Solar spicules in MHD simulations and insights from fluid jets in laboratory

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Nature Physics 18, 595–600 (2022)

1. Motivation

Solar spicules are plasma jets, observed in the interface region between the visible solar surface and the hot corona[Beckers 1972]. Several formation mechanisms (e.g., **solar global acoustic waves, shocks, magnetic reconnection**) are proposed, but they are not able to quantitatively match both the heights and abundance of the observed solar spicules.

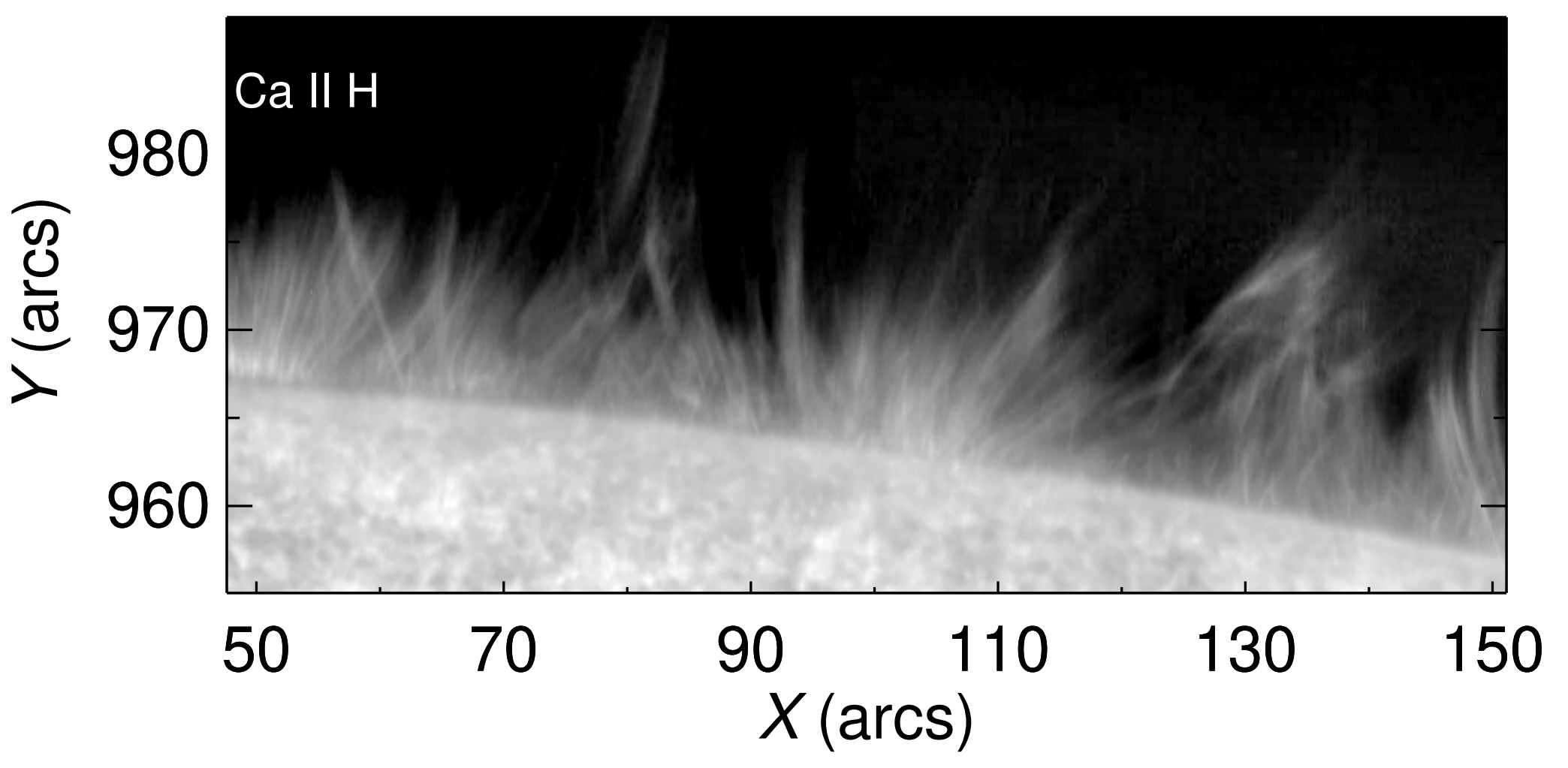


Fig 1: Observed solar jets from Solar Optical Telescope on board of the Hinode spacecraft.

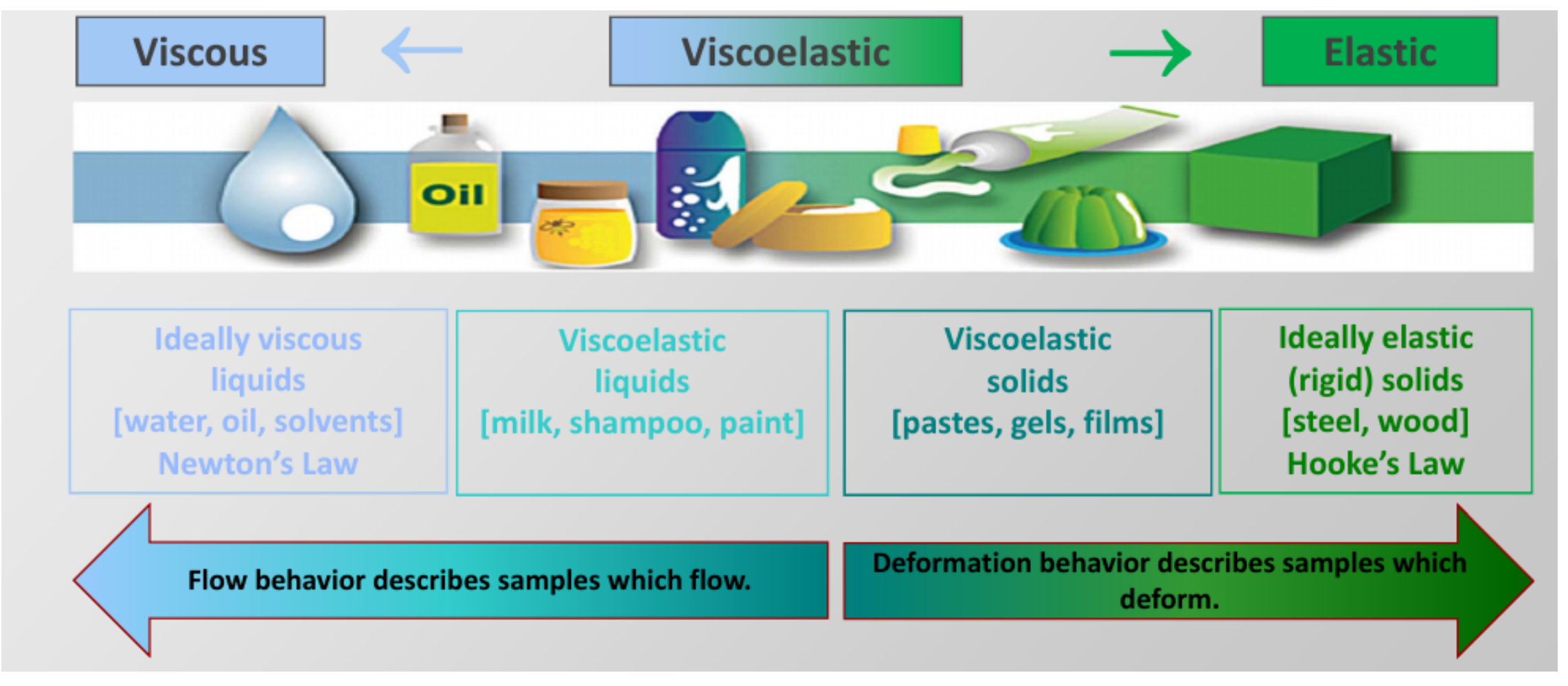
2. Simulation and experiment setup

Radiative MHD simulations using the PENCIL CODE [**Brandenburg et al. 2020**]. Two set-ups with a uniform grid spacing of 16 km and extending from solar sub-surface to corona– (i) sinusoidal driving like solar *p*-mode at the photosphere and, (ii) by self consistently excited solar convection[**Dey et al. 2022**]in presence of a uniform vertical magnetic field.

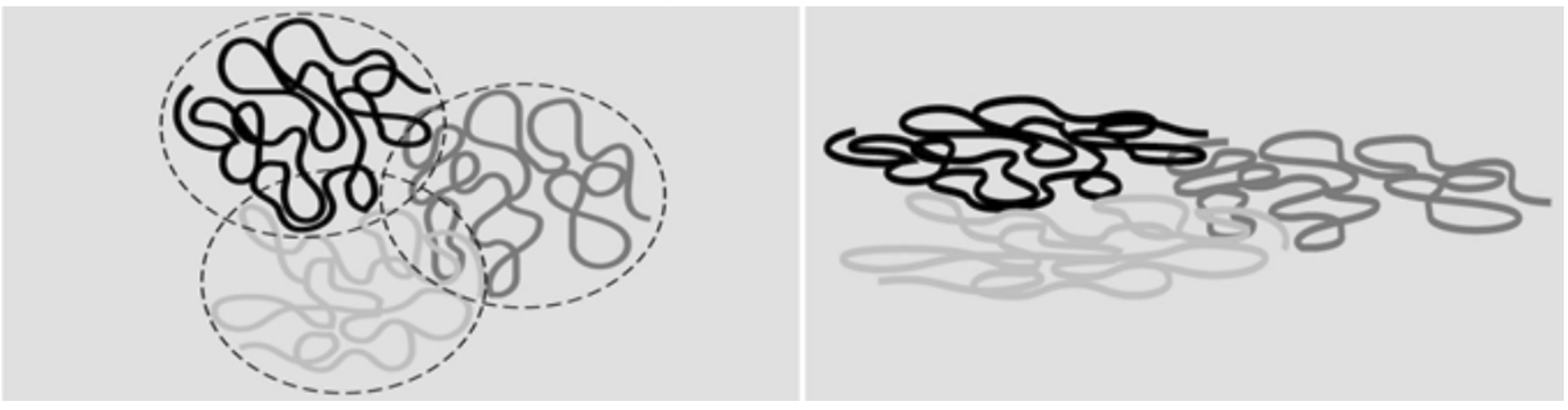
Assumptions: (a) Semi-relativistic Boris correction, (b) LTE radiative transfer, (c) Anisotropic heat conduction[**Chatterjee 2020**].

Laboratory experiments: Newtonian fluids: water, glycerin, and visco-elastic polymers: Polyethylene oxide(PEO), Poly vinyl alcohol(PVA) solutions are subjected to quasi-periodic vibrations by a sub-woofer speaker, known as Faraday excitation [**Faraday 1831**]

3. A quick look into polymer fluids

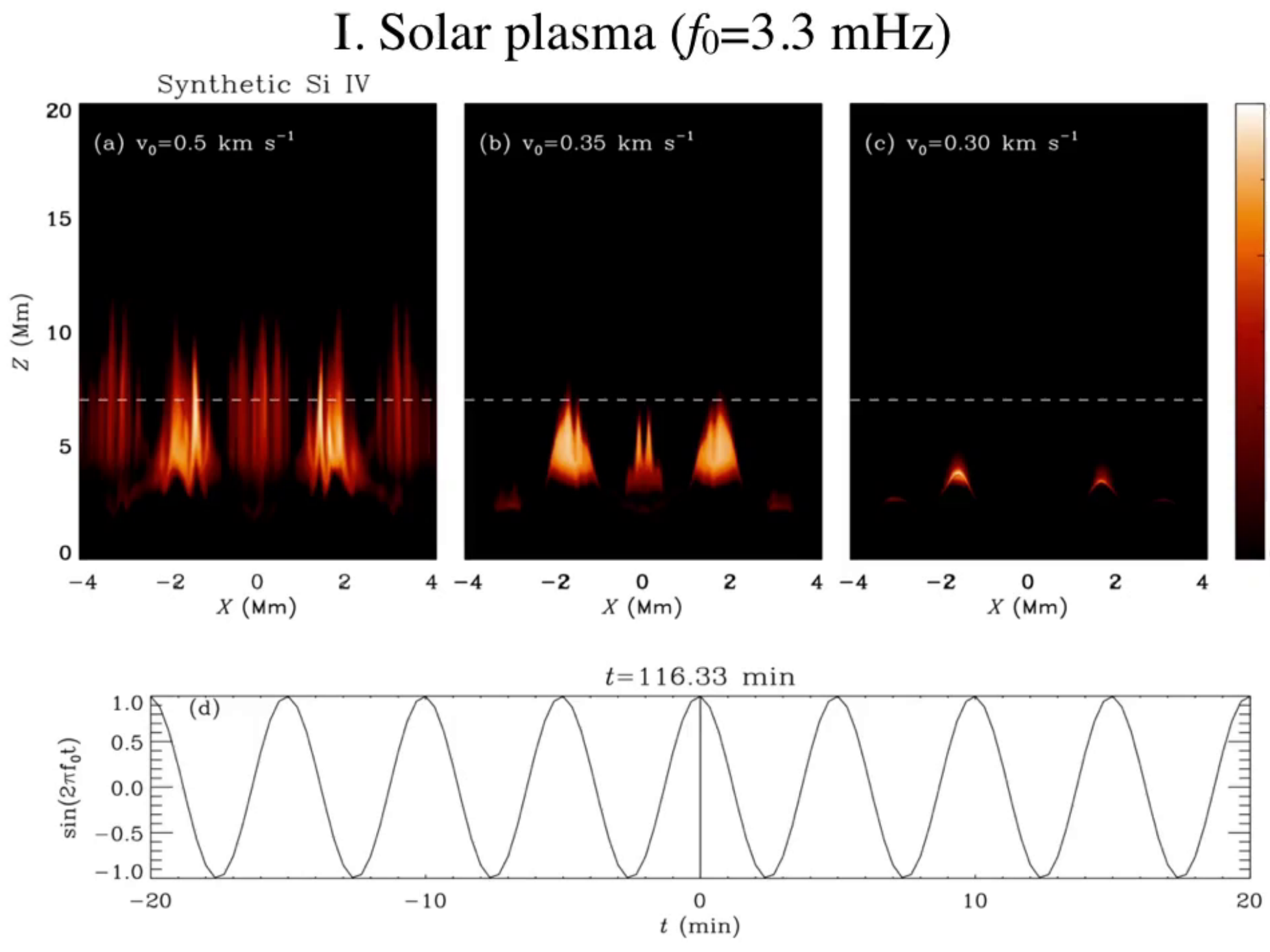


Polymeric solutions consist of long chains of monomer molecules. Uncoiling chains under shear **back reacts** on the fluid flow, similar to the **tension** of magnetic fields acting on the plasma flow.

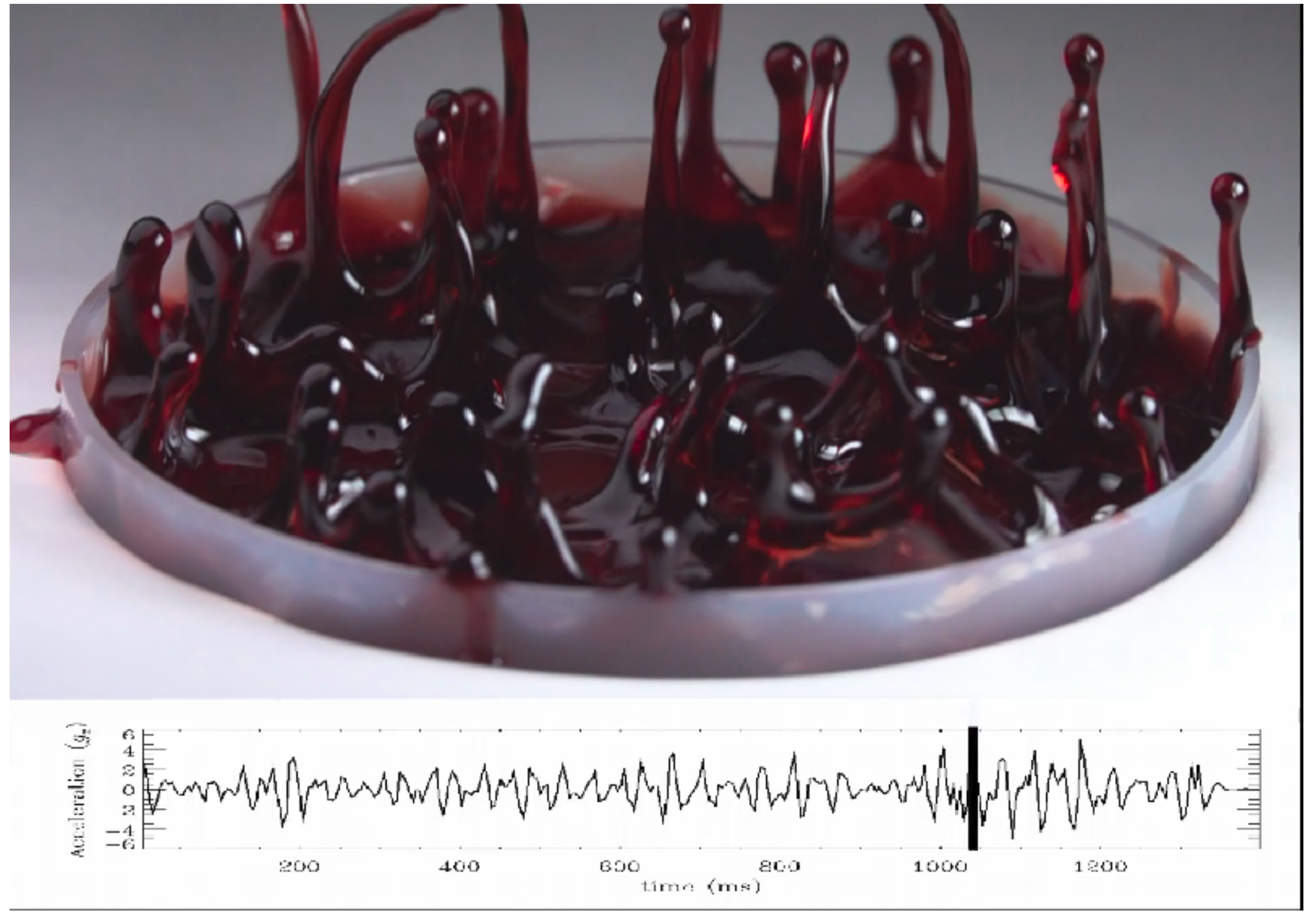


4. Forest of jets and the parallel between Maxwell and Viscoelastic stresses

Driving acceleration decreases ⟶



Polymer fluid jets subjected to 10,000× sped up p-mode (SOHO/MDI) oscillation



$$\frac{\partial \boldsymbol{T}_\mathrm{m}}{\partial t} + \boldsymbol{U}\cdot\nabla\boldsymbol{T}_\mathrm{m} - (\nabla\boldsymbol{U})^\mathrm{T}\cdot\boldsymbol{T}_\mathrm{m} - \boldsymbol{T}_\mathrm{m}\cdot\nabla\boldsymbol{U} = \frac{\eta}{\mu_0}[\boldsymbol{B}\nabla^2\boldsymbol{B} + (\nabla^2\boldsymbol{B})\boldsymbol{B}].$$

$$\frac{\partial \boldsymbol{T}_\mathrm{p}}{\partial t} + \boldsymbol{U}\cdot\nabla\boldsymbol{T}_\mathrm{p} - (\nabla\boldsymbol{U})^\mathrm{T}\cdot\boldsymbol{T}_\mathrm{p} - \boldsymbol{T}_\mathrm{p}\cdot\nabla\boldsymbol{U} = -\frac{1}{\tau}\left(\boldsymbol{T}_\mathrm{p} - \frac{\mu_\mathrm{p}}{\tau}\boldsymbol{1}\right),$$

T_m : magnetic stress, η : magnetic diffusivity

T_p : polymeric stress, τ : relaxation time

Under diffusivity, $\eta \to 0$ and relaxation time, $\tau \to \infty$ approximation, the governing equations in MHD and Oldroyd-B model for dilute polymer (where chain-chain interaction is negligible) [**Ogilvie & Proctor 2003**] become equivalent.

5. A threshold driving acceleration

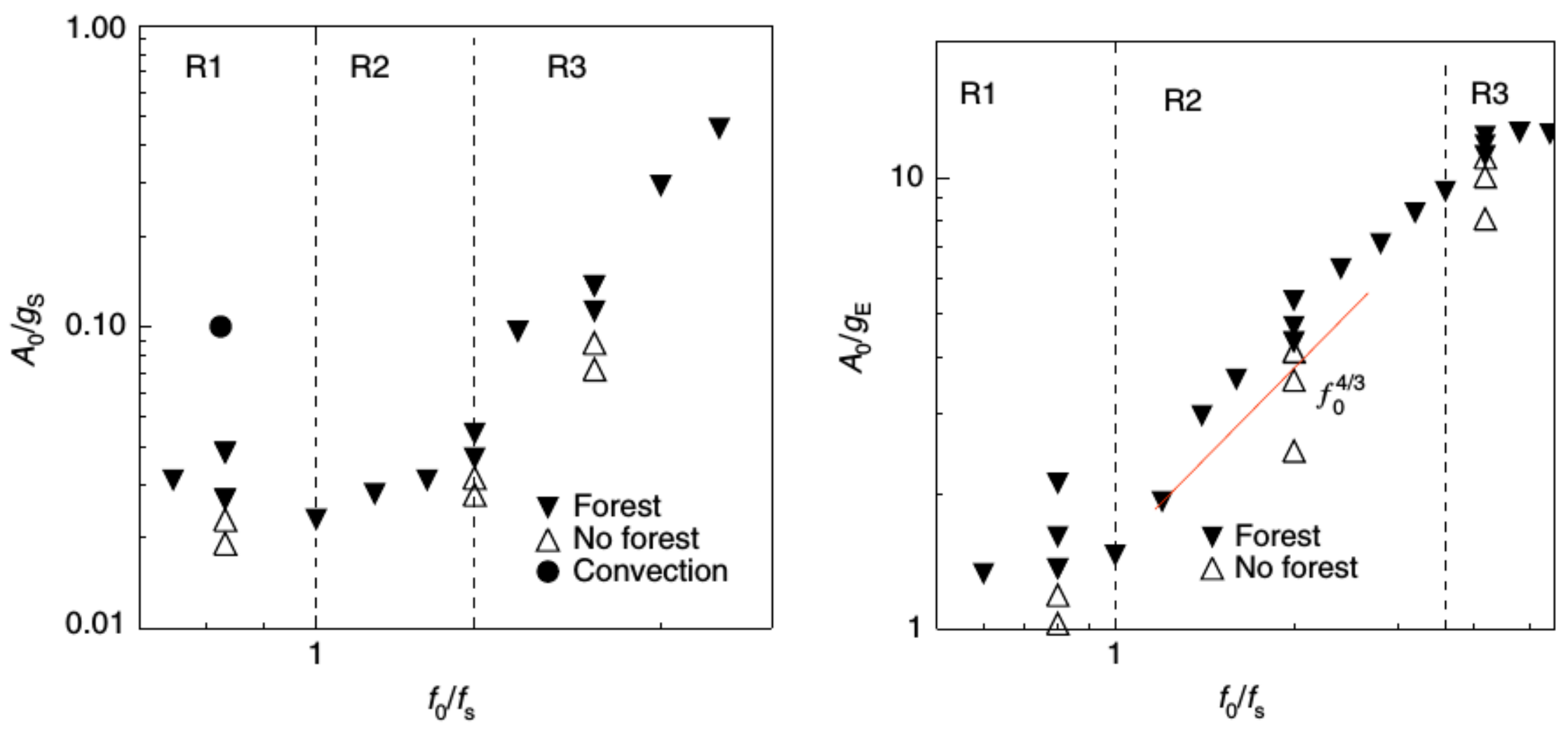


Fig. 2: A phase plot of driving acceleration A_0 vs frequency, f_0 to determine the **threshold acceleration**, A_{min} for both the plasma (left) and polymeric fluid (right) systems. Any simulation with given A_0 and f_0 either produces a forest of jets (filled triangles) when above a threshold or does not (open triangles). The behaviour of the A_0–f_0 curve in region R2 is similar in both mediums.

6. Role of anisotropy to drive jets and quantification of associated turbulence suppression

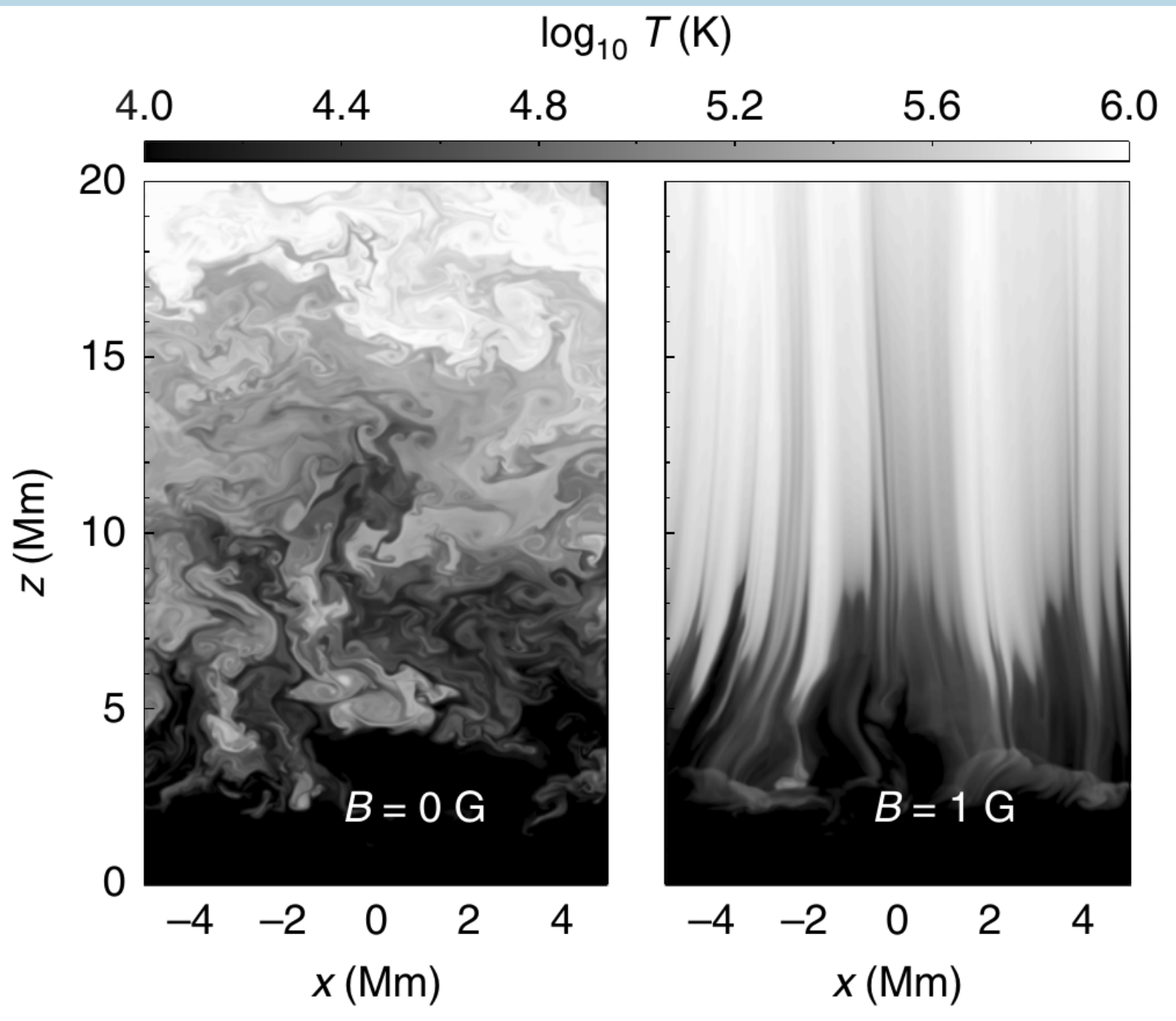
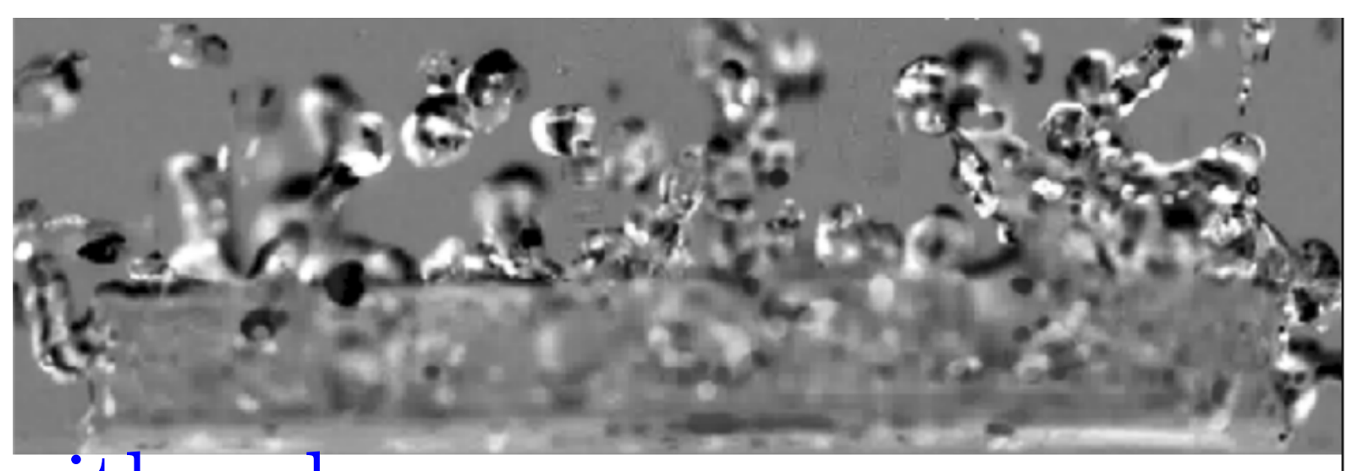


Fig. 3a: Magnetic fields collimate plasma into jet structures via the Maxwell stress, suppressing the Kelvin Helmholtz instability.

without polymer (water)



with polymer

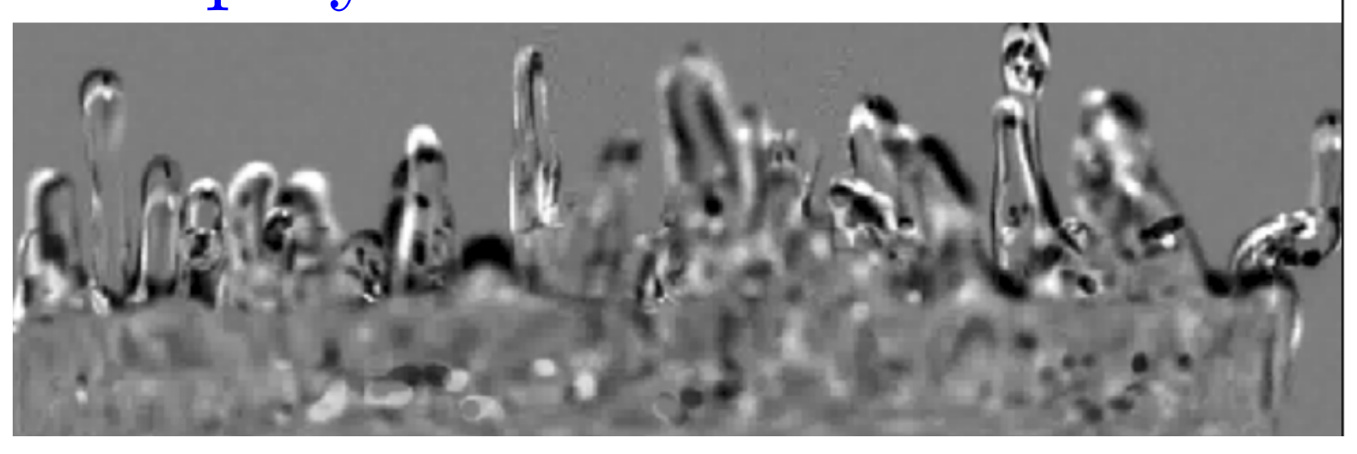


Fig. 3b: The uncoiling polymer chains suppress droplet splashing (Plateau–Rayleigh instability) in fluid by absorbing turbulent energy from flow.

coherency of jet formation increases ⟶

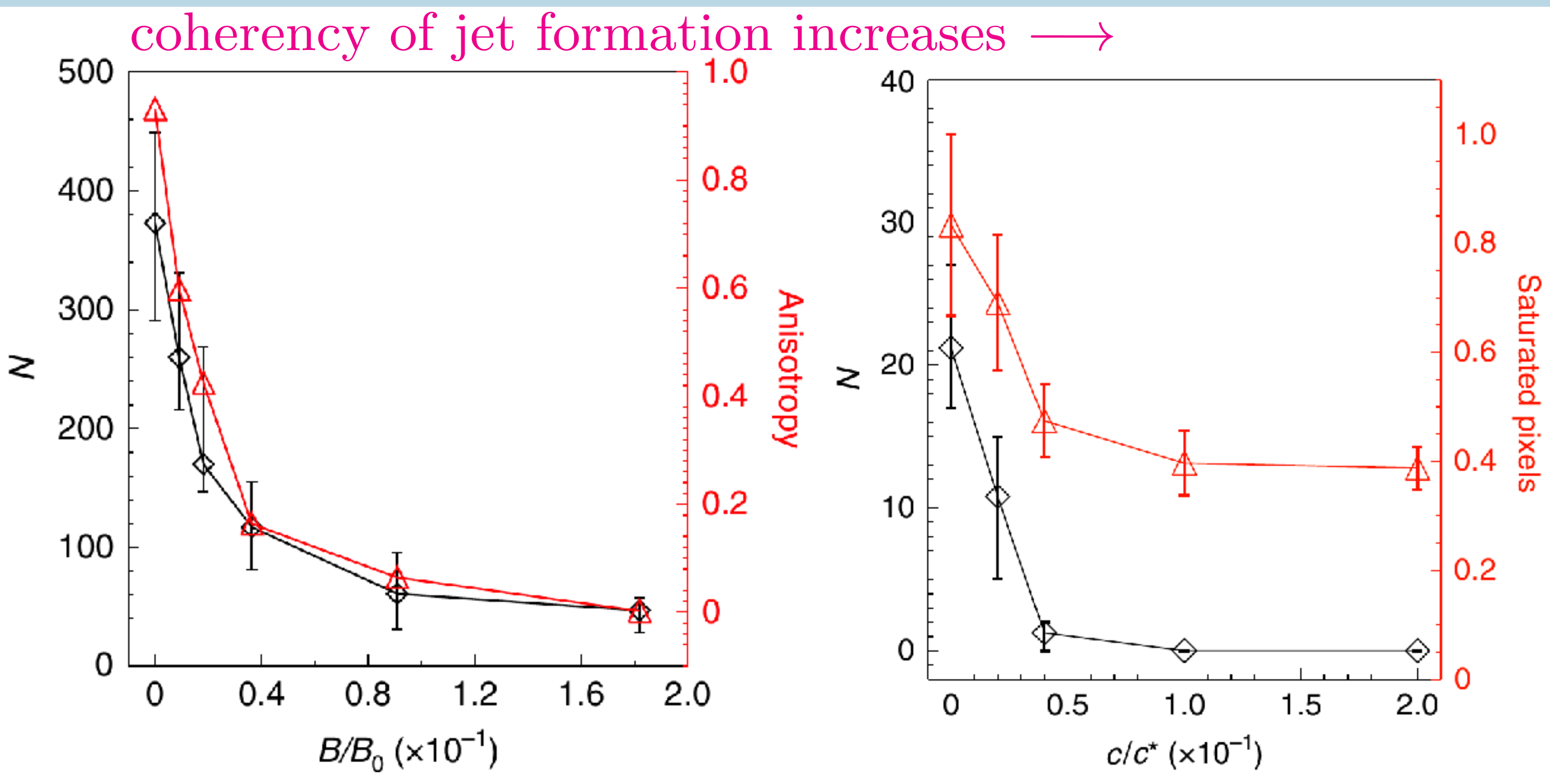


Fig. 4: Quantifying the effect of the imposed **magnetic field** on the anisotropy by measuring the number of vortices, N (left),and effect of polymer **concentration** on number of fluid droplet ejections, N (right).

7. Synthetic intensity of forest of spicules from convection simulation

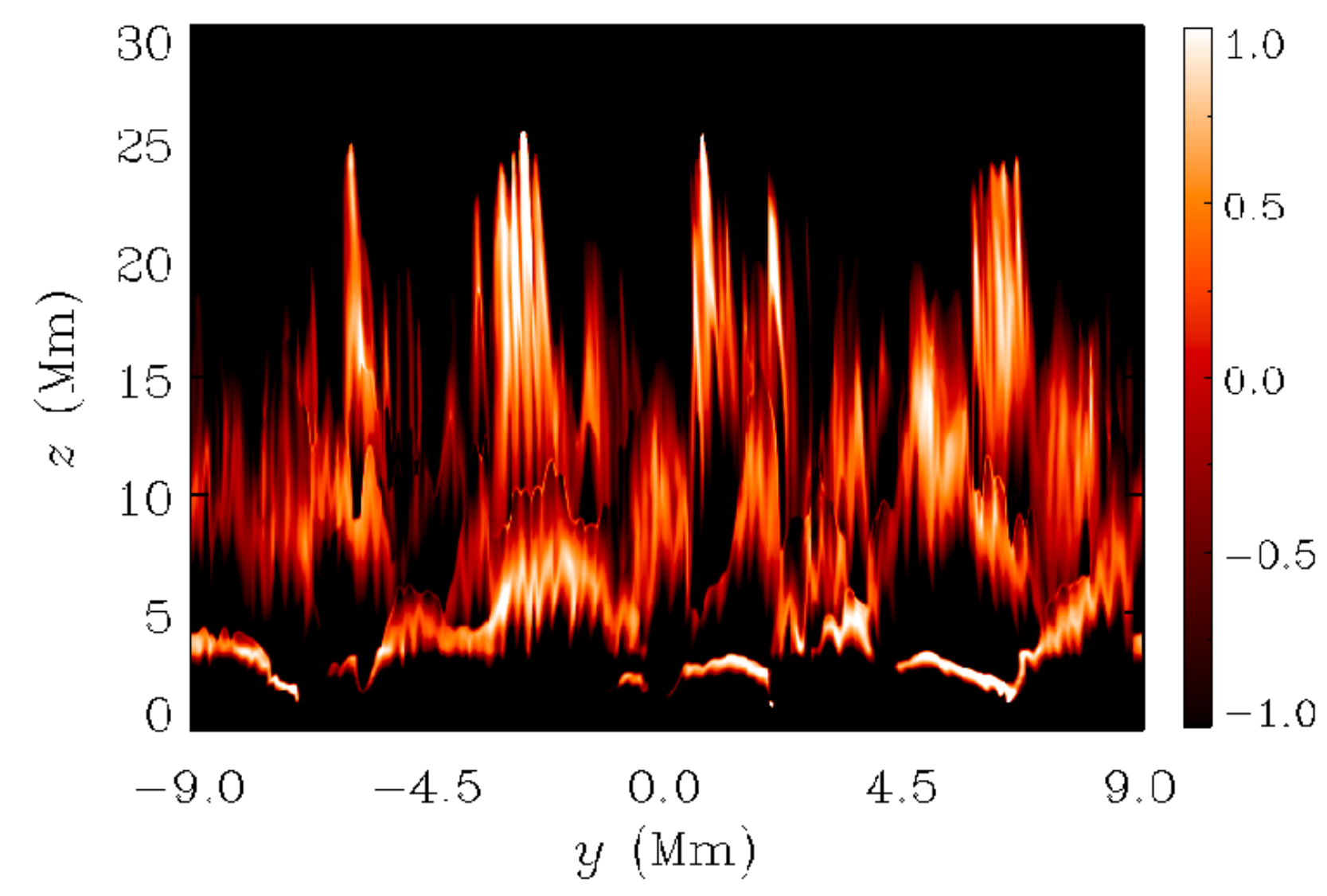
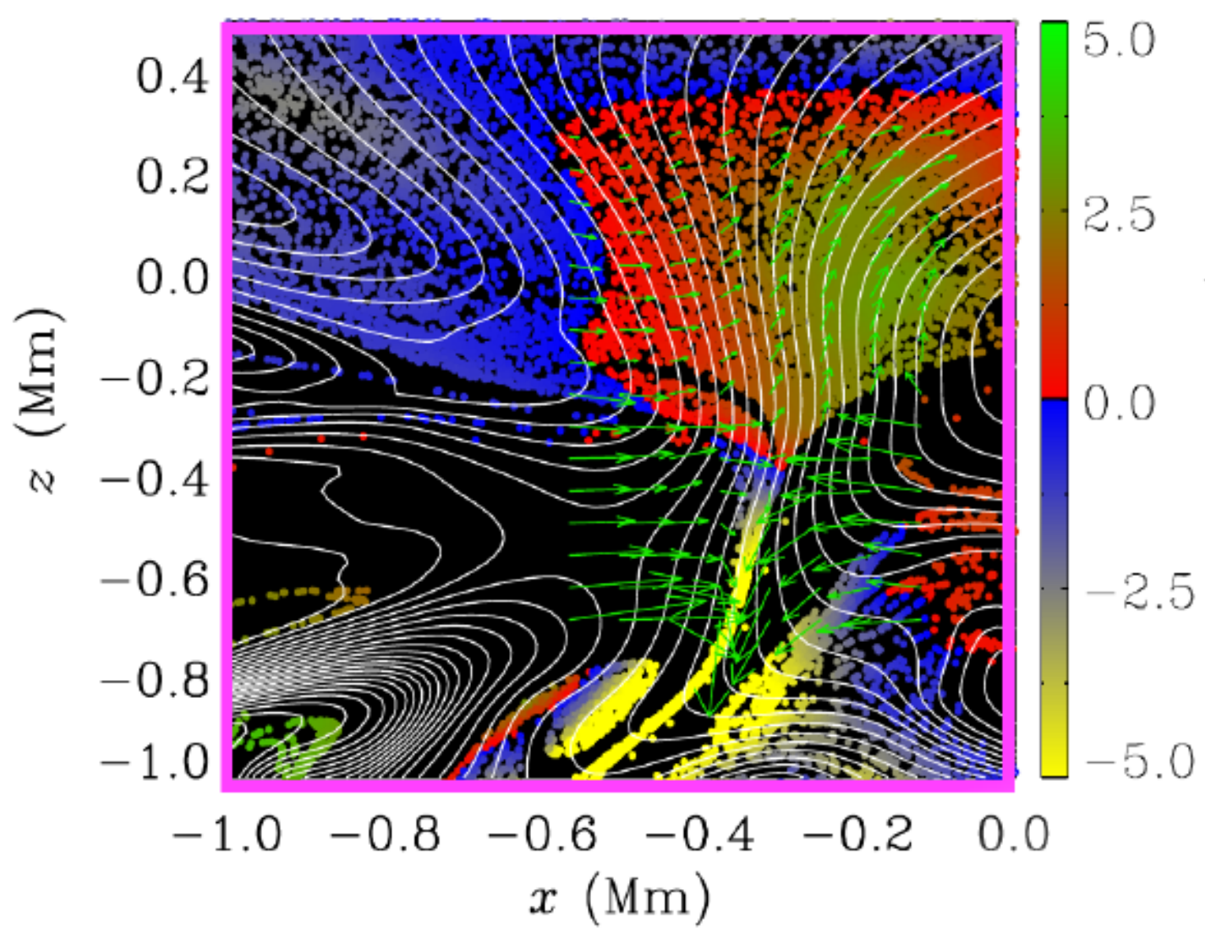


Fig. 5a: Spicules at the limb position folded with Si IV filter (plasma at T = 8 × 10^4 K) and **solar-like convection**(without any external periodic forcing).



white line: magnetic field lines

green arrow: velocity field

Fig. 5b: Formation of spicules by **squeezing a fluxtube** at the two neighbouring granules (analysis by **Lagrangian tracer particles**).

8. Key results

- Four criteria to excite a forest of jets in disparate systems: (a) fluid medium (b) gravity (c) large-amplitude quasi-periodic driving (d) anisotropy of the medium
- We find a forest of spicules in the convection simulation, bearing substantially resemblance to observed solar clusters of jets (**Fig. 5a**)
- Generation of solar jets by (1) collapse of granules and (2) global modes (3) aided by magnetic reconnection processes are triggered by the same agent, solar convection