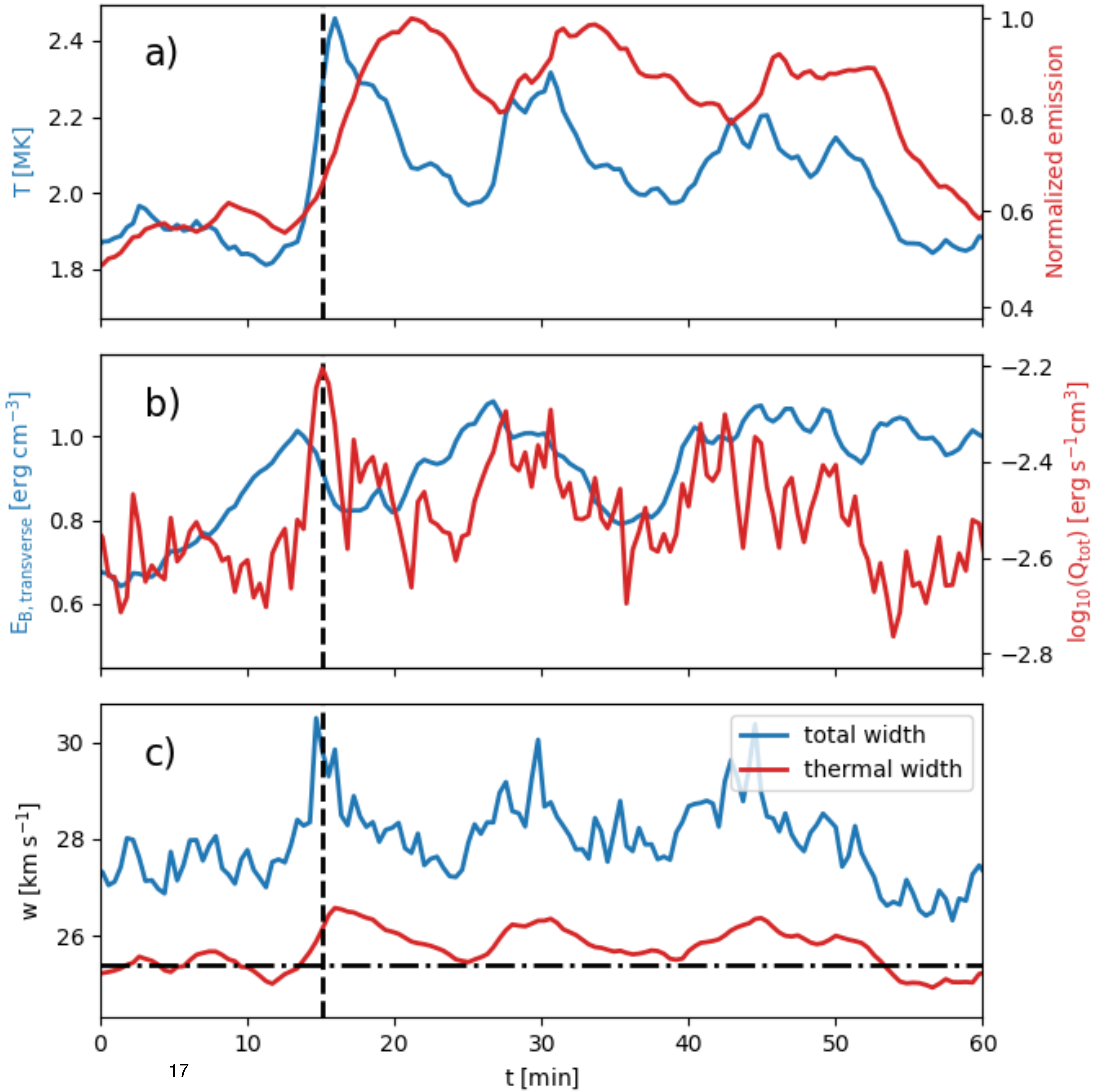


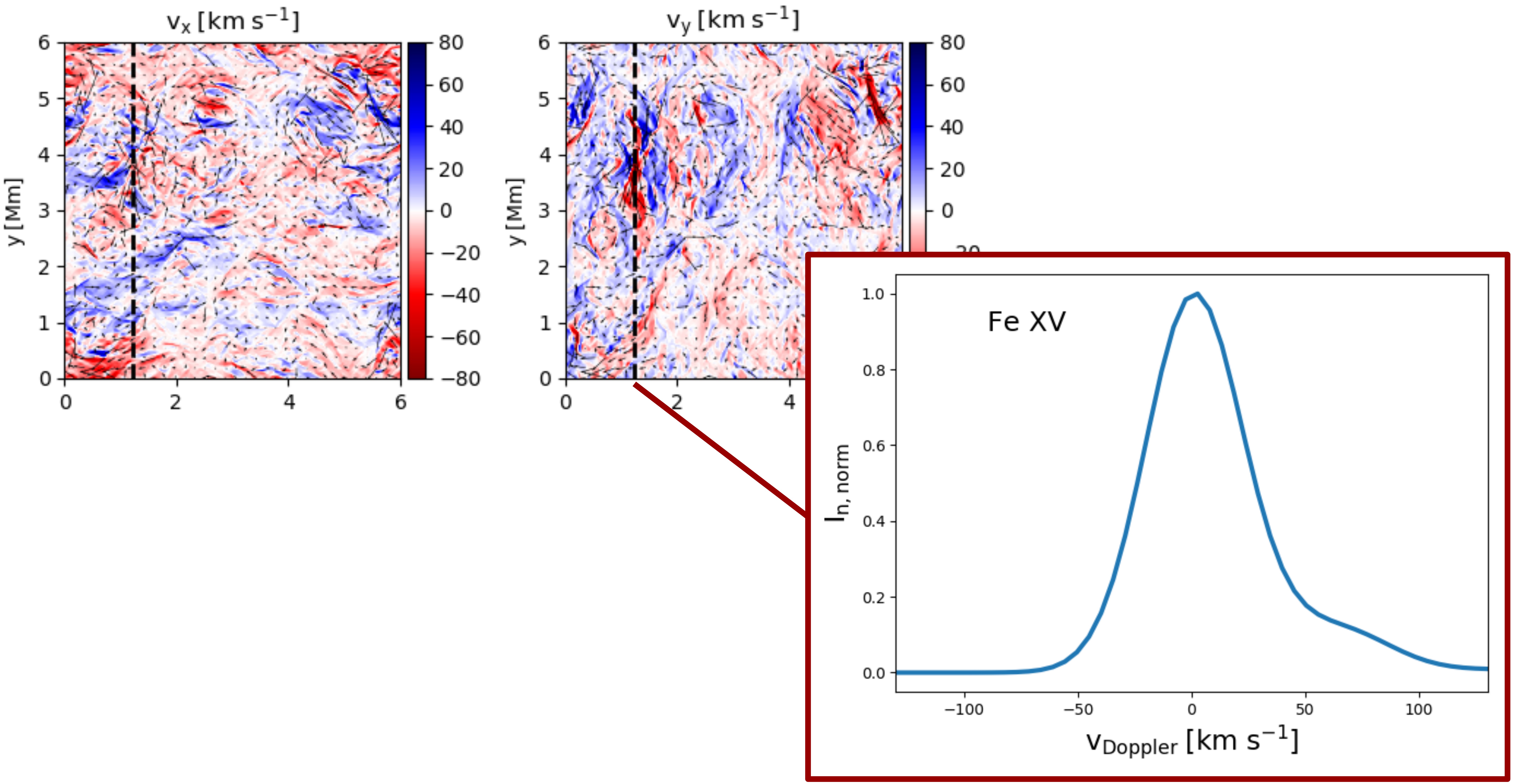


From heating to increased line width

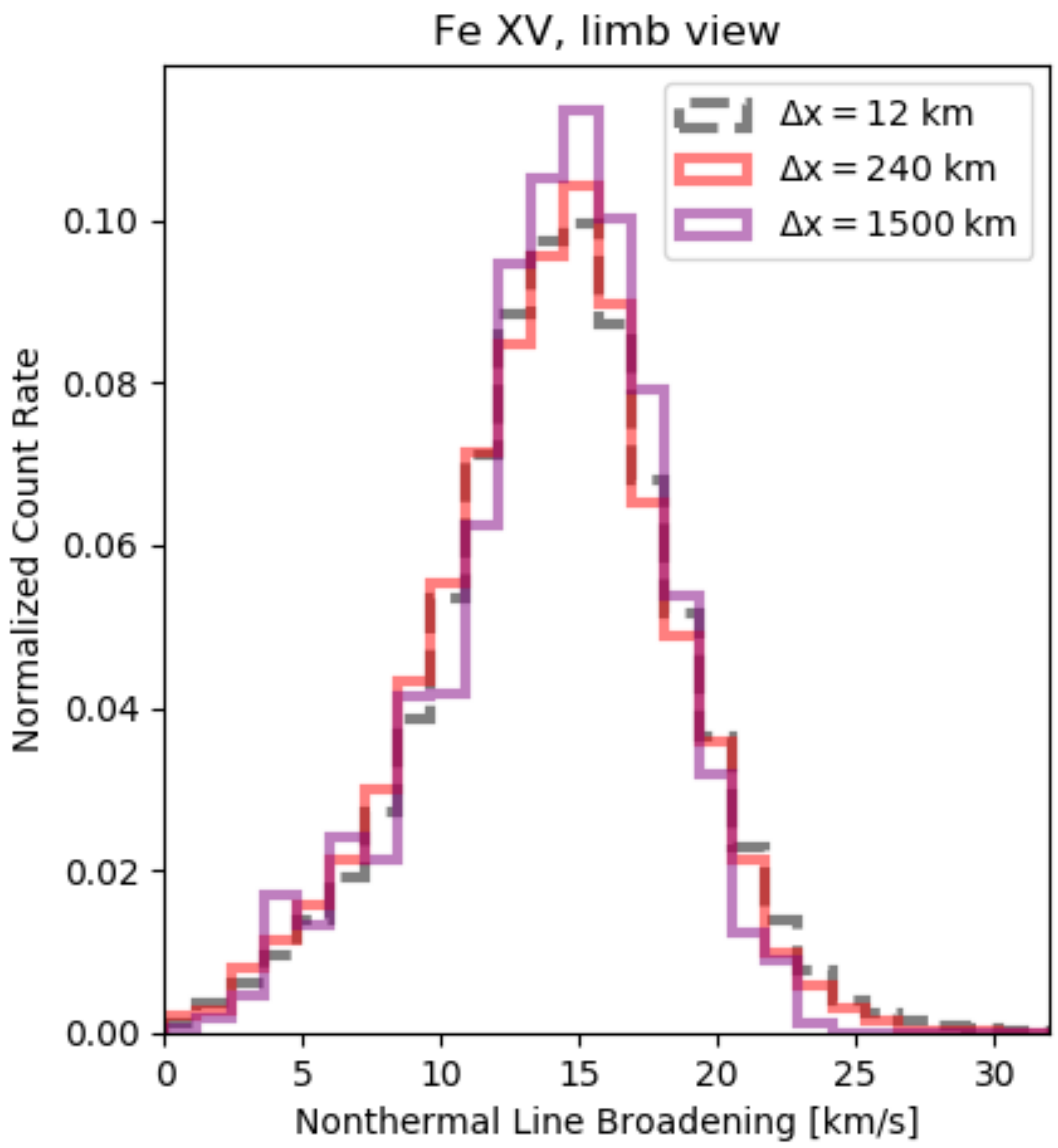




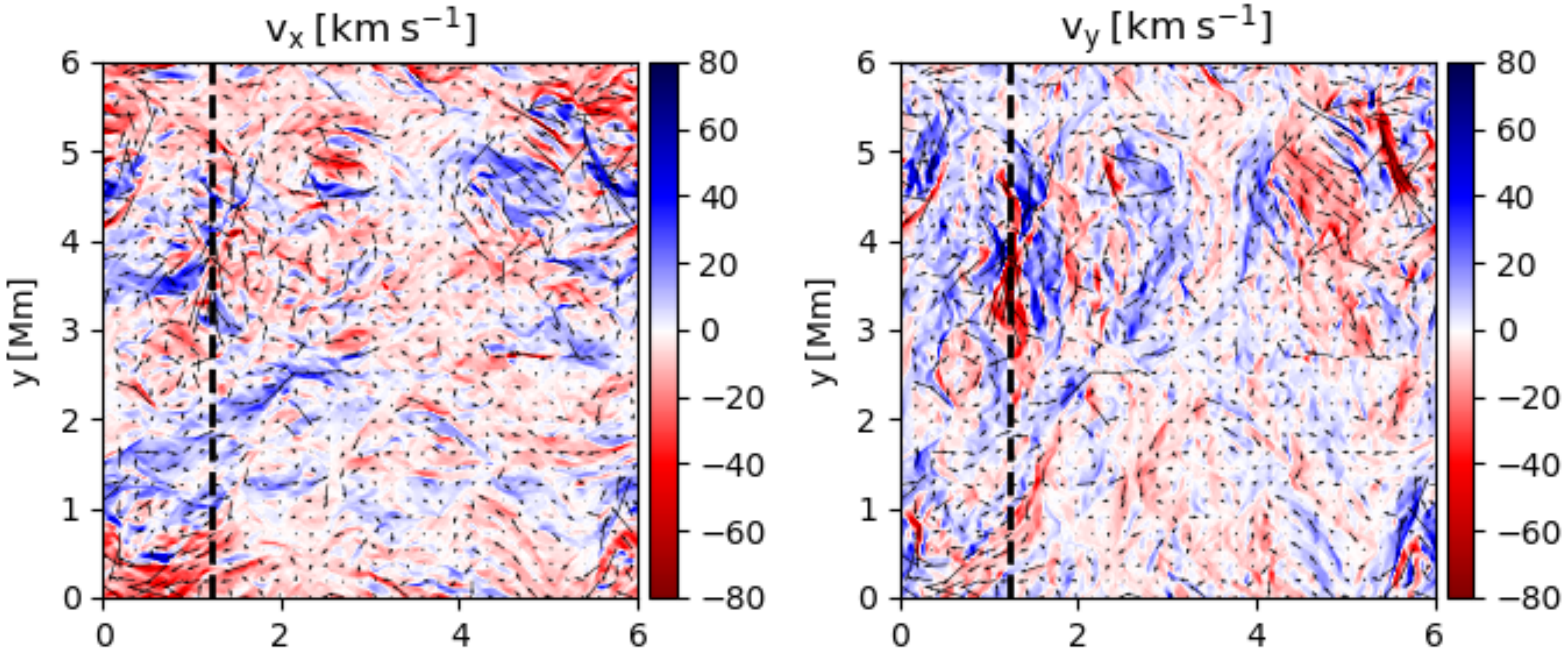
Asymmetric profiles



Dependence on instrument resolution



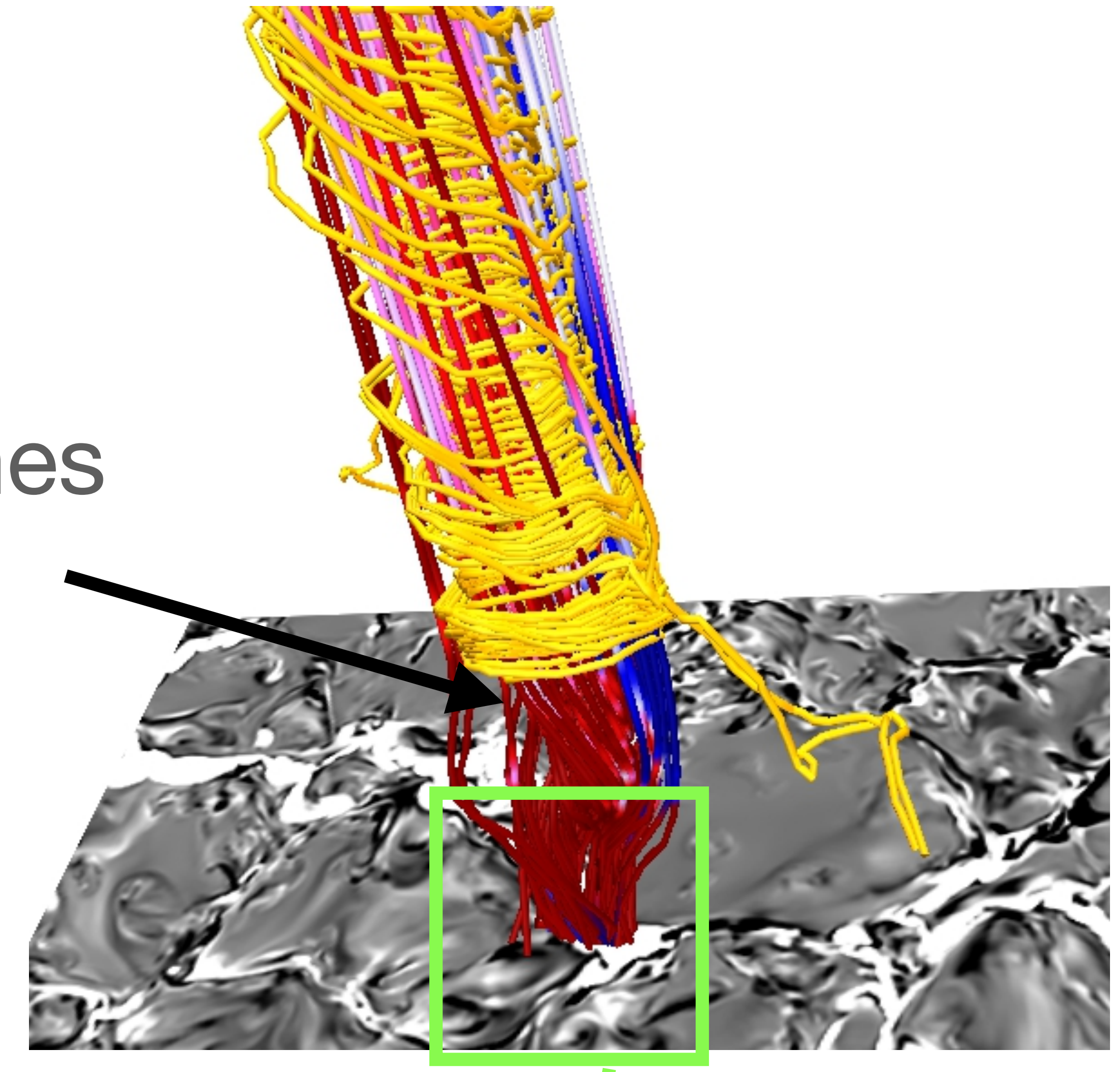
- Line broadening independent of instrument resolution



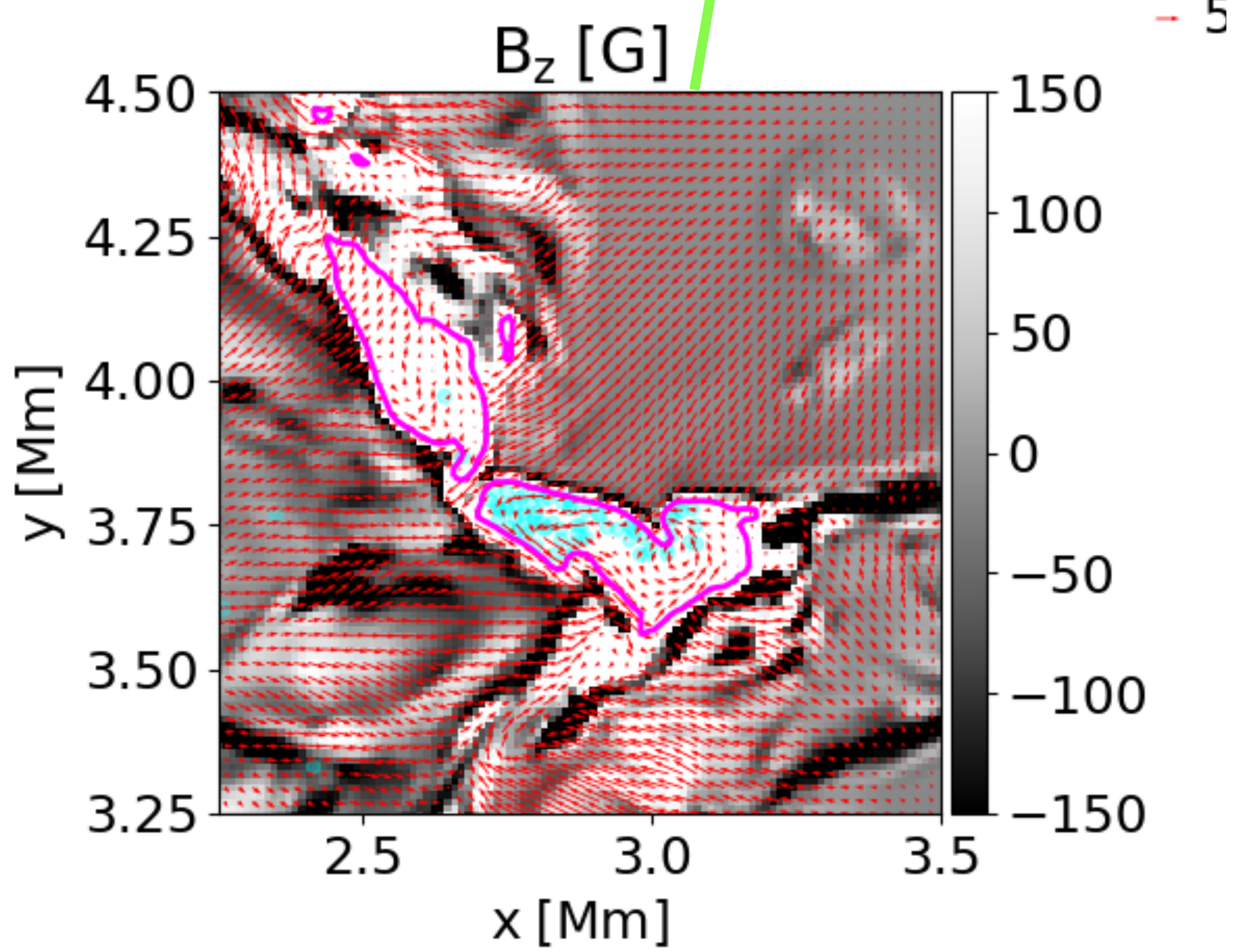
Swirls

- Observed from photosphere to low corona
- Coherent rotating magnetic field structure
- Energy and mass transfer
- Range of scales (km-Mm)
- MUSE: High resolution and cadence

Magnetic field lines



Magnetic and velocity field lines for an atmospheric swirl



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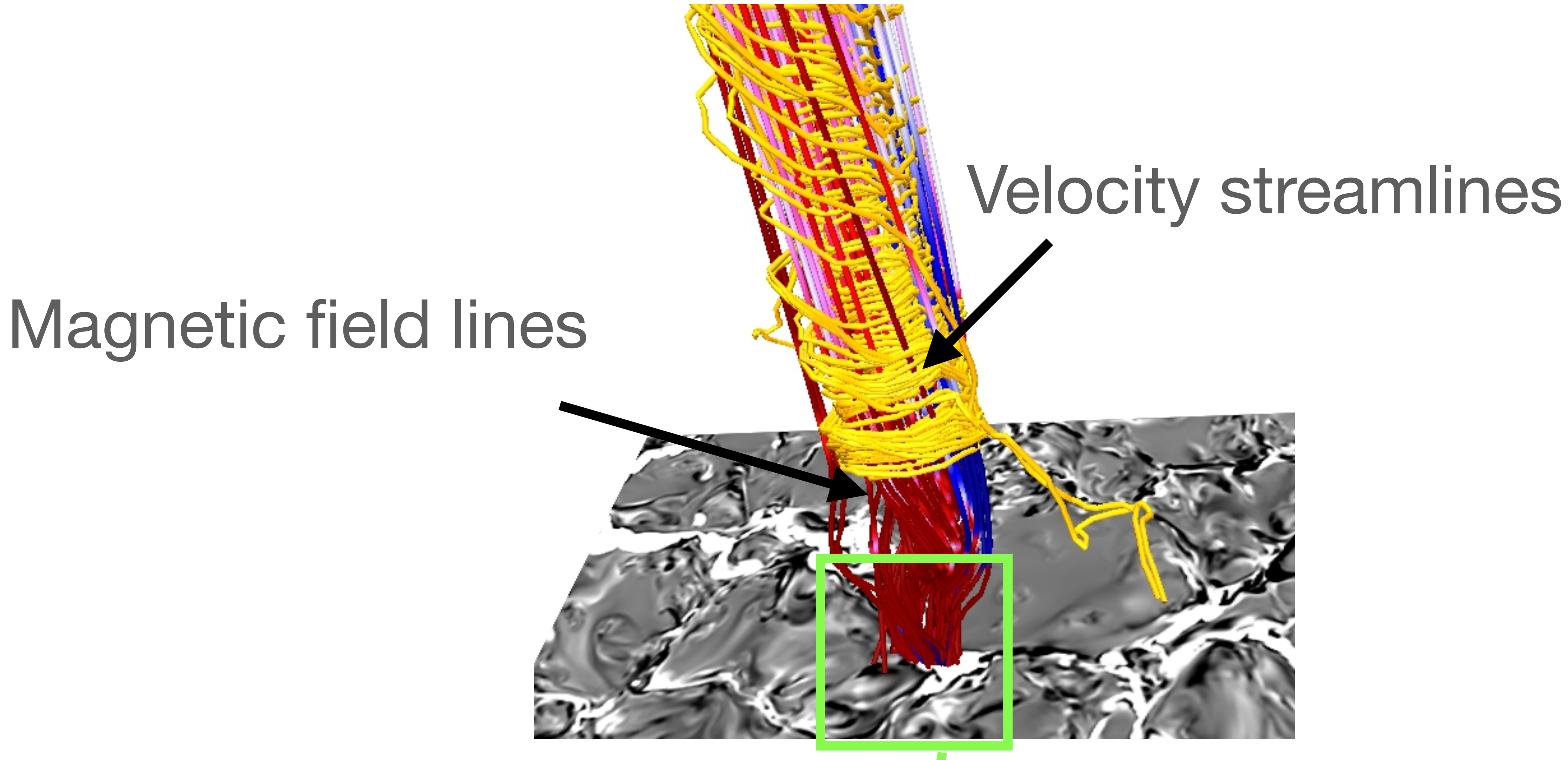

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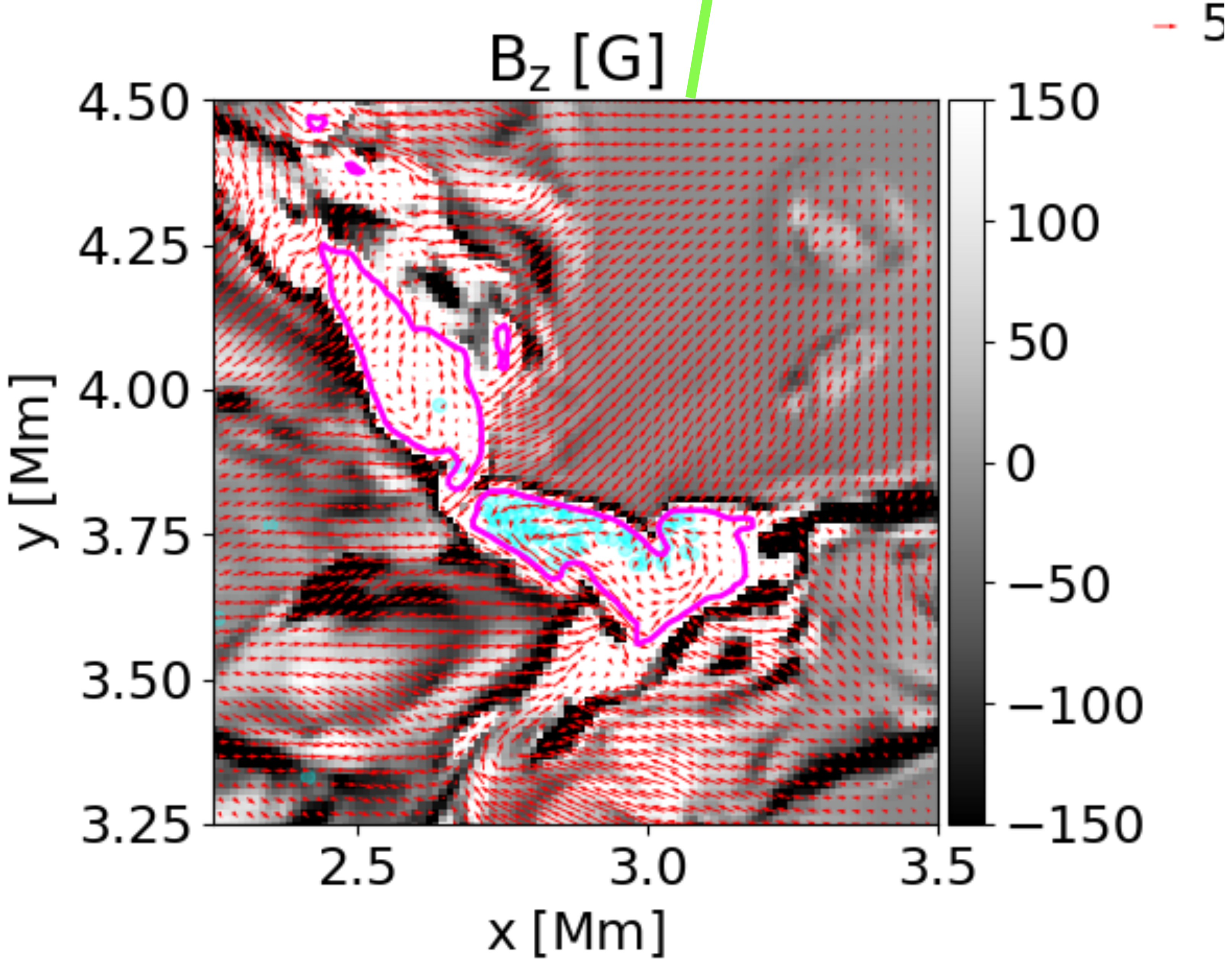

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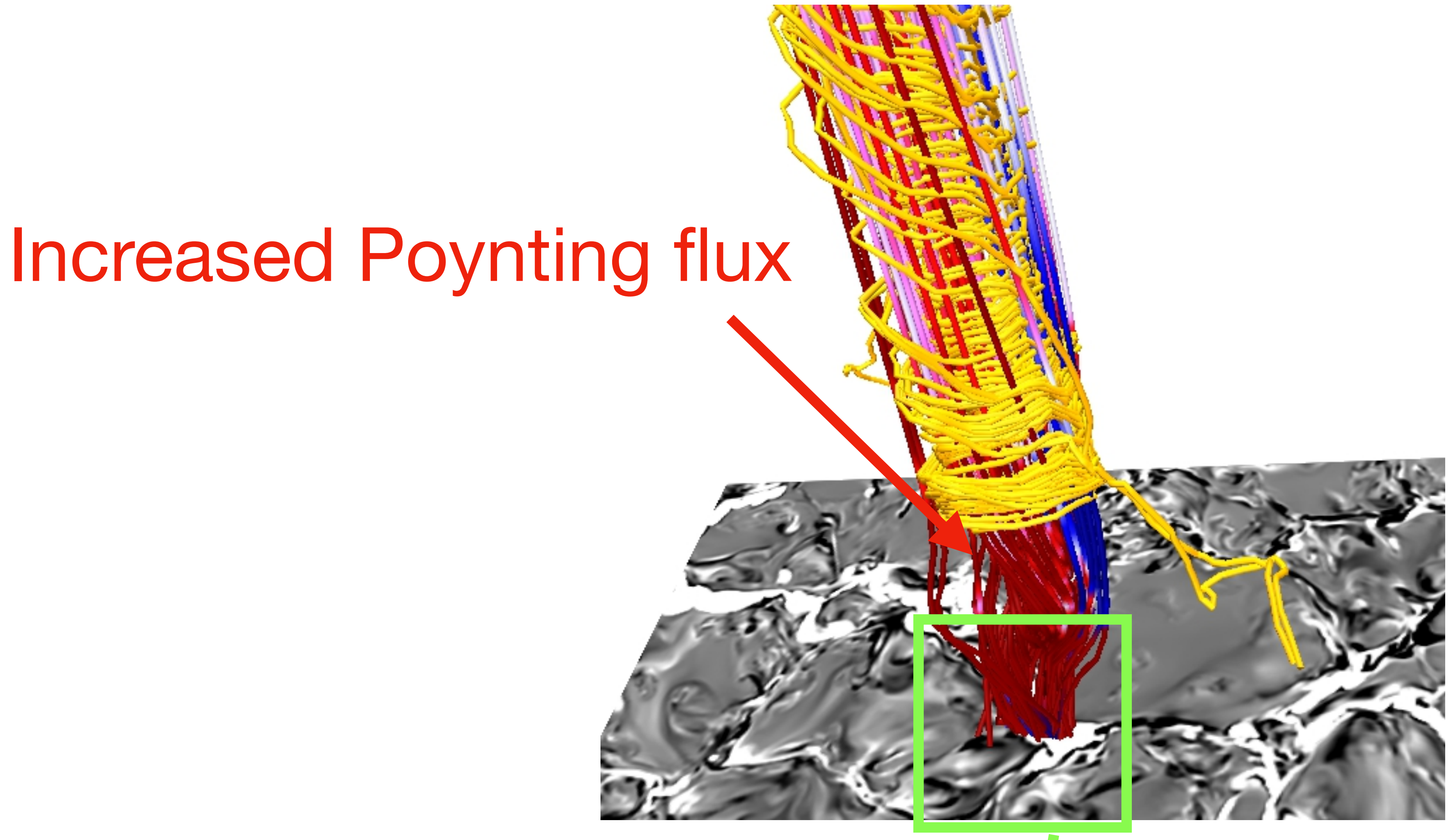

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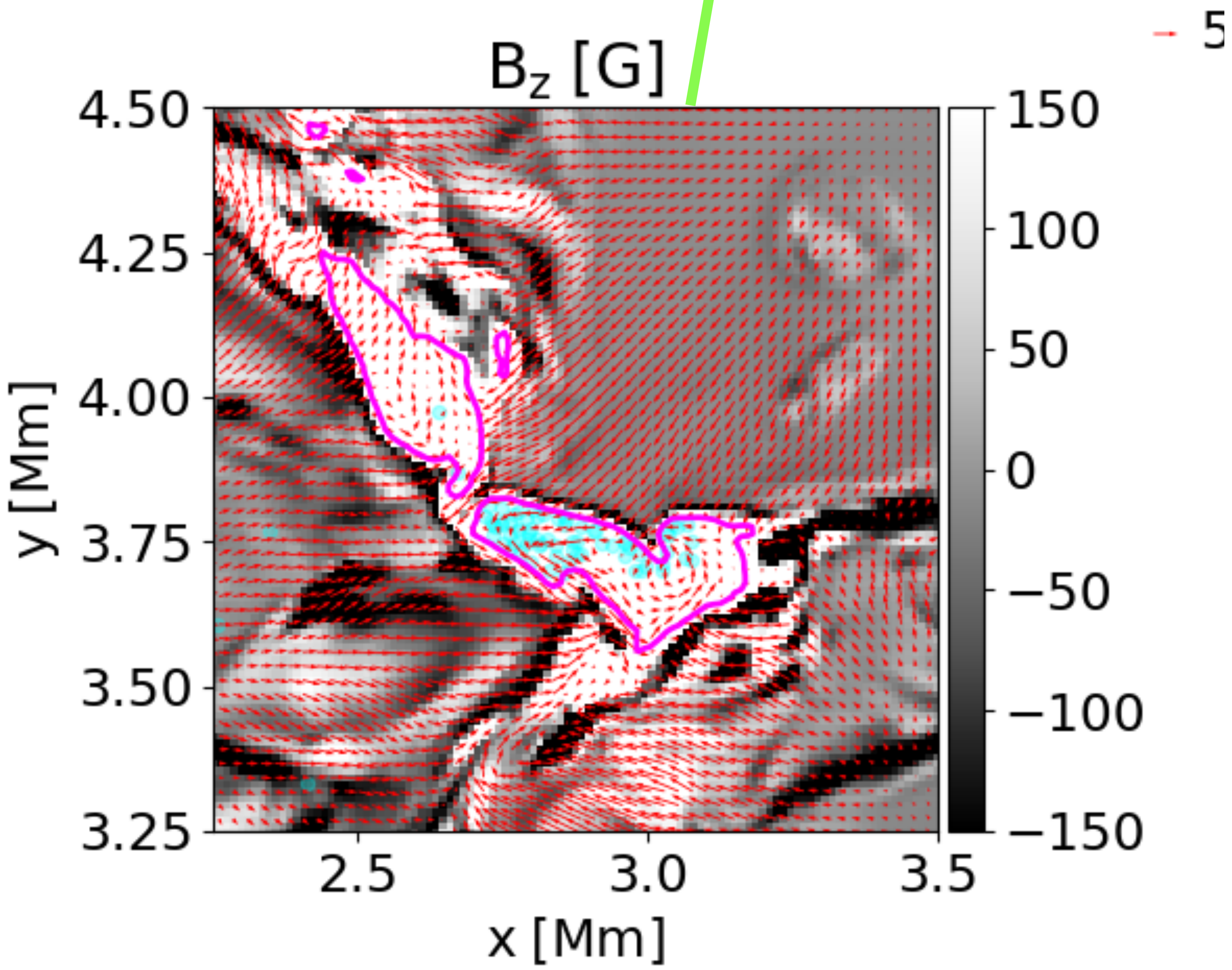
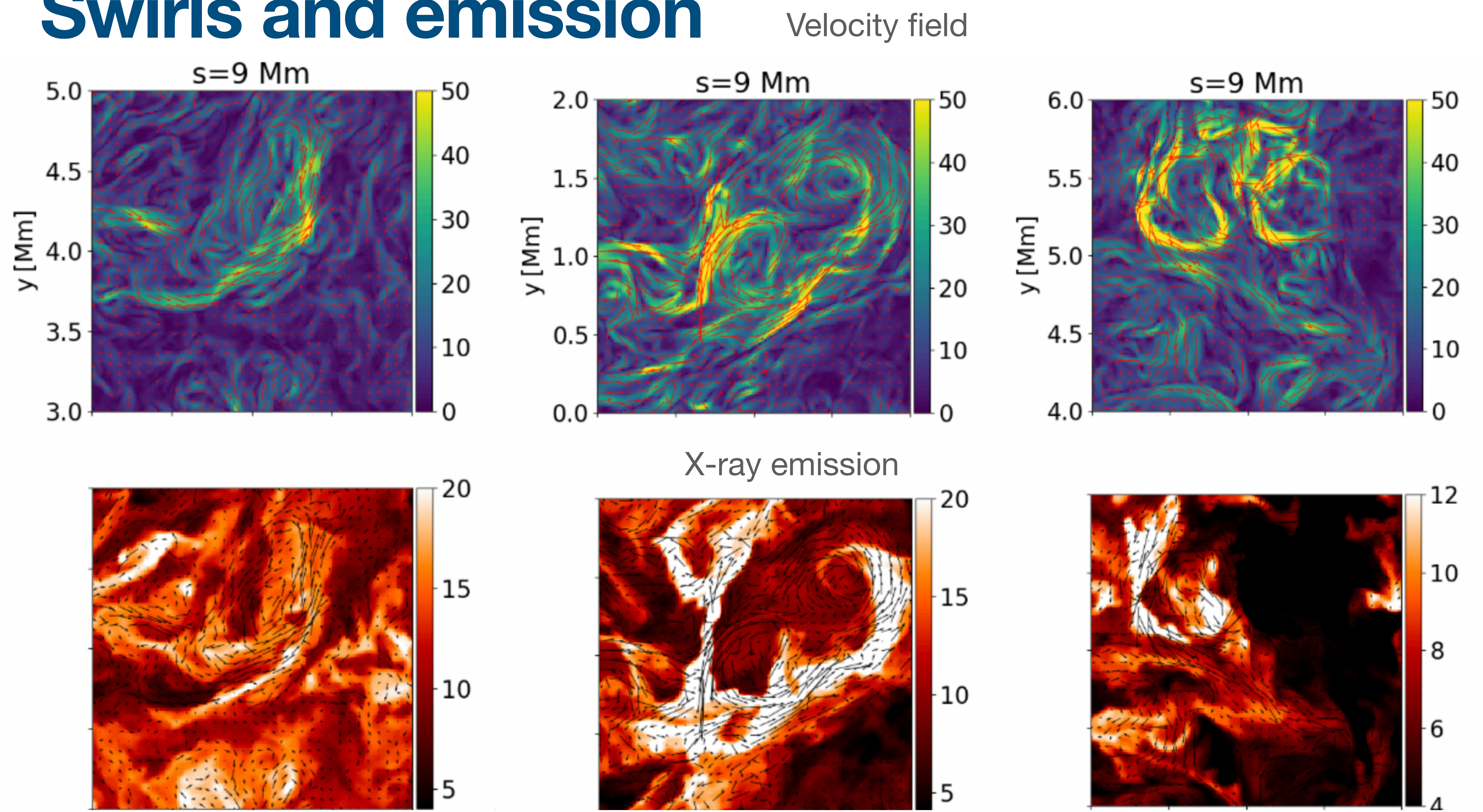


Swirls and emission



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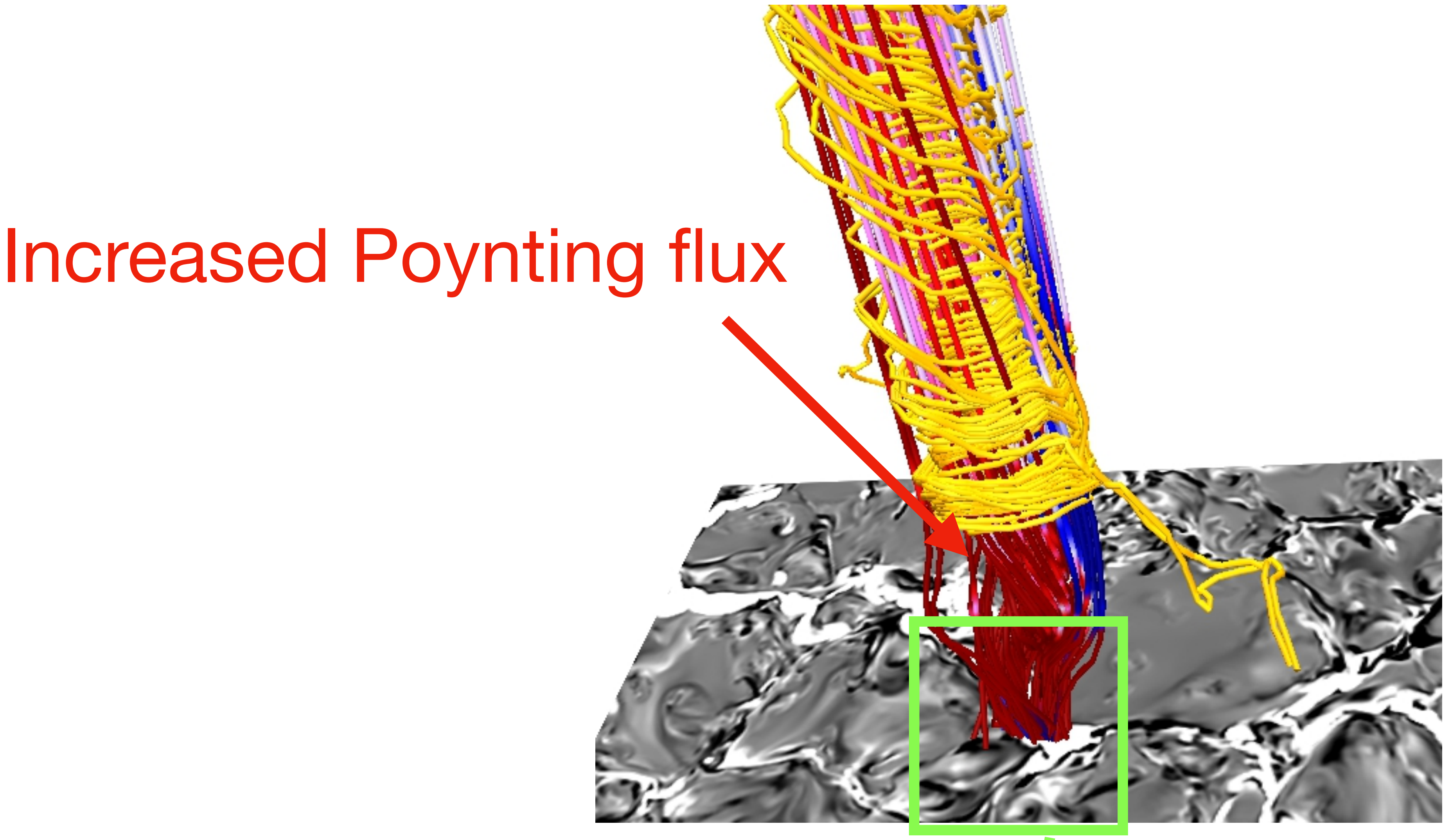
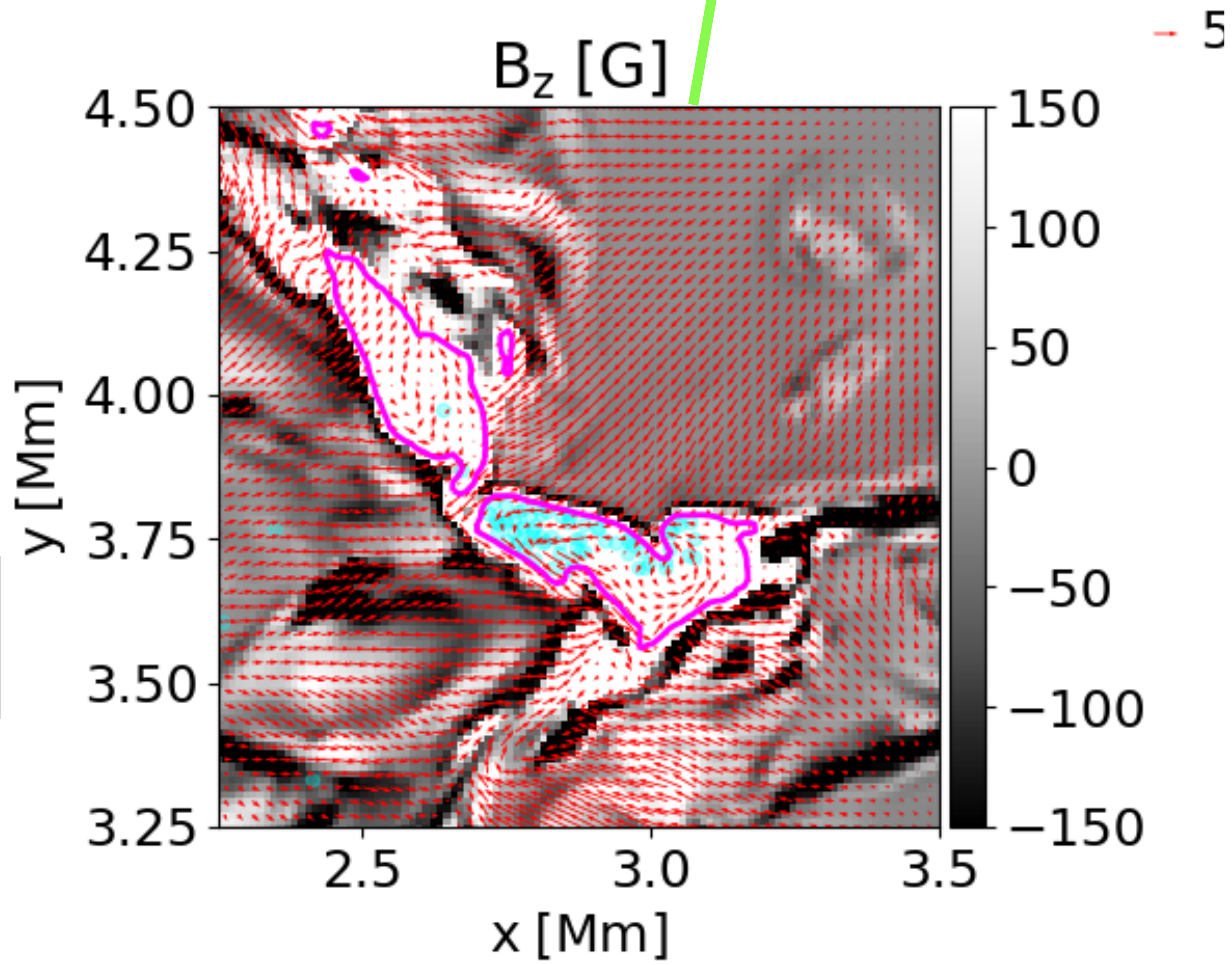
Could MUSE detect atmospheric swirls?

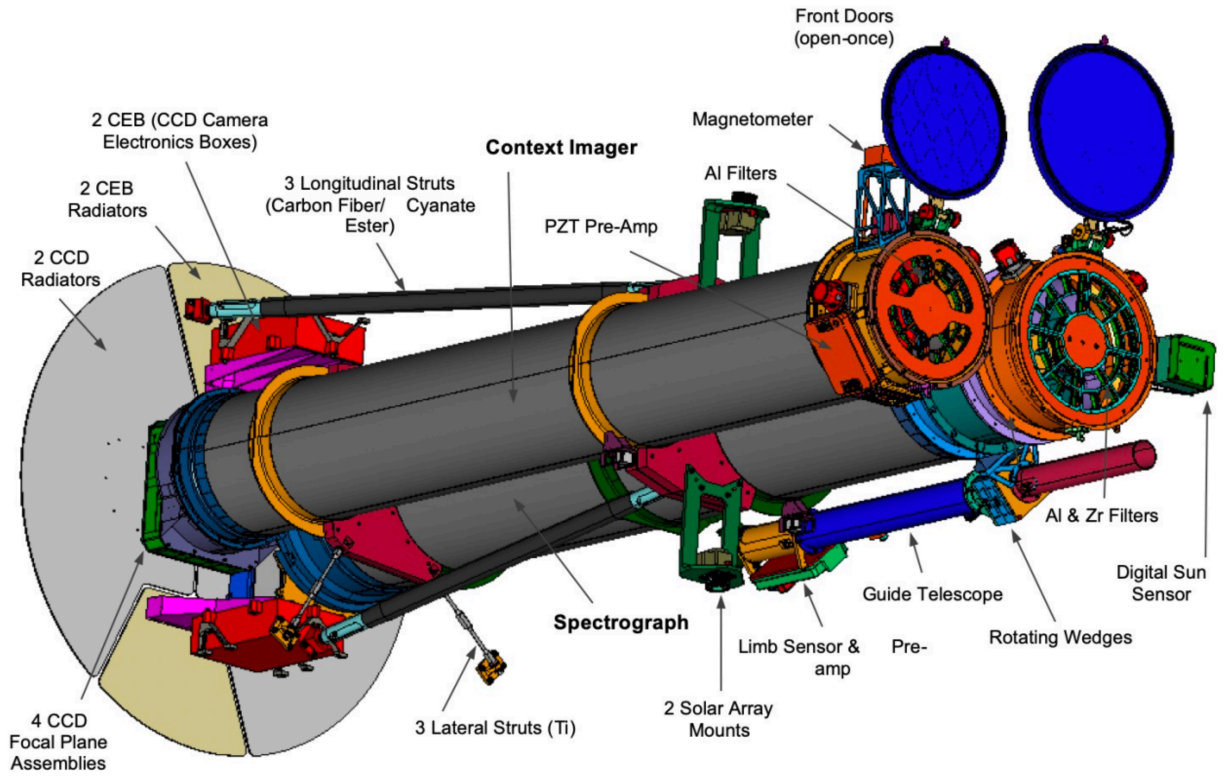


Magnetic and velocity field lines for an atmospheric swirl

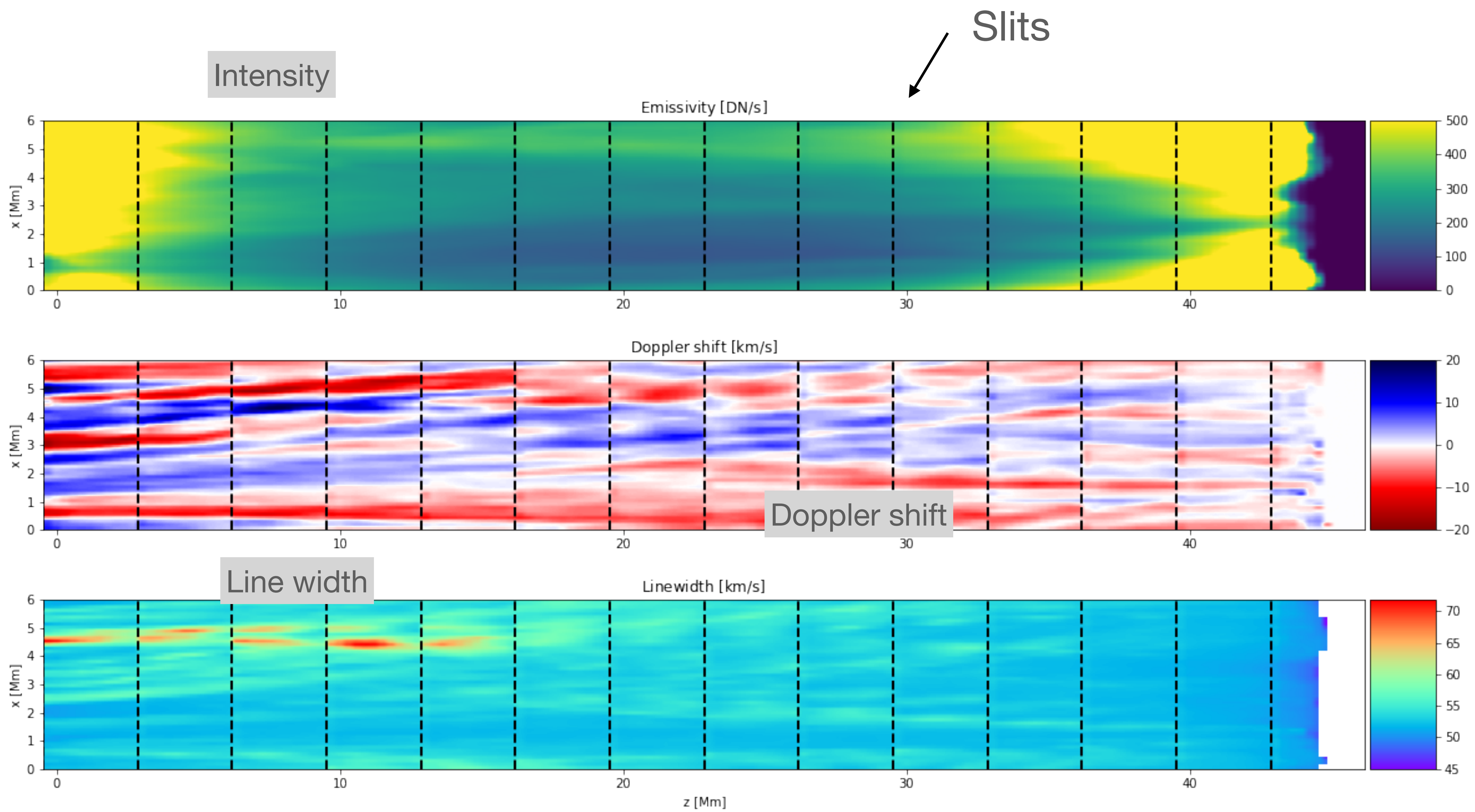


MUSE Raster Scan

- Resolution: (0.4, 0.167)”
- 1s exposure
- Structure showing high line widths + blue- and redshifted emission



Raster Scan



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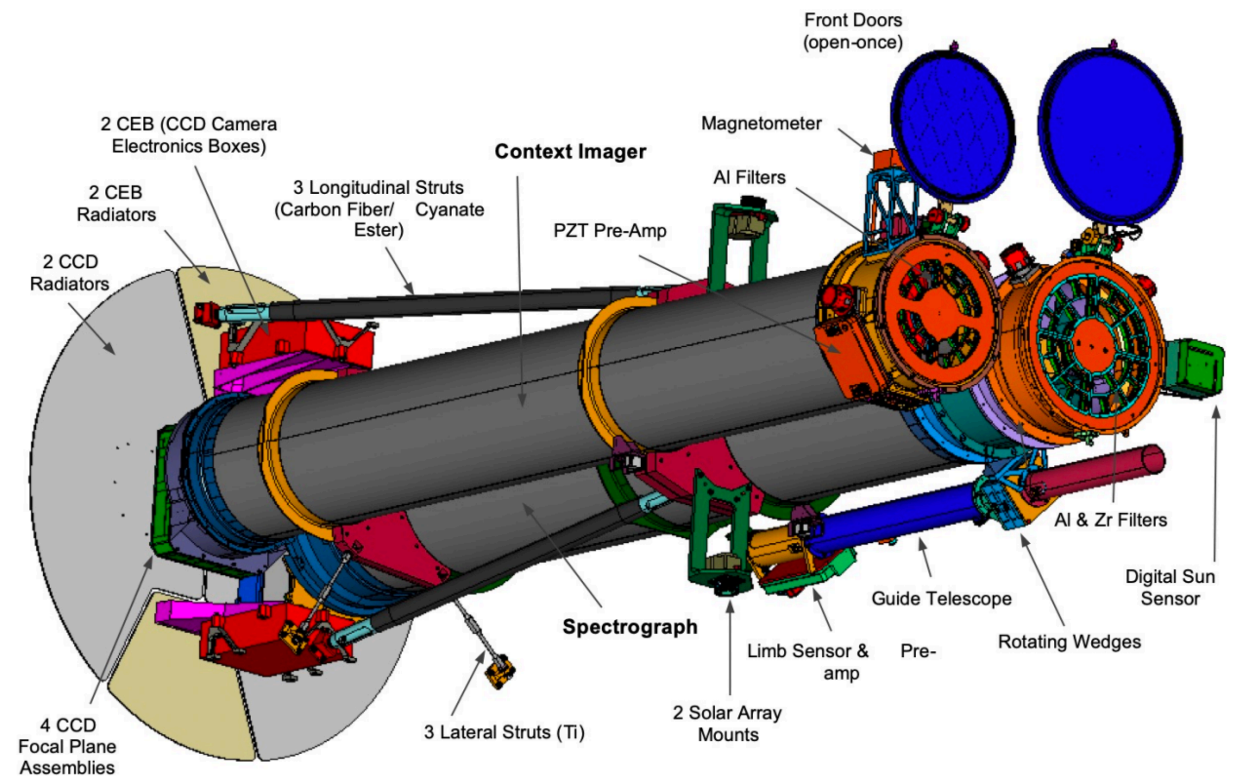

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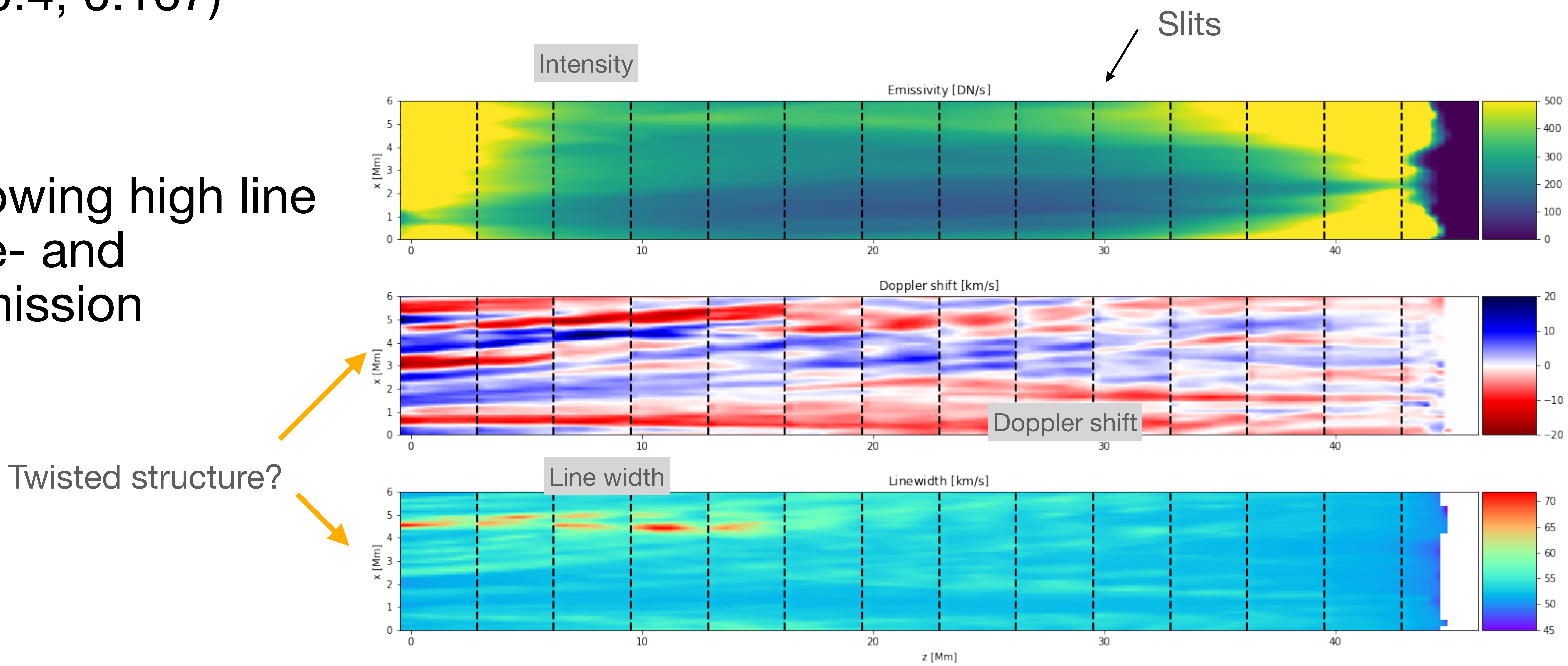
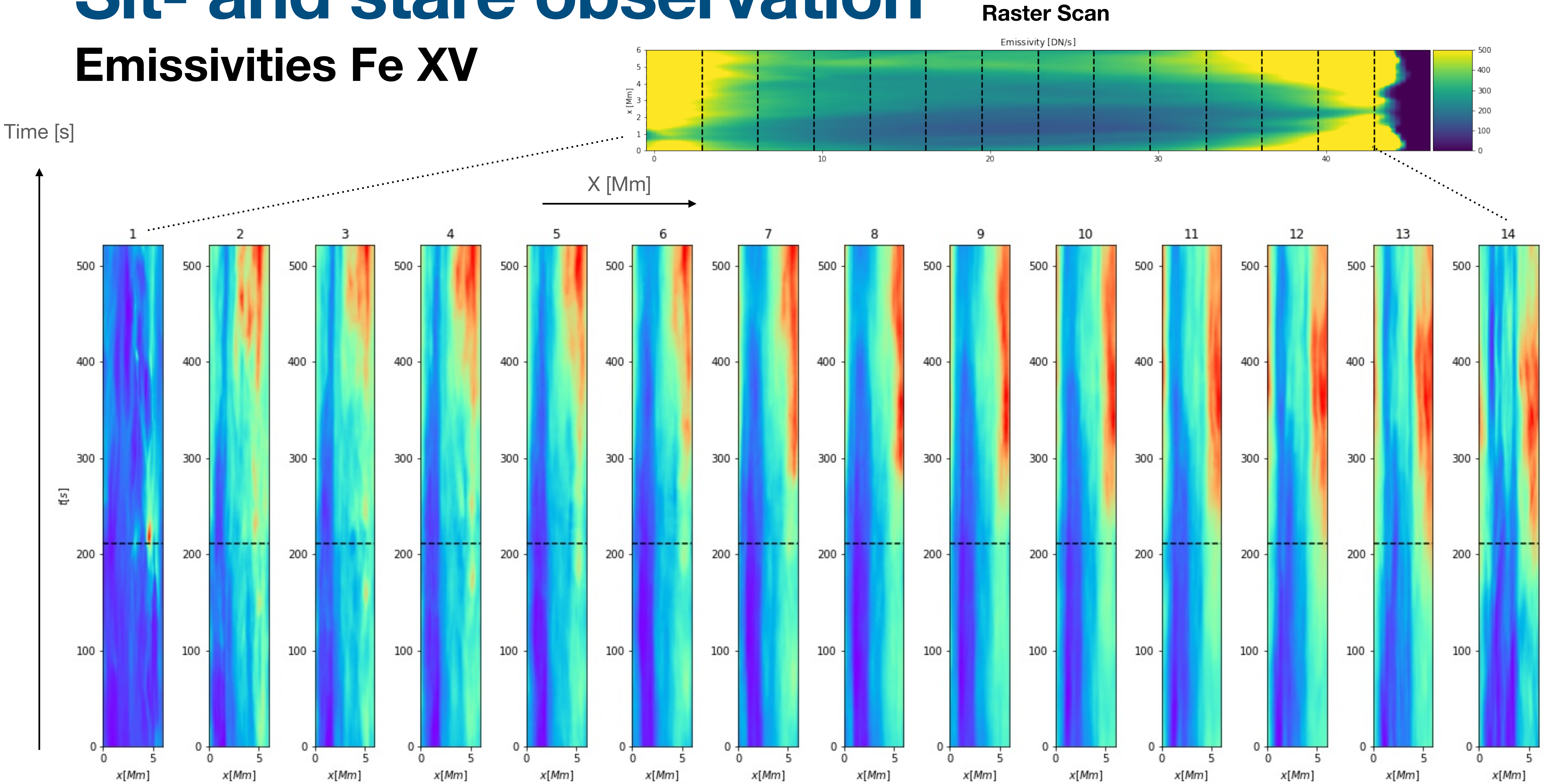


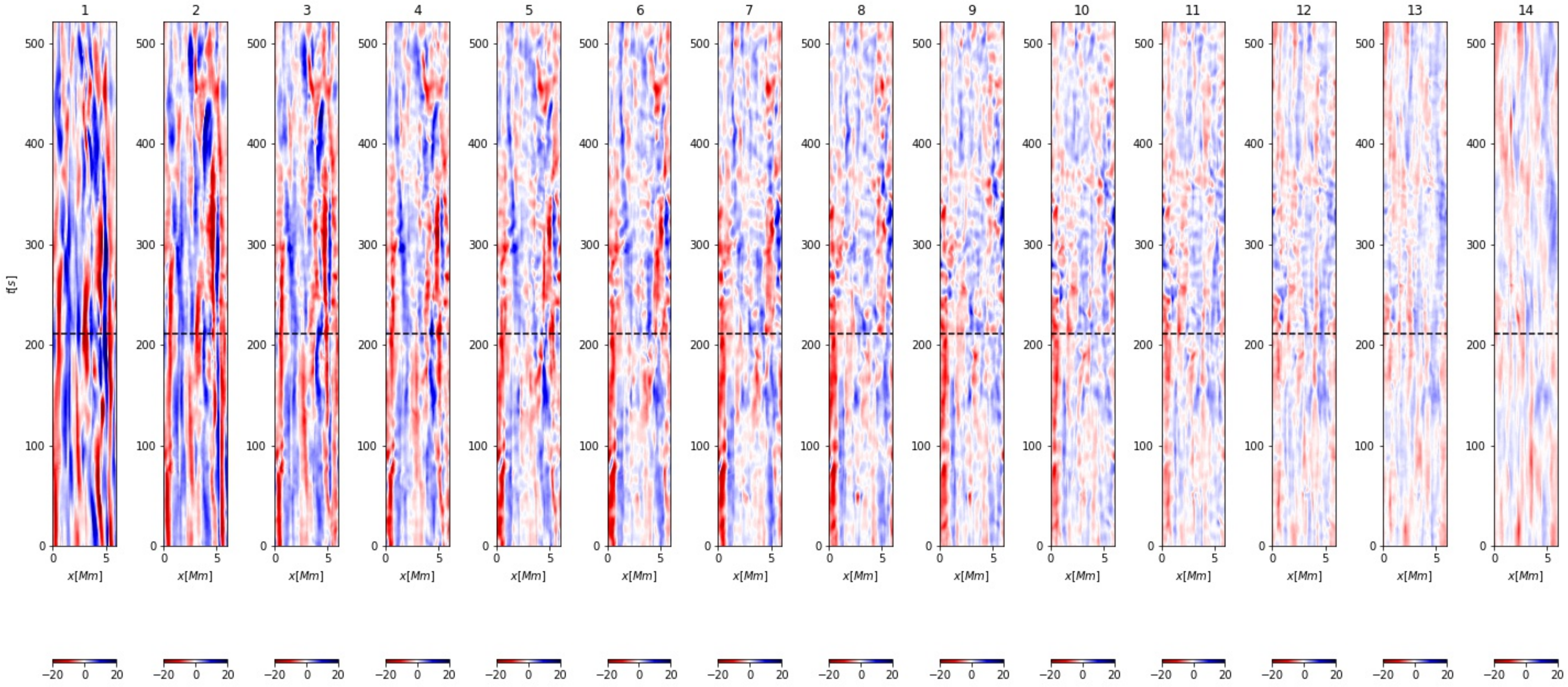
Sit- and stare observation

Emissivities Fe XV



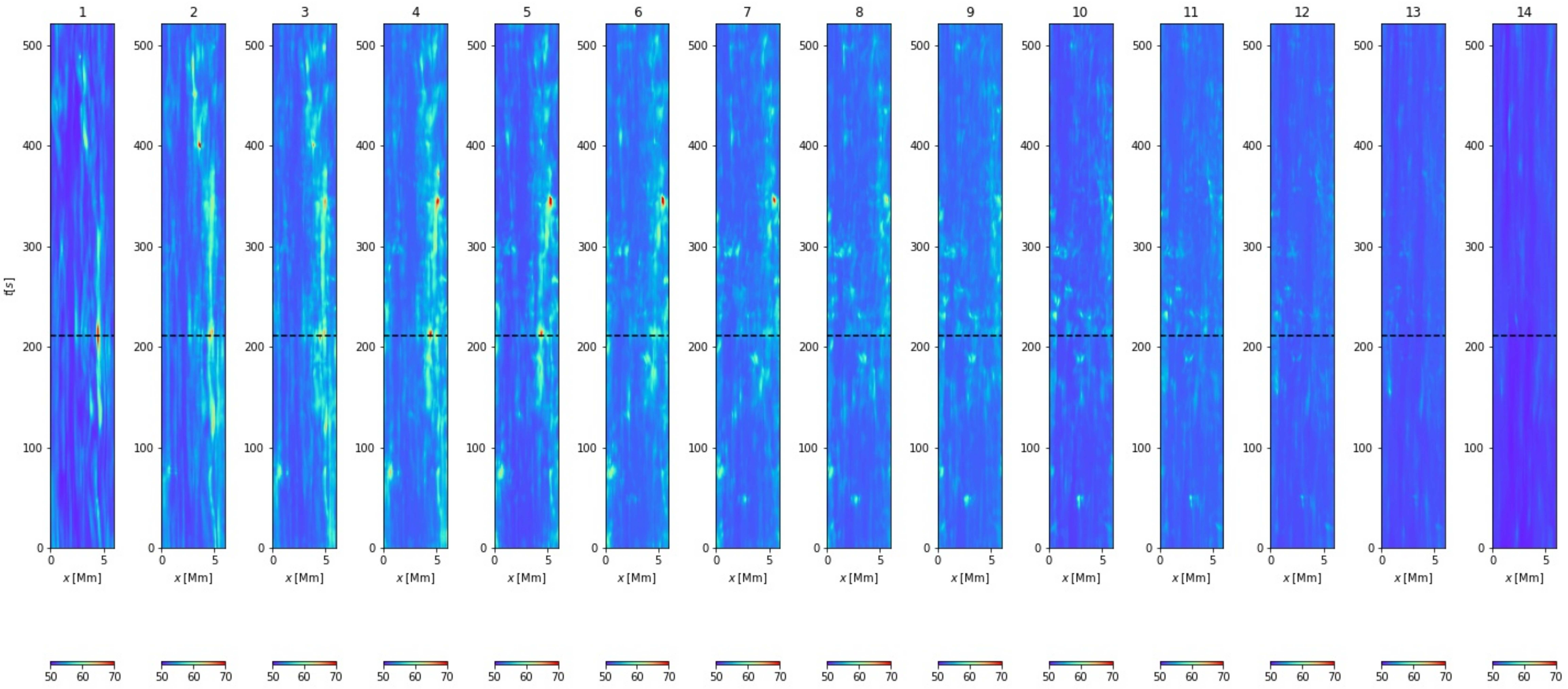
Sit- and stare observations

Doppler velocities Fe XV



Sit- and stare observation

Line widths Fe XV

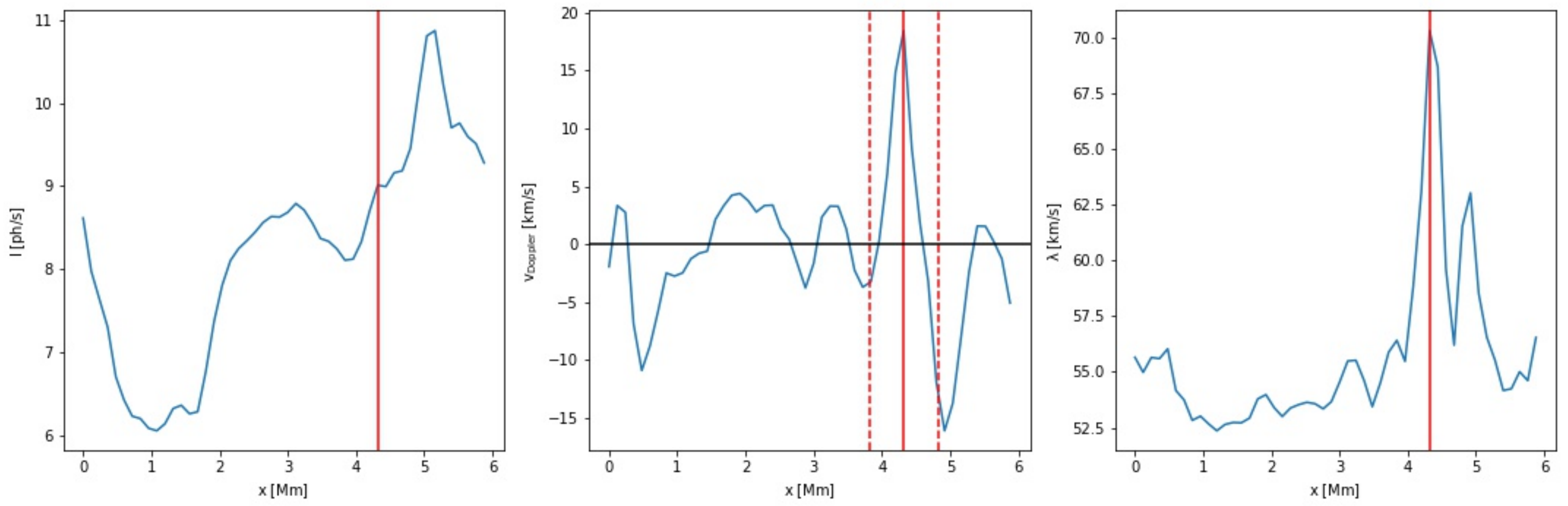


Sit- and stare observation

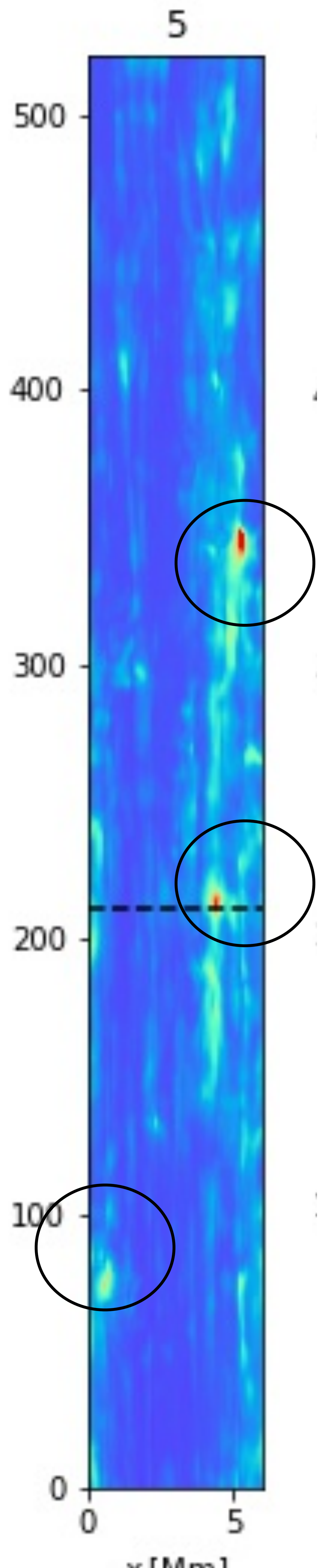
Line widths

Height: 16.5 Mm

- Identify events:
- Peaks in line width (enhanced by at least 10%)



Intensity, Doppler shift and line width



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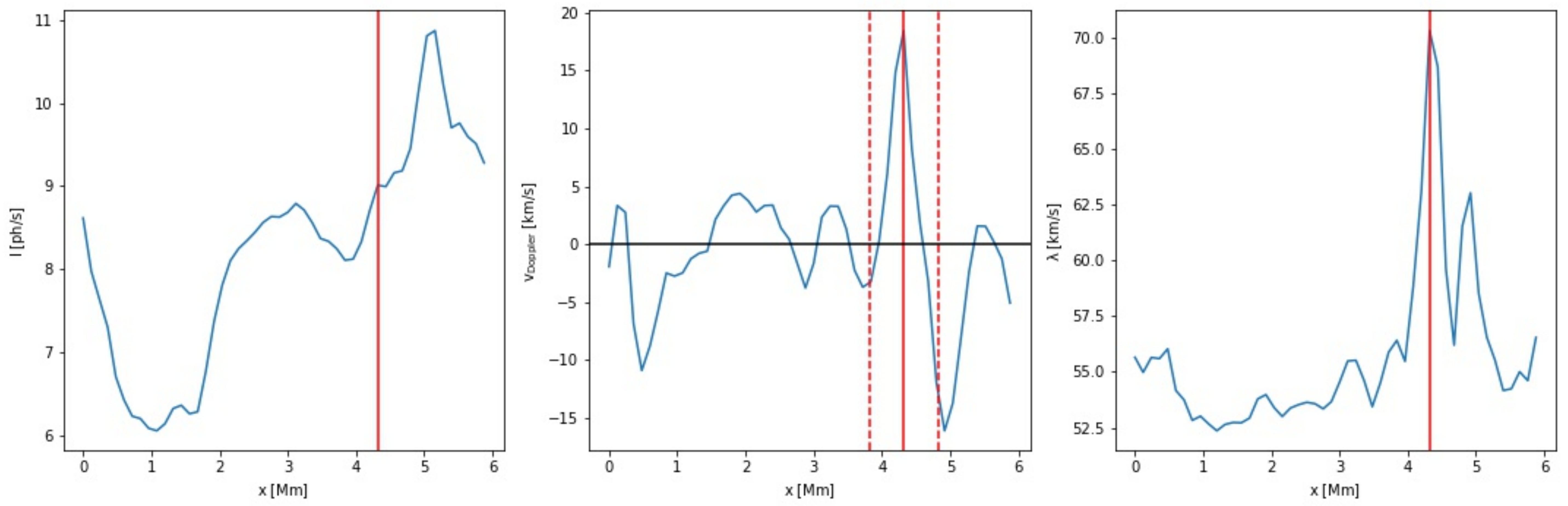

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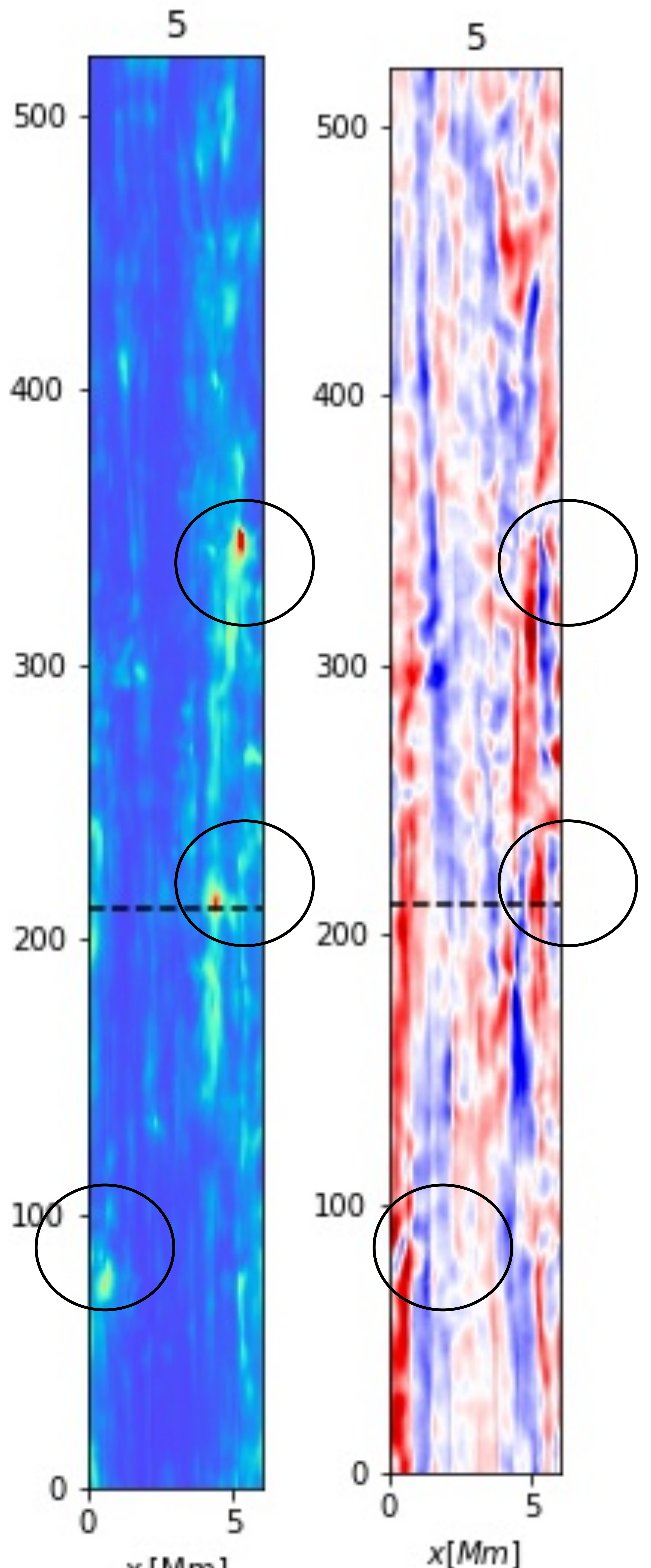
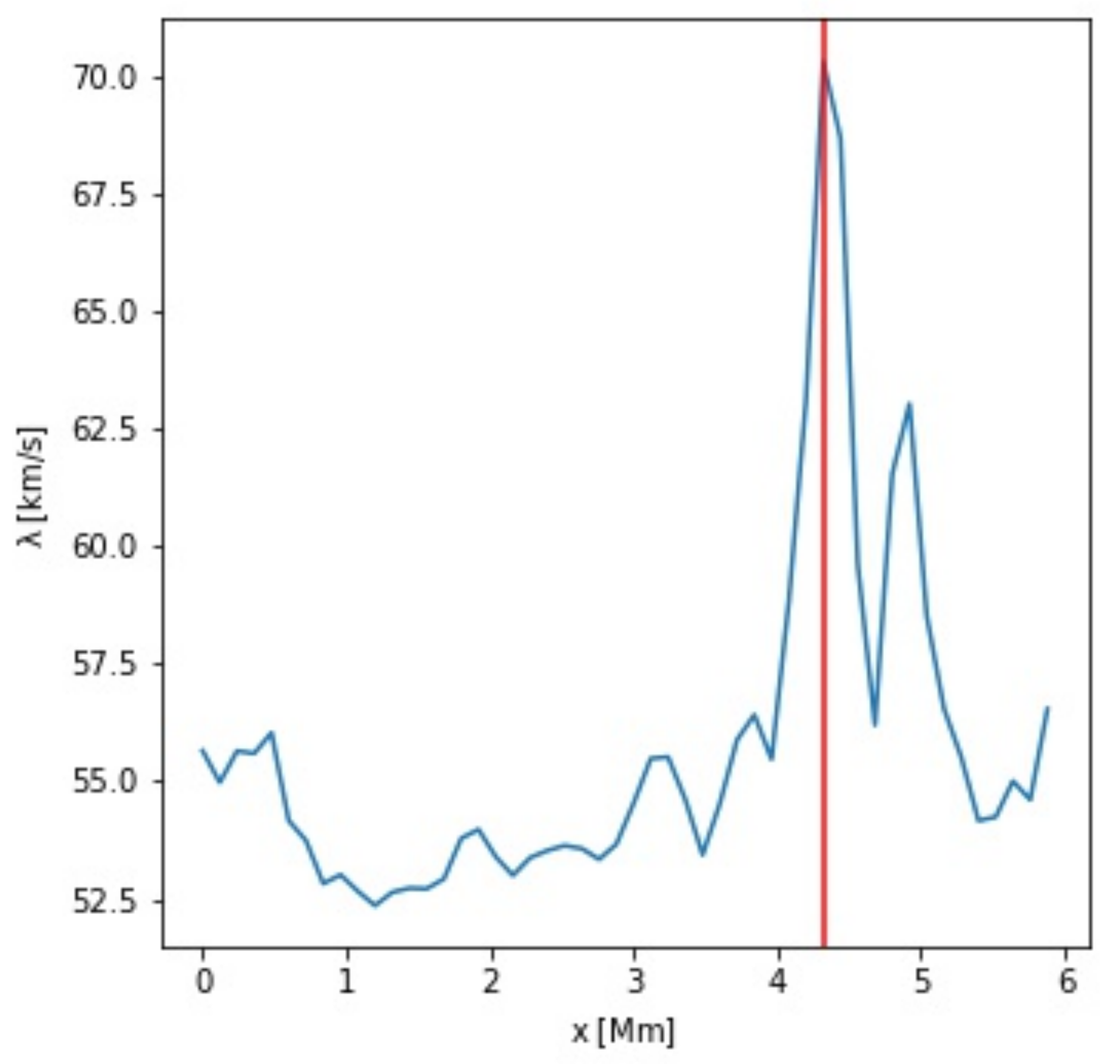
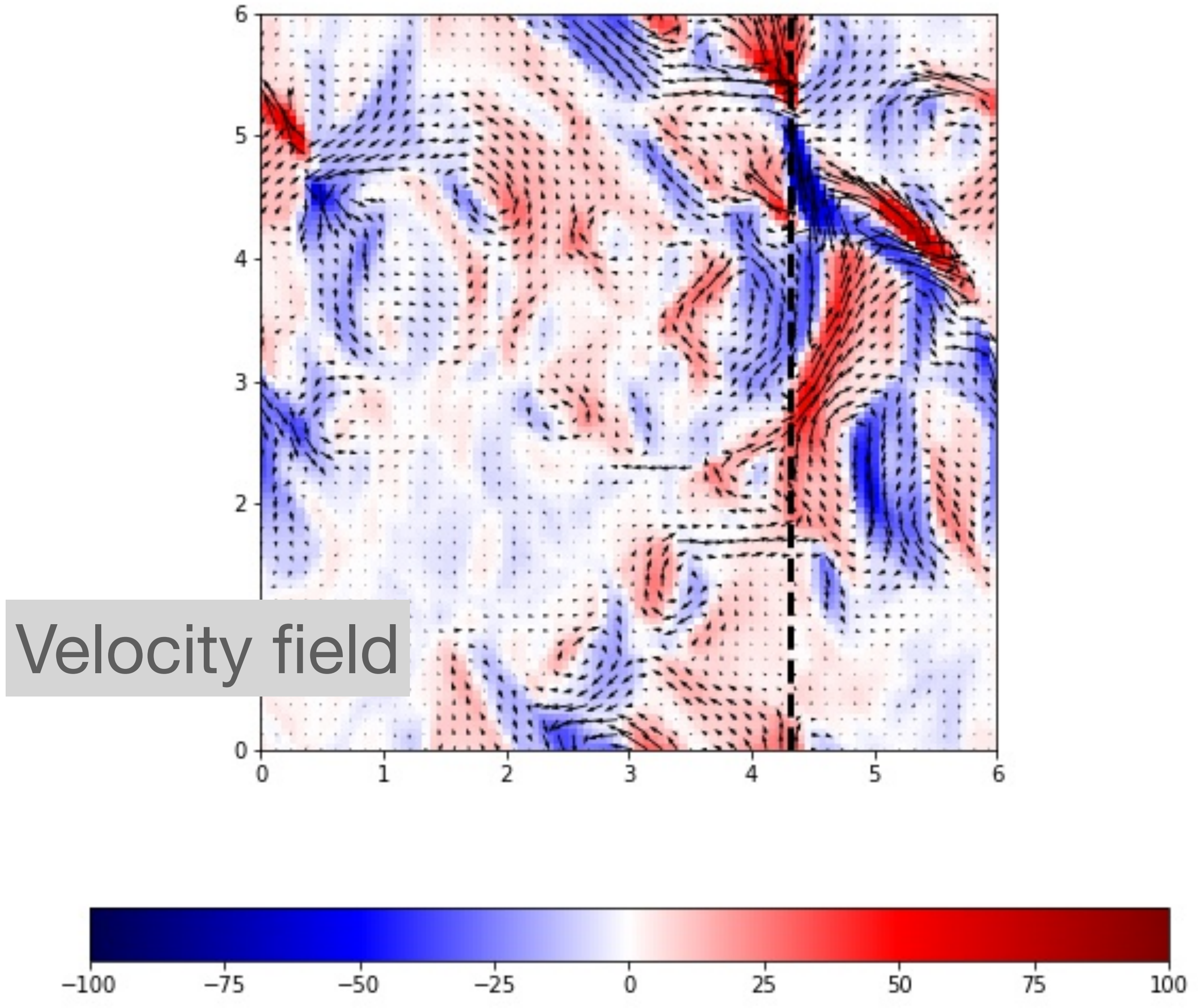


Identifying features

- What happens in the loop interior?
- Twist at locations of high line broadening

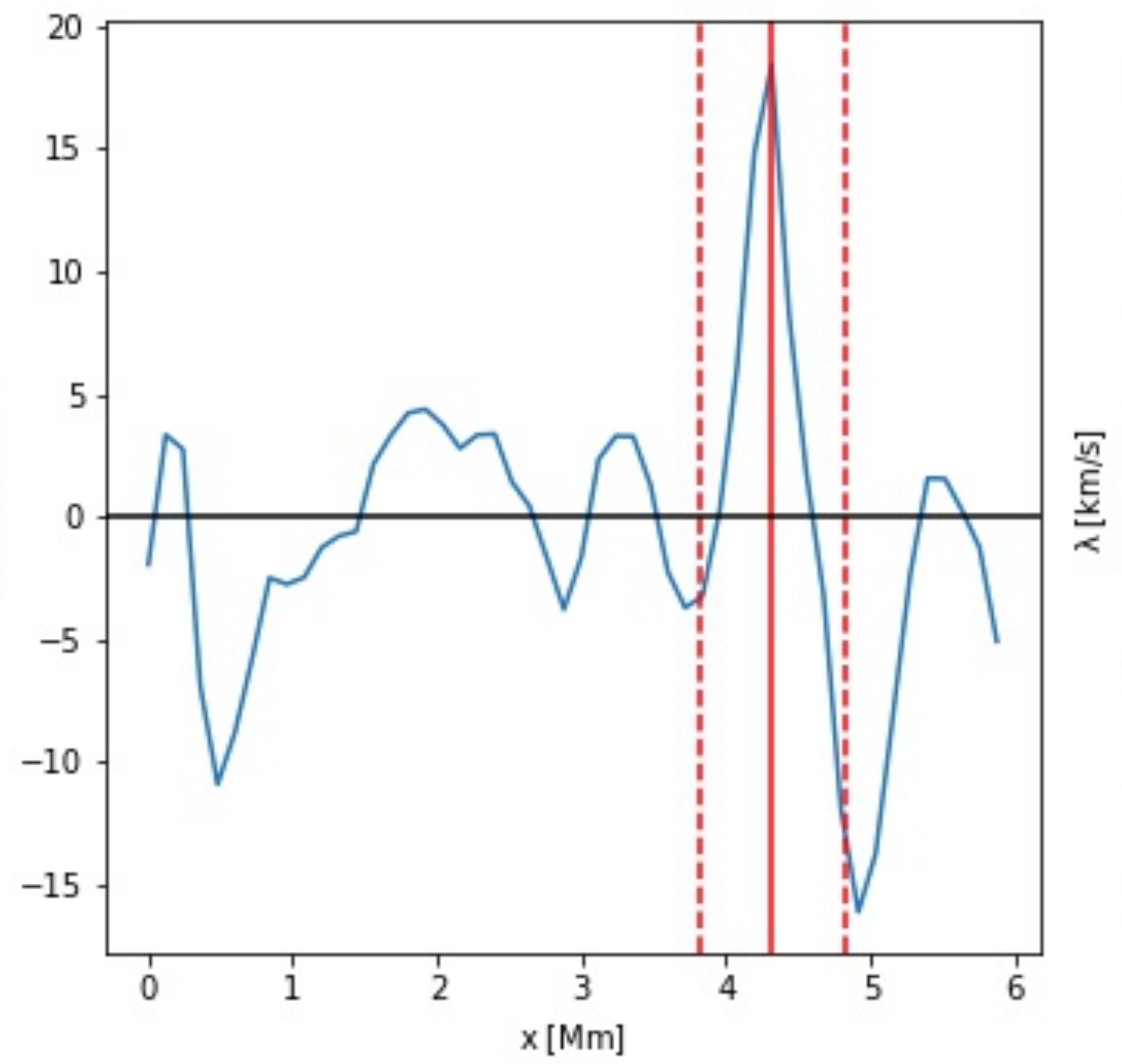
Line width at slit 5





Identifying features

Doppler shift at slit 5



- What happens in the loop interior?
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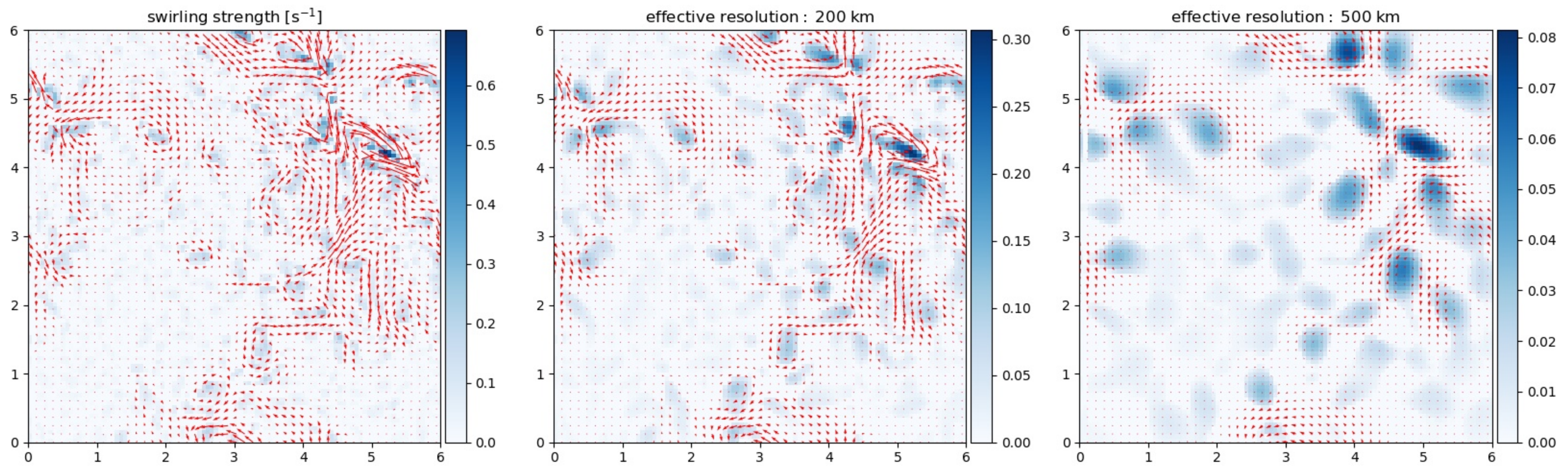
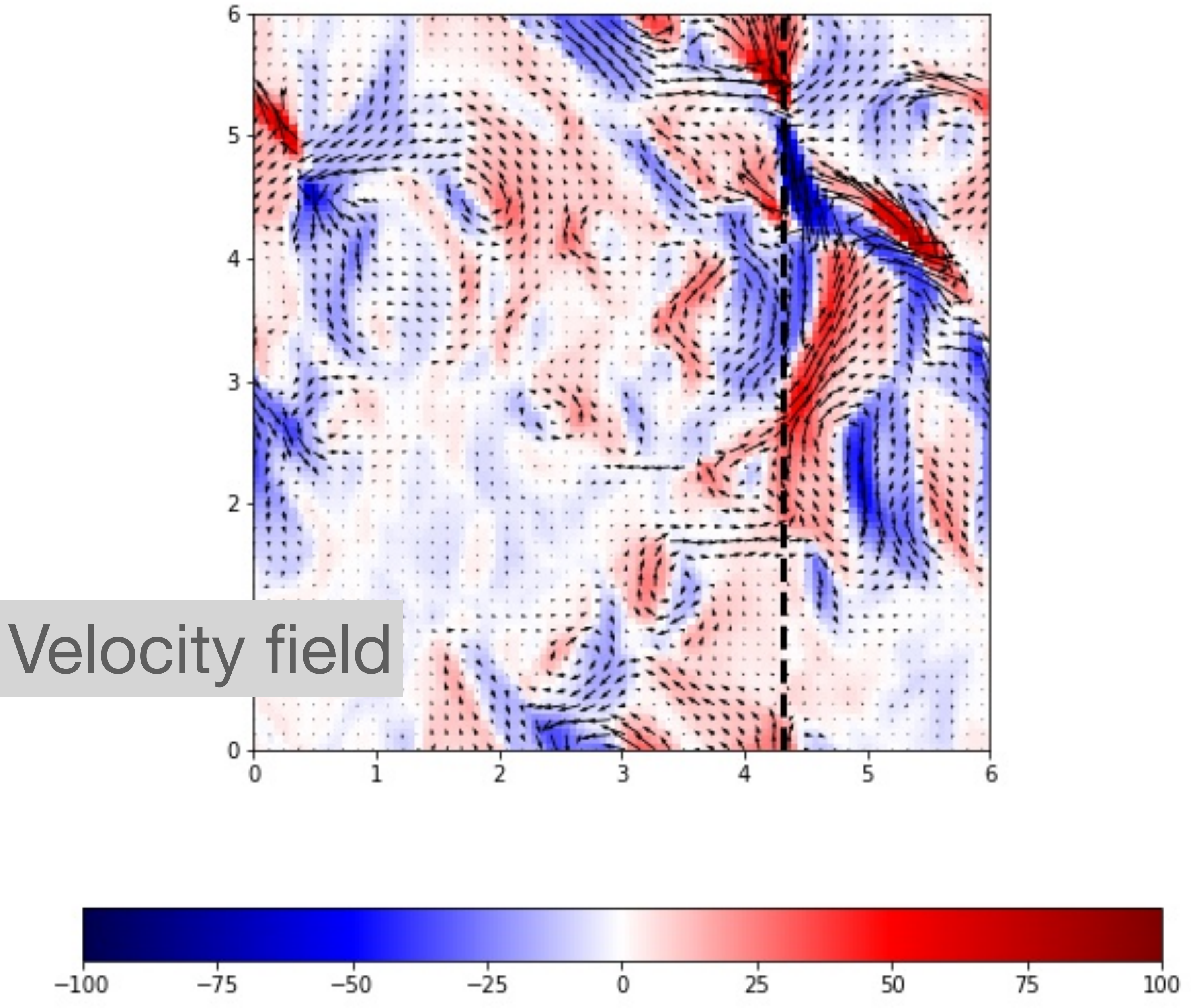
Superposition of swirls

Resolution: 200 km

Resolution: 500 km

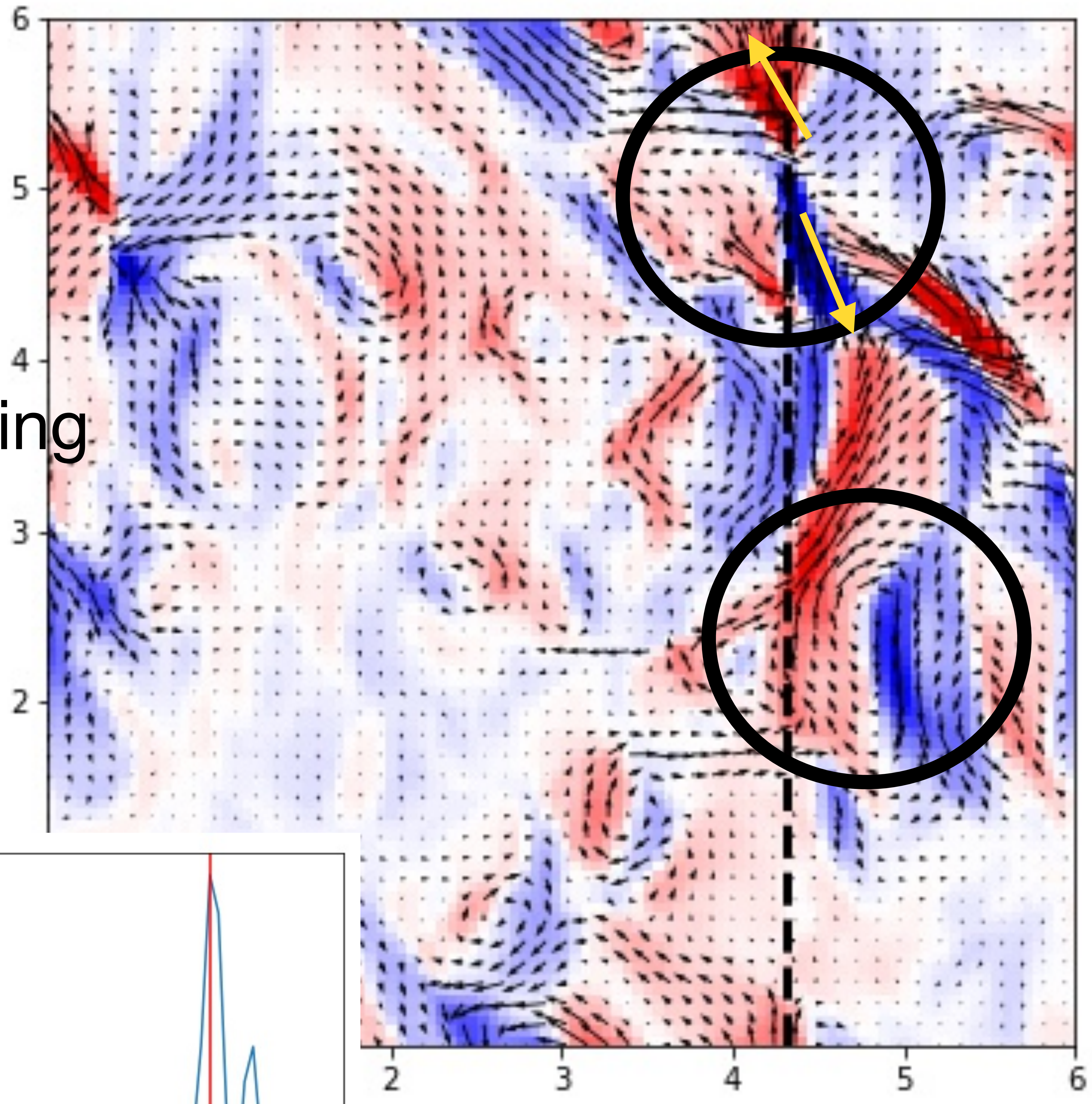


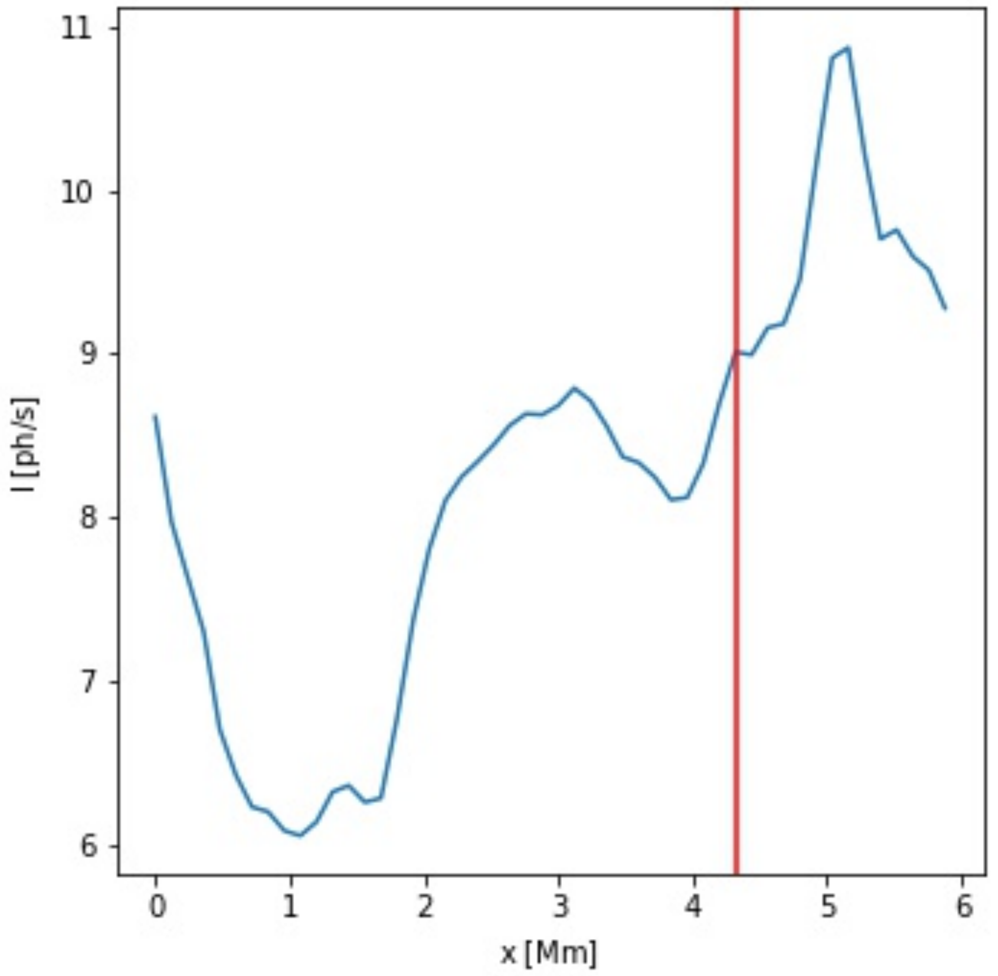


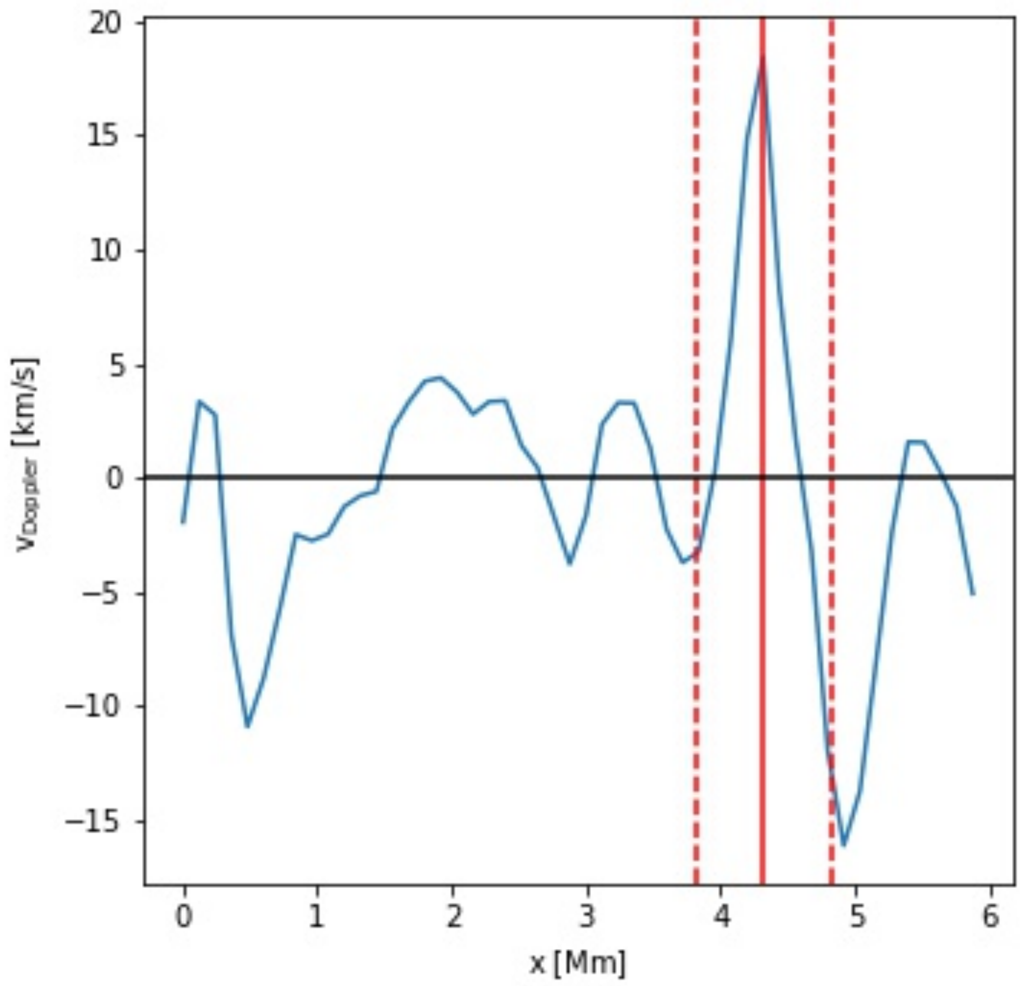
Velocity field

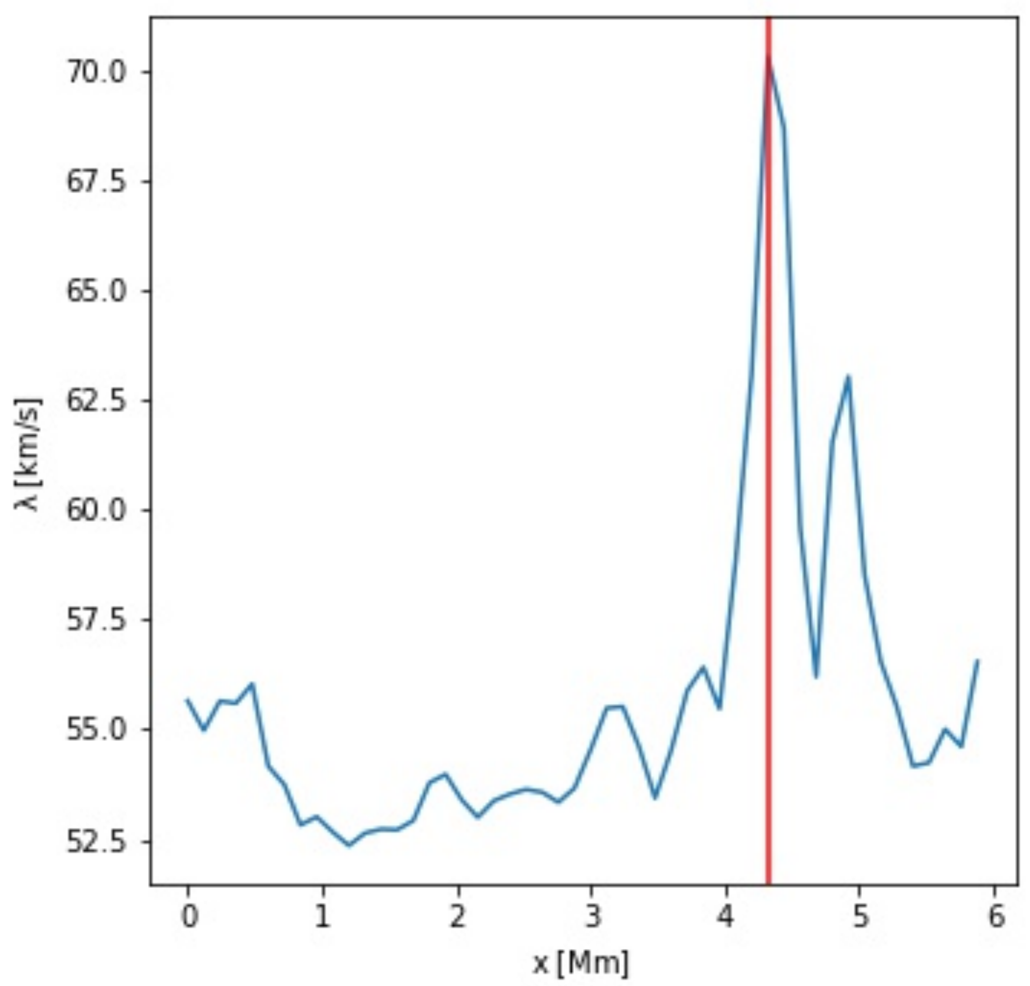
Identifying features

- Twist at locations of high line broadening
- Bidirectional jet



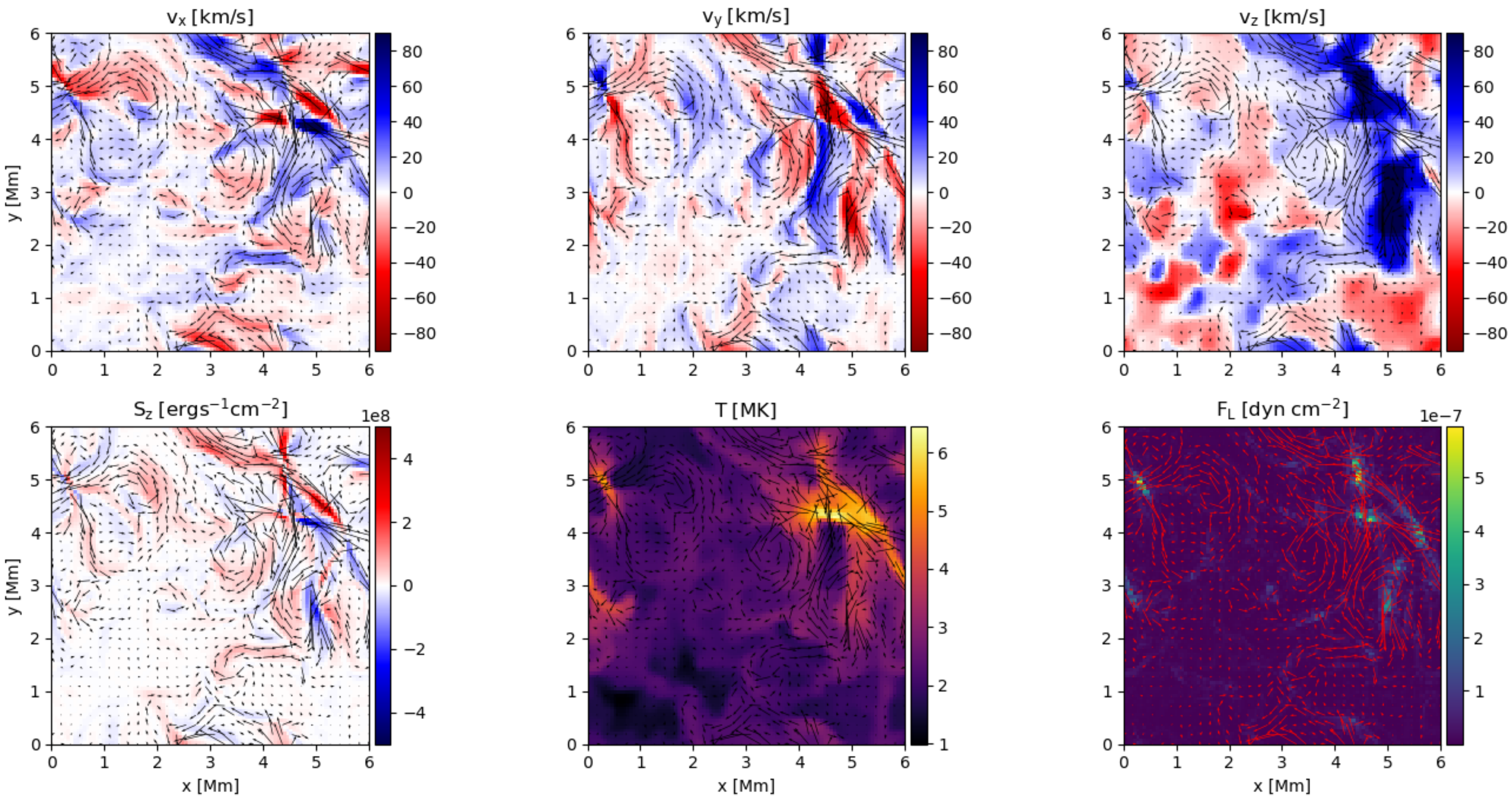




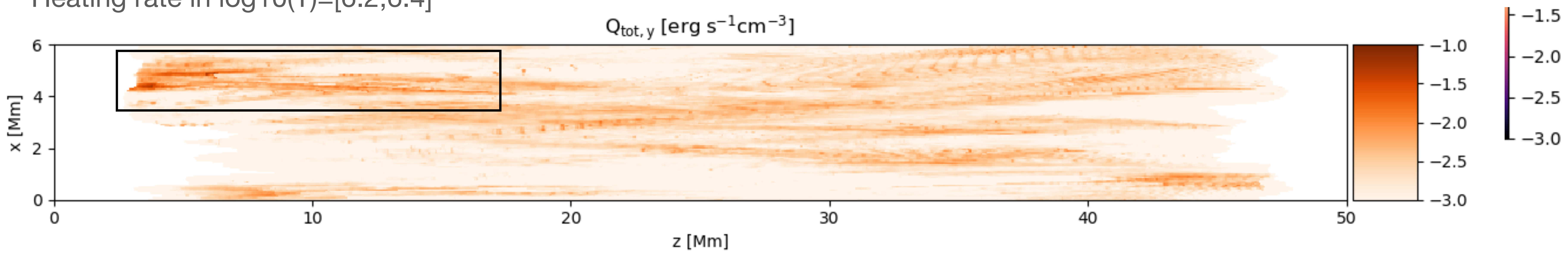


Heating event

- Very hot plasma > 6 MK at heating site
- Energy content: 9x10 erg [27]
- Three strong line broadening events in 500 seconds



Heating rate in log10(T)=[6.2,6.4]



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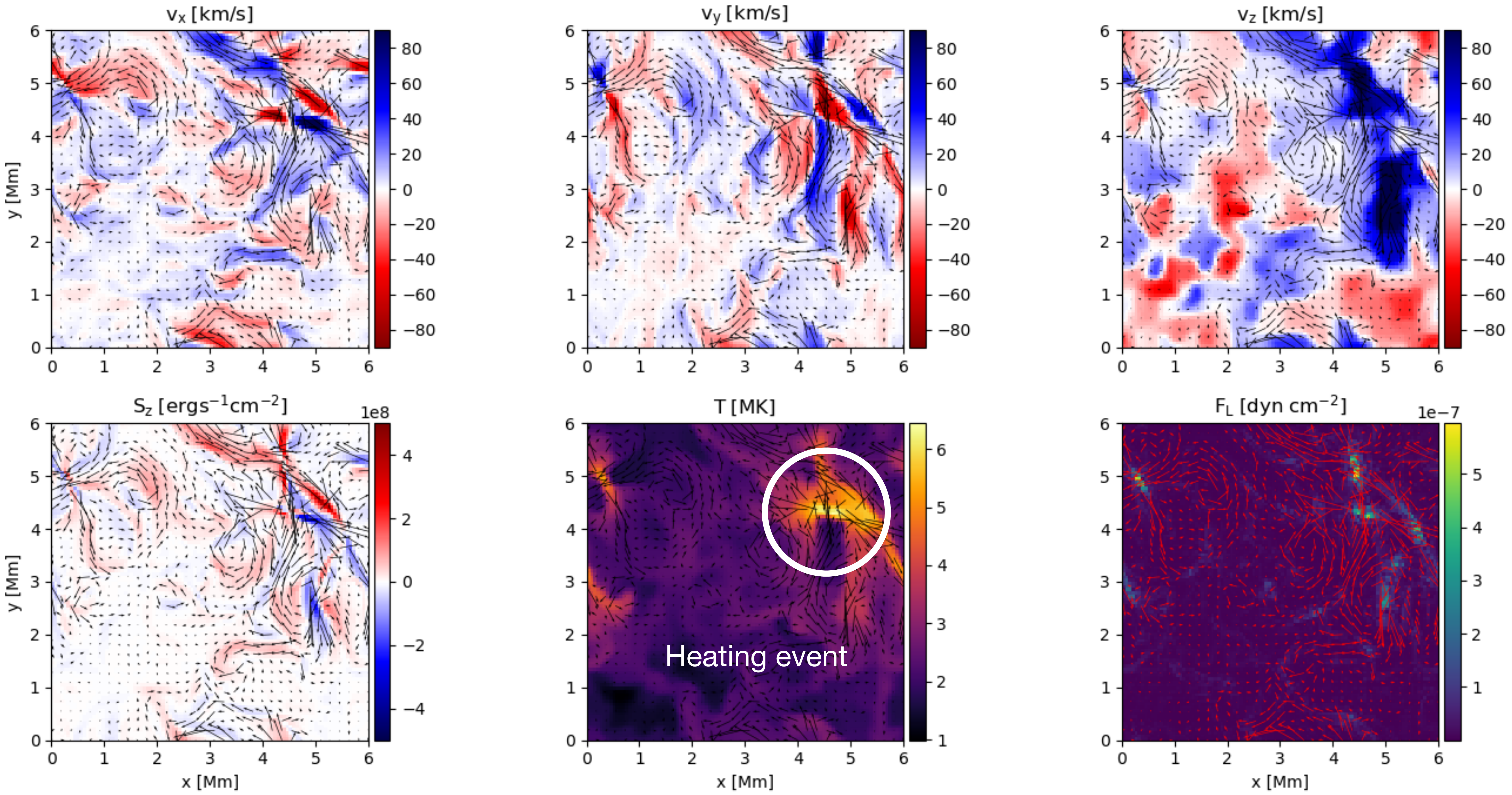

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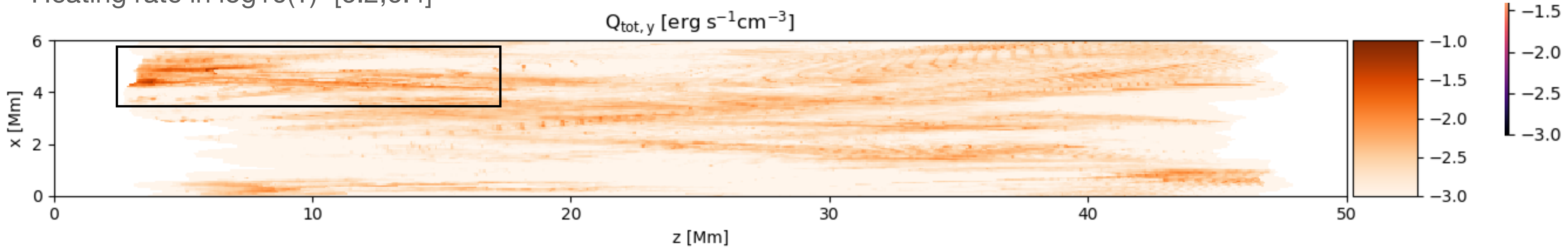
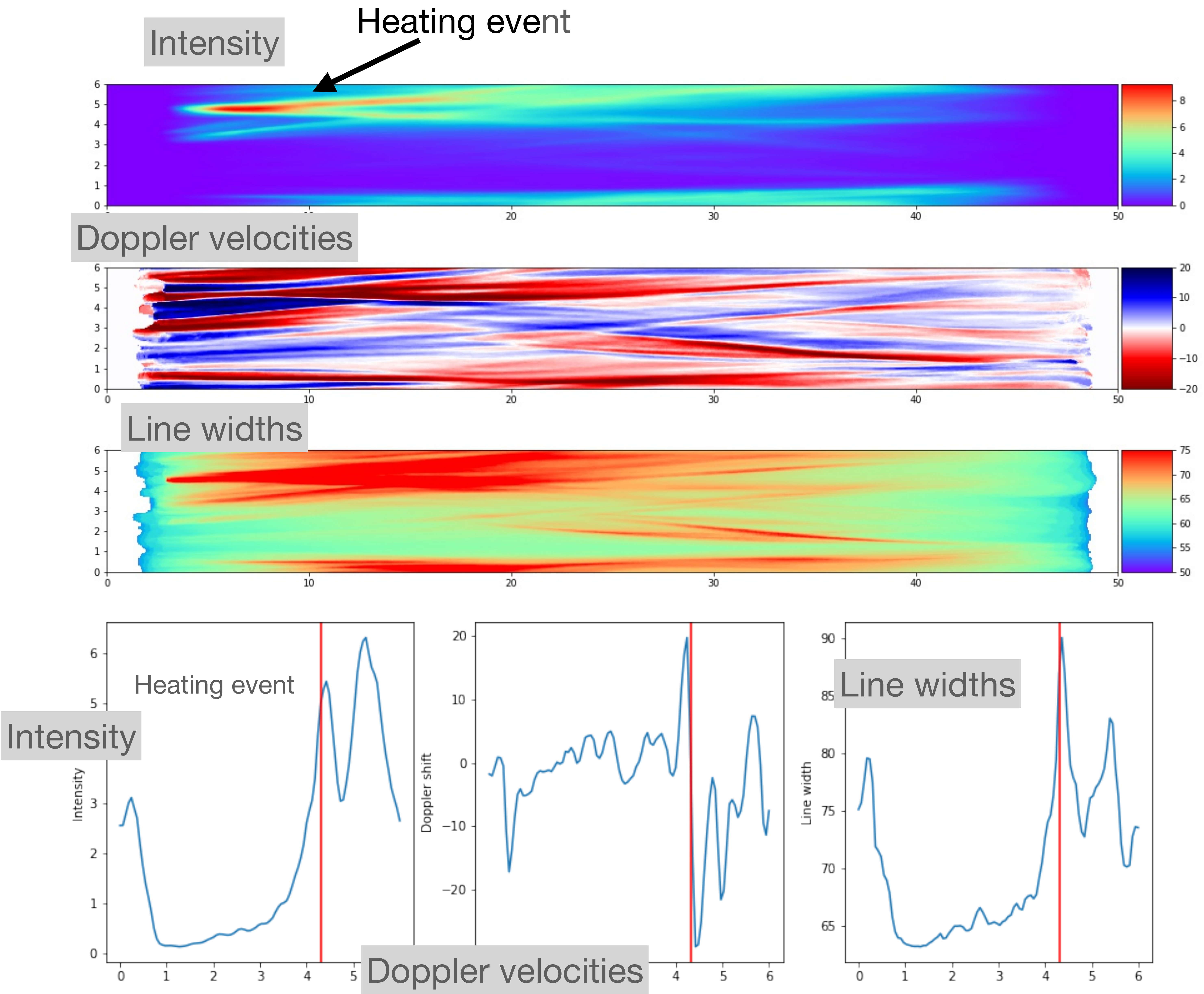


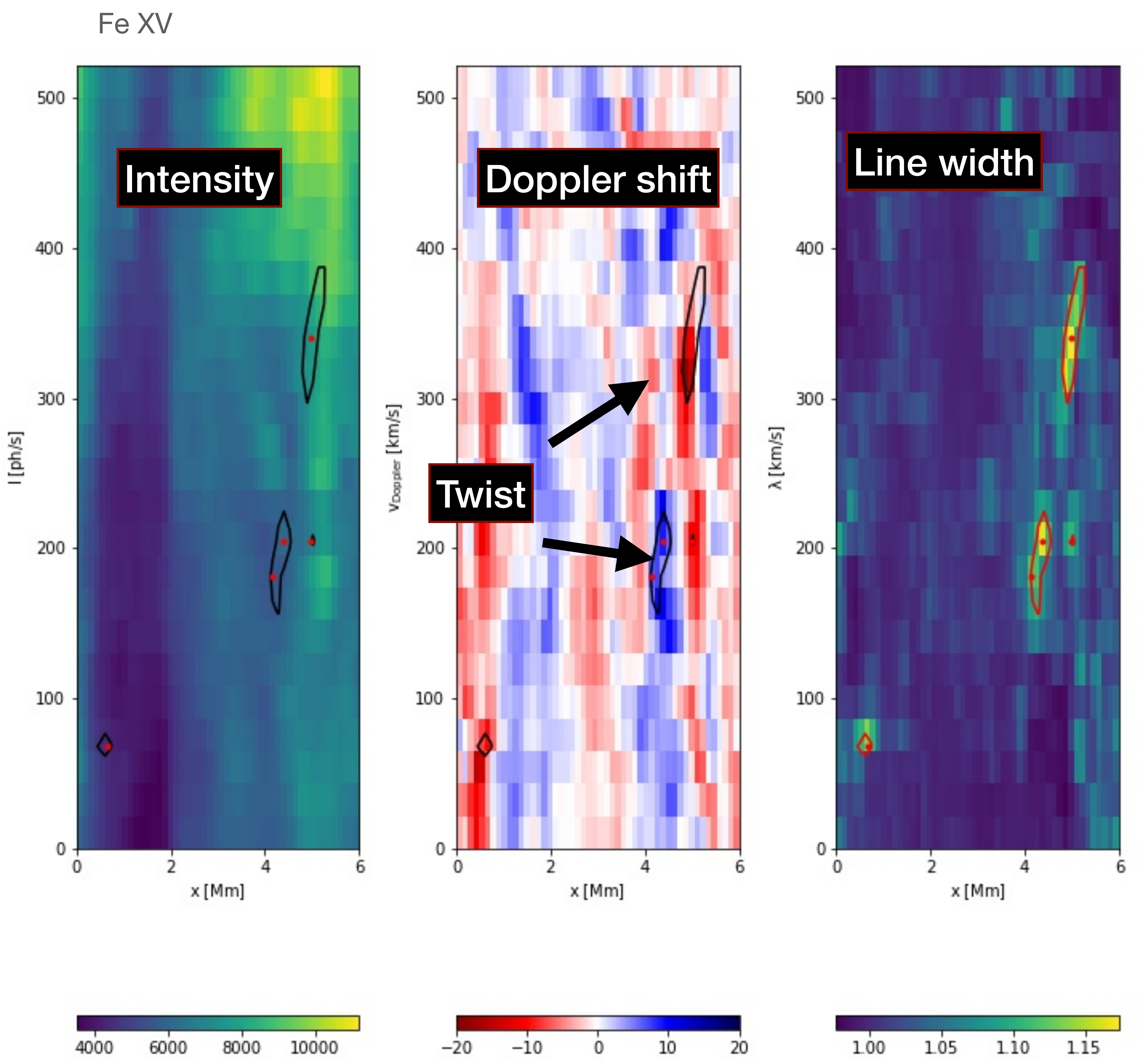
Fe XIX Emission

- Heating events produce plasma > 6 MK
- Emitted by plasma at temperatures of log(T)=[7.0,7.1]
- Low filling factor -> low photon count rates
- Increase exposure time?



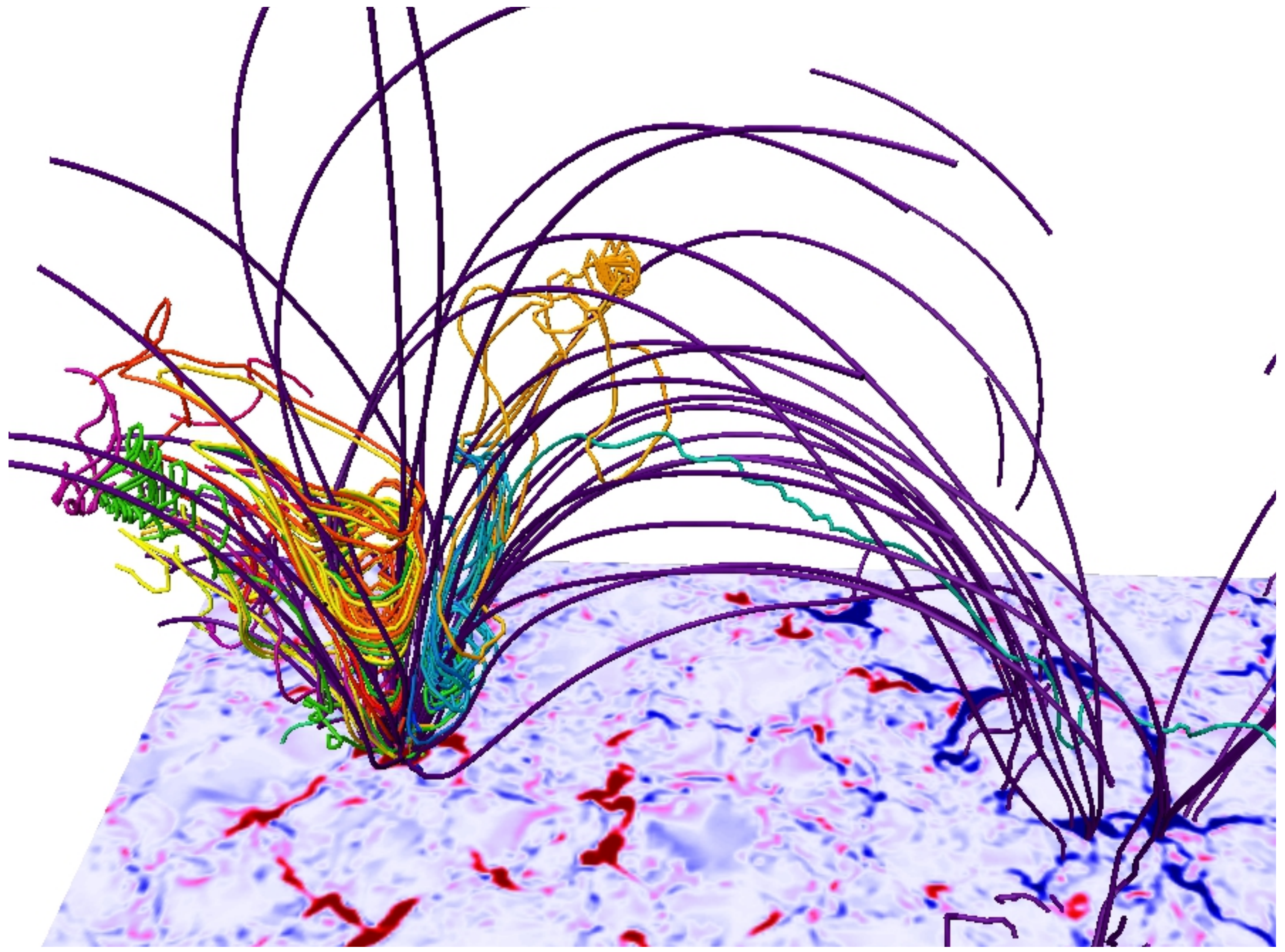
Time integration

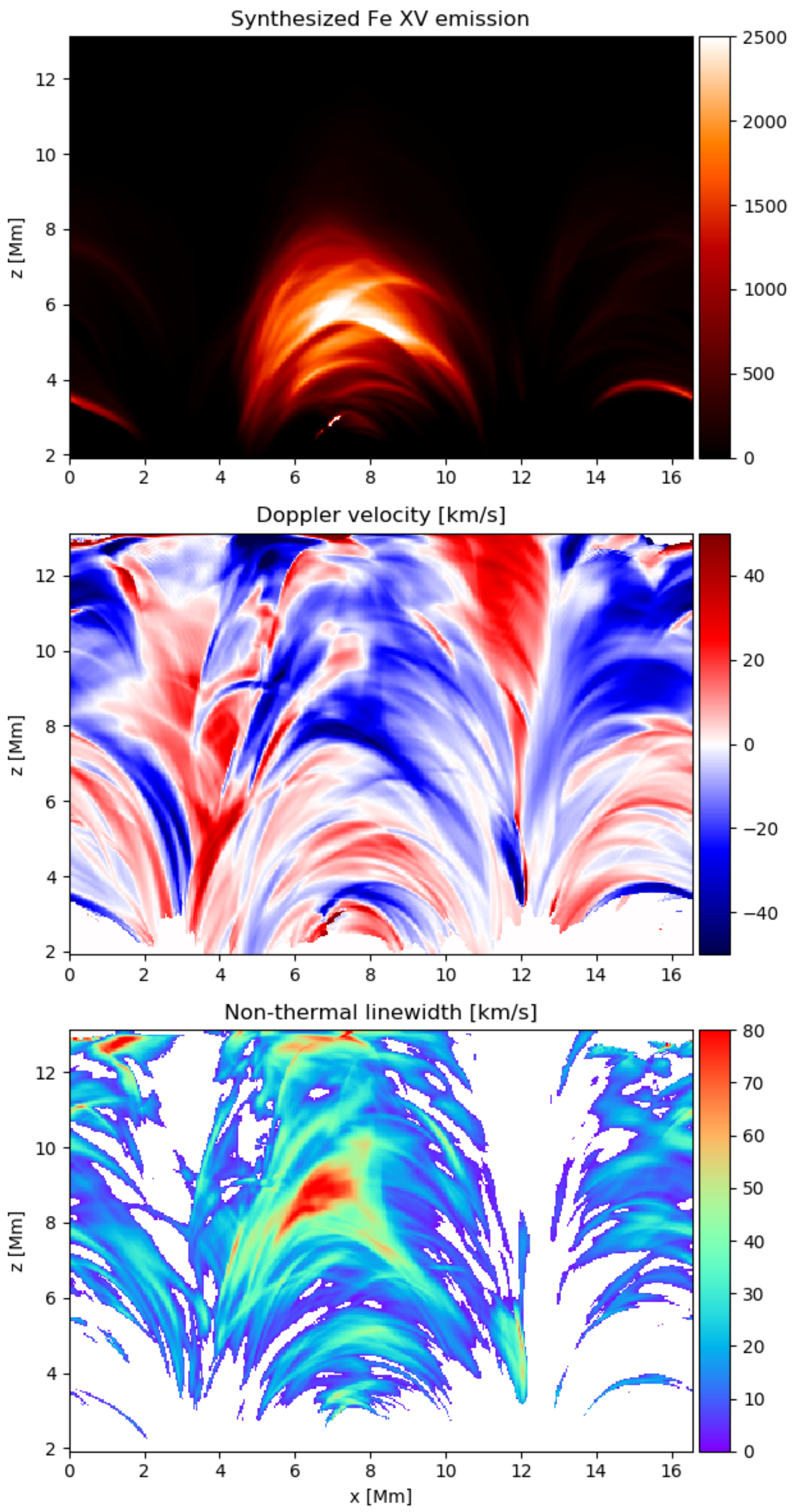
- Integrate to obtain higher photon count
- Integration over ~20 s
- Signal in Doppler shift and line width retained



Outlook

- Distinguish between jets, swirls and shear flows?
- Loop needs to be embedded in larger domain
- Higher grid resolutions -> smaller scales
- Realistic loop geometry
- Signatures of propagation?





Conclusions

- Strands in emission, Doppler shifts and Non-thermal line width
- Increased line width co-occurring with alternating Doppler shift
- Not necessarily associated with brightening
- Velocity field shows swirls and jets
- Problem: low count rates -> need to integrate in time while not smoothing out event
- Swirls produce signatures in line width and Doppler shift, BUT: Swirls and jets can produce similar signatures