University of St Andrews

Solar & Magnetospheric Theory Group
University of St Andrews

Coronal heating with random foot point driving: Understanding time scales

Thomas Howson Ineke De Moortel

AC vs DC heating

Two broad categories:

$\tau_{\text{driver}} < \tau_A \longrightarrow$ **AC heating models** (e.g. phase mixing, wave driven turbulence).

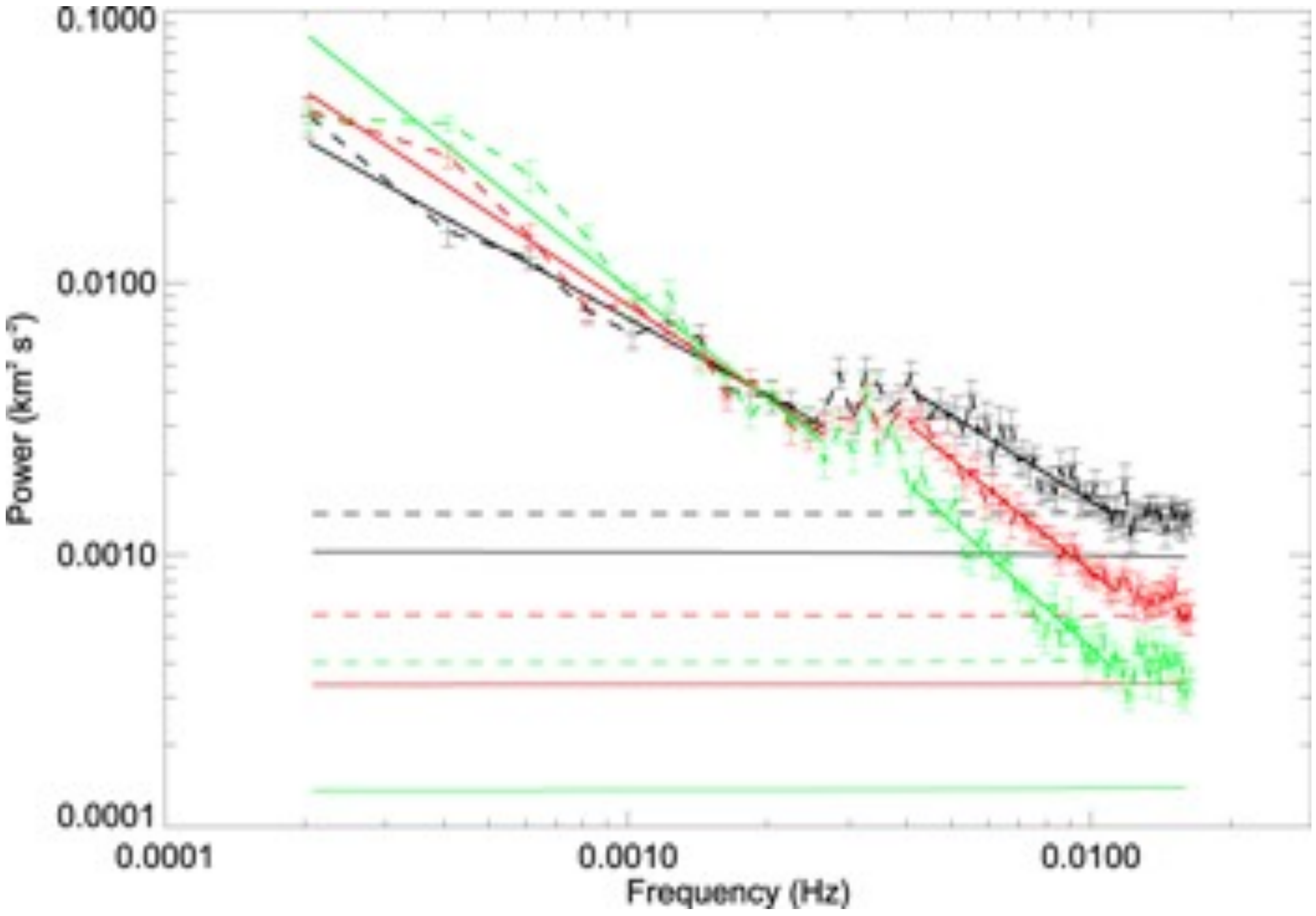
$\tau_{\text{driver}} > \tau_A \longrightarrow$ **DC heating models** (e.g. magnetic reconnection, nanoflares).

What do we want to know?
What are the effects of driving timescales on heating?
Will we be able to tell the difference in real observations?

Are ‘normal’ wave drivers underestimating energy injection as no energy stored in magnetic field?

Observed Time Scales

Observed Oscillatory Power in the Corona



Morton et al. 2016

Suppose loop with parameters:

$$L = 100 \text{ Mm}$$

$$v_A = 1000 \text{ km s}^{-1}$$

$$\tau_A = \frac{L}{v_A} = 100 \text{ s}$$

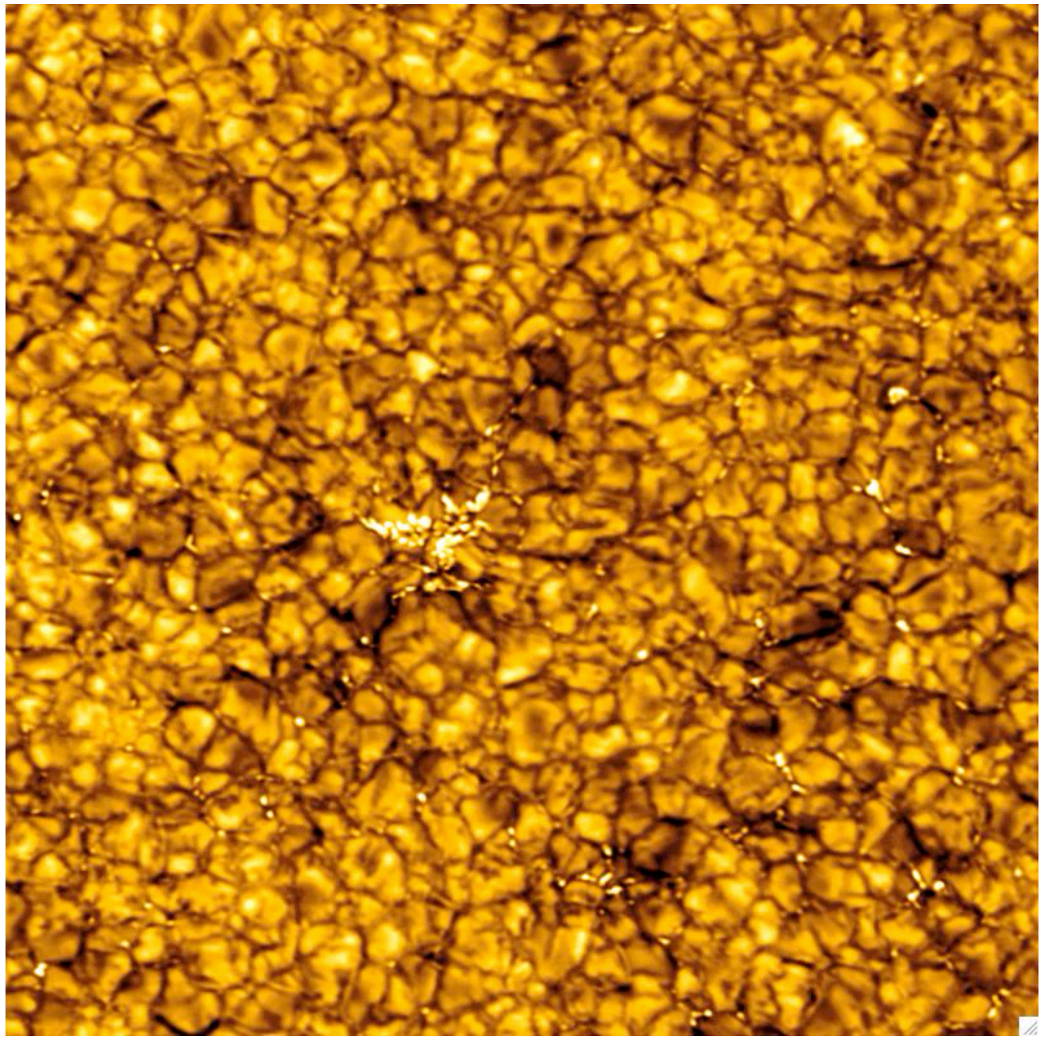
Little power observed at such high frequencies.

Suggests more energy for DC heating.

Energetics

Energy flux (no conduction through boundaries):

$$\mathbf{F} = \underbrace{\frac{\rho v^2 \mathbf{v}}{2}}_{\text{Kinetic Energy Flux}} + \underbrace{\frac{\gamma P \mathbf{v}}{\gamma - 1}}_{\text{Enthalpy Flux}} + \underbrace{\rho \Phi \mathbf{v}}_{\text{Grav. Pot. Energy Flux}} + \underbrace{\frac{\mathbf{E} \times \mathbf{B}}{\mu_0}}_{\text{Poynting Flux}}.$$



Quiet Sun - Observed 18/06/2006 SST
Rouppe van der Voort

Energy conservation:

(Neglecting thermal losses)

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\int_S \mathbf{F} \cdot \mathrm{d}\mathbf{S}.$$

Since $\mathbf{v} \cdot \mathrm{d}\mathbf{S} = 0,$ then

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{1}{\mu_0} \int_S \mathbf{E} \times \mathbf{B} \cdot \mathrm{d}\mathbf{S}.$$

Poynting Flux

Advection of existing flux

$$\eta = 0$$

$$-\frac{1}{\mu_0}\int_S \mathbf{E}\times\mathbf{B}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\mu_0}\int_S \{(\mathbf{B}\cdot\mathbf{v})\mathbf{B} - (\mathbf{B}\cdot\mathbf{B})\mathbf{v}\}\cdot \mathrm{d}\mathbf{S}$$

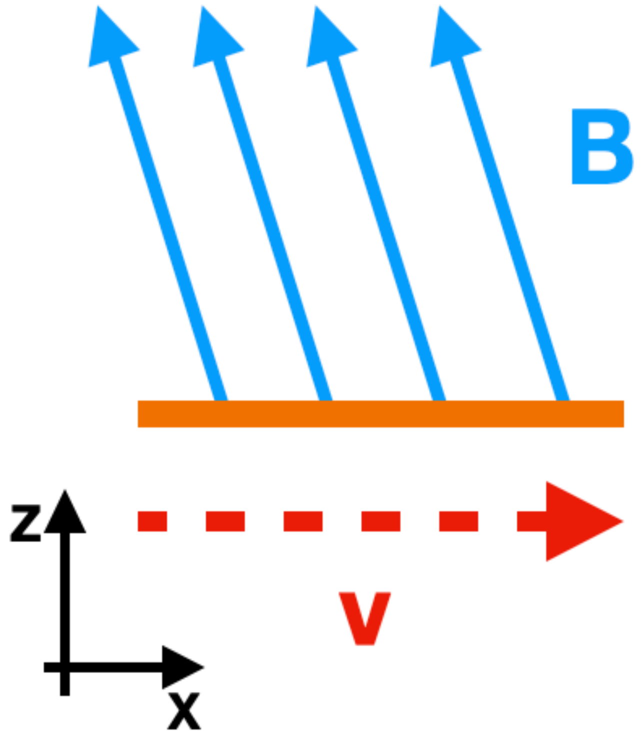
Flux Emergence/Submergence

Now, if $\mathbf{v}\cdot \mathrm{d}\mathbf{S} = 0,$ then

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{1}{\mu_0}\int_A \left(v_x B_x + v_y B_y\right) B_z \mathrm{d}A.$$

The energy injected is sensitive to **both** the imposed driver **v** and the field at the boundary, **B**.

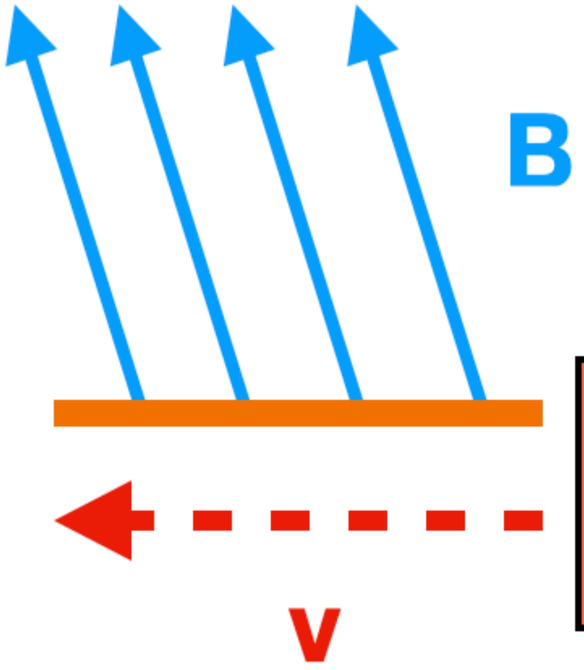
For 1D drivers: $$\boxed{\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{1}{\mu_0}\int_A v_x B_x B_z \mathrm{d}A.}$$



$$v_x > 0,$$
$$B_x < 0,$$
$$B_z > 0,$$
$$\boxed{\frac{\mathrm{d}\Xi}{\mathrm{d}t} > 0.}$$

If v_x, B_x and B_z are random, independent variables with mean 0, then:

$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}t} \right\rangle_t = 0.$$



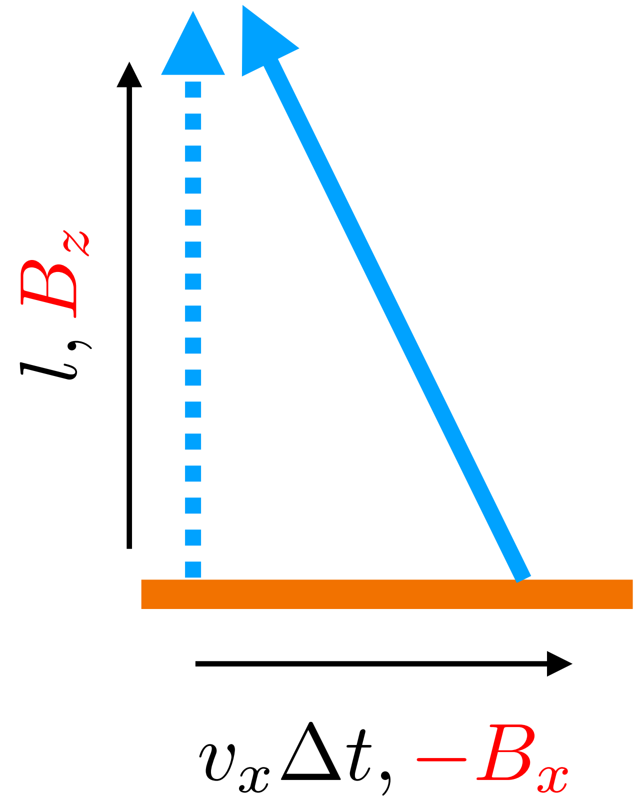
$$v_x < 0,$$
$$B_x < 0,$$
$$B_z > 0,$$
$$\boxed{\frac{\mathrm{d}\Xi}{\mathrm{d}t} < 0.}$$

But… they are not independent!

Drivers act for extended periods so create conditions for energy injection.

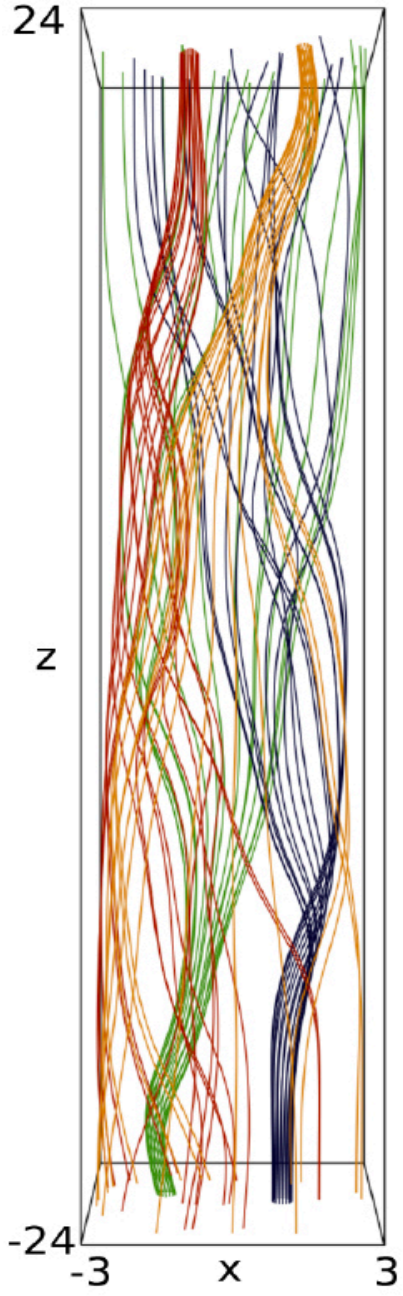
Poynting flux

For 1D drivers: $\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{1}{\mu_0}\int_A v_x B_x B_z \mathrm{d}A.$

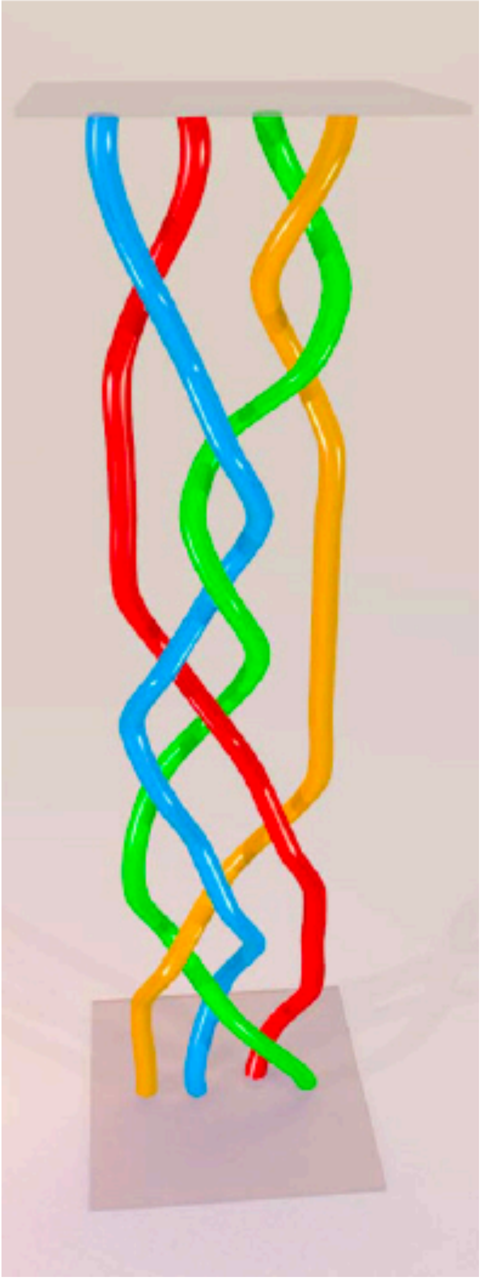


$$B_x \sim \frac{-v_x B_z \Delta t}{l}$$

Note: $l = l(\eta)$



Pontin et al. 2016



Berger & Asgari-Targhi 2009

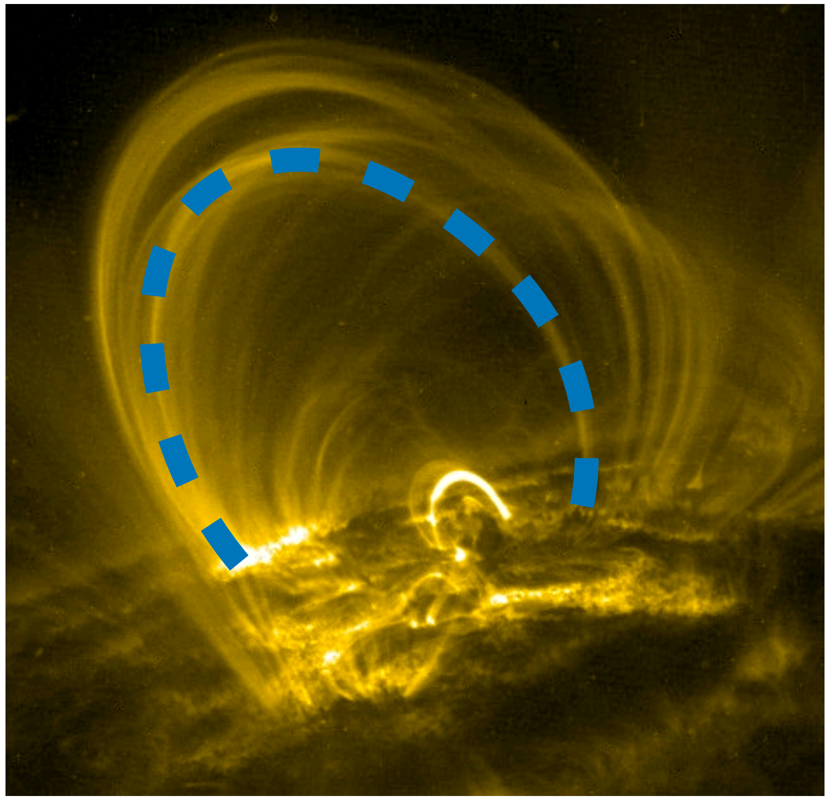
Increase energy injection rates?

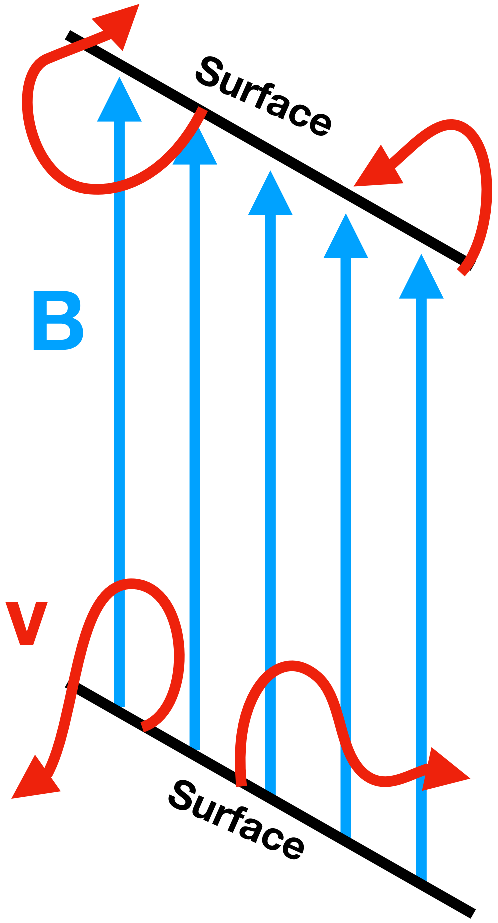
- Higher velocities and/or larger field strength.
- Longer time scales (DC heating instead of AC heating).
- Shorter field lines/‘knots’ in field

What about other foot point/reflections?

Need to store (or immediately dissipate) energy in the corona.

Heating Model





Advance the MHD equations with the numerical code **Lare3D.**

For simplicity, model a coronal loop as a straight structure.

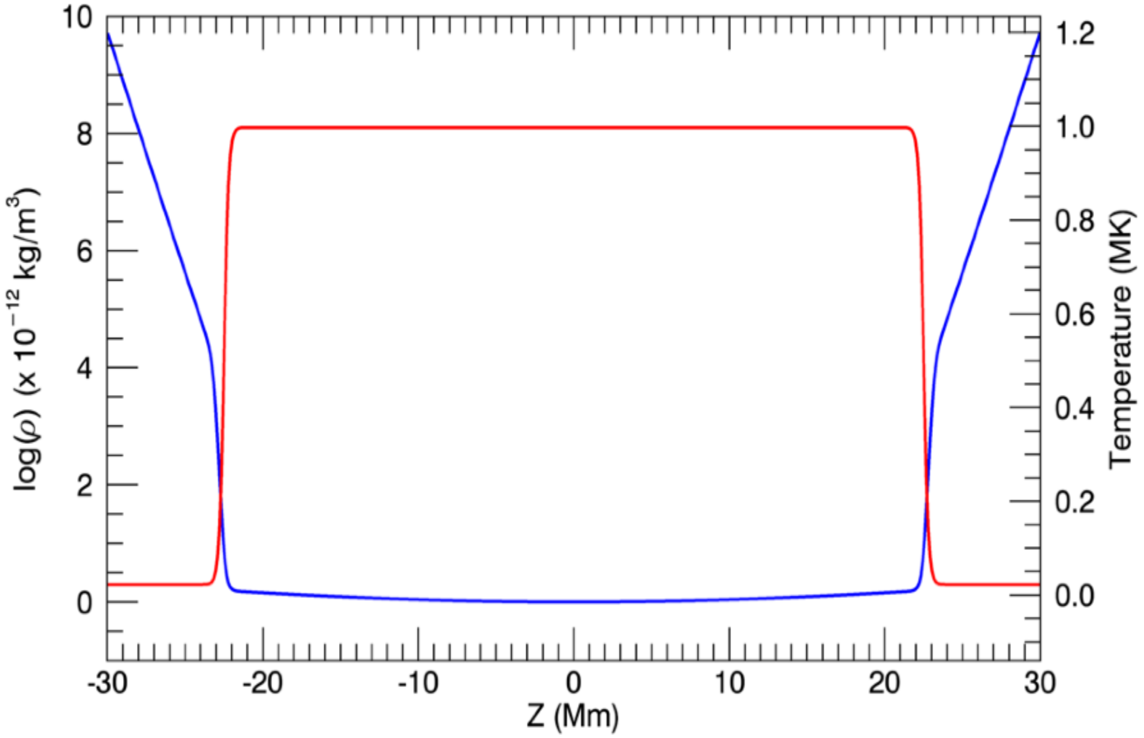
Magnetic Field - uniform 20 G.

Plasma - stratified atmosphere.

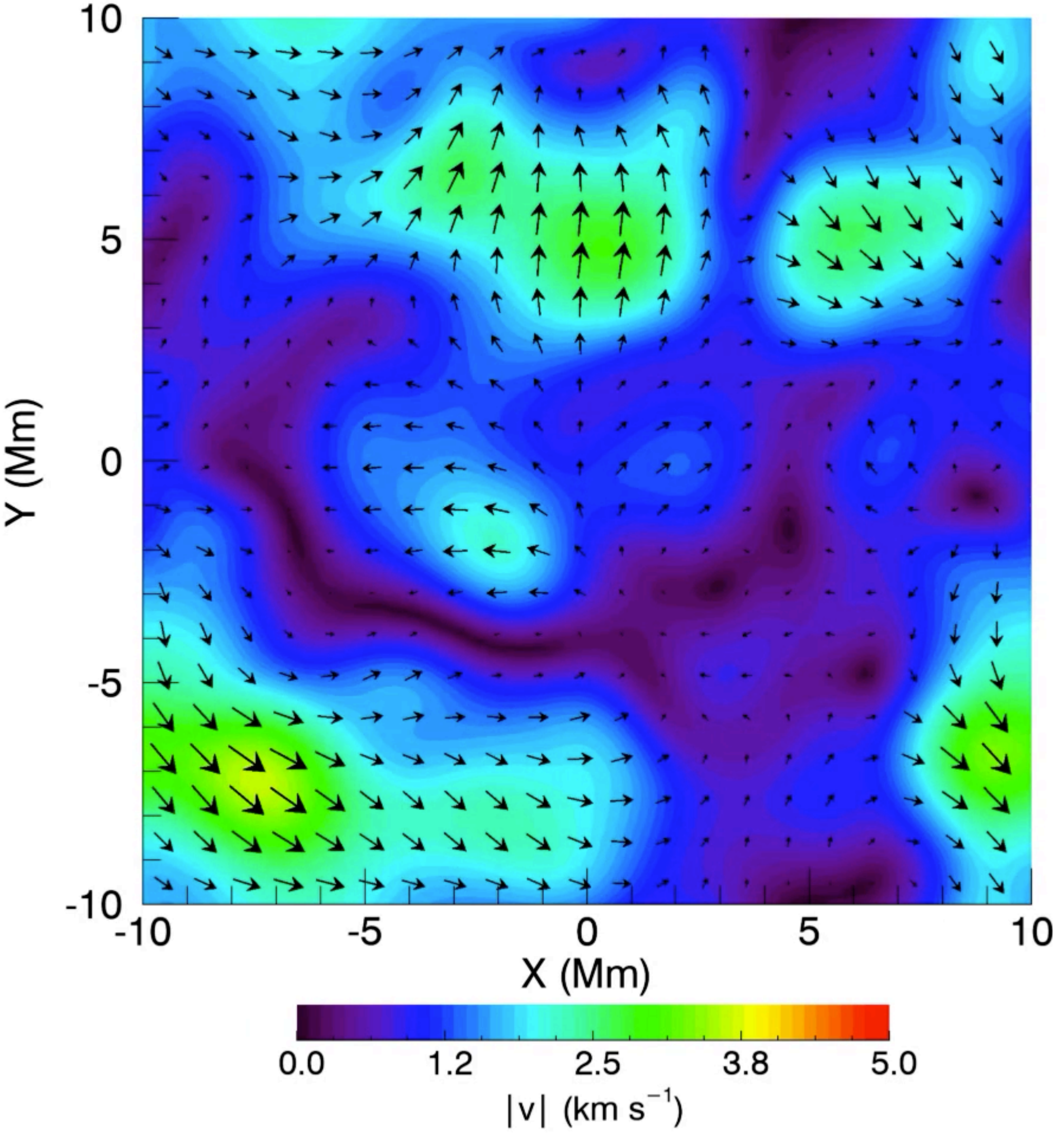
Inject energy by imposing transverse velocity driver on **both boundaries.**

Gravitationally Stratified Atmosphere

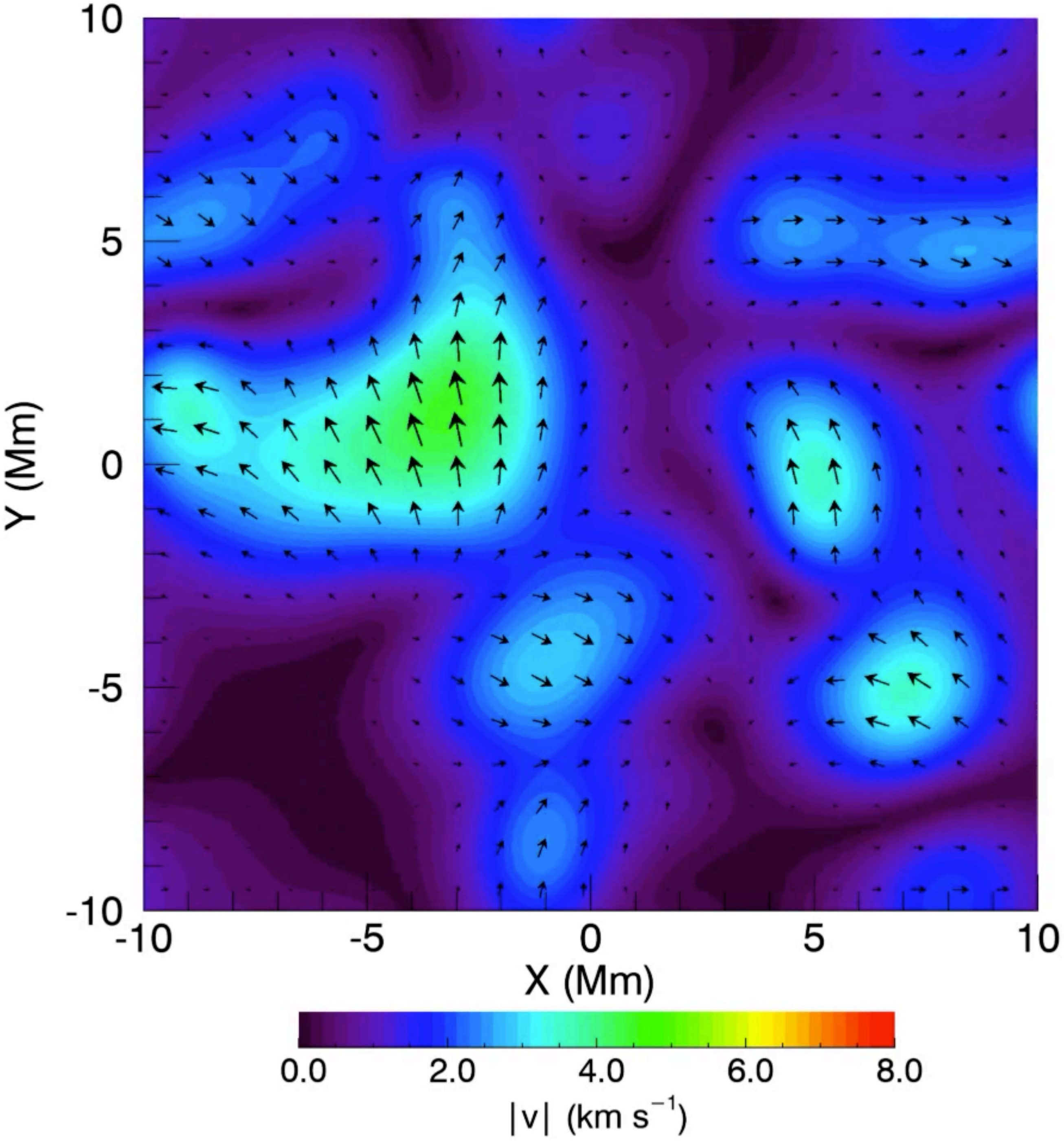
Density & Temperature



Imposed Velocity Driver



DC Driving



AC Driving

For a given amplitude we fix the mean of |**v**| between AC and DC simulations.

Driver Implementation

Want to impose a random driver but with control over characteristic time scales.

$$v_x = \sum_{i=1}^{N} v_i \cos\theta_i \exp\left\{\frac{-(r - r_{0,i})^2}{l_i^2}\right\} \exp\left\{\frac{-(t - t_{0,i})^2}{\tau_i^2}\right\}$$

$$v_y = \sum_{i=1}^{N} v_i \sin\theta_i \exp\left\{\frac{-(r - r_{0,i})^2}{l_i^2}\right\} \exp\left\{\frac{-(t - t_{0,i})^2}{\tau_i^2}\right\}$$

Can change:

- Amplitude, Time Scales, Length Scales, Direction, Complexity.

Driver Parameters

Time Scale - 2 characteristic time scales:

AC driving ~ 70 s

DC driving ~ 1400 s

Amplitude - 3 cases:

High amp ~ 6 km/s

Med amp ~ 4 km/s

Low amp ~ 2 km/s

Direction -

$$\theta_i \sim \mathcal{U}[0, 2\pi]$$

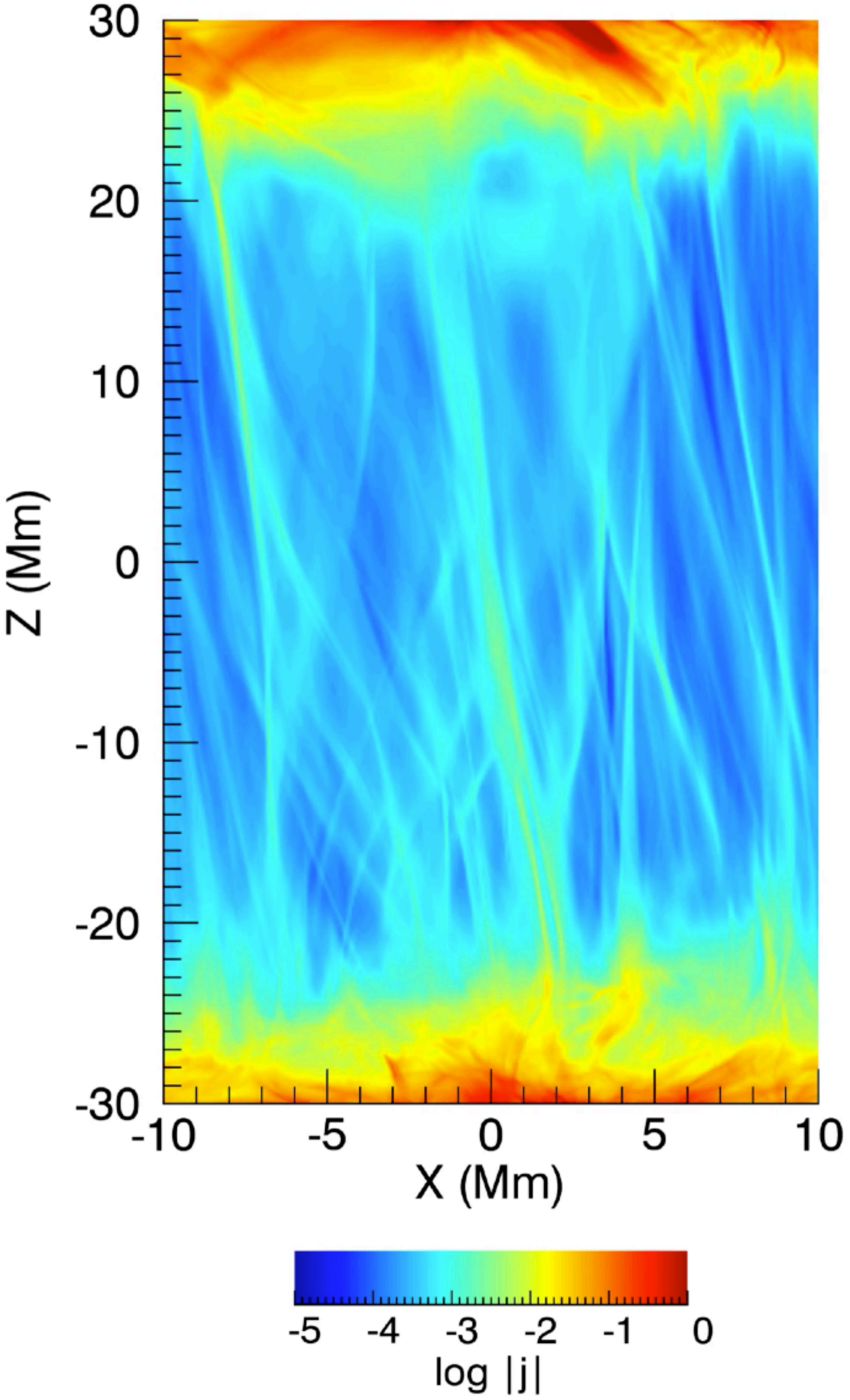
Length Scale -

$$l_i \sim \mathcal{N}(2.5\ \mathrm{Mm}, 0.5\ \mathrm{Mm})$$

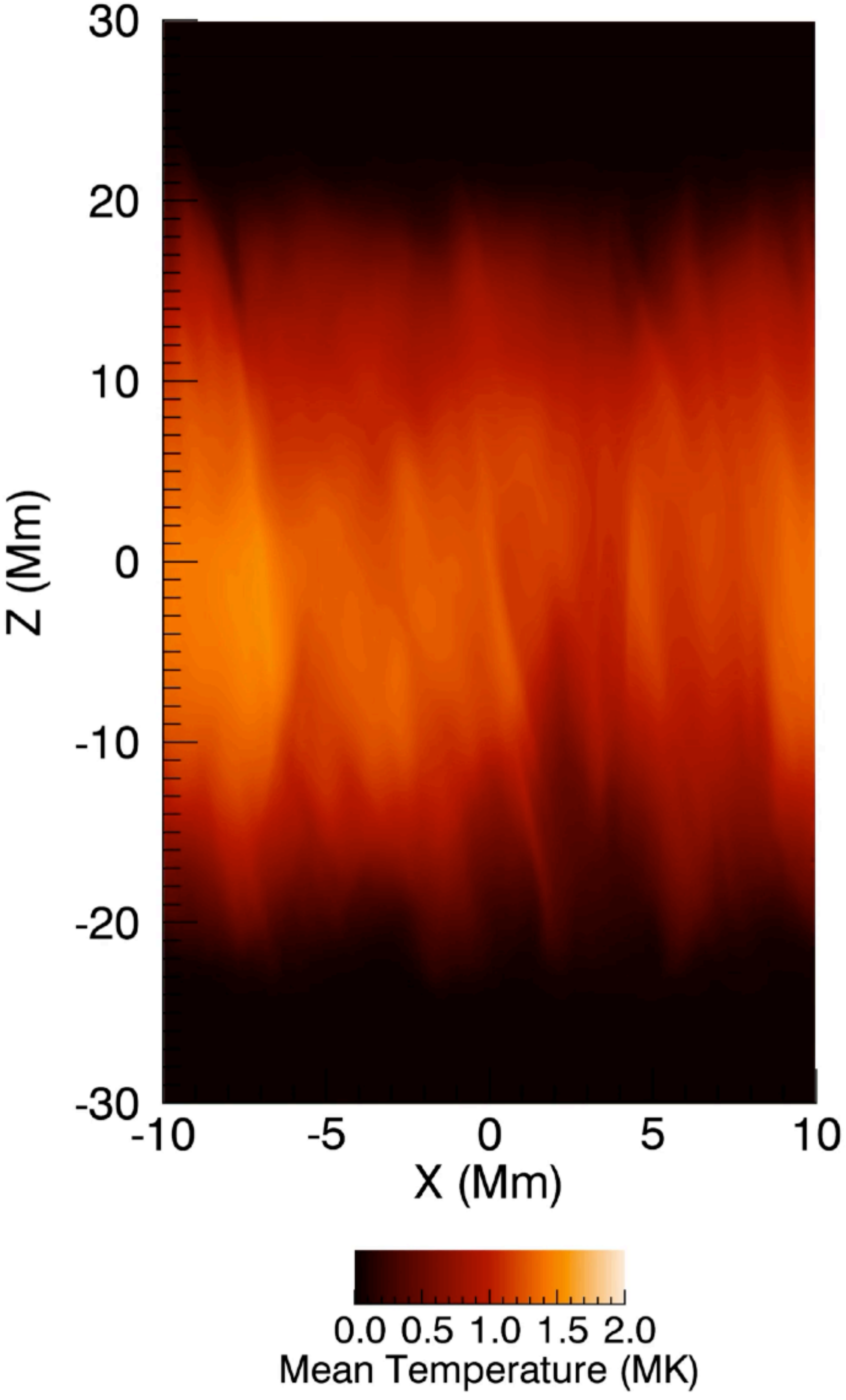
Location - Uniformly distributed over driven boundaries.

Atmosphere: Evolution

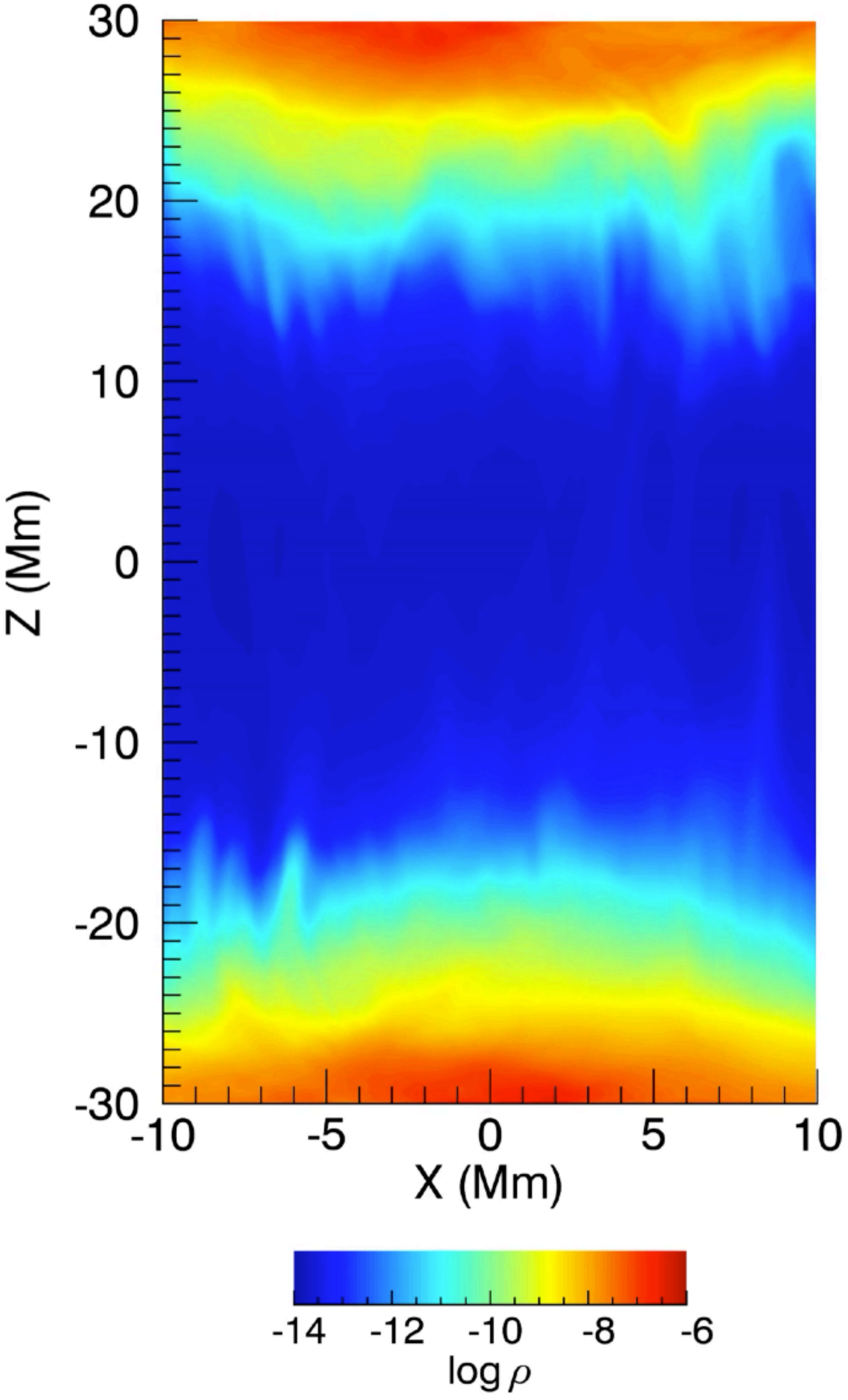
Currents



Temperature

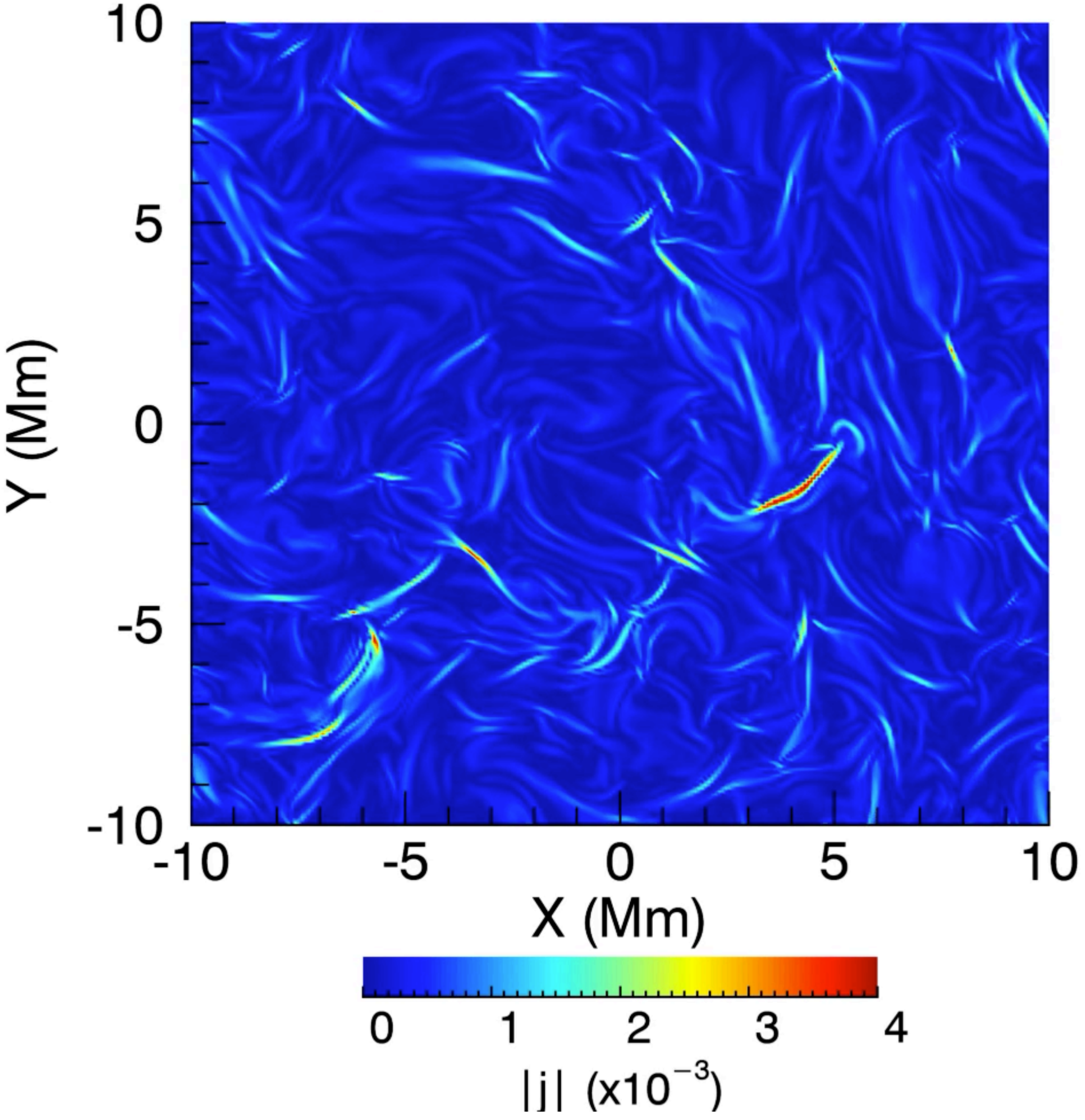


Density

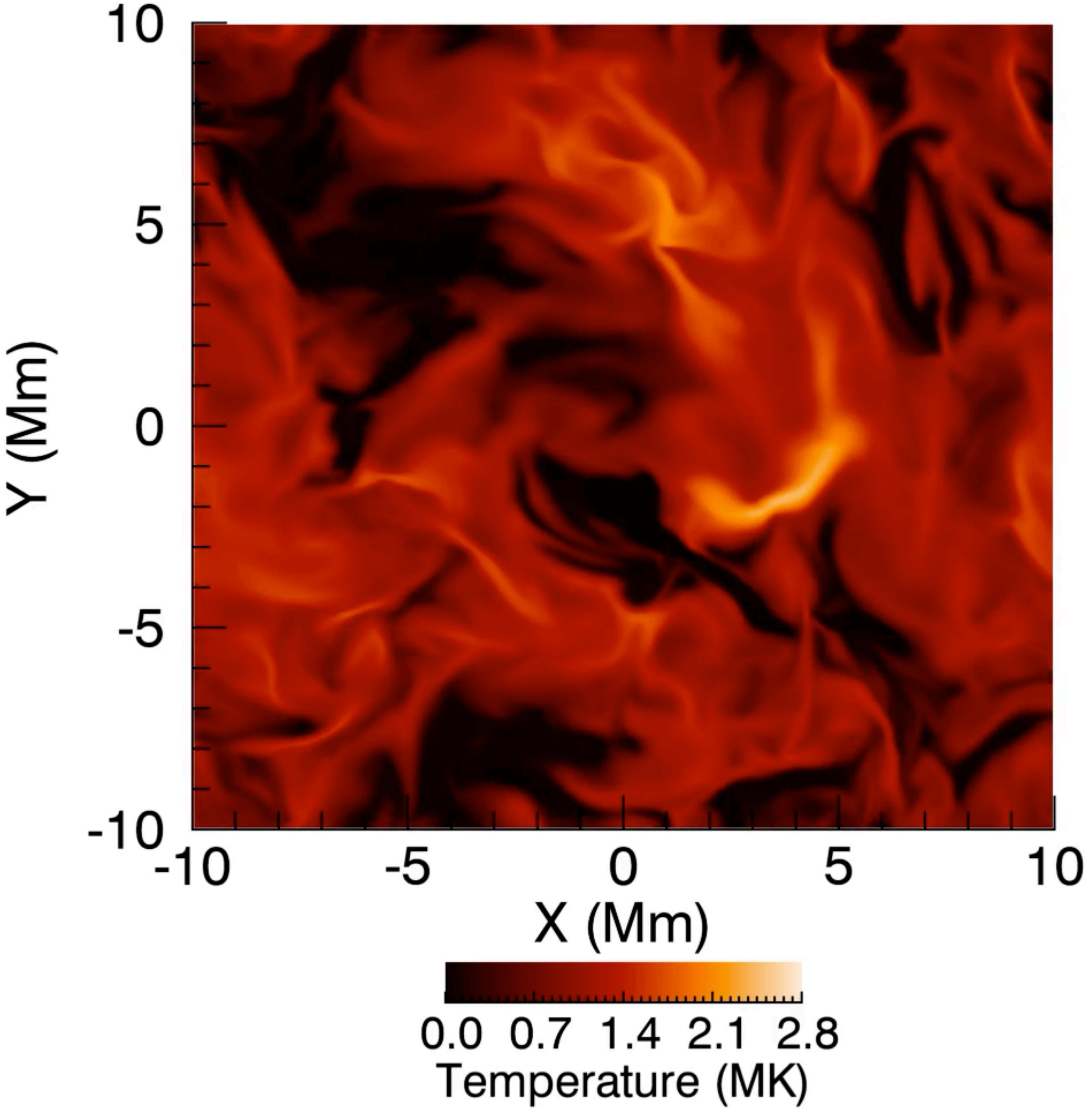


Atmosphere: Evolution

Currents



Temperature

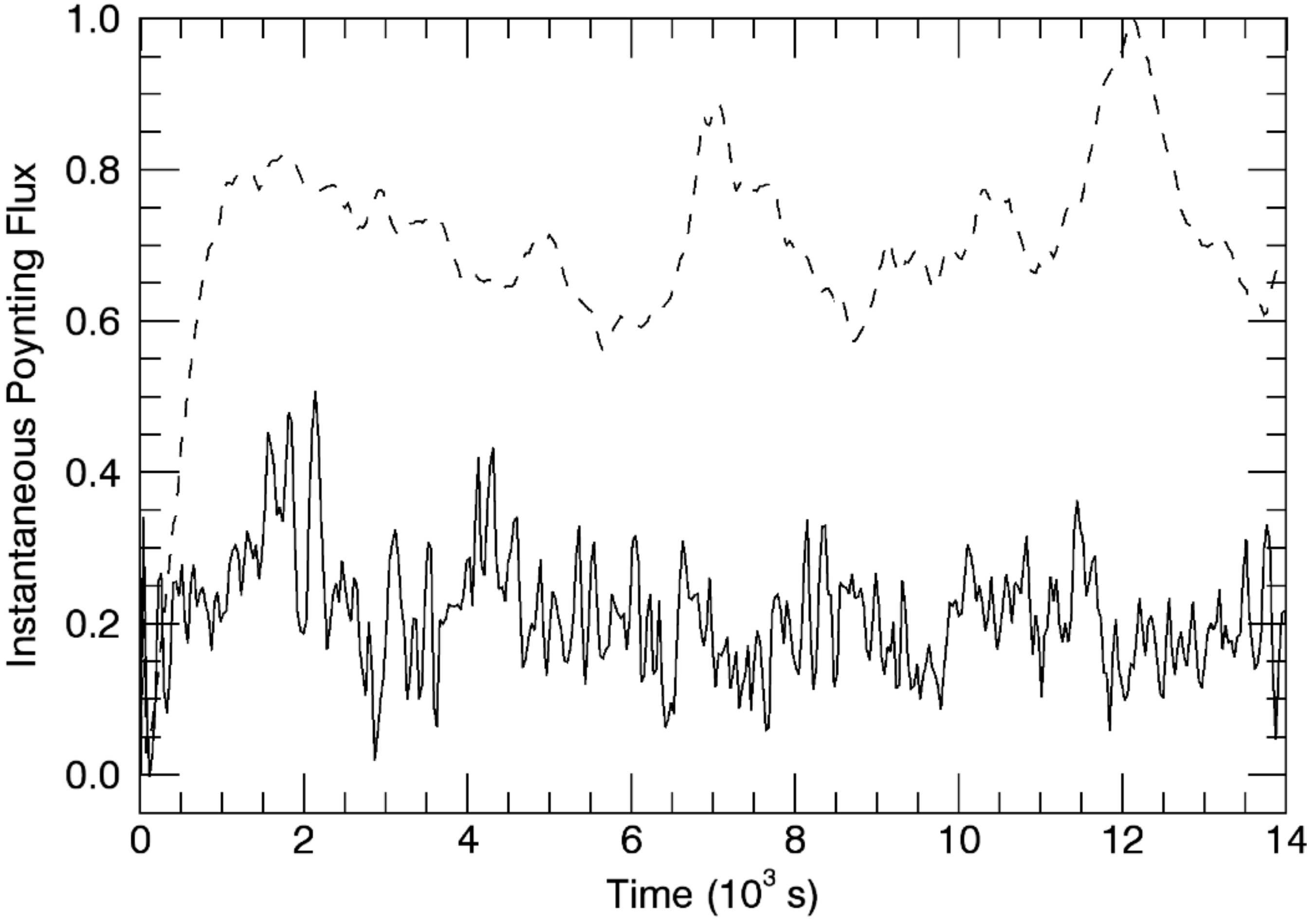


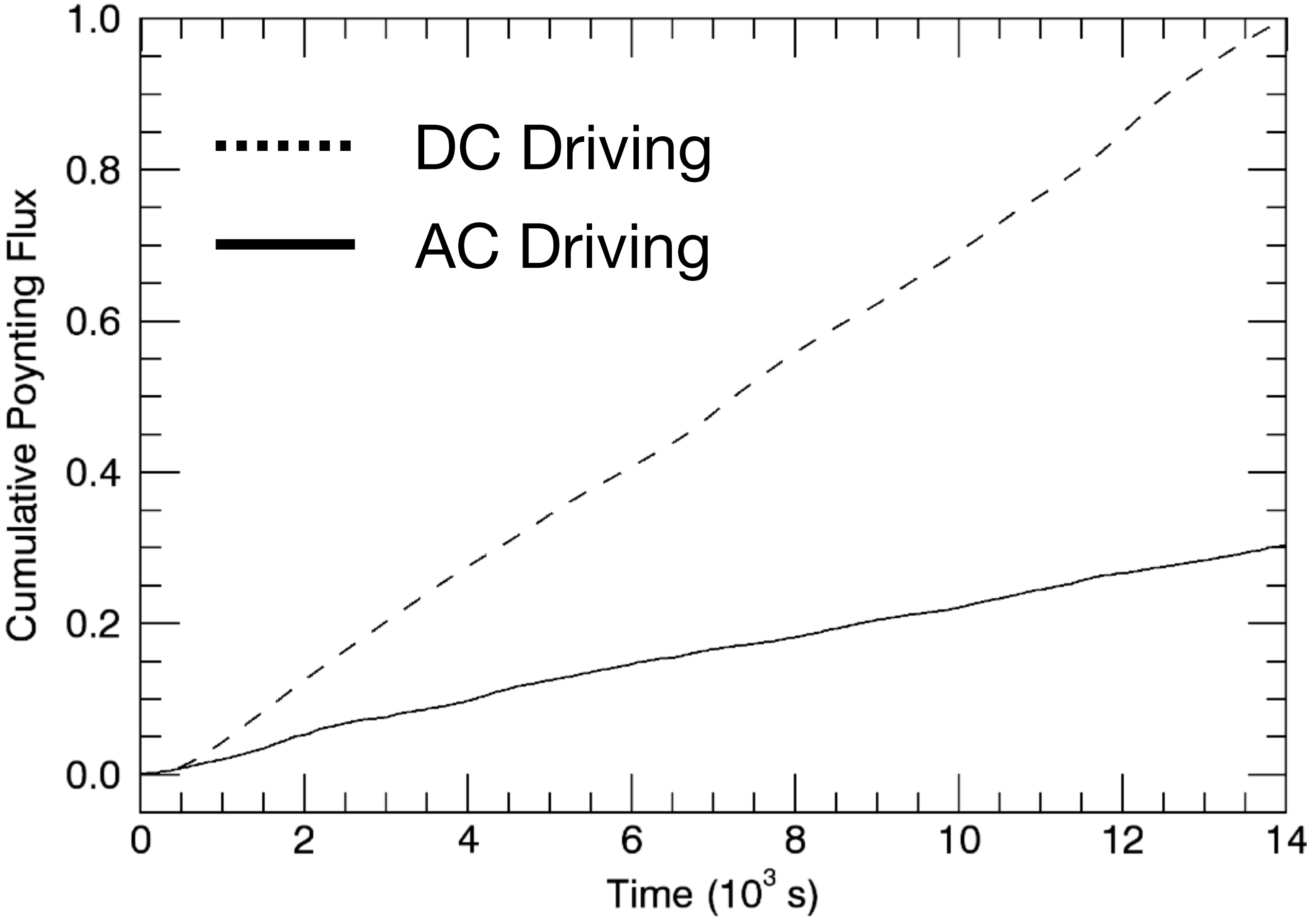
Poynting Flux

When a new velocity component switches on, it is as likely to remove energy from the domain as it is to inject new energy.

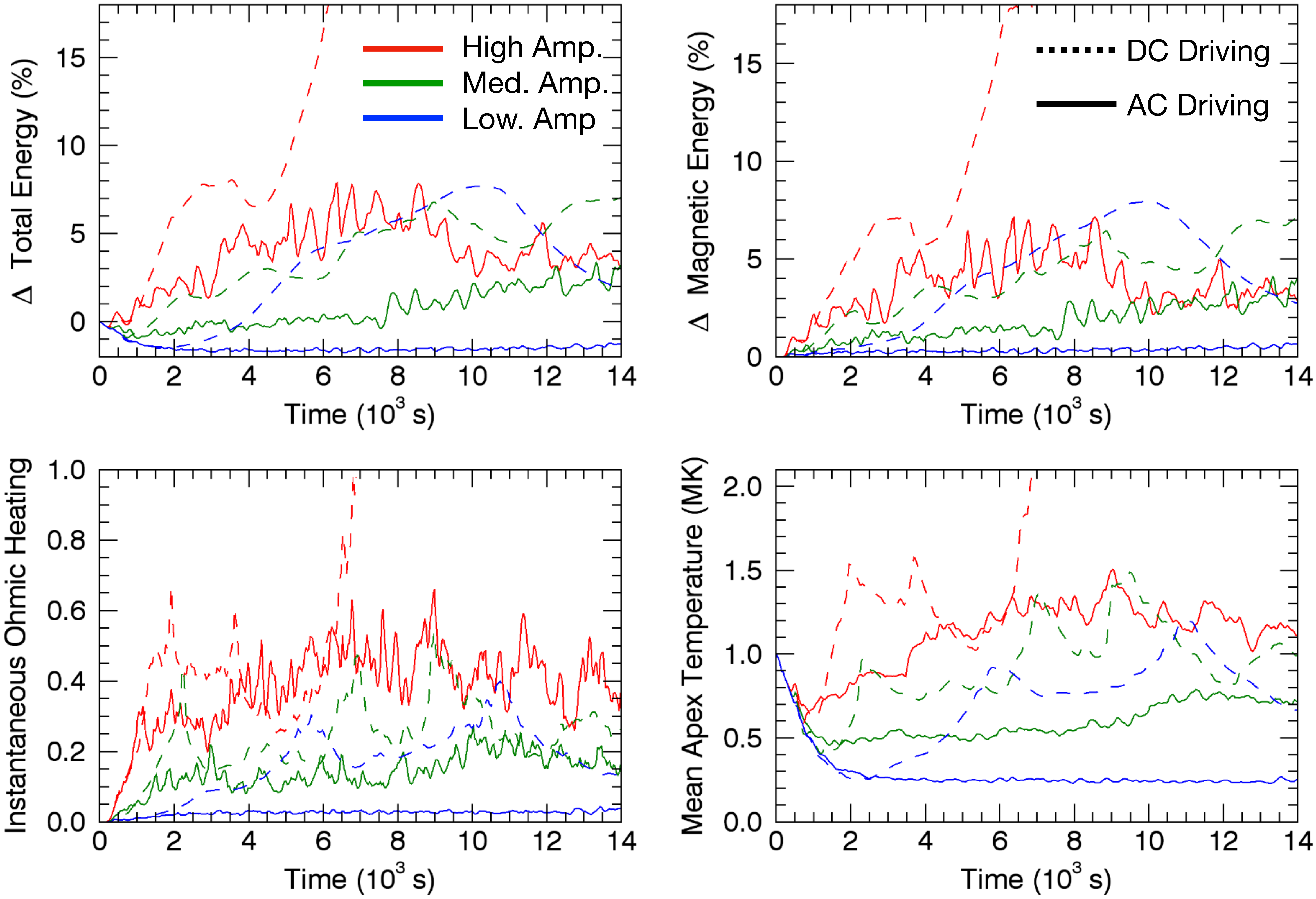
Only the continued action of a component creates the net influx of energy.

As DC components last longer, they tend to inject more energy.



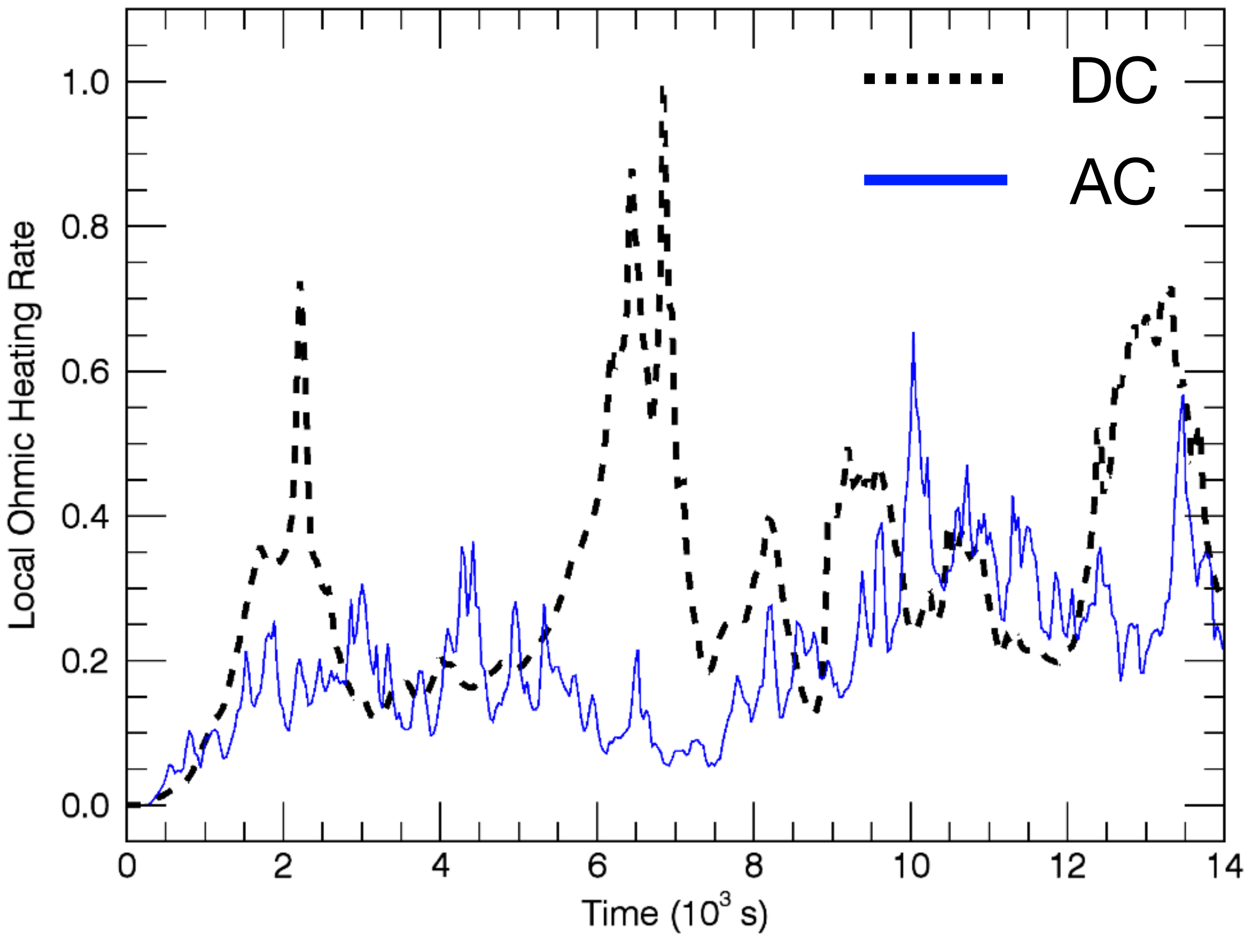


Volume Integrated Energetics

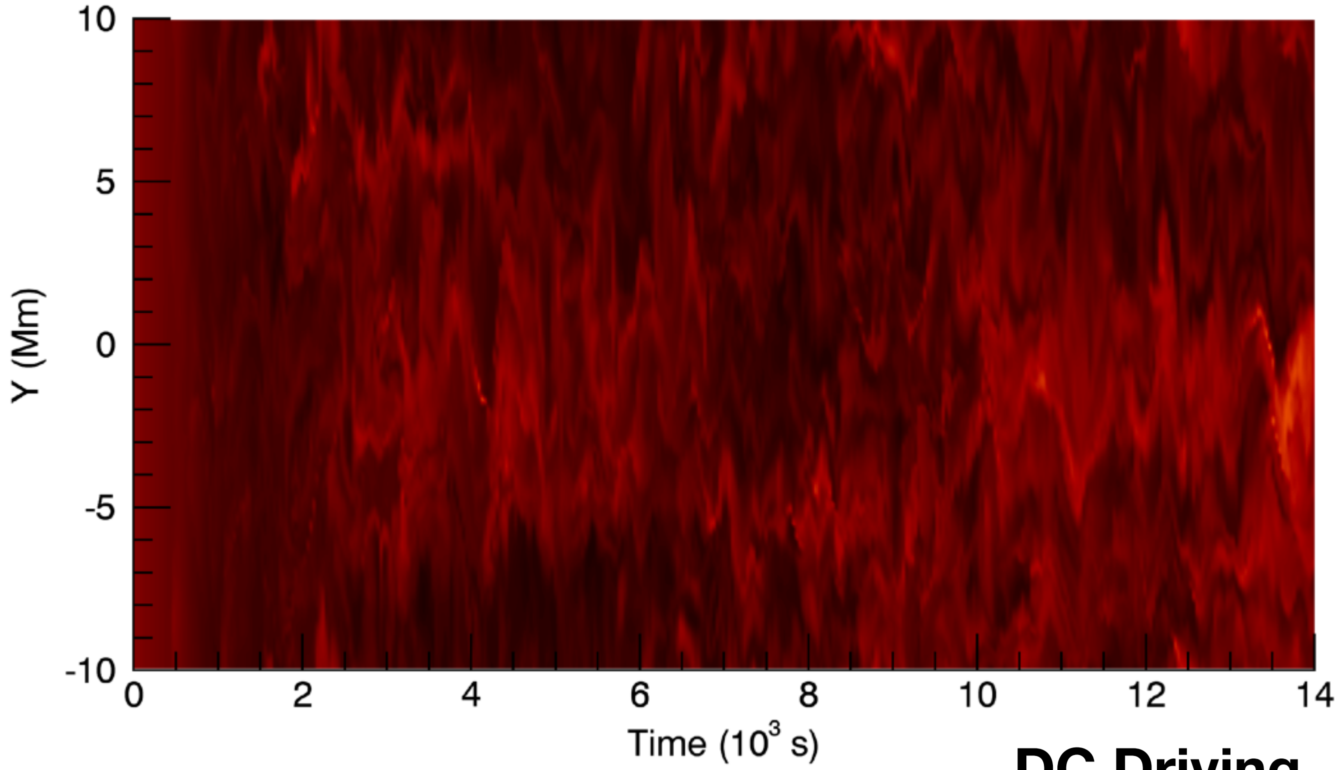


DC drivers inject more energy. Small scales develop leading to heating.
This is greater for large amplitude and long time scale driving.

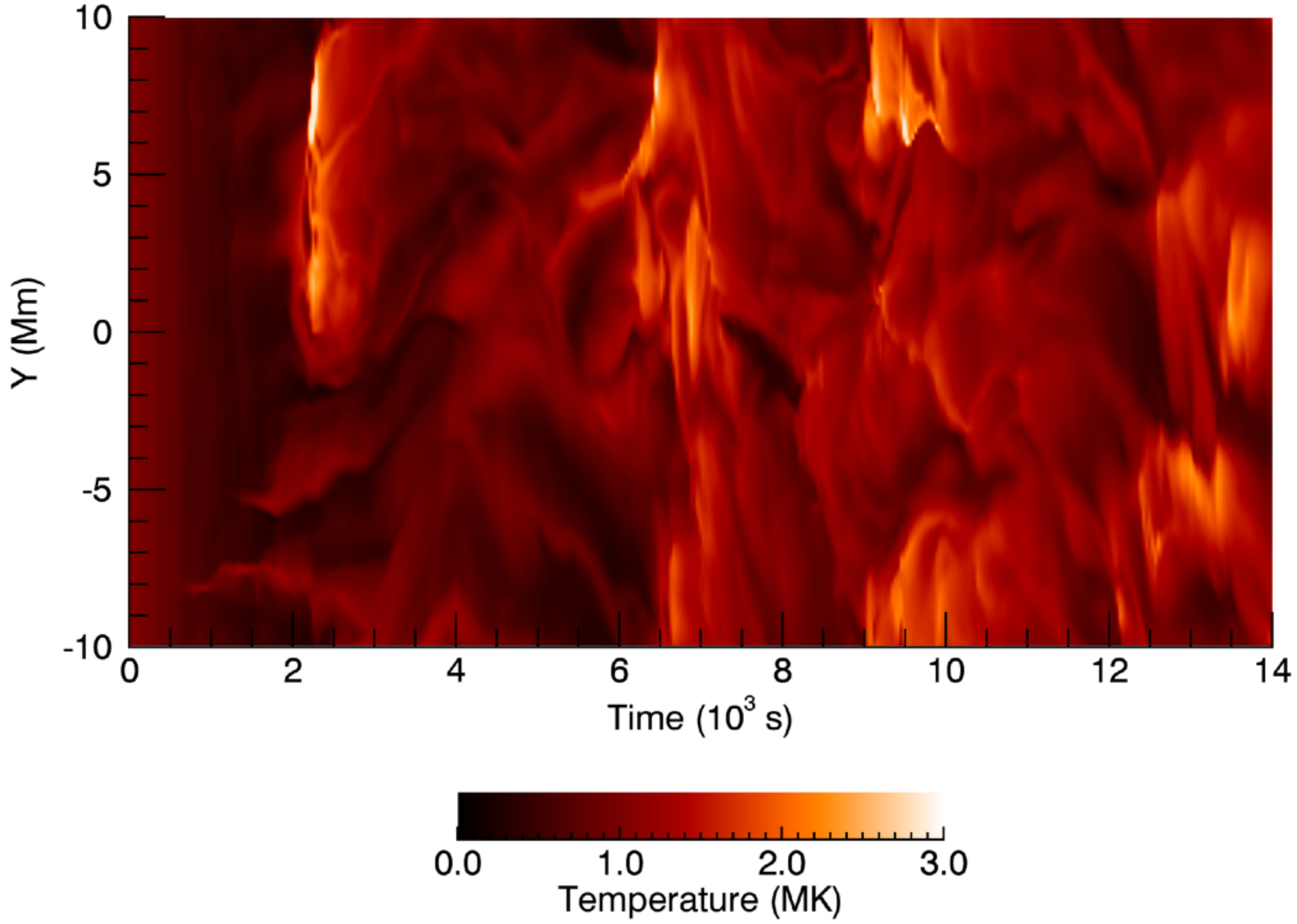
Temporal Profile of Heating



AC Driving



DC Driving



DC heating tends to produce larger, less frequent events.

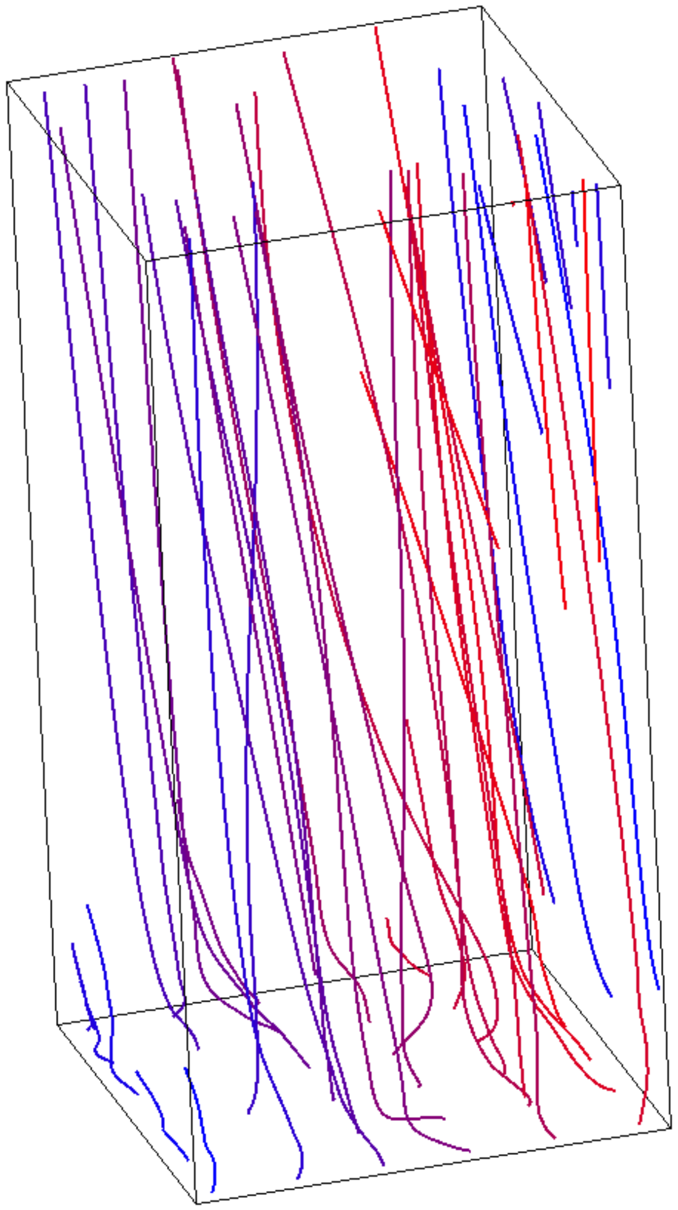
DC driving gives a longer cooling phase - we see higher and lower temperatures in the DC case.

Field Line Analysis

How does the plasma on individual field lines evolve (e.g. temperature profiles)?

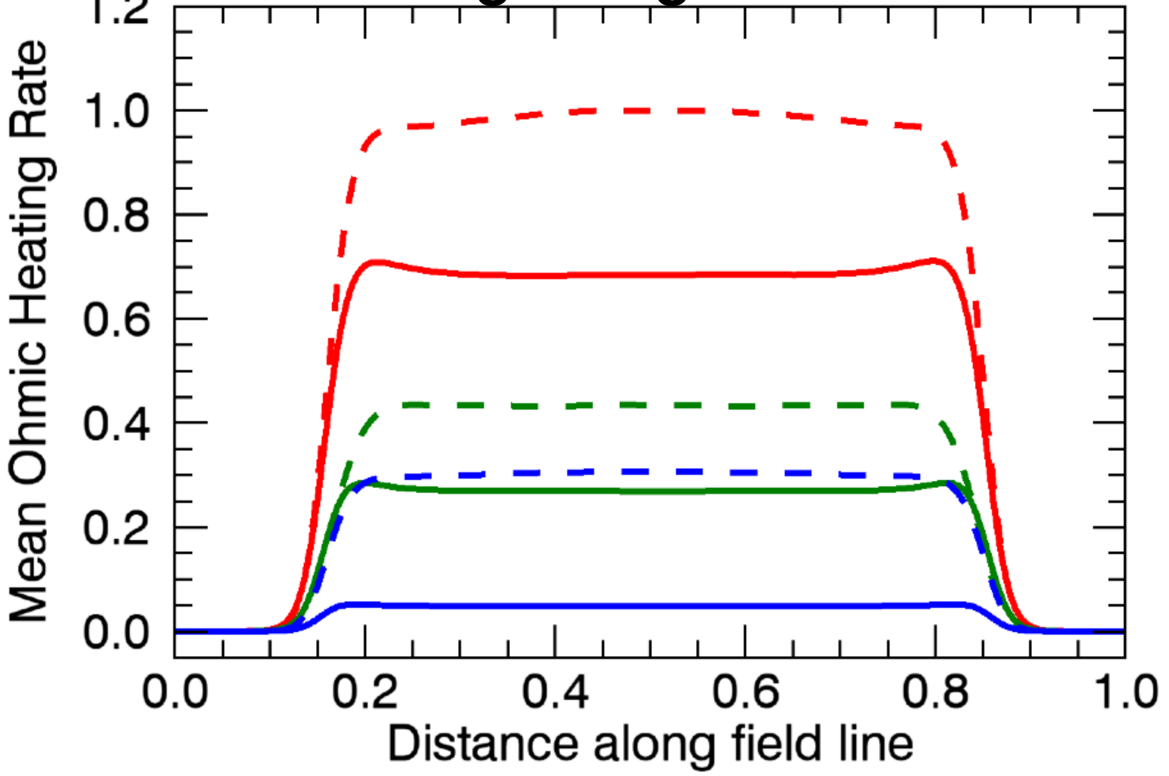
Cannot track the evolution of a single field line (due to cadence, reconnection, slippage).

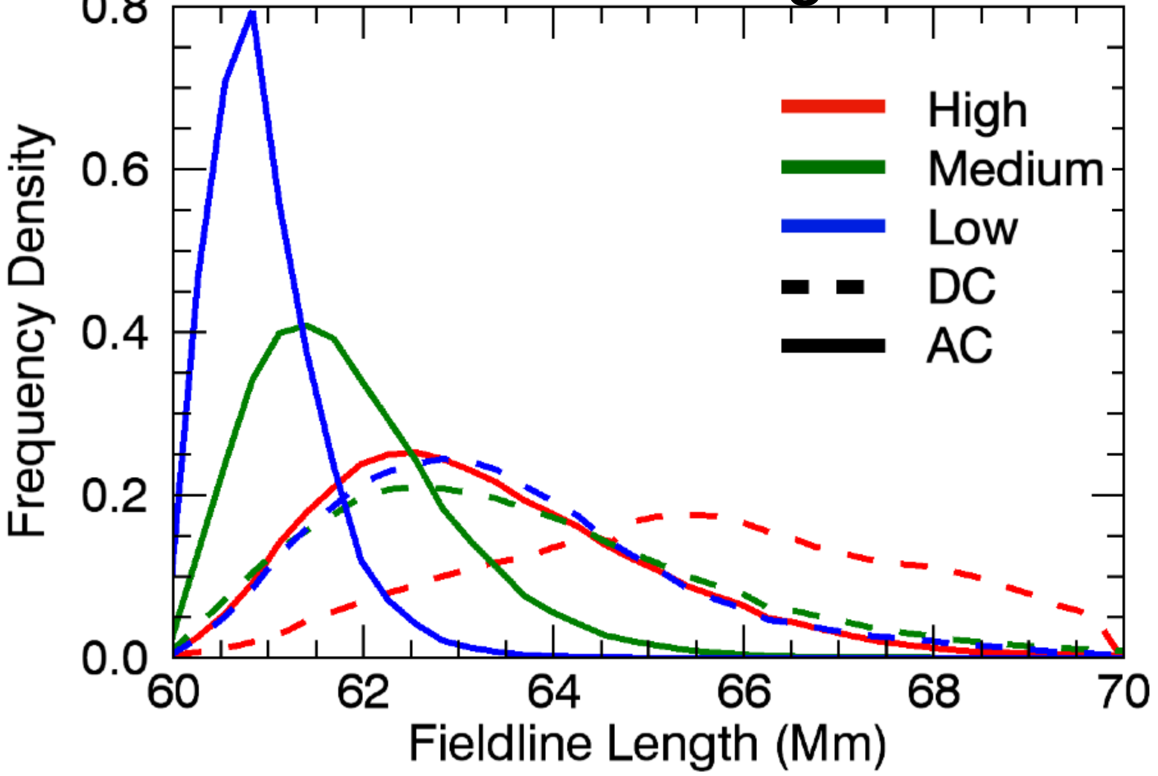
Sample from a grid of 100 x 100 foot points at 400 times during simulations —> 4 million field lines.

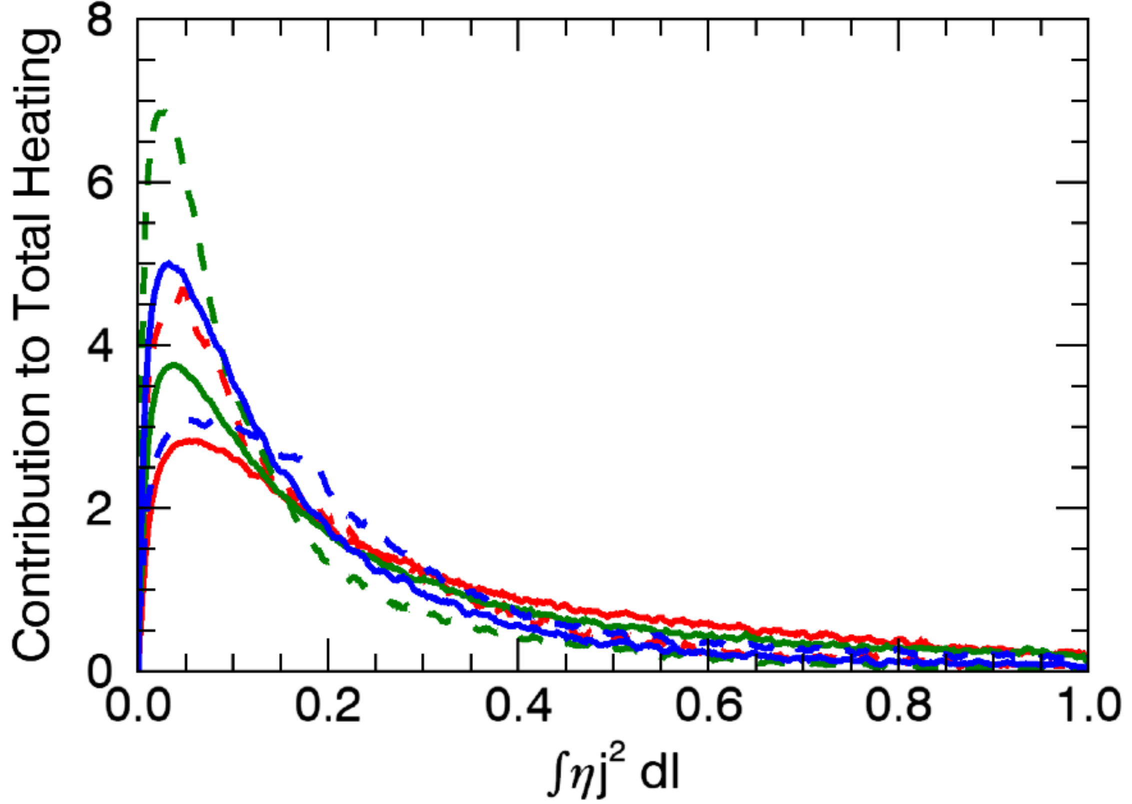


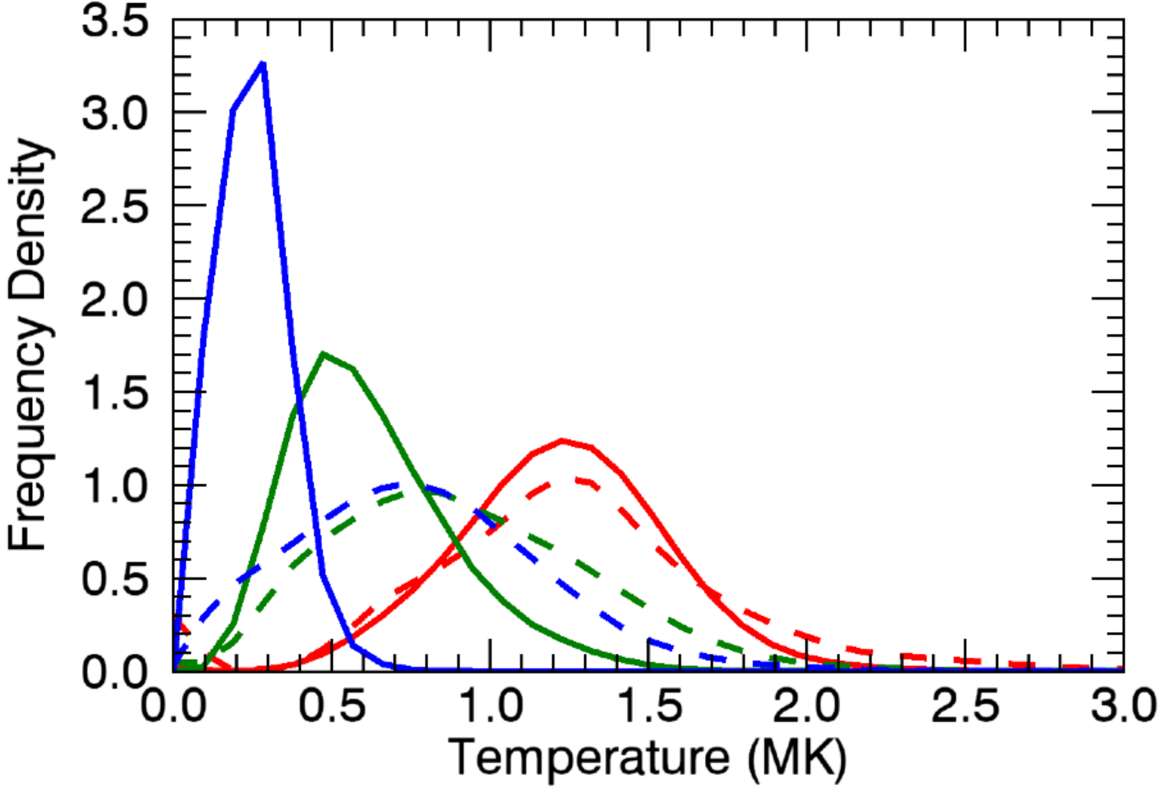
Sample of traced field lines.

Field Line Analysis

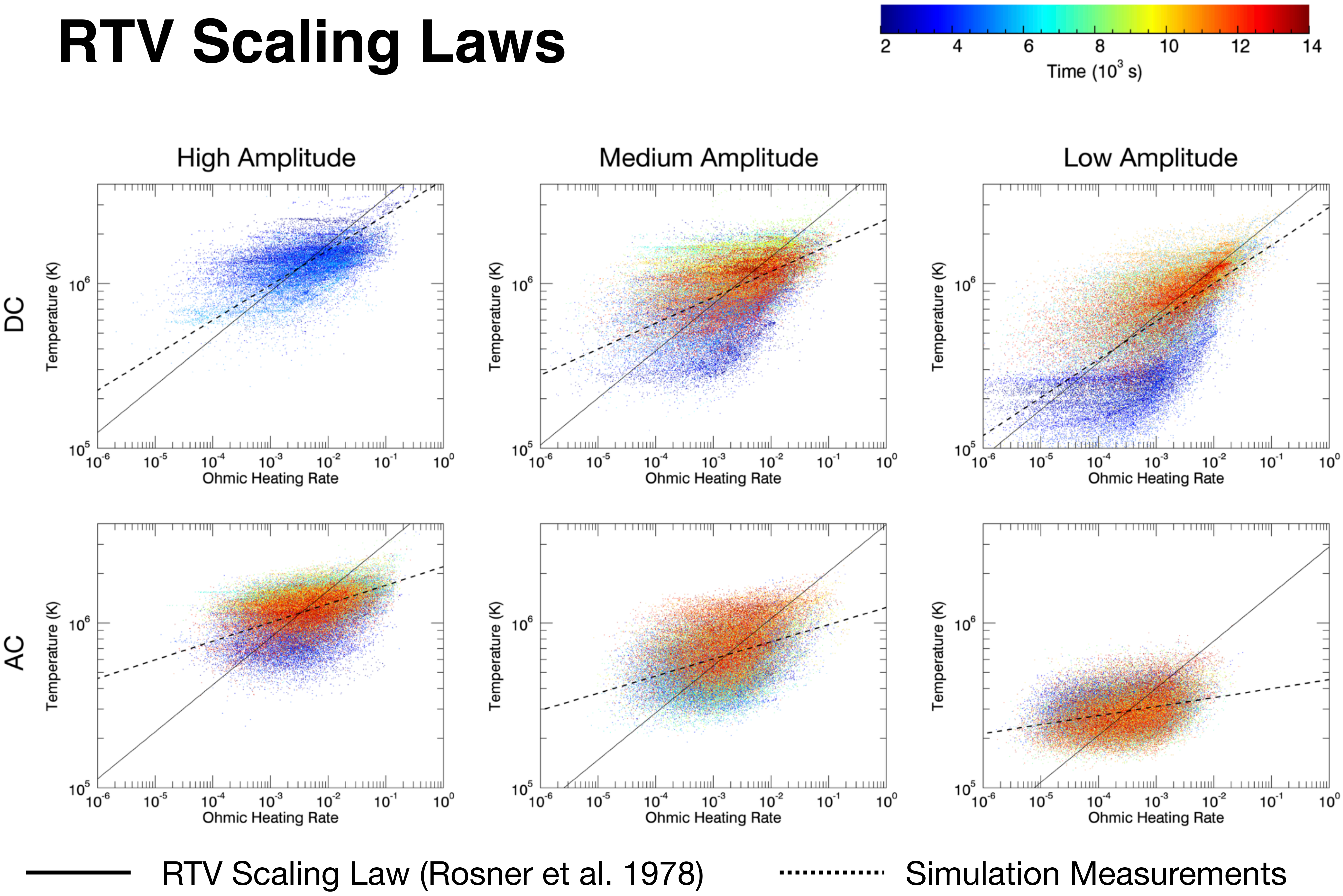

Heating along field lines


Field line length


Contribution of events to total heating


Temperature distribution

RTV Scaling Laws

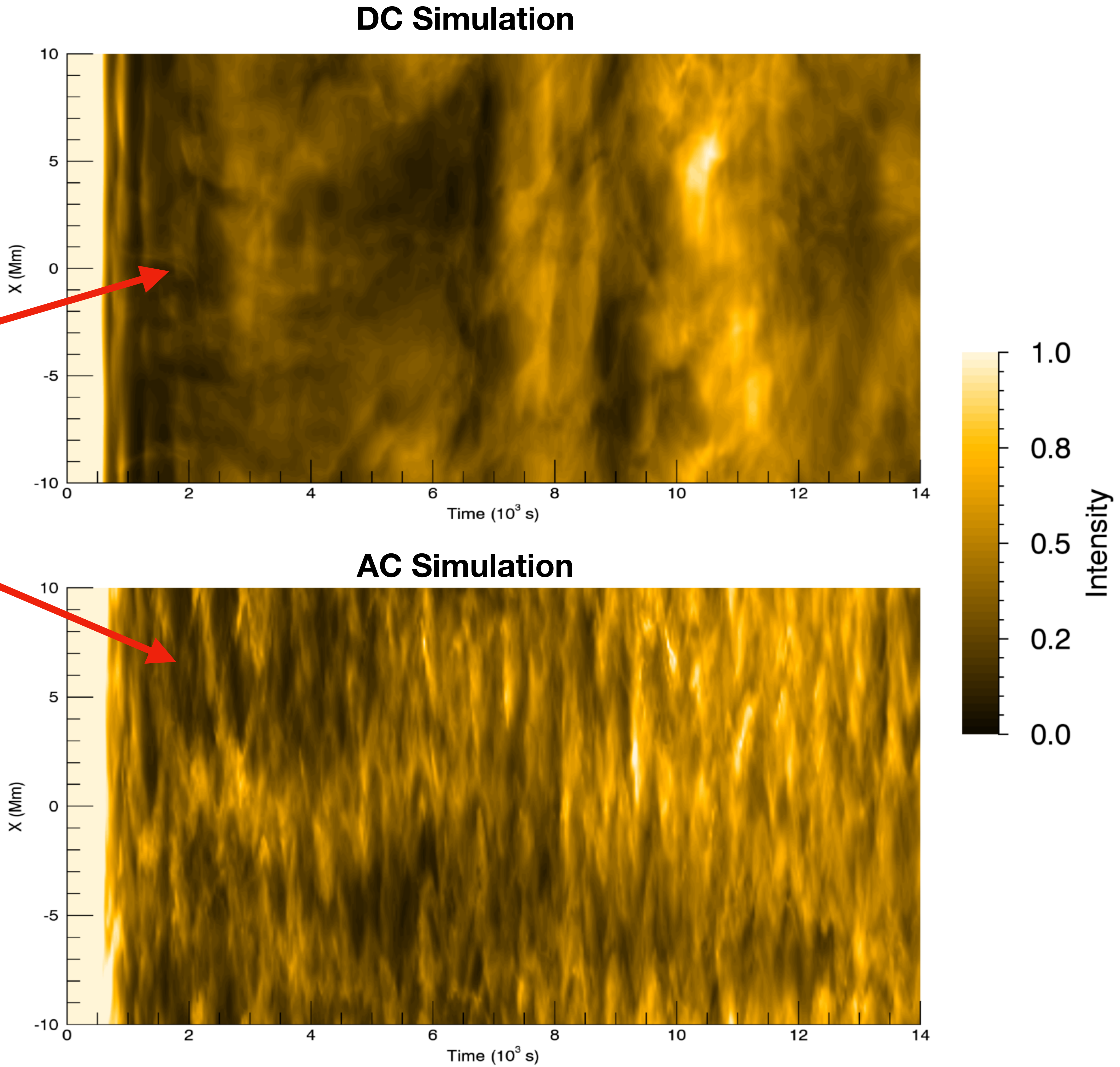


Synthetic Imaging

Slow evolution in DC simulation.

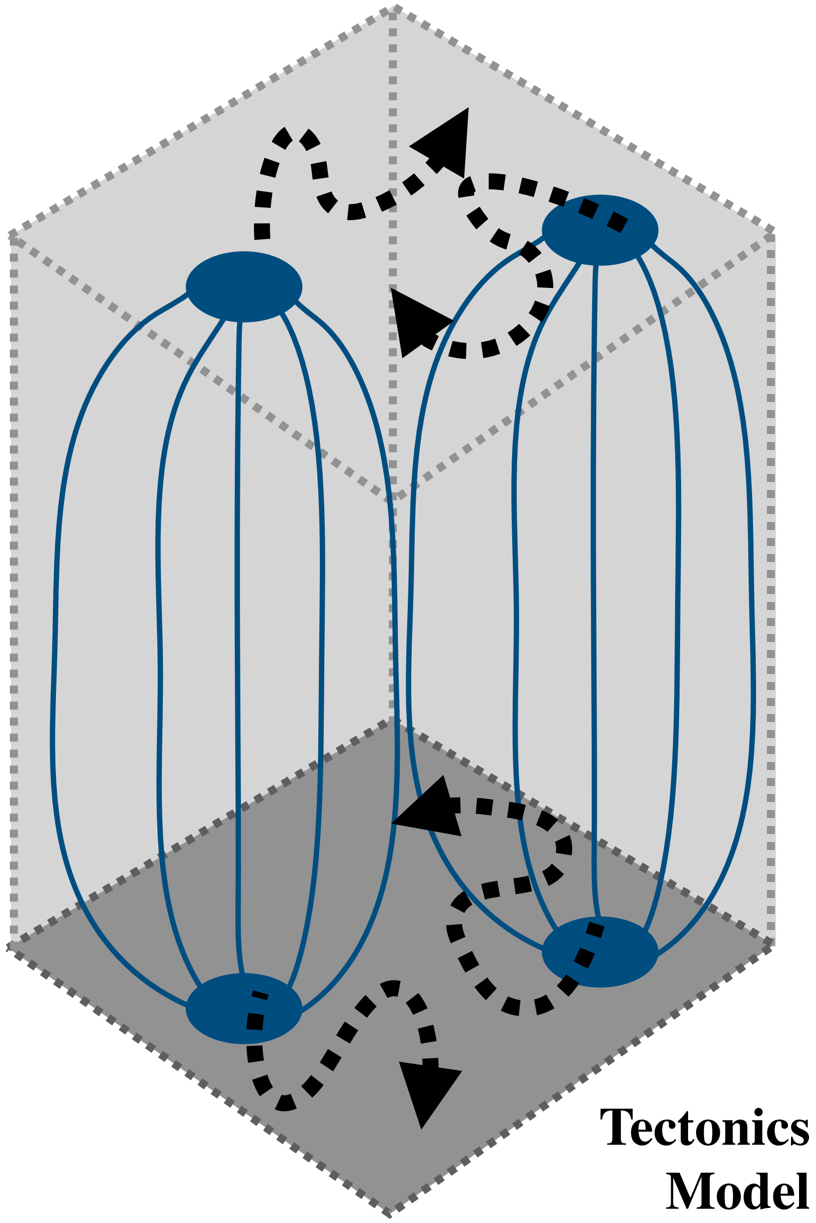
AC case is much more dynamic.

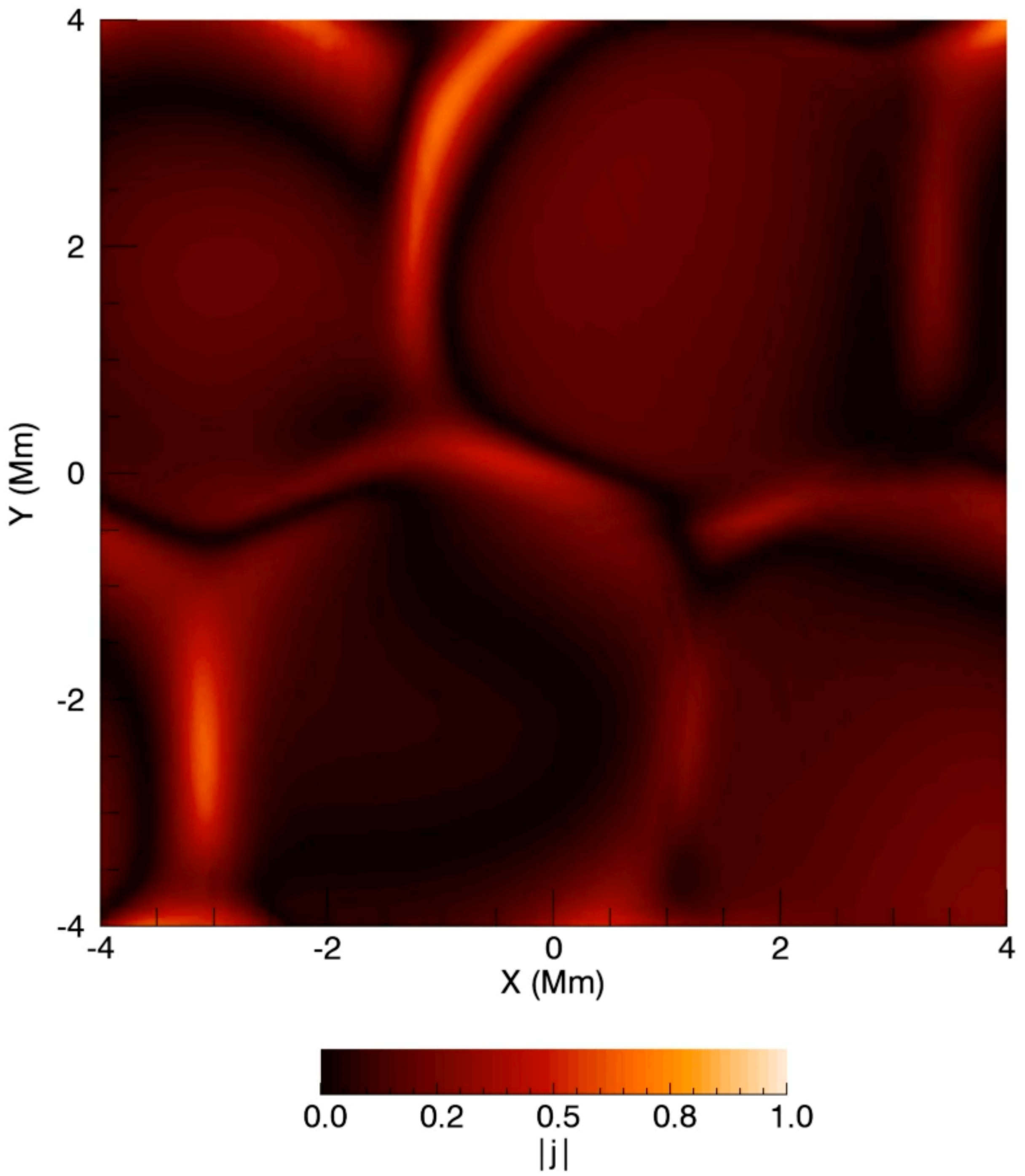
Ongoing: Can we detect other results from the simulation data in the synthetic emission?


DC Simulation

AC Simulation

Effects of Magnetic Field Topology





Currents form preferentially at interface between different flux tubes.

Length scales of driving (compared to flux sources) are important for current formation.

Conclusions & Future Work

DC Drivers inject greater Poynting flux and ultimately cause more heating.

Simulation Differences

- Frequencies of e.g. flows - not particularly useful as short and high frequencies will co-exist.
- Magnitude of heating but the spatial distribution of heating is similar in both cases.
- Support higher coronal temperatures & densities in DC simulations. Also larger volume.
- DC driver tends to produce lower frequency events - may be detectable.

For the Future

- How do these results scale with resistivity?
- To what extent are these differences visible in synthetic emission?
- Are results affected by different field geometries?