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Solar flares and Kelvin-Helmholtz instabilities

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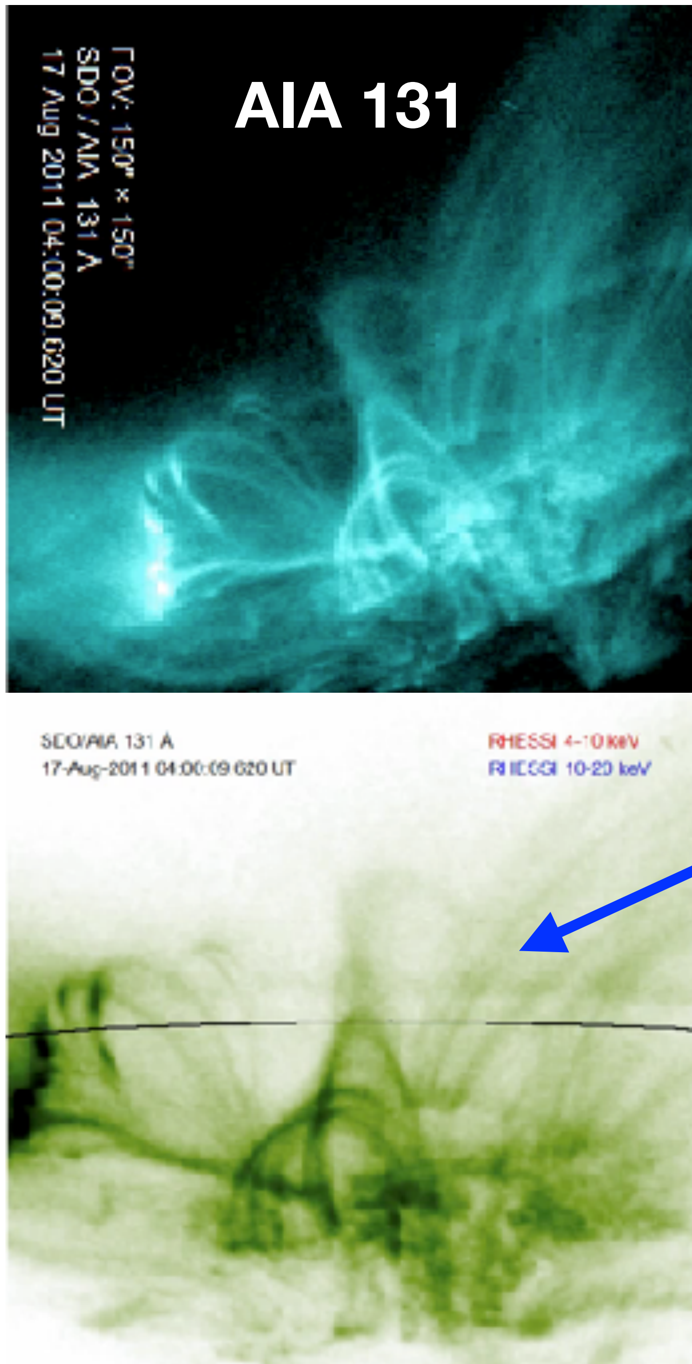
Hard X-ray in solar flares



(From Su et al. 2013)

Flare: impulsive energy release phenomenon in solar atmosphere.
Amount of 10^28 - 10^32 erg magnetic energy is released owing to magnetic reconnection.

Blue contour: Hard X-ray

Part of the flare energy is released via radiation: EUV emission, Soft X-ray, Hard X-ray.

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Hard X-ray & turbulence

Source of Hard X-ray emission:
High energy electrons release their energy via Bremsstrahlung or inverse Compton process

Possible accelerating mechanisms of electrons:

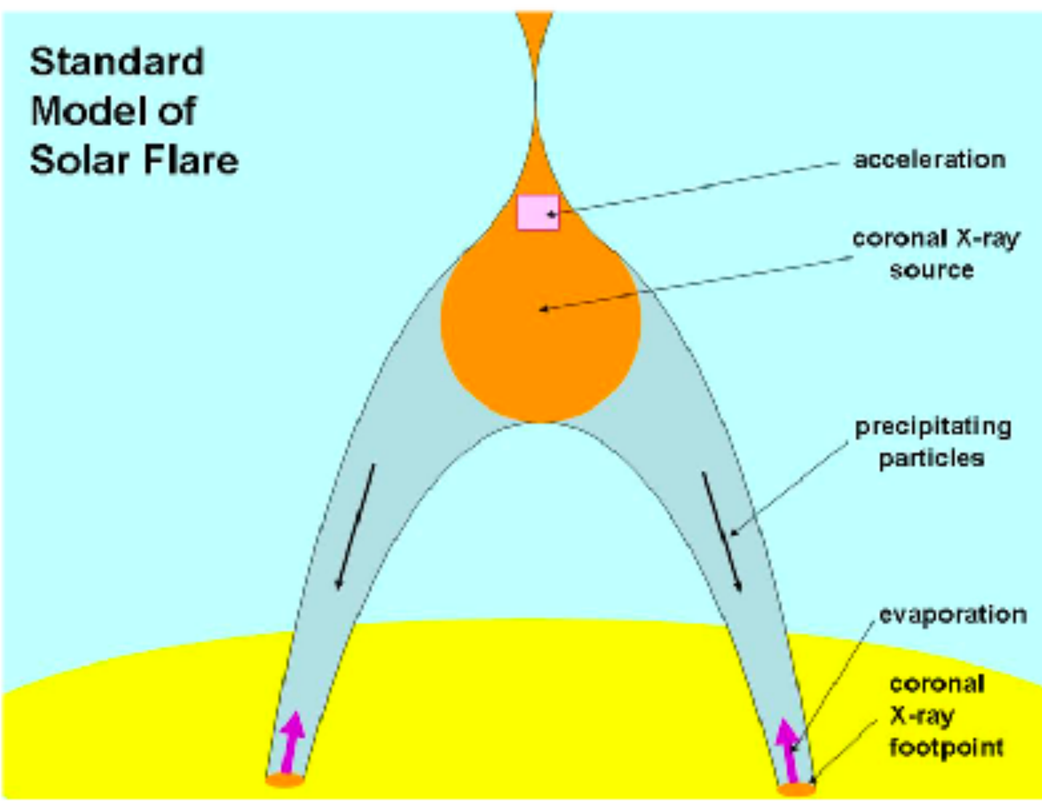
1. **DC field acceleration**
2. **Stochastic acceleration (by turbulences)**
3. **Shock acceleration**

Observations of turbulence in flares:
e.g. Jakimiec et al., (1998); Kontar et al. (2017) …

Question:
Where are the turbulences from?

Turbulence & K-H instability

CSHKP flare model



[Fig from Benz, (2008)]

Fang et al. (2016):
Turbulences are produced by Kelvin-Helmholtz (K-H) instabilities, where K-H instabilities are triggered by high speed evaporation flows.

In our work, we study this idea with the help of numerical simulation. The tigger of K-H instabilities in different condition is also studied.

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Method & Tool

Method: numerical simulation

Tool: MPI-AMRVAC

Governing equations:

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) &= 0, \\
\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v}\boldsymbol{v} + p_{\mathrm{tot}} \boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{\mu_0}\right) &= \rho \boldsymbol{g}, \\
\frac{\partial e}{\partial t} + \nabla \cdot \left(e \boldsymbol{v} + p_{\mathrm{tot}} \boldsymbol{v} - \frac{\boldsymbol{B}\boldsymbol{B}}{\mu_0} \cdot \boldsymbol{v}\right) &= \rho \boldsymbol{g} \cdot \boldsymbol{v} + \nabla \cdot (\boldsymbol{\kappa} \cdot \nabla T) - Q + H, \\
\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v}) &= 0,
\end{aligned}
$$

$$
e = \frac{p}{\gamma - 1} + \frac{\rho v^2}{2} + \frac{B^2}{2\mu_0},
$$

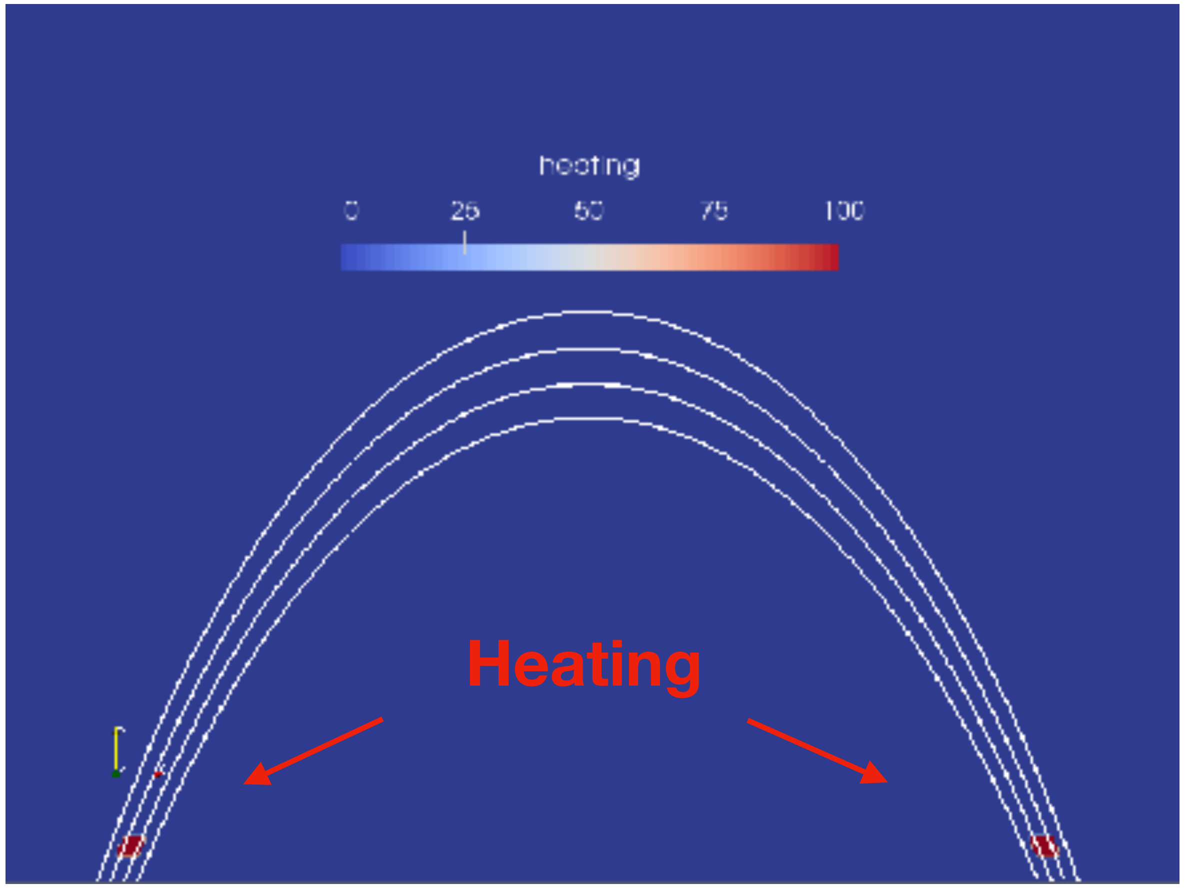
Thermal conduction: $\nabla \cdot (\boldsymbol{\kappa} \cdot \nabla T)$

Heating: H

Gravity: $\rho \boldsymbol{g} \cdot \boldsymbol{v}$

Radiative cooling: Q

Method & Tool

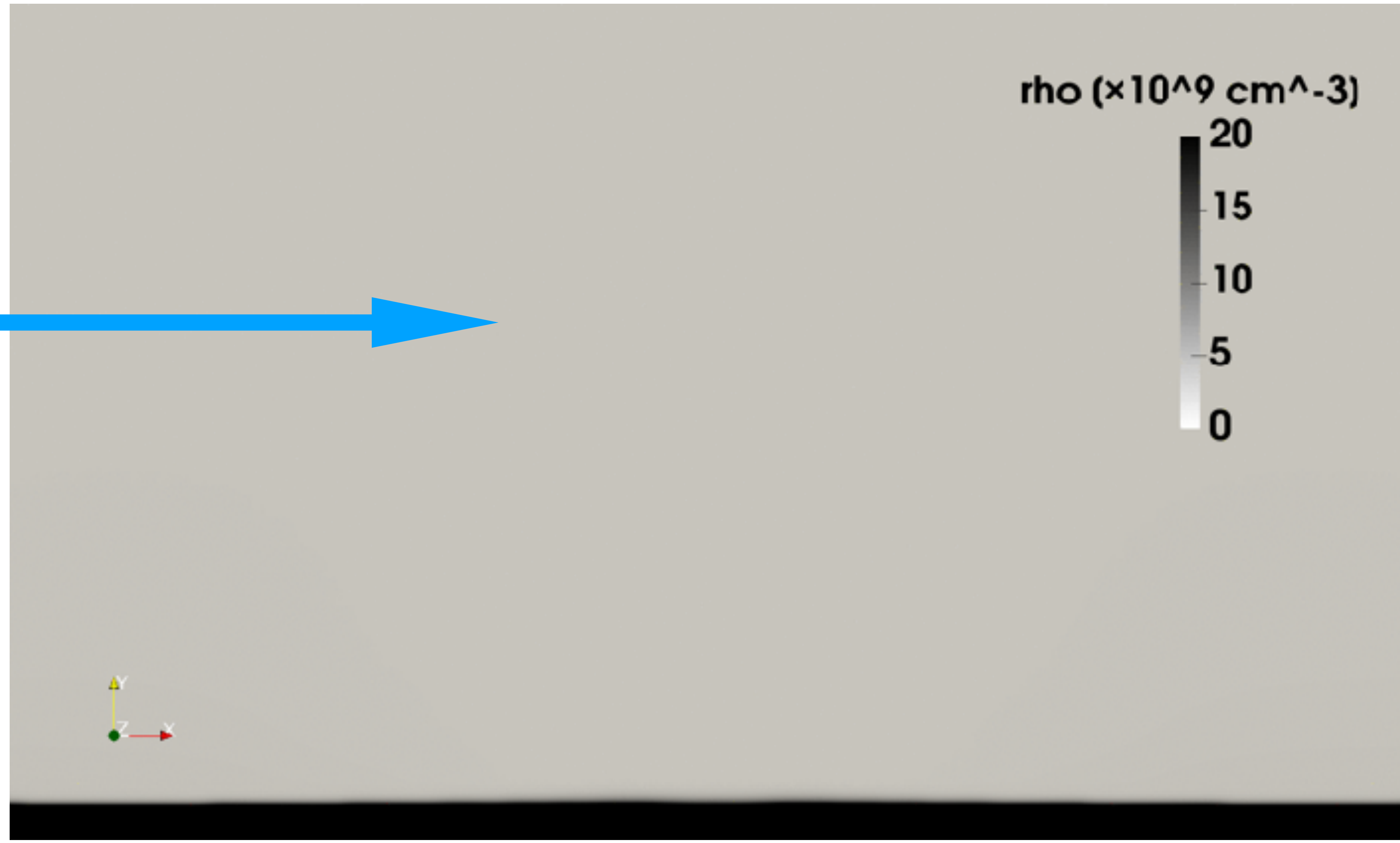


Flare energy is deposited into chromospheric footpoints to trigger evaporation flows.

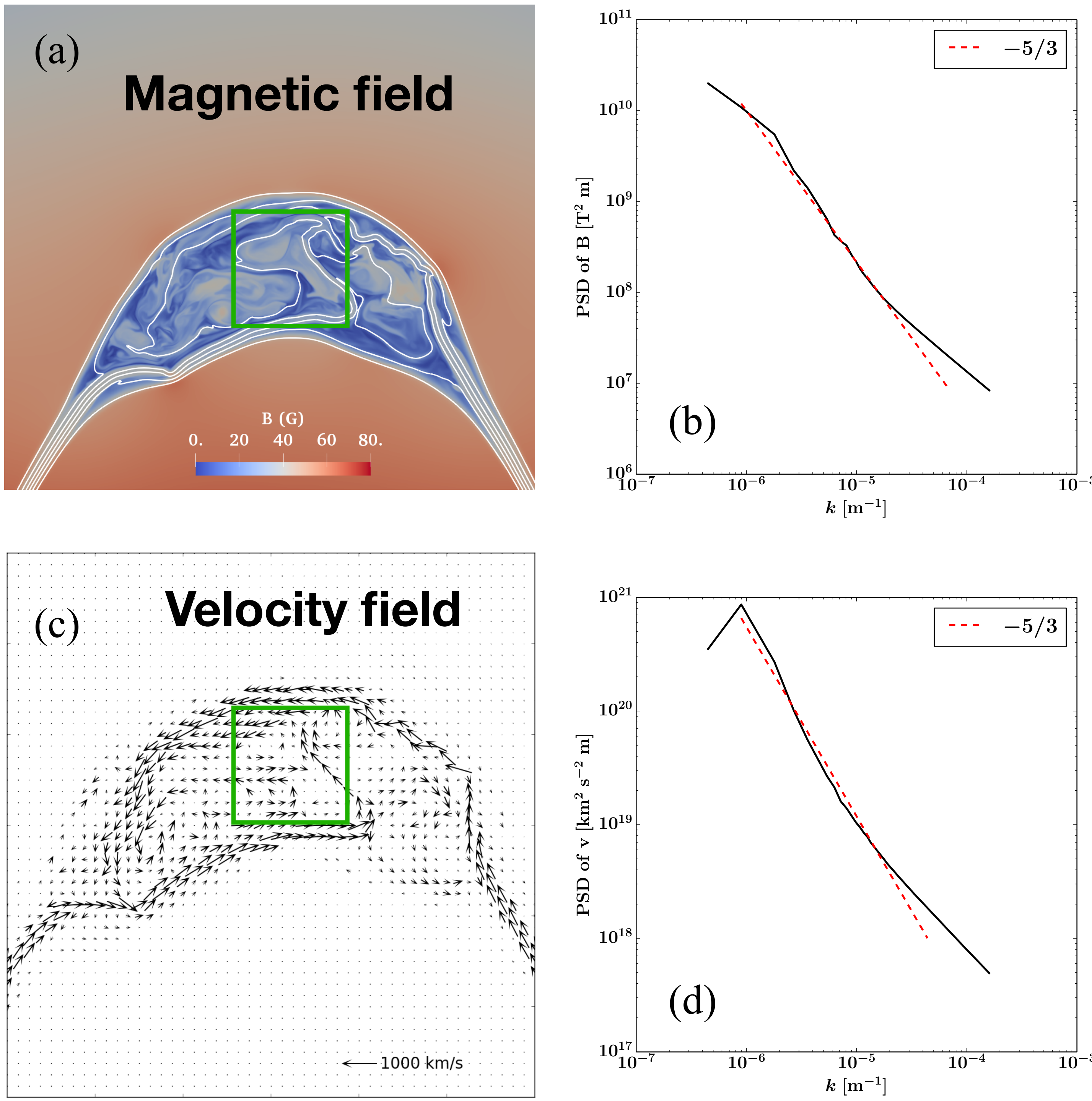
Evolution of flare loop is studied.

Results: evolution of the flare loop

Turbulence is produced via K-H instabilities



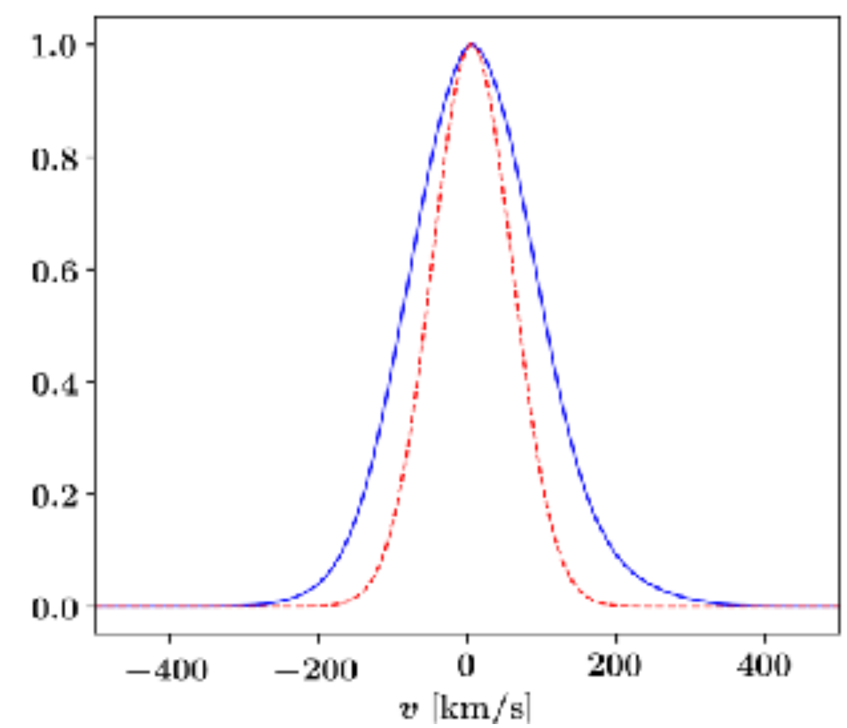
Results: turbulence

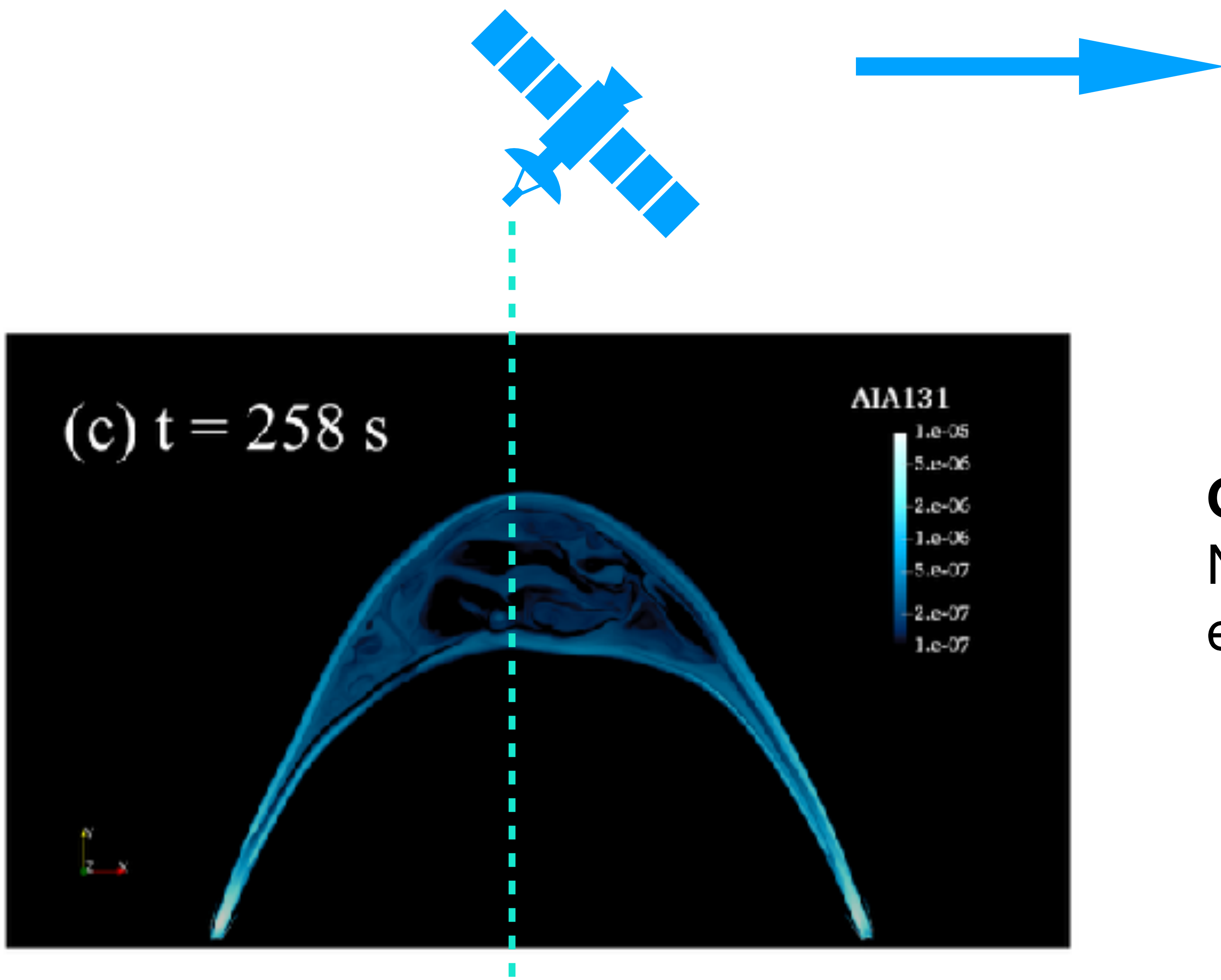


Both magnetic field spectrum and velocity spectrum have an index closed to -5/3

Nonthermal broadening of spectral line

Line width: ~ 120 km/s
Thermal width: ~ 80 km/s
Nonthermal width: ~ 90 km/s





Observation of turbulence in flares:
Nonthermal width ~ 80km/s in Kontar et al. (2017)

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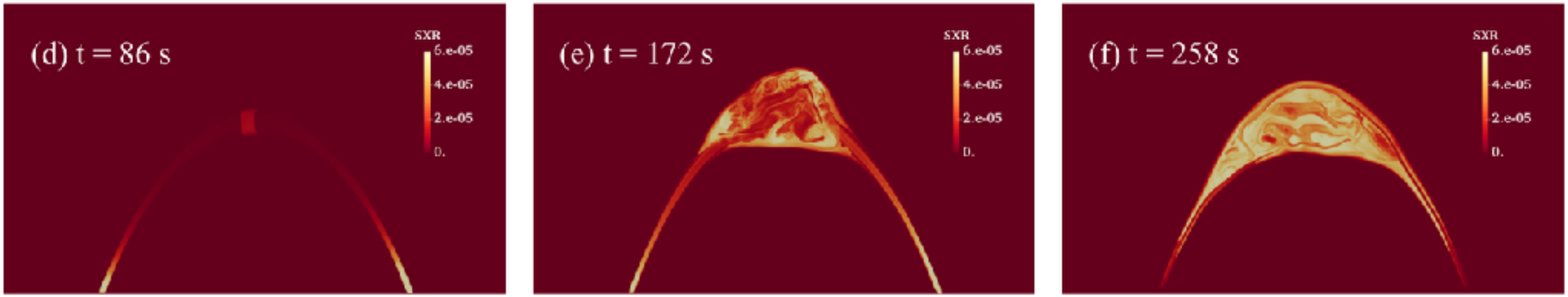
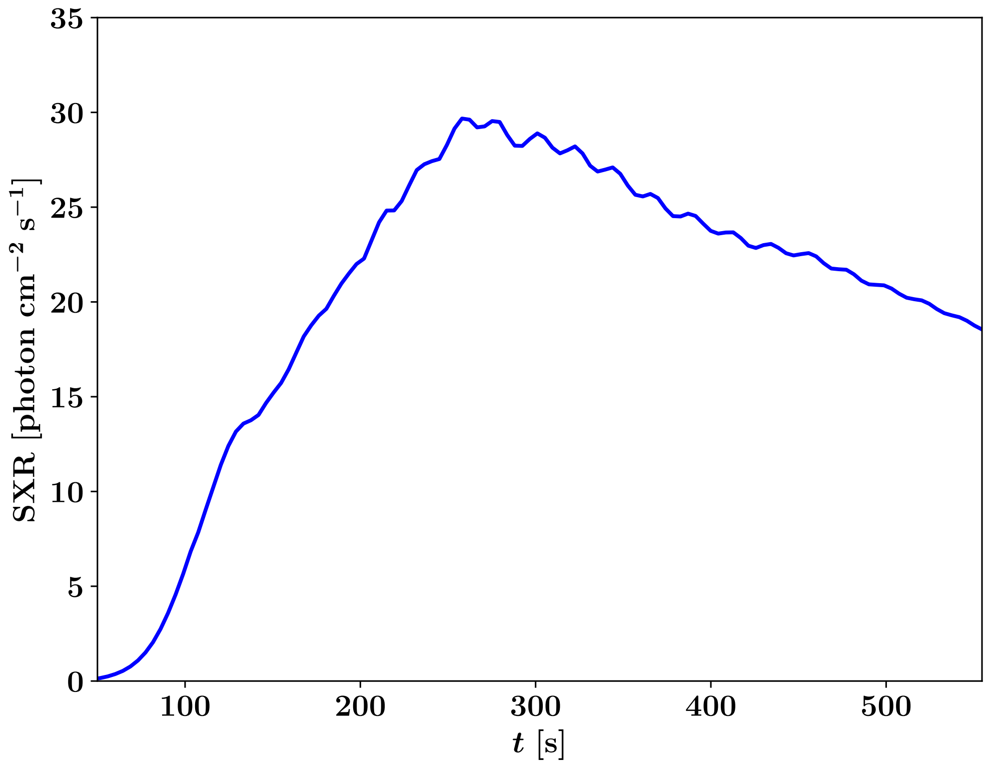
Thermal Soft X-ray emission





Periodic oscillations with period of ~ 25 s can be found in the total flux.
Similar oscillations see Tian et al. (2016)

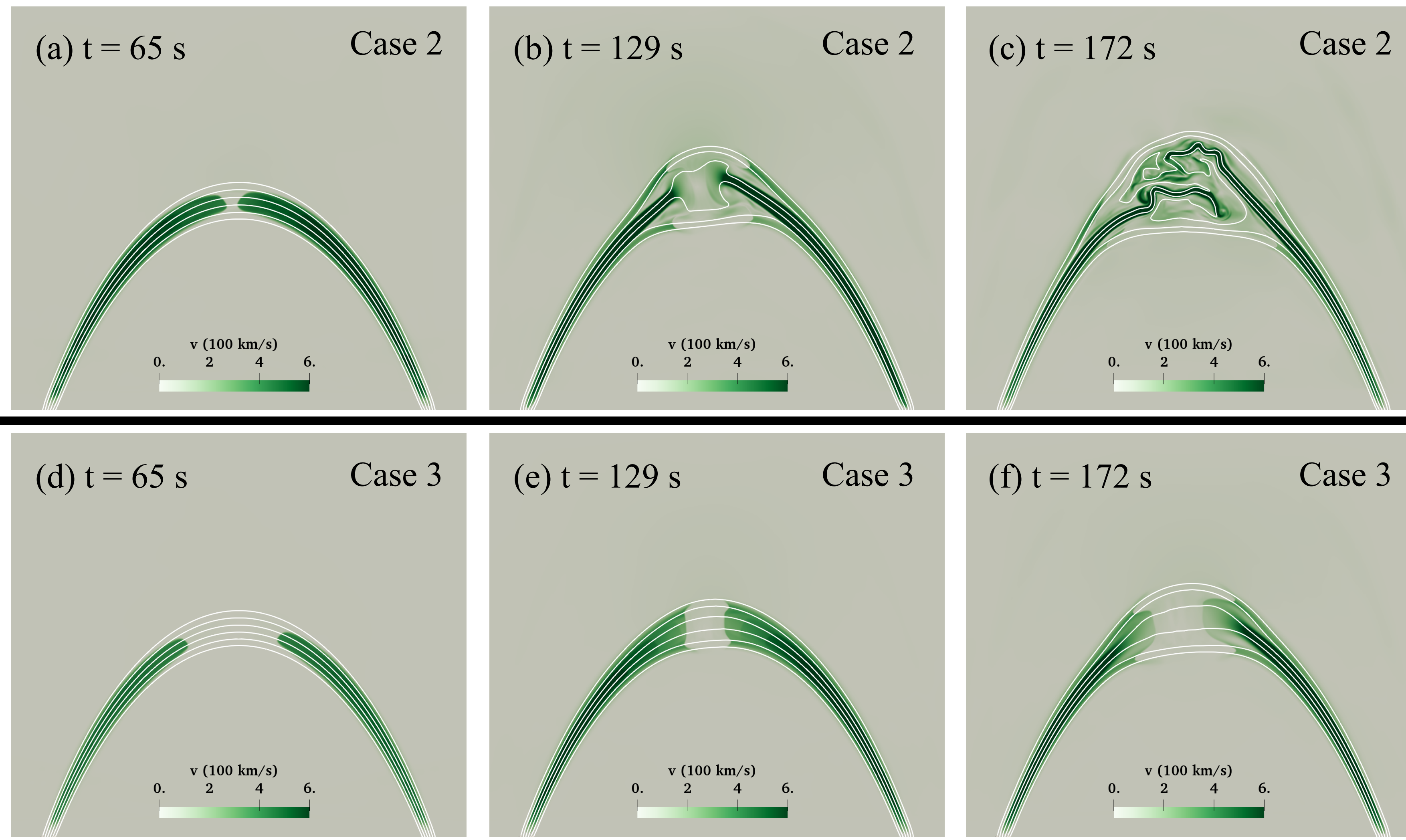
Standing fast sausage wave?

Survey: impulsive heating vs gradual heating

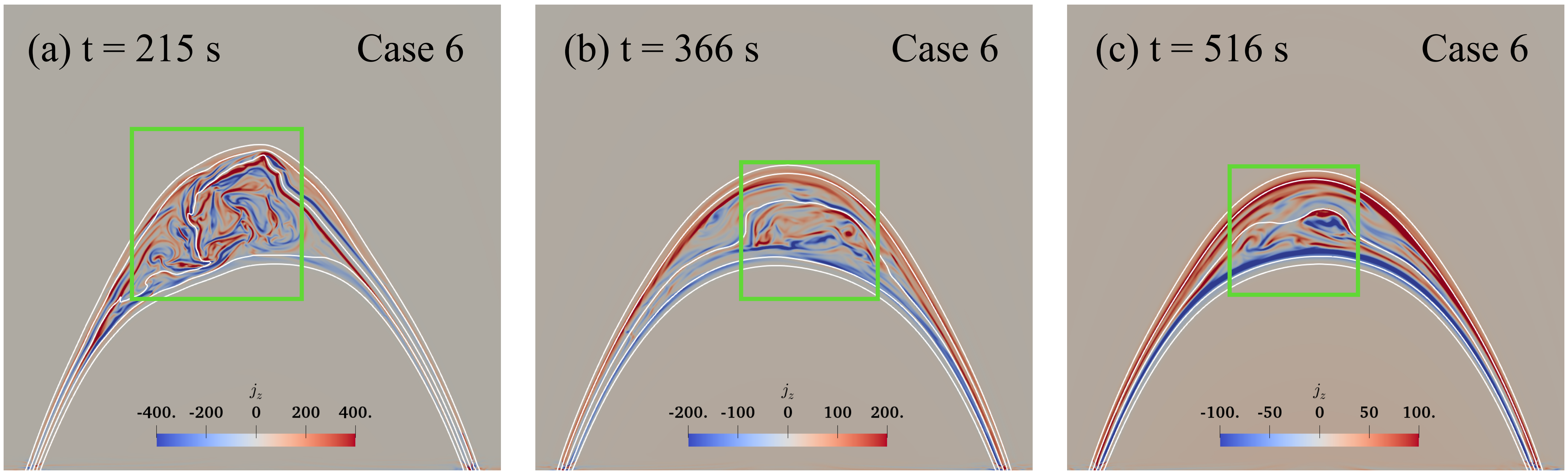
More impulsive heating:
Flare energy is deposited in 4 minutes

Less impulsive heating:
Flare energy is deposited in 6 minutes

Velocity



Survey: asymmetric heating



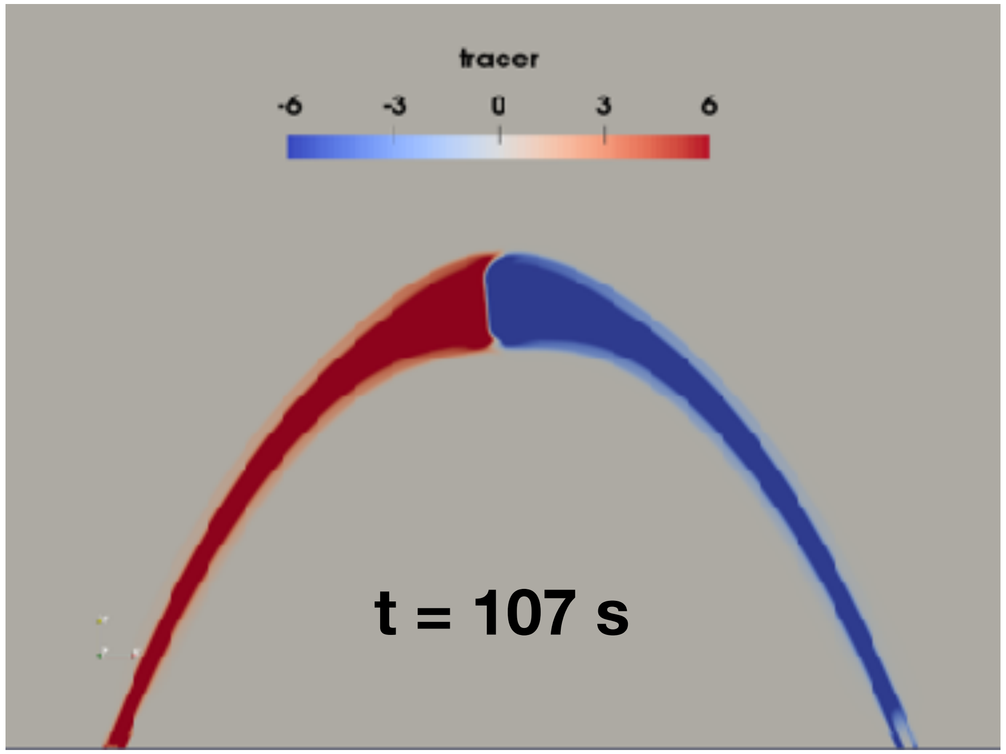
30% of the flare energy is deposited into the left footpoint, 70% is deposited into the right footpoint.

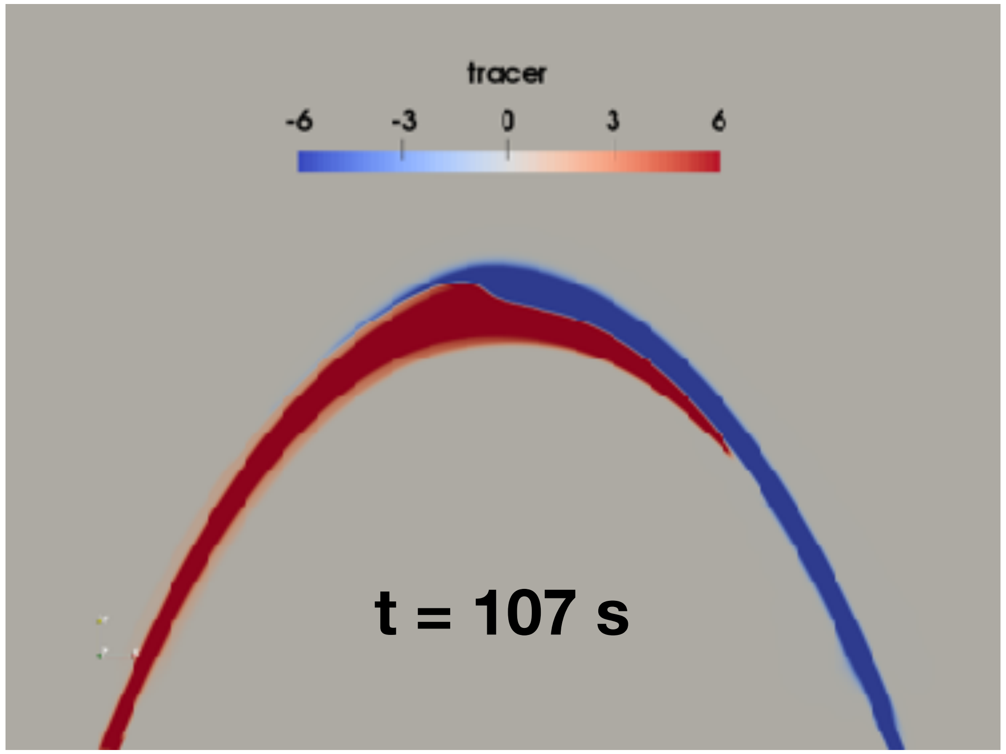
Turbulence is produced in the left of the apex.

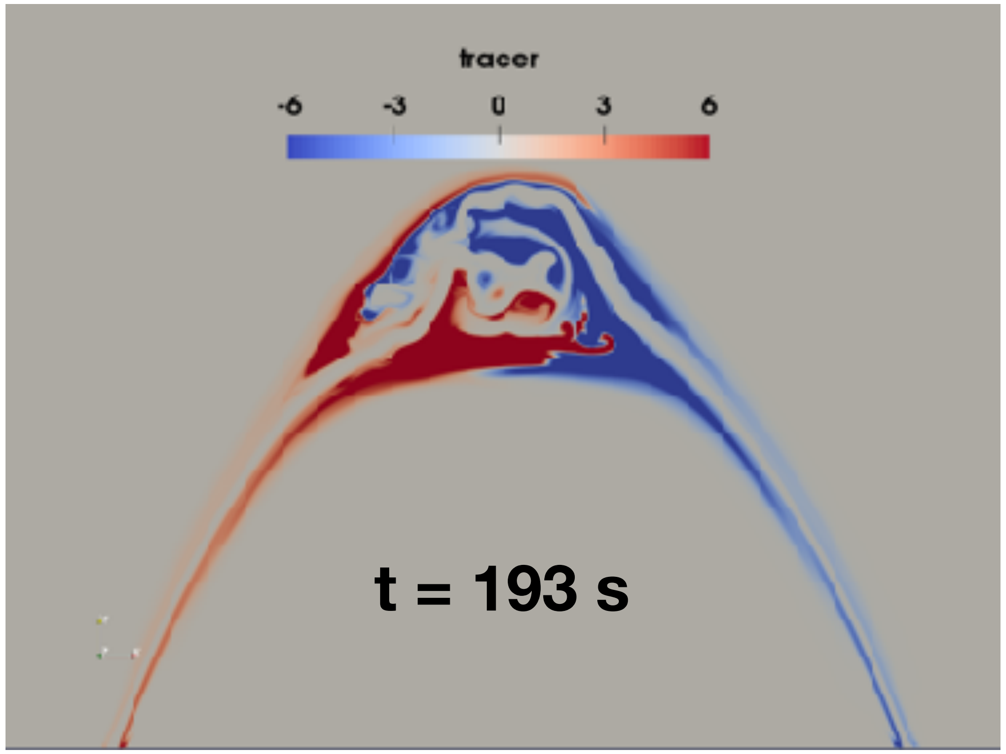
Turbulence region move periodically owing to slow mode wave.

Survey: collision vs shear

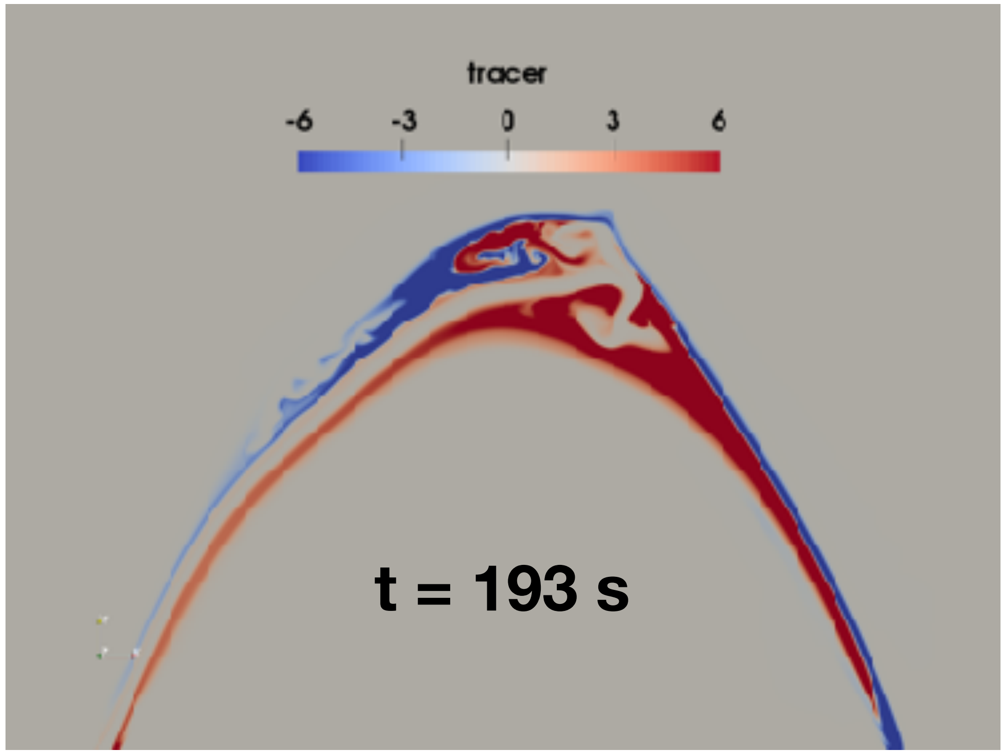
Collision | Shear







Both of them have turbulence



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Conclusions

- In our simulation, turbulence is produced because of K-H instability.
- The turbulence has a spectral index of -5/3 and leads to a non-thermal broadening of emission lines like AIA 131 line.
- Standing sausage wave is found in the flare loop.
- K-H instability is easier to be triggered when the energy deposition is impulsive.
- The location where turbulence is produced is influence by the symmetry of footpoint heating.
- K-H instability can be triggered when the evaporation flows shear/collide with each other.

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Thank you for your attention!