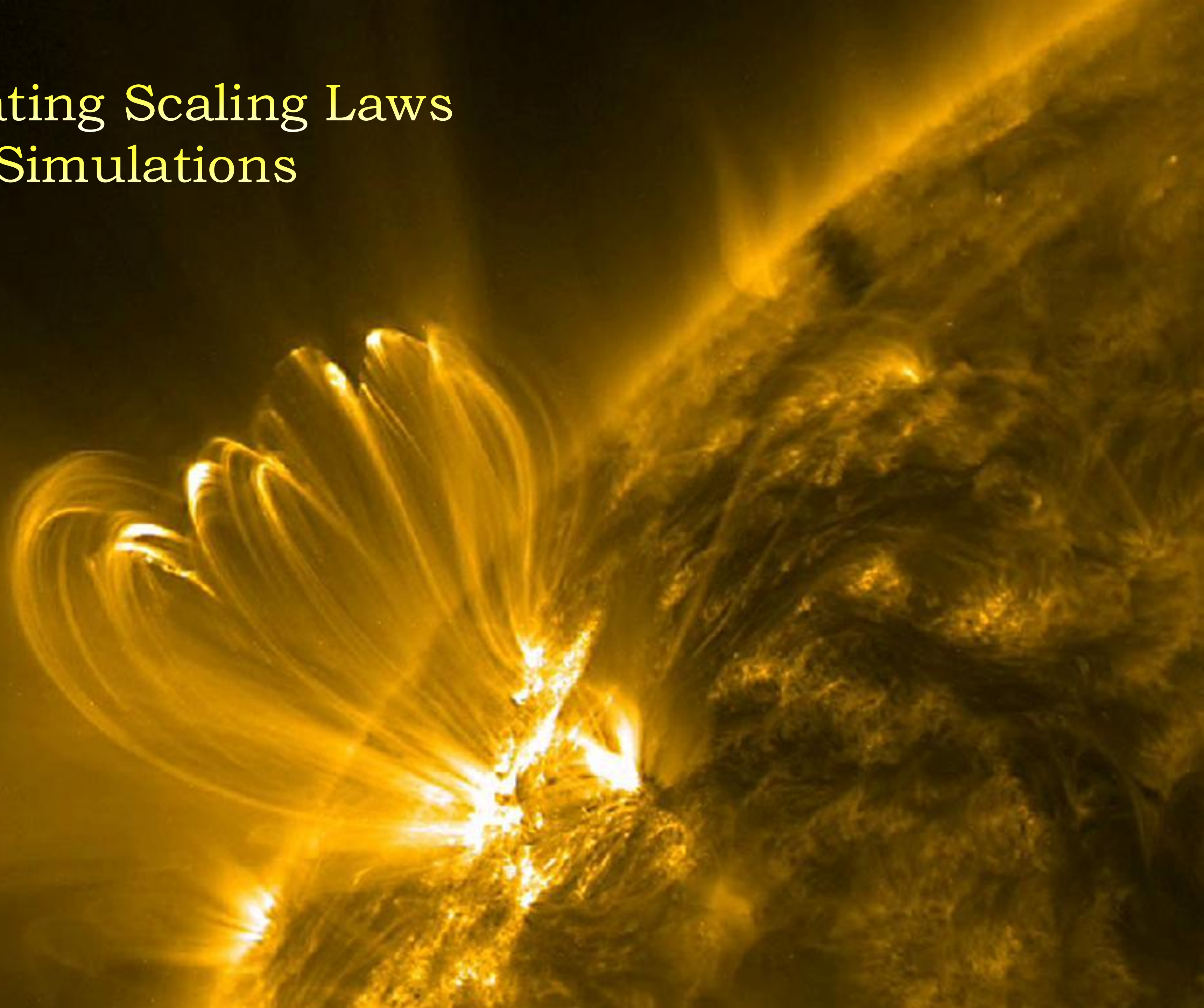
Deriving Coronal Heating Scaling Laws from 3D MHD Simulations



March 18, 2026

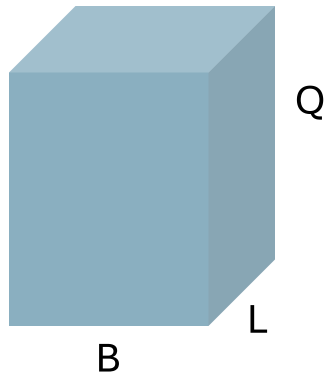
Big picture

Understand *reconnection-driven nanoflares* powering active region (AR) heating.

Build physical insight for predicting solar spectral irradiance variability

Approach

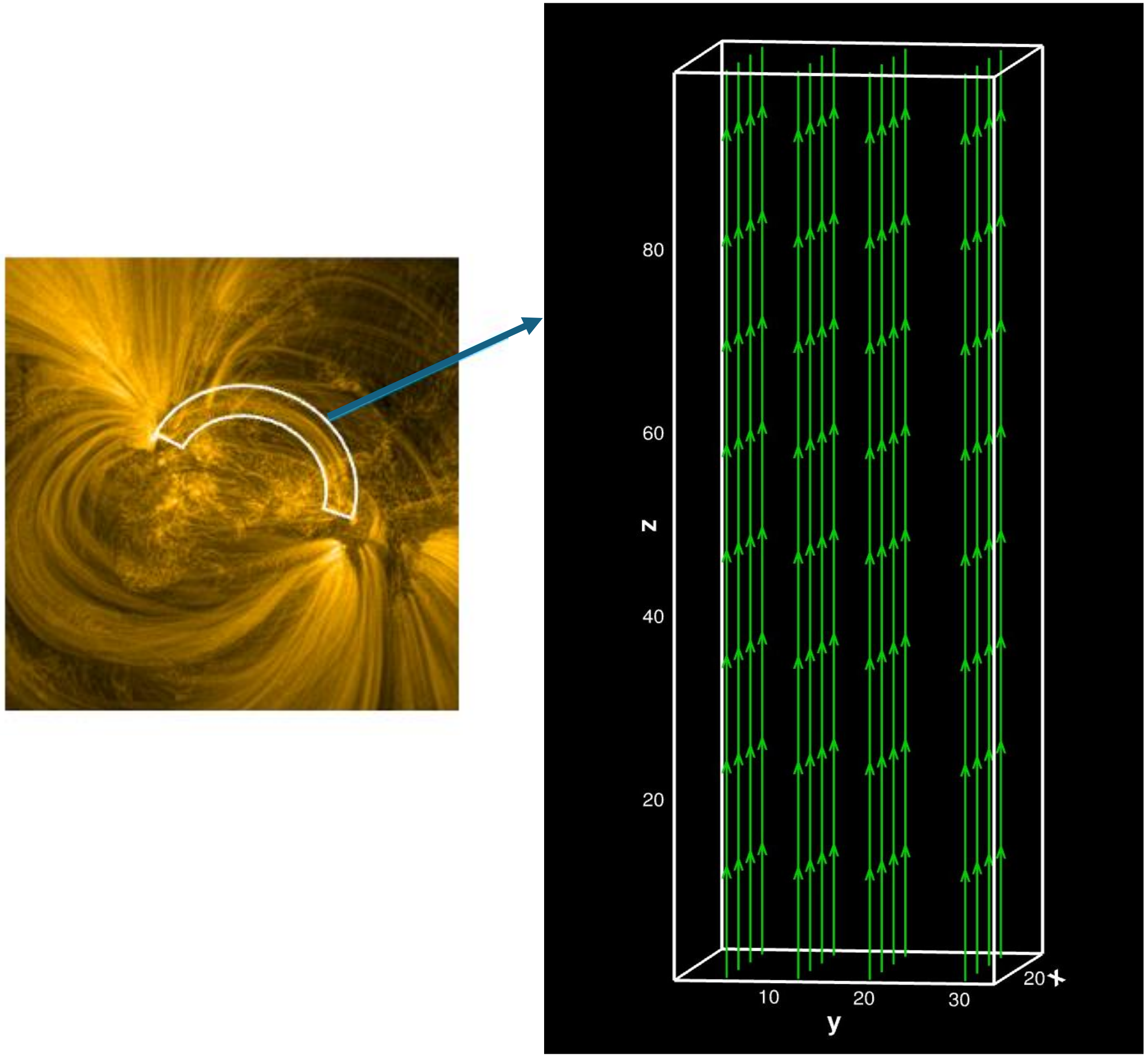
1. Start simple: simulate a small subset of ARs (uniform B and L)
2. Build a large library of multi-strand models across realistic conditions.
   - Each model → time-averaged plasma thermal distribution → $Q(B, L)$
3. Use GX Simulator to model real ARs
   - Input: observed magnetograms → magnetic field extrapolation
   - Populate the magnetic skeleton using best-matching multi-strand models from the library



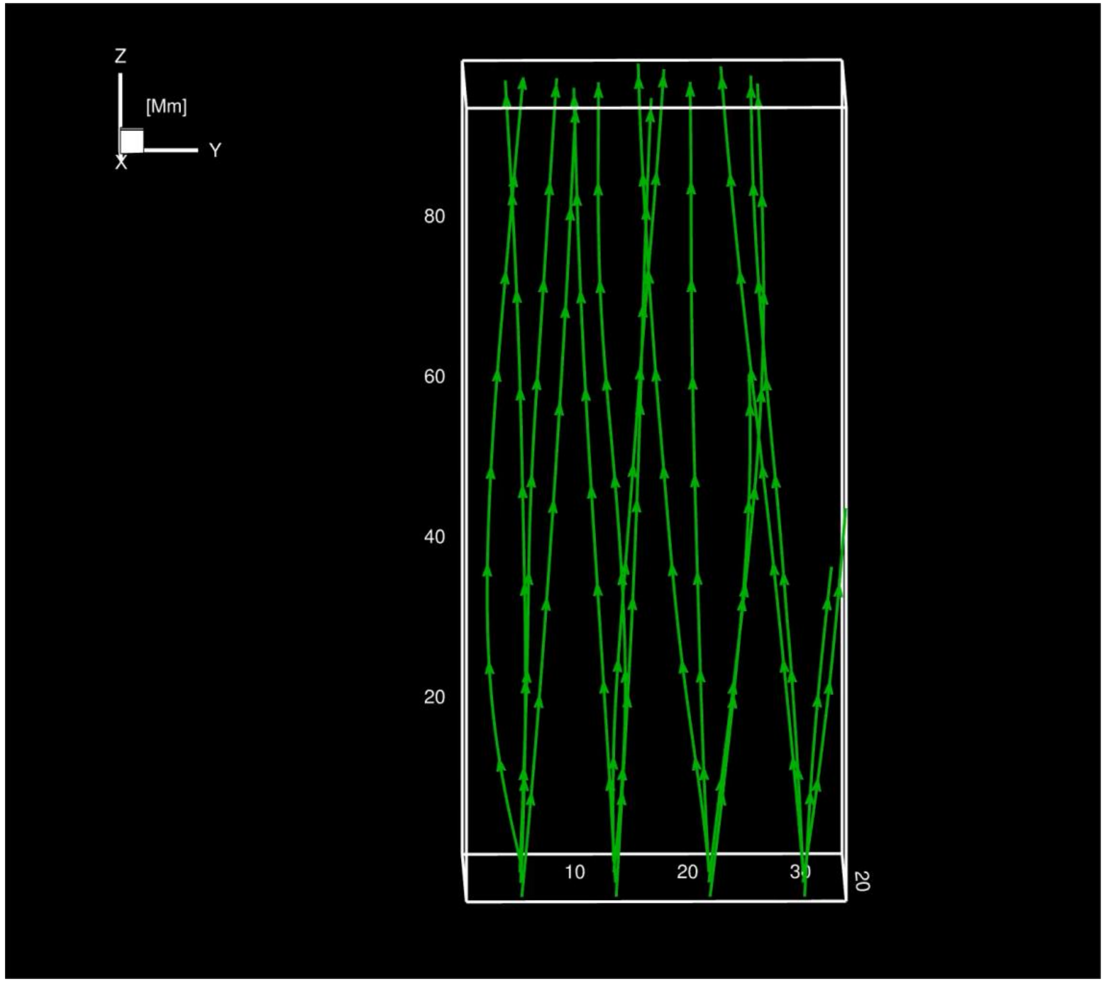
Crucial for *constraining the physical processes* responsible for heating the solar corona.

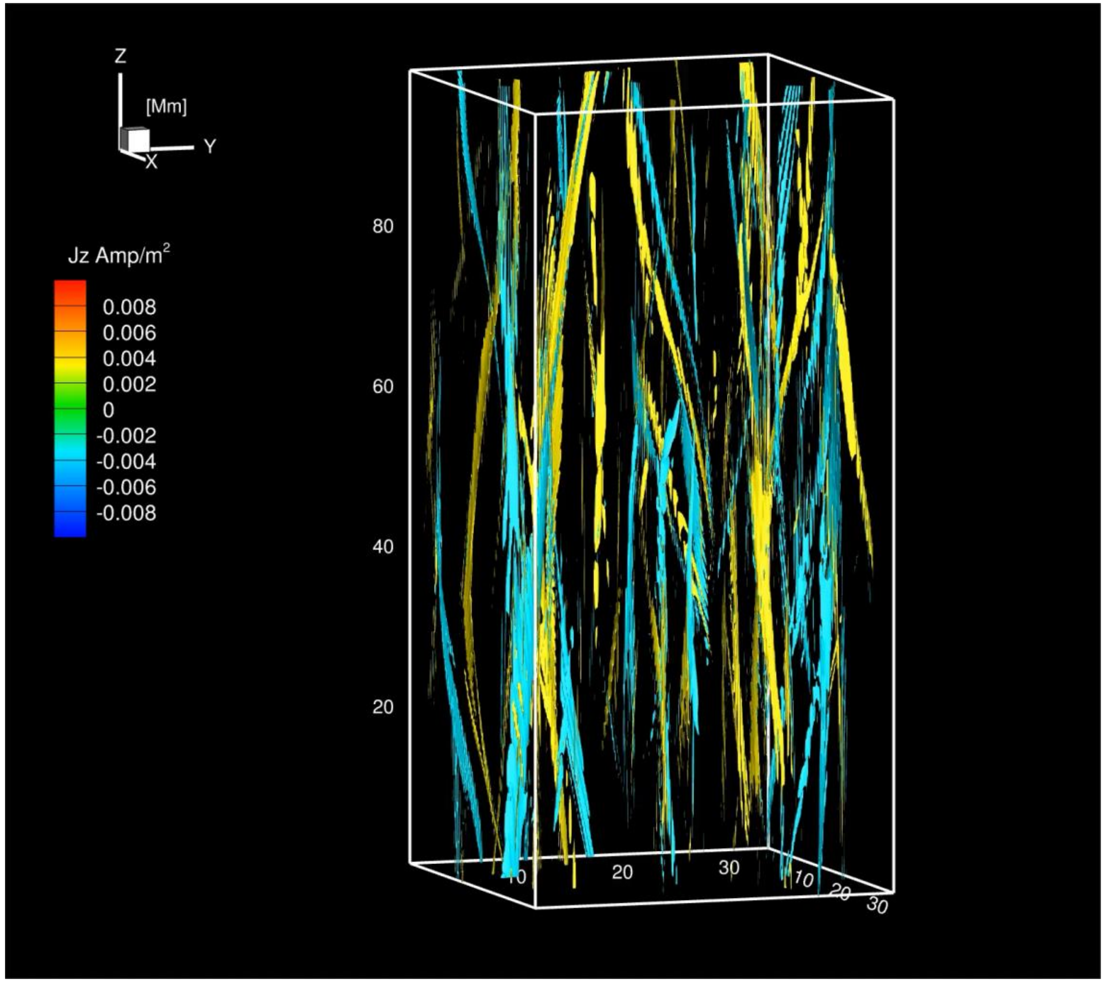
$$Q \propto B^a L^b$$

Simulation of a subset of an Active Region

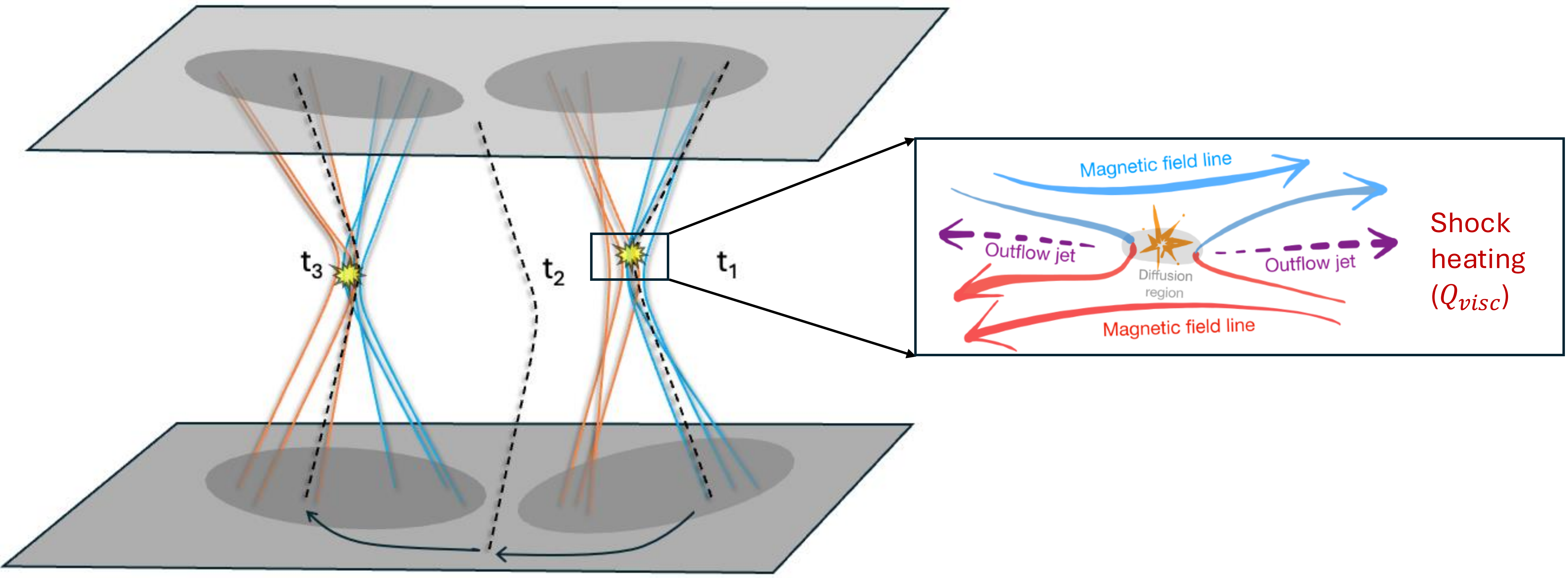


Simulation of a subset of an Active Region

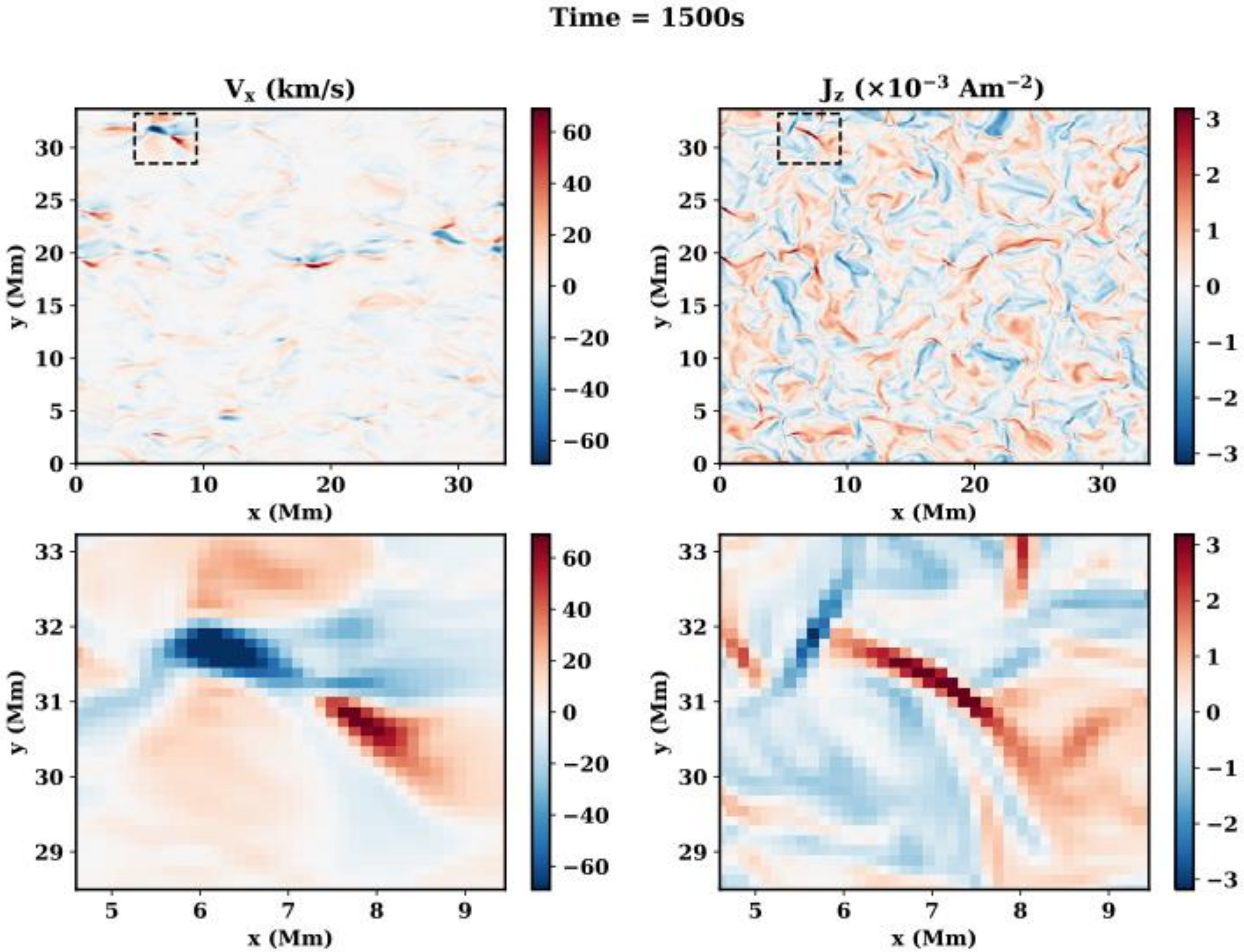




Quantify energy released in reconnection events



Reconnection signatures



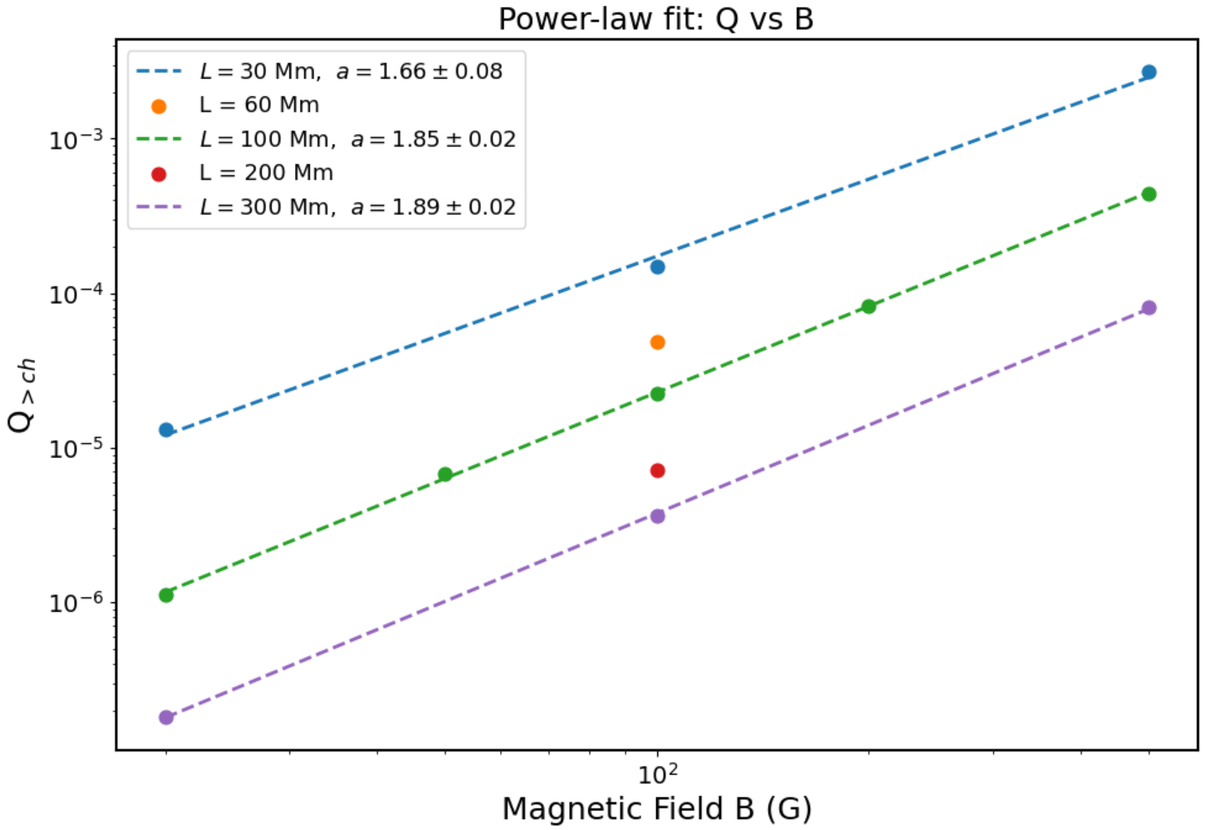
Parameter space

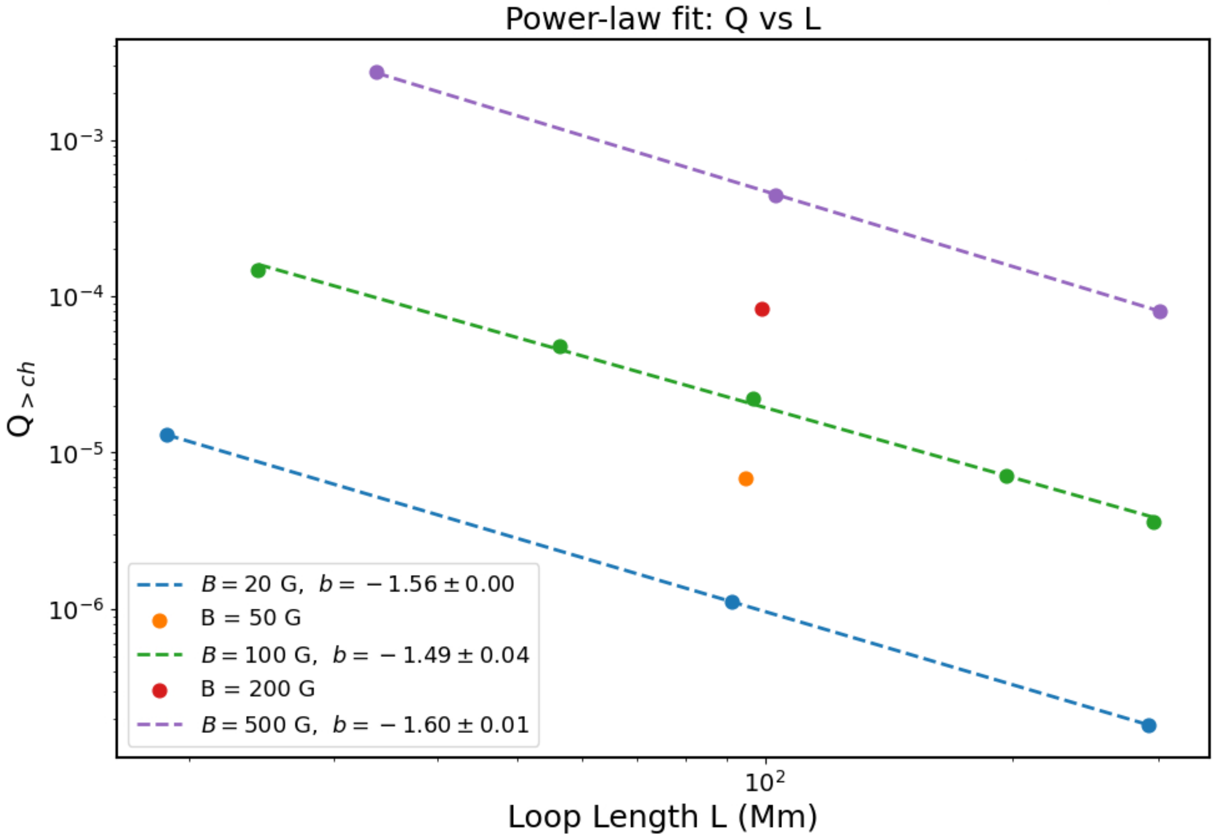
L

B

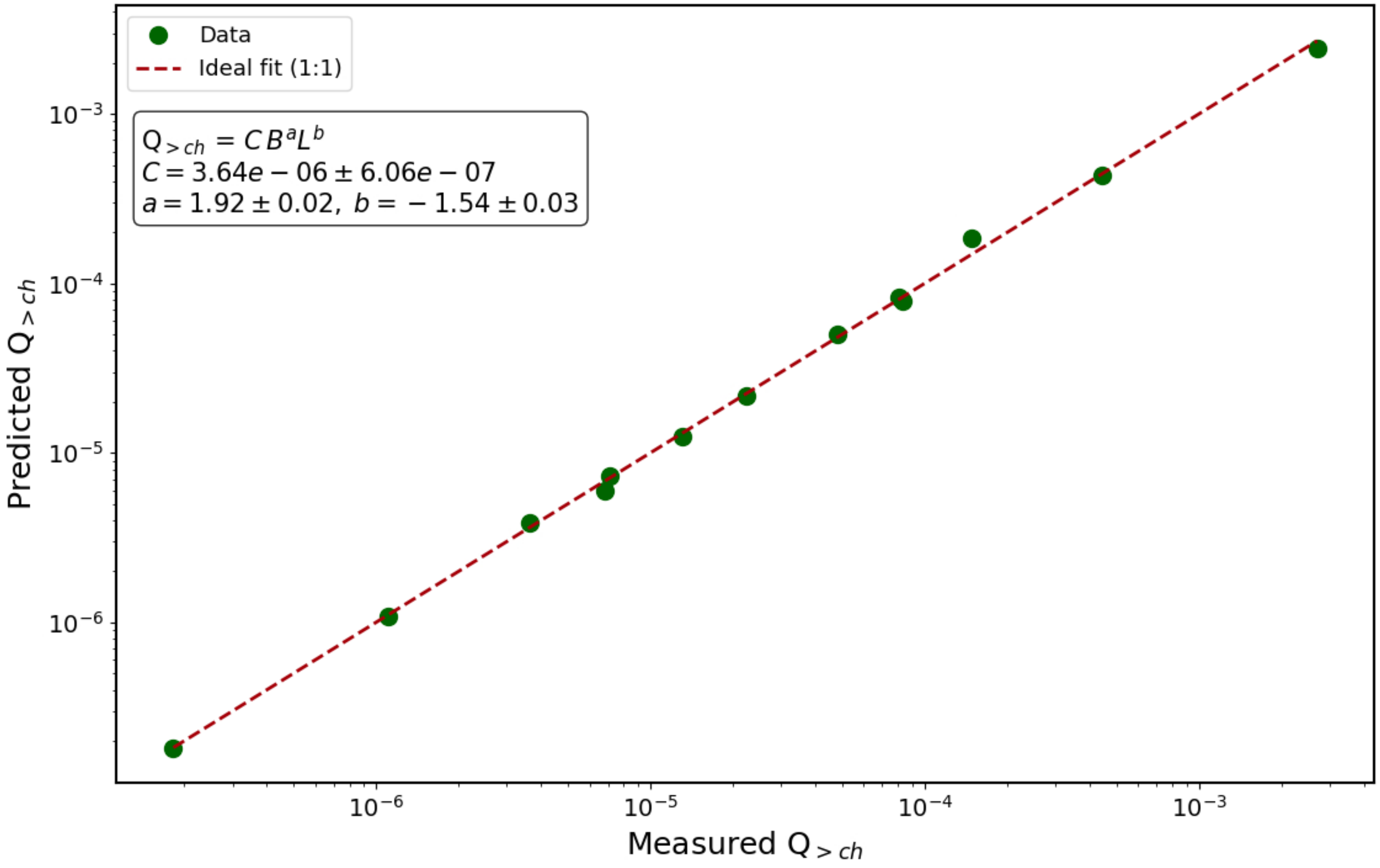
	30 Mm	60 Mm	100 Mm	200 Mm	300 Mm
20 G					
50 G					
100 G					
200 G					
500 G					

Scaling Laws





$$Q = C * B^a * L^b$$



Data
Ideal fit (1:1)
$Q_{>ch} = C B^a L^b$
$C = 3.64e-06 \pm 6.06e-07$
$a = 1.92 \pm 0.02,\ b = -1.54 \pm 0.03$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Predicted $Q_{>ch}$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
Measured $Q_{>ch}$

$$\mathcal{F}(B, L) = C * B^{a} * L^{b}$$

$\mathcal{F}$	C	a	b
$Q_{>ch}(J\ m^{-3}\ s^{-1})$	$3.64 \times 10^{-6} \pm 6.06 \times 10^{-7}$	1.92 ± 0.02	-1.54 ± 0.03

$$\mathcal{F}(B, L) = C * B^{a} * L^{b}$$

$\mathcal{F}$	C	a	b
$Q_{>d}\ (J\ m^{-3}\ s^{-1})$	$2.25 \times 10^{-5} \pm 5.96 \times 10^{-6}$	1.84 ± 0.03	-1.79 ± 0.05
$Q_{>ch}(J\ m^{-3}\ s^{-1})$	$3.64 \times 10^{-6} \pm 6.06 \times 10^{-7}$	1.92 ± 0.02	-1.54 ± 0.03
$Q_{>TR}\ (J\ m^{-3}\ s^{-1})$	$2.94 \times 10^{-6} \pm 5.08 \times 10^{-7}$	1.92 ± 0.03	-1.51 ± 0.030

$$\mathcal{F}(B, L) = C * B^a * L^b$$

$\mathcal{F}$	C	a	b
$Q_{>d}\ (J\ m^{-3}\ s^{-1})$	$2.25 \times 10^{-5} \pm 5.96 \times 10^{-6}$	1.84 ± 0.03	-1.79 ± 0.05
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Coronal Heating Scenario	Scaling Law
Critical angle	$Q \propto B^2\ L^{-1}$
Current sheet loss of equilibrium	$Q \propto B^2\ L^{-2}$
Multi-strand simulation	$Q \propto B^{1.9}\ L^{-1.5}$

$$\mathcal{F}(B, L) = C * B^a * L^b$$

$\mathcal{F}$	C	a	b
$Q_{>d}\ (J\ m^{-3}\ s^{-1})$	$2.25 \times 10^{-5} \pm 5.96 \times 10^{-6}$	1.84 ± 0.03	-1.79 ± 0.05
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Volumetric heating rate

Poynting flux

$$Q\ (J\ m^{-3}\ s^{-1}) = \frac{S\ (J\ m^{-2}\ s^{-1})}{L\ (m)} \quad \Rightarrow \frac{Q}{S} \propto L^{-1}$$

Loop length

$$\mathcal{F}(B,L) = C * B^{a} * L^{b}$$

$\mathcal{F}$	C	a	b
$Q_{>d}\ (J\ m^{-3}\ s^{-1})$	$2.25 \times 10^{-5} \pm 5.96 \times 10^{-6}$	1.84 ± 0.03	-1.79 ± 0.05
$Q_{>ch}(J\ m^{-3}\ s^{-1})$	$3.64 \times 10^{-6} \pm 6.06 \times 10^{-7}$	1.92 ± 0.02	-1.54 ± 0.03
$Q_{>TR}\ (J\ m^{-3}\ s^{-1})$	$2.94 \times 10^{-6} \pm 5.08 \times 10^{-7}$	1.92 ± 0.03	-1.51 ± 0.030
$\frac{Q_{>d}}{S_d}$	$3.77 \times 10^{-7} \pm 1.79 \times 10^{-8}$	-0.022 ± 0.006	-0.945 ± 0.009
$\frac{Q_{>ch}}{S_{ch}}$	$3.89 \times 10^{-7} \pm 1.01 \times 10^{-8}$	-0.030 ± 0.004	-0.945 ± 0.005
$\frac{Q_{>TR}}{S_{TR}}$	$3.82 \times 10^{-7} \pm 1.34 \times 10^{-8}$	-0.031 ± 0.005	-0.937 ± 0.006

Summary

We have performed a parameter study using 3D MHD simulations of a subset of an active region to investigate the dependence of the coronal heating rate on B and L.

By varying the magnetic field strength and loop length, we quantify the dependence of the time-averaged volumetric heating rate (Q) and derive a scaling law of the form $Q \propto B^a L^b$ with $a \sim 1.9$ and $b \sim -1.5$

The obtained scaling exponents fall within the range expected from coronal heating scenarios : Critical angle & current sheet loss of equilibrium.

The results offer constraints for theoretical models of coronal heating and can be incorporated into other models (e.g., active region or global corona) that rely on parameterized heating prescriptions.