

# Stirring the Base of the Solar Wind – Energy Transfer in the Solar Atmosphere with Bifrost

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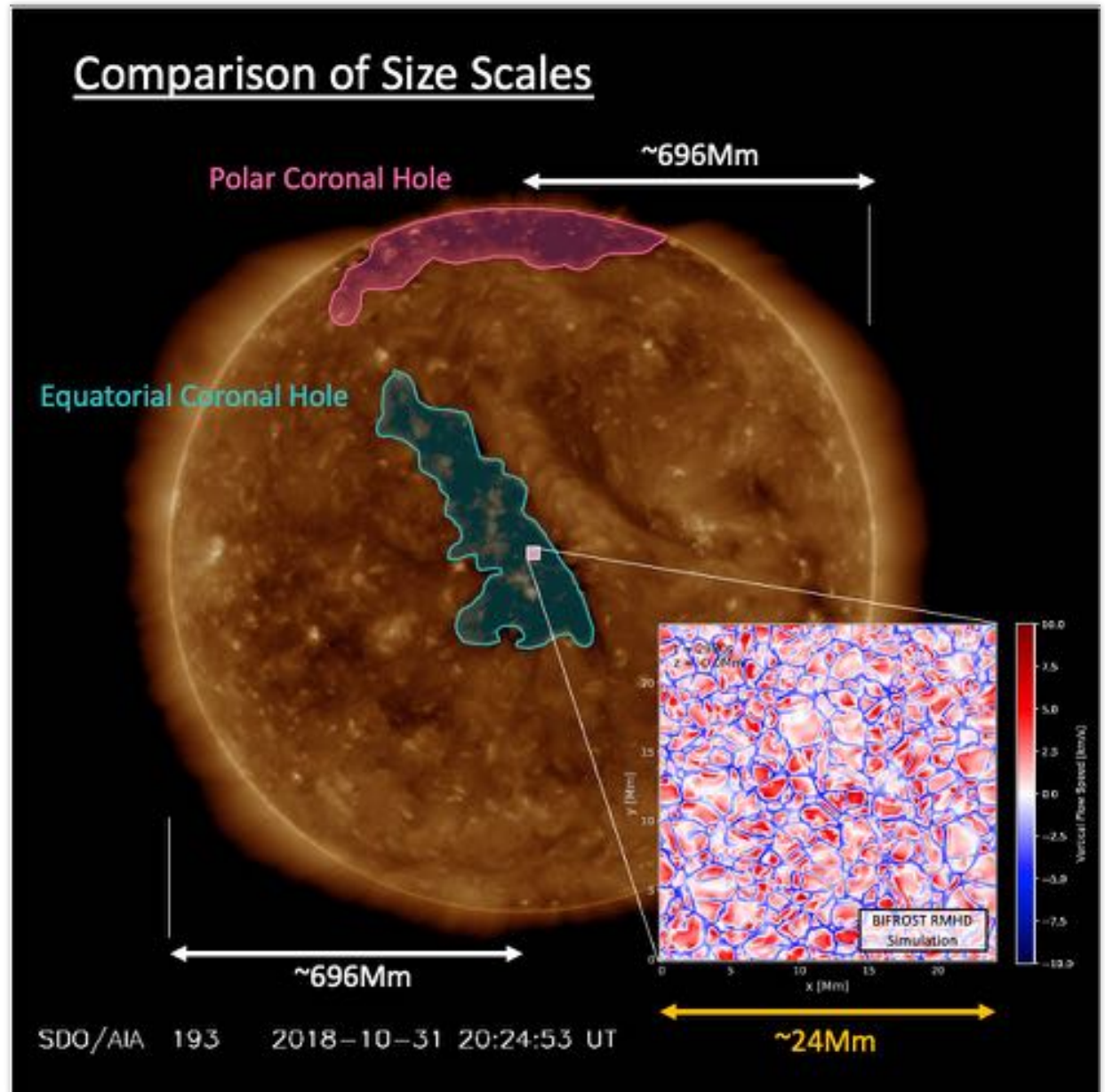


**WholeSun** Synergy Grant



# Overview:

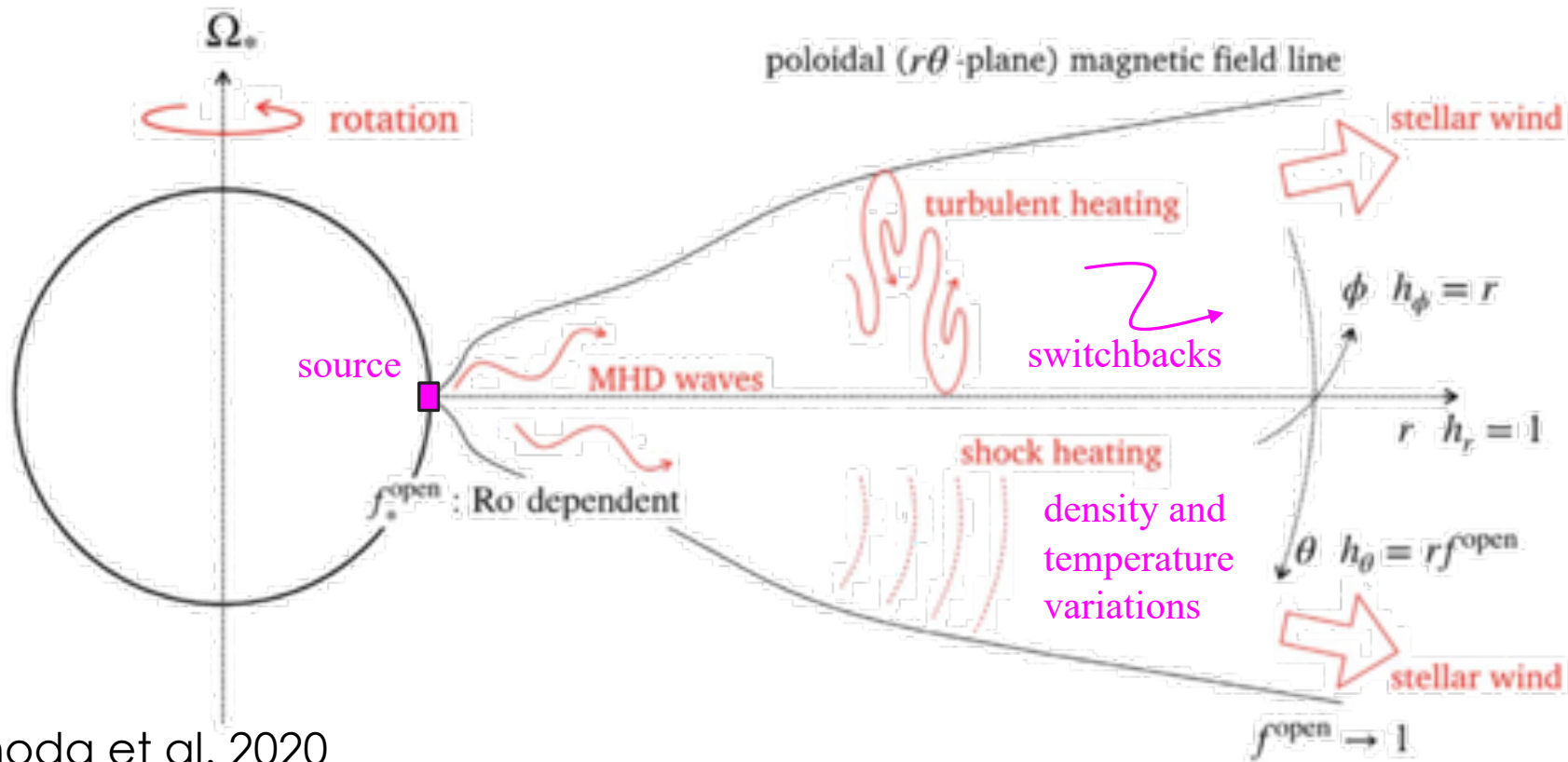
1. Introduction
2. Bifrost Simulation(s)
3. Connection to the Solar Wind
4. Future Work
5. Conclusions



# Introduction

Alfvén-wave Turbulence, Solar Wind Models, Switchbacks

# Solar Wind Heating and Acceleration



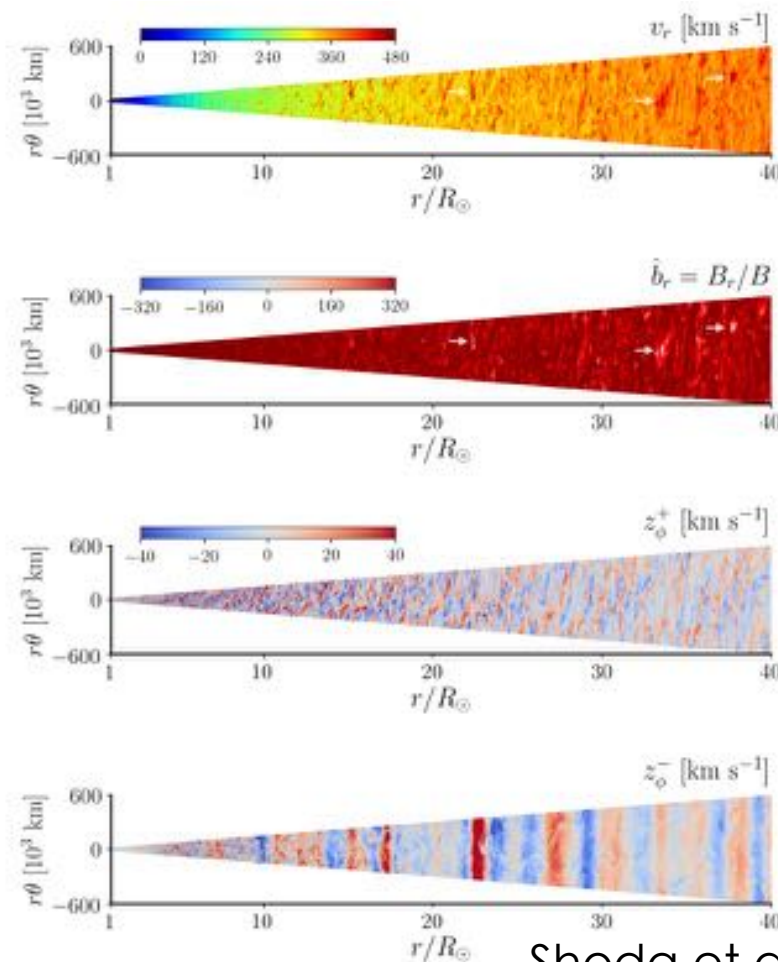
- Thermal Pressure
- Shocks
- Turbulence**
- Alfvén Waves**
- Fieldline Expansion

Shoda et al. 2020

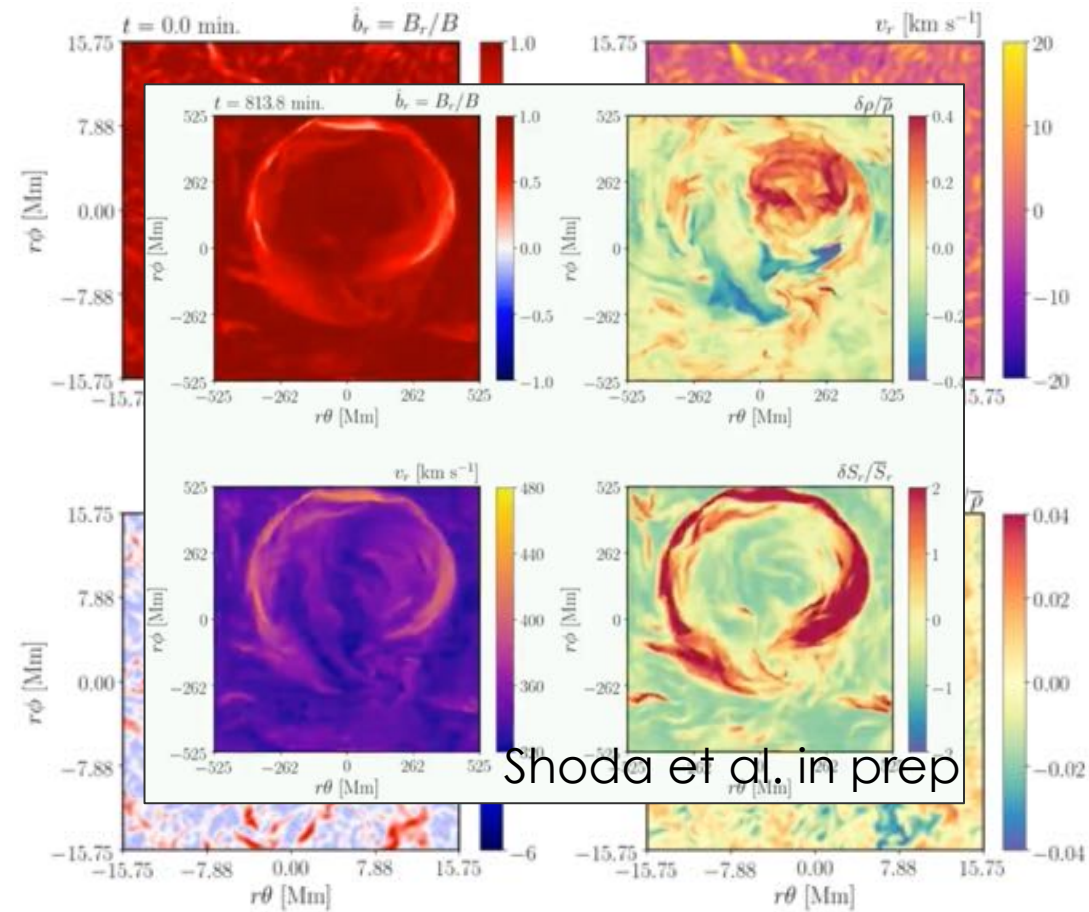
# Turbulent Generation of Switchbacks

Dissipation of Alfvén wave energy into momentum and energy of the solar wind.

Also has been shown to produce folds or “switchbacks” in the simulation. But not enough to match observations!



Shoda et al. 2021



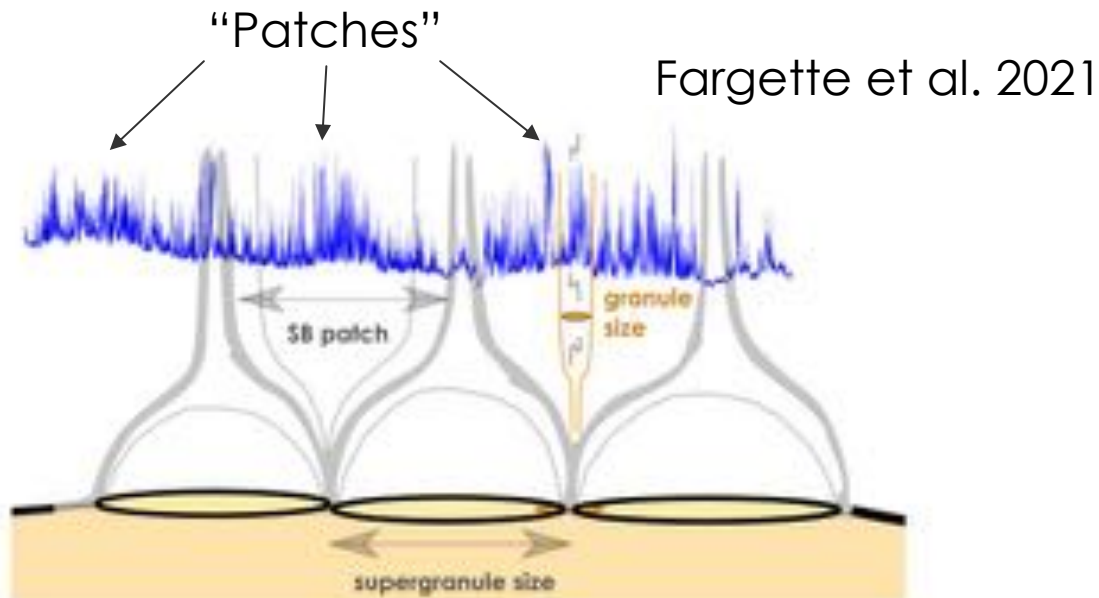
Shoda et al. in prep

Shoda et al. 2019

# Organisation of Switchbacks

Observations mapped down to the surface reveal:

Bale et al. 2021



Fargette et al. 2021

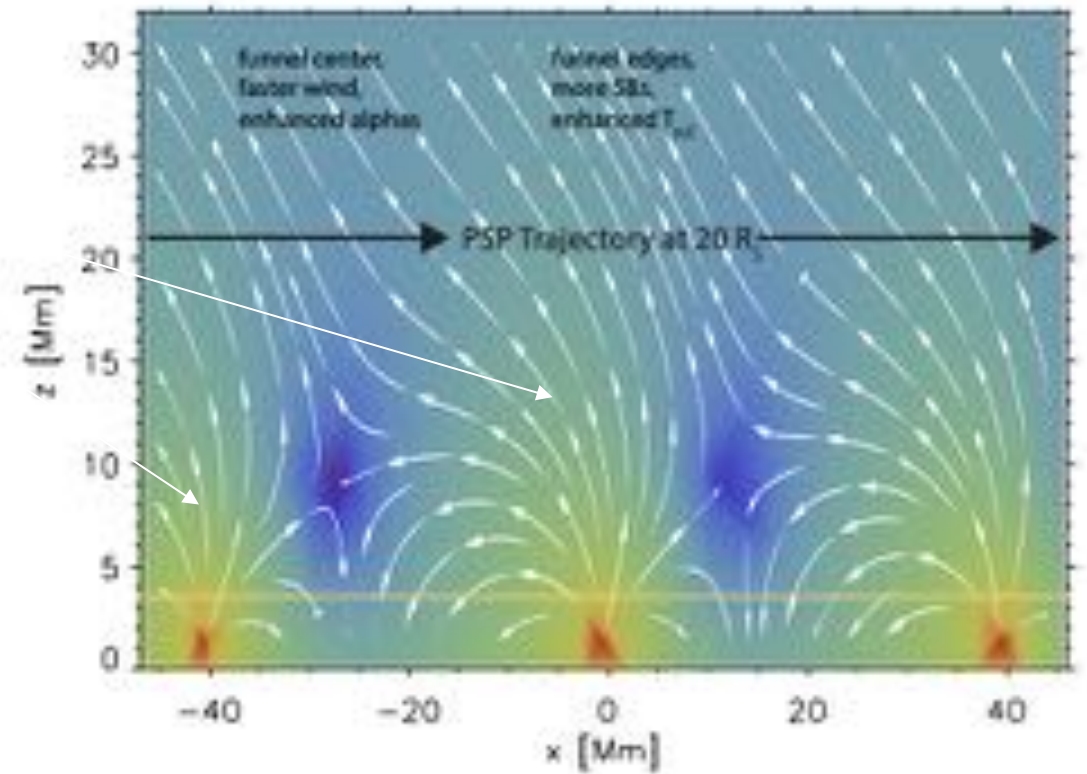


Figure 6. Illustration of switchback modulation by granules and supergranules, with the quantity  $B_z(z) / (E_z)$  overlaid in blue for clarity. Gray lines denote magnetic field lines, with thicker ones indicating the separation between closed and open field lines.

# **Bifrost Simulation(s)**

All Credit to the Bifrost Team!

# The Coronal Hole Patch

Solve the RMHD equations in a Cartesian box.

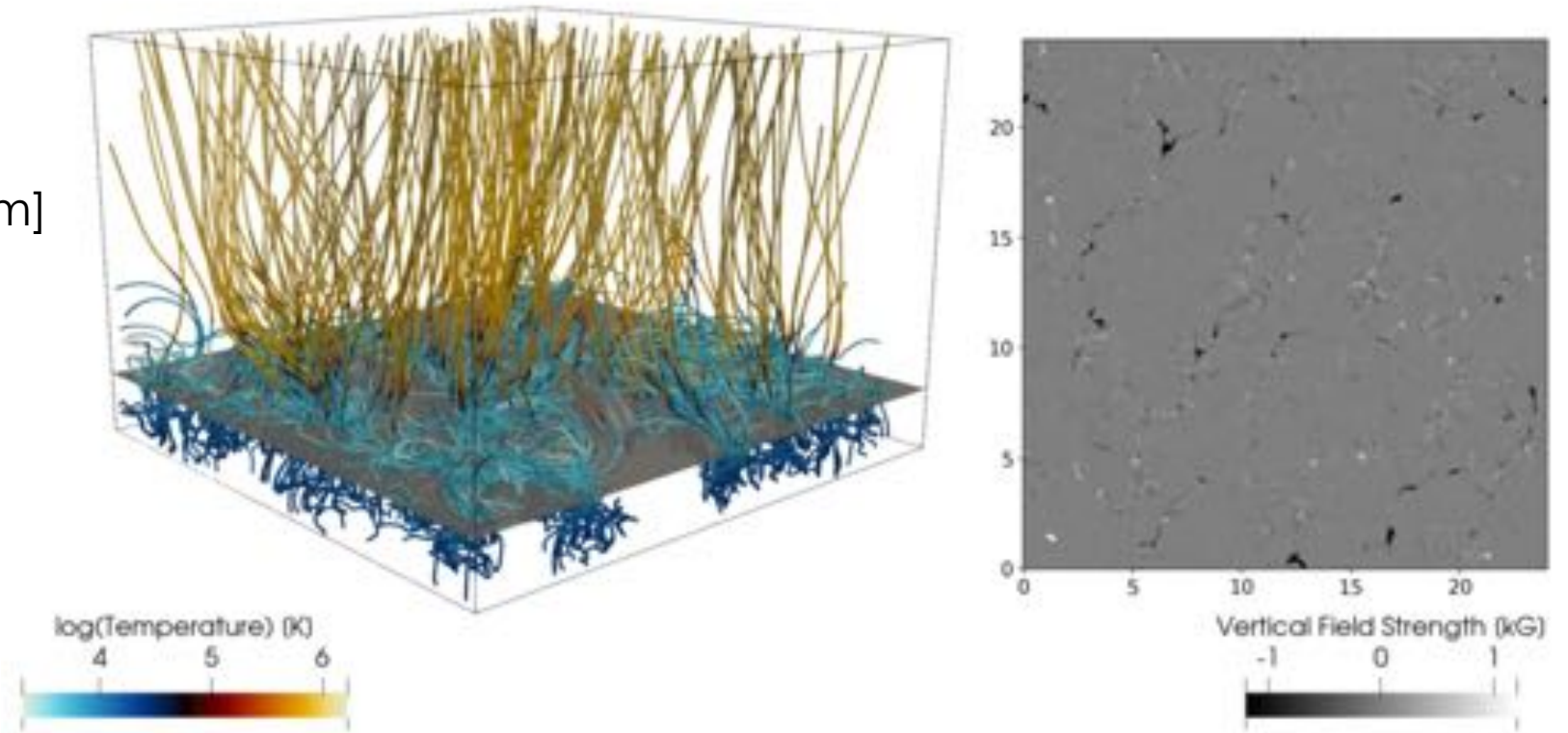
24Mm x 24Mm x [-2.5Mm, 14.5Mm]

768 x 768 x 768 grid cells

40G unsigned flux at the base.

No bipoles.

5G vertical field added.





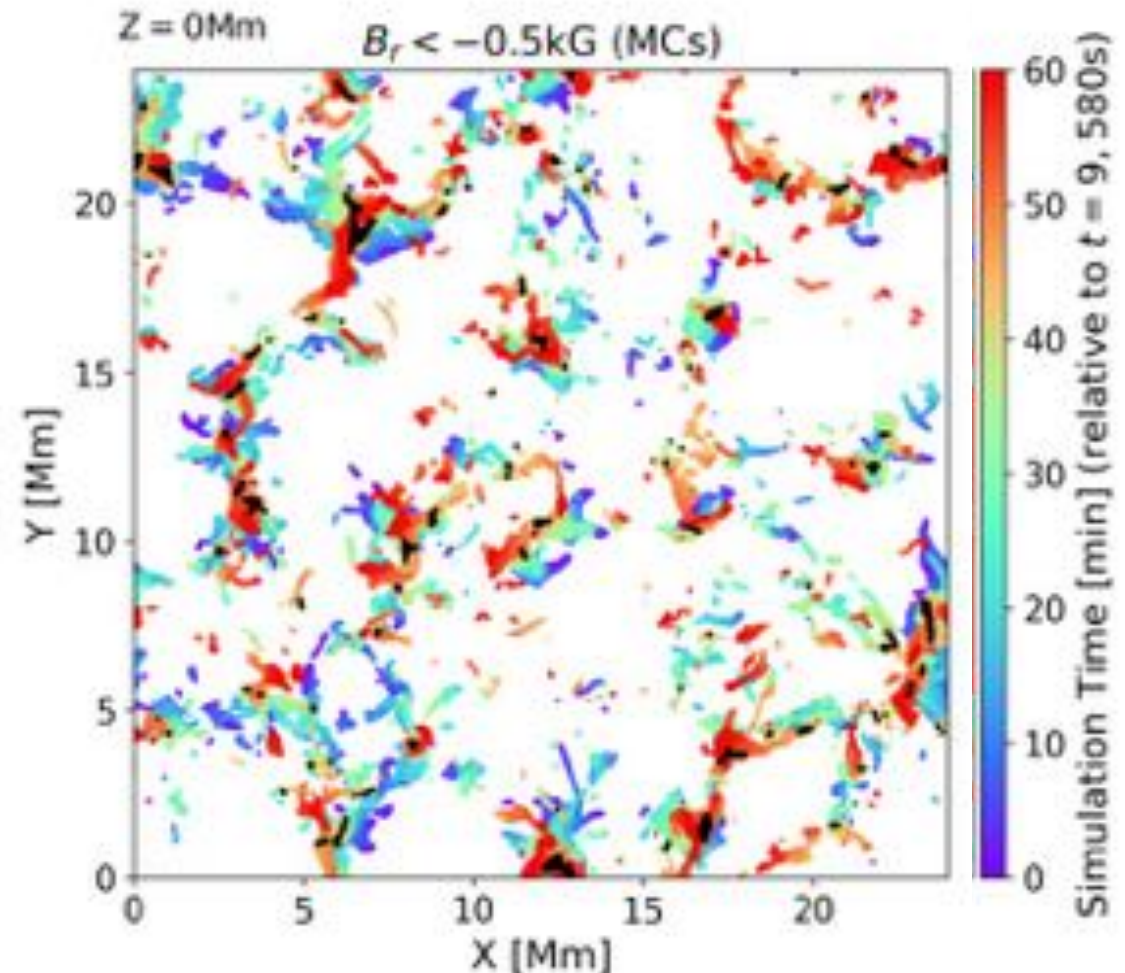
# Organisation of the Magnetic Field

Magnetic flux is expelled into intergranular lanes.

Connected to Magnetic Funnel structures above.

Convective motions shuffle the flux concentrations around the network.

Leads to twisting and magnetic energy building up.

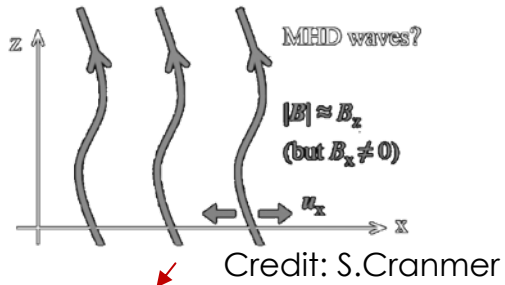
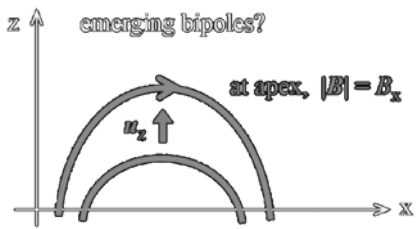


# Organisation of the Magnetic Field

Flux Emergence term: Field Shaking term:

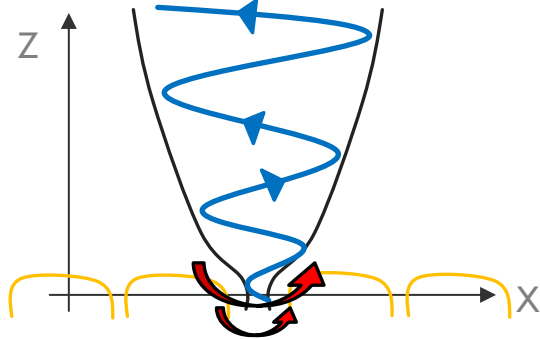
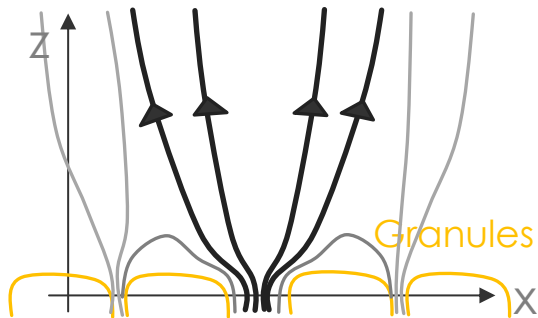
$$S_z = \frac{v_z(B_x^2 + B_y^2)}{\mu_0}$$

$$S_z = \frac{-B_z(v_x B_x + v_y B_y)}{\mu_0}$$

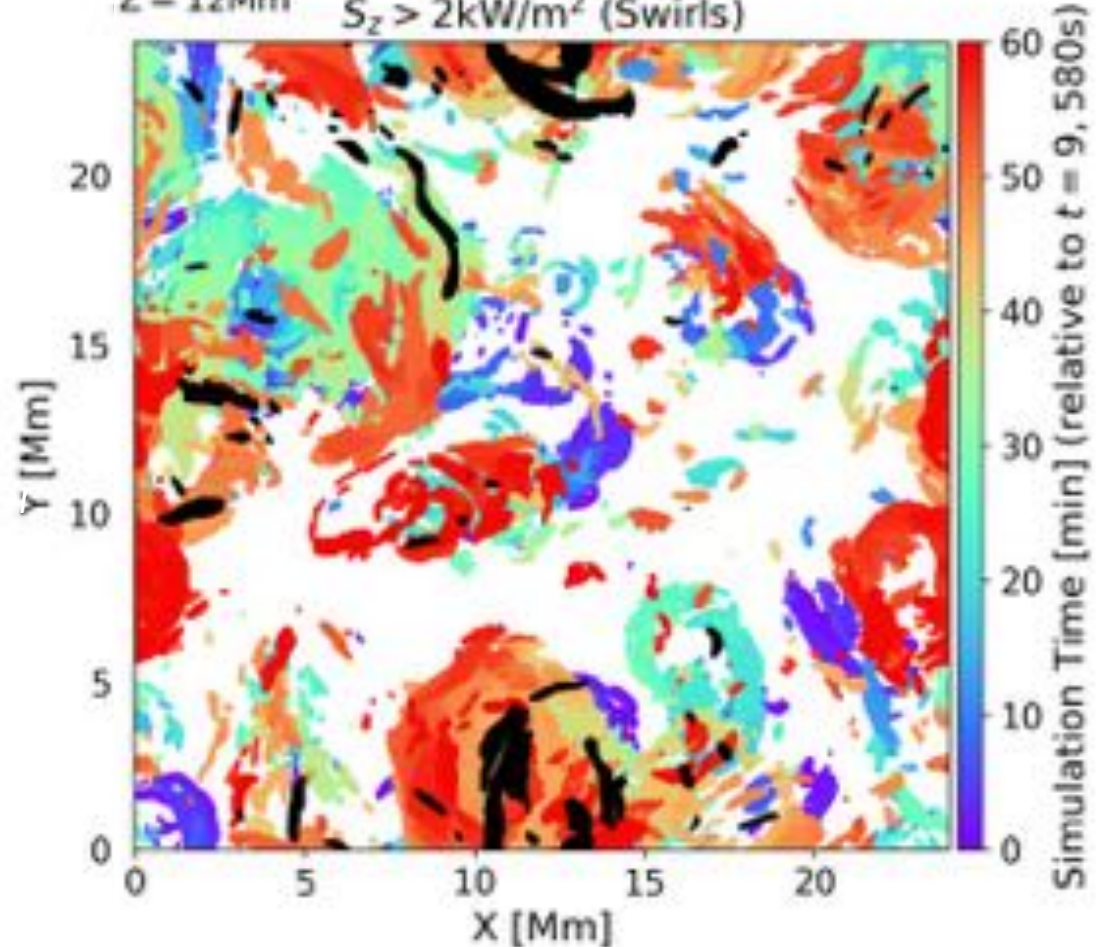


Funnel Structure

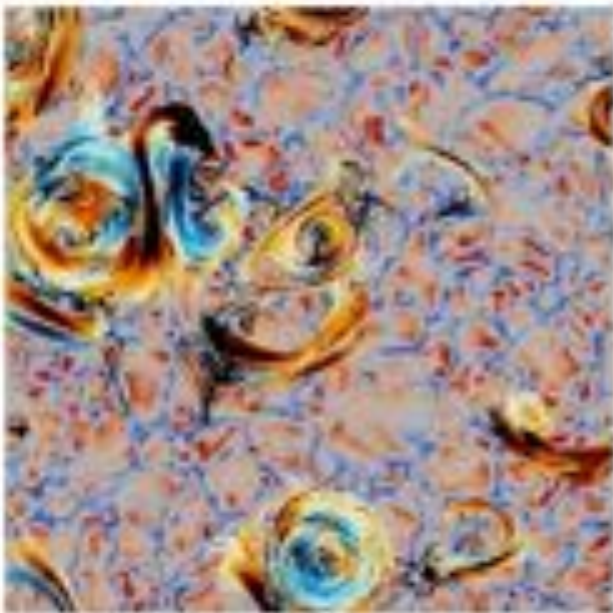
Stirring Motions:



Z = 12Mm  $S_z > 2\text{kW/m}^2$  (Swirls)



Top-down View

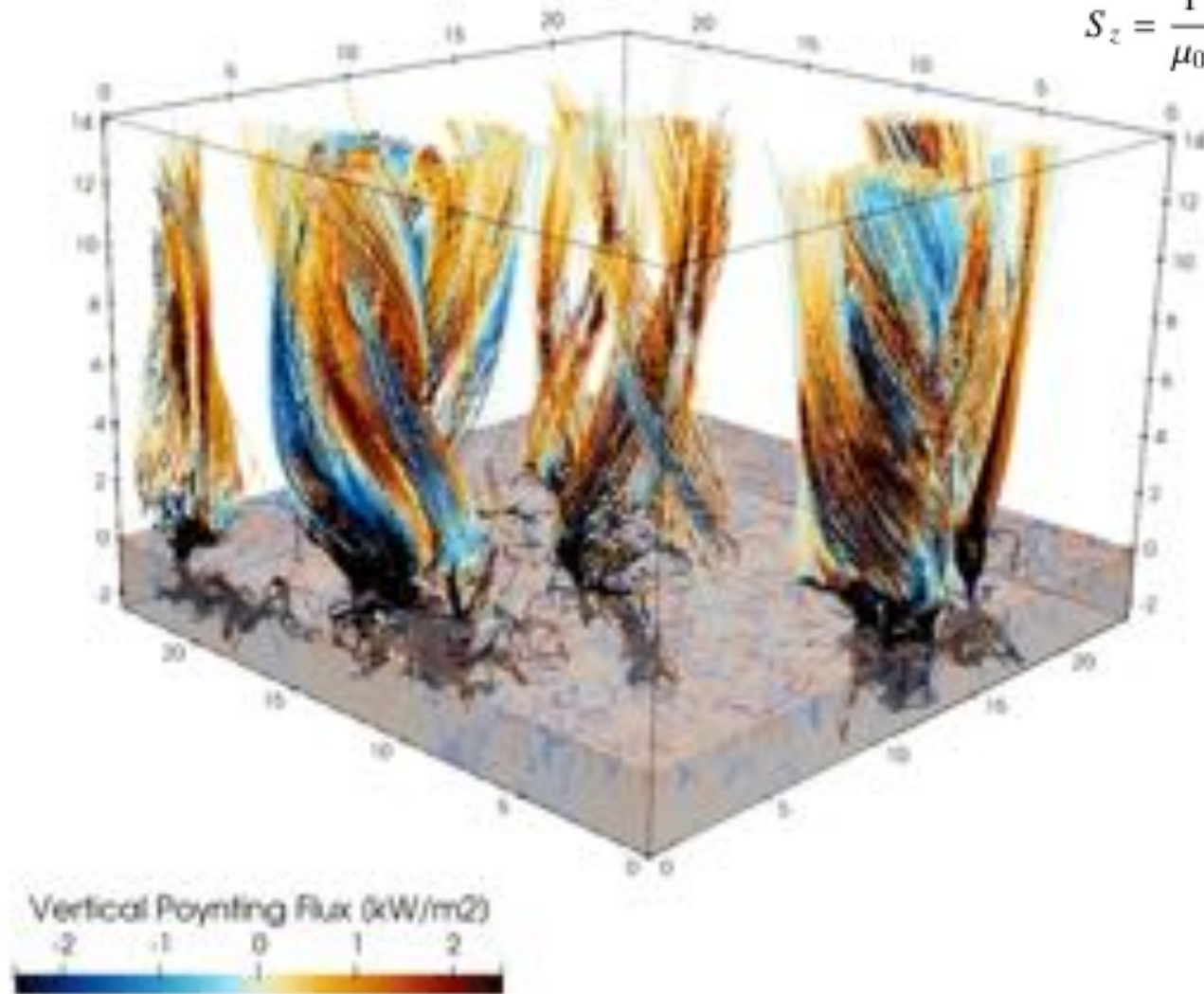
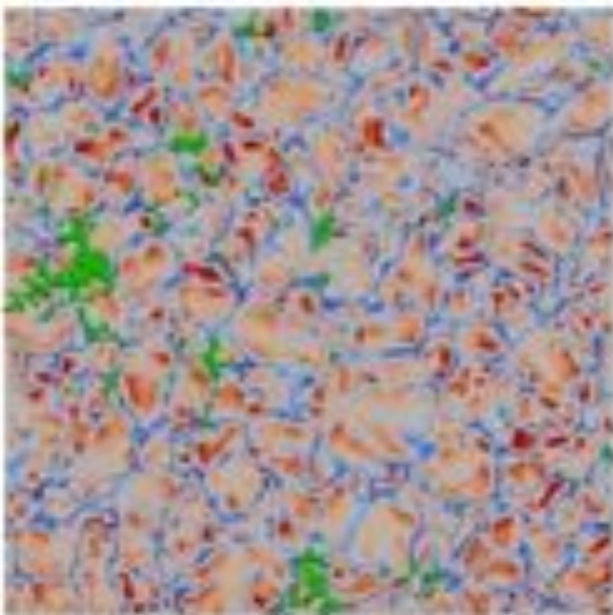


# Twisting and Braiding of the Field

Select Only the Strongest Poynting Fluxes (flux of magnetic energy):

$$S_z = \frac{1}{\mu_0} (\mathbf{E} \times \mathbf{B})_z$$

Footpoints

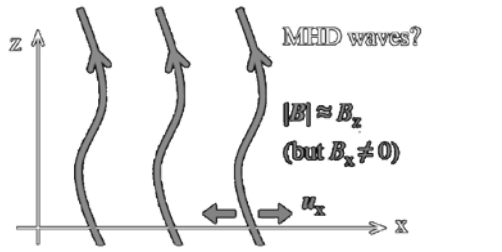
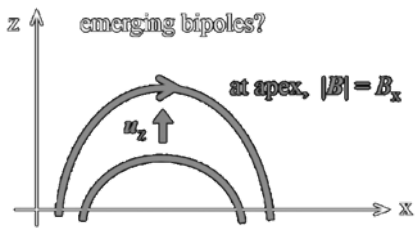


# Organisation of the Magnetic Field

Flux Emergence term: Field Shaking term:

$$S_z = \frac{v_z(B_x^2 + B_y^2)}{\mu_0}$$

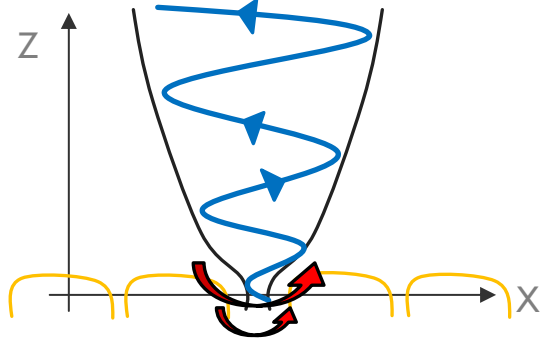
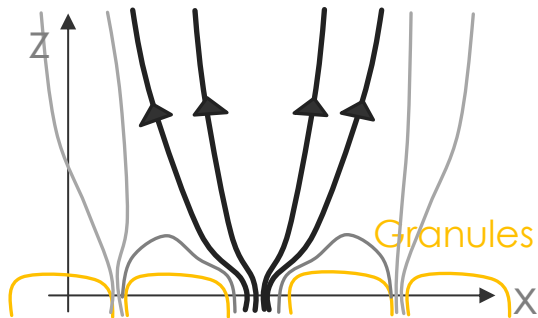
$$S_z = \frac{-B_z(v_x B_x + v_y B_y)}{\mu_0}$$



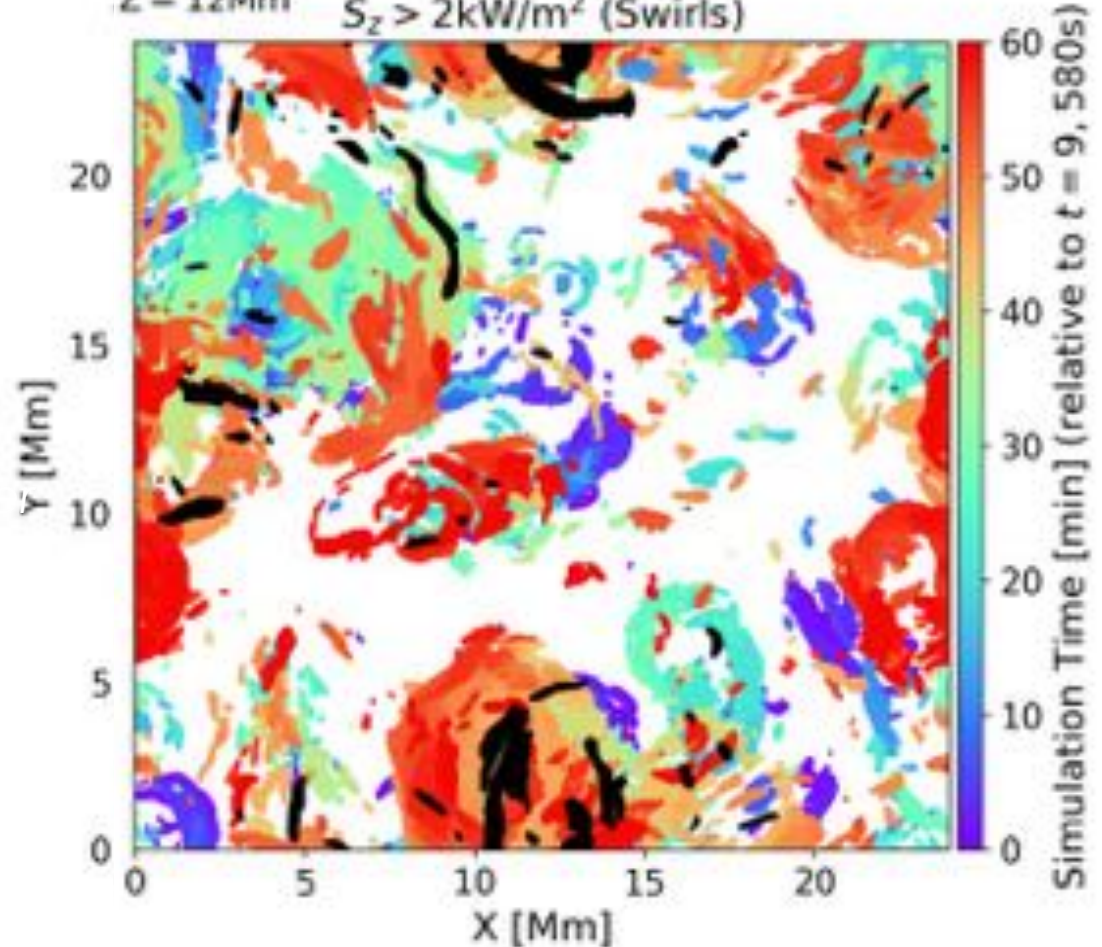
Credit: S.Cranmer

Funnel Structure

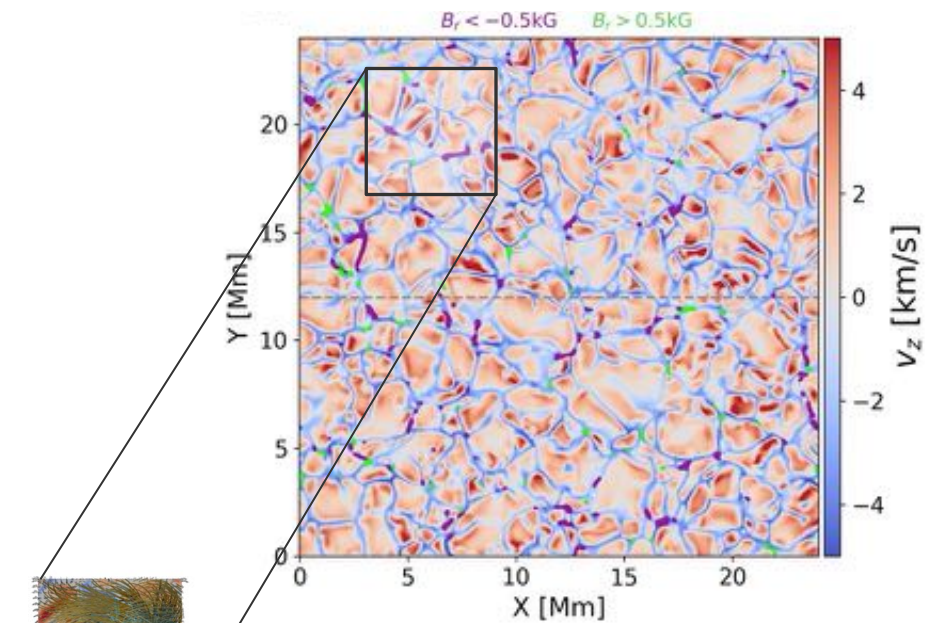
Stirring Motions:



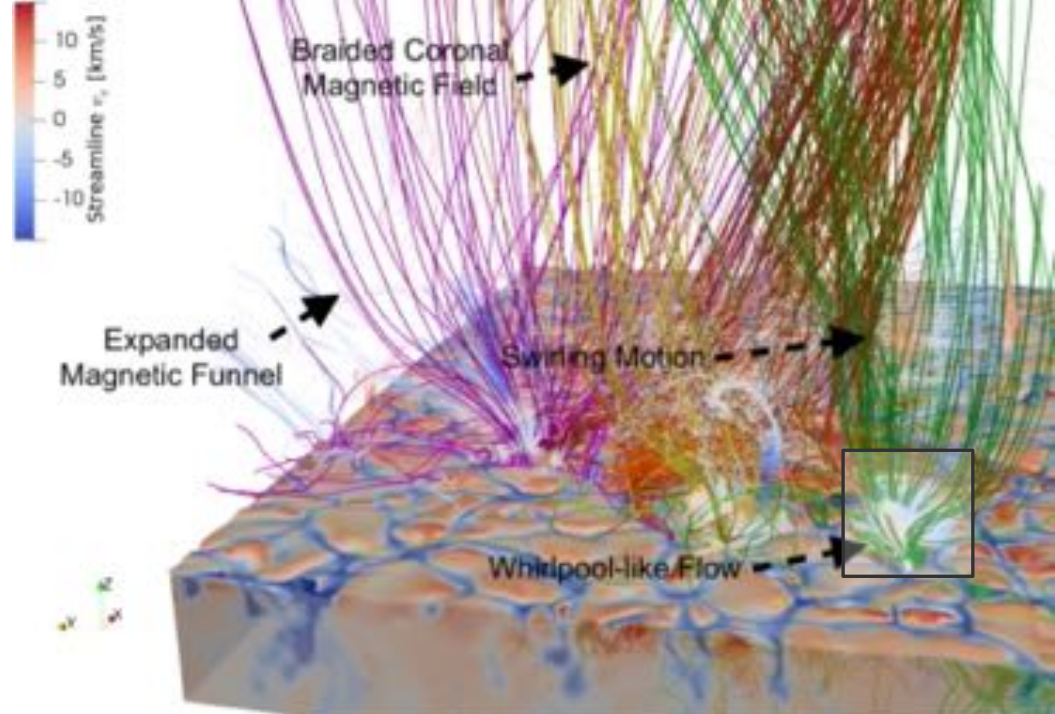
Z = 12Mm  $S_z > 2\text{kW/m}^2$  (Swirls)



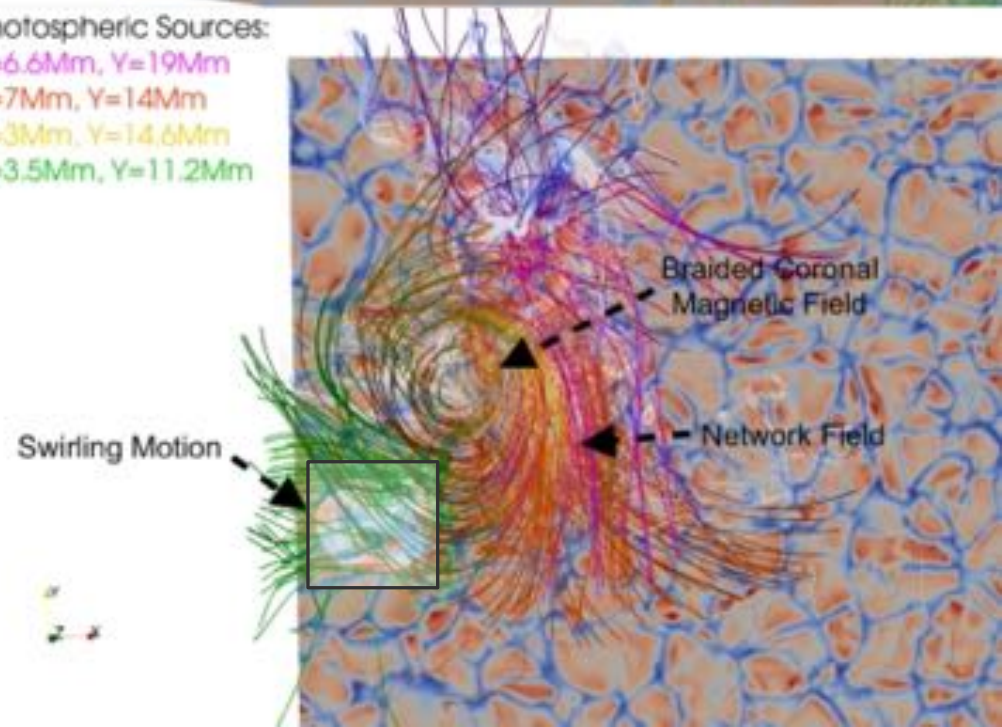
# Swirling Events



# Larger-scale Braiding



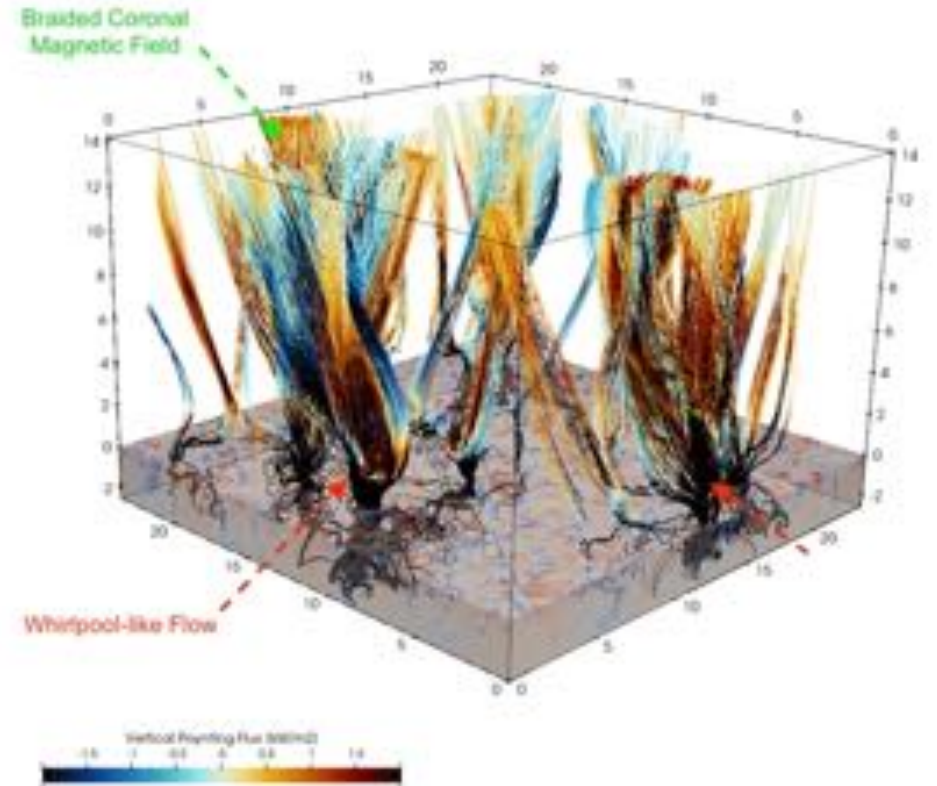
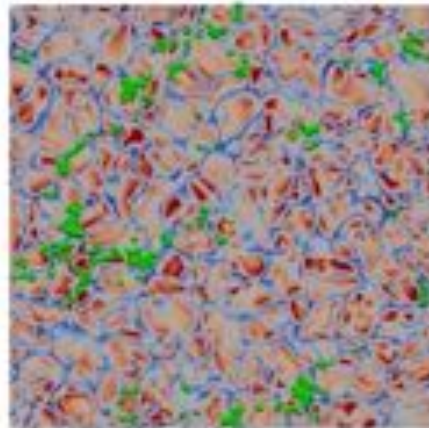
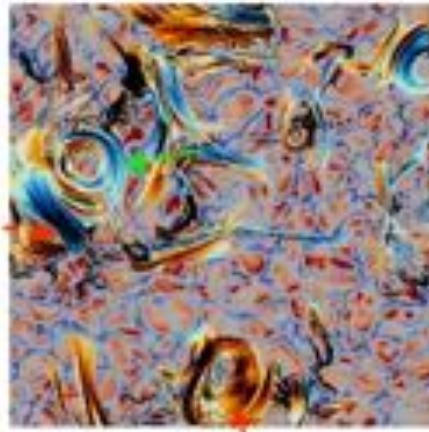
Photospheric Sources:  
X=6.6Mm, Y=19Mm  
X=7Mm, Y=14Mm  
X=3Mm, Y=14.6Mm  
X=3.5Mm, Y=11.2Mm



# Twisting and Braiding of the Field

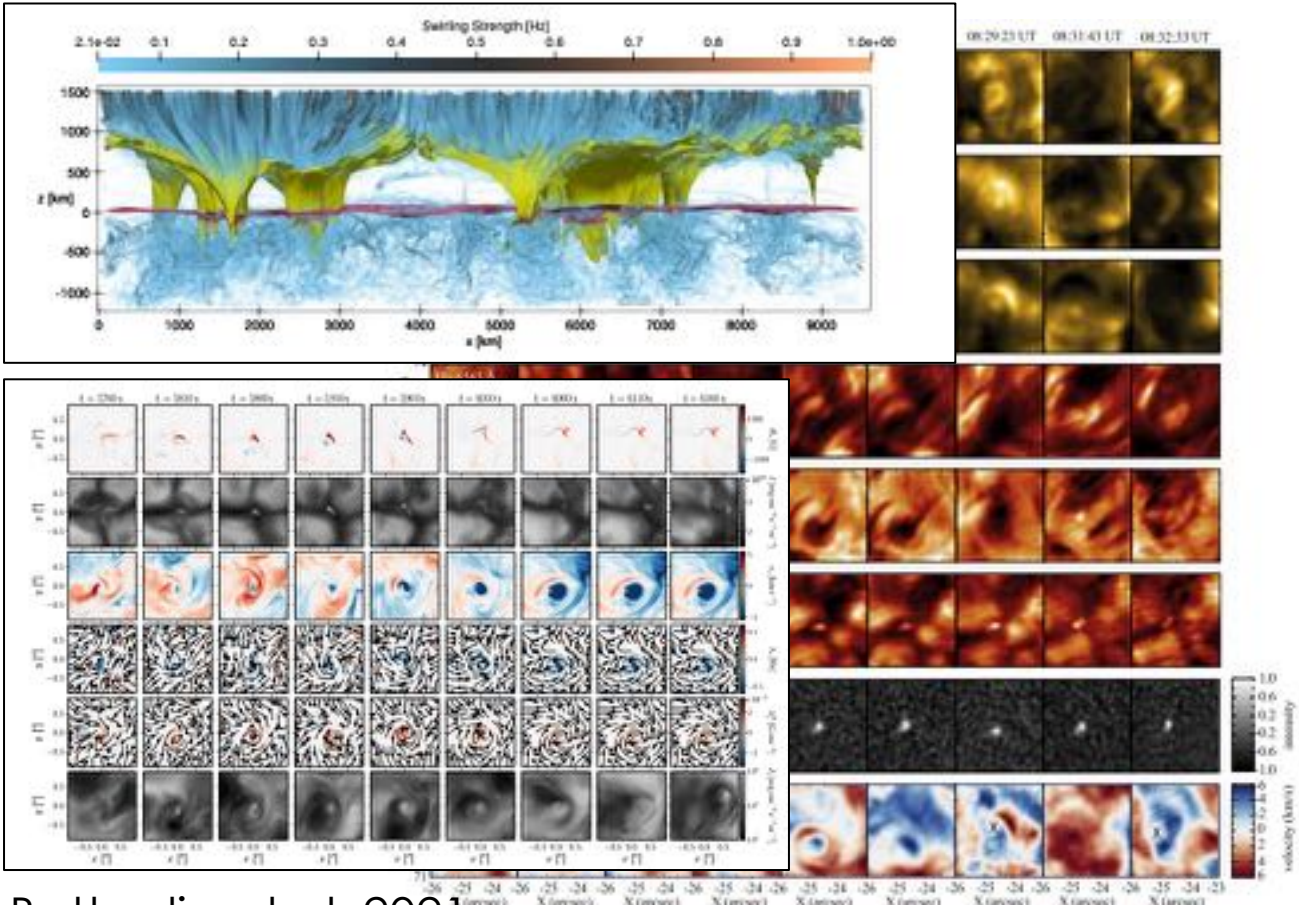
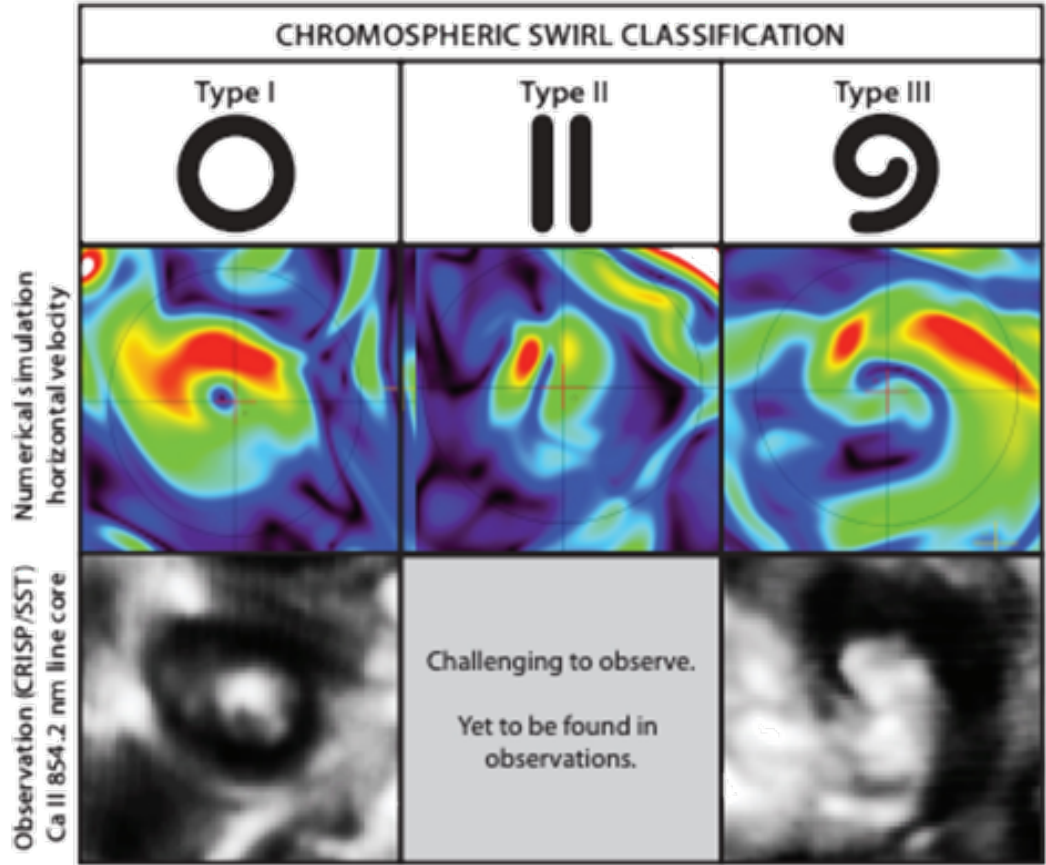
Large-scale “**tangling**” of the field, **organises** the large-scale heating.

Individual **Swirling Events**, driven by whirlpool-like flows in Magnetic Concentrations **provide the heating**/energisation.



# Chromospheric Swirls

Wedemeyer et al. 2013

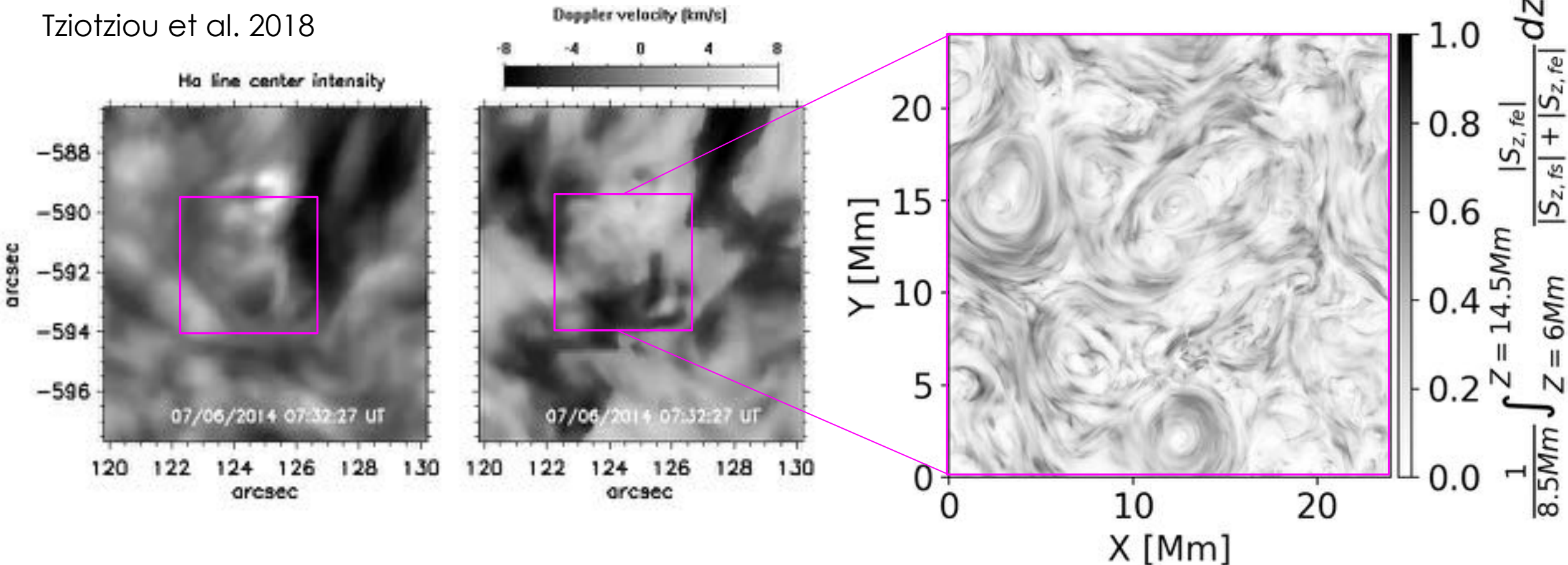


Battaglia et al. 2021

Shetye et al. 2019

# Chromospheric Swirls

Tziotziou et al. 2018



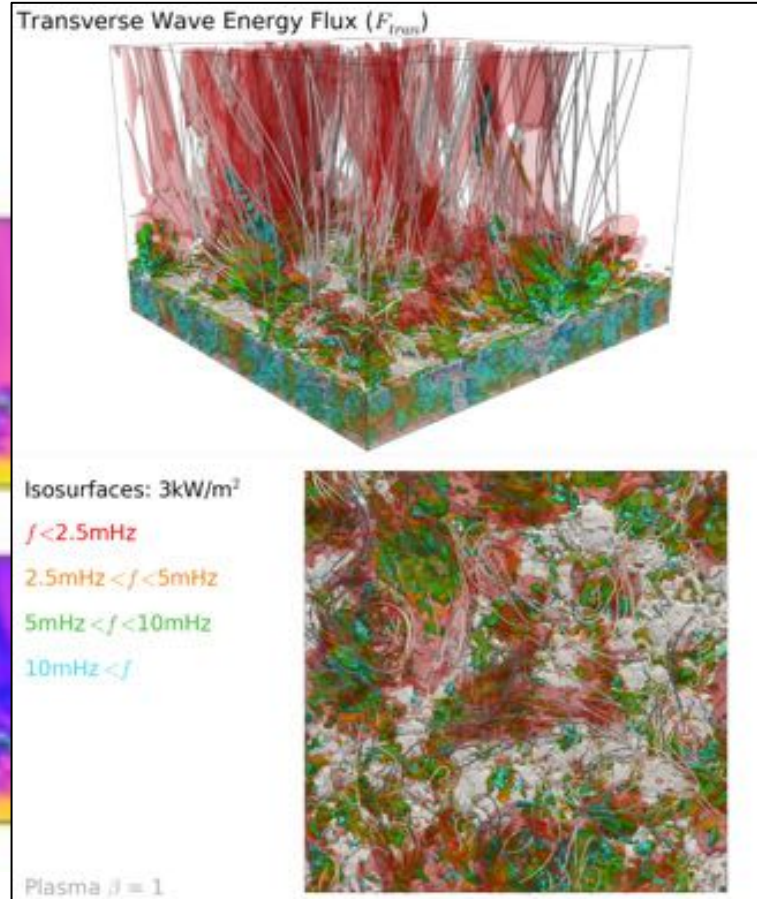
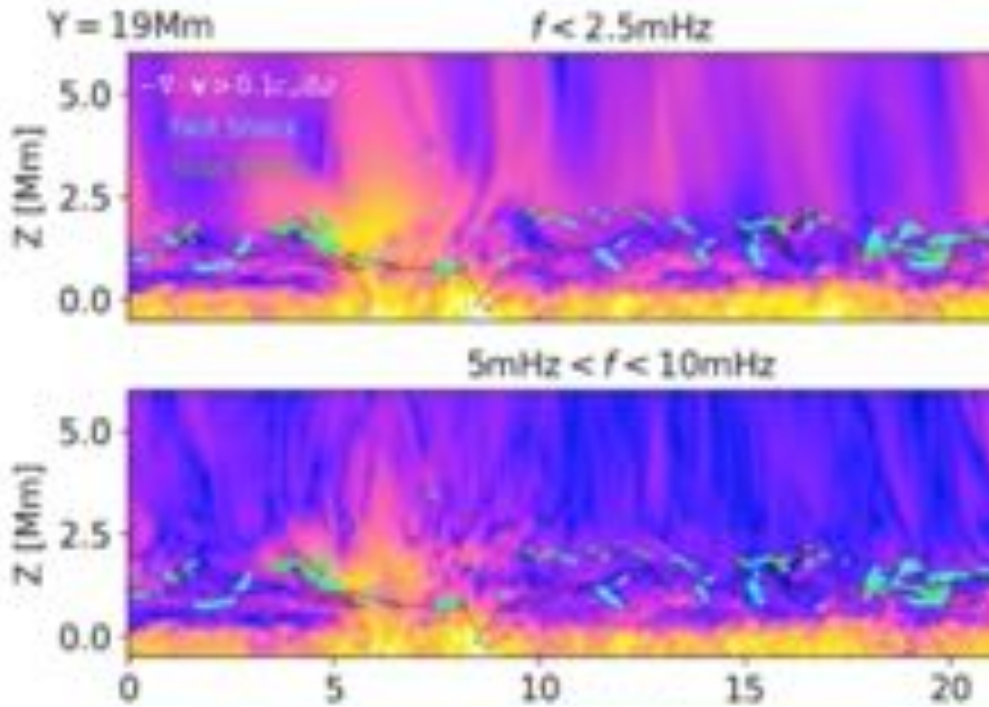


# Implications for the Solar Wind

Structure in the Solar Wind

# Influence of Funnel Network on Waves

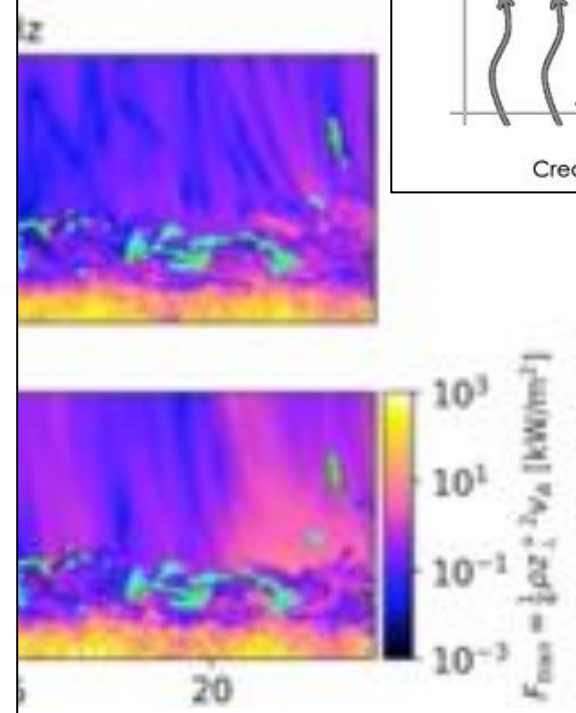
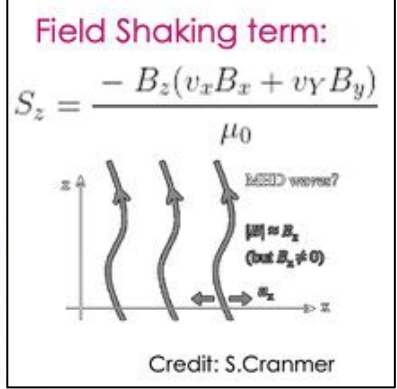
## Transverse (Alfvénic) Wave Energy-flux



Parameterise the Alfvén wave-turbulence

$$\frac{\partial \mathcal{E}^\pm}{\partial t} + \nabla \cdot ([v \pm v_A] \mathcal{E}^\pm) =$$

$$\mathcal{E}^\pm = \rho \frac{|z^\pm|^2}{4} \quad z^\pm = \delta$$



# Structure in the Energy Injection

Temperature and density variations ( $\pm 20\%$ ) on the same scale. Plus **structure** in the injection of Alfvénic Fluctuations!!!

Fargette et al. 2021

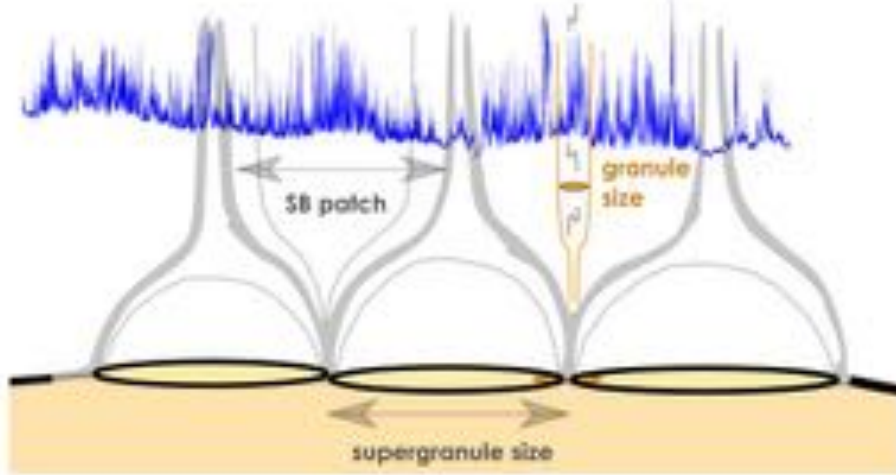
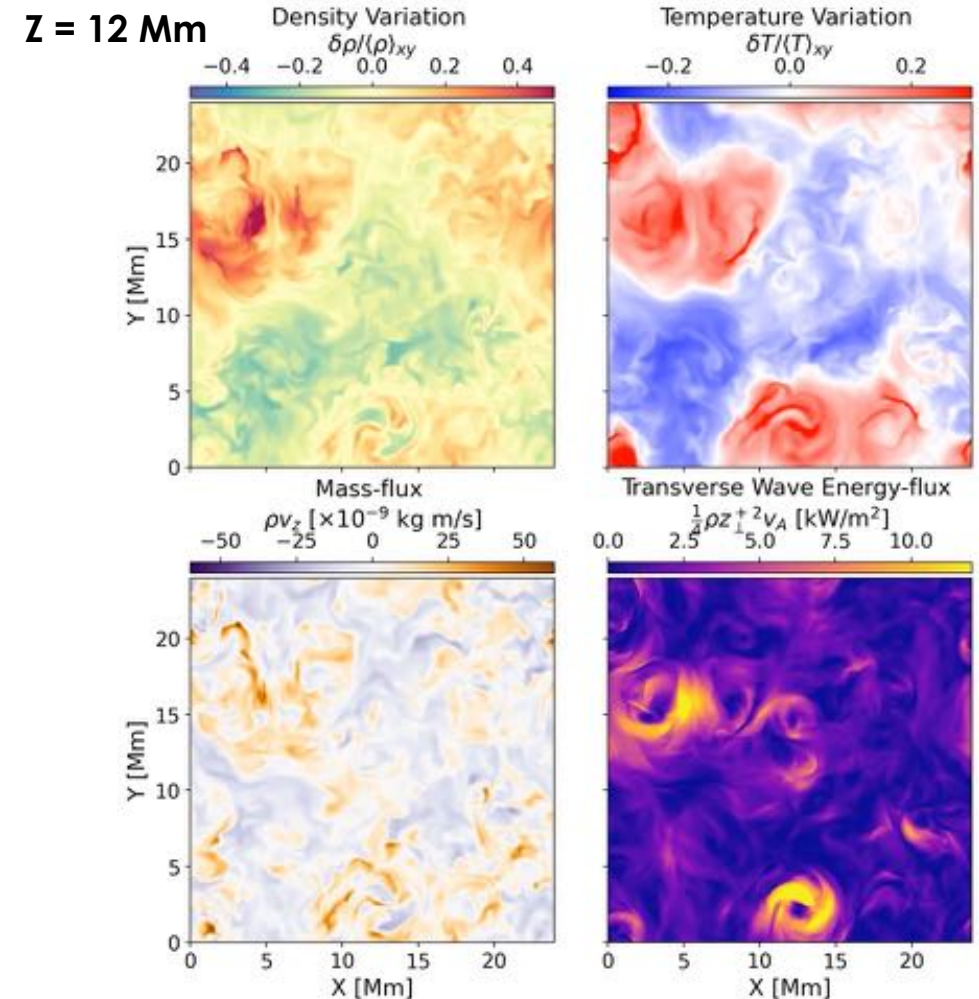


Figure 6. Illustration of switchback modulation by granules and supergranules, with the quantity  $\beta_{\text{ext}}(z)$  overlotted in blue for clarity. Gray lines denote magnetic field lines, with thicker ones indicating the separation between closed and open field lines.



# Future Work

Bigger Boxes, Flux Emergence, Impact on the Solar Wind, and What about other Stars?

# Large Simulation Domain + Structure

Larger simulation domain.

Added again a vertical field to create an open low-corona.

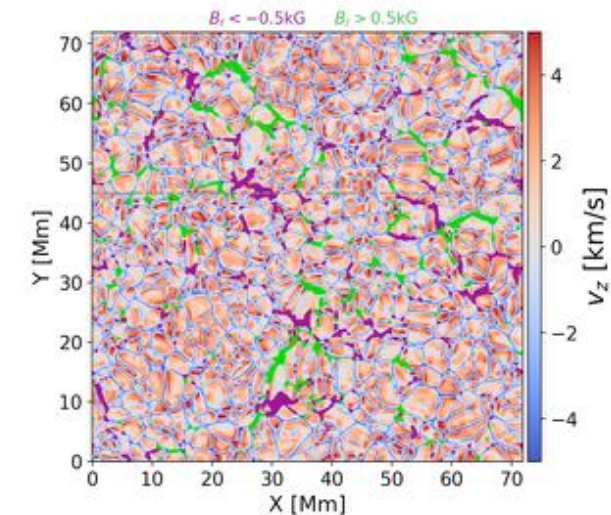
Second version without adding flux at the bottom boundary?

Despite a much larger volume, similar number of grid cells (influence on the scale of the vorticity etc).

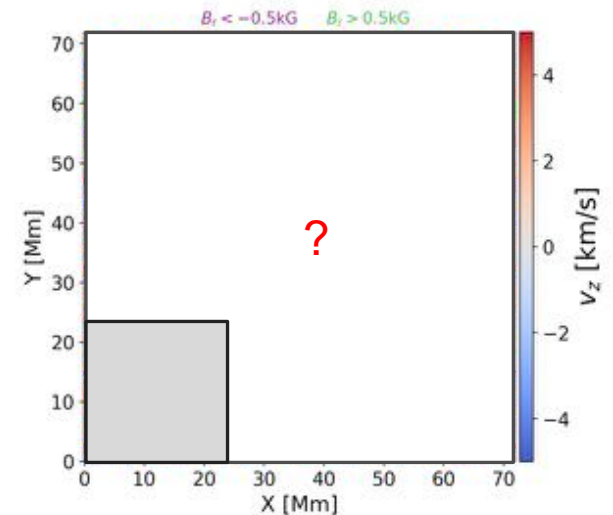
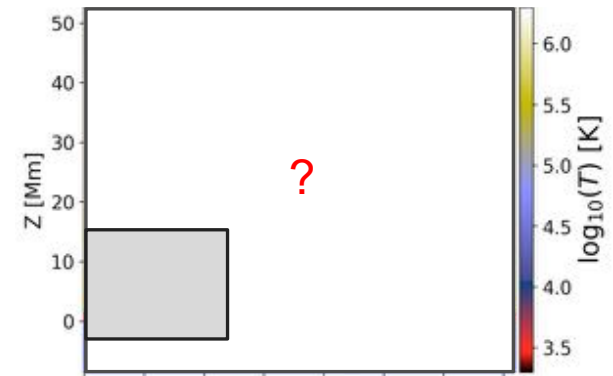
Access to higher-up in the Atmosphere

Structured Magnetic Field + Stronger Field!

Active Flux Emerge.



Without Flux Emerge.



# Conclusions

WholeSun Synergy Grant



European Research Council  
Established by the European Commission



- Stirring the Base of the Solar Wind – (Finley et al. *Submitted!*):
  - Self-consistent braiding and swirling of the magnetic field in a coronal hole patch.
  - Structuring the properties at the coronal base, from which the solar wind is launched.
  - Generates Alfvénic fluctuations that are needed to power the solar wind.
  - The torsional nature of the fluctuations is needed to increase the turbulent generation of switchbacks in the solar wind (up-to the observed frequency from PSP).
- In future we aim to expand this kind of study to other set-ups, like the larger domain, etc.

