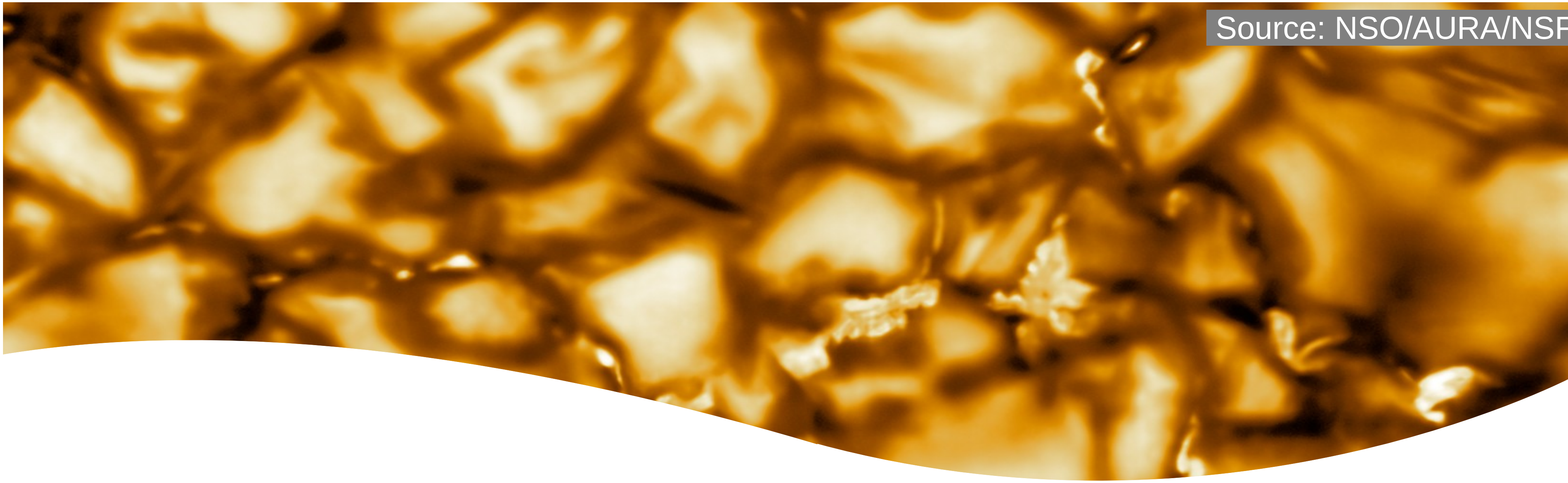

On the dynamics of vortices in the solar atmosphere

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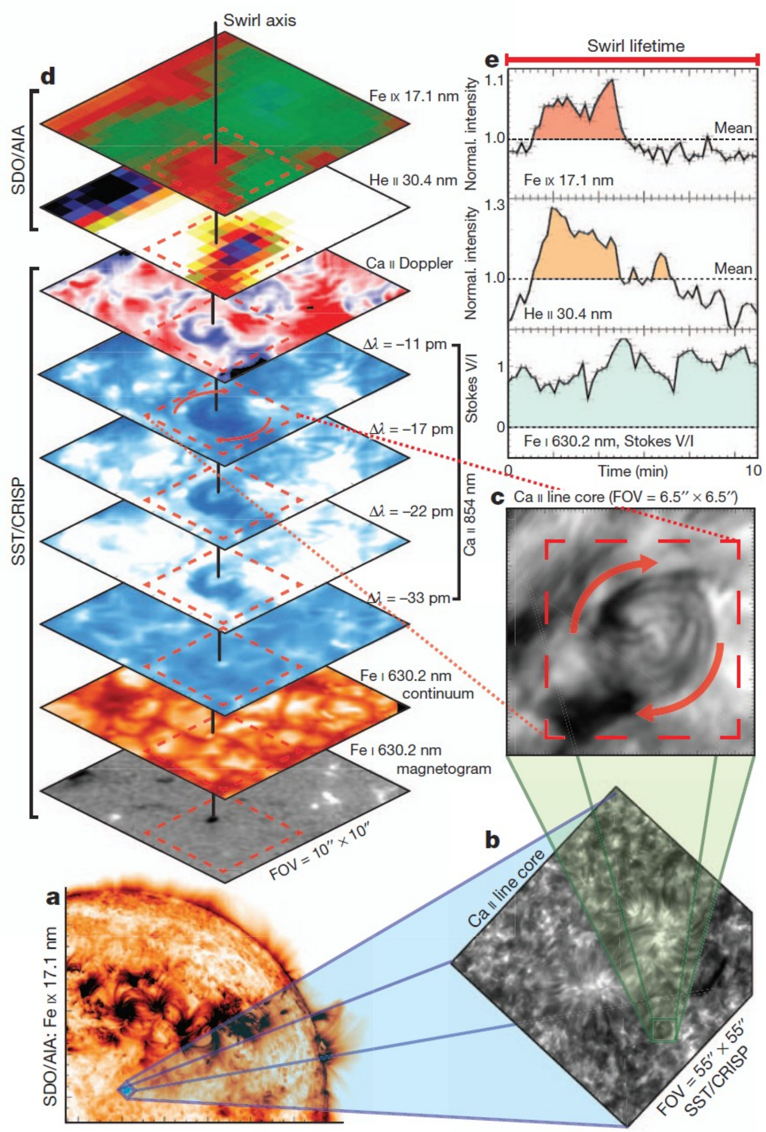
José R. Canivete Cuissa
jose.canivete@irsol.usi.ch
Oskar Steiner
steiner@leibniz-kis.de

In collaboration with:
Andrea F. Battaglia
Flavio Calvo
Aleksi A. Bossart

IRSOL
Istituto Ricerche Solari Locarno

José R. Canivete Cuissa
IRSOL
Istituto Ricerche Solari Locarno

Introduction



Source: Wedemeyer-Böhm et al., 2013

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

Energy channels from the convection zone to the upper layers?

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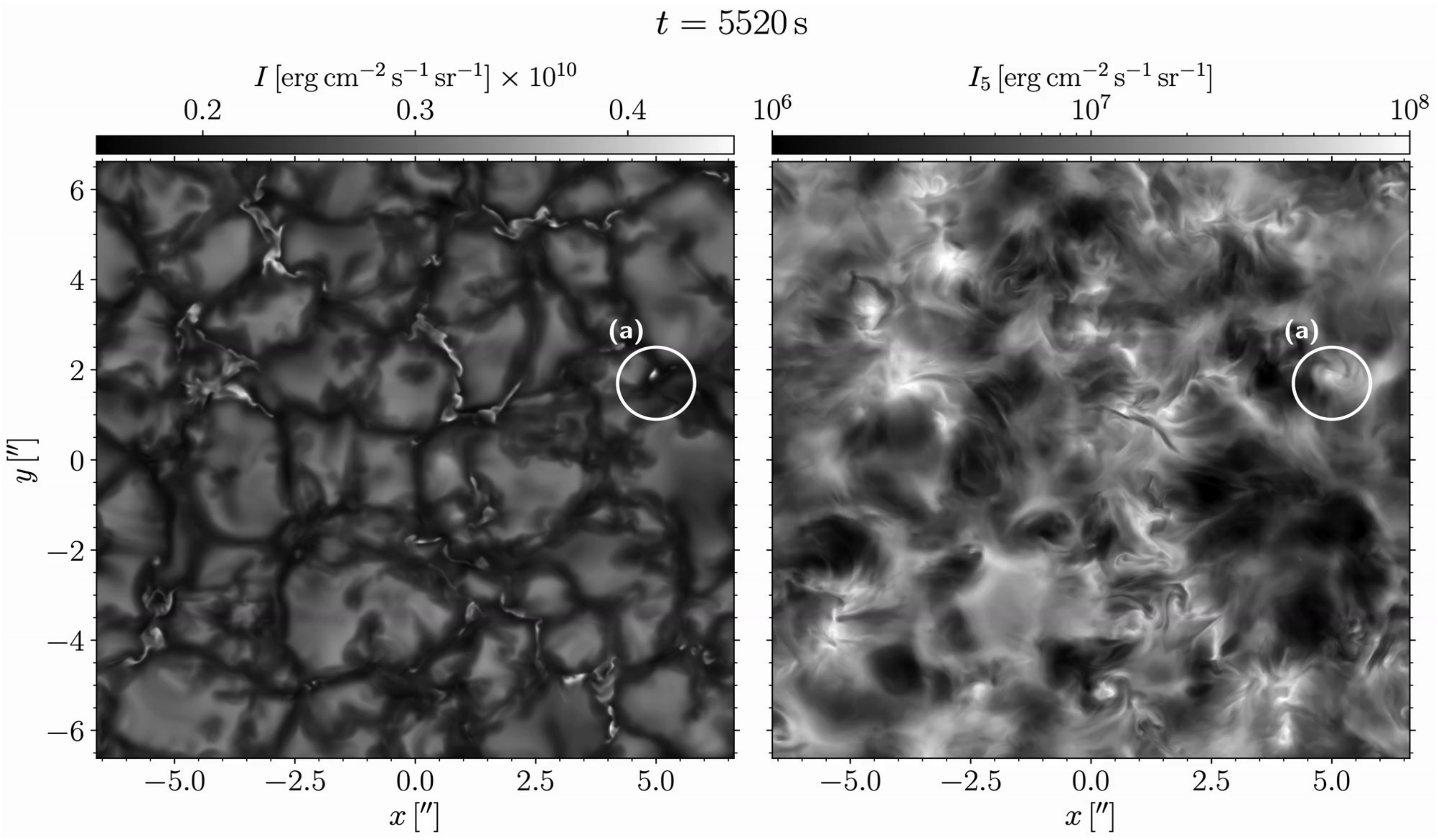
Simulations



Source: Battaglia et al., 2021

Synthetic intensity maps from a CO5BOLD simulation (9.6 x 9.6 x 2.8 Mm^3)

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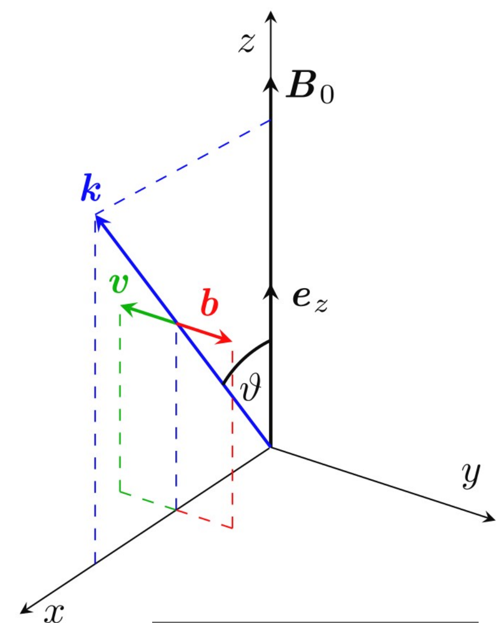
Detection methods

- <u>Vortices</u>
  - Swirling strength λ
    - "Better version" of vorticity
    - Evolution equation

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

Source: Canivete Cuissa & Steiner, 2020

- <u>Alfvén waves</u>
    - Orientation of perturbations (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

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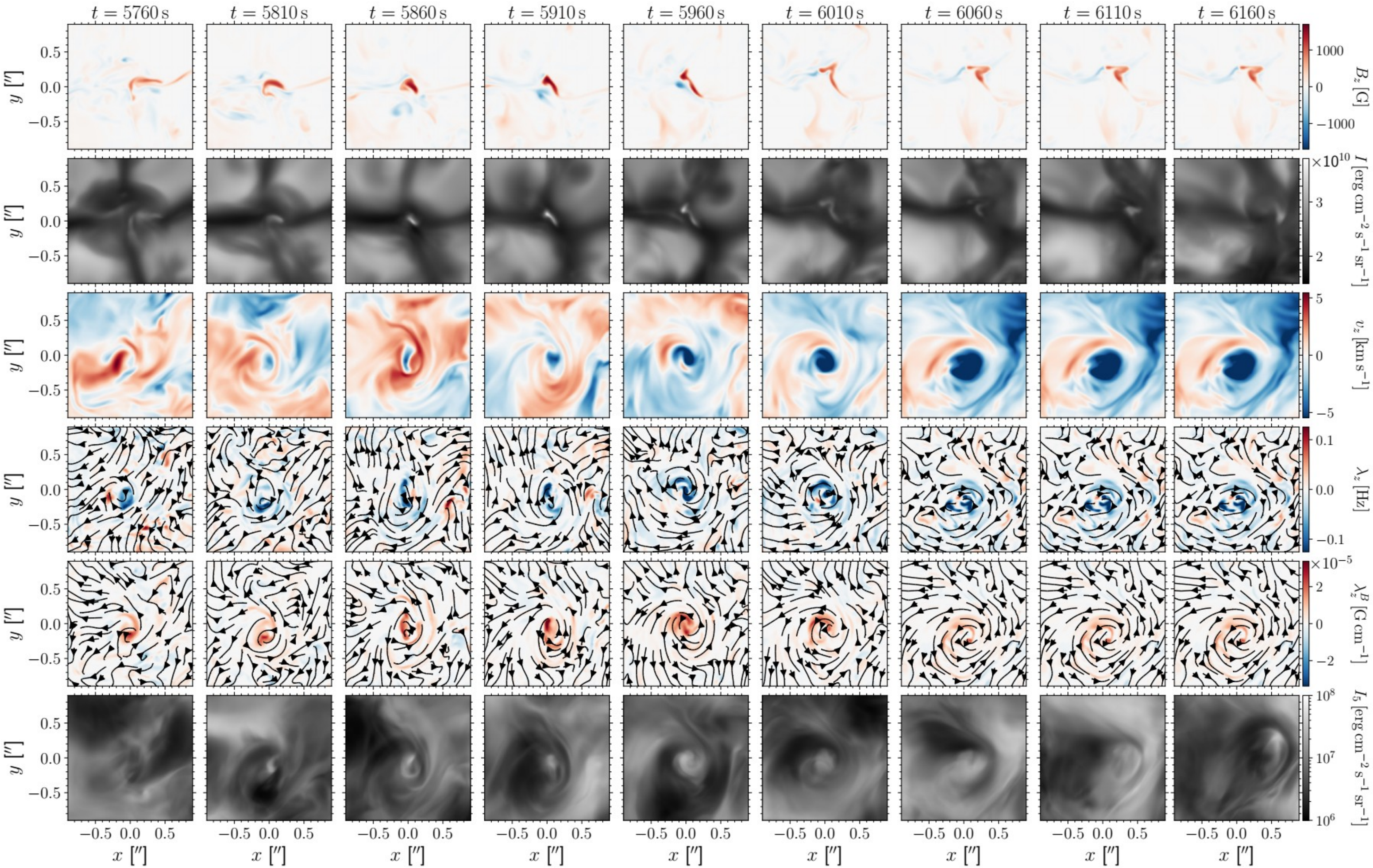
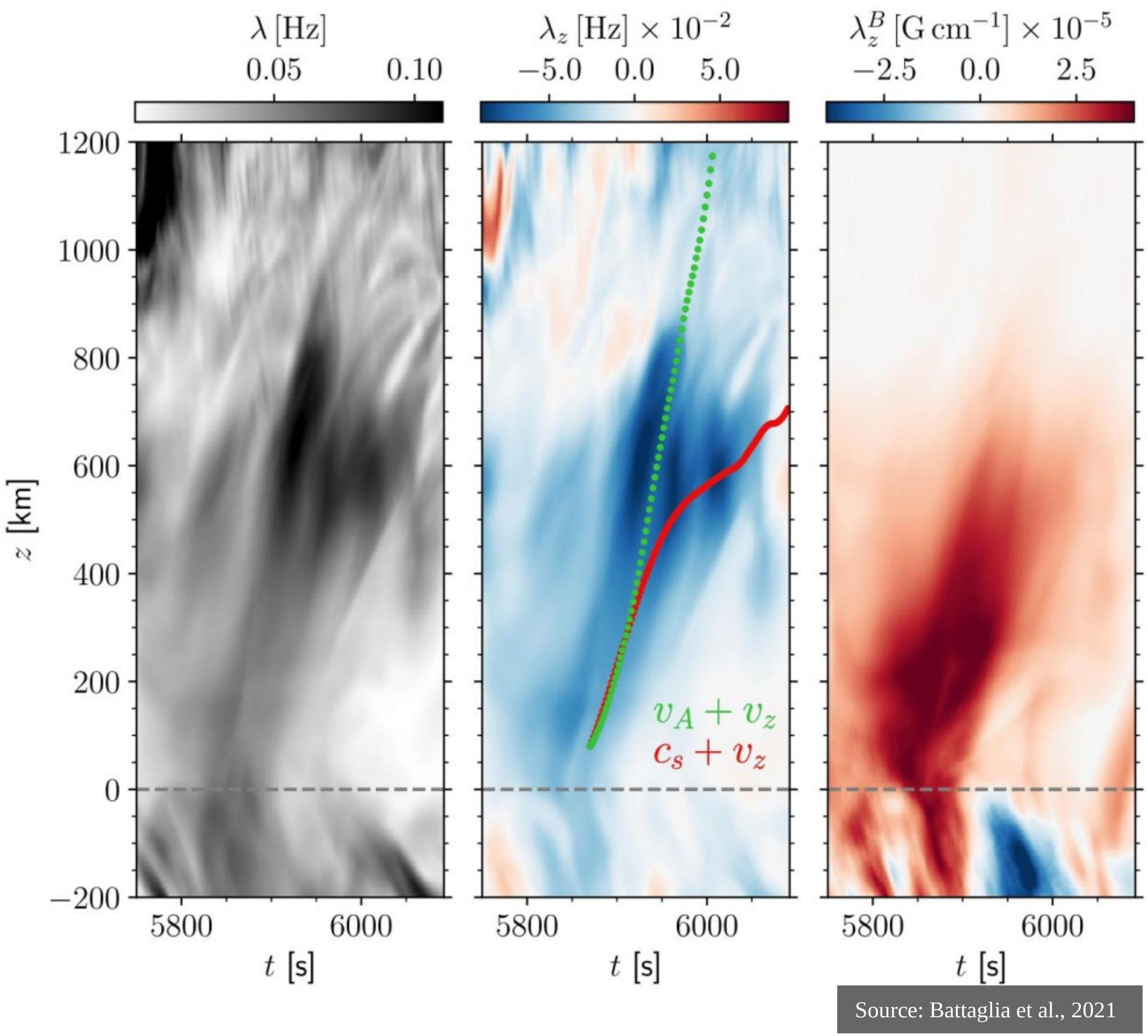
Swirl event



Time sequence of the swirl event at z=0 km (B_z) and z=700 km (v_z, λ_z, λ_z^B)

Source: Battaglia et al., 2021

Swirl event – Perturbation propagation



Averaged time-distance diagrams over 150 x 150 km²

- Vertical swirl
- Photospheric origin
- **Upward propagation**
- “**Pulse**” (not oscillatory)

✔ Propagation at Alfvén speed

✔ Magnetic field twist opposite to vortex rotation

❓ Driven by magnetic tension

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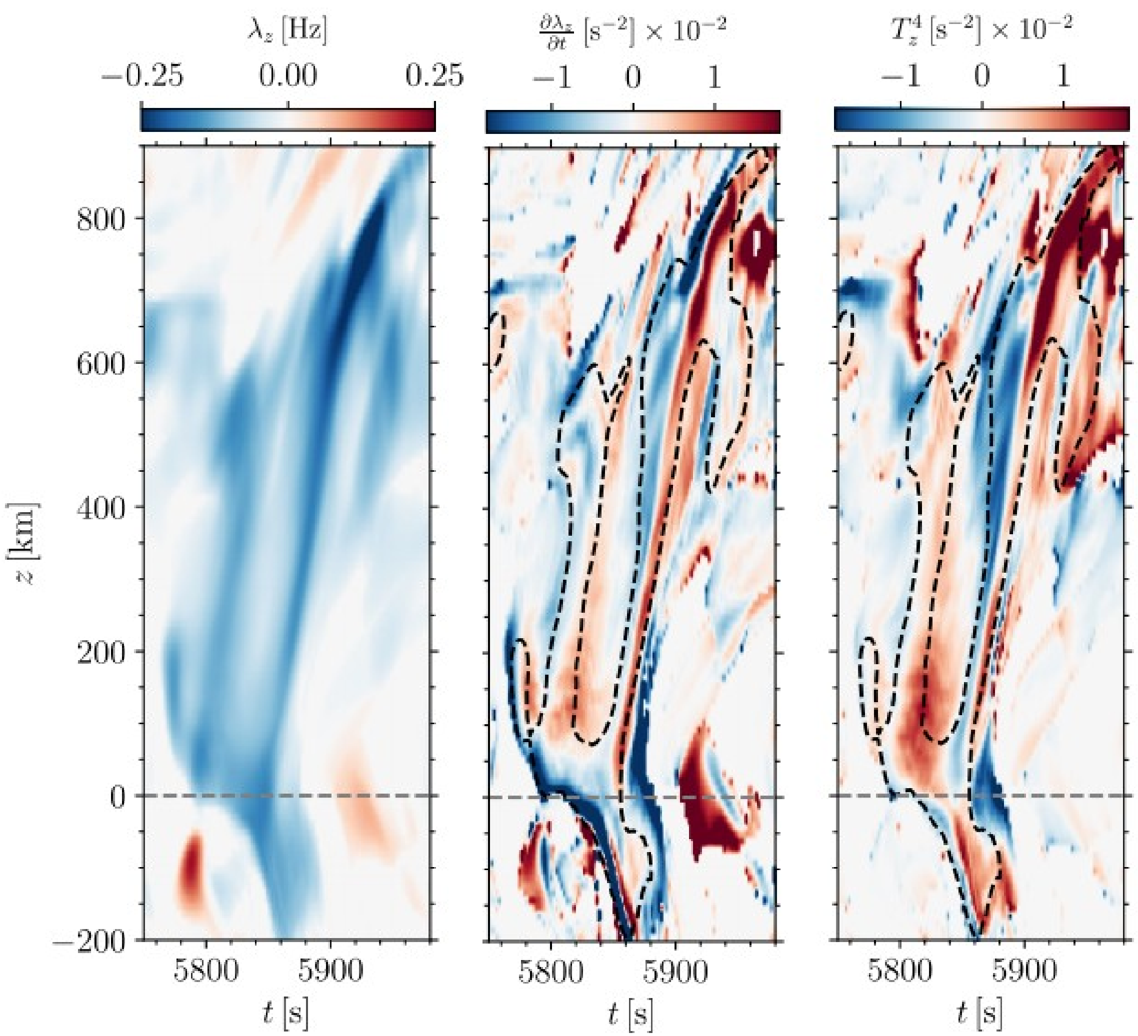
Swirl event - Dynamics



Source: Battaglia et al., 2021

Single line-of-sight time-distance diagrams

- **Local production** of λ corresponds to propagation of pulses
- Propagation: **Magnetic tension**

✔ Propagation at Alfvén speed

✔ Magnetic field twist opposite to vortex rotation

✔ Driven by magnetic tension

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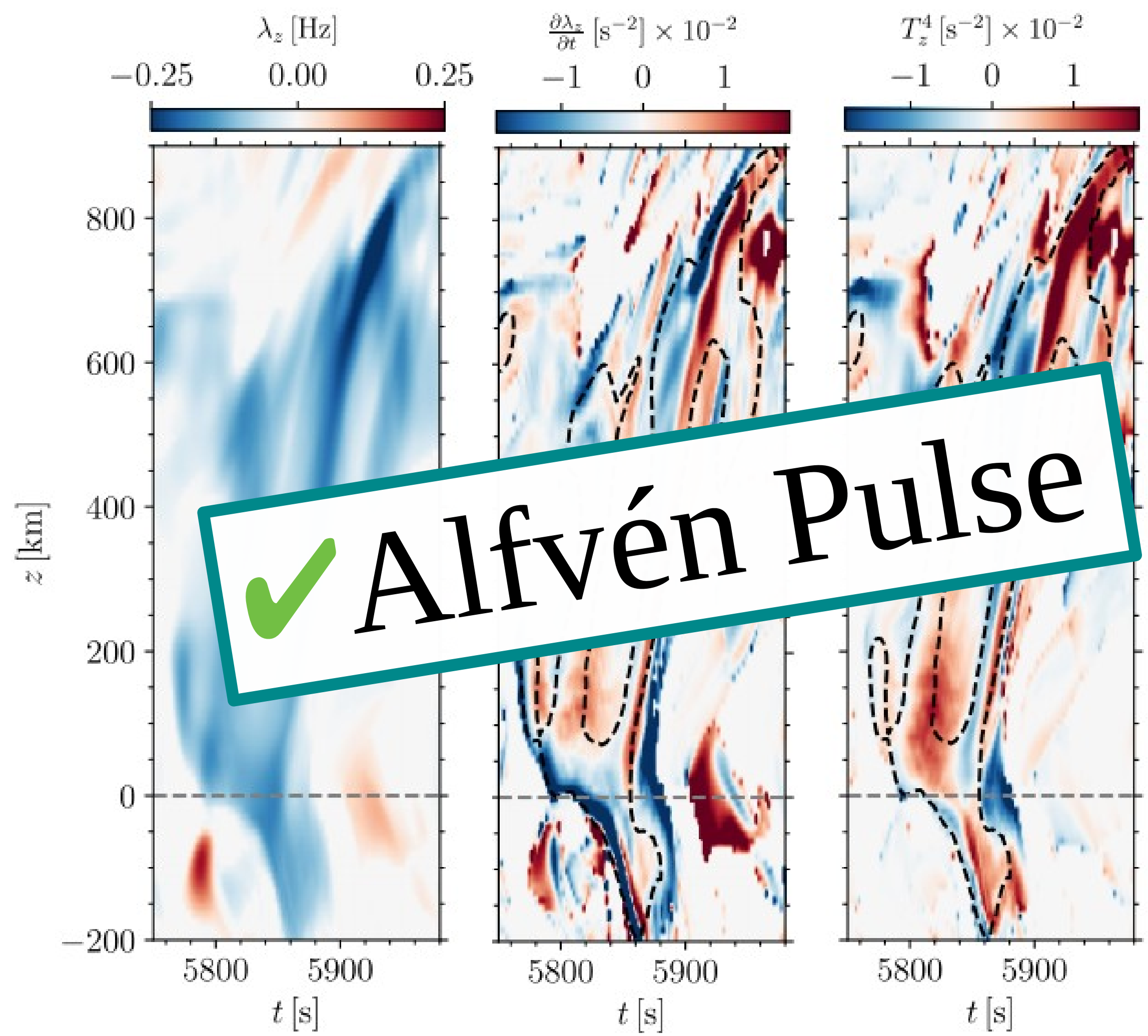
Swirl event - Dynamics



Source: Battaglia et al., 2021

Single line-of-sight time-distance diagrams

- **Local production** of λ corresponds to propagation of pulses
- Propagation: **Magnetic tension**

> ✔ Propagation at Alfvén speed
> ✔ Magnetic field twist opposite to vortex rotation
> ✔ Driven by magnetic tension

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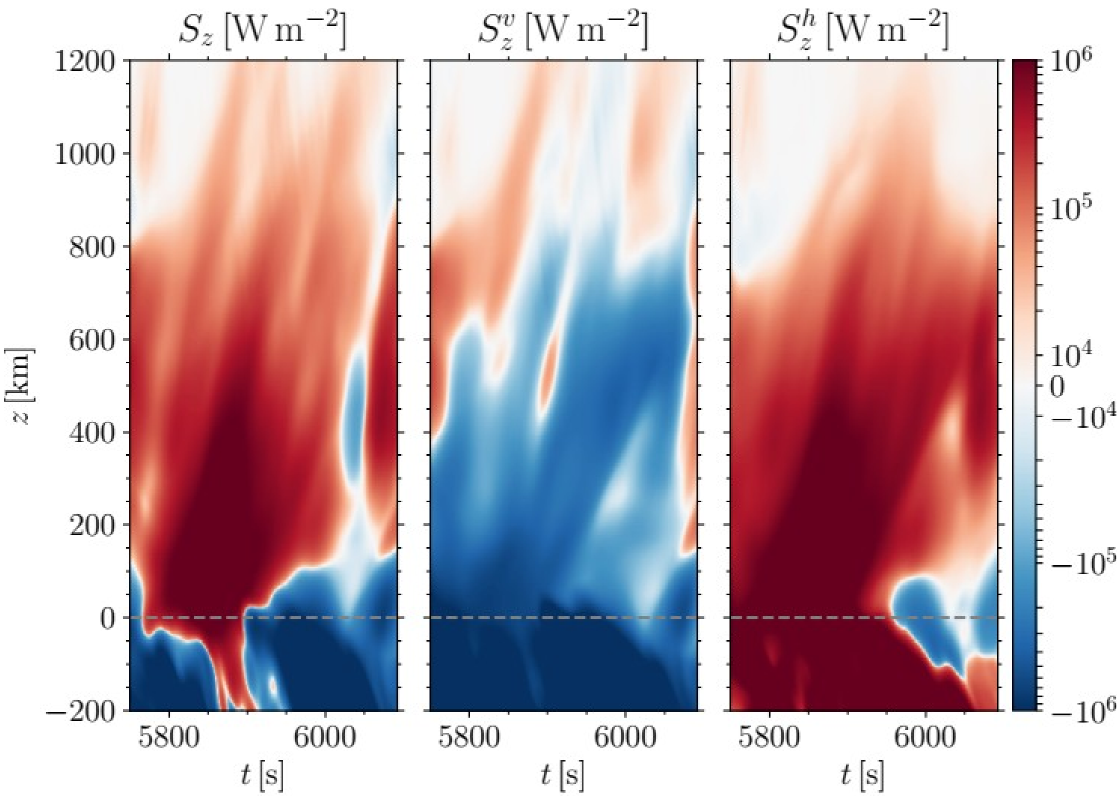
Swirl event - Energetics

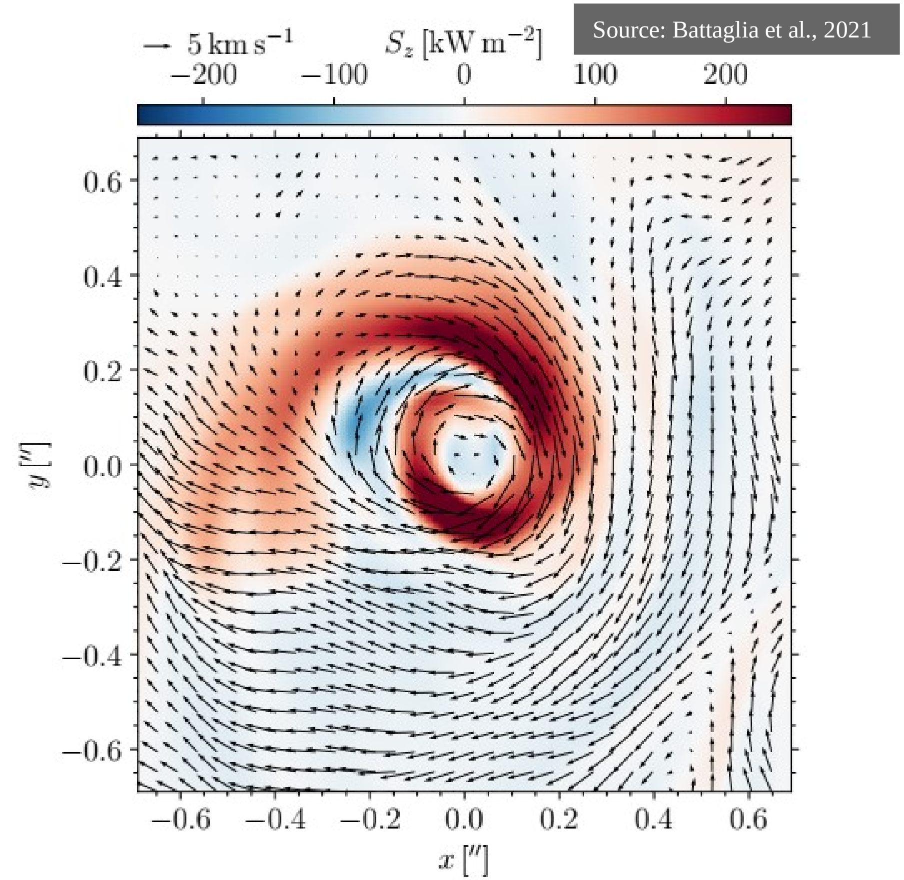
- Poynting flux :

$$S_z = \underbrace{\frac{1}{4\pi} v_z (B_x^2 + B_y^2)}_{S_z^{\mathrm{v}}} - \underbrace{\frac{1}{4\pi} B_z (v_x B_x + v_y B_y)}_{S_z^{\mathrm{h}}}$$



Source: Battaglia et al., 2021

Averaged time-distance diagrams



Horizontal section at z = 700 km

➢ Swirling motions carry up energy

➢ At base of chromosphere :

$$\bar{S}_z = 1.2\,\mathrm{kW\,m^{-2}}$$

✗ Not enough to compensate radiative losses!

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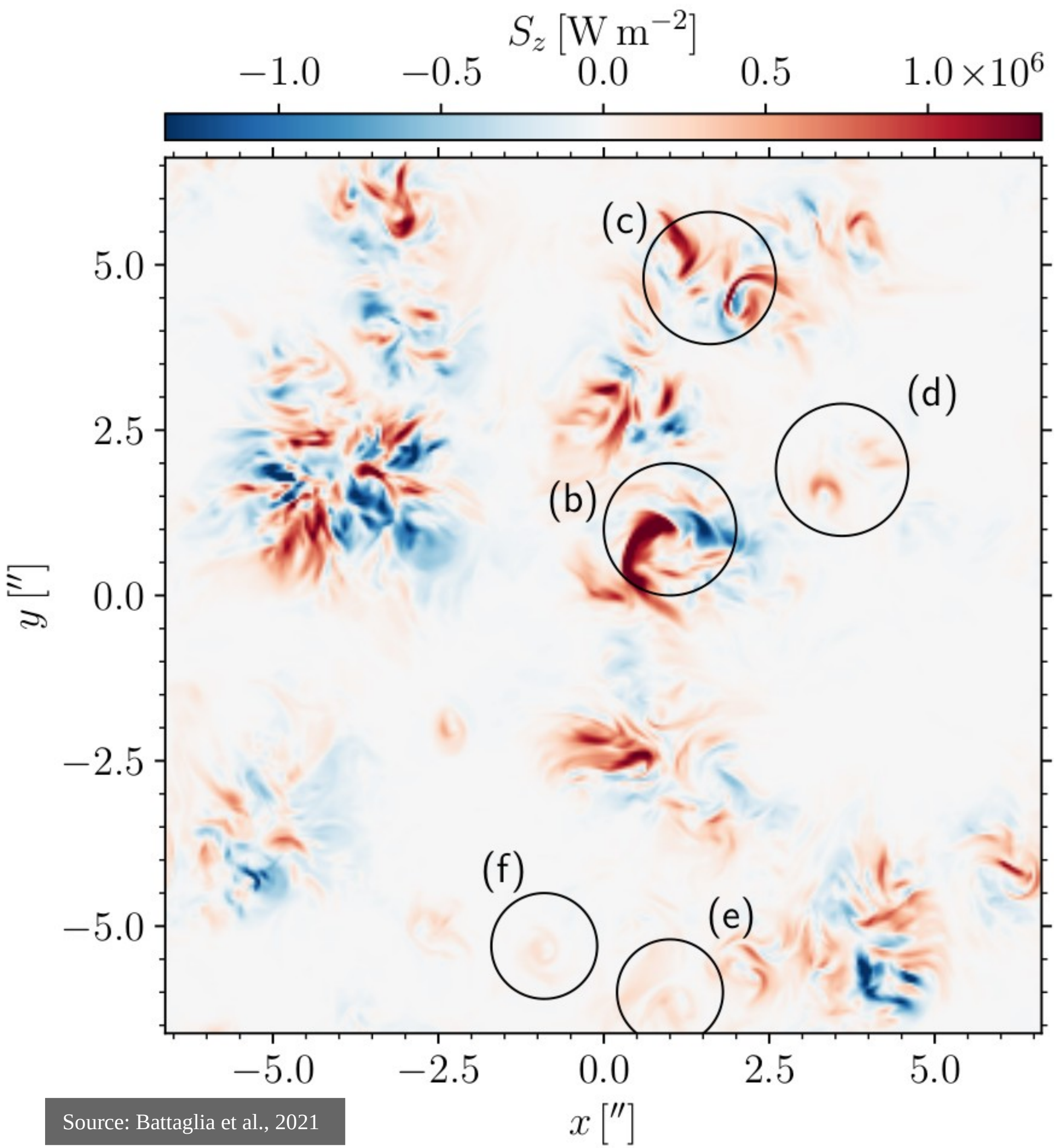
Energetics – the whole picture



Horizontal section at z = 700 km

- Contribution of single, isolated swirls (e,d,f) is small
- Large contributions come from **large and complex magnetic footpoints** (b,c)
- Multiple swirls can be seen contemporaneously in these regions

  "**Superposition of swirls**"

- ➢ At base of chromosphere:

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

- ✔ Enough to compensate radiative losses!

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Conclusions

- The event studied has **Alfvénic nature**:
  - Magnetic twist has opposite orientation to plasma rotation
  - Upward propagation with local Alfvén speed
  - Magnetic tension is the driving force

    “**Alfvén pulse**”

- Vertical positive Poynting flux due to swirling motions
  - Most contributions from large and complex magnetic regions
  - Potentially contribute to **heat the upper layers**

➢ Canivete Cuissa, J. R. & Steiner, O. 2020, A&A, 639, A118
➢ Battaglia, A. F., Canivete Cuissa, J. R., Calvo, F., Bossart, A. A., & Steiner, O.2021, A&A, 649, A121