Deutsches Zentrum für Luft- und Raumfahrt

Smart particle dynamics observed in a complex (dusty) plasma

Sergey K. Zhdanov

" 1. PK4 symposium"

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outline

•*complex plasmas and experimental setups*

•*patterns, nonlinear waves, solitons , shocks and turbulence*

•*mode coupling instability*

•*odd „kind of sympathy“ in particles*

•*single extra-particles: Mach cones*

•*cooperative dynamics of particles in complex plasmas*

•**Summary**

Complex or dusty plasmas are weakly ionized gases containing micron-size particles called dust particles or microparticles. Complex plasmas are ideal model systems for phase transitions, self-organization and transport processes. This complex system often self-organizes in a rhythmic pattern of alternating in-phase and anti-phase oscillating chains of particles. Spontaneous synchronization and symmetry breaking, resulting from a delicate repulsion-attraction balance (‘wake effect’), are typical behaviors in such large populations of interacting units. In particular, new types of collective excitations have been recently discovered in a single layer complex plasma crystal - spontaneous pairing and spin of particle pairs (“torsion”). They can be used as a diagnostic tool for plasma wakes or as a model of a 2d system of vortices.

complex plasmas

and

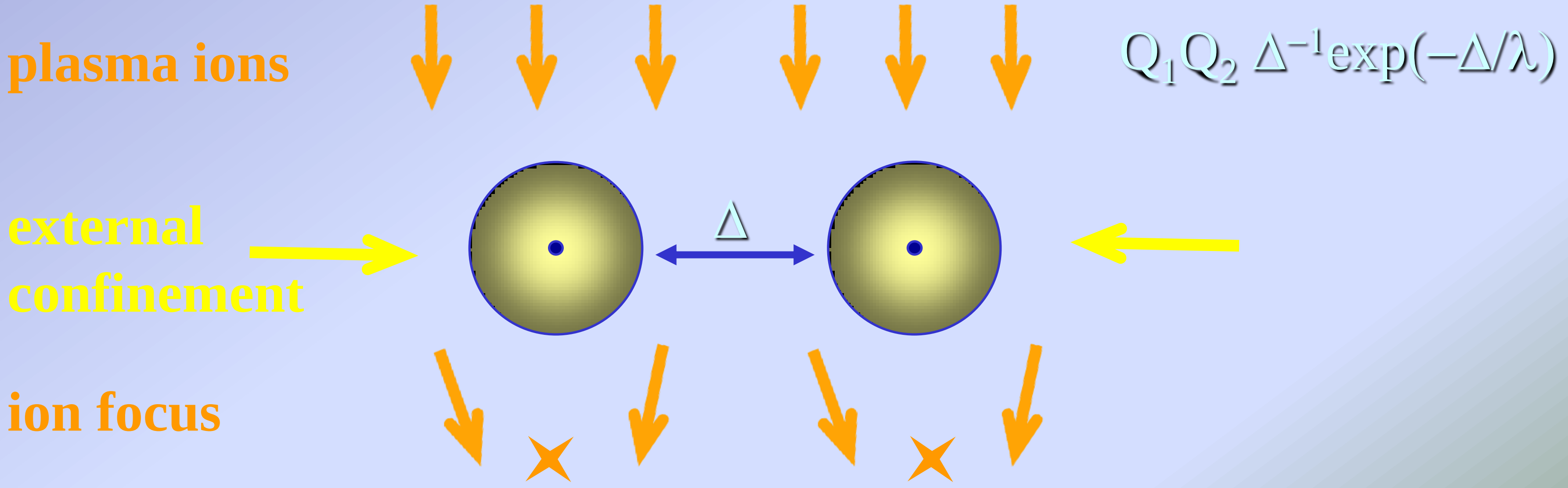
experimental setups

complex plasmas

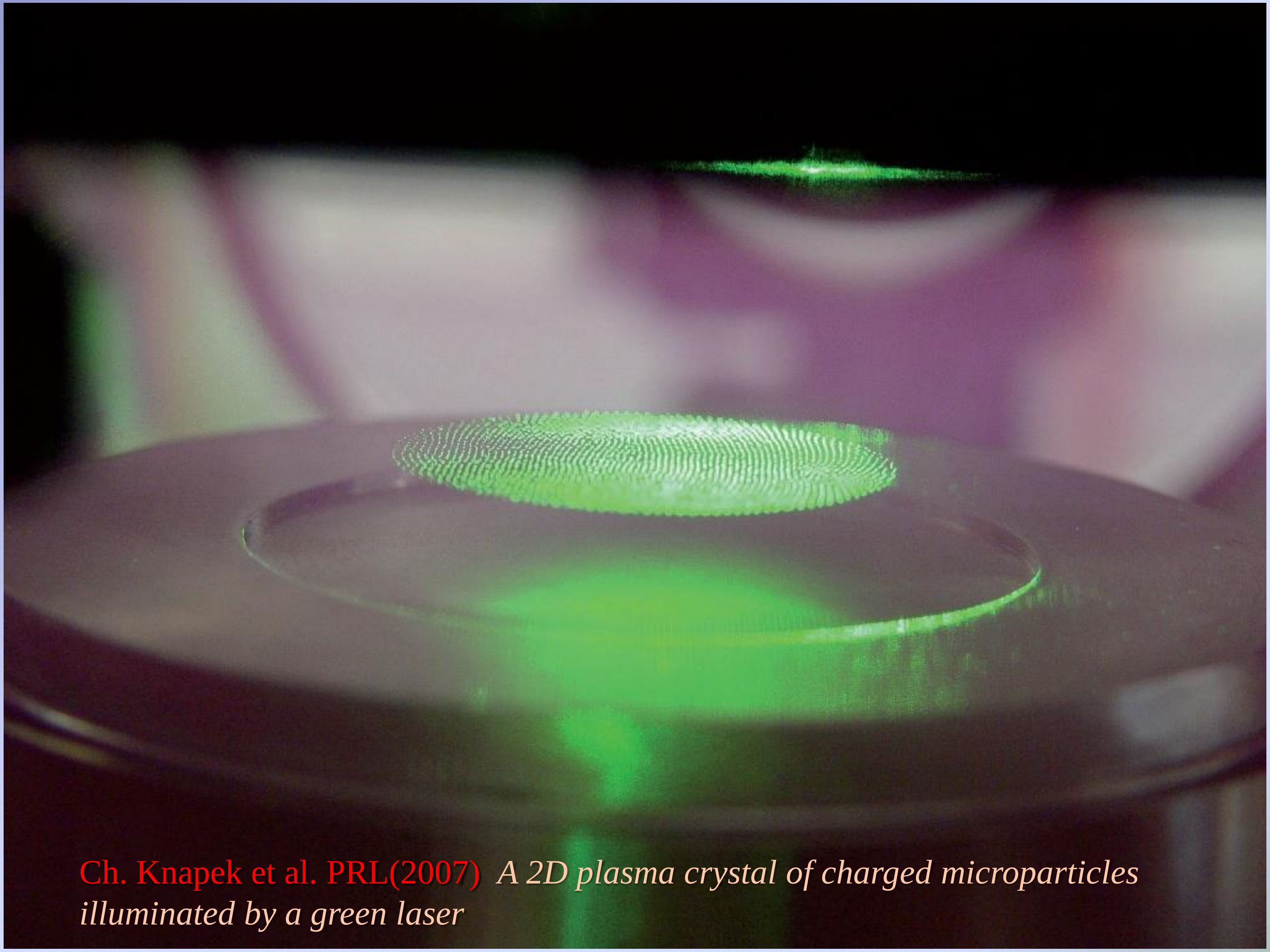
Complex plasmas can be ´engineered´ as amorphous or crystalline *solids* of varying type and description.

They can also be enginereed as (one phase) *liquids*, with properties (e.g. viscosity) quantitatively ´designed´ from elementary kinetic interactions.

And they can, of course, be engineered as Coulomb or Yukawa *plasmas* of different type, for a wide range of coupling strengths.

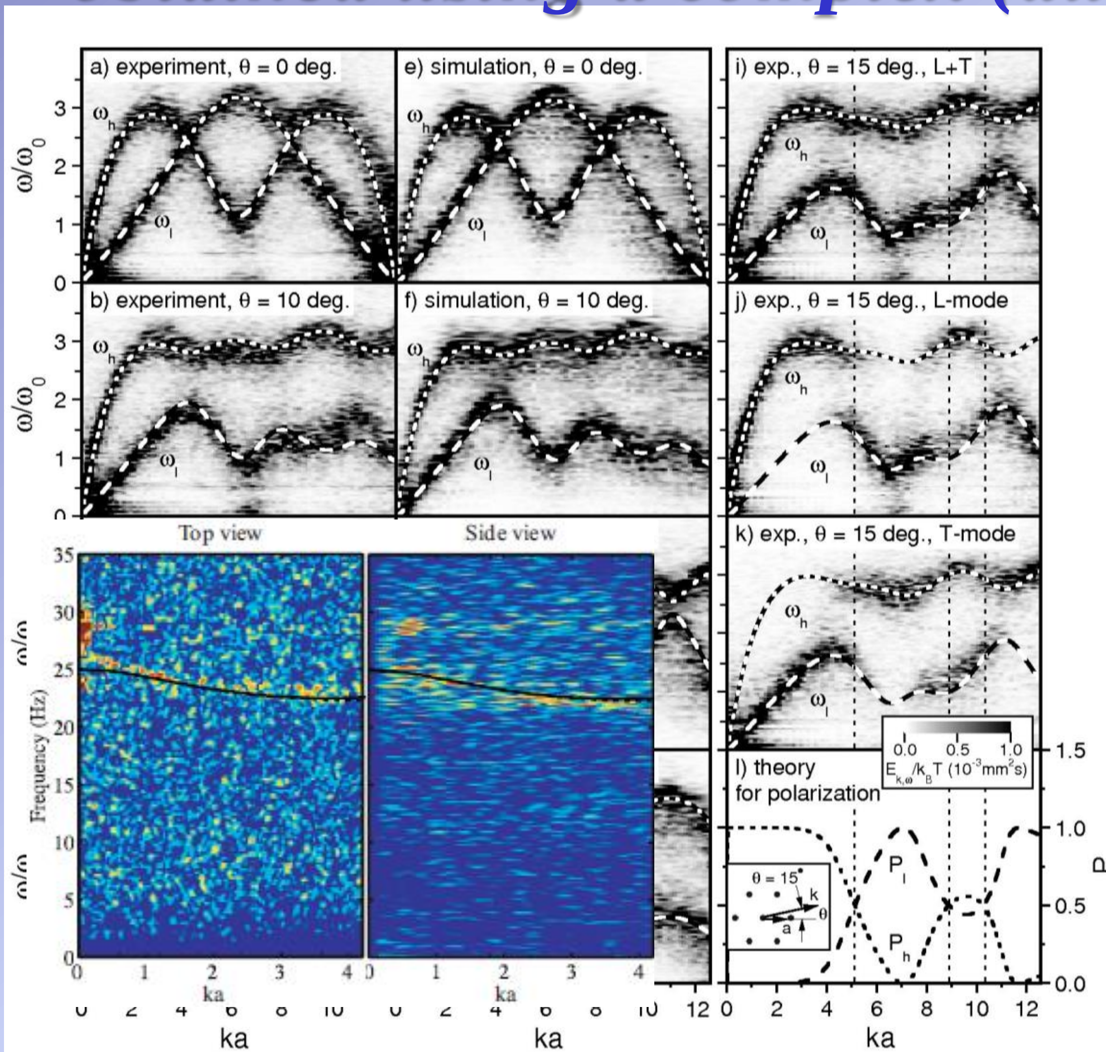


experimental 2D plasma crystal



Ch. Knapek et al. PRL(2007) *A 2D plasma crystal of charged microparticles illuminated by a green laser*

wave modes of a 2D hexagonal lattice obtained using a complex (dusty) plasma



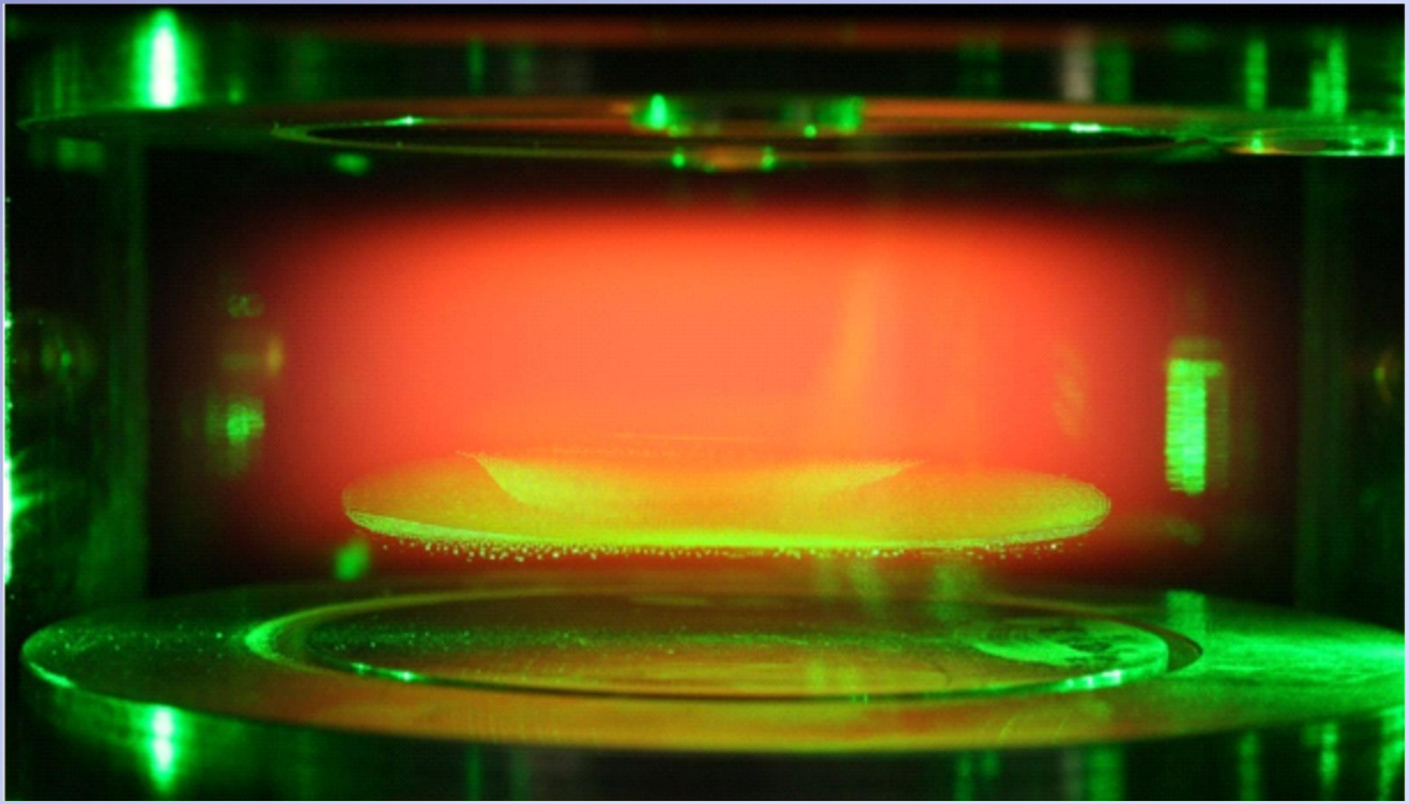
(a)–(d) experiment (*left*)
(e)–(h) simulation (*middle*)
Theory: the dotted and the dashed lines
(i) Phonon spectra of the waves propagating at 15° measured experimentally (*right*): (j) longitudinal and (k) transverse propagation.
(l) Polarization of the modes predicted by the theory.

At an arbitrary wave number the modes have *mixed polarization*.

S. Zhdanov, S. Nunomura, D. Samsonov, and G. Morfill (PRE 2003)

S. Zhdanov, L. Couedel, V. Nosenko, and G. Morfill (PRE 2014)

experimental 3d complex plasmas

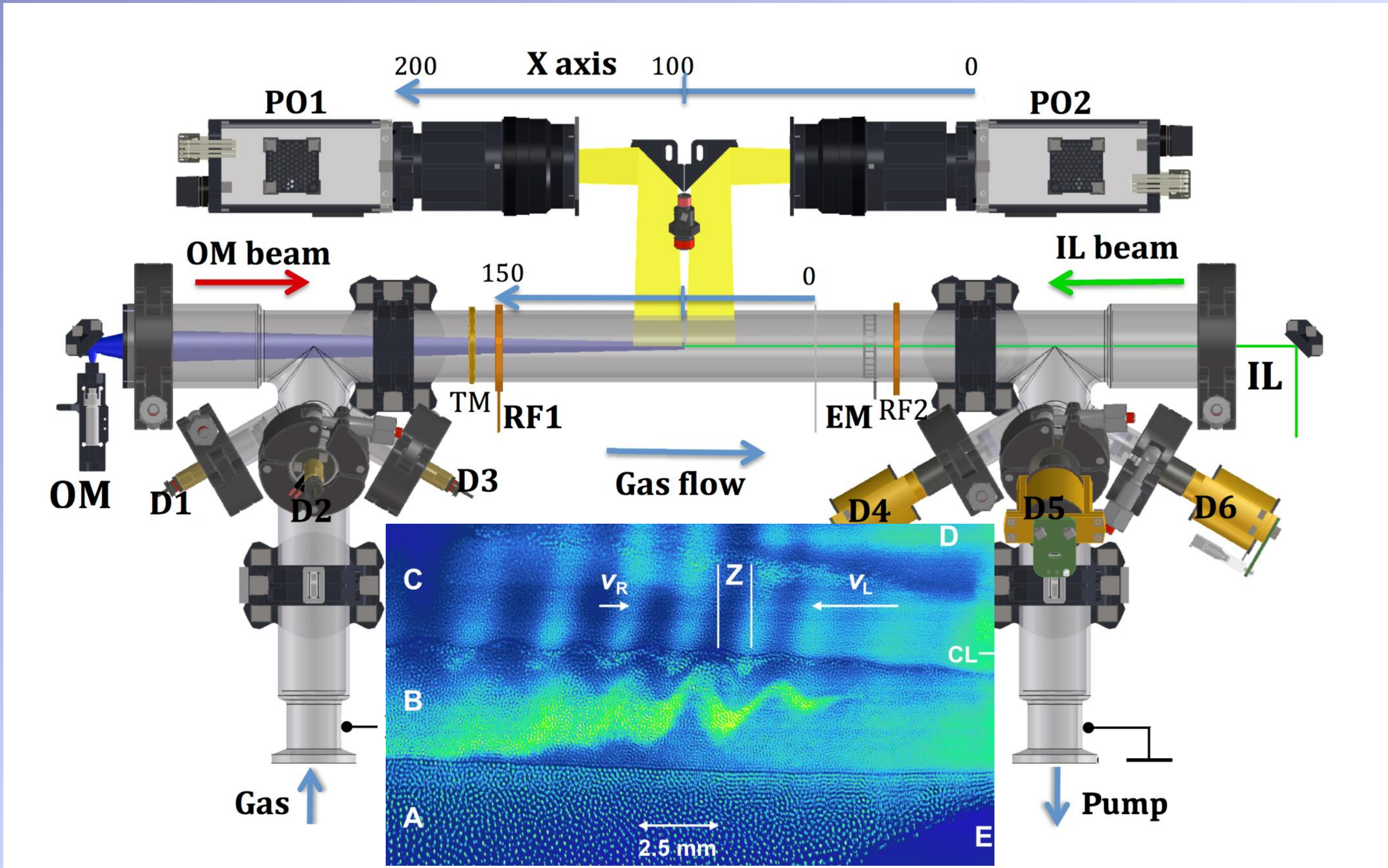


R. Heidemann et al. (IEEE 2011): The neon complex plasma illuminated by a green laser diode

Complex plasmas consist of *ions, electrons, charged microparticles, neutral gas* in charge equilibrium.

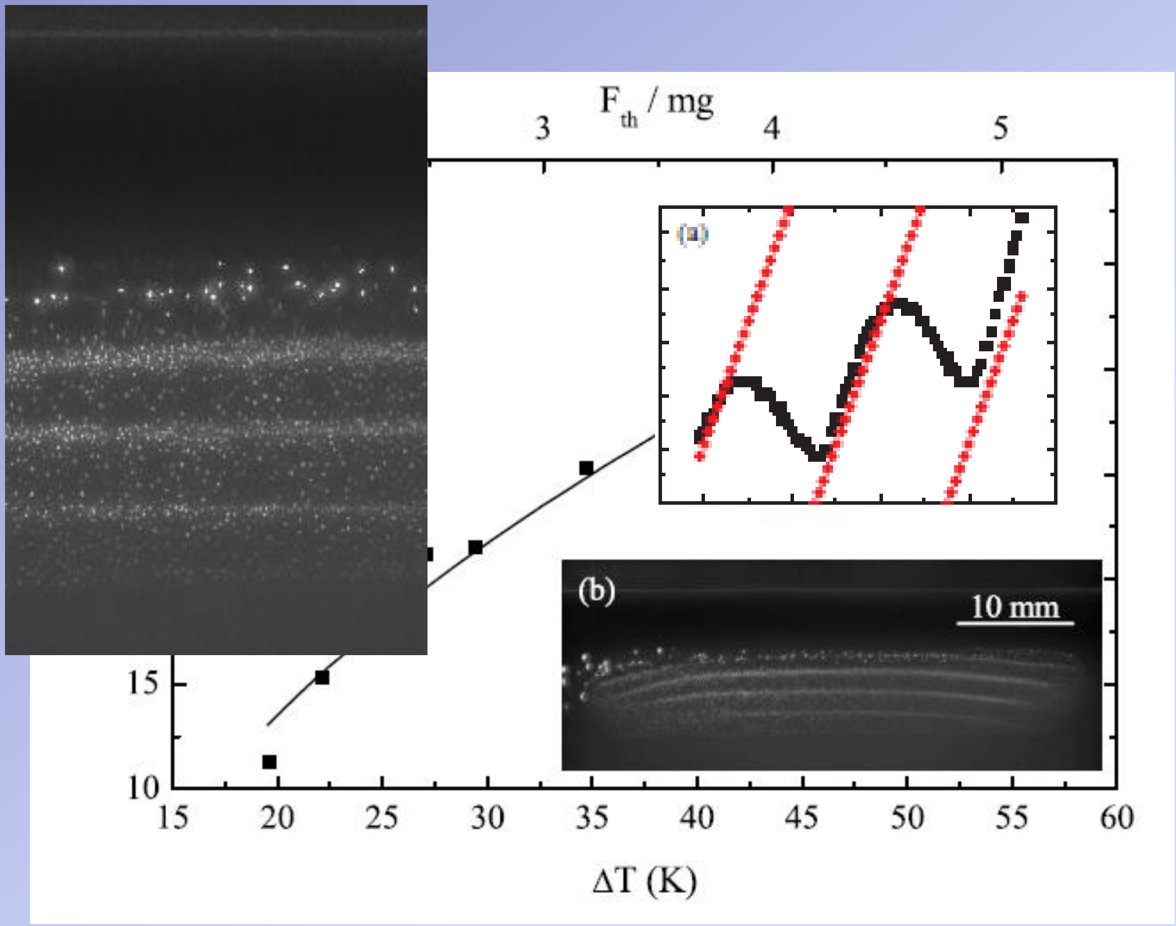
They are thermodynamically open systems, and, in principle, non-Hamiltonian.

experimental dc-discharge design



M. Kretschmer, T. Antonova, S. Zhdanov, M. Thoma IEEE (2016)

dust density waves: symmetry breaking bifurcation



The self-excited waves revealed by the complex plasma compensated thermophoretically for gravity

M. Schwabe et al. (PRL 2007), (NJP 2007)

***A*rgon, pressure 10-40 Pa**

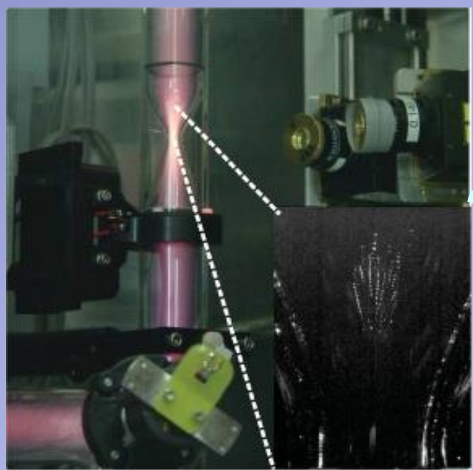
ΔT = 20-55 °C

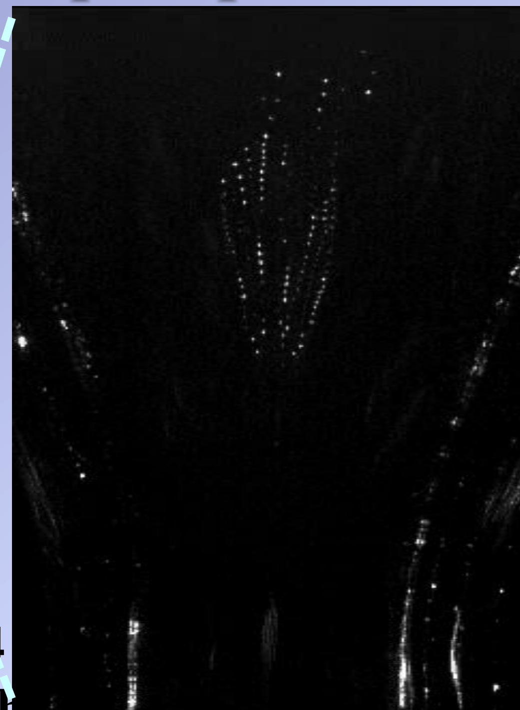
MF microparticles of 1.28± 0.06 μm diameter
M= 3.9 × 10^{-13} g

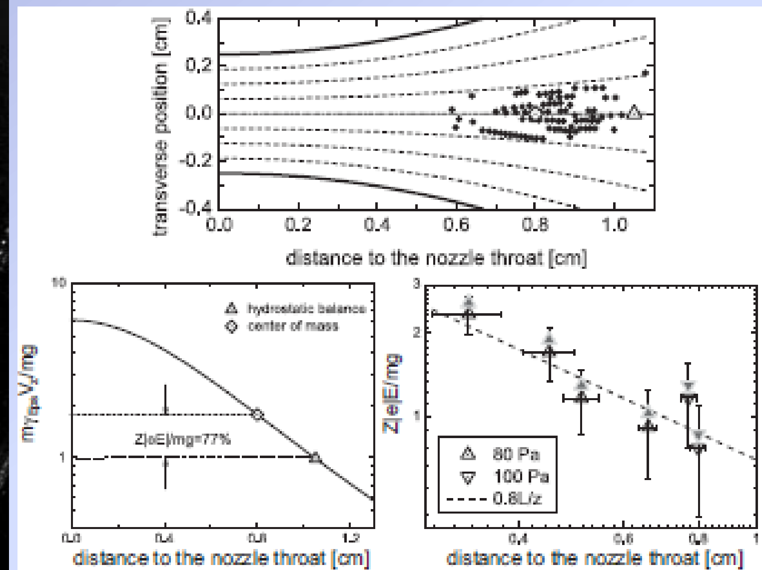
The cloud's dynamics is recorded with a Photron Fastcam-1024 PCI camera at a rate of 1000 fps
Spatial resolution of 1 Mpx at 45.6 μm/px

pearl-necklace-like structures of microparticle strings observed in a dc complex plasma

neon gas at a pressure of 100 Pa and MF particles with a diameter of 3.43 μm.







The heart of the PK-4

The straight part of the glass discharge tube with a diameter of 30mm and a length of 350mm is oriented vertically. The glass nozzle implemented inside the tube with a diameter of 5 mm in the nozzle throat. The field of view is 12.67 × 9.50 mm^2.

Upper The nozzle and the gas flow lines with the particle positions (black dots).

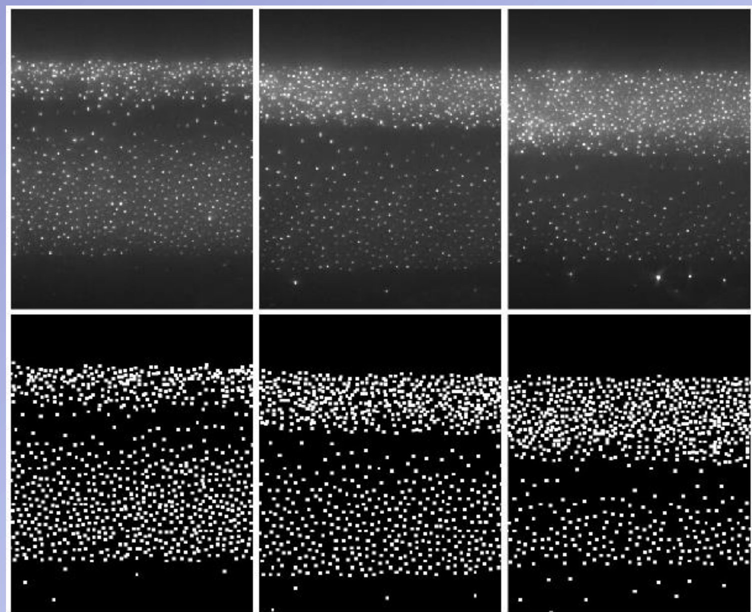
Lower Sketch of the electric force diagnostics.

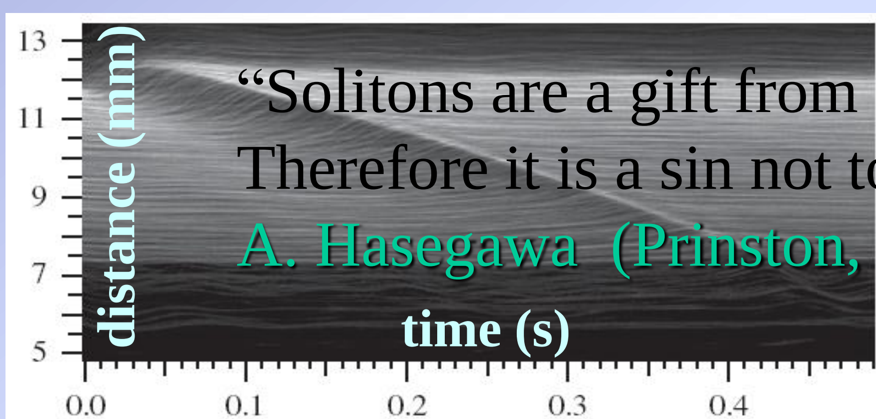
M.A. Fink, S.K. Zhdanov, M.H. Thoma, H. Höfner, and G. Morfill PRE (2012)

patterns, nonlinear waves, solitons, shocks and turbulence

dissipative dark solitons in complex plasmas

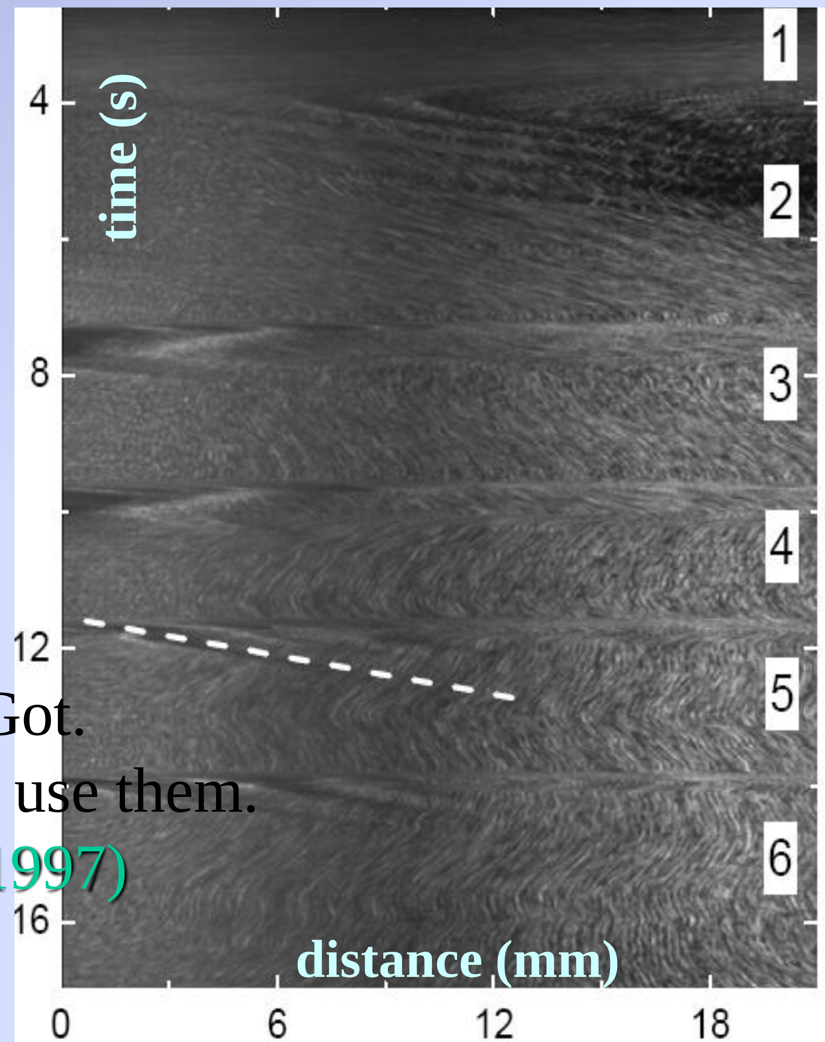
RF-discharge (PK3 Plus)





R. Heidemann et al. PRL (2009)

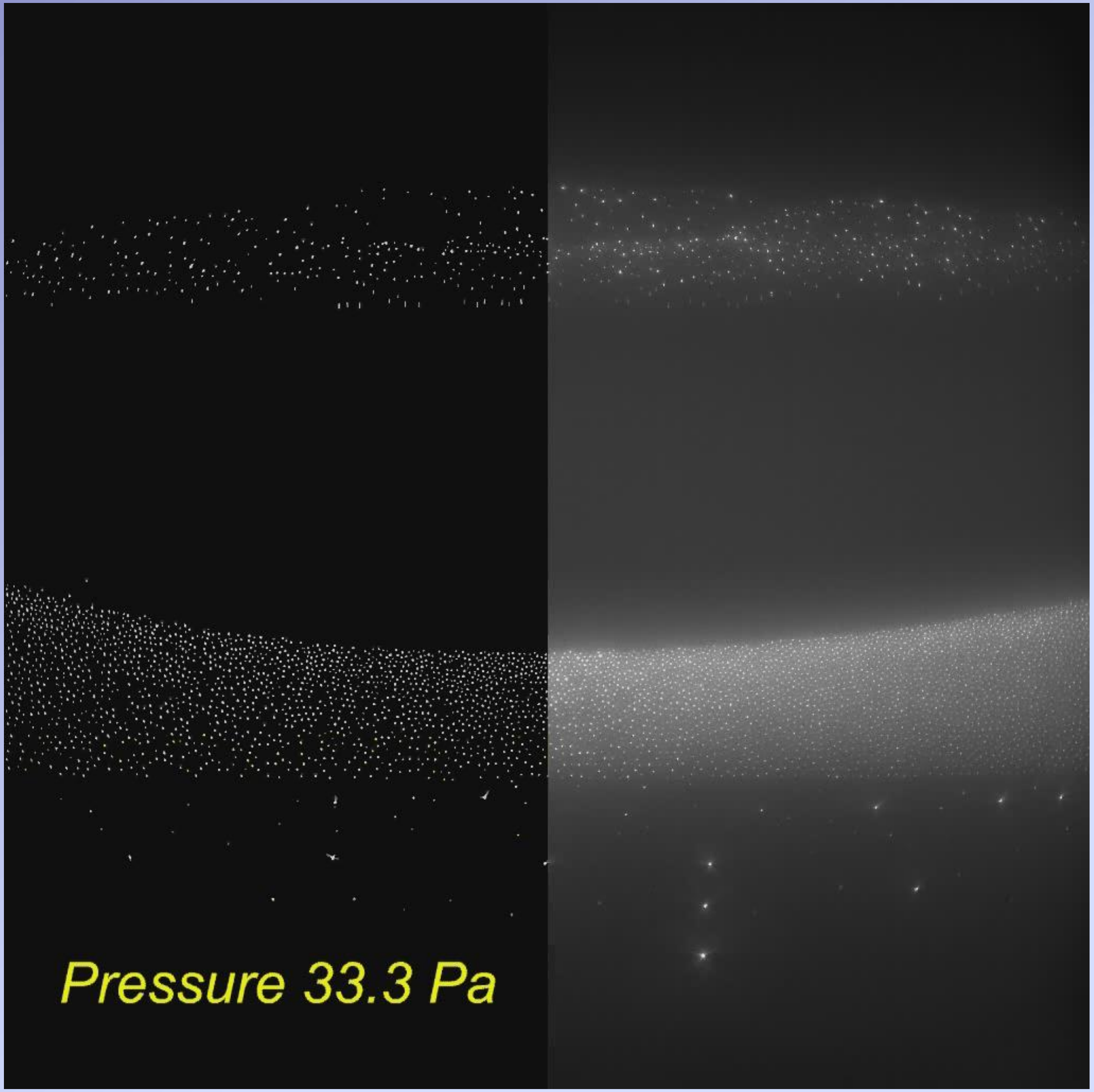
DC-discharge (PK4)



S. Zhdanov et al. EPL (2010)

“Solitons are a gift from Got.
Therefore it is a sin not to use them.
A. Hasegawa (Prinston, 1997)

dissipative dark solitons in complex plasmas



A rarefactive solitary wave observed for a pressure range in a dense complex plasma cloud compensated for gravity by thermophoresis.

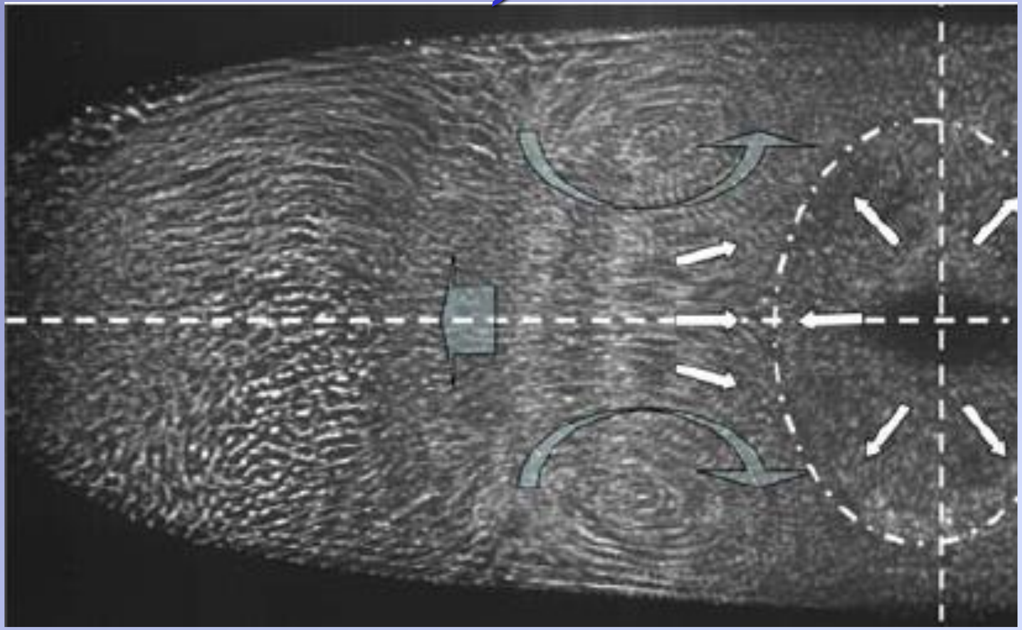
Traveling speed ~2 cm/s

Maximal decompression factor D~ 7.8

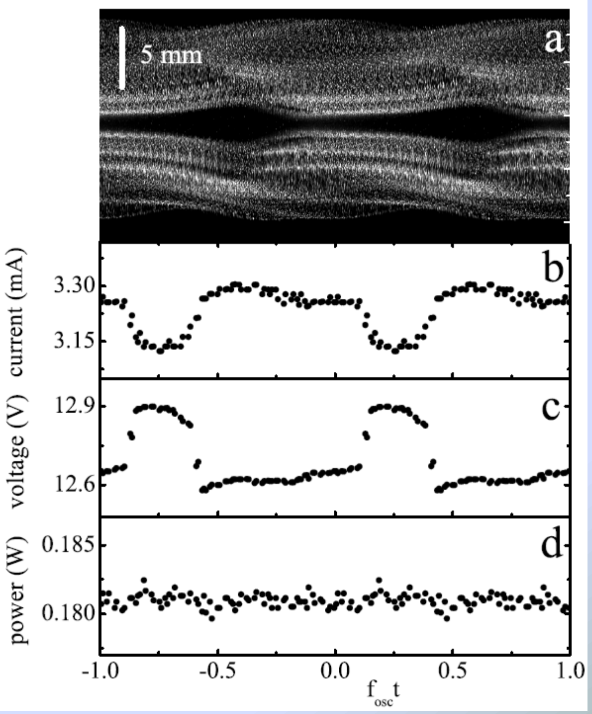
Sound speed
$C_s = AD^{1/2}/(D-1) \sim 2.1 cm/s$

R. Heidemann, S. Zhdanov, R. Suetterlin, H.M. Thomas, and G.E. Morfill PRL (2009)

auto-oscillating complex plasma (experiment on board the ISS)



The field of view is 17.6x34.7 mm^2. The illuminating laser sheet FWHM is about 80 μm
10 superimposed images of the cloud (an oblate spheroid in shape) shifted by one period in time
Dominant particle motion is as indicated by the arrows

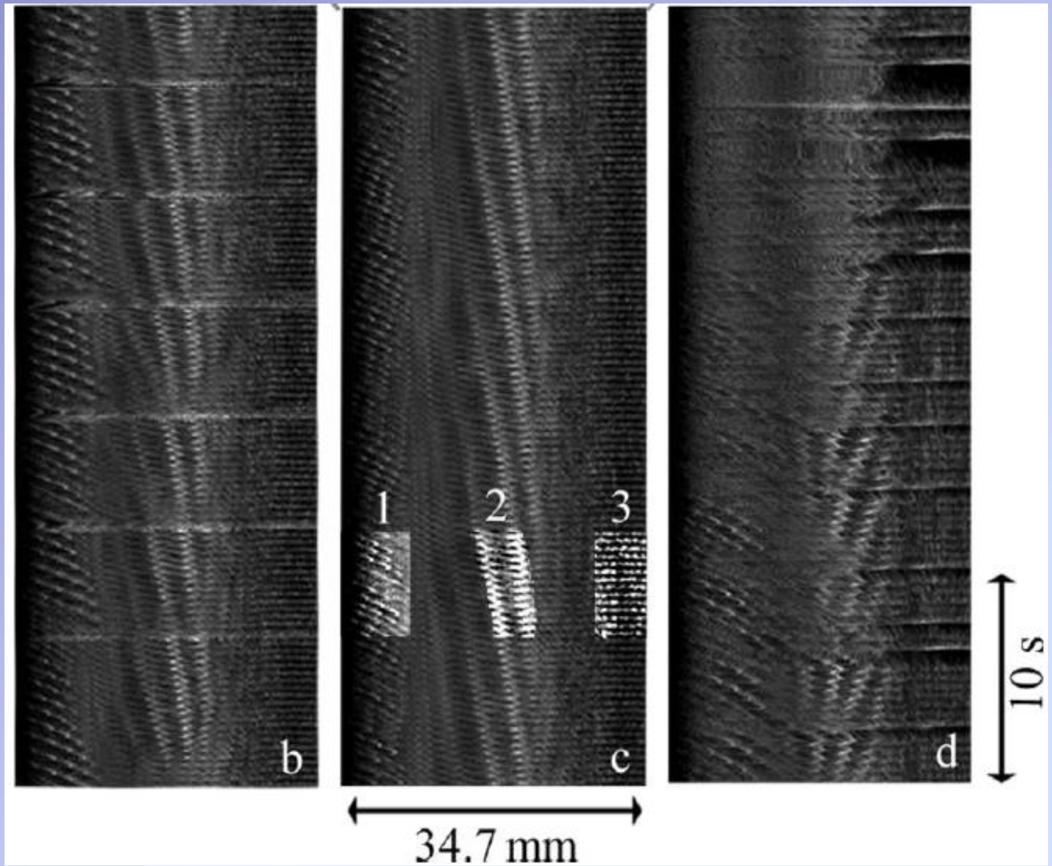


The main elements of this 'dynamo-machine' are:

- a void (the dark elliptic-shaped area to the right) with a quasi-spherical halo
- counter-rotating global vortices
- a waveguide in-between the vortices with oscillons
- a'buffer' zone with weak waves to the left.

S.K. Zhdanov et al. (NJP 2010); R. Heidemann et al. (PoP 2011)

oscillons in an rf complex plasma



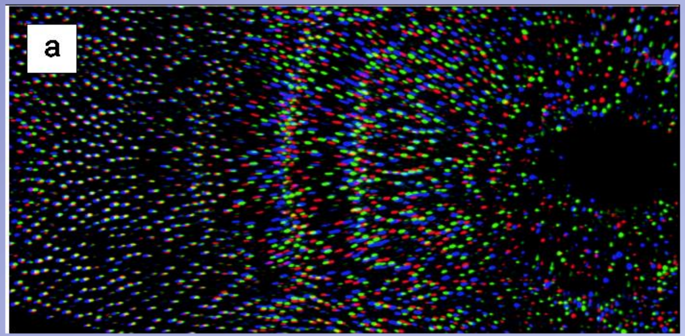
Oscillons are ”feed” by the CPV oscillatory energy.

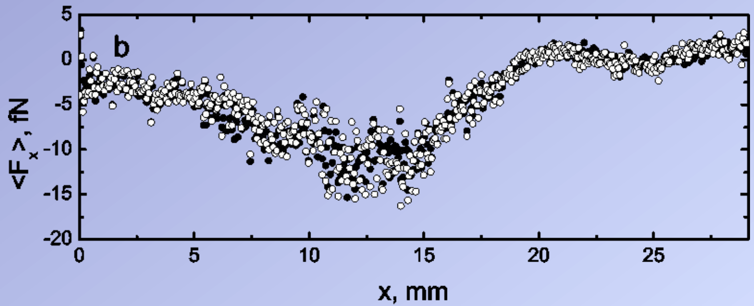
The lifetime of the oscillons is 20 s, i.e. about 200 damping times!

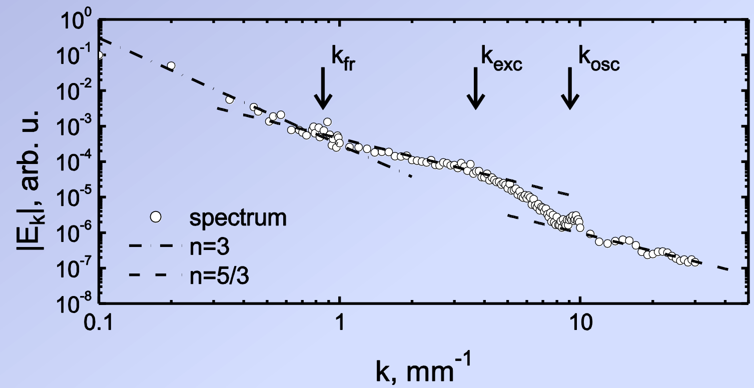
1. Fast edge-wave ridges (left part of the cloud)
2. Slowly propagating oscillons, well seen by enhanced particle density)
3. Pulsating void (horizontal periodic black-white stripes to the right)

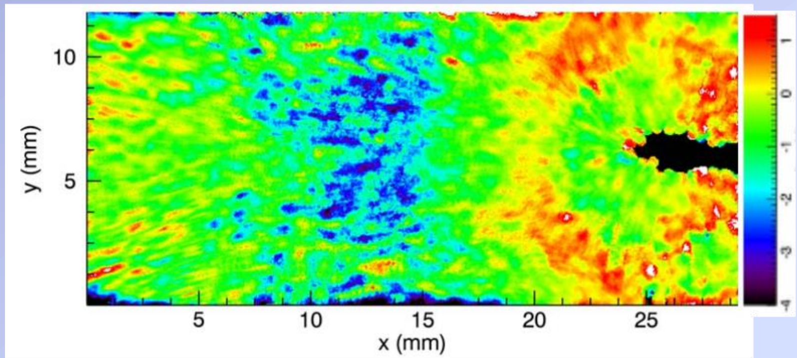
S.K. Zhdanov et al. (NJP 2011, EPL 2015); R. Heidemann et al. (PoP 2011)

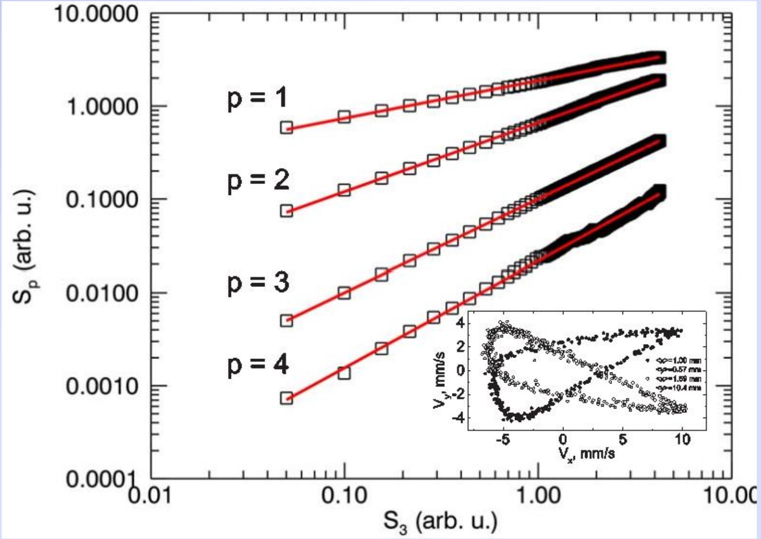
“oscillons” turbulence











1. **Effective wave dispersion** $\omega \propto k^{2/3}$
2. **Extended self-similarity** $S_p \propto S_3^{p/3}$
3. **Multi-cascade forced turbulence**

M. Schwabe et al. (PRL 2014); S.K. Zhdanov et al. (EPL 2015)

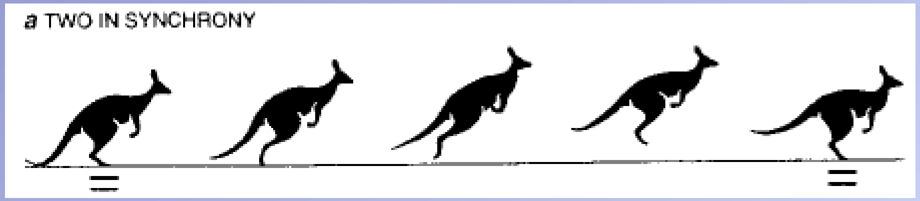
odd „kind of sympathy“

in microparticles

synchronization process

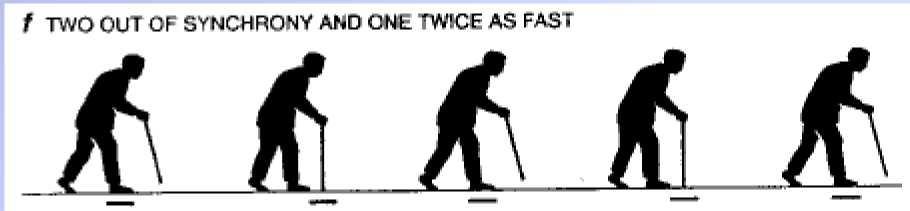
- An odd ’kind of sympathy’ in pendulum clocks discovered about 350 years ago by C. Huygens, was rigorously explained in further as a specific synchronization process between the weakly-coupled close-frequency oscillators.
- Synchronization phenomena have become an important topic in explorations of biological, physical, chemical, cybernetical and many other dynamical systems.
- Spontaneous emergence of synchronized signals and spontaneous symmetry breaking are typical behaviors in such non-linear systems.
- Analytical studies and computational simulations predict a non-linear dynamical phase transition in such systems.
- In this sense, complex plasmas are ideal systems to observe the synchronization process generically in all it complexity and diversity at an ’atomistic’ scale and in real time.

"Symmetry breaking governs the ways that coupled oscillators can behave"



synchronous

antisynchronous

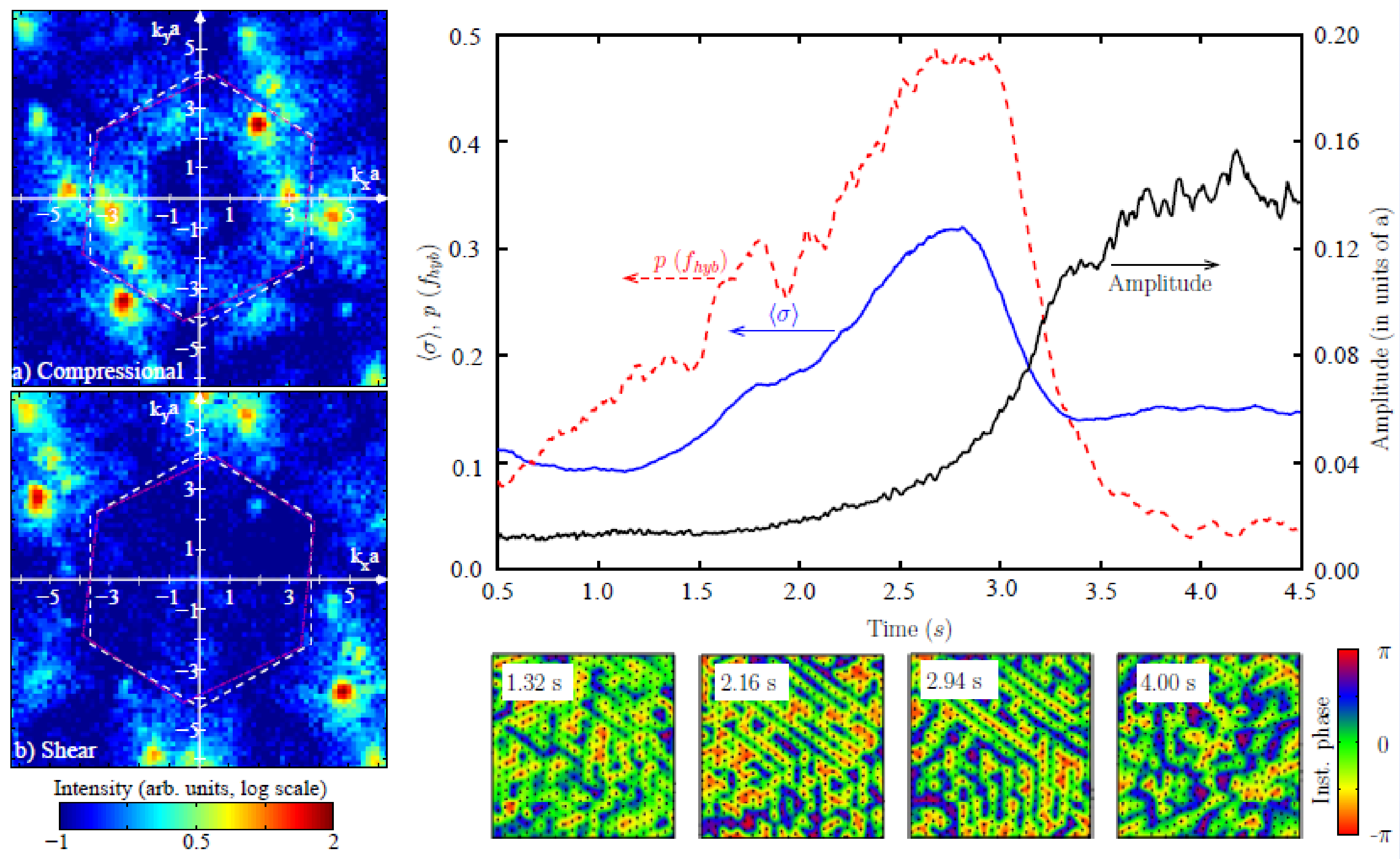


more oscillators,
more synchronization
ways

Steven H. Strogatz and Ian Stewart, Scientific American (1993)

MCI and synchronization of particle oscillations

Gaseous electronics conference (GEC) chamber, rf-discharge: Ar 0.92 Pa, 12W
9.1 mkm MF particles, particle charge -18600e, lattice constant a=0.47 mm



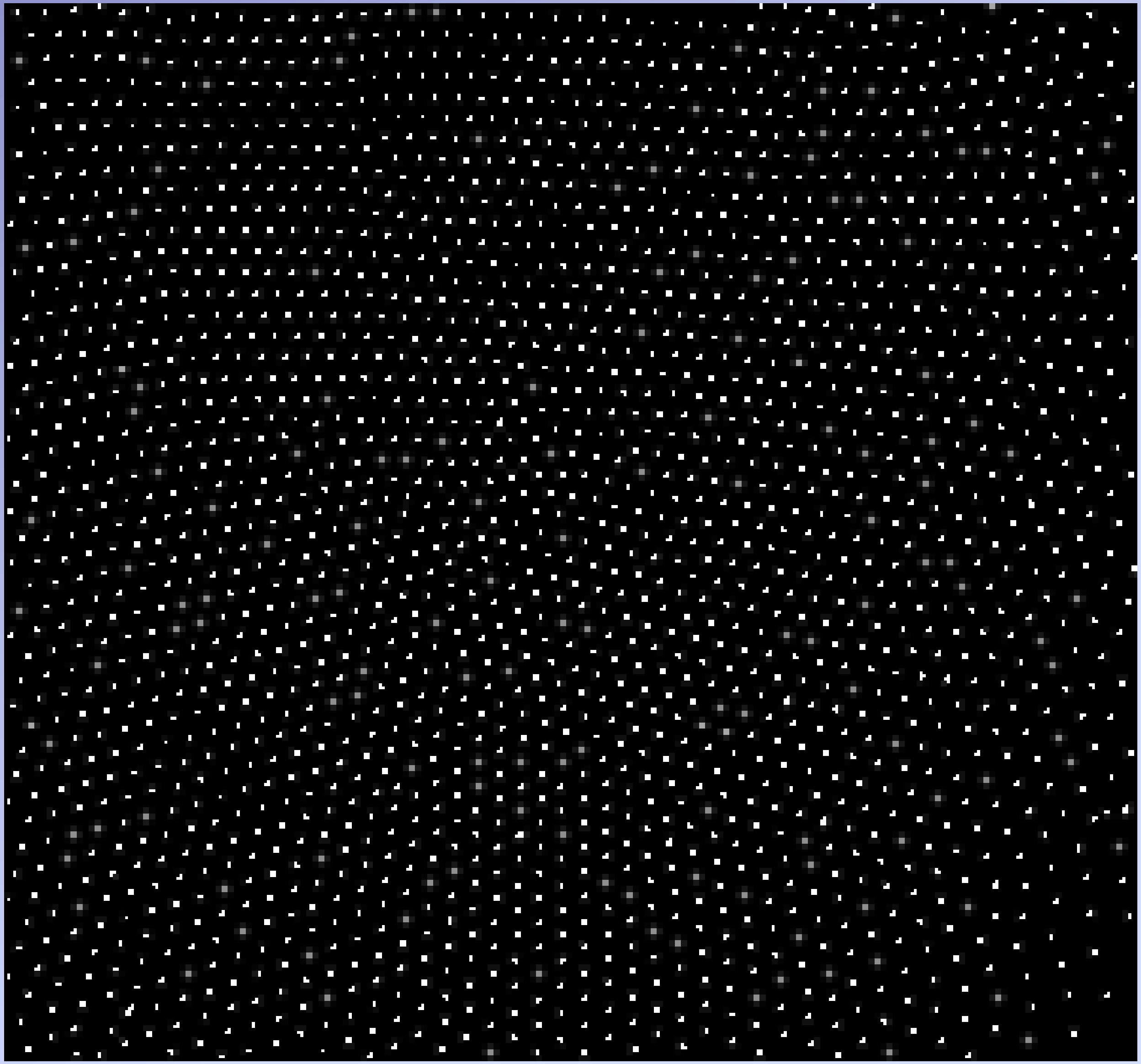
(left) Velocity fluctuation spectra; (top) mean amplitude of the particle oscillations (black) and probabilities of frequency (red) and phase synchronization (blue); (bottom) instantaneous phase distributions.

L. Couëdel, S.K. Zhdanov, V. Nosenko, A.V. Ivlev, H. Thomas, and G. Morfill PRE (2014)

single extra-particles:

Mach cones

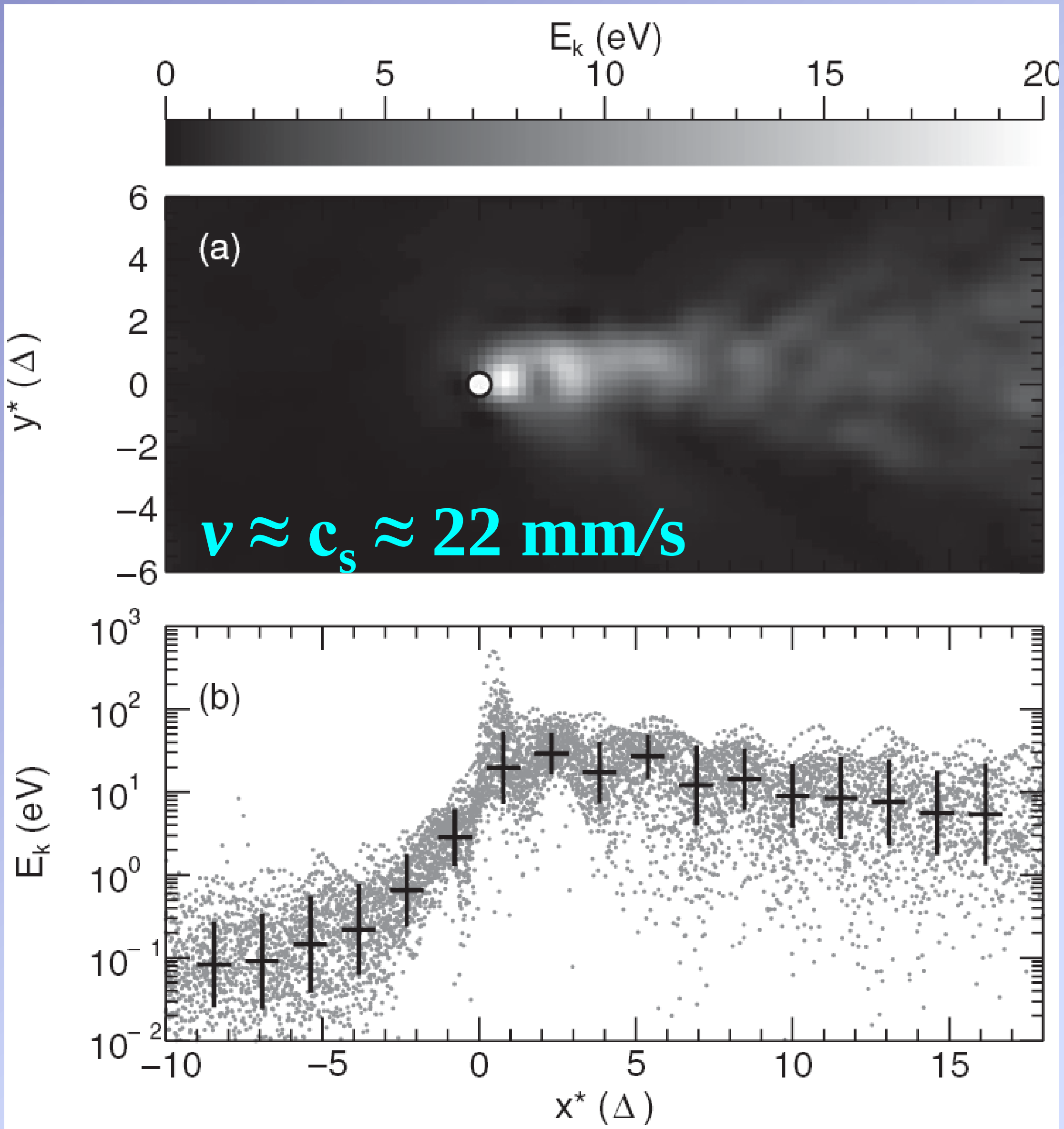
channeling of an upstream particle in a 2D plasma crystal



rf discharge
20W, 0.65 Pa Argon
Polystyrene particles
11.36 ± 0.12 μm
Gas friction rate 0.91 s^{-1}

Ch. Du, V. Nosenko, S.K. Zhdanov, H.M. Thomas, and G. MorfillL (PRE 2014)

anomalous energy transport in a 2D plasma crystal



1D heat transport balance:

$\chi = 2\gamma L^2 + vL$

Thermal conductivity:

$\chi = 16\ mm^2/s$

Damping rate: $\gamma = 0.91\ s^{-1}$

In-channel transport scales behind the particle:

$L^{exp} = 6\text{-}7mm < L^{theory} = 12mm$

in front of the particle:

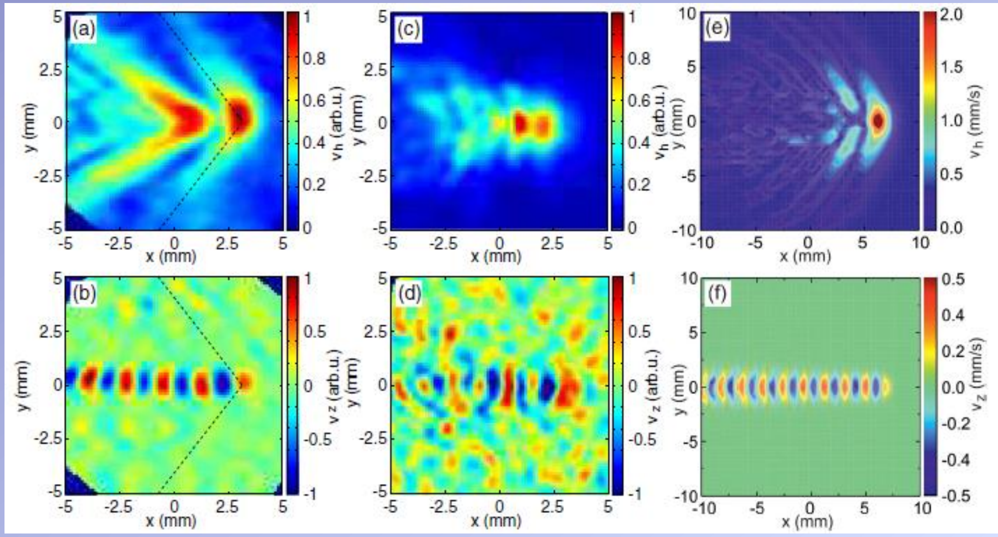
$L^{exp} = 0.75mm = L^{theory}$

Transverse transport:

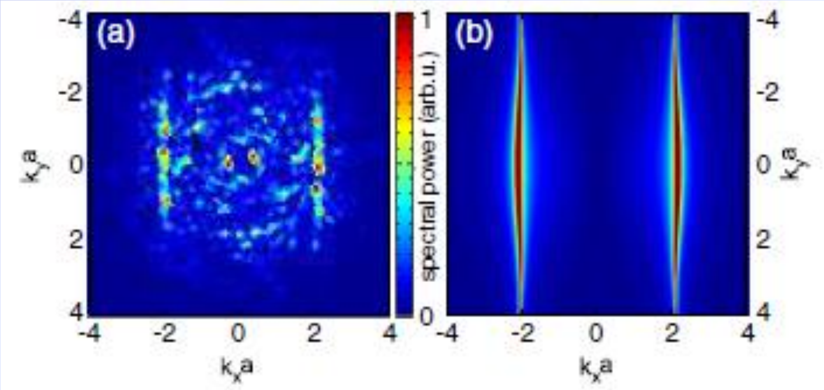
$L^{theory} = 3mm$

Ch. Du, V. Nosenko, S.K. Zhdanov, H.M. Thomas, and G. MorfillL (PRE 2014)

three-dimensional structure of Mach cones in monolayer complex plasma crystals



2D Fourier transform of the vertical velocity (a), and its theoretical prediction (b):

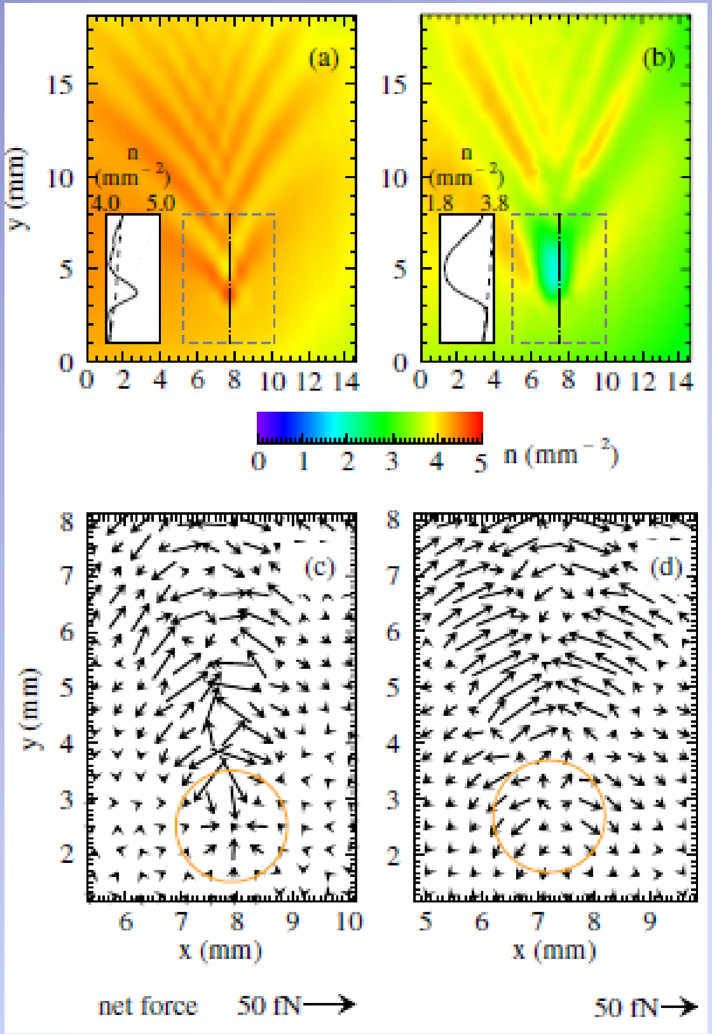


Velocity maps: (a,b) supersonic experiment; (c,d) subsonic experiment, and (e,f) supersonic simulation. The black dashed line in (a),(b) represents the theoretical longitudinal Mach cone. The perturbation moved from left to right in all cases.

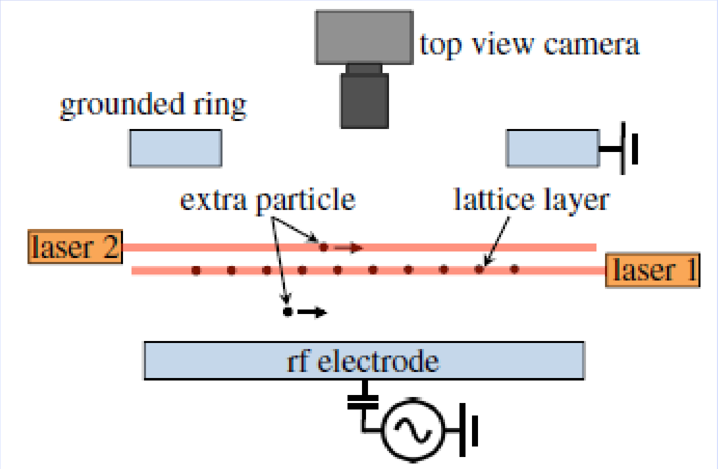
***z-Mach cone* is explained by excitation of the vertical transverse wave in the wake of the projectile. *z-Mach cones* can serve as a tool to measure the resonance wavelength of the vertical transverse wave.**

L. Couëdel, D. Samsonov, C. Durniak, S. Zhdanov, H.M. Thomas, and G. Morfill PRL (2012)

interaction of two-dimensional plasma crystals with upstream and downstream charged particles



Type-I (left) and type-II (right) Mach cone. The insets: density profiles along the axis. The net force at the apex of the Mach cone is shown in panels (c) and (d).

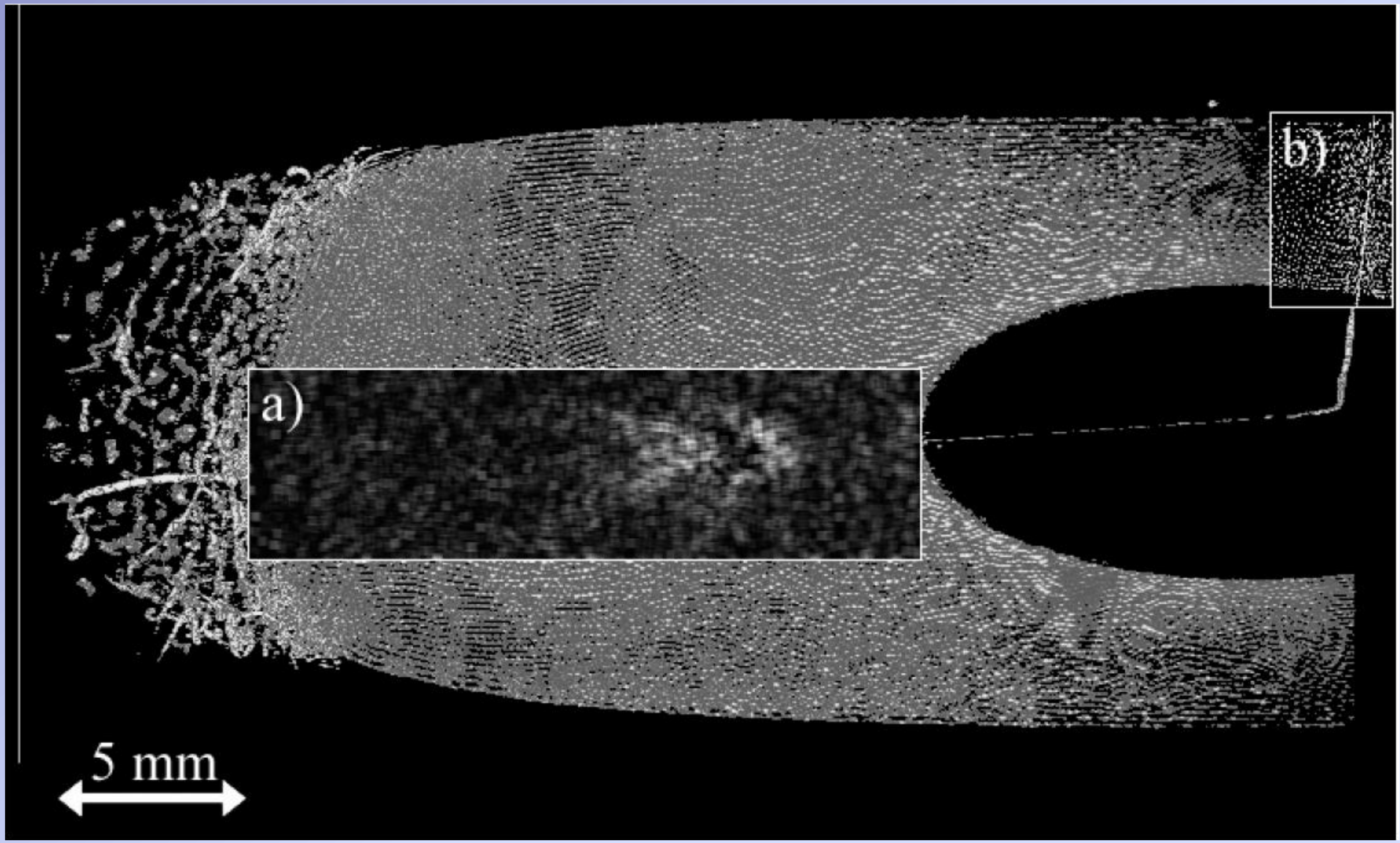


Sketch of experimental setup with a modified GEC chamber

MF particles:	**9.19±0.09 µm (1.51 g/cm^3)**
PS particles:	**11.36±0.12 µm (1.05 g/cm^3)**
Gas pressure (Ar):	**0.65Pa**

C.-R. Du, V. Nosenko, S. Zhdanov, H.M. Thomas, and G. Morfill EPL (2012)

…and in a 3D complex plasma (experiment onboard the ISS)



Main cloud: MF particles 1.55 μm, Ze=2400e, C_{DAW}=28mm/s
Fast extra-particle: V_p=37.5mm/s

M. Schwabe, K. Jiang, S. Zhdanov, P. Huber, A.V. Ivlev, A.M. Lipaev, V.I. Molotkov, O.F. Petrov, H.M. Thomas,V.E. Fortov, G.E. MorfillL, A. Skvortsov, and S. Volkov (EPL 2011)

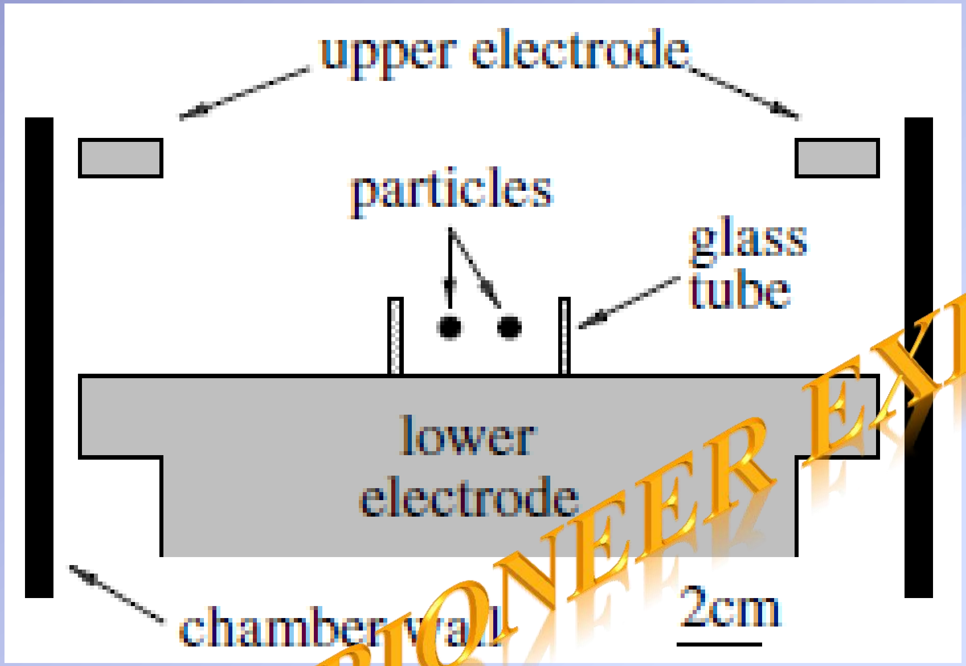
cooperative dynamics

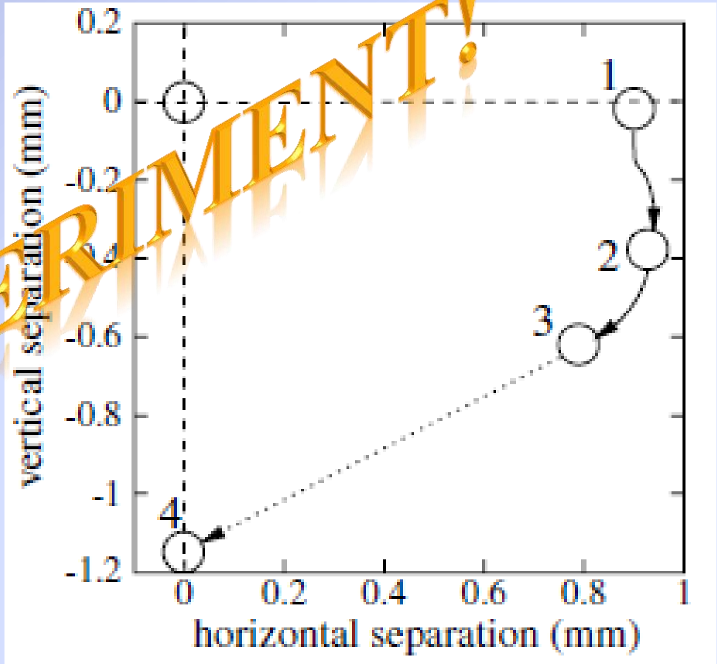
of particles

in complex plasmas

pairing instability: two identical particles

Experiments were conducted in argon at a pressure of 2Pa. Particle diameters of 7.6±0.1 µm (polystyrene microspheres). To confine the particles, a quartz glass cylinder is used. **Particle charge ~10000e**



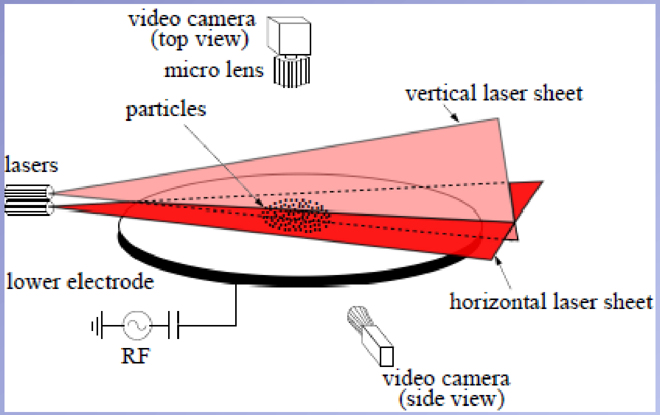


PIONEER EXPERIMENT!

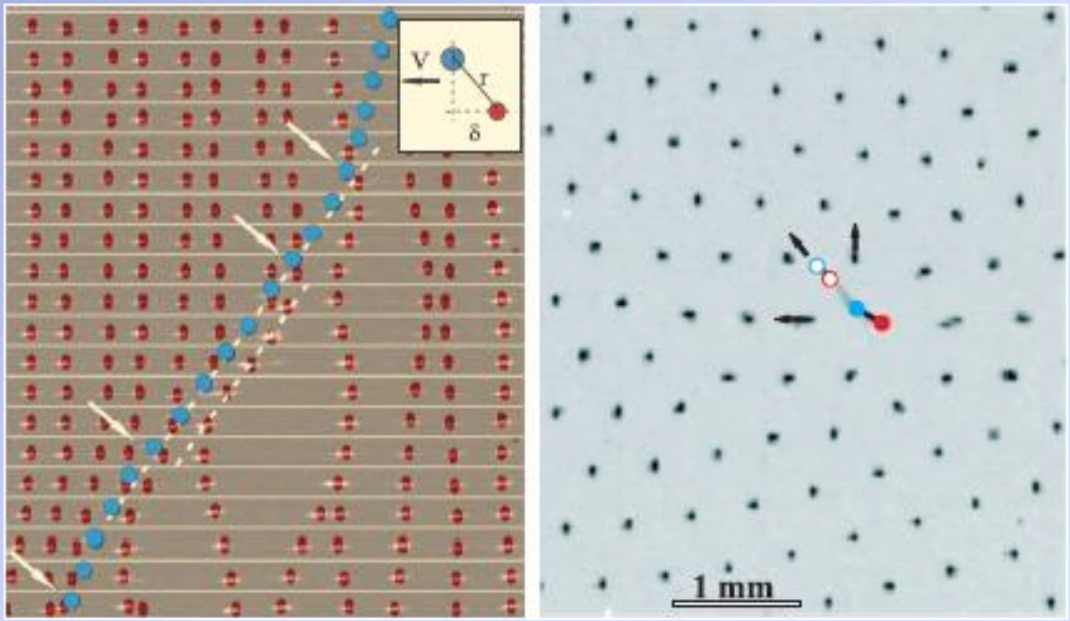
(left) experimental setup; (right) sequence of the relative particle positions during the pairing instability as the discharge voltage decreases in a sequence (1) 55 V (2) 45 V (3) 37 V (4) 36 V.

V. Steinberg, R. Sütterlin, A. Ivlev, G. Morfill, PRL (2001)

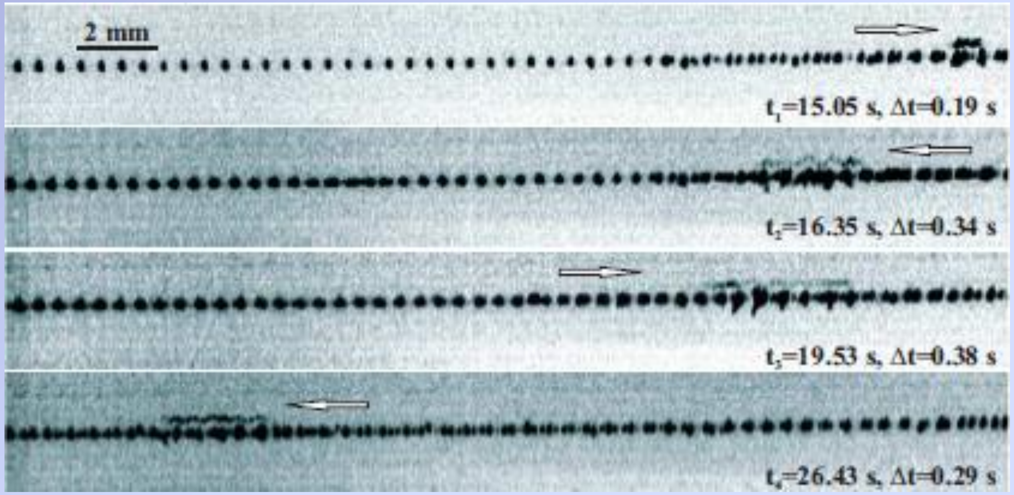
spontaneous particle pairing in a 2D plasma crystal



Experimental setup. Plastic microspheres (9.*19μm)* are confined in a stable single layer



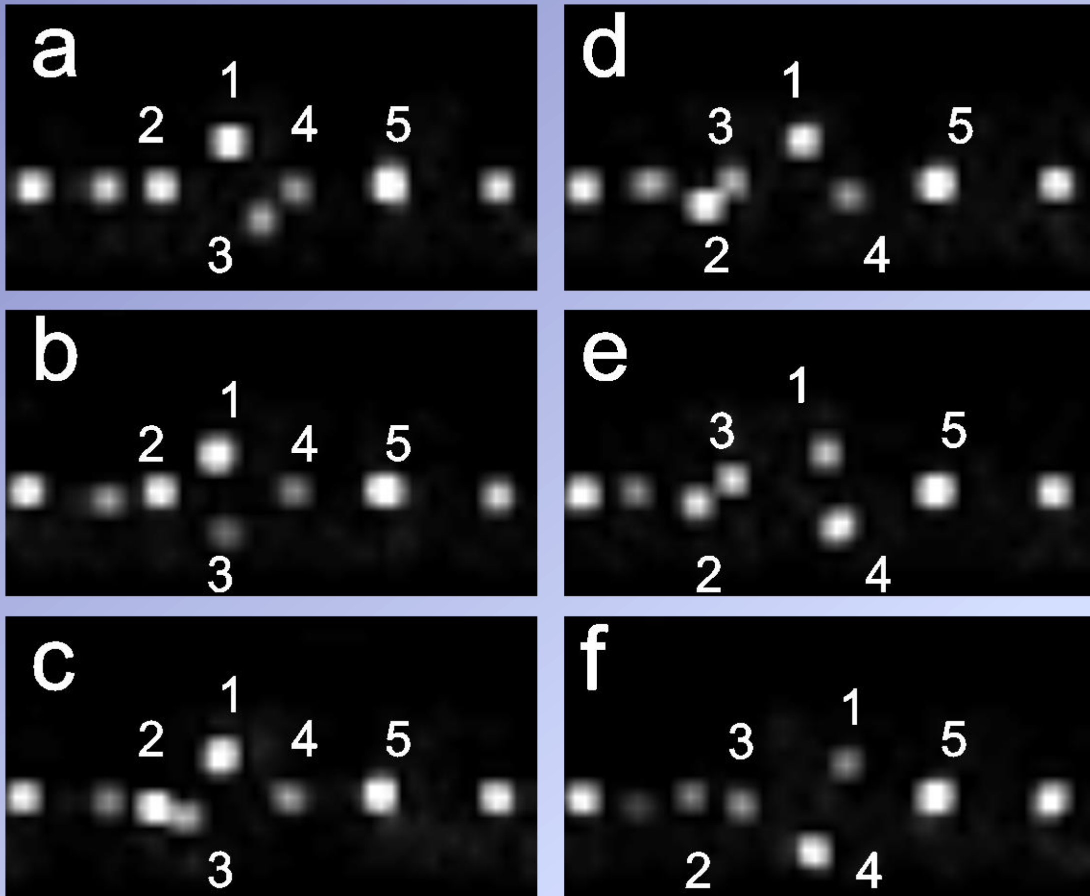
Pairing of an upstream particle with intralayer particles (side view)



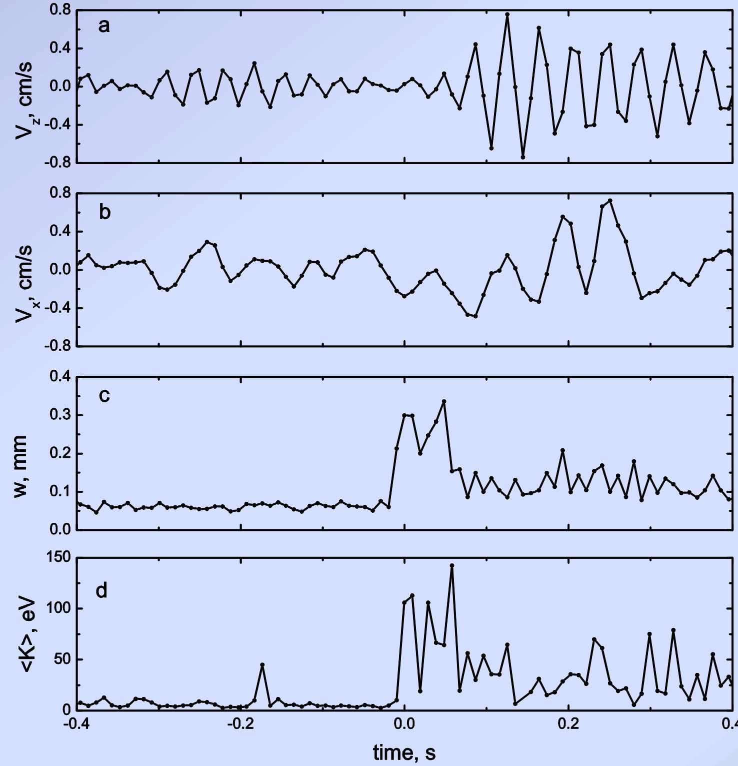
Traces of the fast-moving upstream particles

S. Zhdanov, V. Nosenko, H.M. Thomas, G. MorfillL, and L. Couëdel (PRE 2013)

entanglement events observed in a 2D plasma crystal



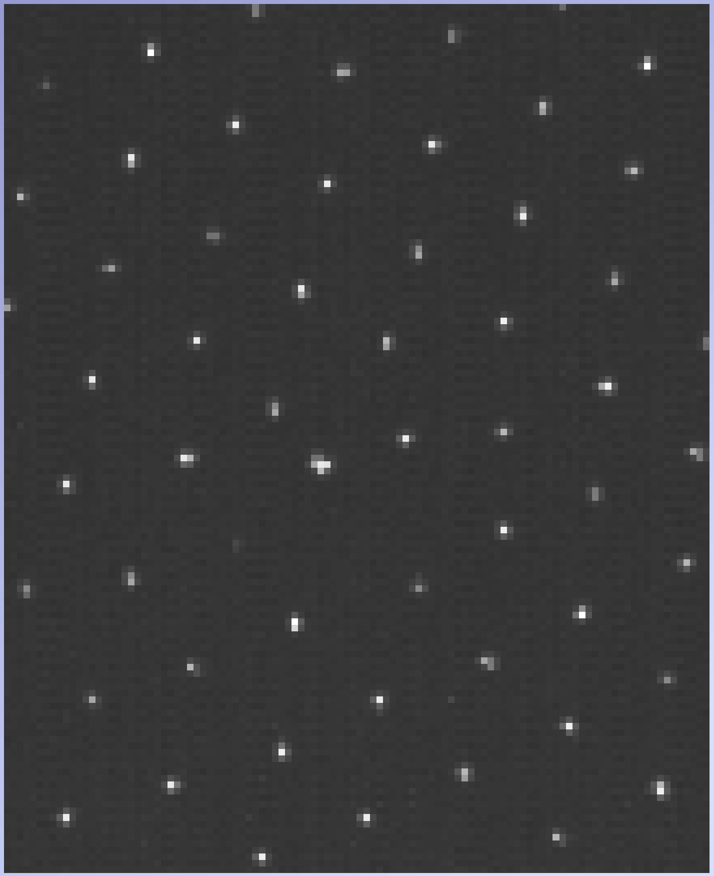
#5 works as a tracer:



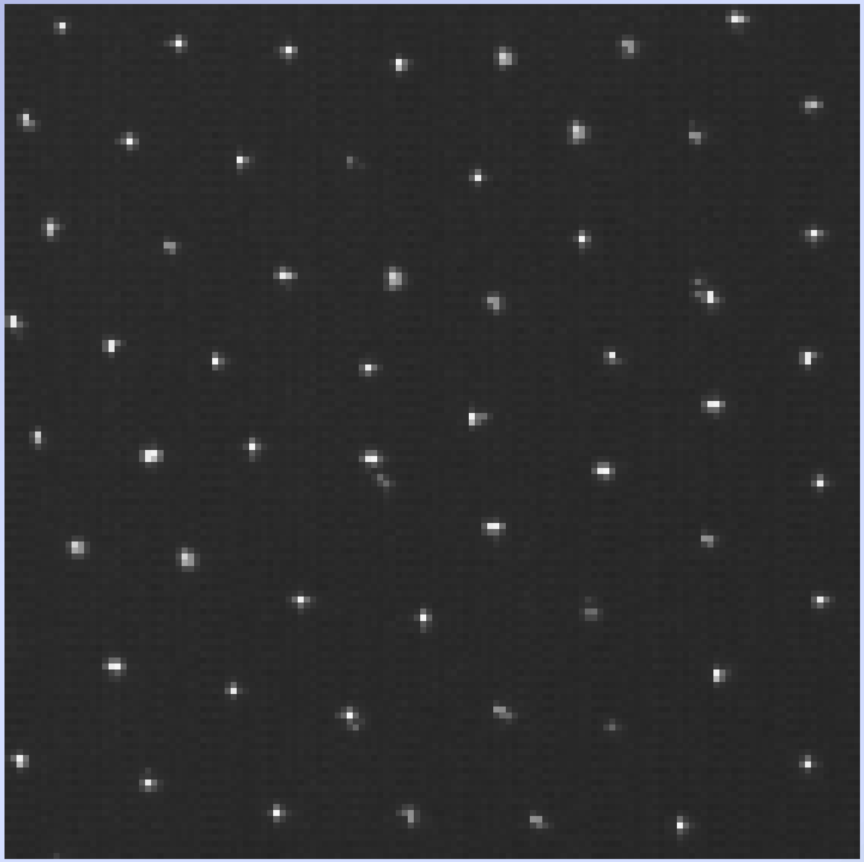
Wake-mediated entanglement of paired particles: Formation of a 'chain-train' of collisions resulting in successive interchange in the particle positions. The lifetime of entanglement is ~0.1 s.

S. Zhdanov, L. Couëdel, V. Nosenko, H.M. Thomas, G. MorfillL (Physics of Plasmas 2015)

problem of the entanglement lifetime: "torsions"



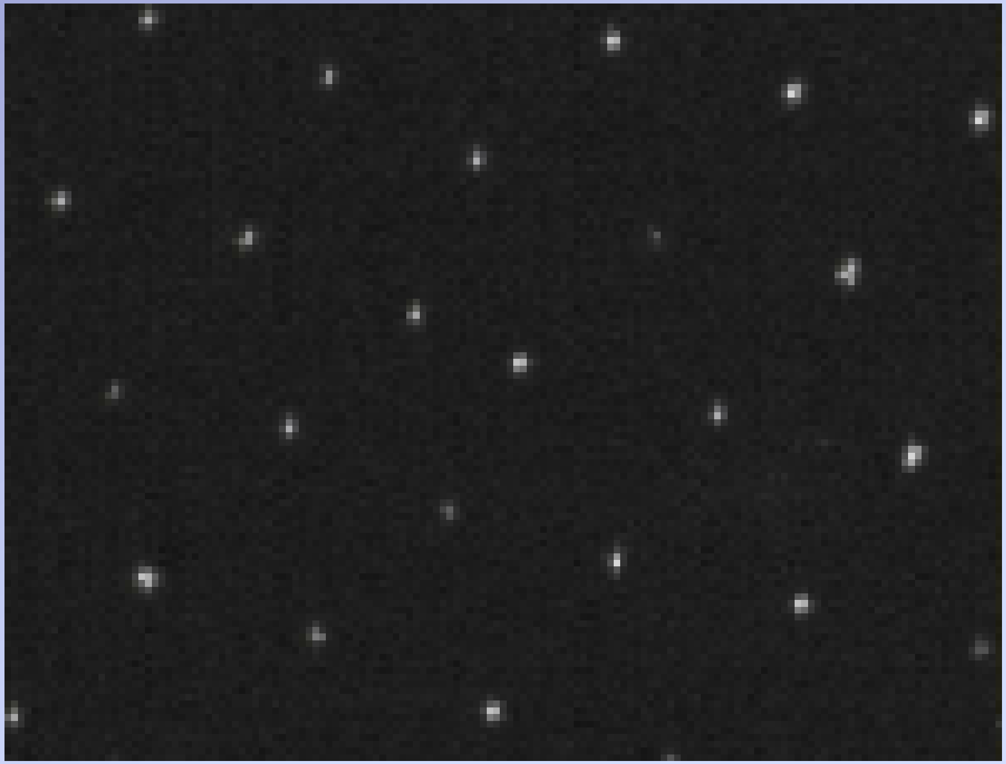
multiple events (recording time ~3 s)



single events (recording time ~0.7 s)

Courtesy V. Nosenko

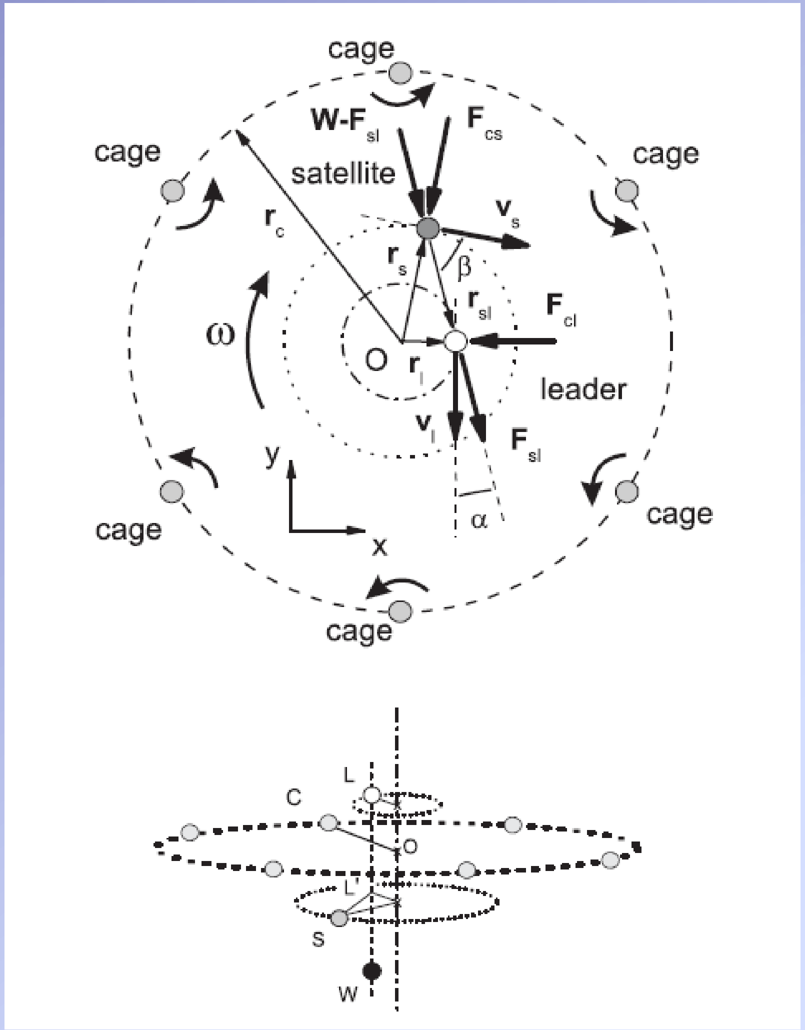
nucleation of a “torsion”

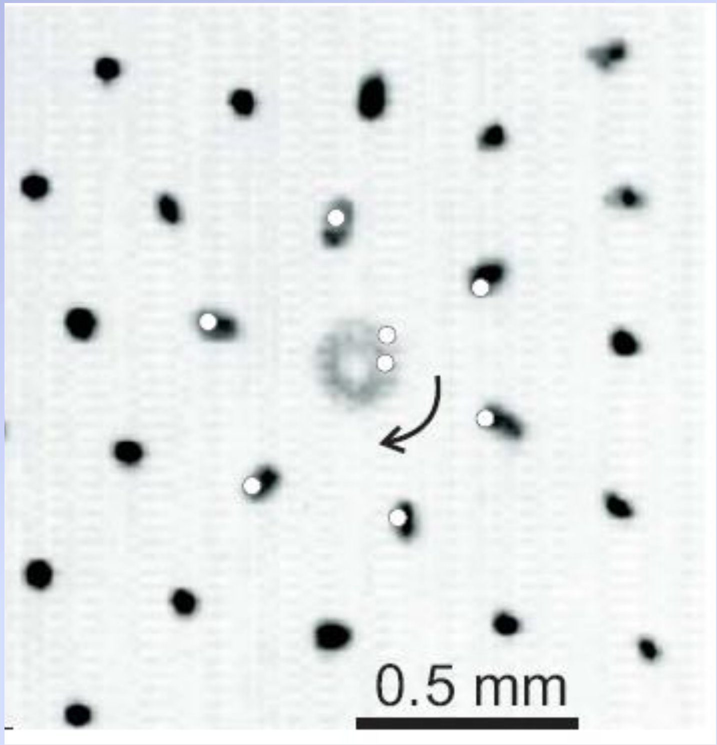


nucleation time ~0.3 s, revolution period ~7 Hz (recording time ~1.3 s)

Courtesy of V. Nosenko

simple model of a "torsion"

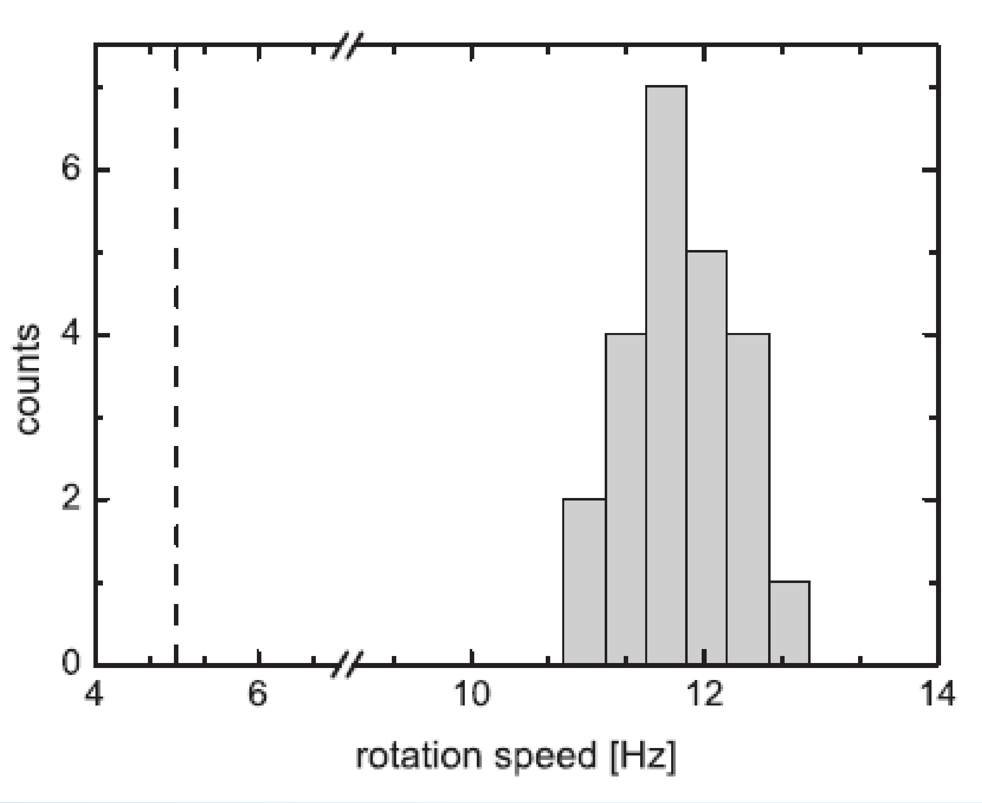




Spinning pair of particles (torsion) in a single-layer plasma crystal revealed by a superposition of 90 frames. The open circles indicate instantaneous positions .

V. Nosenko, S.K. Zhdanov, H.M. Thomas, J. Carmona-Reyes, and T.W. Hyde PRL (2015)

torsion rotation speed



Mean torsion rotation speed is

$\langle f \rangle$ = 11.8 Hz.

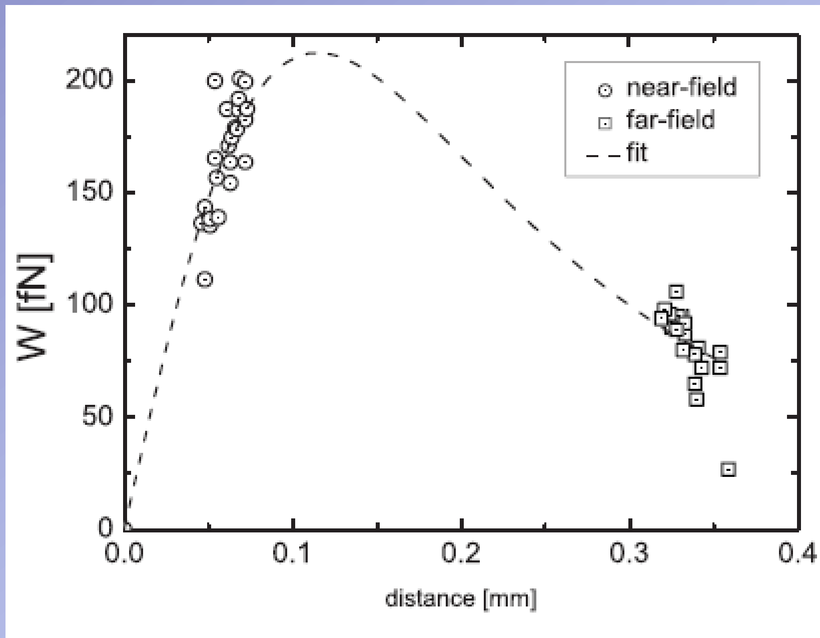
The vertical dashed line indicates the lower rotation speed limit

f_{min} = 5.0 Hz

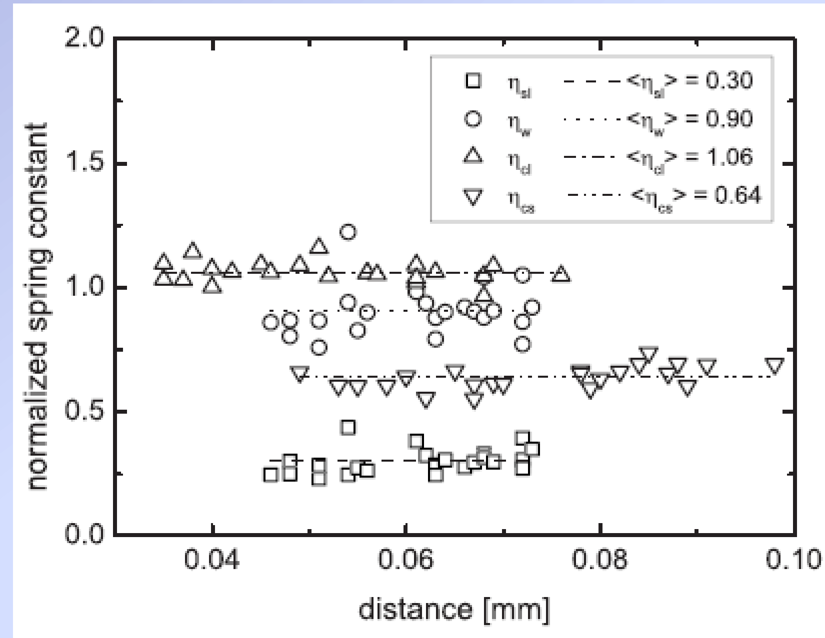
predicted by the theoretical model.

V. Nosenko, S.K. Zhdanov, H.M. Thomas, J. Carmona-Reyes, and T.W. Hyde PRL (2015)

spring constants and a wake field of a torsion



Wakefield force as a function of distance.
Lattice constant a=0.314 mm, particle charge Z=13700e, interaction range κ=1.17.



Spring constants of the wakefield (η_w) and interparticle interactions: satellite–leader (η_{sl}), cage–leader (η_{cl}) and cage–satellite (η_{cs}).

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“*Kill the flies and you starve the cats*.”

J. Walls “The Glass Castle”

summary:

- ***Energy and symmetry are favorable and reliable guides to study ‘delicate’ dynamic phenomena in complex plasmas.***
- ***Plasma crystals are perfectly suited to study symmetry alternations, linear and non-linear wave dynamics and synchronic oscillatory patterns.***
- ***Smart particles are a gift from Got. Therefore it is a sin not to use them.***

The submitted manuscript floating in the ISS. The apparatus on the left and the laptop in the background belong to the complex plasma experiment.

Photograph courtesy of RSC-Energia