Development of turbulence in a dusty plasma

Mierk Schwabe, Sergey Zhdanov, Christoph Räth

German Aerospace Center (DLR)

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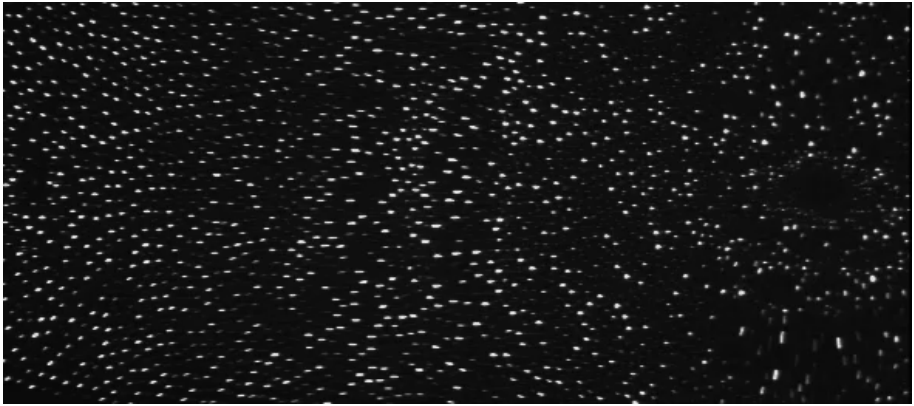

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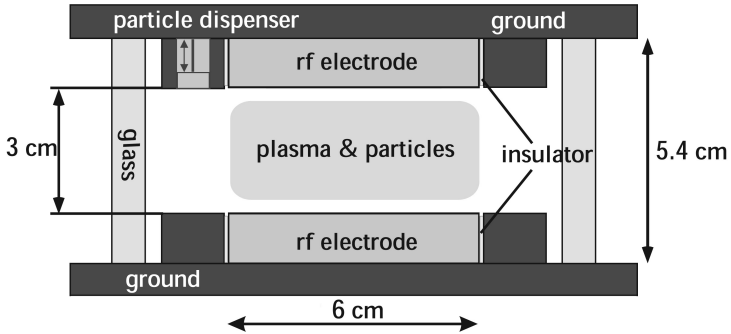
We performed experiments in the PK-3 Plus Laboratory on the ISS.



capacitively coupled plasma chamber

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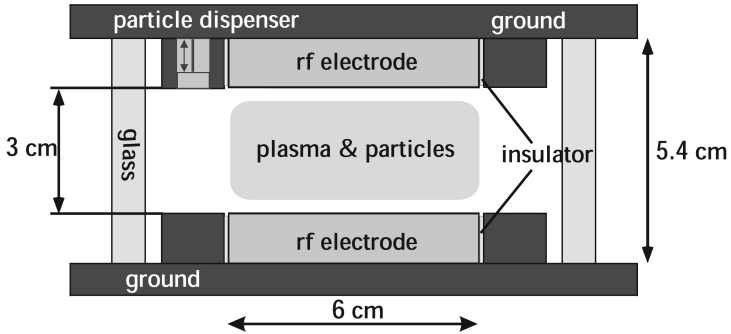

RF voltage on electrodes

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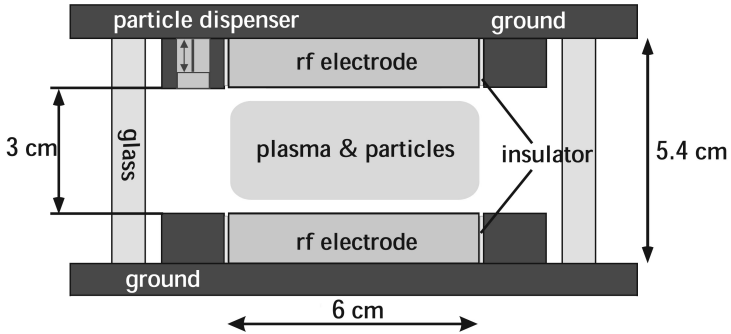

inject microparticles via dispensers

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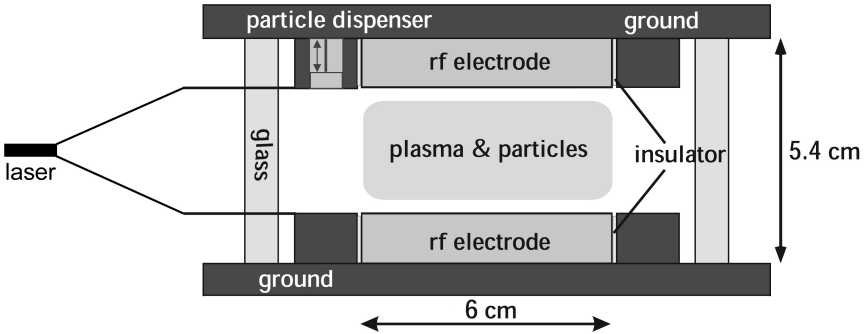
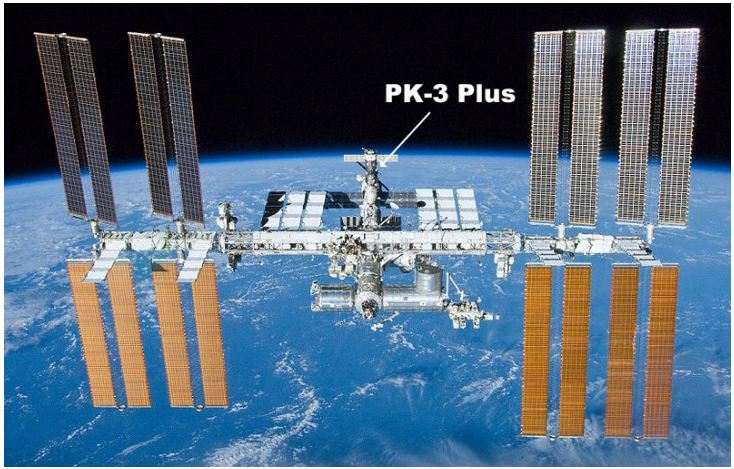


illuminate with laser from the side, trace particles

The PK-3 Plus Laboratory was hosted on the ISS from 2005 – 2014.



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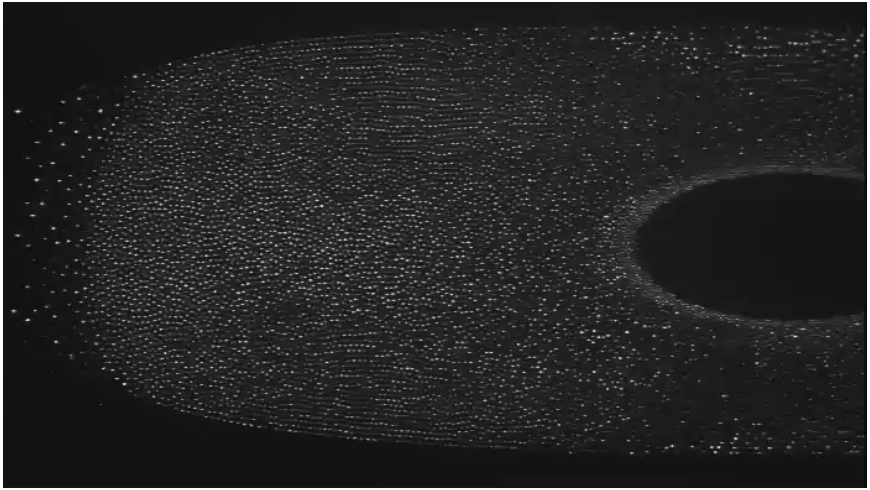
The system is often in a fluid state. Then vortices can form.



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The Reynolds number determines the character of a fluid flow.

$$\mathcal{R} = LV/\nu$$

L: characteristic length
V: characteristic velocity
ν: kinematic viscosity

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ν large, $\mathcal{R}$ small: viscosity damps out velocity variations

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ν small, $\mathcal{R}$ large: nonlinear effects dominate, e.g. small scale movement develops, which leads even smaller scale movement, ...

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The Reynolds number in complex plasmas is very low.

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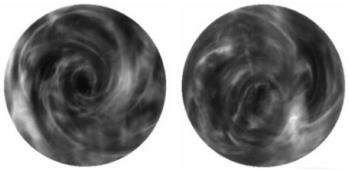
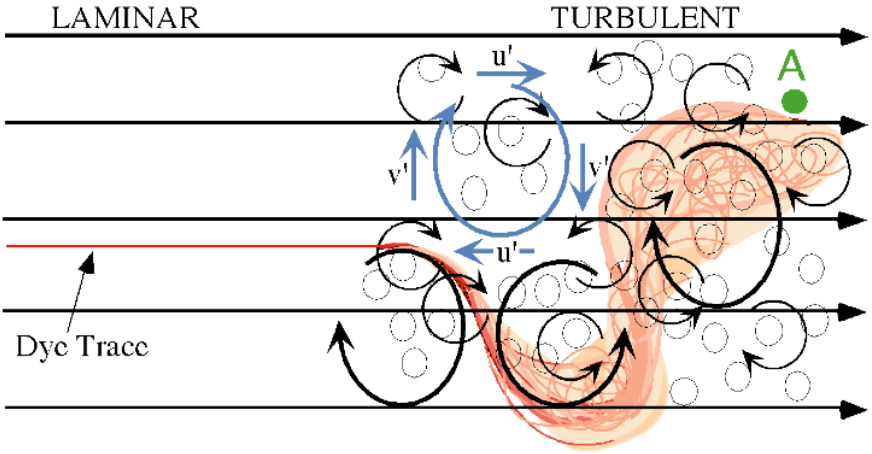


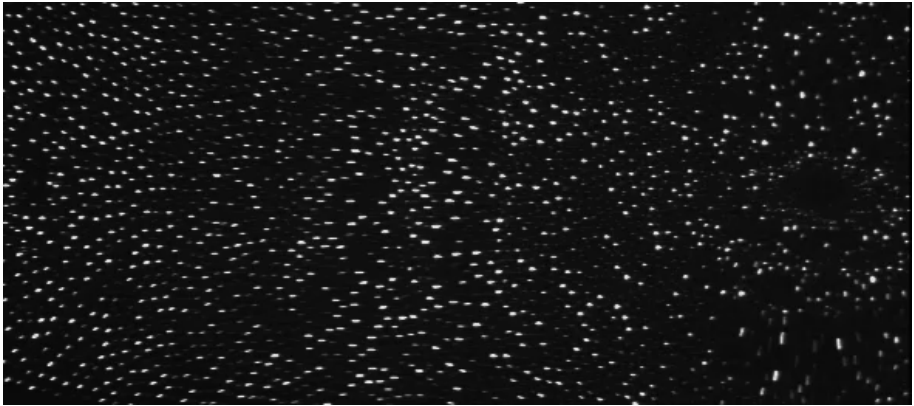
polymer solution with $\mathcal{R} = 0.7$
Groisman and Steinberg, Nature (2000)

Turbulence is a superposition of movement on many scales.



NEPF Lab, MIT

Experimental: A heartbeat instability causes waves and oscillons.



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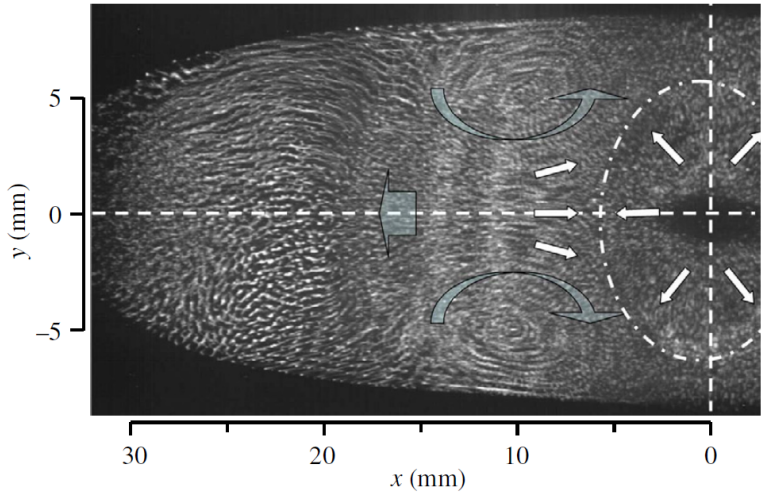

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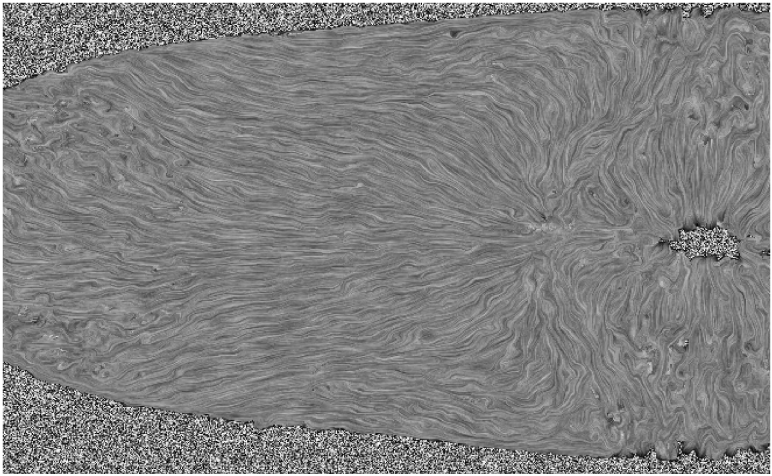

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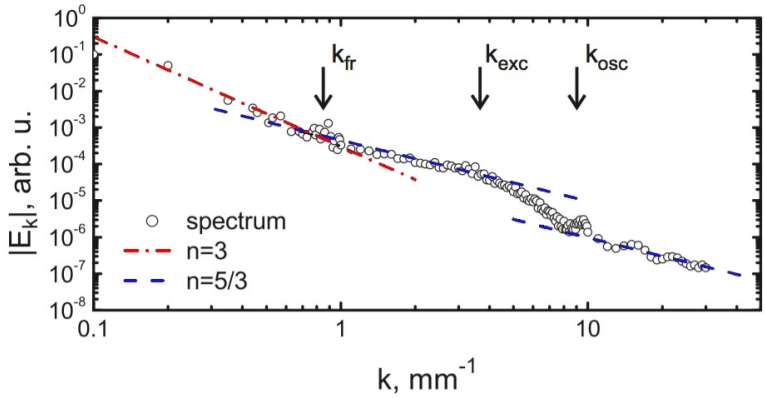
The energy spectrum is dominated by three wave numbers.



$k_{\mathrm{fr}} = \frac{\gamma_{\mathrm{damp}}}{2C_{\mathrm{DAW}}} \approx 0.84\,\mathrm{mm}^{-1}$ scale defined by friction, transition at $k < k_{\mathrm{fr}}$ to $E_{\mathrm{k}} \propto k^{-3}$ caused by friction

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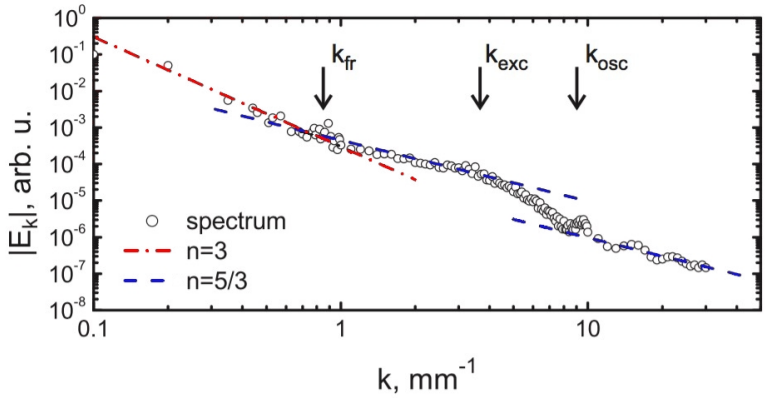

$k_{exc} = \frac{2\pi f_{HB}}{C_{DAW}} \approx 2.7\,\mathrm{mm}^{-1}$ scale defined by heartbeat

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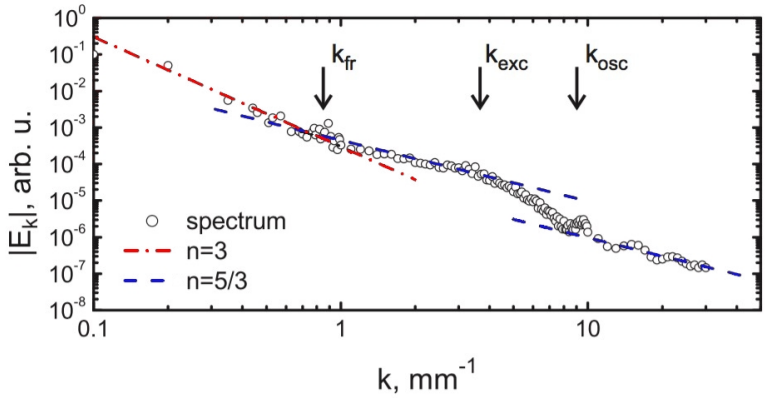
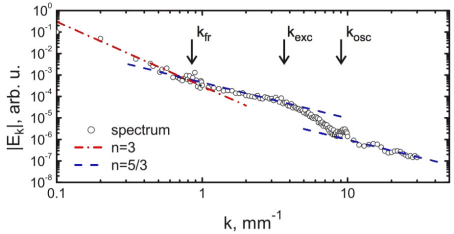


$k_{osc} = \frac{2\pi}{w_{osc}} \approx 9.0\,\mathrm{mm}^{-1}$ scale defined by oscillons

modulational instability causes oscillons

The knee at k_{exc} resembles a double cascade predicted for forced turbulence.



external force input at k_{exc} leads to

- inverse cascade of kinetic energy to $k \ll k_{exc}$ ($E \propto k^{-5/3}$)
- direct cascade of enstrophy to $k \gg k_{exc}$ ($E \propto k^{-3}$)

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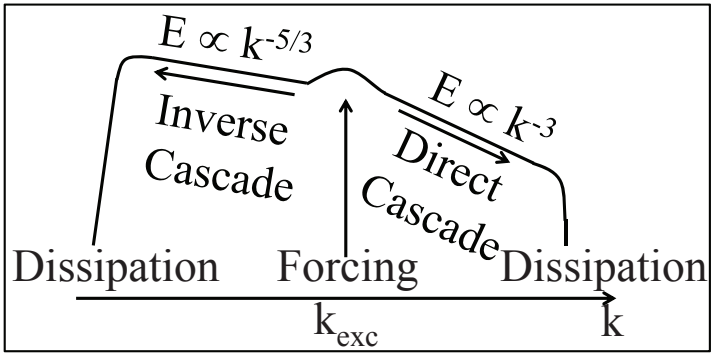
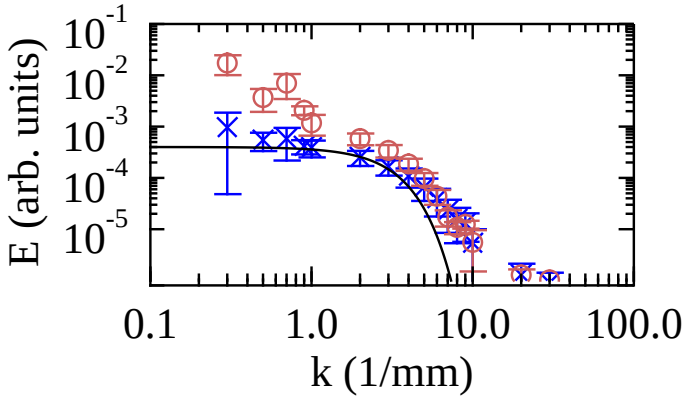


after Laurie et al. (2012)

The energy spectrum changes dramatically with the onset of the instability.



blue crosses: before / red circles: after the onset of the instability

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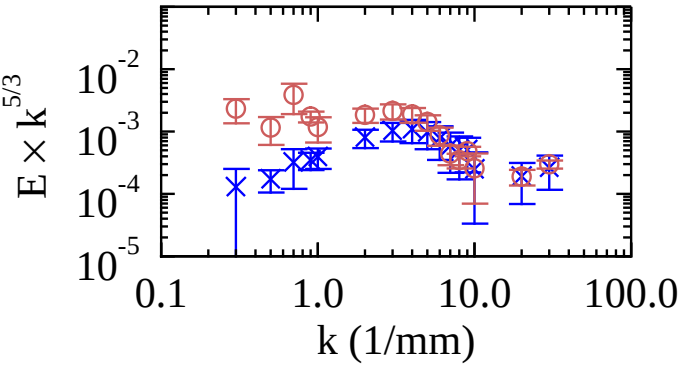

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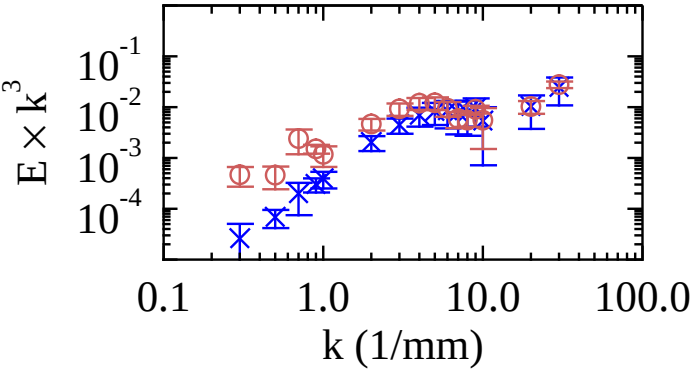

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We calculate the reduced rates of energy and enstrophy transfer.

inverse cascade: $E = C\epsilon^{2/3}k^{-5/3} = \epsilon'^{2/3}k^{-5/3}$

ϵ: rate of cascade of kinetic energy / mass

direct enstrophy cascade: $E = \tilde{C}\eta^{2/3}k^{-3} = \eta'^{2/3}k^{-3}$

η: rate of cascade of mean-square vorticity (enstrophy)

The ratio of the reduced rates of transfer indicates the excitation wave number.

$$\kappa^2 = \eta'/\epsilon' = \left(\frac{Ek^3|_{k_2}}{Ek^{5/3}|_{k_1}} \right)^{3/2}$$

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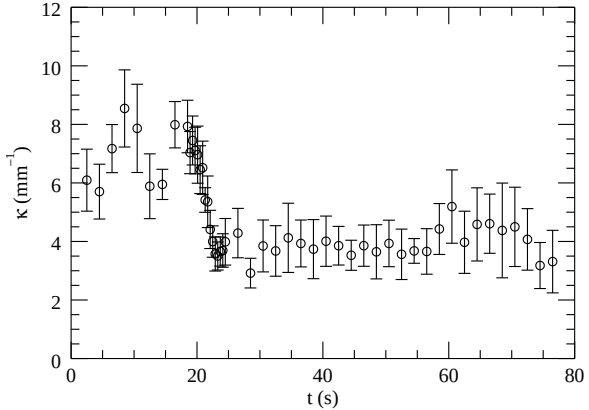

$$\kappa = k_{exc} = 3.9 \pm 0.5 \text{ mm}^{-1}$$

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Conclusion

observed a double cascade in a dusty plasma with heartbeat instability

change in spectrum when instability sets in

calculated excitation wave number

still a lot to do! e.g., study fluxes, movement of particles, . . .

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Accessory Slides

Enstrophy is a common quantity used in turbulence research.

$$\Omega_{kl} = \left(\frac{1}{n} \sum_{i=0}^{n} \omega_i \right)^2$$

(k, l): grid cell coordinates
$\omega_i = (\text{curl } v)_i$: vorticity
n: number of particles in cell

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$\rightarrow$ potential density related to the kinetic energy that corresponds to dissipation effects in the fluid