An innovative and automated vortex identification method based on the estimation of the center of rotation

Application to solar simulations

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What is a vortex? How do we identify it?

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> *"A vortex consists in a multitude of material particles rotating around a common center"* Lugt, 1979

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Two common strategies for vortex detection:

- Mathematical criteria (e.g. vorticity)
- Morphological methods (e.g. winding-angle)

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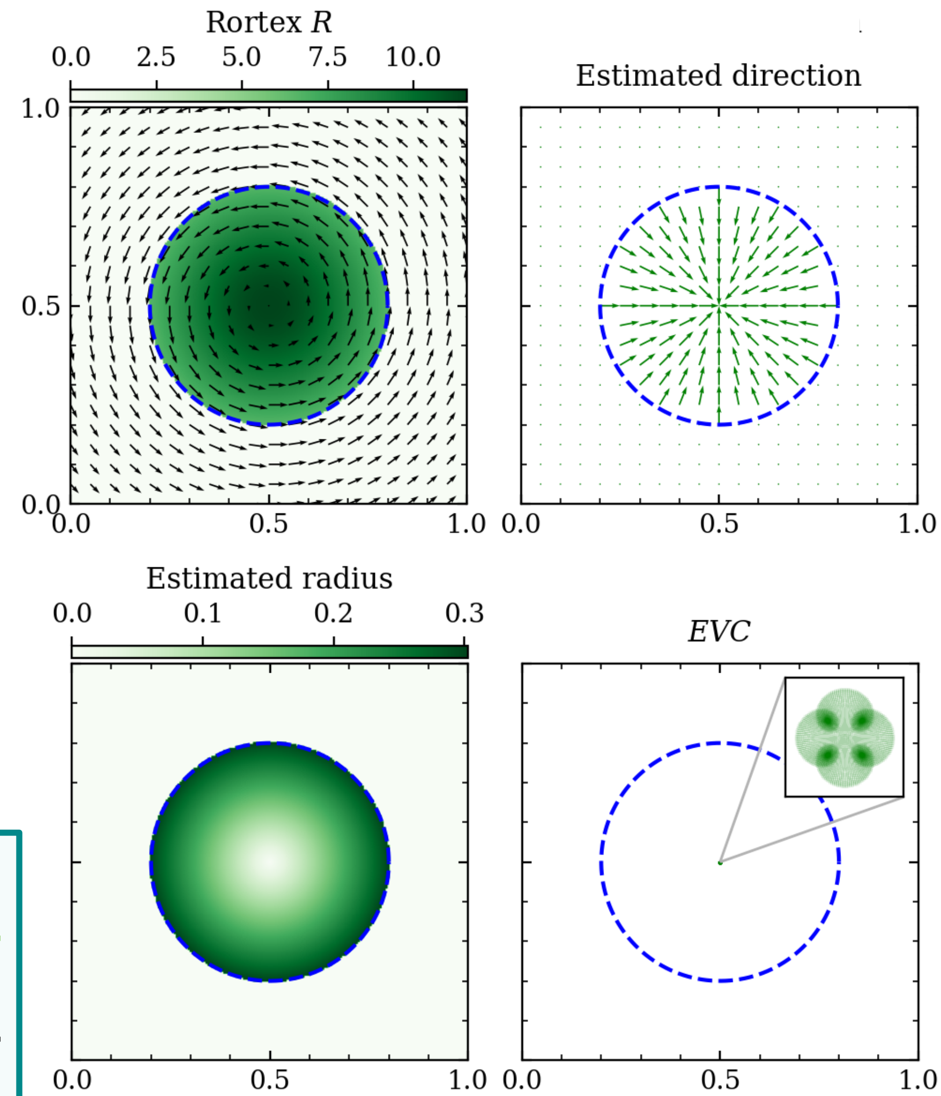
We merge the two strategies into one:

Estimated Vortex Center (EVC) Method

We estimate the **center of rotation** for every “rotating particle” (grid-cell) using the **Rortex criterion** (similar to *vorticity*) and the **flow characteristics**.

Vortices can then be identified by **clusters** of **Estimated Vortex Center** (EVC) points.



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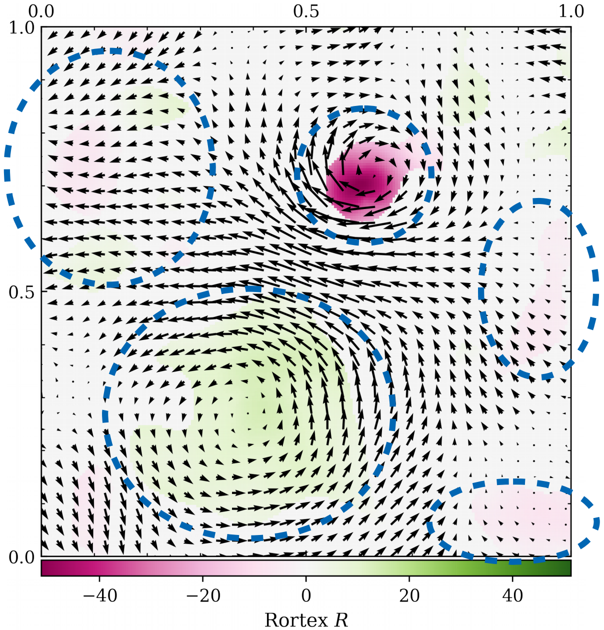
Automated vortex detection with EVC method



Many local curvature regions in the velocity field

All vortices? Noise?

- Use the **Rortex criterion** (Tian et al., 2018) to identify **curvature** in local velocity field

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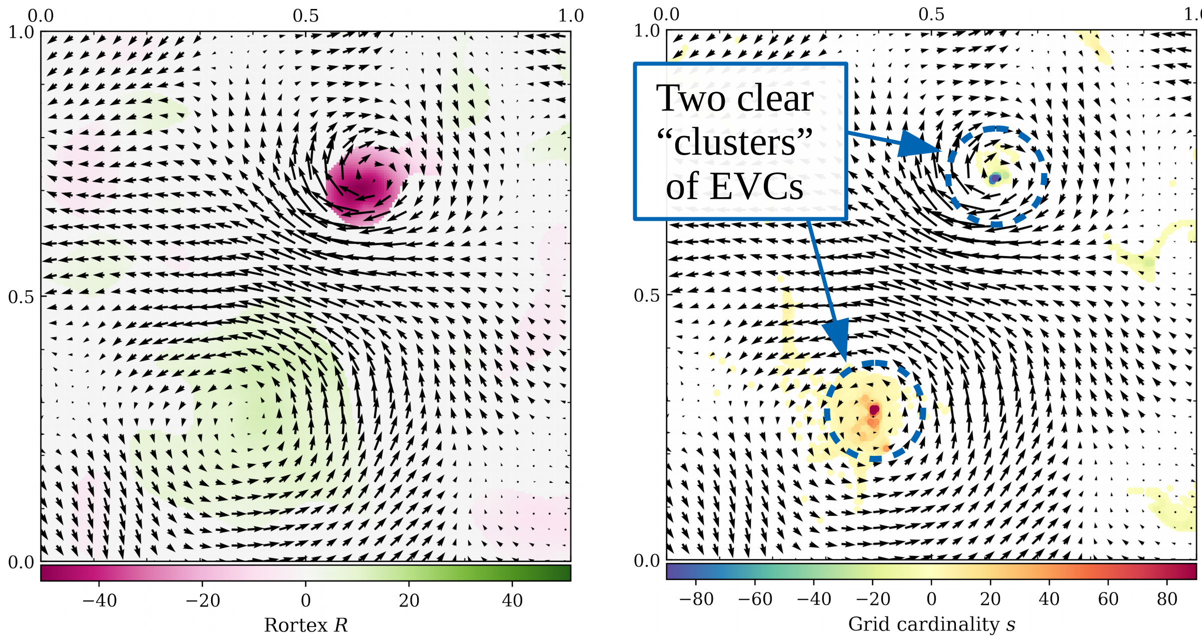

- Use the **Rortex criterion** (Tian et al., 2018) to identify **curvature** in local velocity field
- Use the **Rortex criterion** and the curvature of the **local velocity field** to estimate **EVCs**

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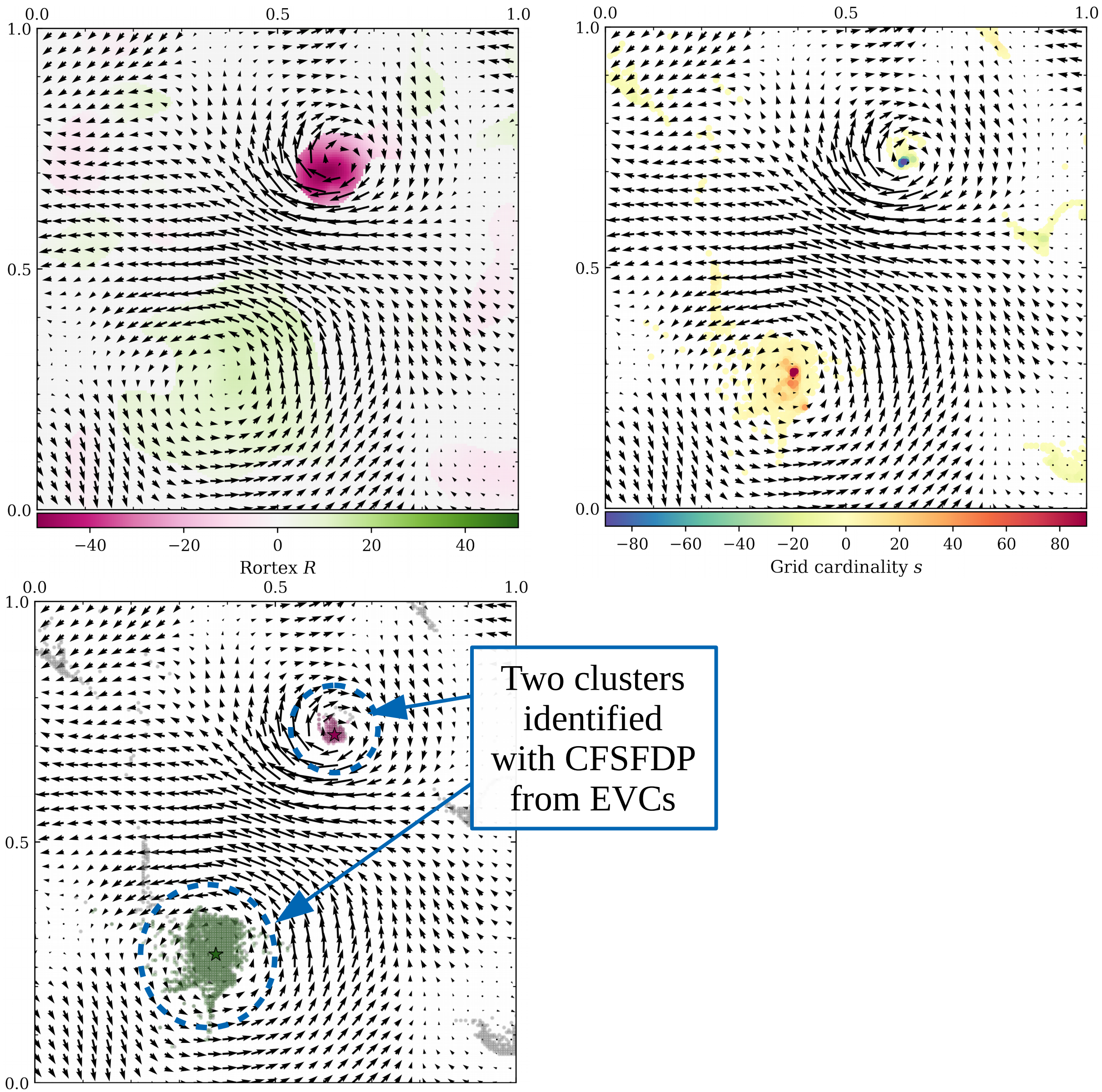

- Use the **Rortex criterion** (Tian et al., 2018) to identify **curvature** in local velocity field
- Use the **Rortex criterion** and the curvature of the **local velocity field** to estimate **EVCs**
- **Cluster EVCs** with a grid-based adaptation of the Clustering by Fast Search and Find of Density Peaks (**CFSFDP**) algorithm (Rodriguez & Laio, 2014)

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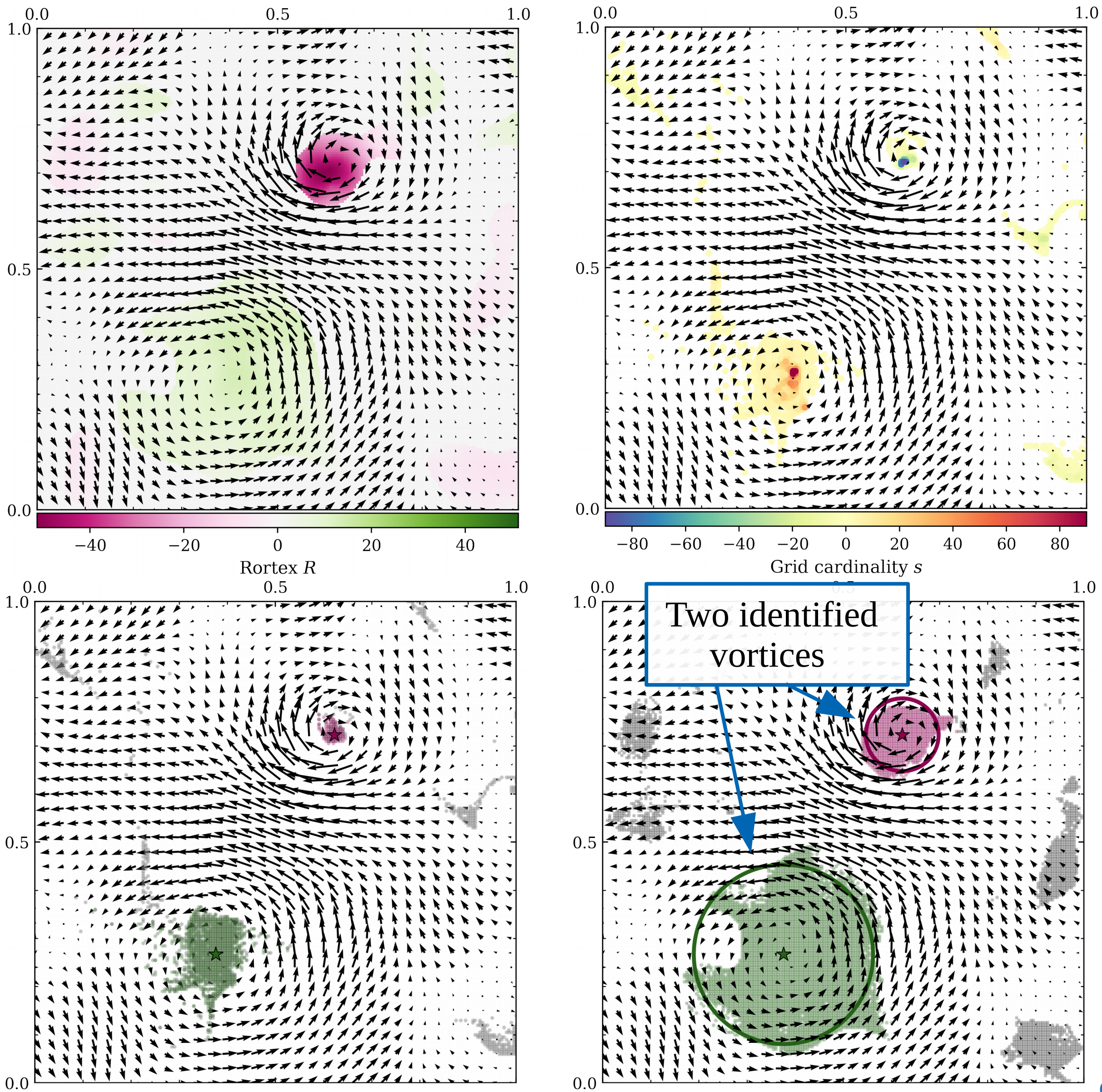

- Use the **Rortex criterion** ([Tian et al., 2018]) to identify **curvature** in local velocity field
- Use the **Rortex criterion** and the curvature of the **local velocity field** to estimate **EVCs**
- **Cluster EVCs** with a grid-based adaptation of the Clustering by Fast Search and Find of Density Peaks (**CFSFDP**) algorithm (Rodriguez & Laio, 2014)
- Each **EVC cluster** corresponds to a group of **grid cells** forming a **vortex**

➢ **Python implementation**: *https://github.com/jcanivete/swirl*

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Application to numerical simulations

3D Radiative MHD numerical simulations of the solar atmosphere (CO5BOLD code, Freytag et al., 2012)

- 9.6 x 9.6 x 2.8 Mm3 (960x960x280)
- Surface at z~1.2 Mm

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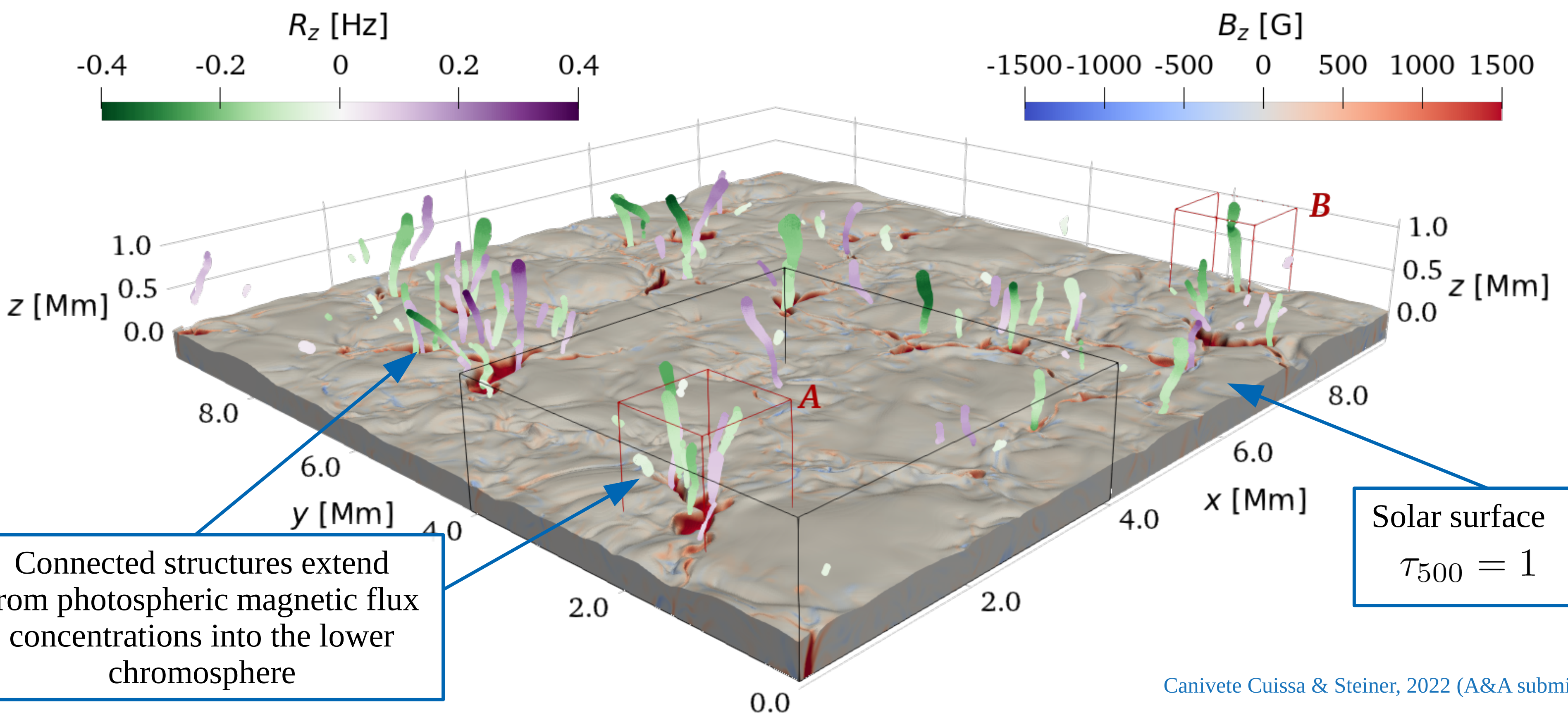

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Statistics

- Statistics over 30 snapshots covering 2h of physical time show

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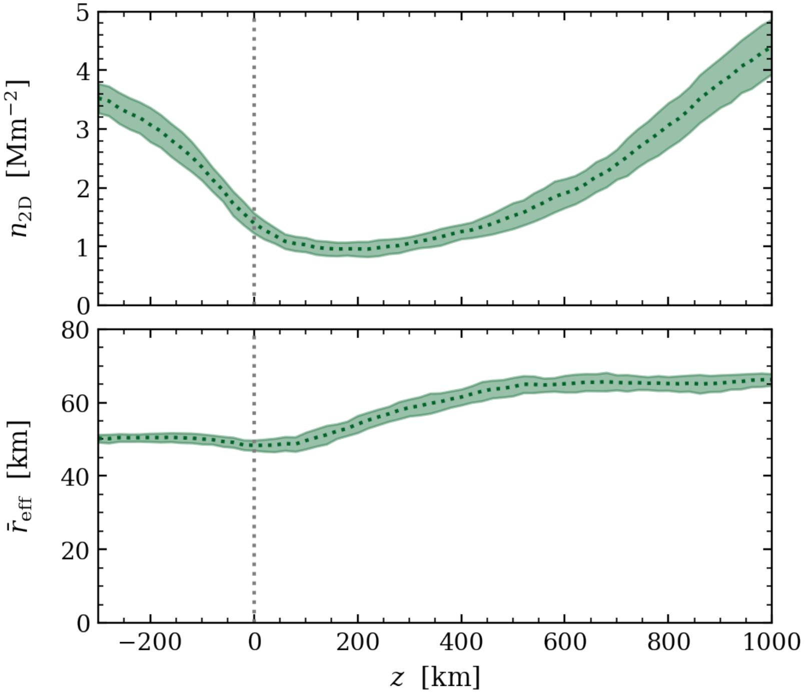

- Statistics over 30 snapshots covering 2h of physical time show
  - **More swirls** (~ 1 Mm^{-2} in the photosphere)
  - **Smaller radii** (~ 50 km in the photosphere)

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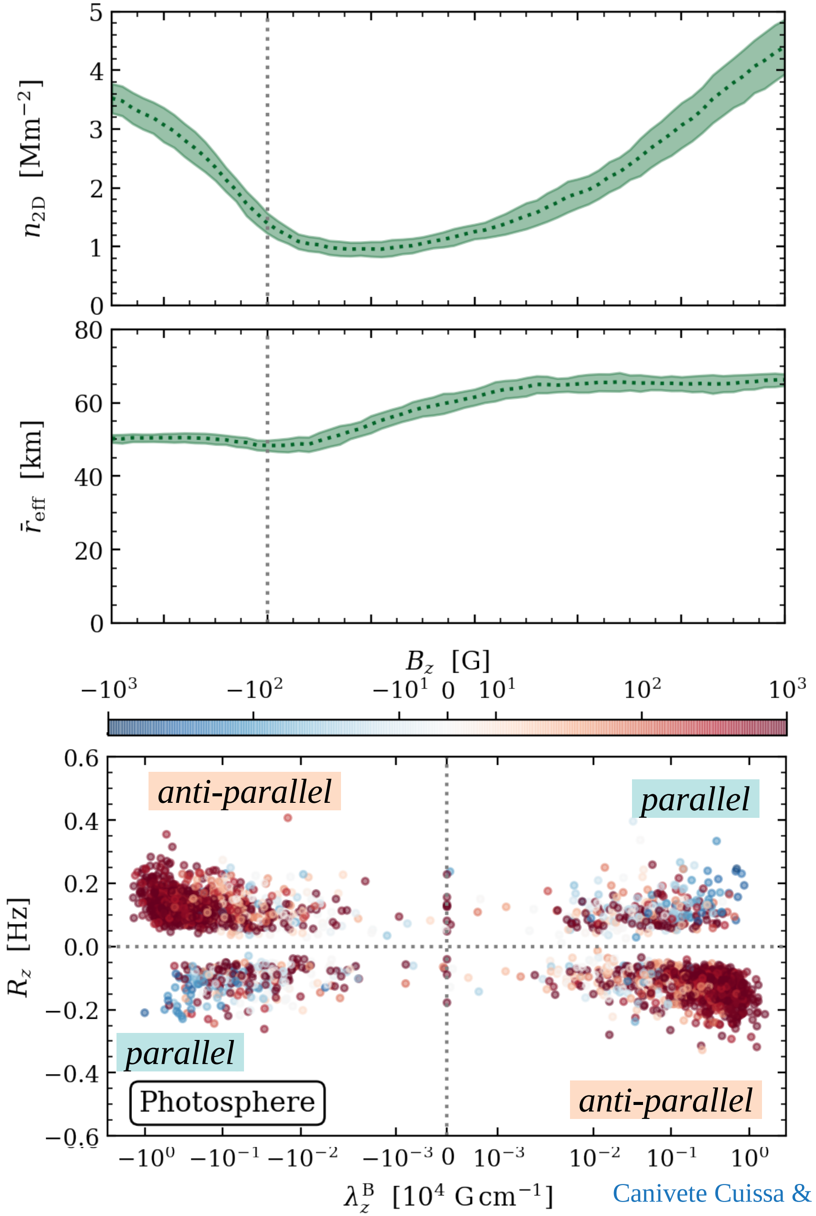

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- Statistics over 30 snapshots covering 2h of physical time show
  - **More swirls** (~ 1 Mm^{-2} in the photosphere)
  - **Smaller radii** (~ 50 km in the photosphere)

  - **Photospheric swirls** correlate with **twists** in the **magnetic field**
  - **~ 80%** of photospheric swirls and magnetic field twists are compatible with **Alfvénic pulses** (see Battaglia et al., 2021)

$$\boxed{\mathrm{sign}(\mathrm{R}_z \lambda_z^{\mathrm{B}}) = -\mathrm{sign}(B_z)}$$

Plasma swirl

Magnetic field lines twist

Magnetic flux concentration

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Conclusions

- The **EVC method** combines mathematical criteria and morphological methods to **accurately identify vortices** from 2D velocity fields
- A **publicly available** Python implementation is available
  https://github.com/jcanivete/swirl
- Application to **CO5BOLD simulations** of the solar atmosphere shows:
  - **More swirls** with **smaller radii** than previous studies
  - Perturbations in the magnetic field compatible with **Alfvénic pulses**
- For more details:
  Canivete Cuissa & Steiner (2022), A&A, submitted

Thank you for your attention

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