A Coronal Loop Braided by Realistic Photospheric Motions

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Motivation

- Which processes heat coronal loops to temperatures of several million Kelvin?
- How are mass and energy exchanged between chromosphere and corona?
- How are coronal loops magnetically connected to the photosphere?
- What determines the substructure of a coronal loop?

Current coronal models of active regions do not resolve internal loop structure, dynamics and turbulence
→ Model an isolated loop in a Cartesian box

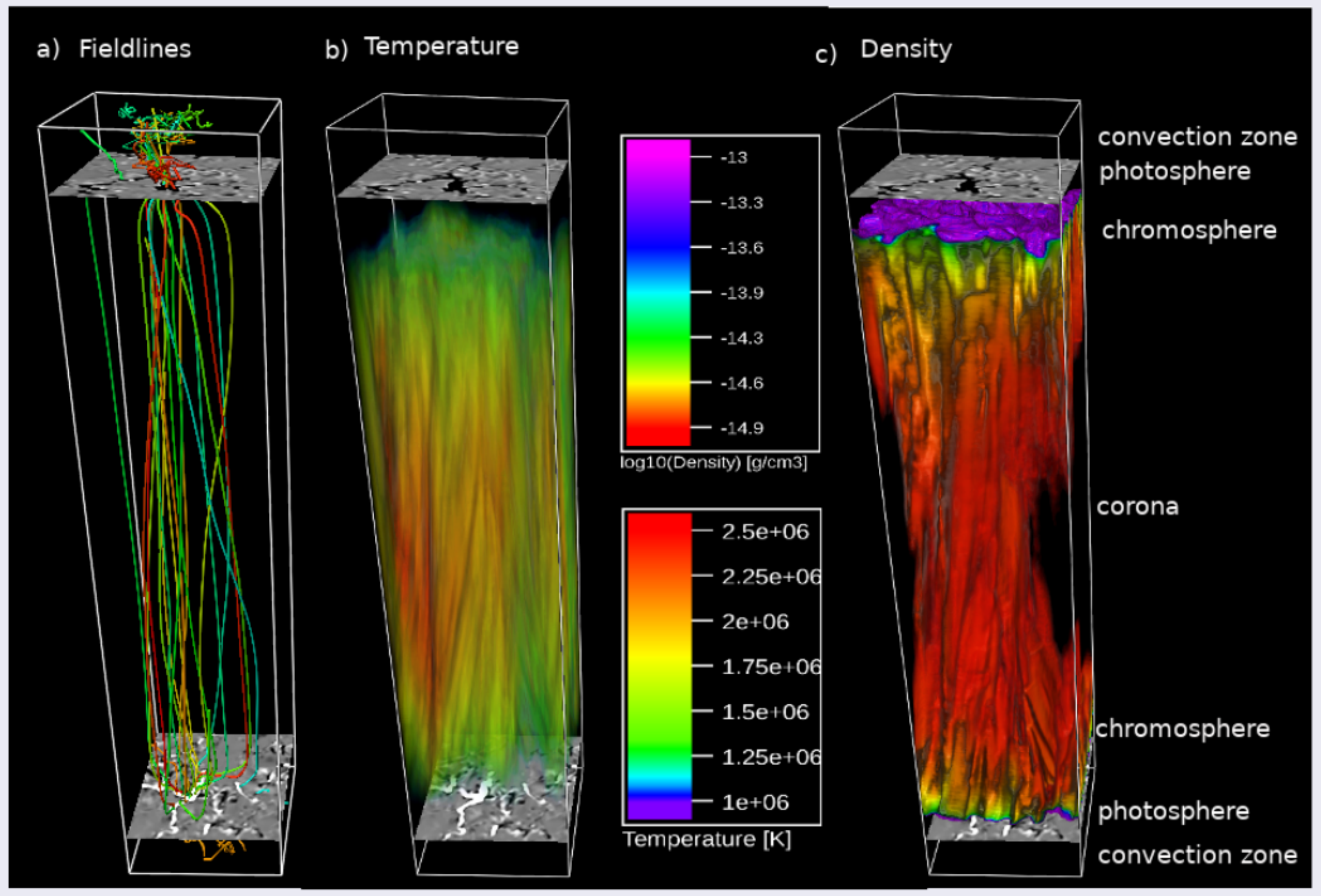
Methods

- 3D resistive MHD simulations
- MURaM code [1, 2, 3]
- Self-consistent convection zone and photosphere
- Adapted for straightened loop setup
- Computational Box: $6 \times 6 \times 57$ Mm ($100 \times 100 \times 950$ Gridpoints)
- $\Delta x = \Delta y = 60$ km
- Spitzer heat conduction
- Grey radiative transfer (photospheric layers)
- Optically thin radiative losses (corona)

The energisation of the loop is self-consistently driven by the near-surface convection.

Loop Model

- Stratified atmosphere for a semicircular loop
- Uniform magnetic field along loop axis
- B = 30 G



Simulation setup. (a) Example magnetic field lines in the simulation box traced from locations with strong magnetic field. The vertical magnetic field is plotted on a horizontal cut at the average photospheric height. (b) Volume rendering of the loop temperature. (c) Volume rendering of the loop density. The z-axis (along the loop) has been compressed by a factor of two for better visibility. The magnetic field lines show signs of twisting and braiding.

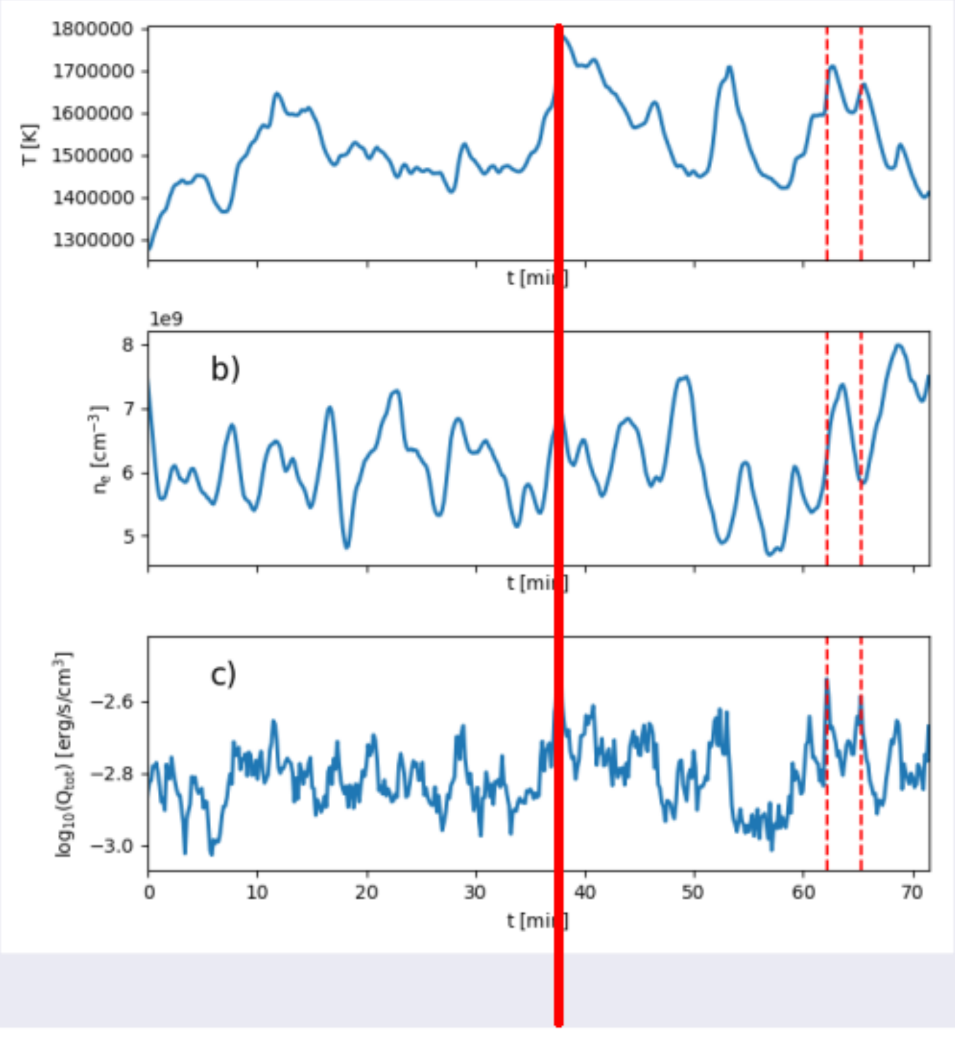
References

[1] A. Vögler, S. Shelyag, M. Schüssler, F. Cattaneo, T. Emonet, and T. Linde. Simulations of magneto-convection in the solar photosphere. Equations, methods, and results of the MURaM code. , 429:335–351, Jan 2005.

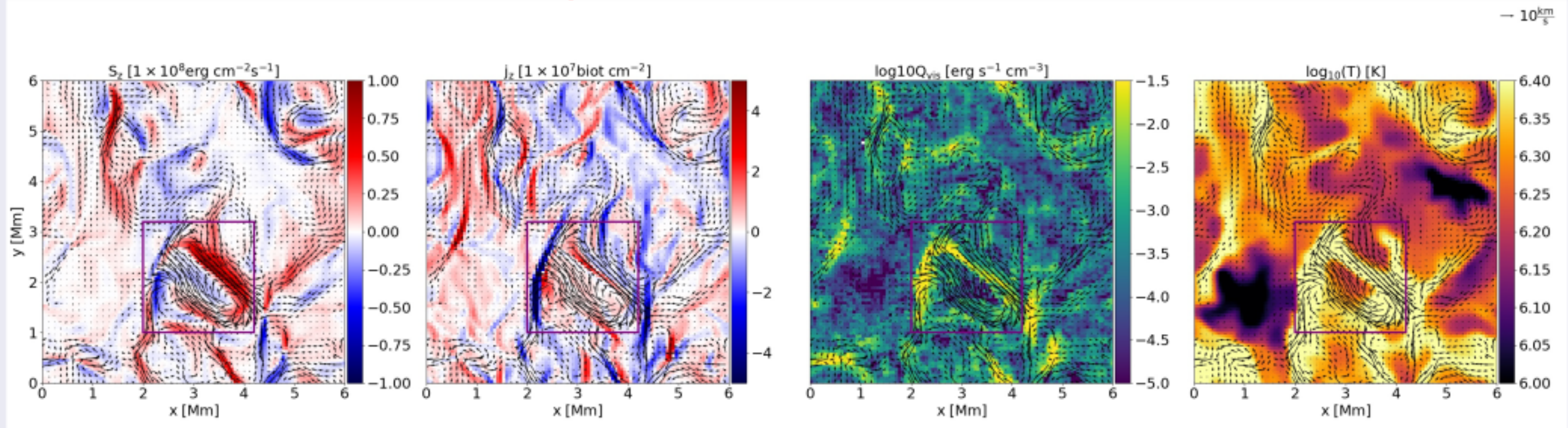
[2] M. Rempel. Numerical Simulations of Quiet Sun Magnetism: On the Contribution from a Small-scale Dynamo. , 789(2):132, July 2014.

[3] M. Rempel. Extension of the MURaM Radiative MHD Code for Coronal Simulations. , 834(1):10, January 2017.

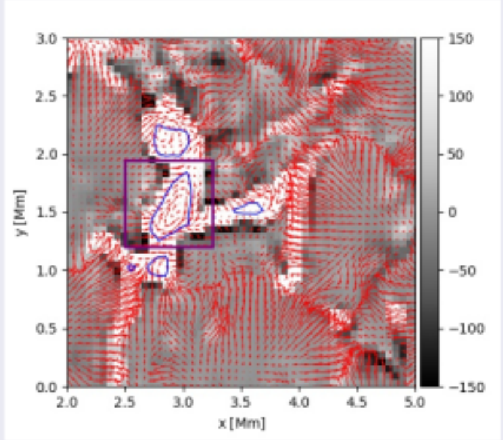
Heating Events



Averaged quantities in the coronal part of the simulation domain as a function of time. Panel a) shows the temperature, panel b) the electron density and panel c) the sum of viscous and resistive heating. All quantities have been averaged over regions with densities below 10^{-12} g/cm^3. The vertical dashed lines highlight several strong heating events. The heating is bursty, energy is injected in short pulses ranging from seconds to minutes in duration. The corona responds with an increase in temperature and density through chromospheric evaporation.



Cross section perpendicular to the loop axis at a height of 14.5 Mm at 37.7 min. From left to right: Axial component of the Poynting flux, axial component of the current density, viscous heating rate and temperature. The purple box highlights the location of a tube with enhanced heating rate and temperature at the edges.



Vertical magnetic field at the photosphere. The Poynting flux causing the heating event at originates from small-scale motions within the magnetic concentrations in the intergranular lanes.
The heated strand is rooted in the vortex highlighted by the purple box. Vortices form a connection between the photosphere and corona.

Synthetic Observables

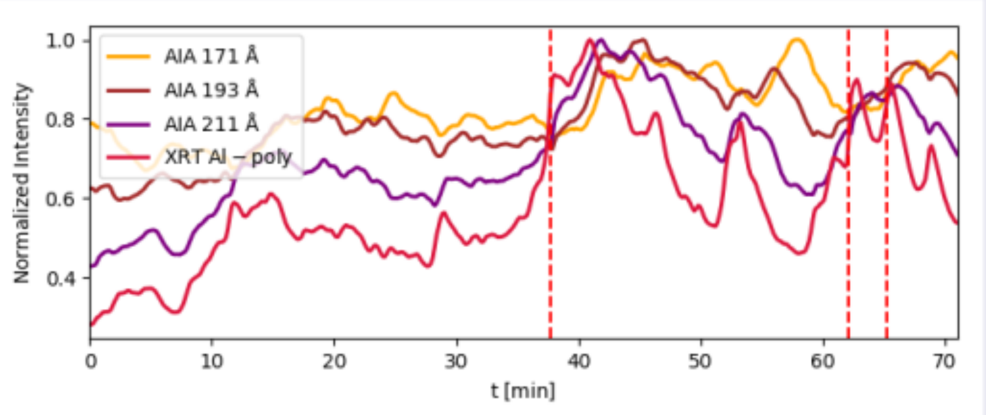
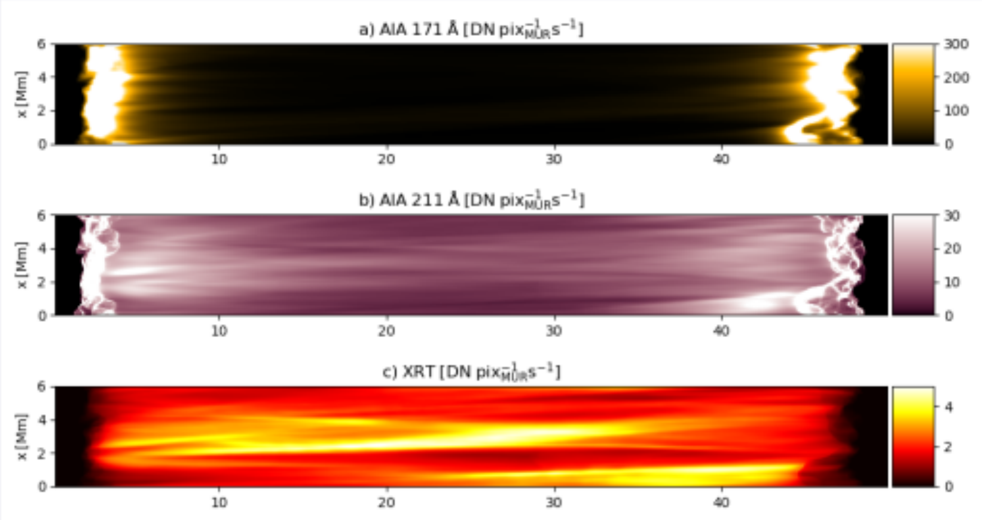


Figure:

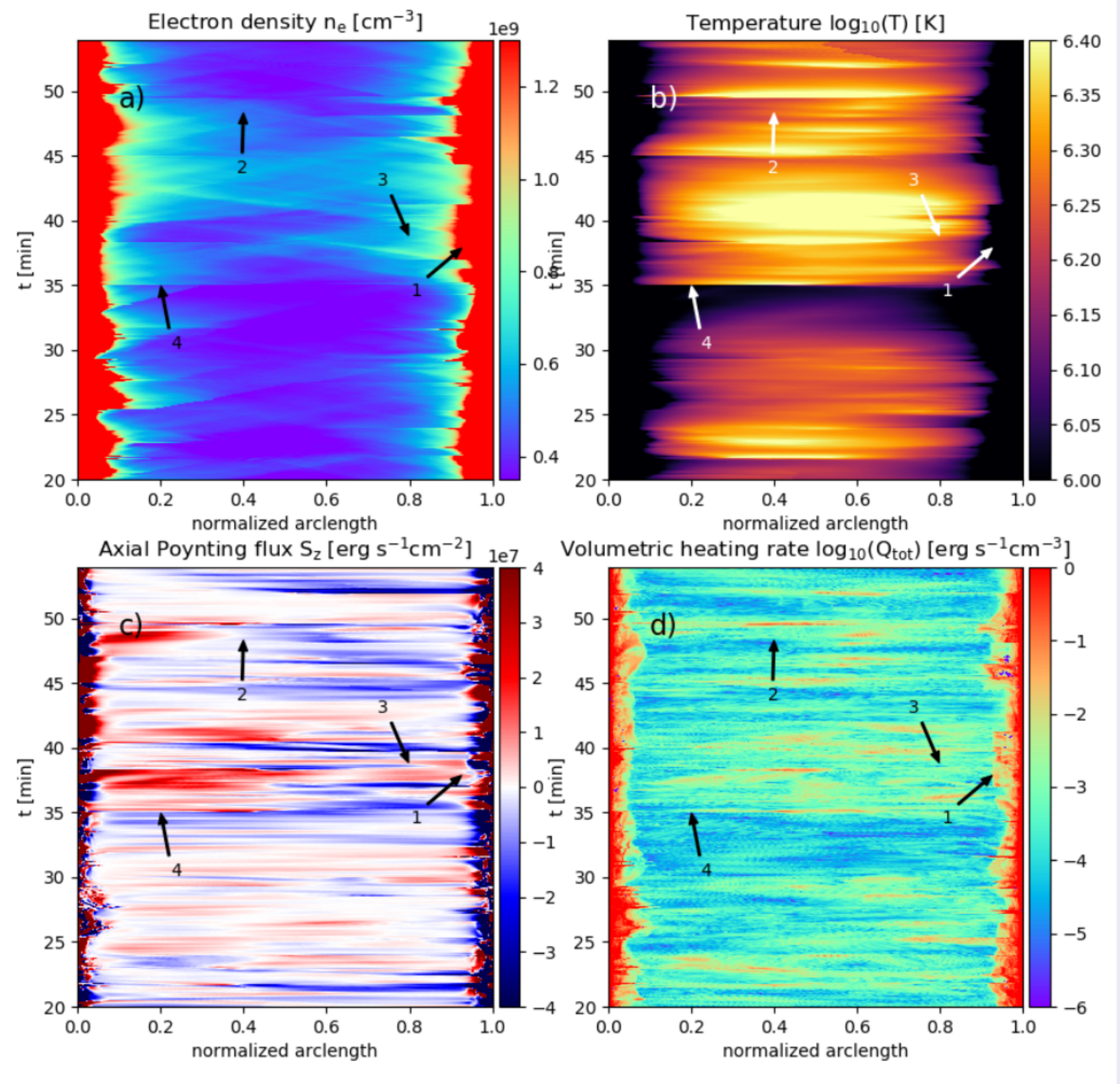
Normalized intensity integrated over the coronal part of the simulation domain as a function of time for the 171 Å and 211 Å AIA bands as well as the Al-poly filter of XRT. The vertical dashed lines highlight the three strongest heating events.



View of the simulated loop from the side as seen in EUV and X-ray observations.

- Coronal Emission in EUV and X-Ray shows clear substructure
- Bright thin, transient strands with a width of 105-900 km (AIA) and 170-740 km (XRT)

Evolution along a Fieldline



Spatio-temporal evolution along a single field line. The quantities shown are electron density a), temperature b), axial component of the Poynting flux c) and total heating rate d). The arrows mark locations of Poynting flux reaching the opposite chromosphere (1), dissipation (2) and reconnection (3).

Conclusion

- Self-consistent simulation of a coronal loop in a box including the photosphere
- Poynting flux originates from strong magnetic elements showing coherent internal motions
- Vortices channel Poynting flux into the corona
- Heating events lead to thin transient strands of hot plasma seen in synthesized emission

Outlook

- What spatial scales and timescales dominate coronal heating?
- What role do waves play?
- What non-thermal line broadening results from flows in the loop?
- What drives upflows/jets at the loop footpoints?
- Extremely high resolution simulation (3-6 km) using GPU version of MURaM

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