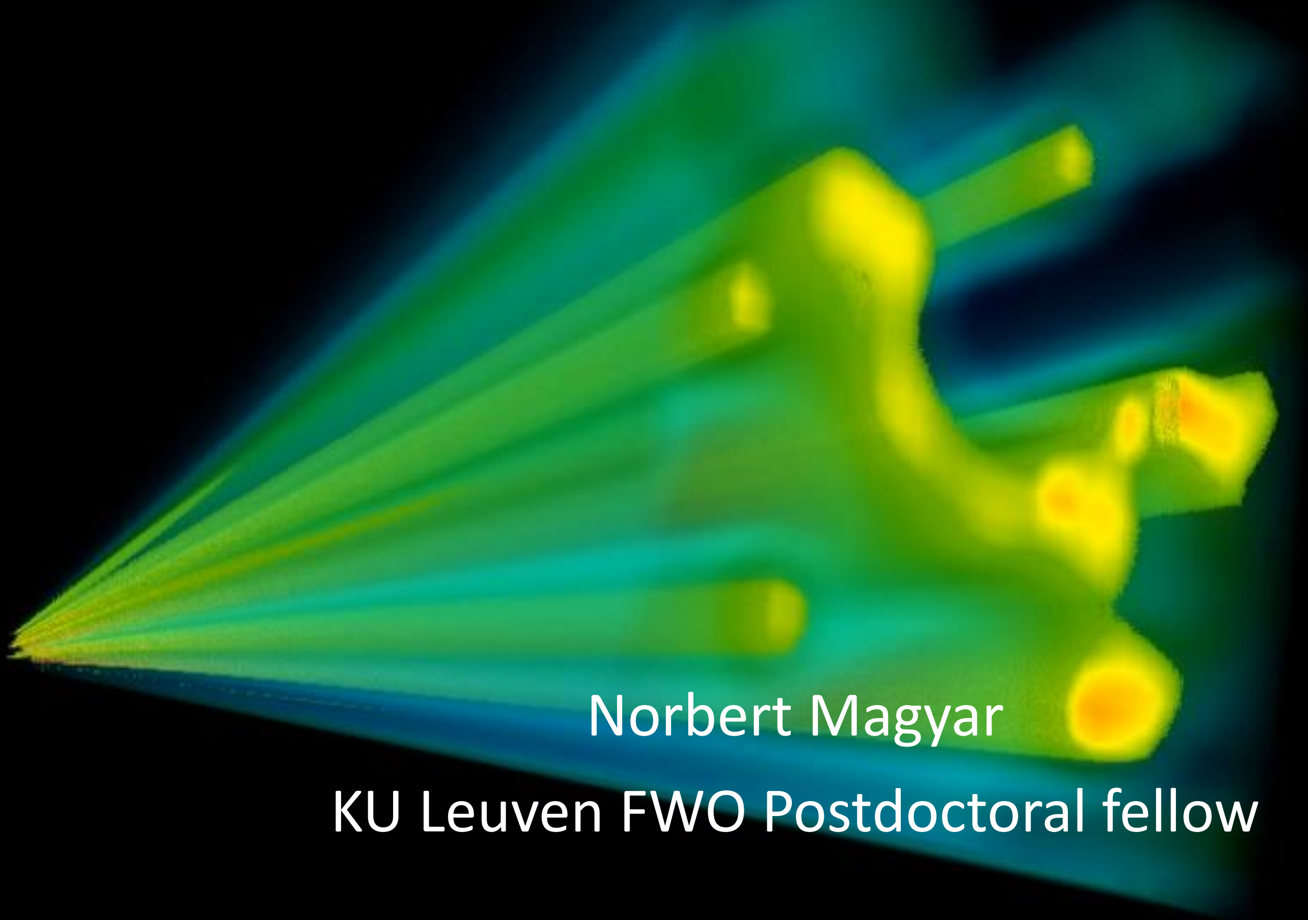
Three-dimensional Simulations of the Inhomogeneous Low Solar Wind



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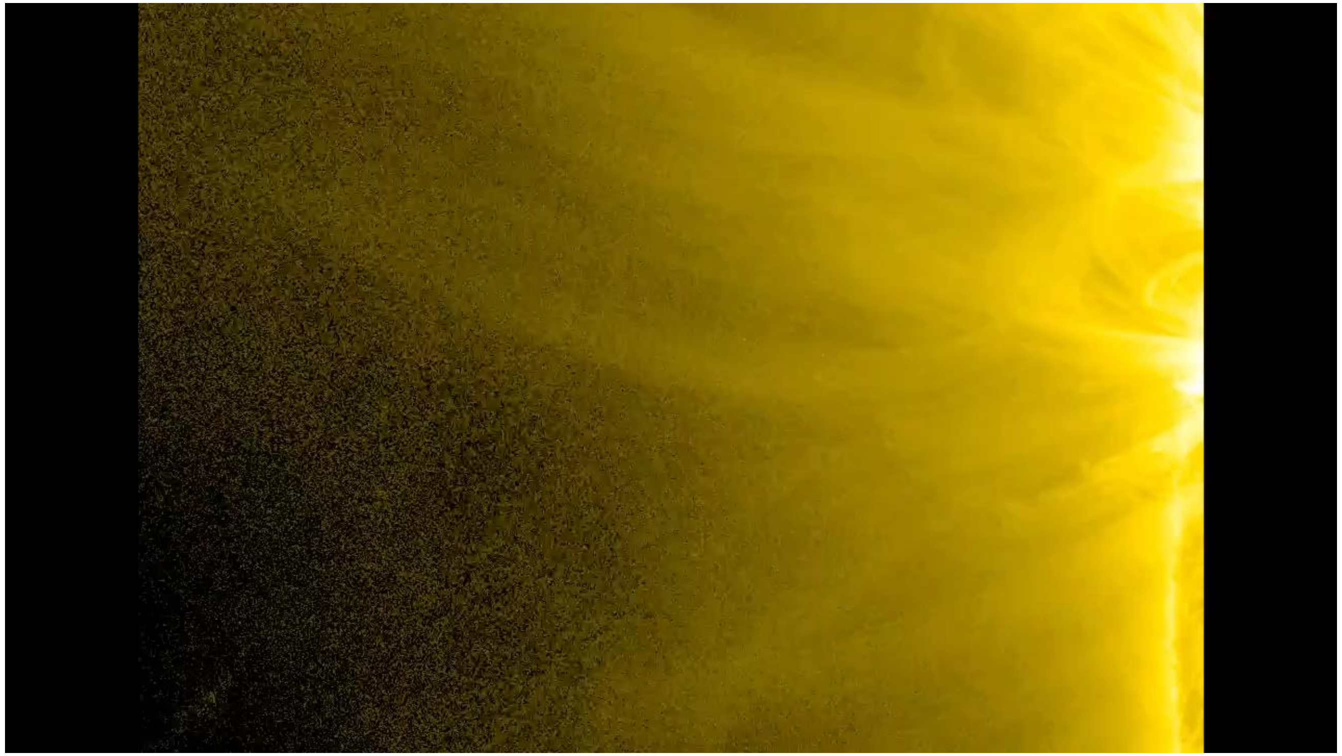
The solar wind is inhomogeneous across **B**

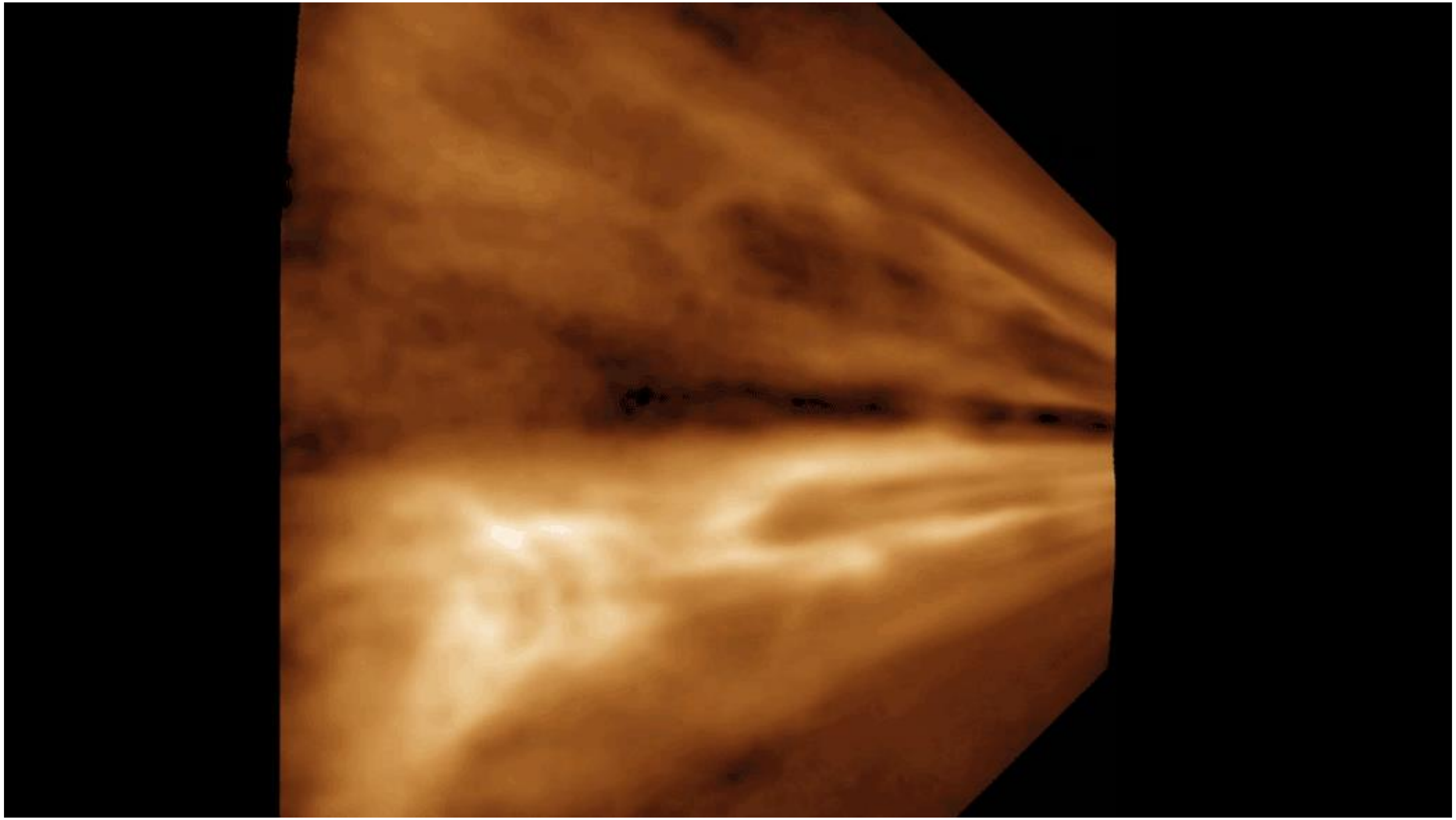
- To date, all models consider a homogeneous background across the magnetic field, however there is plenty of evidence for plasma structuring in the solar corona/wind.

e.g., Comet Lovejoy, 2011, passing at ~150 Mm above the photosphere



Data credit: SDO/NASA

The solar wind is inhomogeneous across **B**



4 to 10
Solar radii

Data credit: (STEREO-A) /COR2, Craig DeForest, SwRI

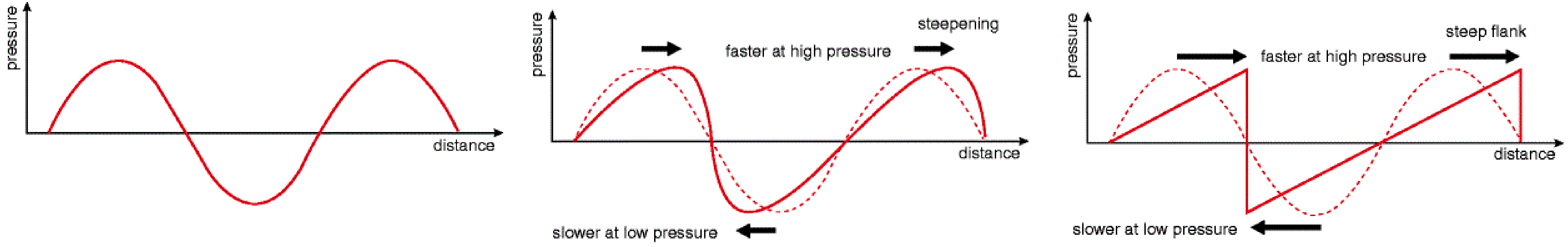
Inhomogeneous MHD allows for:

- Surface and global waves (e.g., surface Alfvén, kink)
- Mode coupling
- Phase mixing
- Resonant absorption
- **Turbulence of unidirectionally propagating waves**

Turbulent cascade of unidirectionally prop. waves

- **Key takeaway**: waves other than pure Alfvén waves (linear or fully nonlinear in incompressible MHD) perturb **both Elsässer variables** as they propagate → **self-cascade of waves** (Magyar et al., 2017,2019a,b).

- E.g., nonlinear wave steepening (cascade along B):



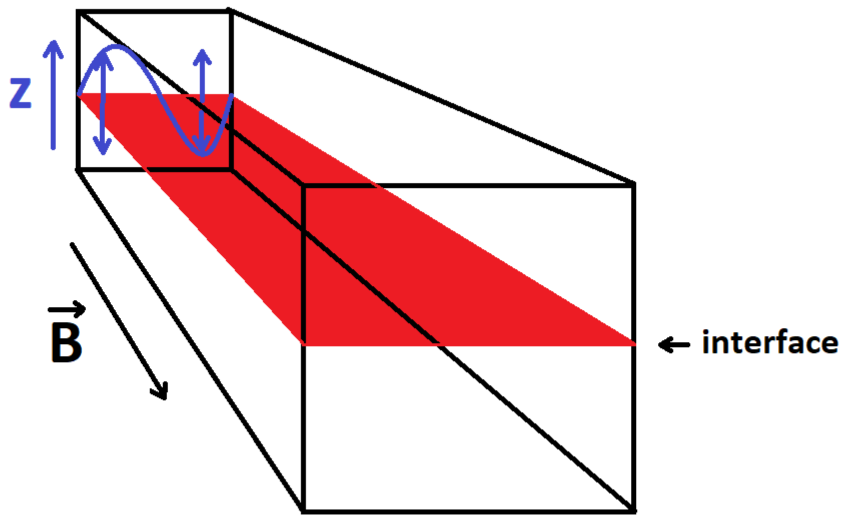
Turbulent cascade of unidirectionally propagating waves

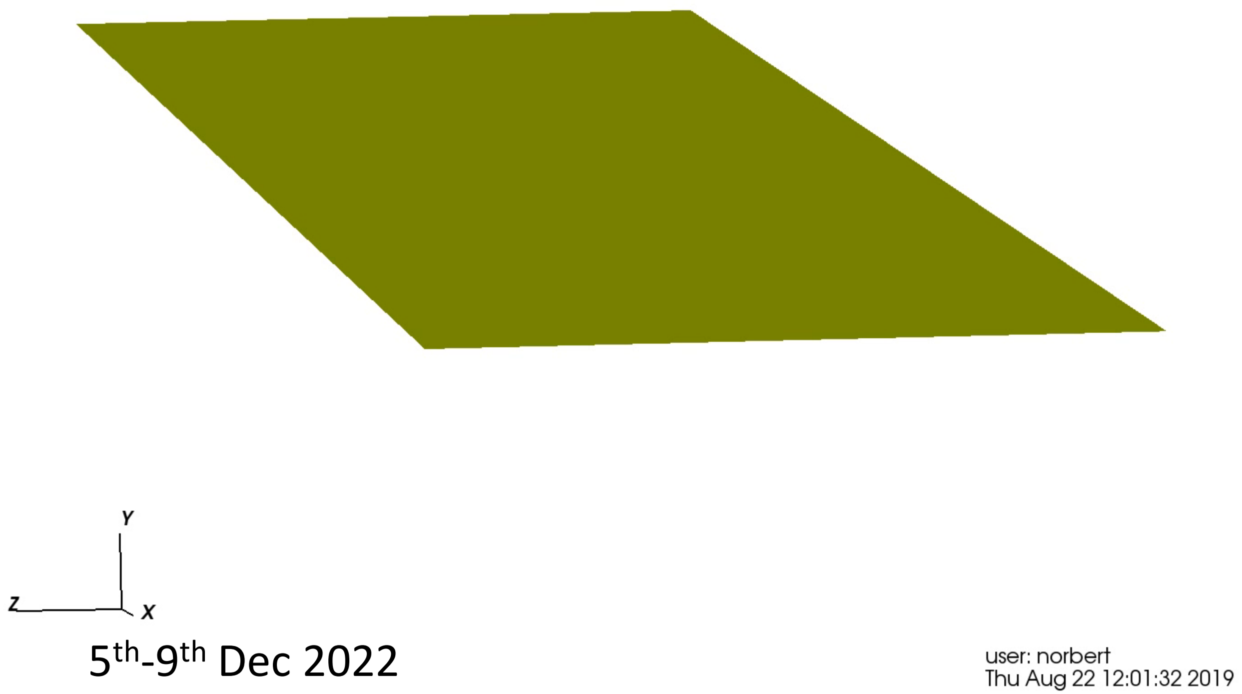
- Transverse MHD waves owing their existence to structuring, e.g., **kink waves** on flux tubes or **surface Alfvén waves** on magnetic interfaces, nonlinearly self-cascade perpendicularly to B as they propagate – referred to as ‘uniturbulence’ .

Turbulent cascade of unidirectionally propagating waves

E.g., surface Alfvén waves

$$v_{ph} = \sqrt{\frac{\rho_i v_{Ai}^2 + \rho_e v_{Ae}^2}{\rho_i + \rho_e}}$$

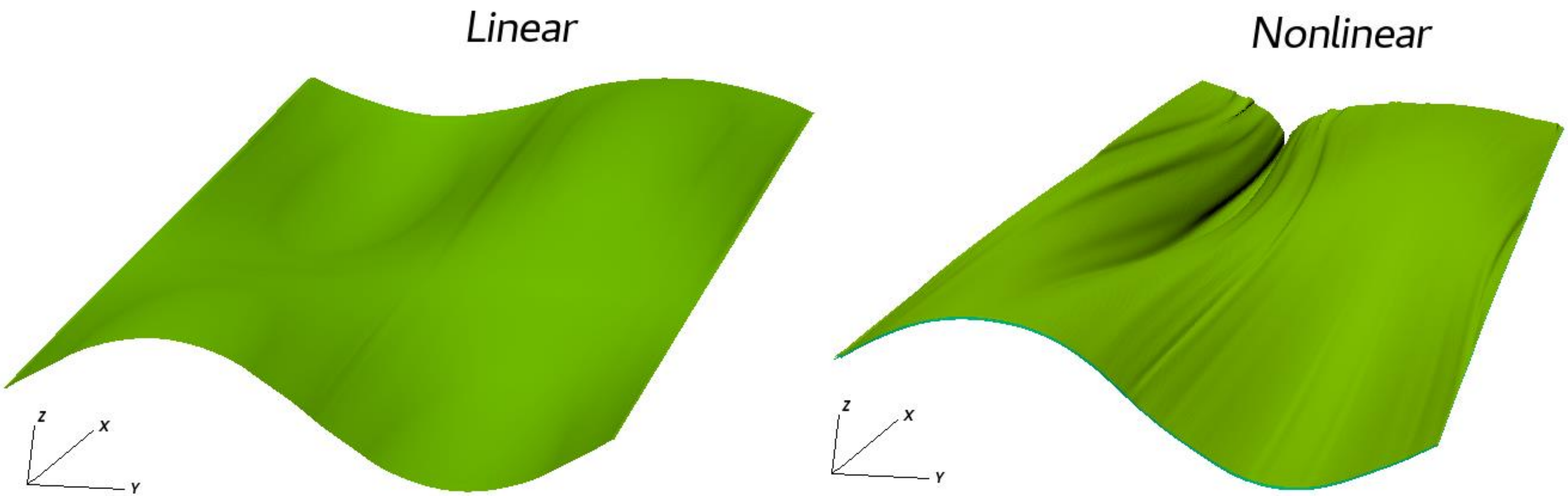




Turbulent cascade of unidirectionally propagating waves

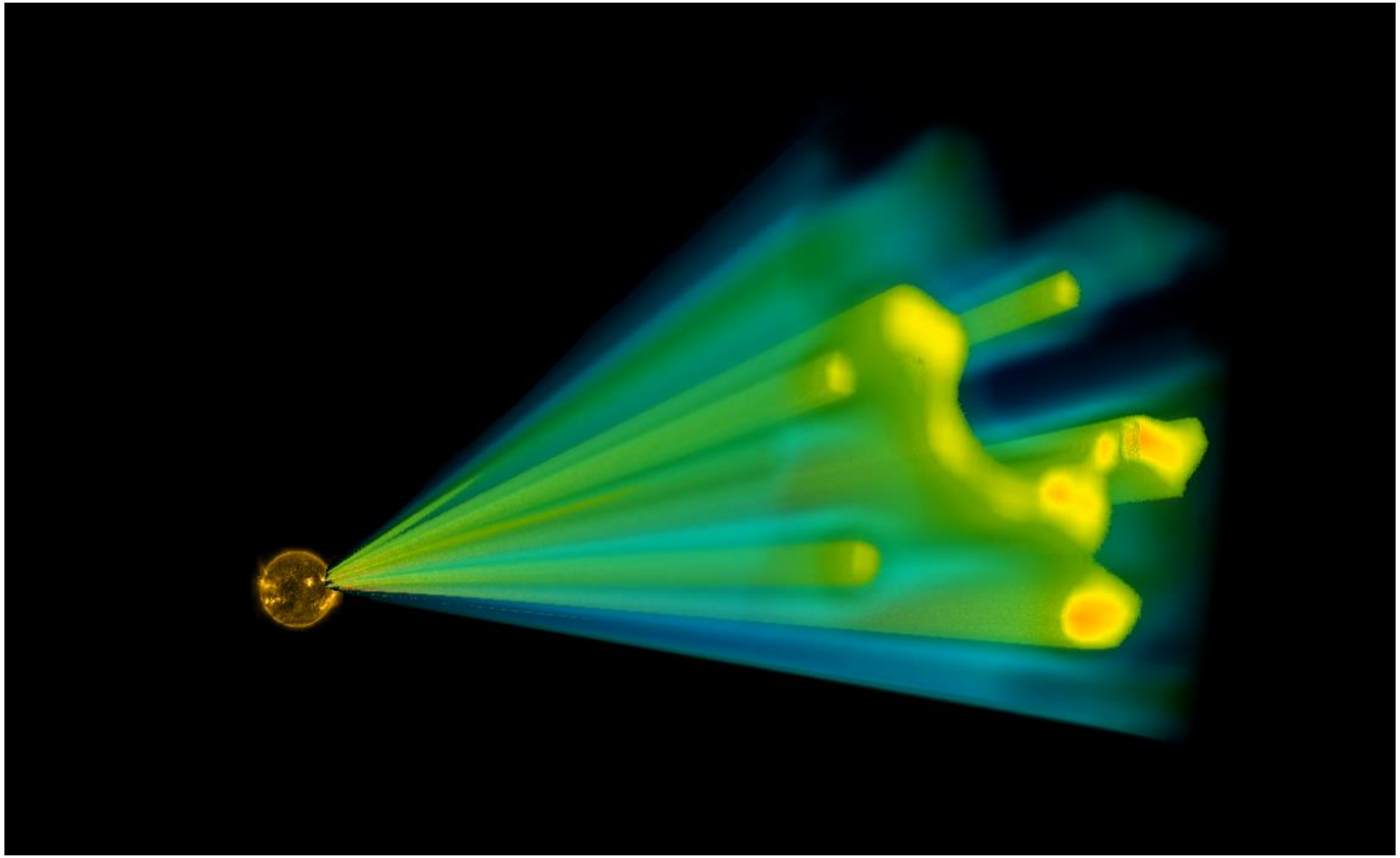
Nonlinear evolution:

surface Alfvén wave



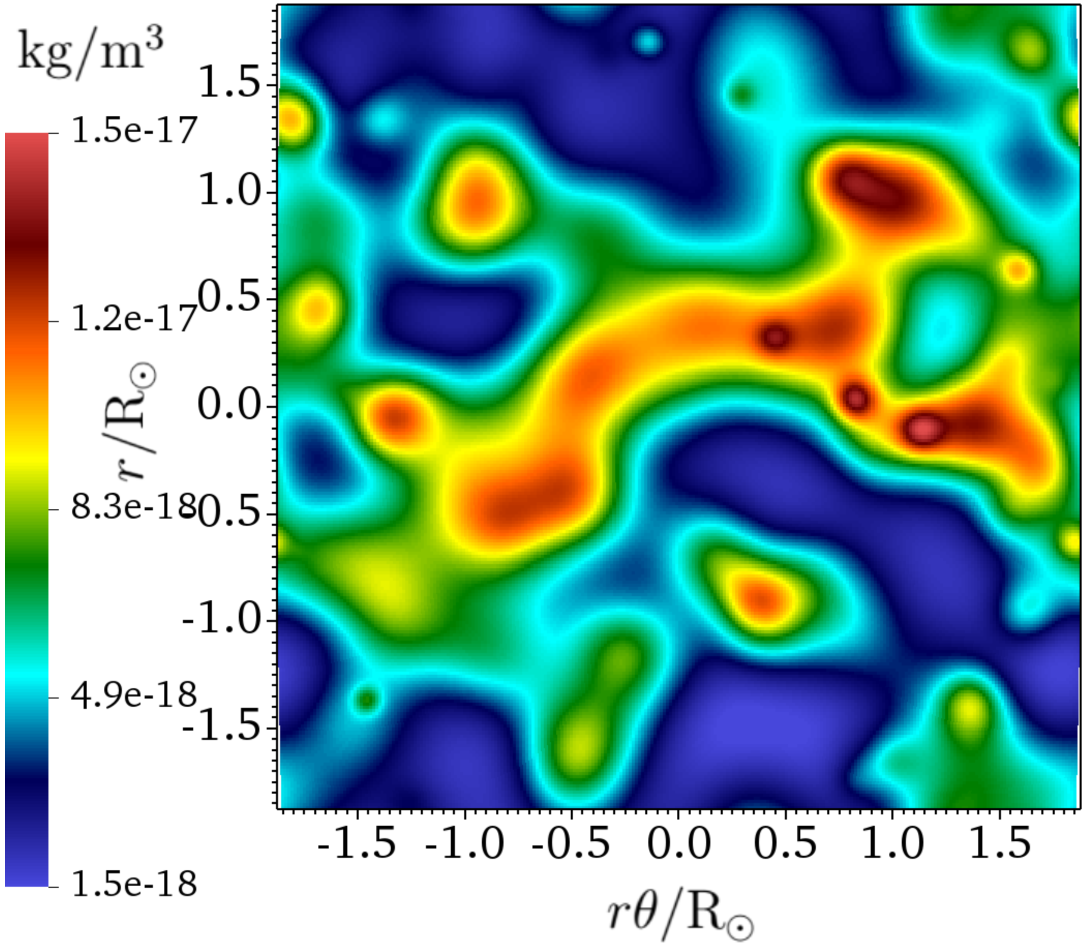
Inhomogeneous 3D MHD solar wind simulation:

- Full 3D MHD
- 1 to 15 R⊙
- 18° wide
- Alfvén point at 12 R⊙
- Relaxed to steady inhomogen. wind
- Driver with k=1-4 at bottom bound.
- Vrms ≈ 15 km/s
- 1024x256^2



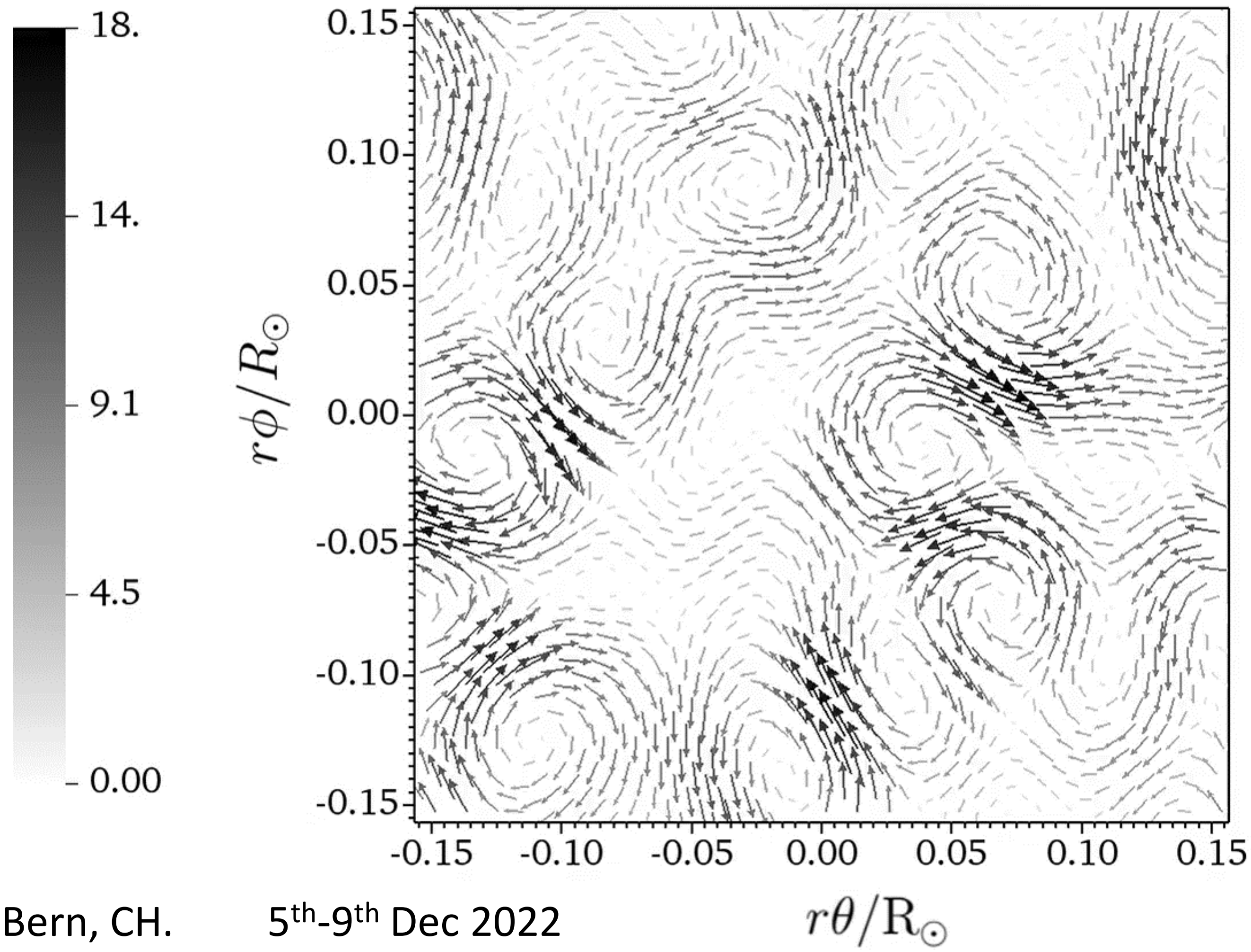
Inhomogeneous 3D MHD solar wind simulation:

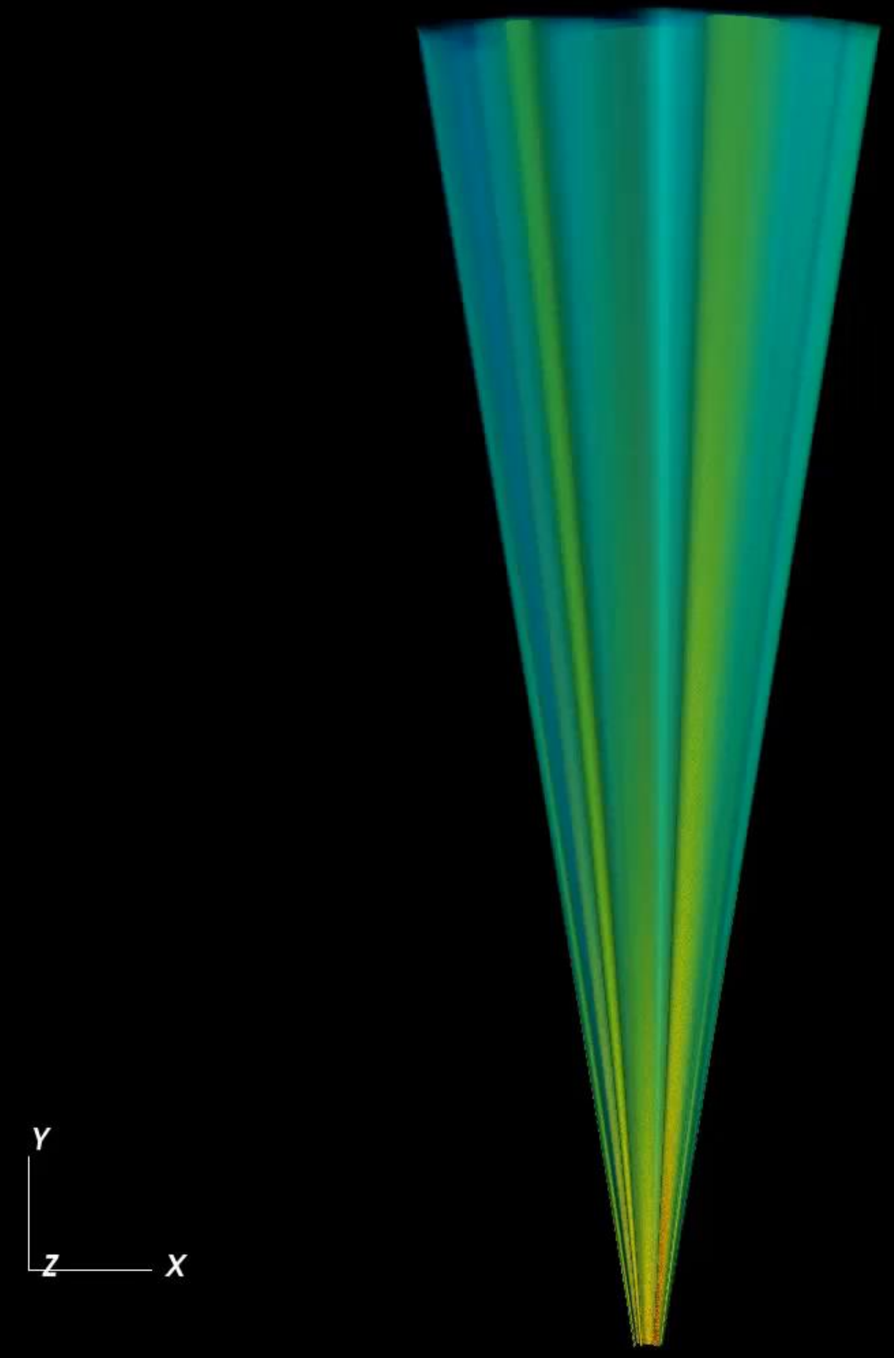
- Inhomogeneous temperature (pressure) boundary condition at the coronal bottom.
- External inhomogeneous heating function
- Similar background wind solution with thermal conduction from bottom boundary.

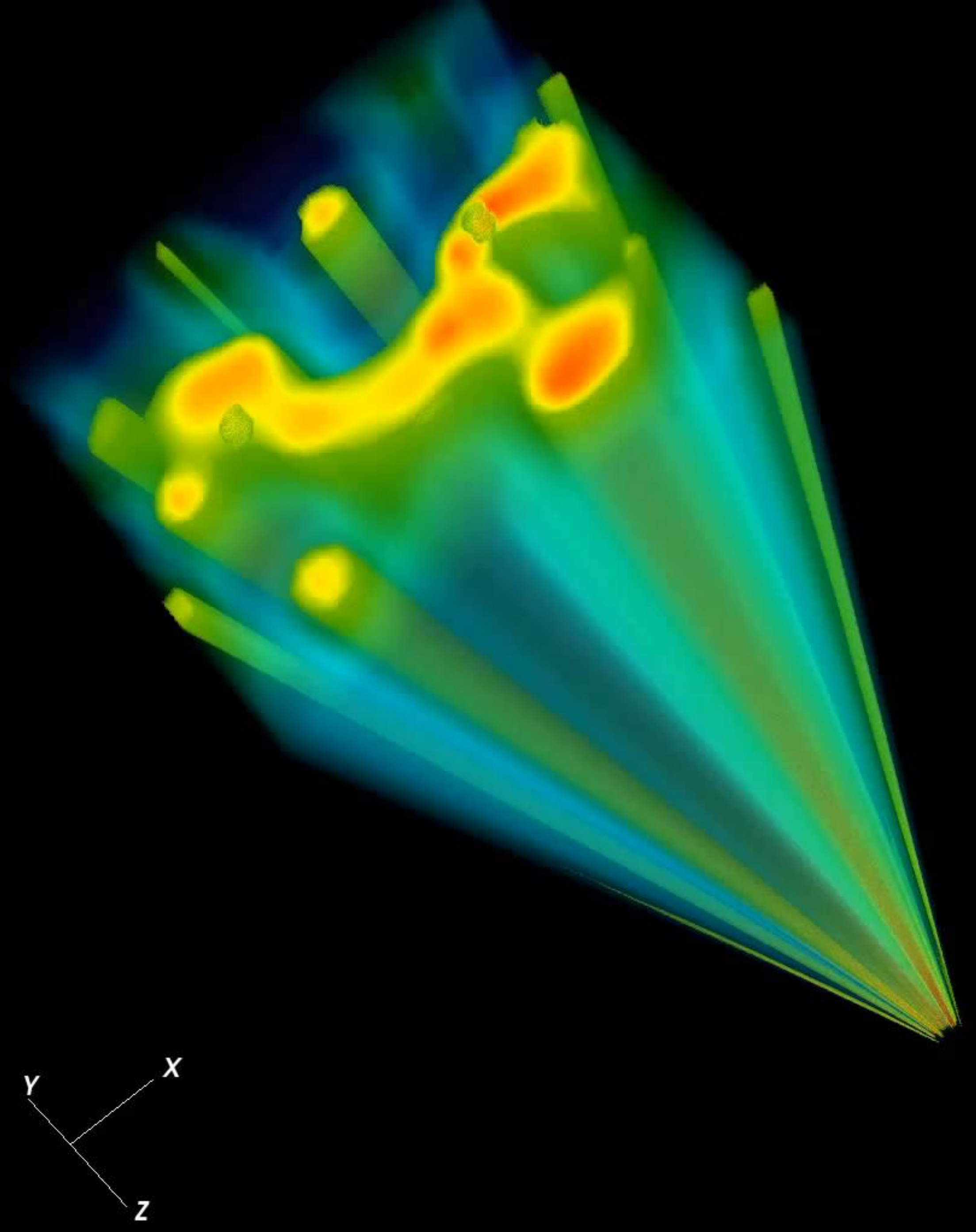


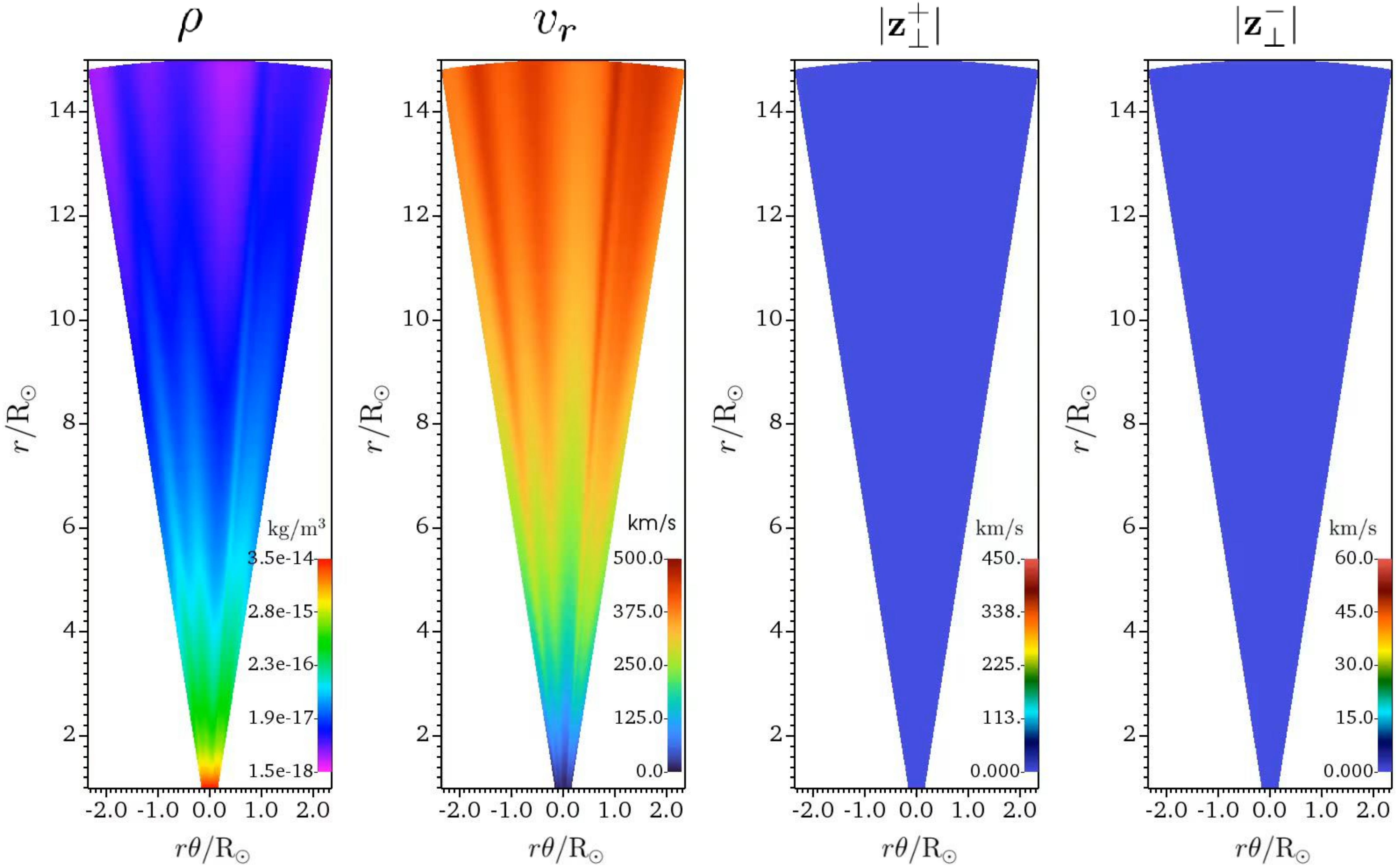
Inhomogeneous 3D MHD solar wind simulation:

Velocity driver at the bottom adds a time and space-varying solenoidal and purely angular velocity field at selected modes, following an Ornstein–Uhlenbeck stochastic process with a finite autocorrelation time (Federrath et al. 2010).

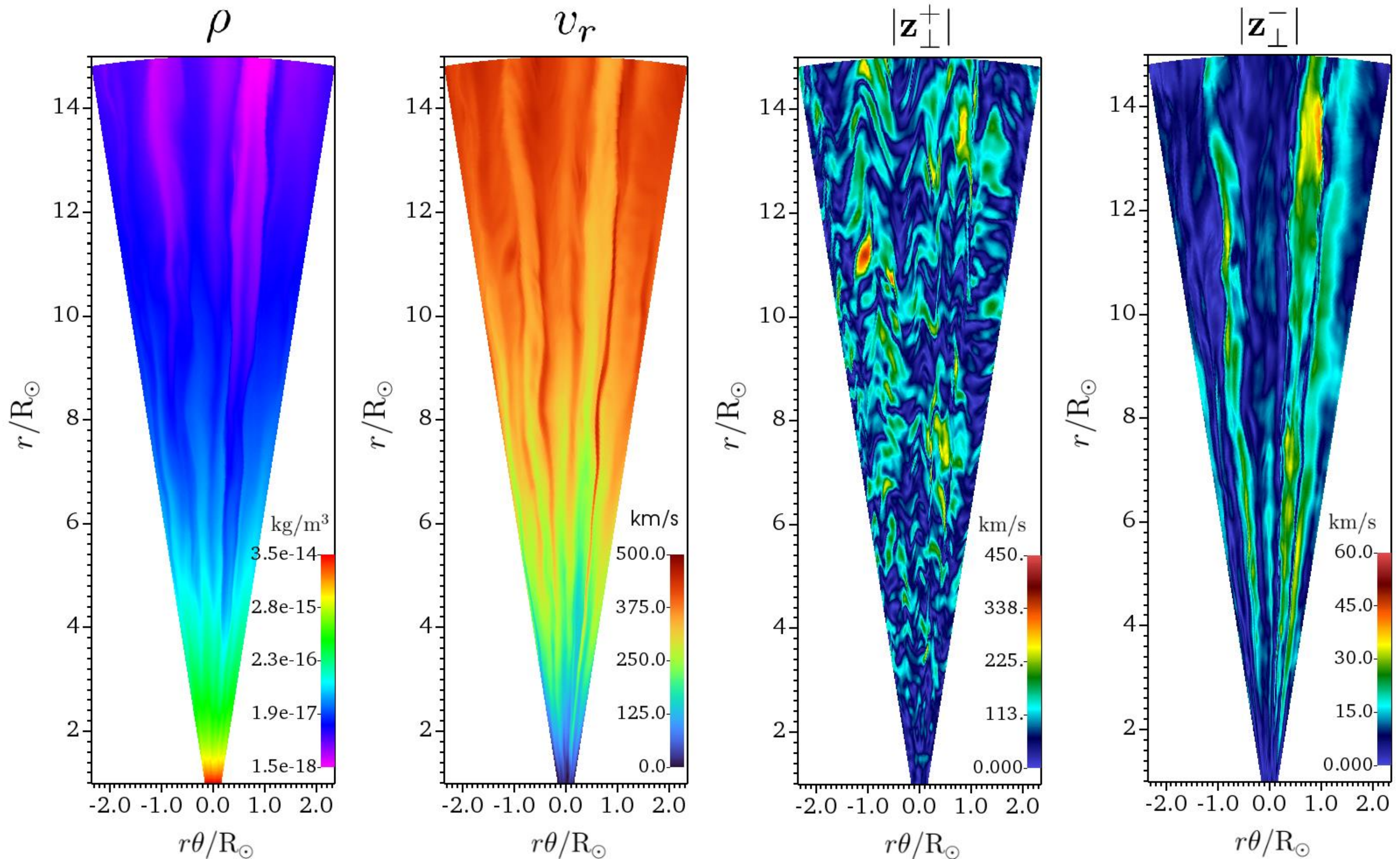



Y
Z
X


Y
X
Z



ρ
v_r
$|\mathbf{z}_\perp^+|$
$|\mathbf{z}_\perp^-|$
$r/\mathrm{R}_\odot$
$r\theta/\mathrm{R}_\odot$
kg/m^3
3.5e-14
2.8e-15
2.3e-16
1.9e-17
1.5e-18
km/s
500.0
375.0
250.0
125.0
0.0
km/s
450.
338.
225.
113.
0.000
km/s
60.0
45.0
30.0
15.0
0.000



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0.000
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60.0
45.0
30.0
15.0
0.000

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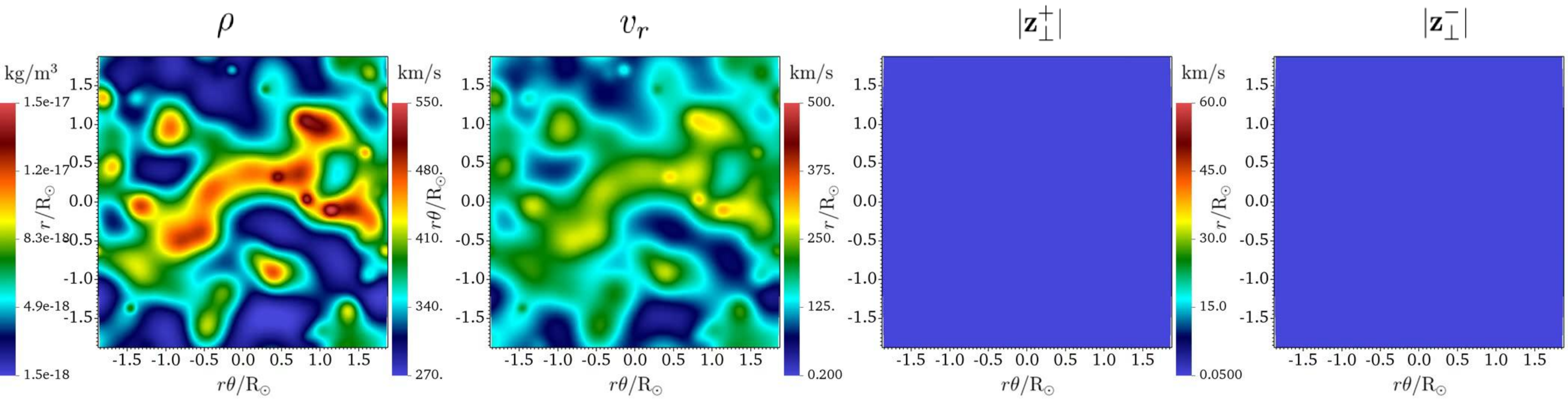
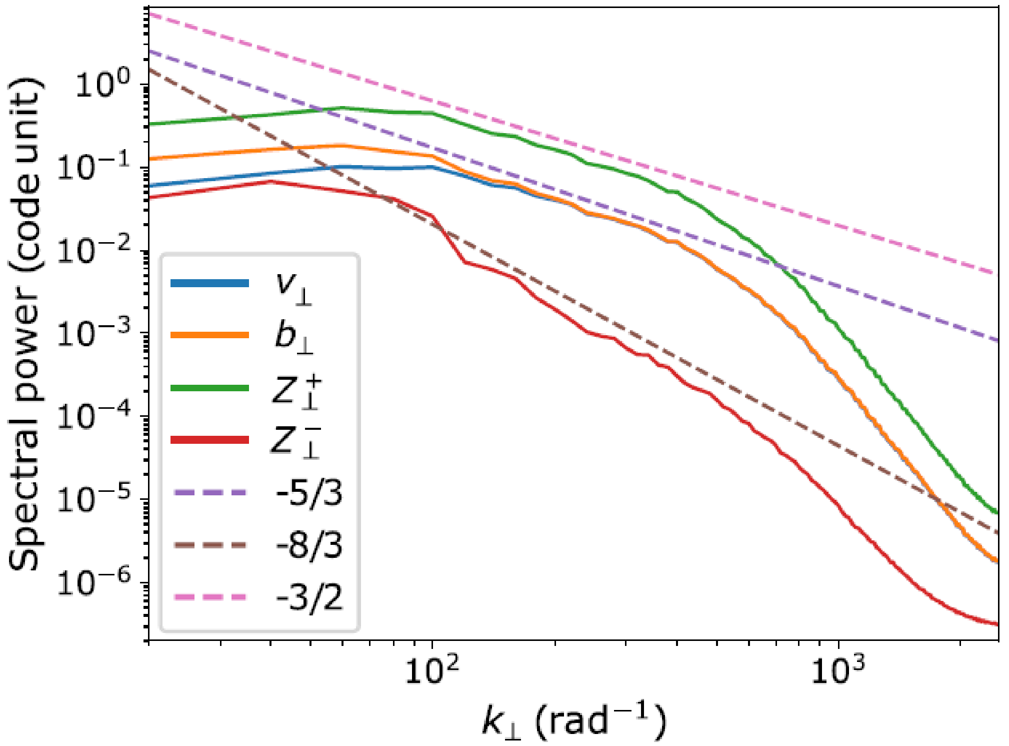
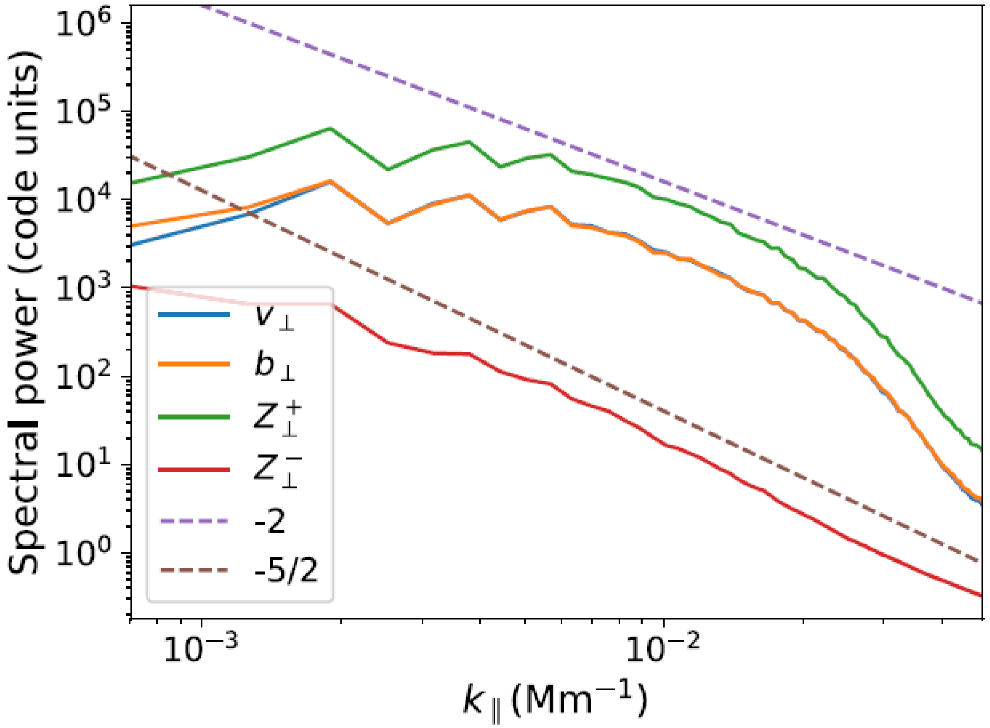
Slice at r = 12 $R_\odot$



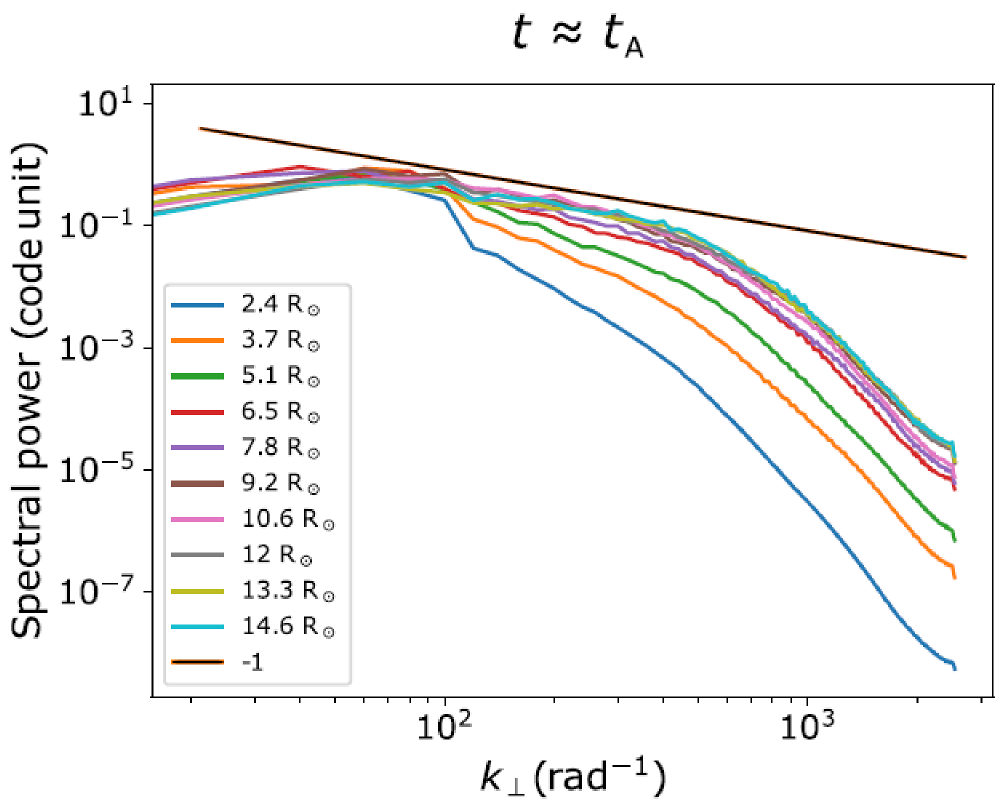
Energy spectra

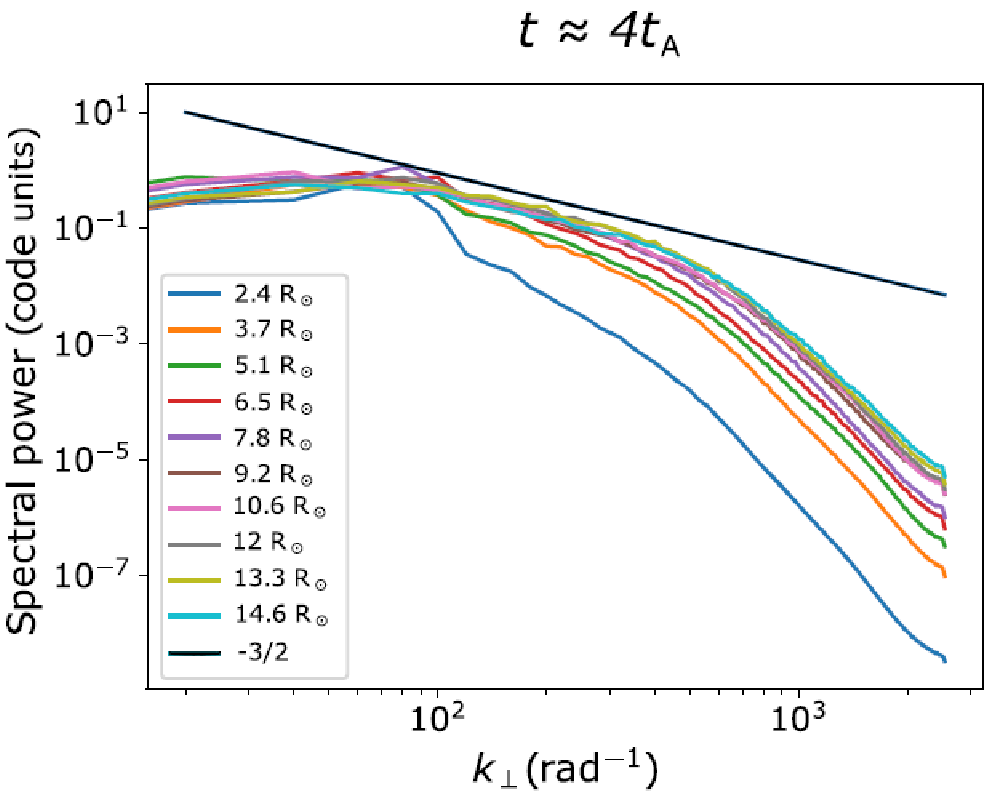




- Perp. Energy spectra -3/2 or -5/3 ✓ Par. energy spectra -2 ✓
- Magnetic field spectra steeper than vel. ✓
- z^{-}spectra steeper than measured ?

Energy spectra evolution in time and with r

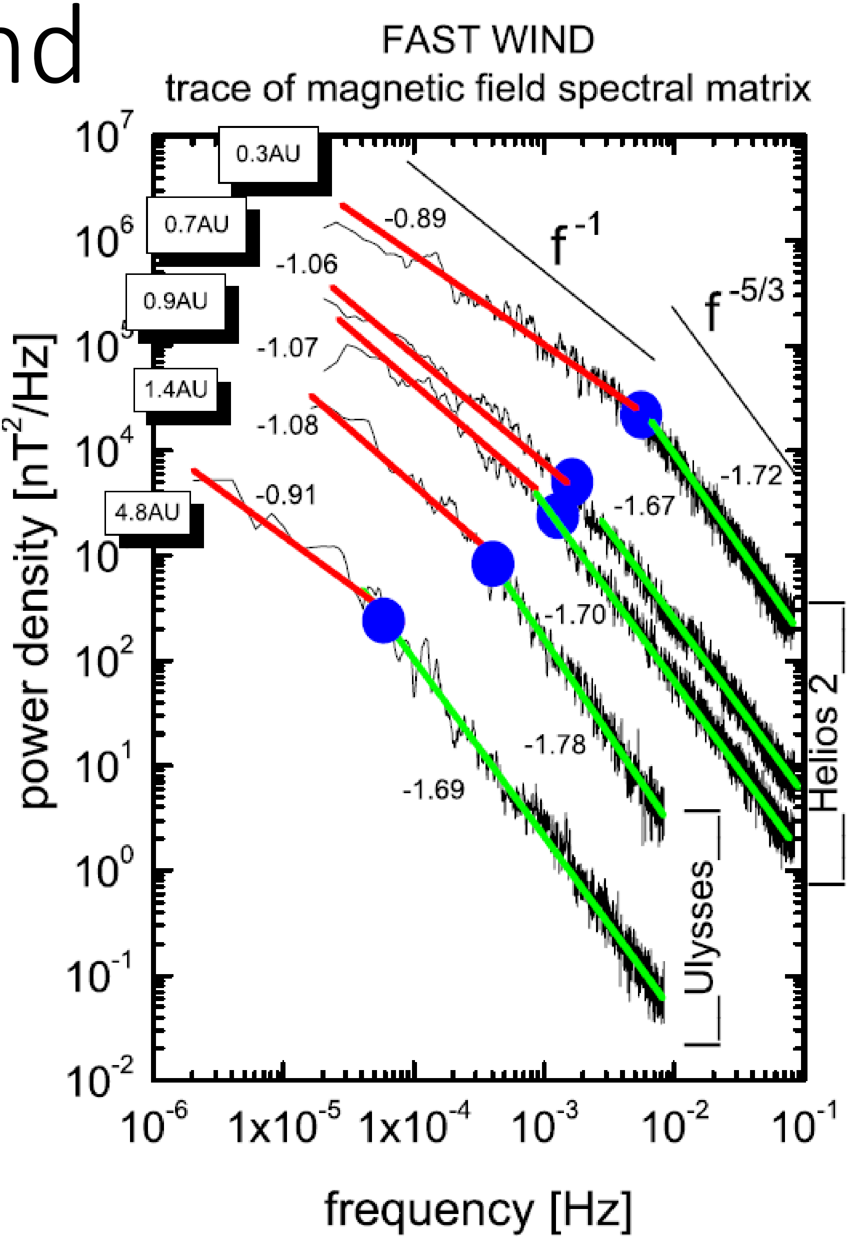




- Initially a 1/f spectrum due to linear phase mixing
- In the statistically steady state, it evolves towards -5/3.

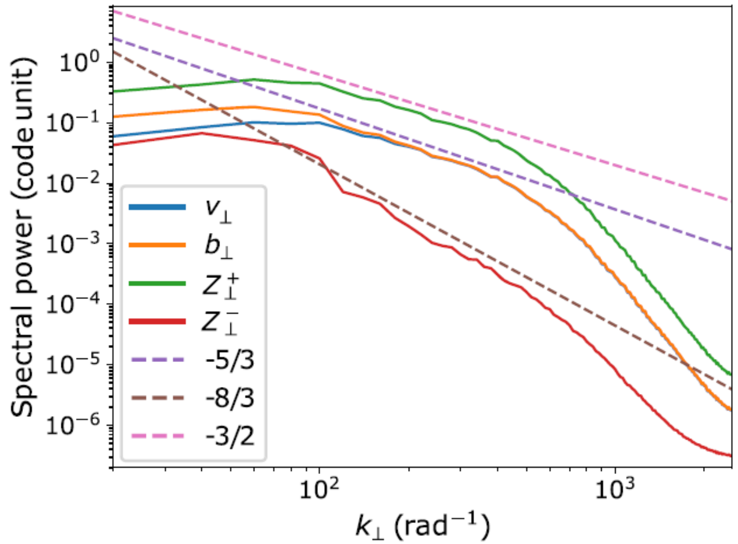
Energy spectra evolution in time and with r

- The origin of the 1/f spectra of long wavelength waves in the fast solar wind is not clear.
- It could originate from long-wavelength, weakly nonlinear, phase-mixed waves which gradually cascade as they propagate outwards (Magyar et al. 2022).

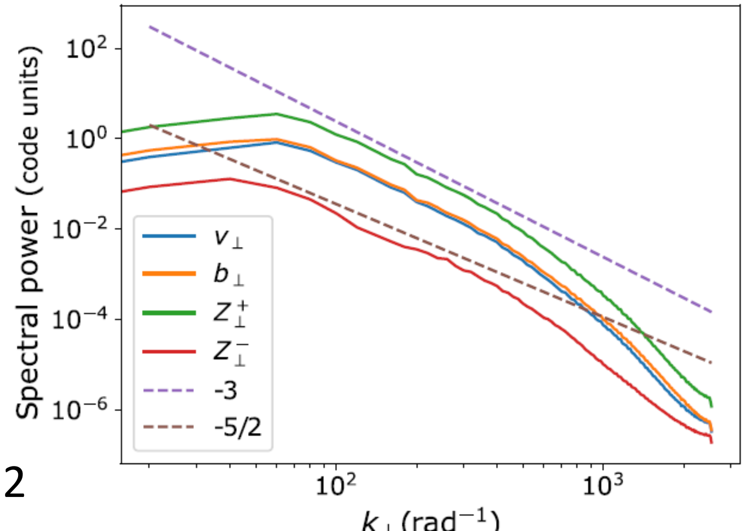


Homogeneous vs. inhomogeneous turbulence

- Same domain, same wave driver, no structuring
  - Energy spectra in the homogeneous setup at the end of the simulated time ≈ -3
    - Cascade to smaller scales, both linear and nonlinear, much faster in the inhomogeneous setup → uniturbulence cascade rate higher than AWT.



inhom.



hom.

Correlation between nonlinear advection, Alfvén speed gradients, radial currents

3D cross-correlation from r = 12-15 $R_\odot$

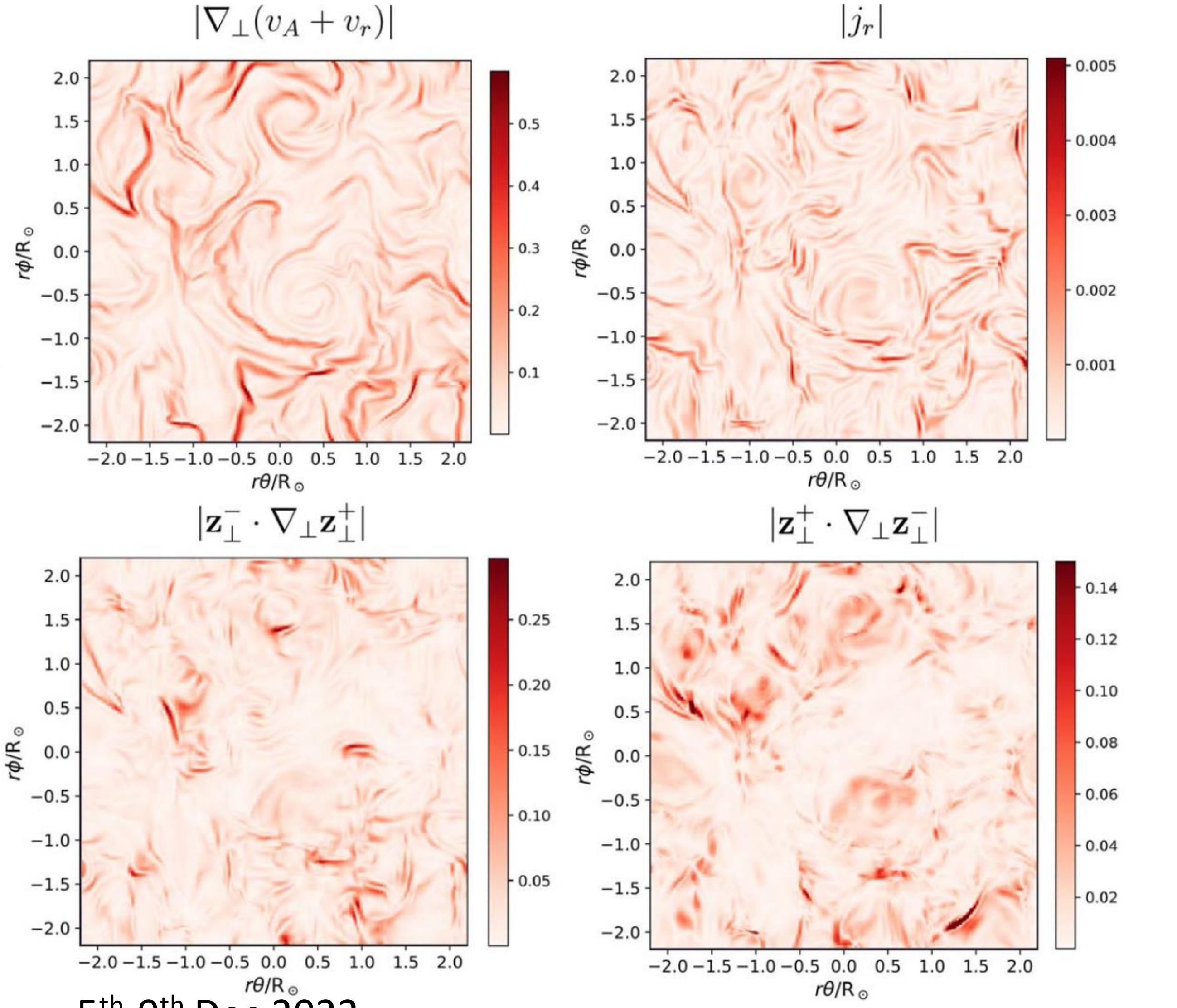
$$\nabla v_A \star |j_r| \approx 0.23$$

$$\nabla v_A \star z^+_{NL} \approx 0.17$$

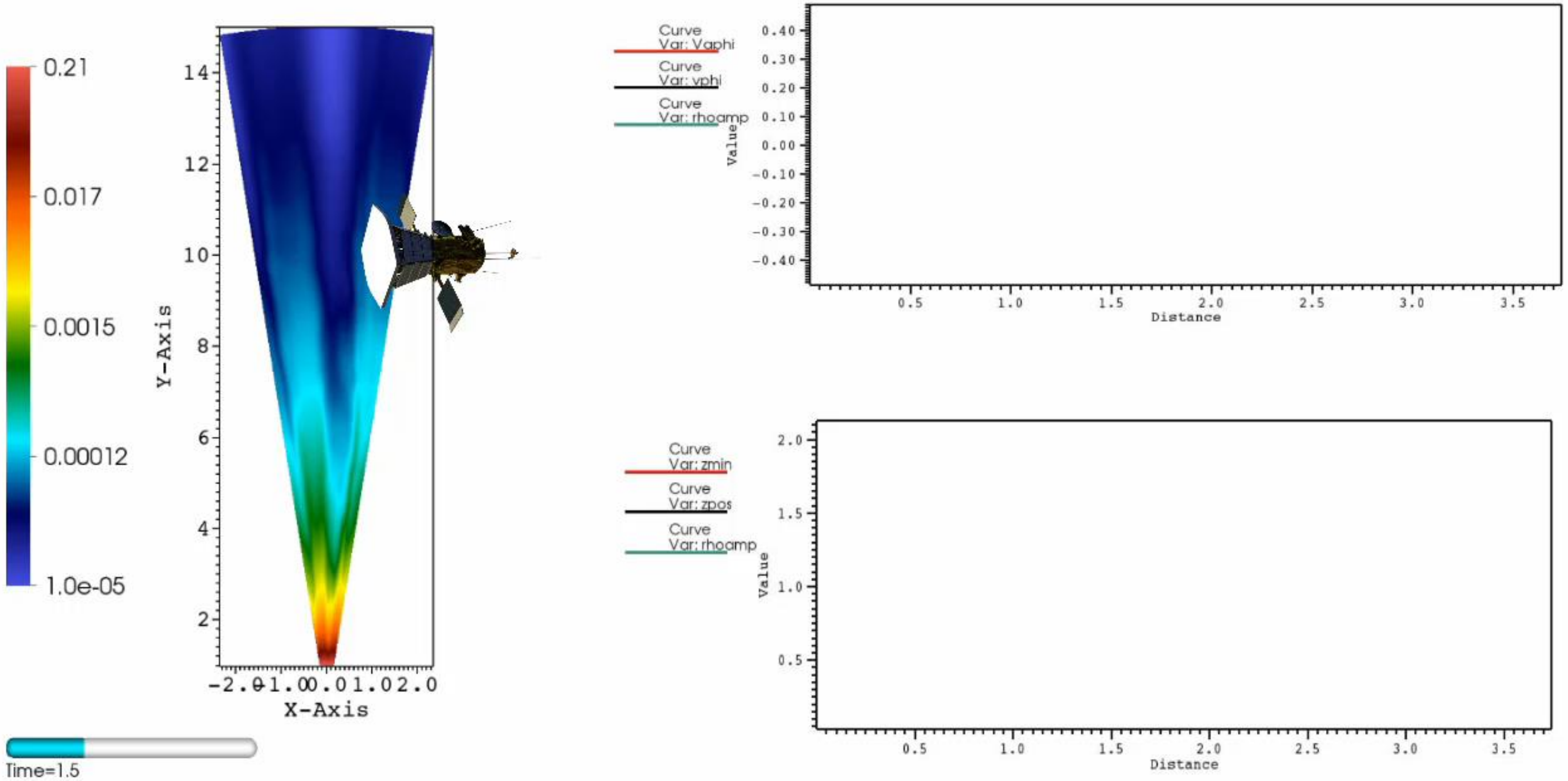
$$\nabla v_A \star z^-_{NL} \approx 0.23$$

$$|j_r| \star z^+_{NL} \approx 0.47$$

For comparison, Alfvénic correlation: $v_\phi \star b_\phi \approx 0.9$



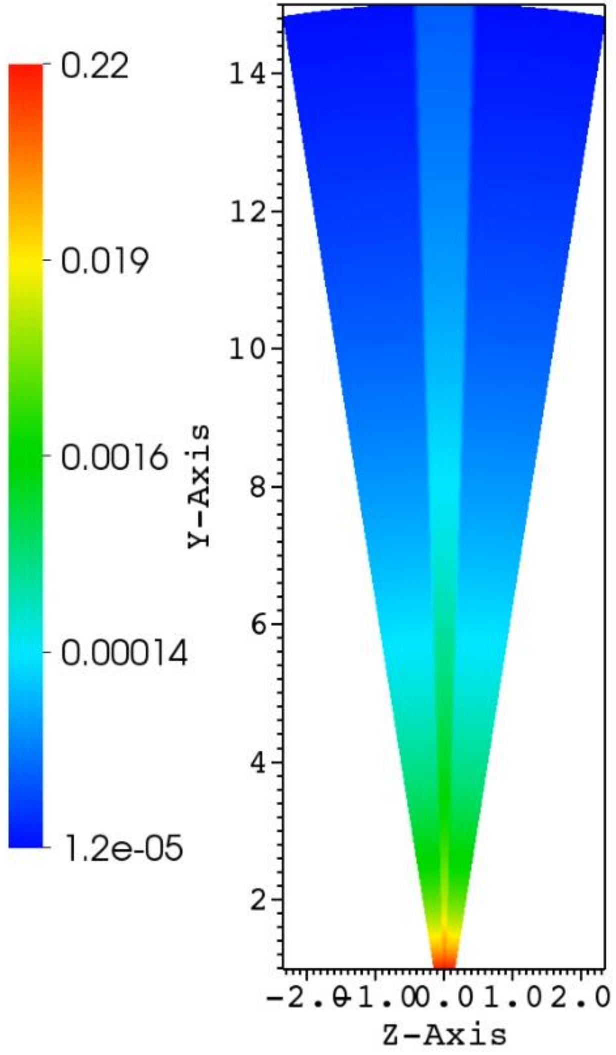
Simulated PSP data acquisition



Simplified setups

- The presented simulation is too complex to clearly identify all the different mechanisms and nonlinear cascade channels at play.

- We consider now a setup with a single cylindrical plume.

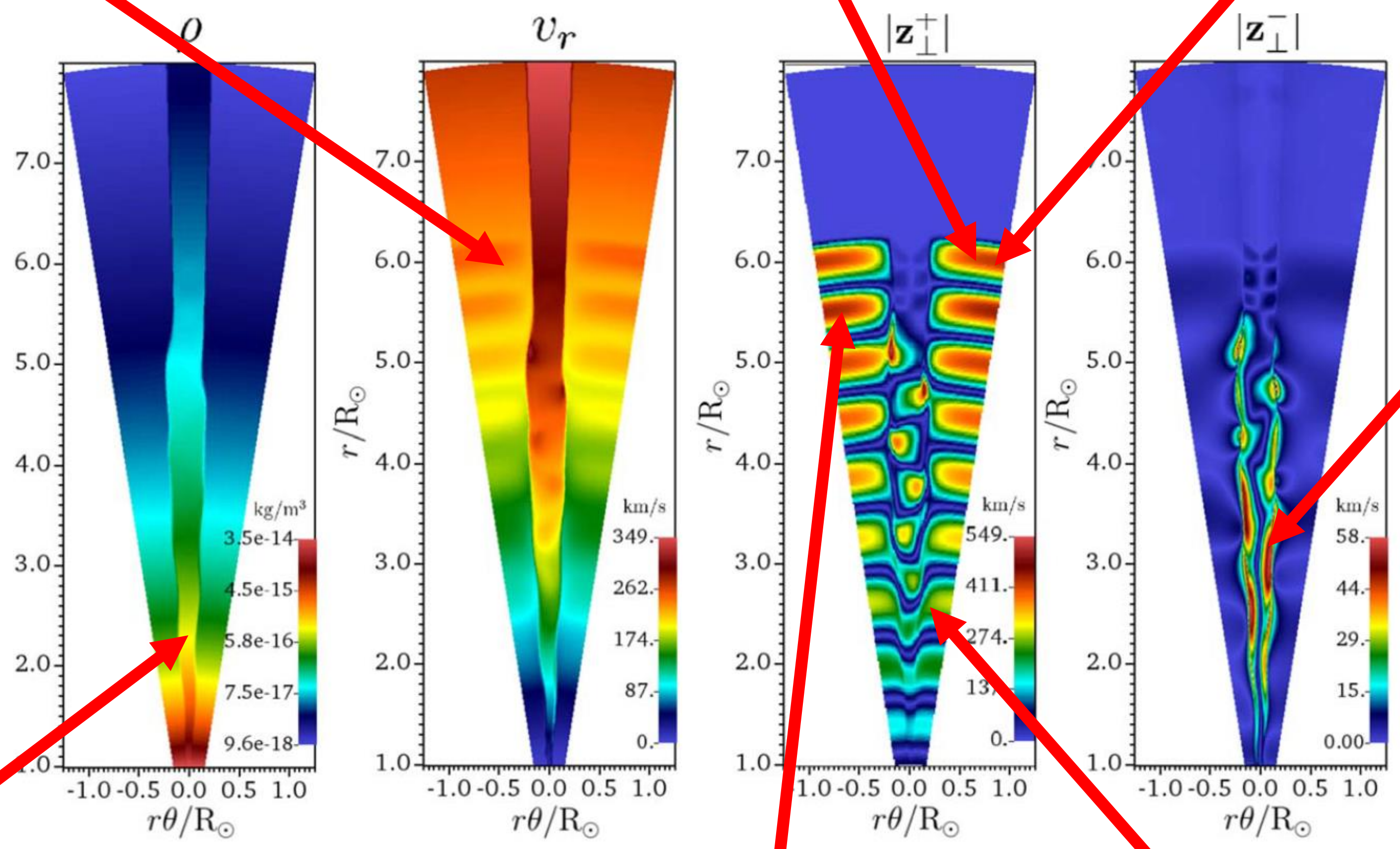


Uniform linearly-polarized wave driver

Ponderomotive flows

Wave steepening

Amplification (WKB)



z^-component of kink wave

kink wave

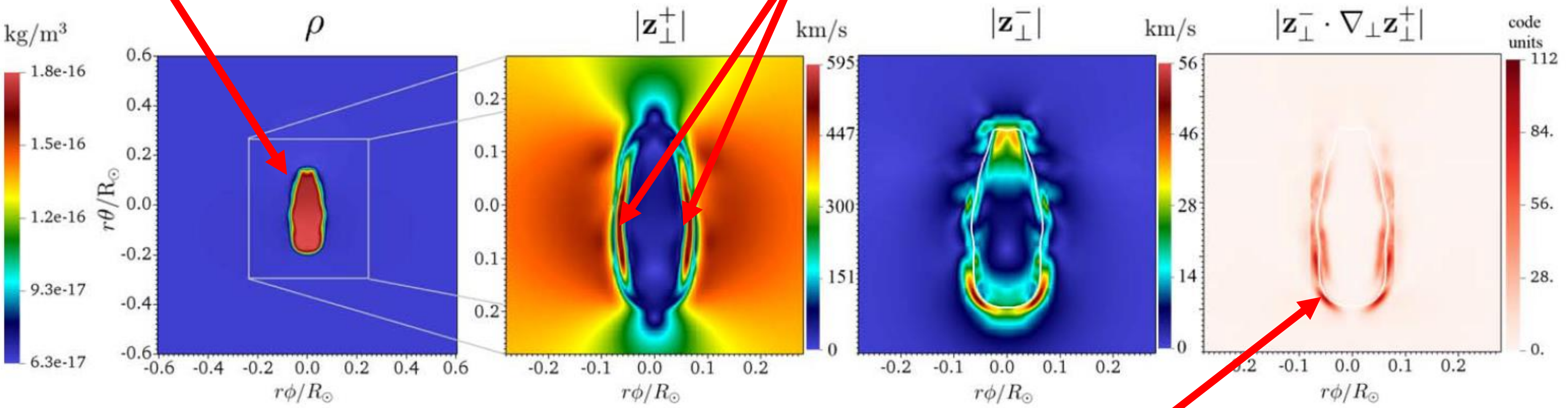
Alfvén wave

phase mixing (not Heyvaerts & Priest 1983)

Uniform linearly-polarized wave driver

Deformation

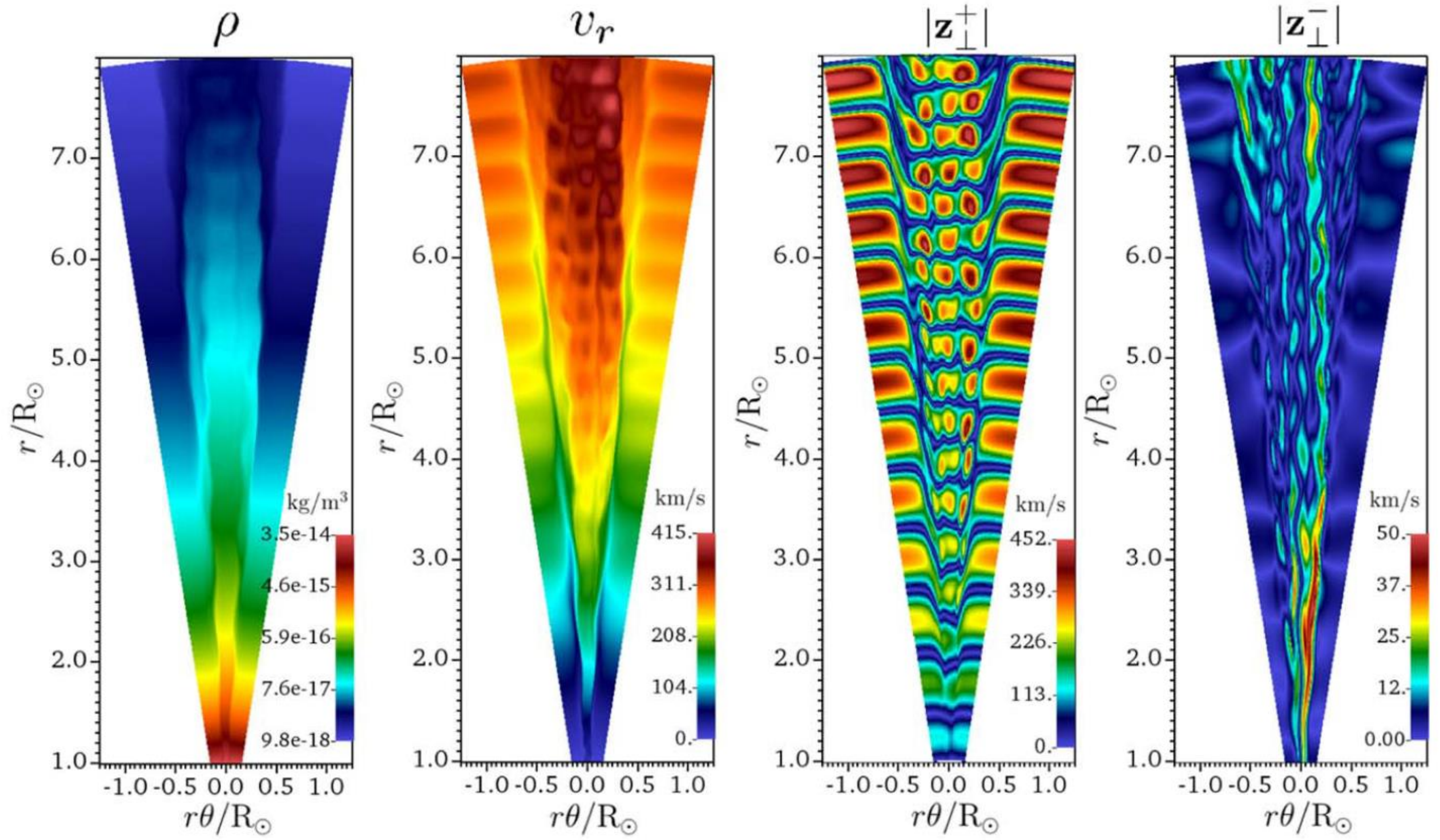
Resonant absorption



Nonlinear advection confined to the plume edge

Uniform linearly-polarized wave driver – advanced

- Note small-scale generation throughout the plume, while Alfvén waves relatively unchanged.



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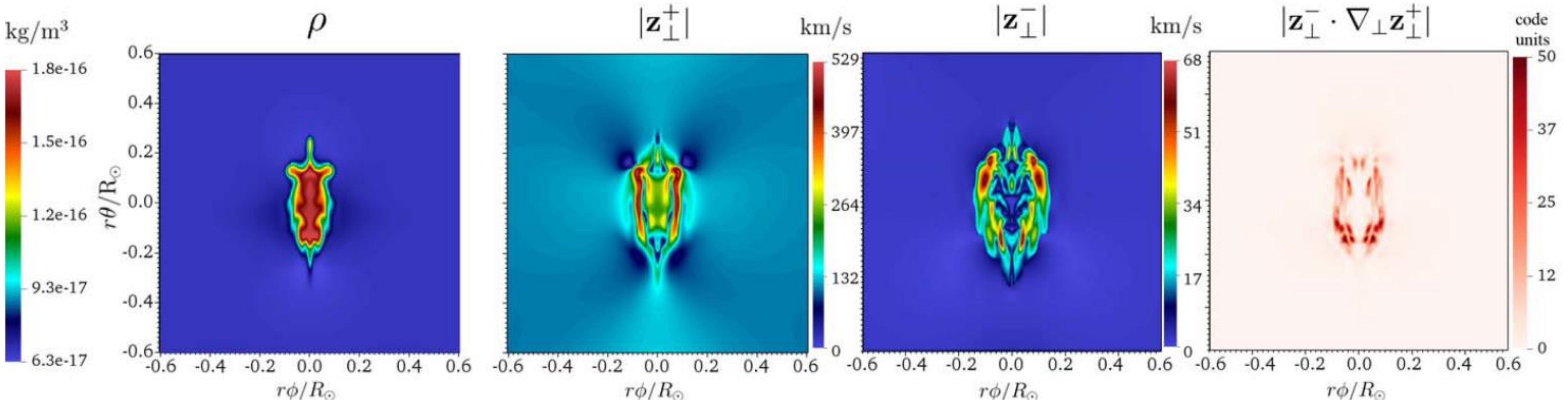
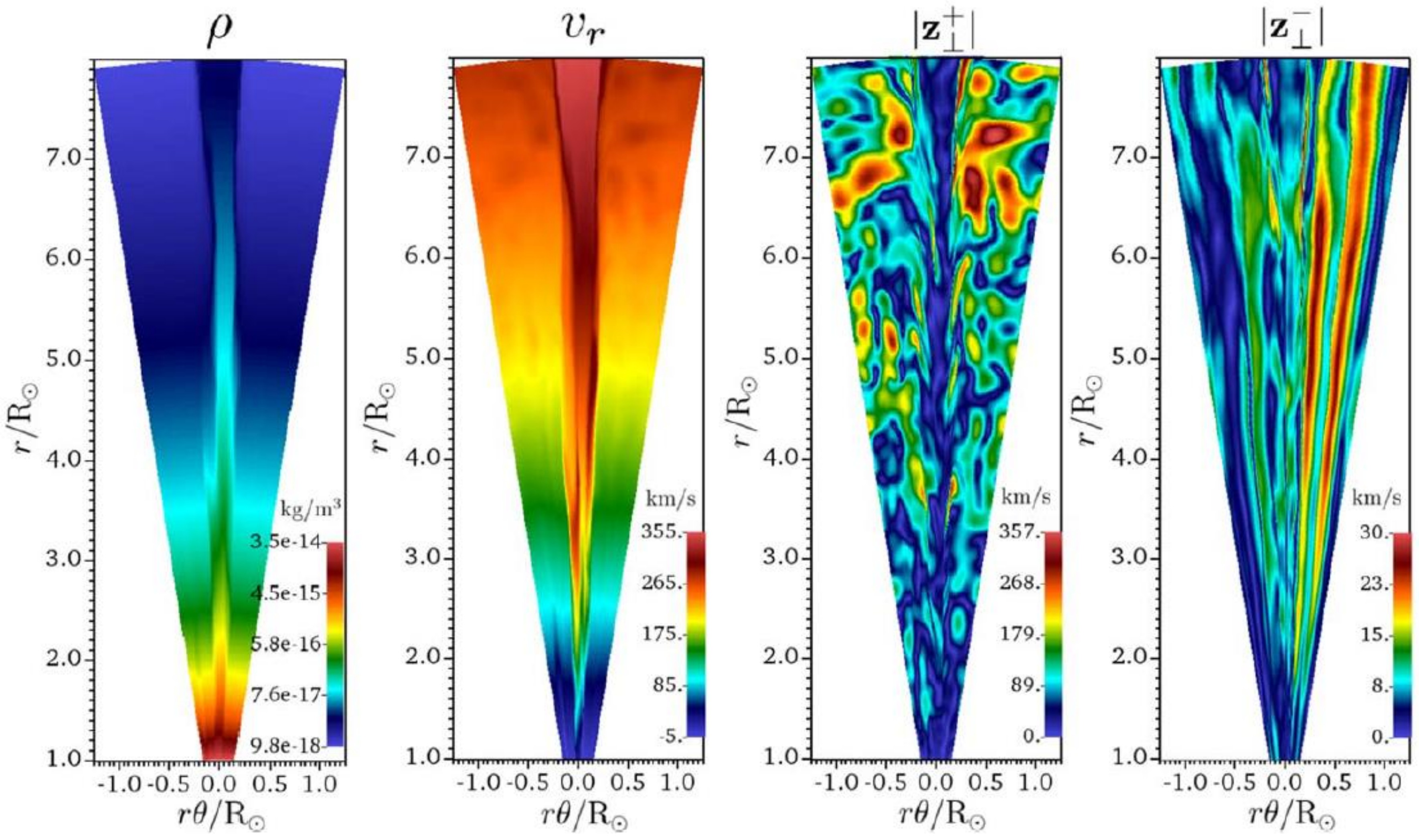
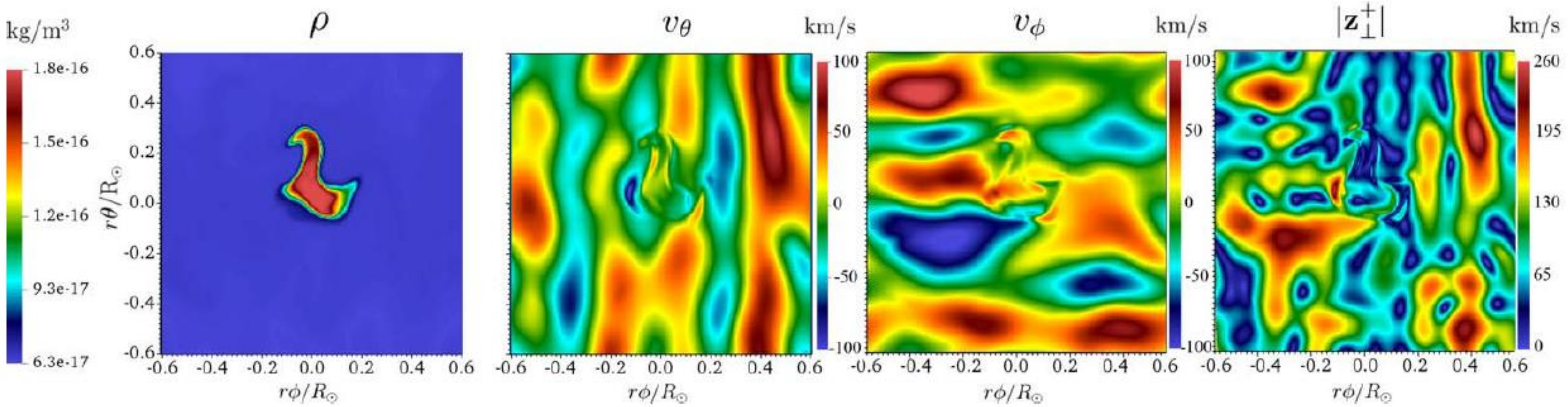


Stochastic wave driver

- Alfvén waves polarized in the same direction do not interact nonlinearly with their reflections – run realistic wave driver

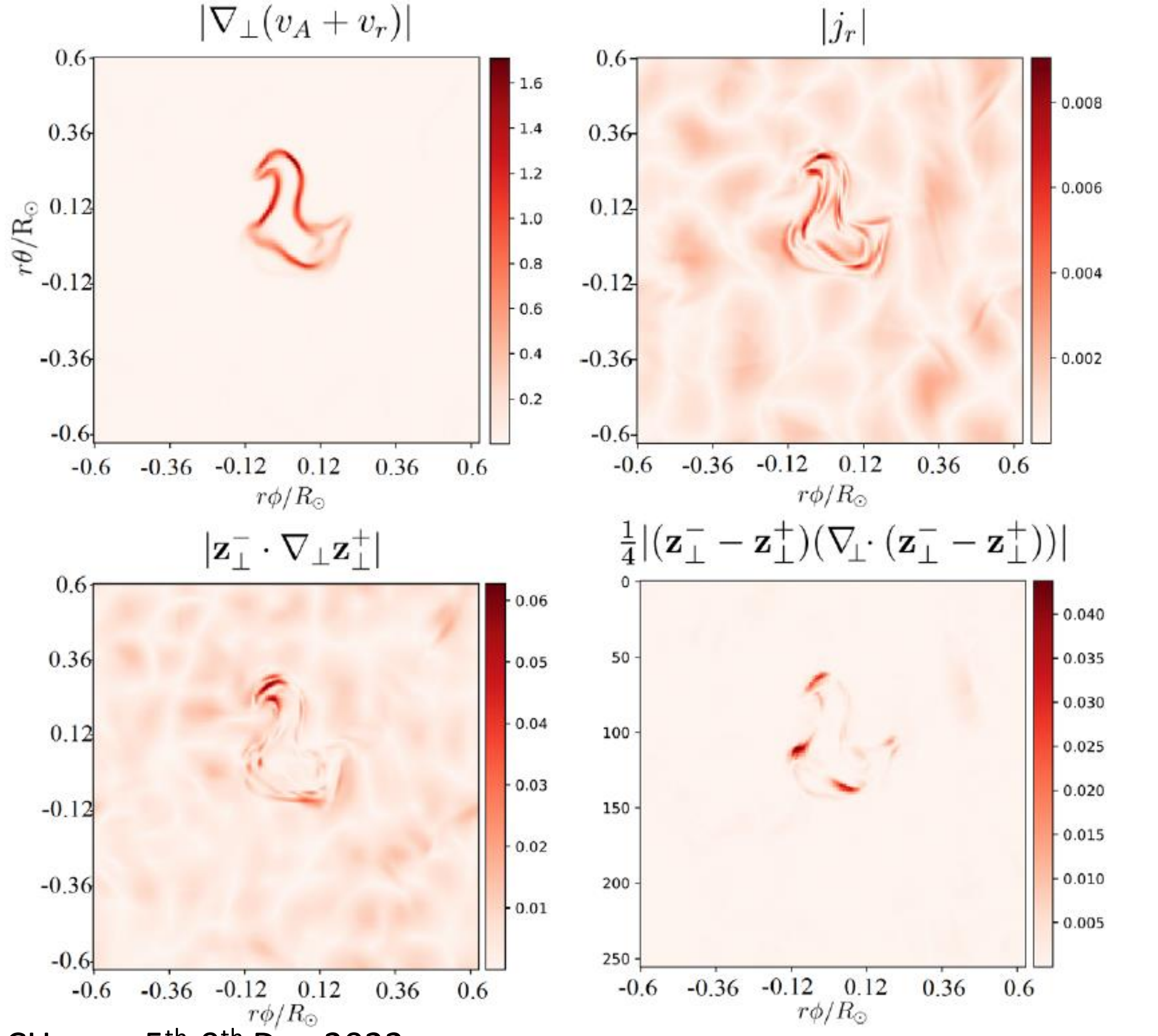


Stochastic wave driver



Bern, CH. 5^{th}-9^{th} Dec 2022

Stochastic wave driver



- Clear correlation of strong currents and nonlinear evolution with density gradient. Alfvén waves in the outer region are also cascading... but at a slower rate.

Conclusions

- Background structuring has a strong effect on the evolution of MHD turbulence in the nascent solar wind, on faster timescales than in the perpendicularly homogeneous case.

- 1/f spectrum may be due to phase mixing of slowly cascading waves.

- Self-cascade of kink waves the dominant nonlinear cascade channel in the pristine solar wind?

- Remaining questions: heating? is the self-cascade identifiable in in-situ data?