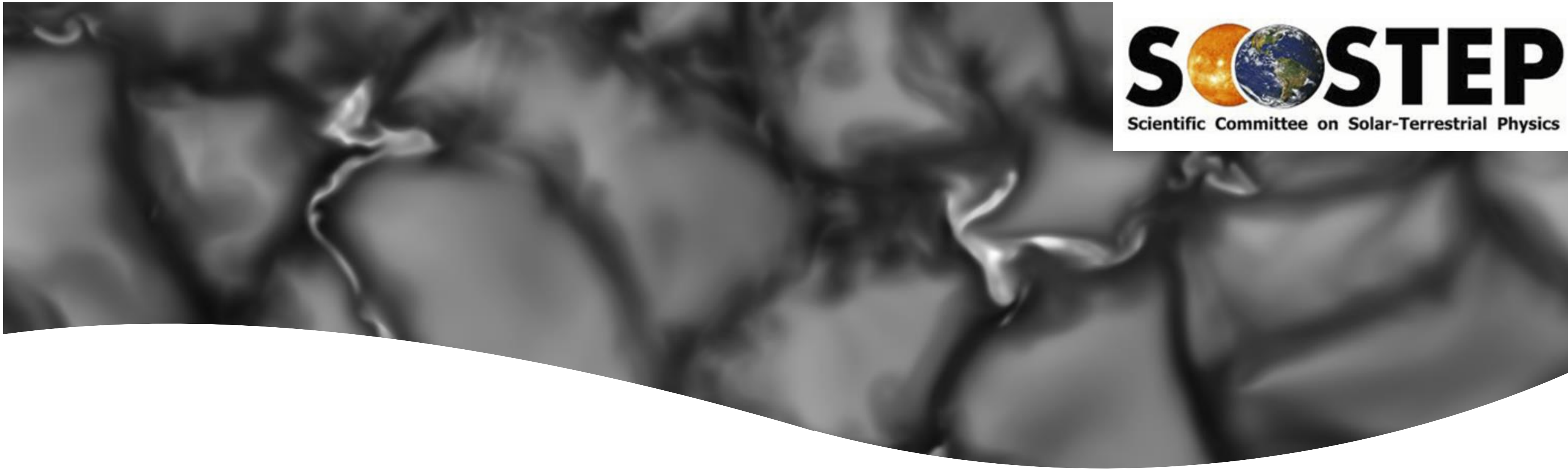

SCOSTEP
Scientific Committee on Solar-Terrestrial Physics

Vortices and Alfvénic pulses in the simulated solar atmosphere

5th Swiss SCOSTEP Workshop, 16th of May, 2023

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In collaboration with: Andrea Battaglia, Flavio Calvo, Aleksi Bossart

- *e-mail*: *jose.canivete@irsol.usi.ch*

USI

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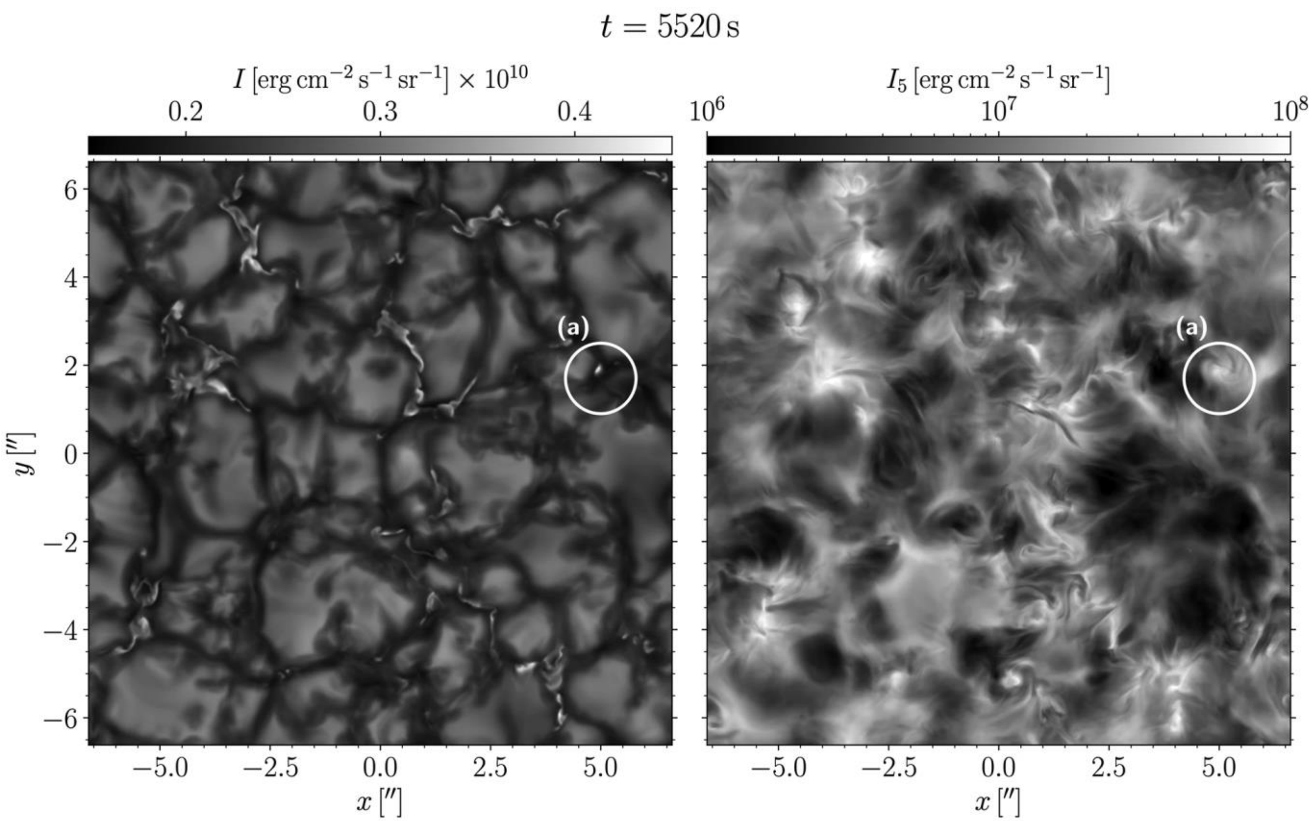
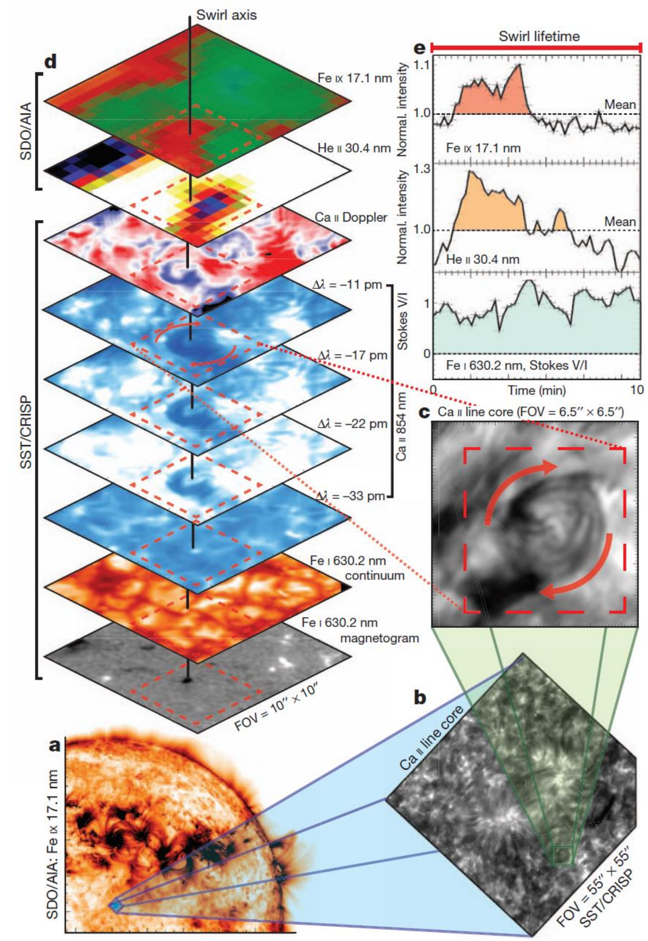
Introduction



Source: Battaglia et al., 2021



Source: Wedemeyer-Böhm et al., 2013

- Small-scale **swirling motions** in the **quiet solar atmosphere** observations and simulations
- Footpoints in intergranular lanes
- Correlated with **magnetic fields** (Bright points)
  - "Magnetic Tornadoes"

Energy channels
from the convection zone to the upper layers?

Methods

- **3D r-MHD CO5BOLD simulations**

Methods

- **3D r-MHD CO5BOLD simulations**
- **Vortex identification**
  - **Swirling strength**
    - “Better version” of the vorticity
    - Local quantity
    - Evolution equation
  - **SWIRL Algorithm**
    - Automated identification of 2D swirls
    - Based on local and global properties of the flow

$$
\begin{aligned}
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&= -2\lambda\lambda_{\mathrm{cr}} && T_\lambda^1 \\
&\quad -2\mathrm{Im}\left\{\mathcal{P}^{-1}\left[\nabla\left(\frac{1}{\rho}\nabla p_{\mathrm{g}}\right)\right]\mathcal{P}\right\}_{22} && T_\lambda^2 \\
&\quad -2\mathrm{Im}\left\{\mathcal{P}^{-1}\left[\nabla\left(\frac{1}{\rho}\nabla p_{\mathrm{m}}\right)-\left(\nabla\frac{1}{\rho}\right)(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}\right]\mathcal{P}\right\}_{22} && T_\lambda^3 \\
&\quad +2\mathrm{Im}\left\{\mathcal{P}^{-1}\left[\frac{1}{\rho}\nabla\left((\boldsymbol{B}\cdot\nabla)\boldsymbol{B}\right)\right]\mathcal{P}\right\}_{22} && T_\lambda^4 \\
&\quad -2\mathrm{Im}\left\{\mathcal{P}^{-1}\left[\nabla\left(\nabla\Phi\right)\right]\mathcal{P}\right\}_{22}. && T_\lambda^5
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Source: Canivete Cuissa & Steiner, 2020

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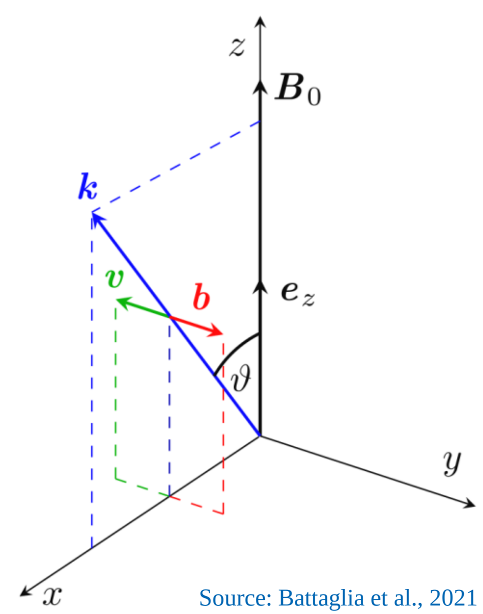
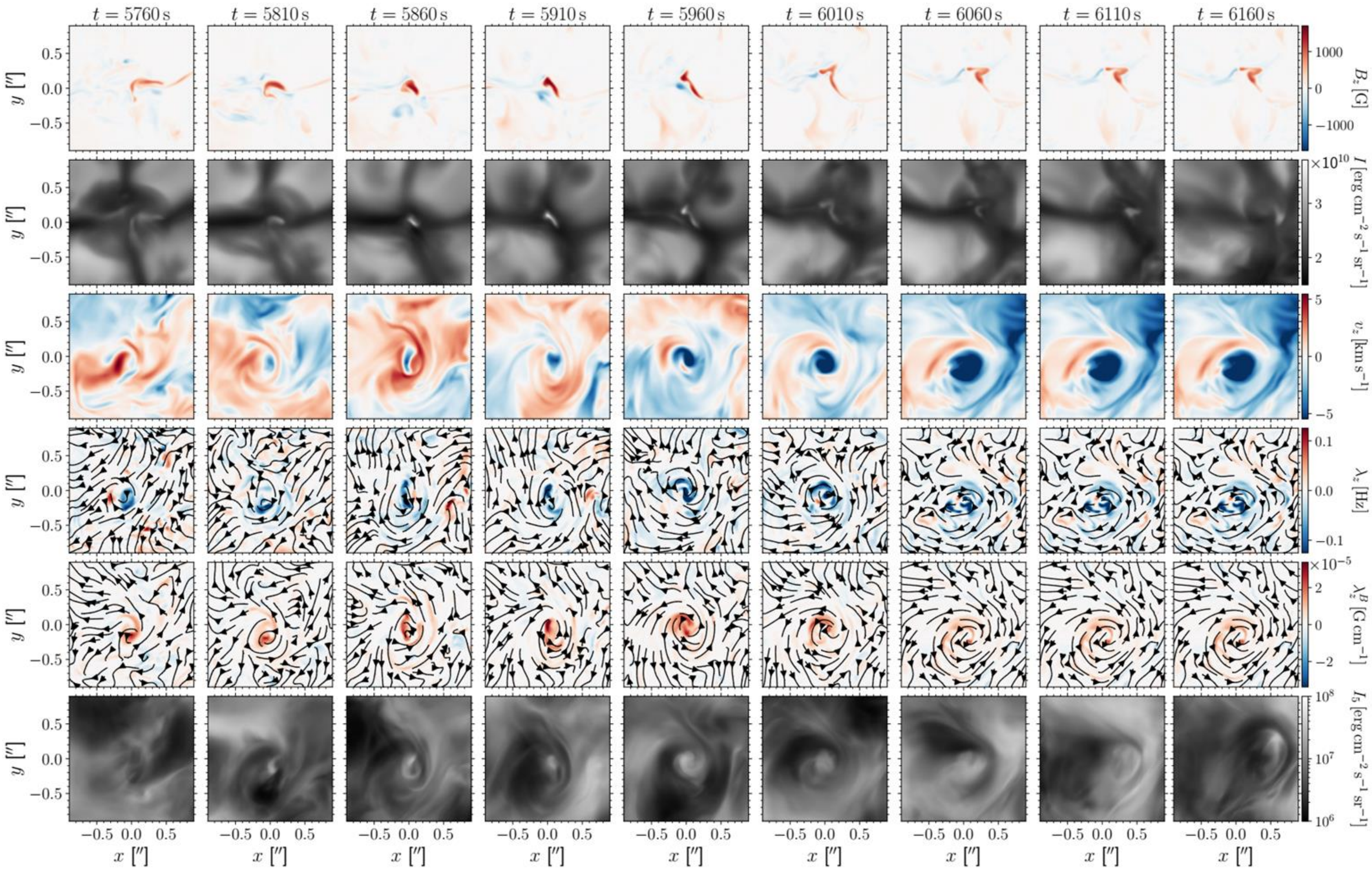
Source: Canivete Cuissa & Steiner, 2020

- **Torsional Alfvén waves**
  - **Properties used for identification**
    - Phase of perturbations in $\boldsymbol{v}$ and $\boldsymbol{B}$ (magnetic swirling strength λ^B)
    - Propagate at Alfvén speed $v_{\mathrm{A}} = B_0/\sqrt{4\pi\rho}$
    - Driven by magnetic tension



Source: Battaglia et al., 2021

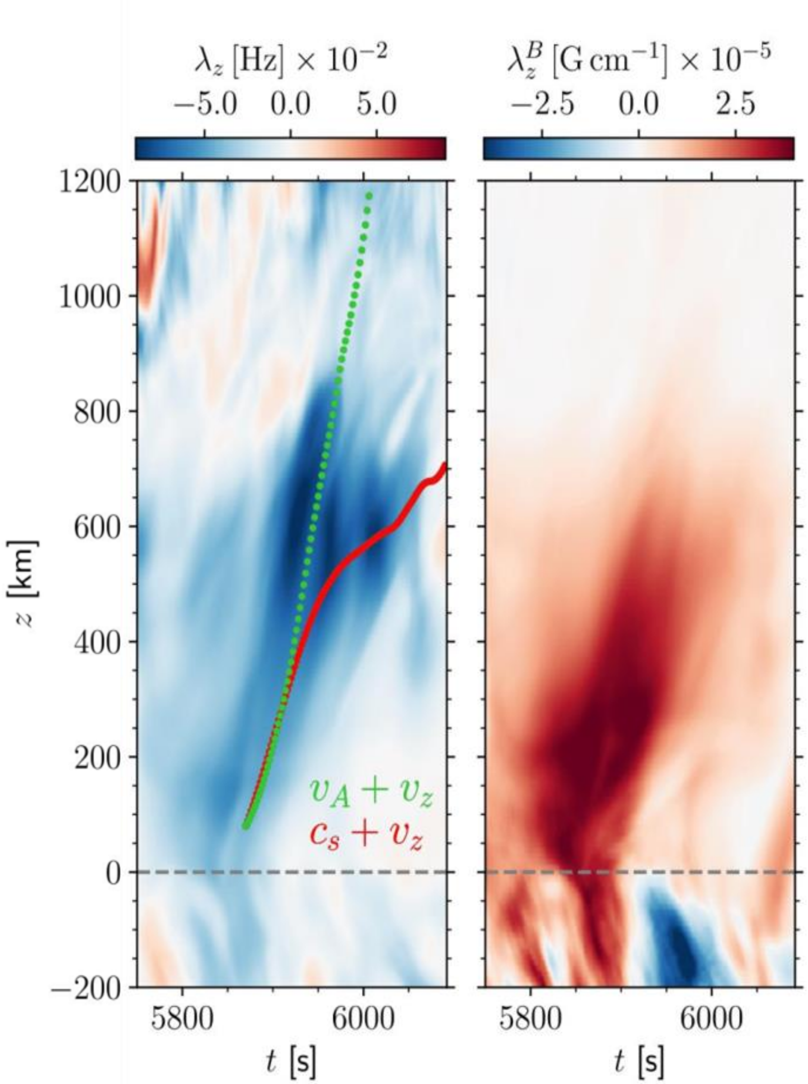
Swirl event



Time sequence of a swirl event at $z = 0$ km (B_z) and $z = 700$ km ($v_z, \lambda_z, \lambda_z^B$) in CO5BOLD simulations

Source: Battaglia et al., 2021

Swirl event - Propagation

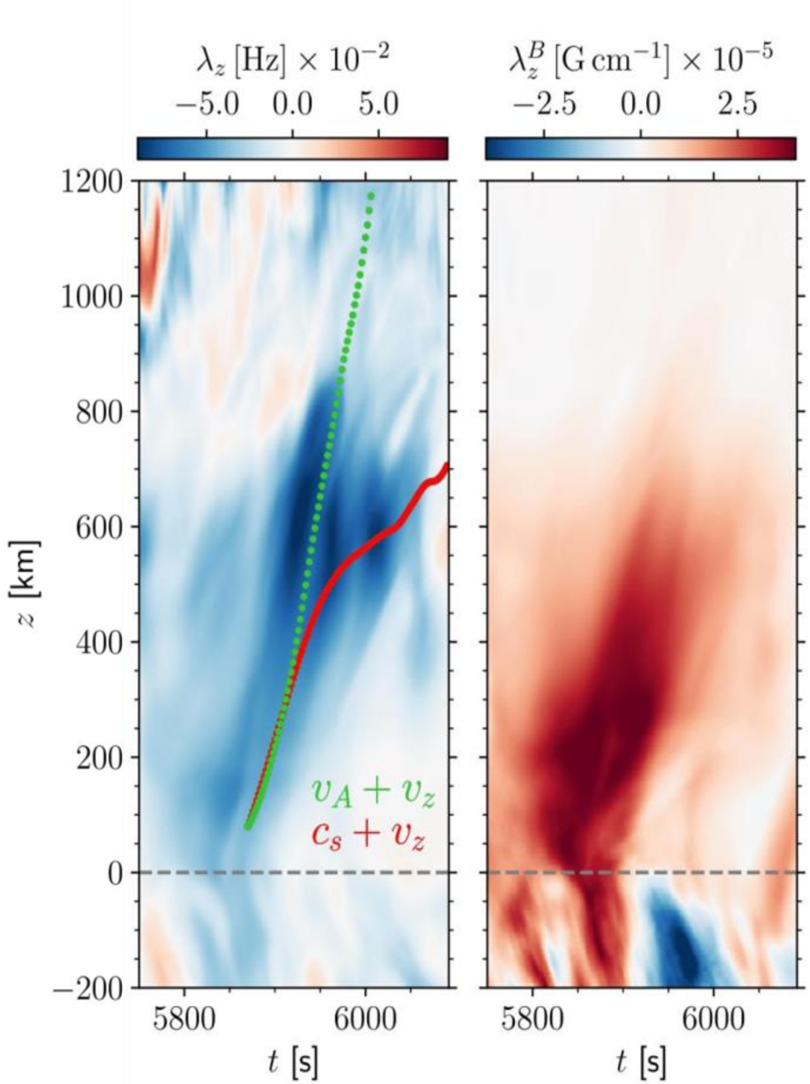


Time-distance diagrams averaged over 150 × 150 km² of the vertical component of the swirling strength and of the magnetic swirling strength

Source: Battaglia et al., 2021

- Photospheric origin
- **Upward propagation**
- "**Pulse**" (not oscillatory)
- Swirling str. eq. analysis

Swirl event - Propagation



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✓ Propagation at Alfvén speed

✓ Magnetic field twist opposite to vortex rotation

✓ Driven by magnetic tension

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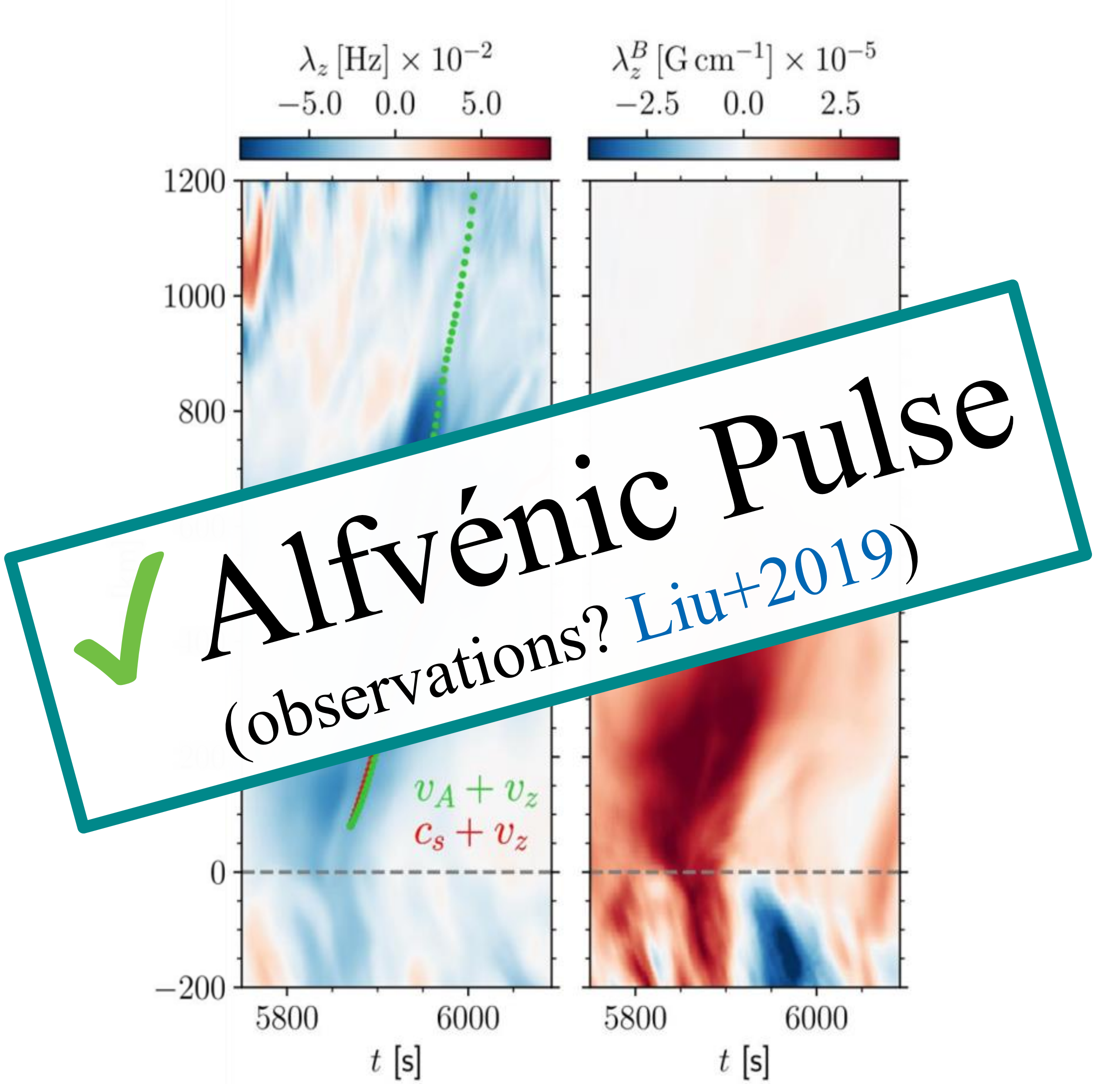

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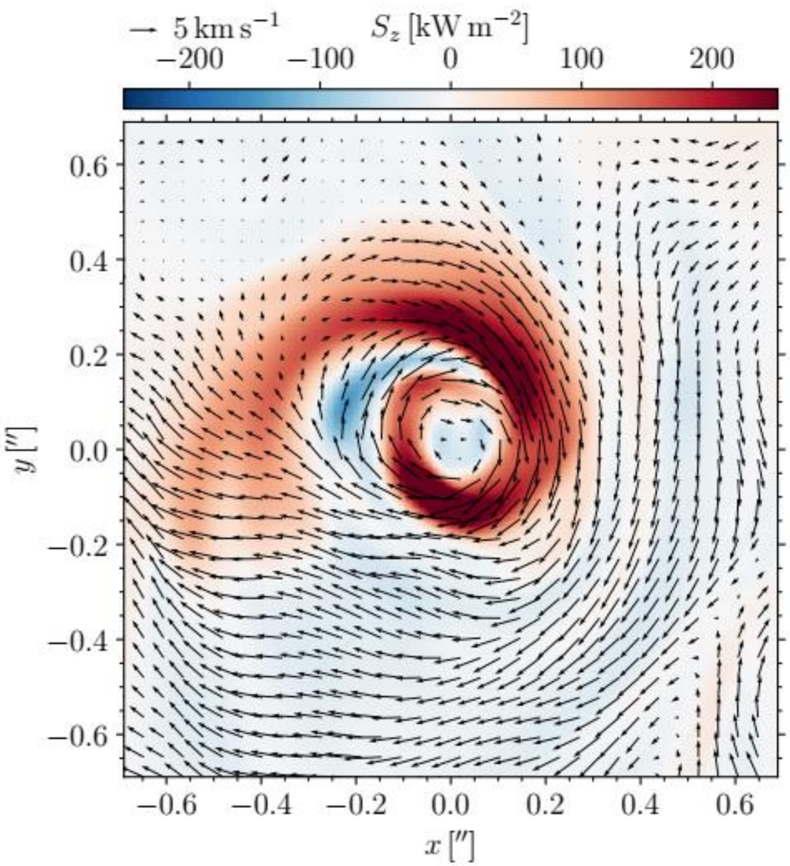
Swirl event - Energetics

- Study vertical transport of energy with **Poynting flux** S_z



Horizontal section at z = 700 km of the vertical Poynting flux

Source: Battaglia et al., 2021

> ➢ Swirling motions carry up energy

Swirl event - Energetics

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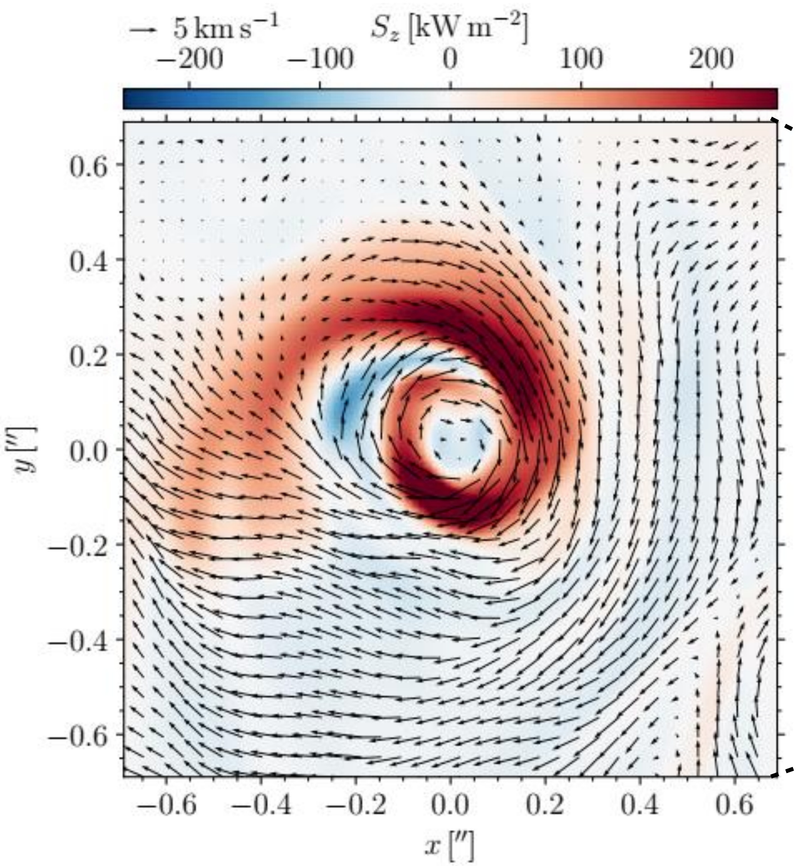

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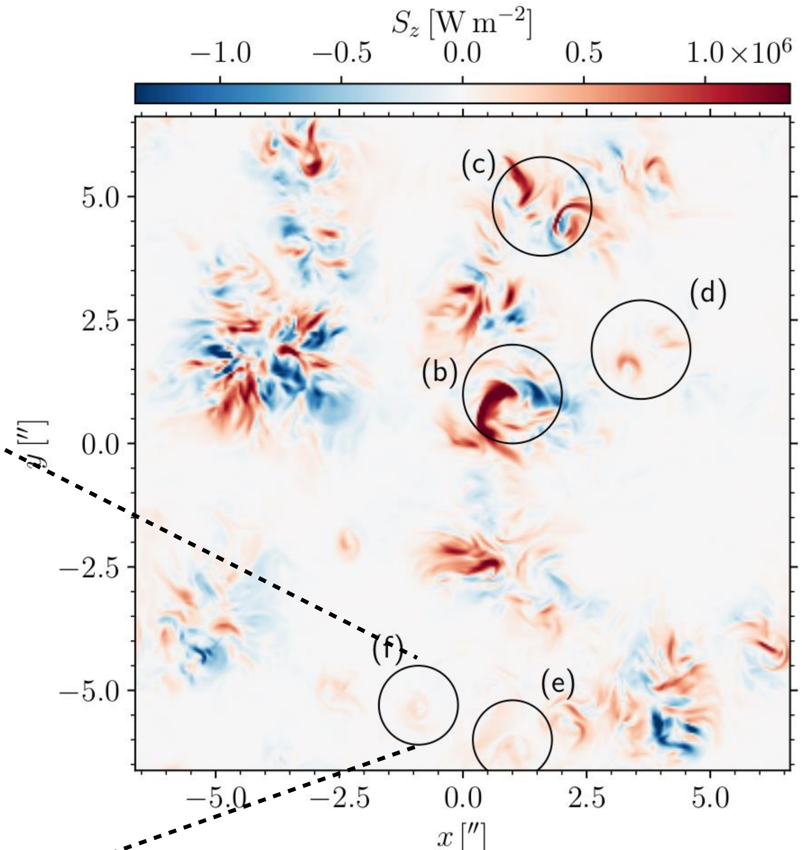

- Largest contributions come from more **complex magnetic footpoints** where **multiple swirls** can cohexist

➢ Swirling motions carry up energy

$$\bar{S}_z = 12.8 \pm 6.5\,\mathrm{kW\,m^{-2}}$$

✓ Enough to compensate radiative losses in the chromosphere!

Automated identification

- We seek a **robust** and **automated** vortex identification method based on the **velocity field only** to perform **statistical analysis** of swirls
    - New method: **Estimated vortex centers** (EVC)

Automated identification

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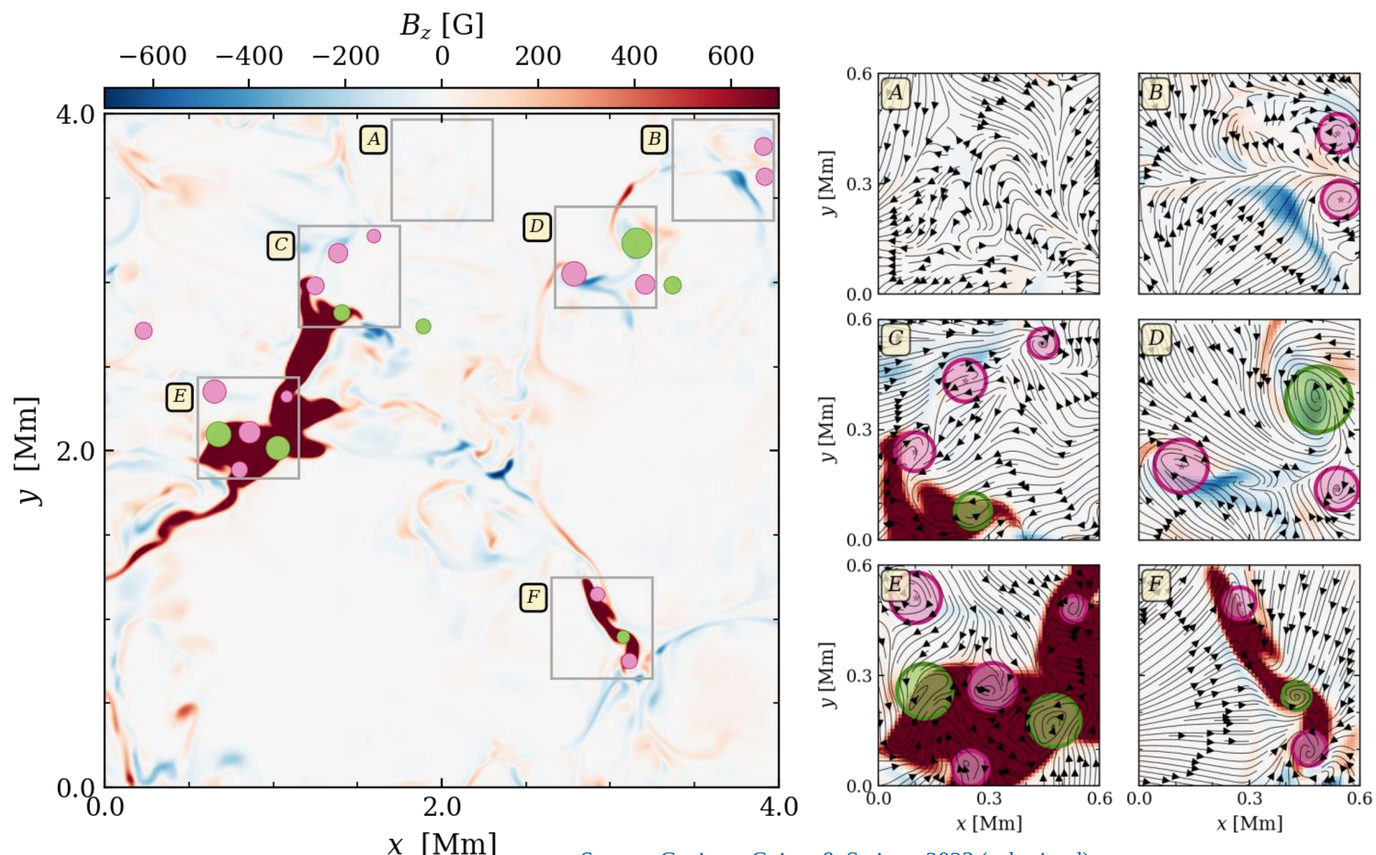
It accounts for the local and global characteristics of the flow

New!

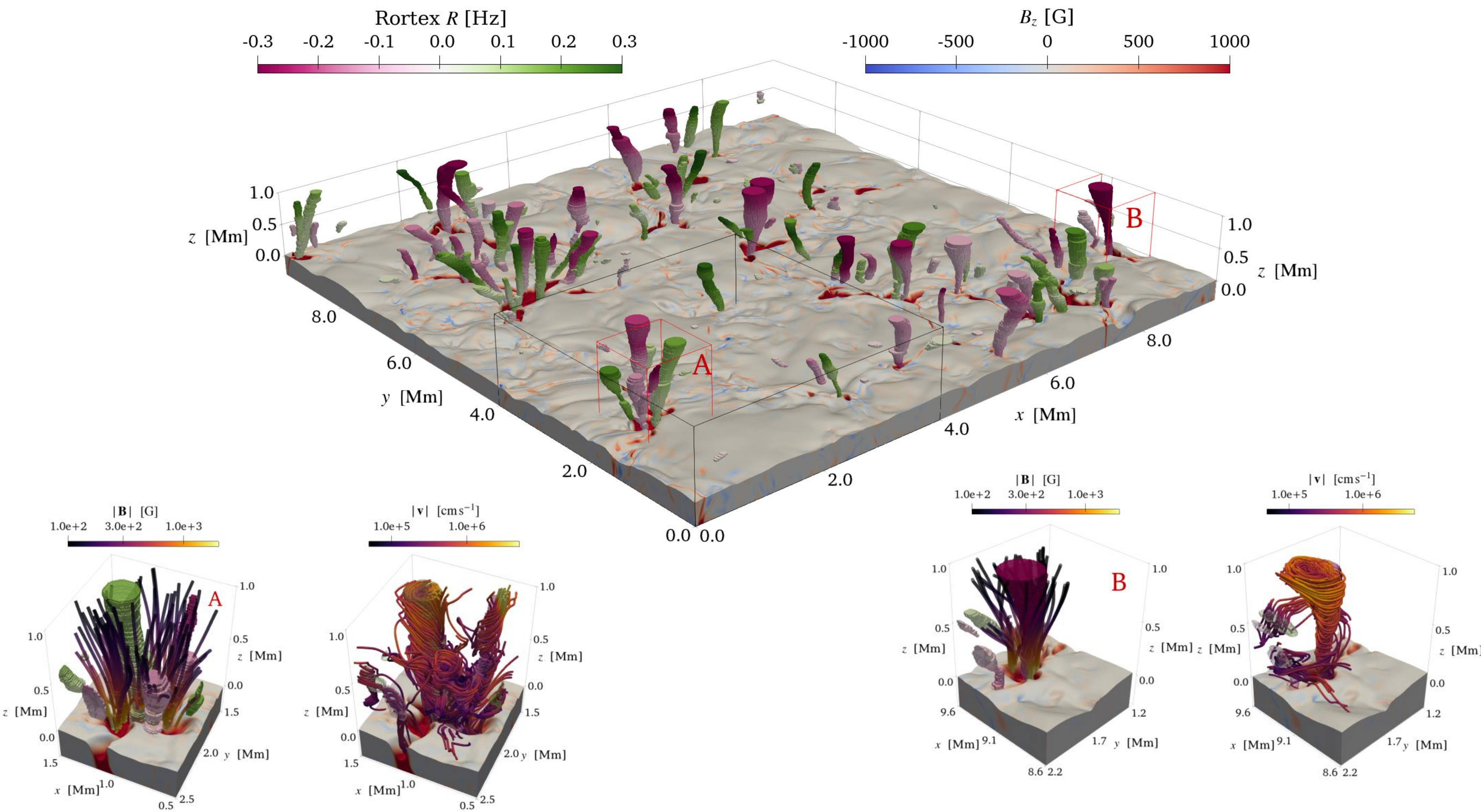
See: Canivete Cuissa & Steiner 2022, A&A 668, A118



Source: Canivete Cuissa & Steiner, 2023 (submitted)

- Open-source Python implementation:
  SWIRL algorithm
  https://github.com/jcanivete/swirl
- Given the **velocity field**, the SWIRL code **correctly identifies** most of the swirls in the simulated photosphere.

Automated identification



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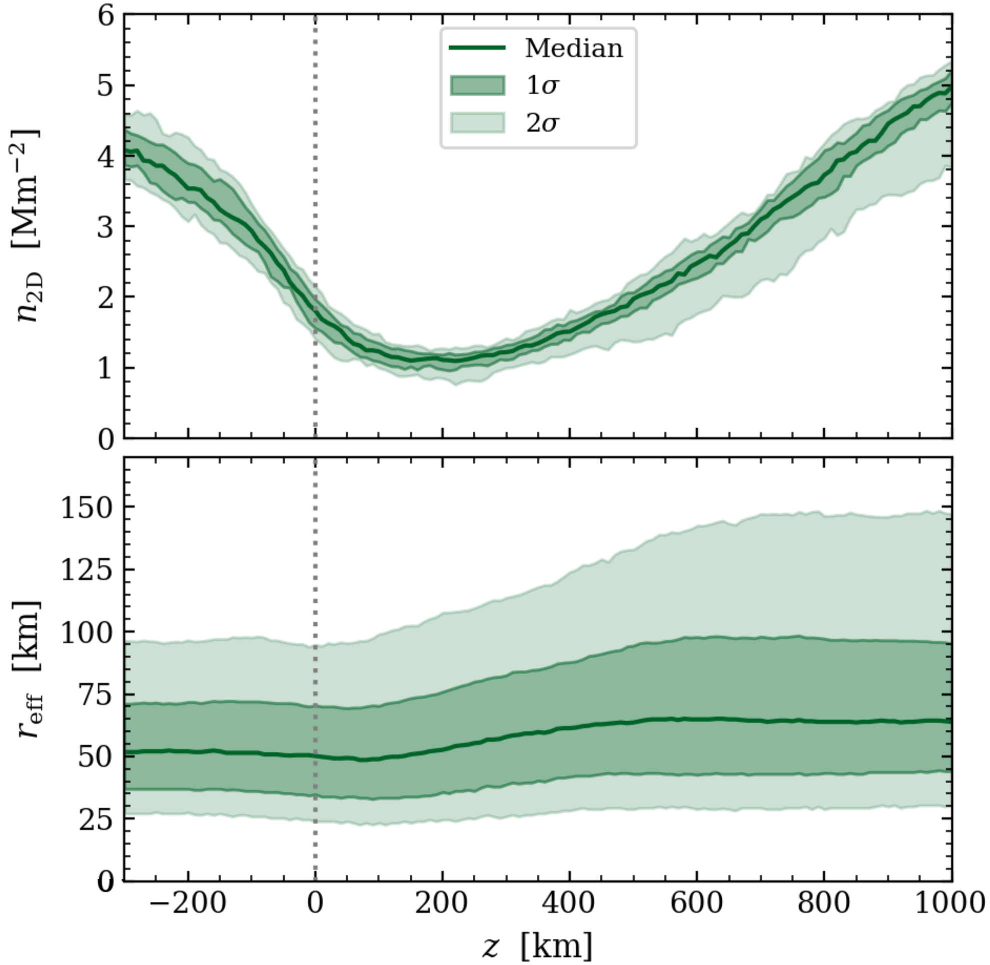
Swirl statistics

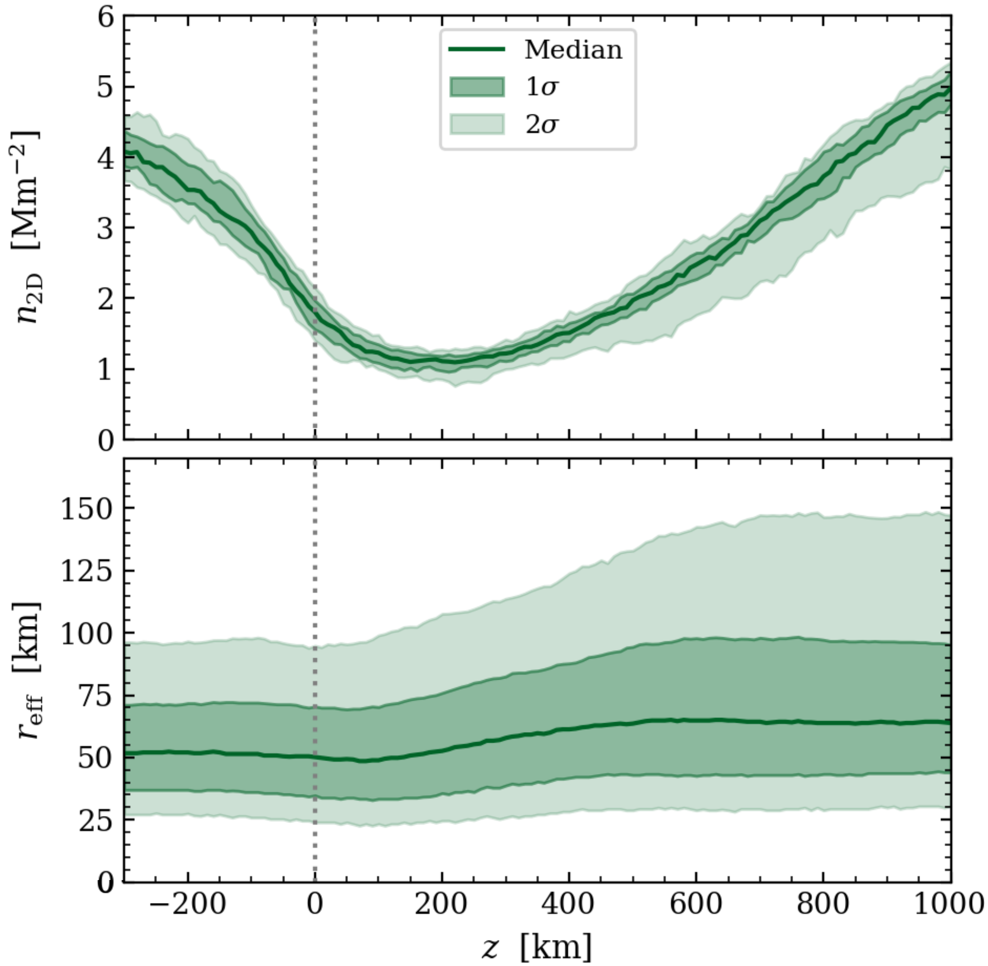


Vertical profiles of the average number density and radius of the swirls identified with the SWIRL code in CO5BOLD simulations

Source: Canivete Cuissa & Steiner, 2023 (submitted)

- Statistics over 30 snapshots covering 2h of physical time

Swirl statistics



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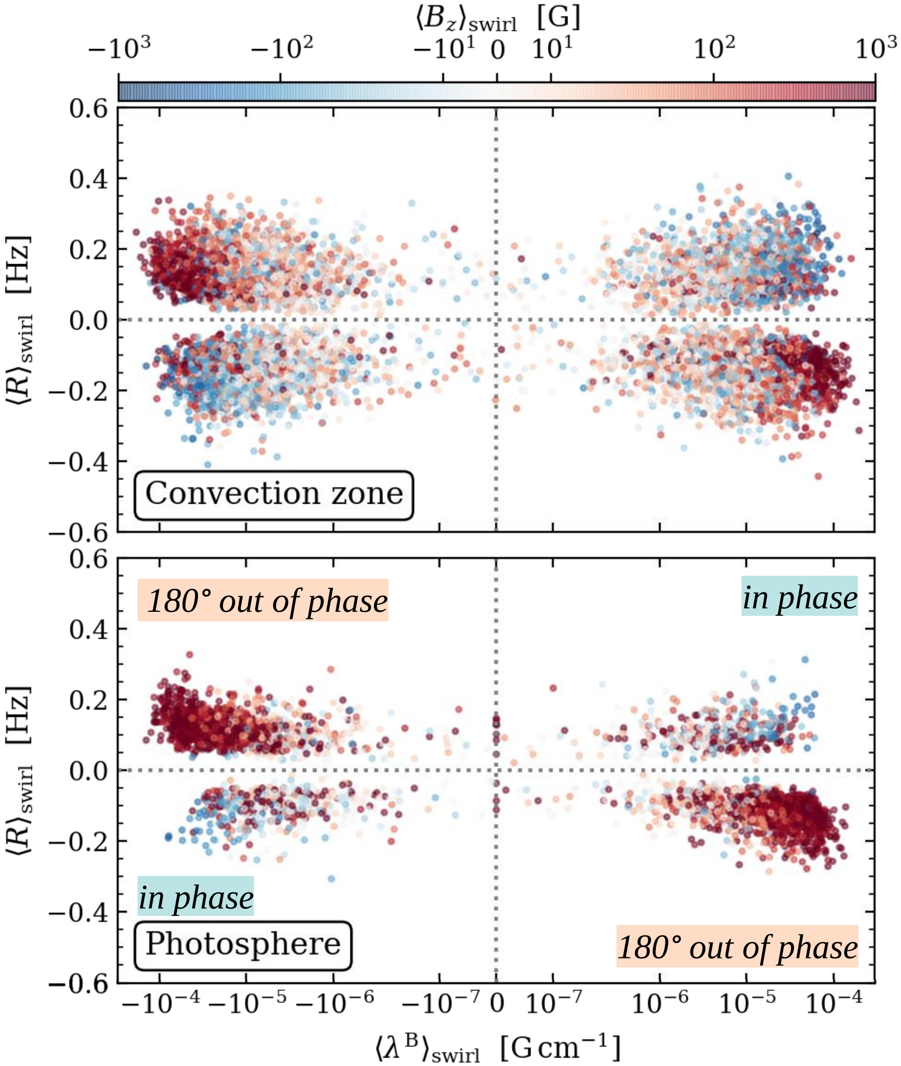
- Statistics over 30 snapshots covering 2h of physical time
  - **Swirls are ubiquitous** in the numerical simulations. Many **more** if compared with previous studies (e.g. Liu et al., 2019 : $n_{2D} \sim 10^{-2}$ Mm^{-2})
  - **Four times more swirls** in the chromosphere than in the photosphere
  - **Smaller swirls** on average. (e.g. Liu et al., 2019 : r ~ 200 km)
  - **Resolution** probably plays an important role in simulations (see Yadav et al. 2020)

Swirl statistics – Alfvénic swirls



Bivariate distribution of vortices according to swirling strength, magnetic swirling strength, and vertical magnetic field values

Source: Canivete Cuissa & Steiner, 2023 (submitted)

- For an upward propagating torsional Alfvén wave

$$\boldsymbol{v} = -\frac{v_A}{B_0}\boldsymbol{b}$$

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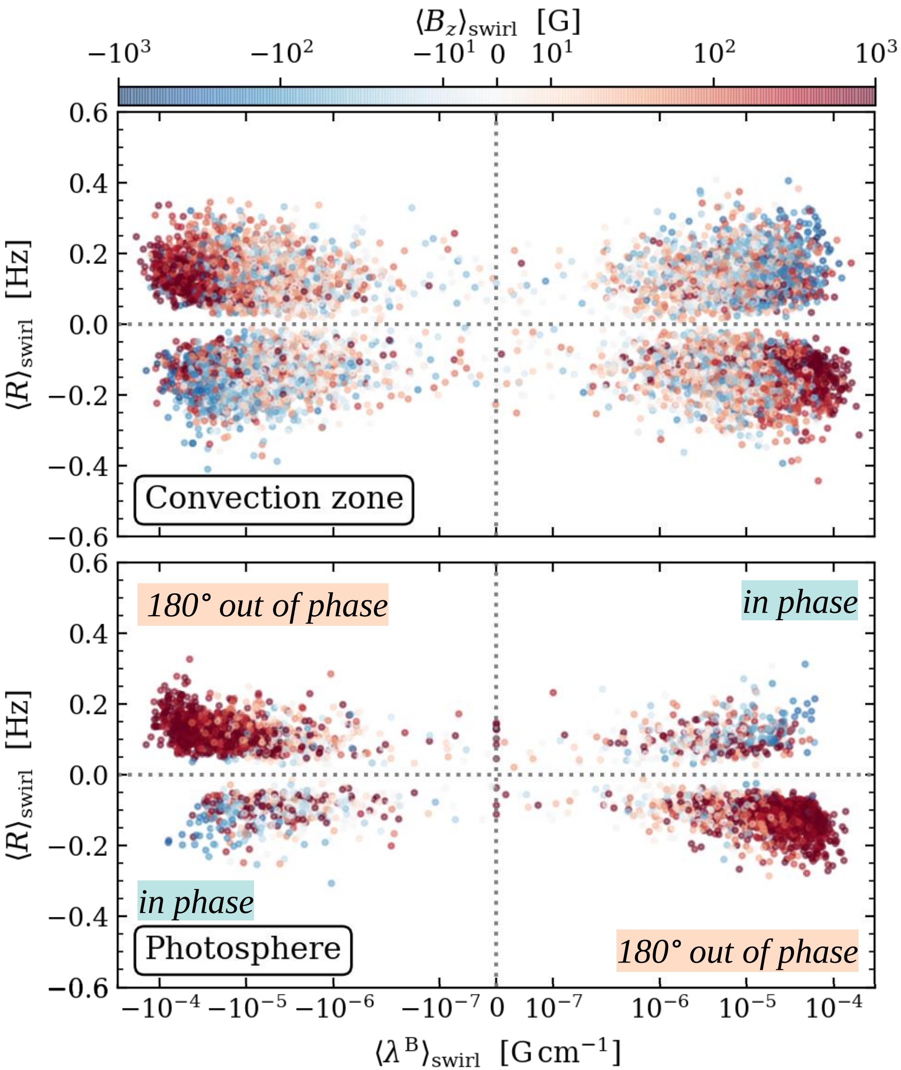

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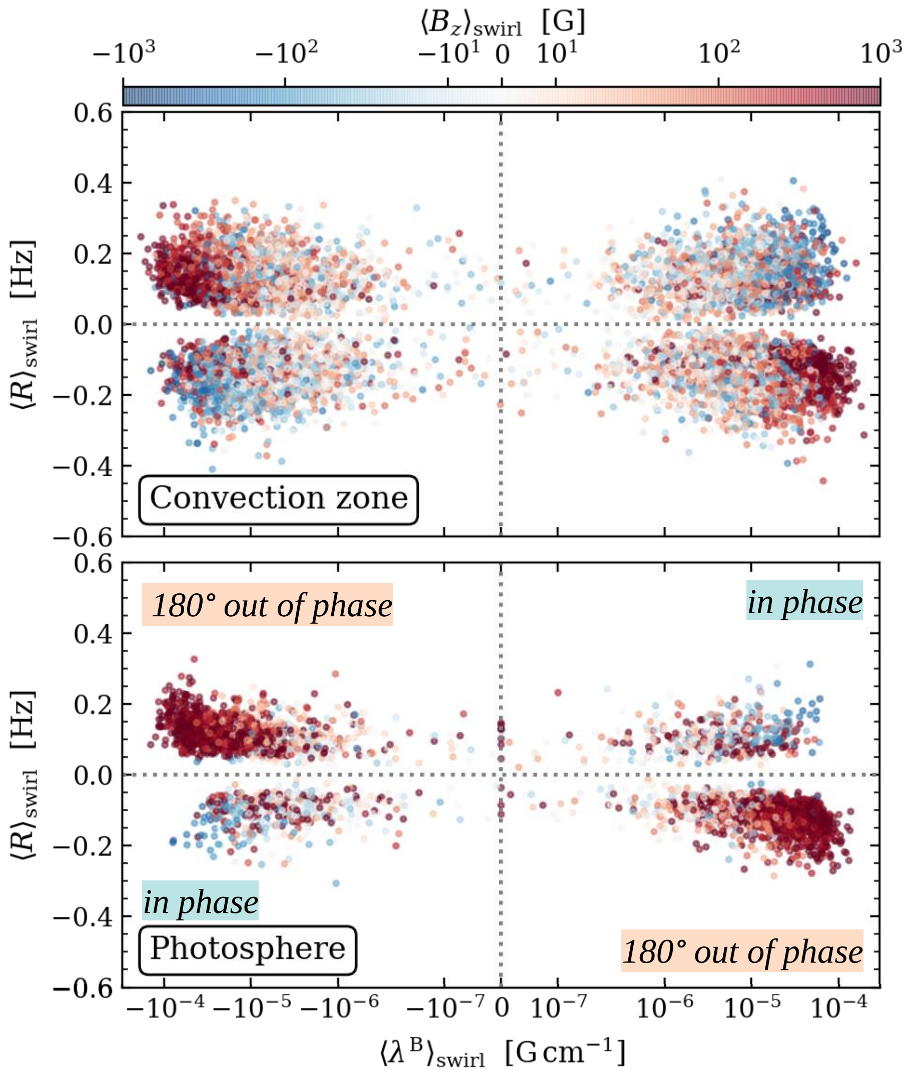
$$\boldsymbol{v} = -\frac{v_A}{B_0}\boldsymbol{b}$$

- Then $\boldsymbol{v}$ and $\boldsymbol{B}$ are **in phase** or **180° out of phase** depending on the **polarity** of the magnetic guide B_0
- Using R_z and λ_z^B as proxys, we obtain

$$\text{sign}\left(R_z\, \lambda_z^{\text{B}}\right) = -\text{sign}(B_0)$$

Swirl statistics – Alfvénic swirls



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- Most of the **identified photospheric swirls** (~80%) present perturbations in velocity and magnetic field which phase is compatible with **Alfvénic waves**
- **Less correlation** in the convection zone (turbulence) and in the chromosphere (shocks? reflected waves?)

Conclusions

- A detailed study of an atmospheric swirl revealed its **Alfvénic nature**
  - Phase between magnetic twist and plasma rotation
  - Upward propagation with local Alfvén speed ➤ **Alfvénic pulse**
  - Magnetic tension is the driving force
- Vertical positive **Poynting flux** associated with **swirling motions**
  - Most contributions come from more complex magnetic regions
- Statistical analysis on CO5BOLD simulations with **SWIRL** code
  - Open source Python implementation (https://github.com/jcanivete/swirl)
  - More and smaller swirls than previous studies
  - ~80% photospheric swirls are compatible with Alfvénic pulses (phase analysis only)

- Canivete Cuissa, J. R. & Steiner, O., 2020, A&A, 639, A118
- Battaglia, A. F. et al., 2021, A&A, 649, A121
- Canivete Cuissa, J. R. & Steiner, O., 2022, A&A, 668, A118
- Canivete Cuissa, J. R. & Steiner, O., 2023, A&A, submitted

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