Intro to Fusion Energy and Plasma Physics Course
PPPL SULI, June 25, 2020

Complex (Dusty) Plasmas

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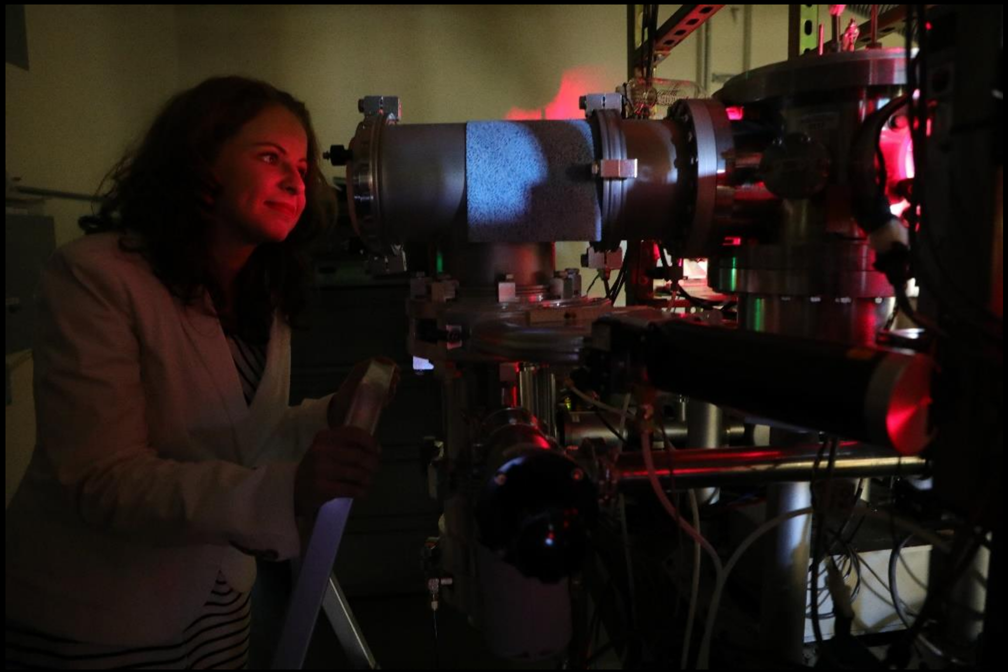
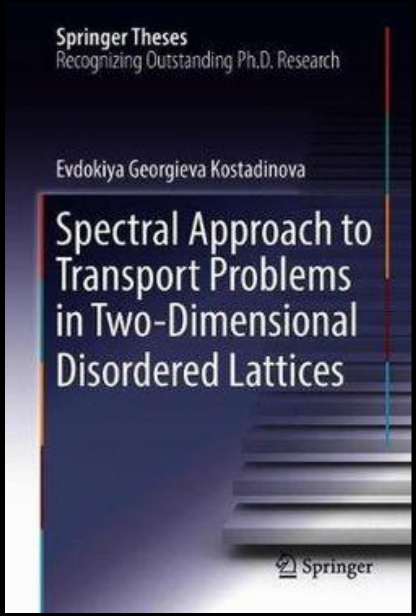
Outline

- **Part I:** It's a dusty Universe
- **Part II:** Experiments and phenomena
- **Part III:** Dusty plasma theory
- **Part IV:** Order and disorder

Evdokiya (Eva) Kostadinova

- Assistant Research Professor, Baylor
- PhD Physics, Baylor, Dec 2017
- Transport problems in disordered matter with nonlocal interactions → dusty plasma



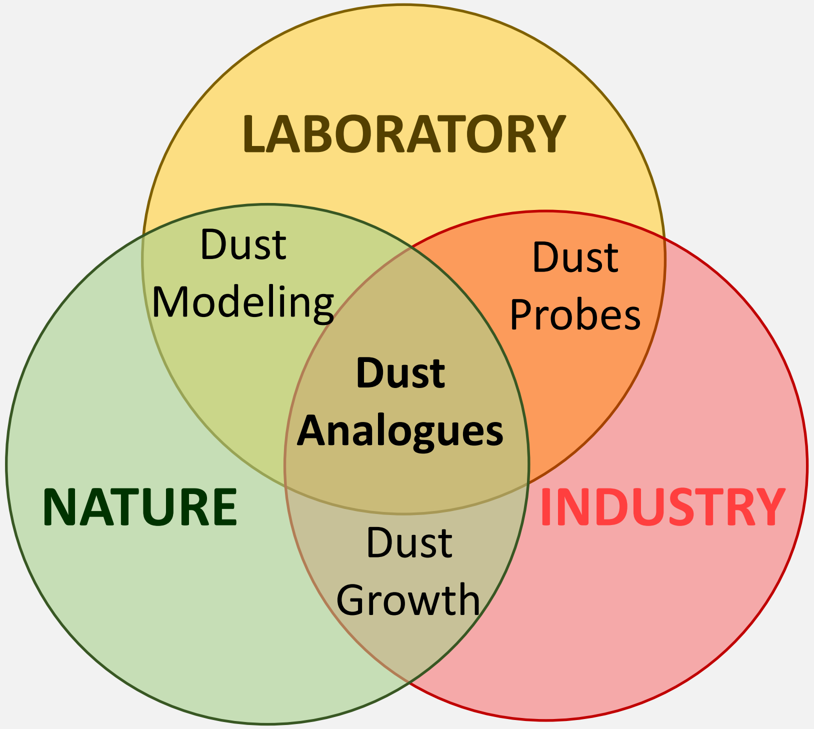


- Female international student
- BS from Furman University (small, liberal arts school)
- Interdisciplinary research b/w math and physics

Part I: It’s a dusty Universe

Scope of Dusty Plasma Research

- Dusty plasmas are four-component plasmas consisting of electrons, ions, neutrals and charged, solid or liquid particulates (“dust”).
- Dust particles can appear in plasmas over vast scales – from laboratory to astrophysical systems.



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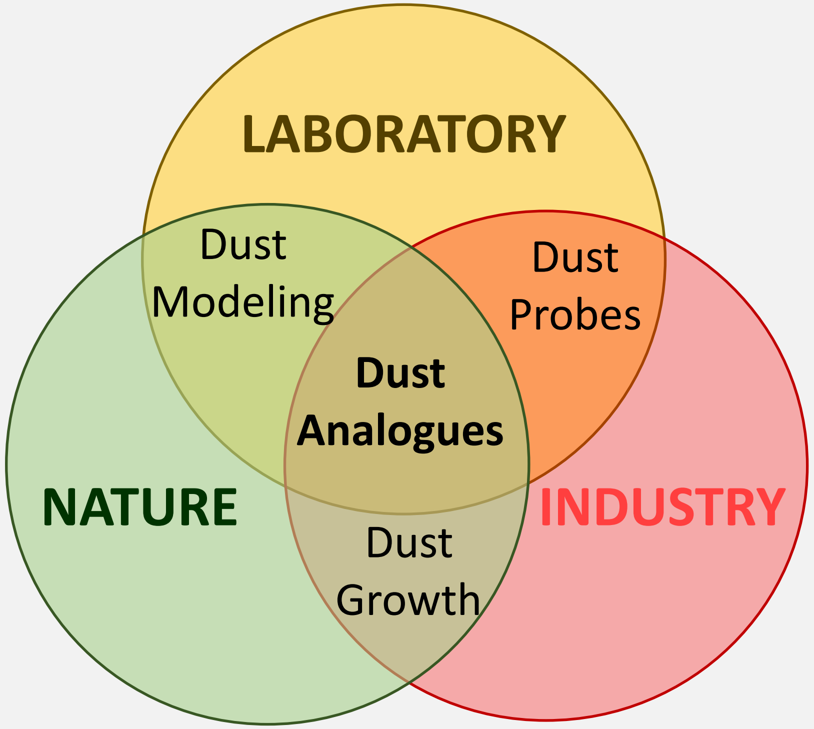

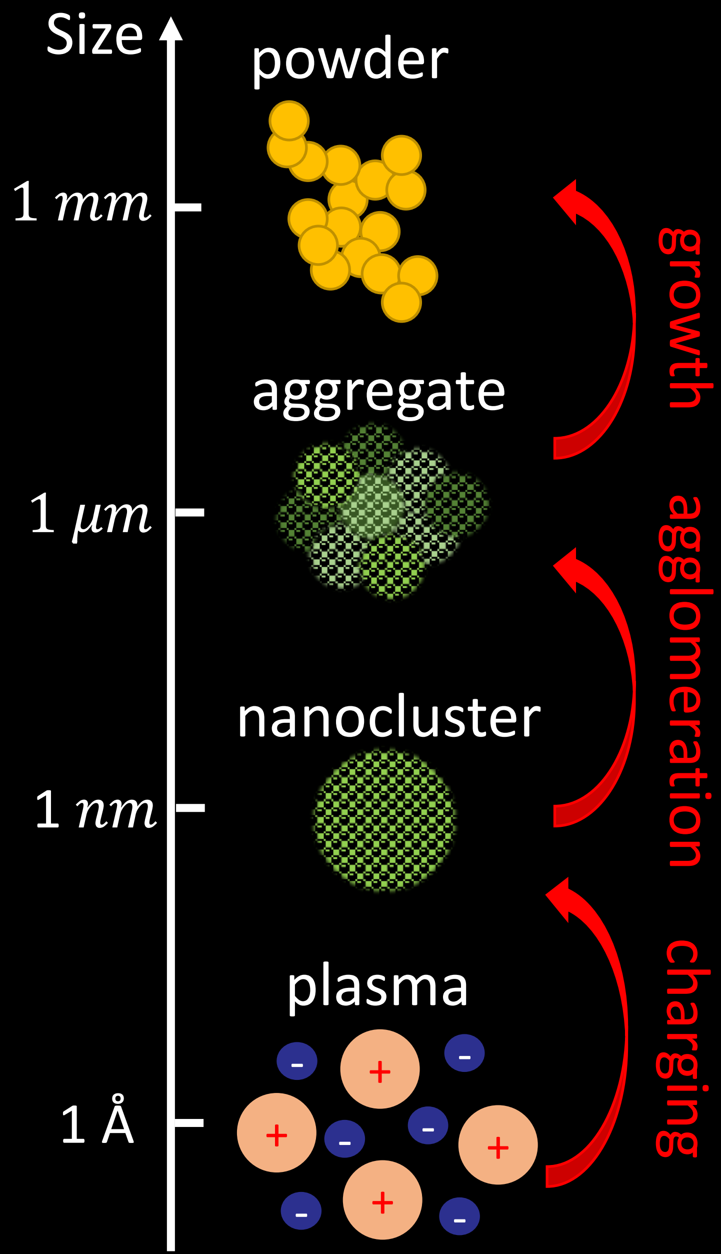

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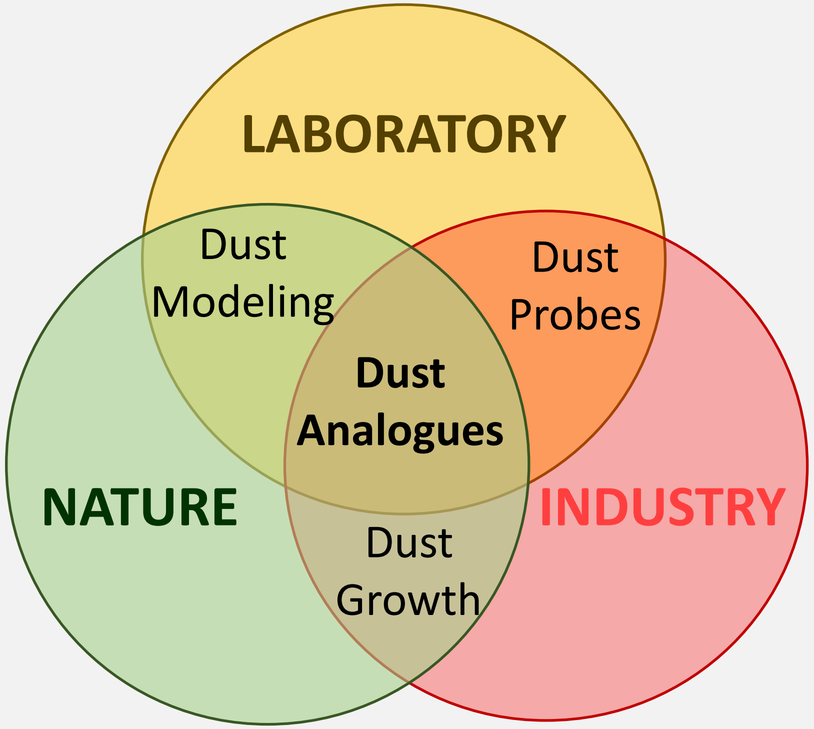
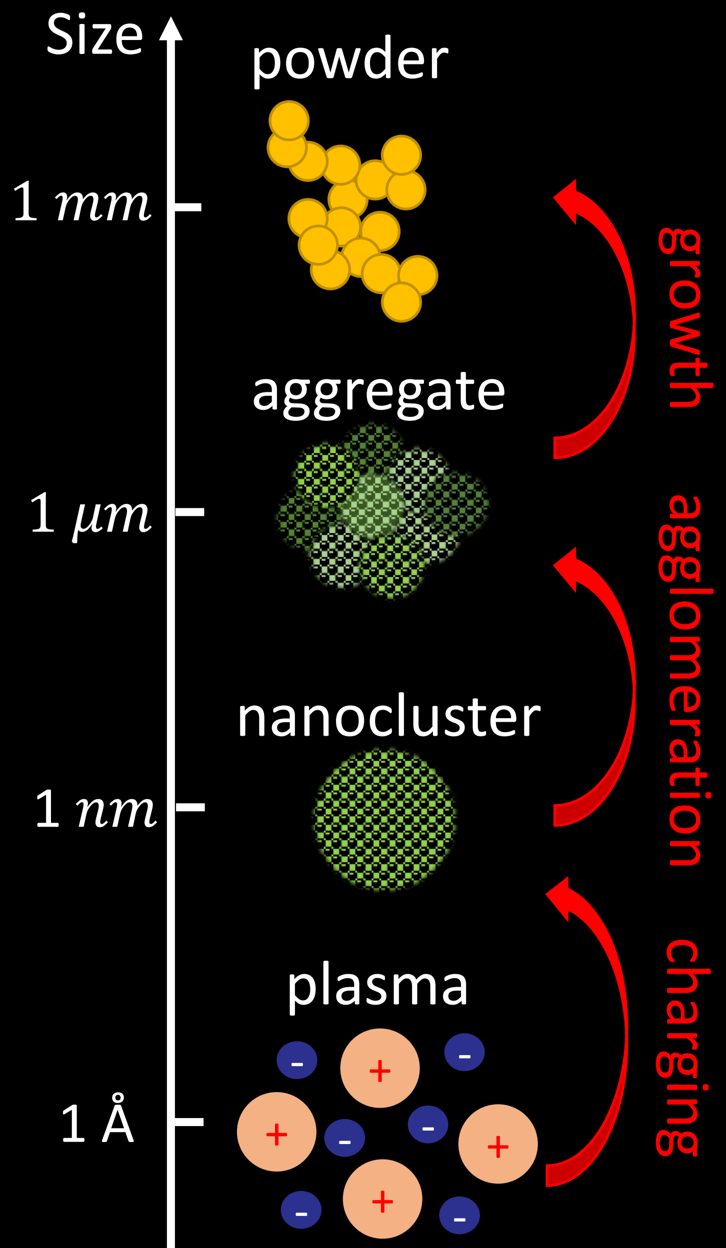
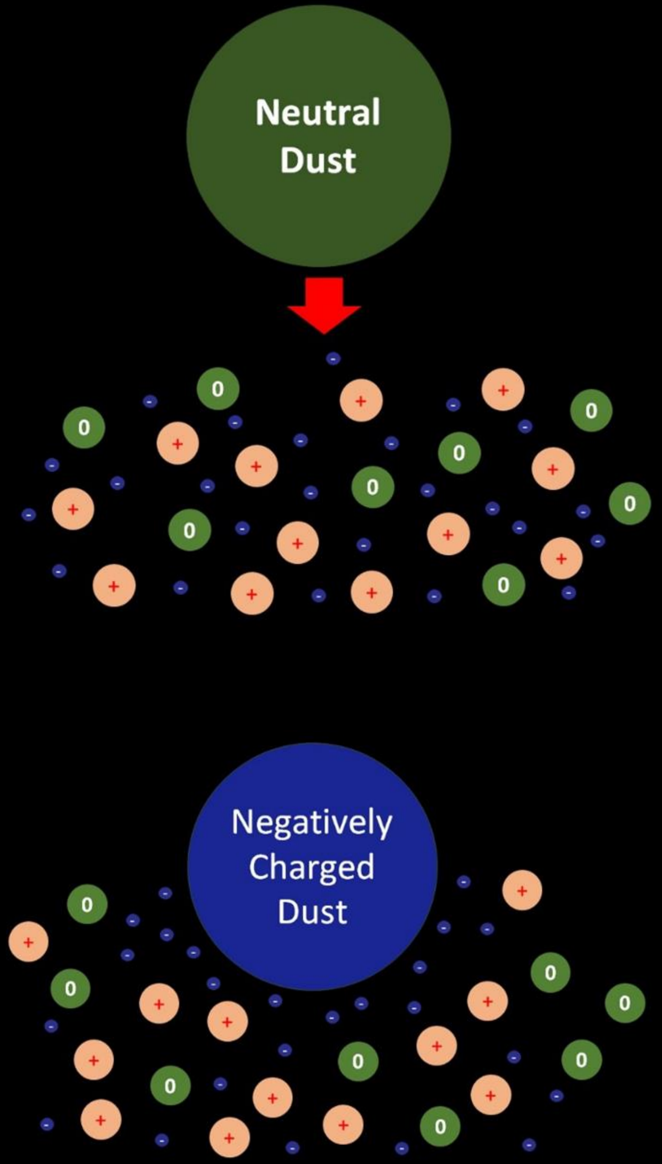
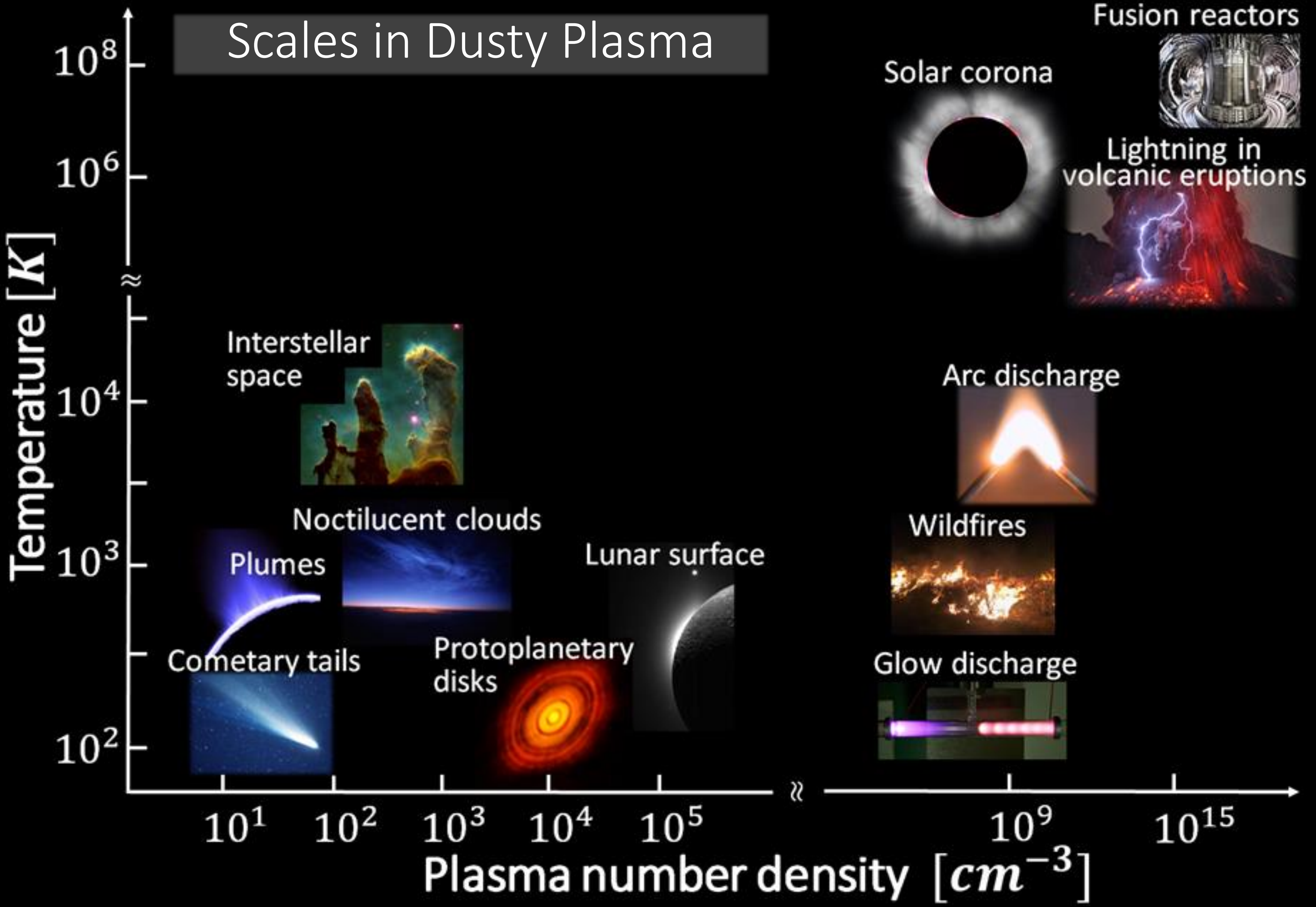


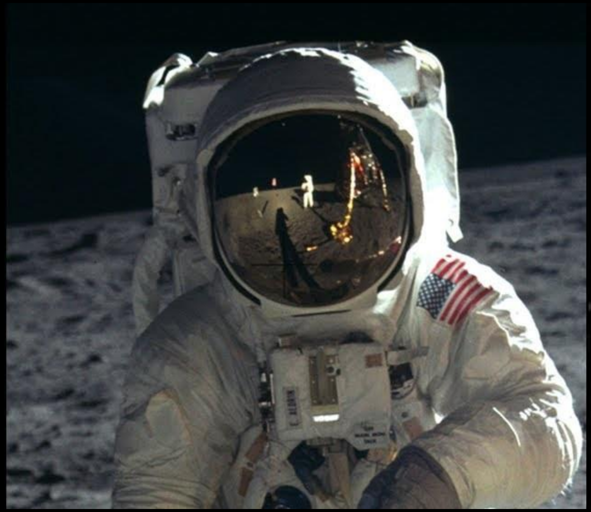


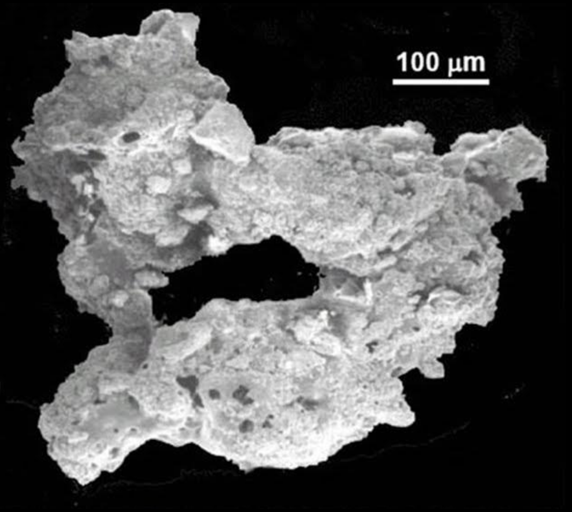


Scales in Dusty Plasma



Dusty Plasmas on the surface of the Moon





"…lunar dust, itself the Number 1 environmental problem on the Moon."

O'Brien, B. J., & Gaier, J. R. (2009, November). Indicative Basic Issues About Lunar Dust in the Lunar Environment. In *Annual Meeting of the Lunar Exploration Analysis Group* (Vol. 1515, p. 52).

Lunar tattoos (swirls)

Credit: NASA, JPL, USGS

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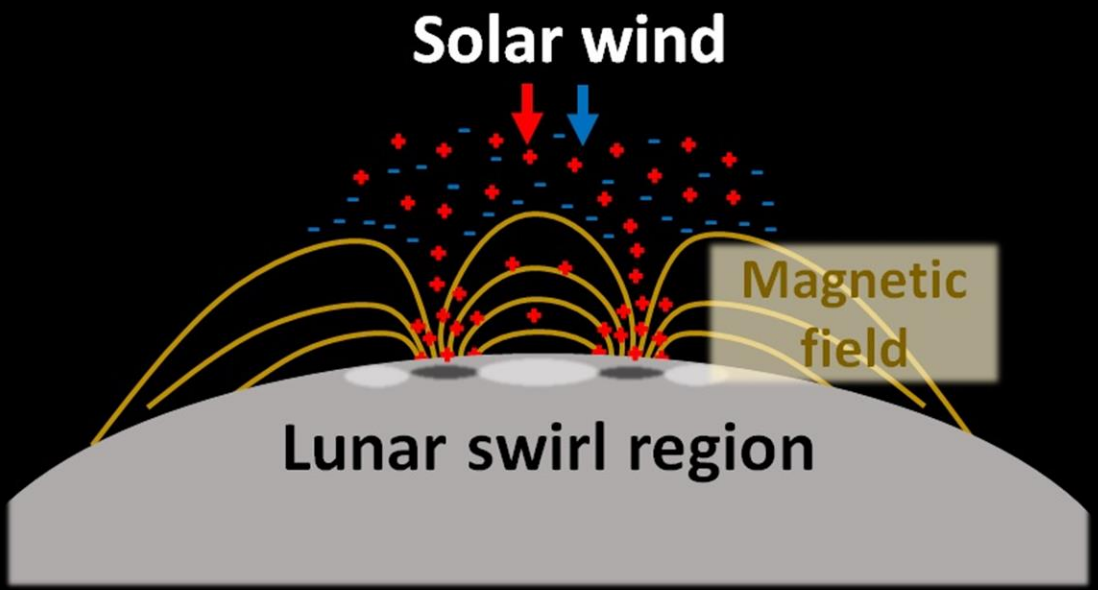

Lunar tattoos (swirls)

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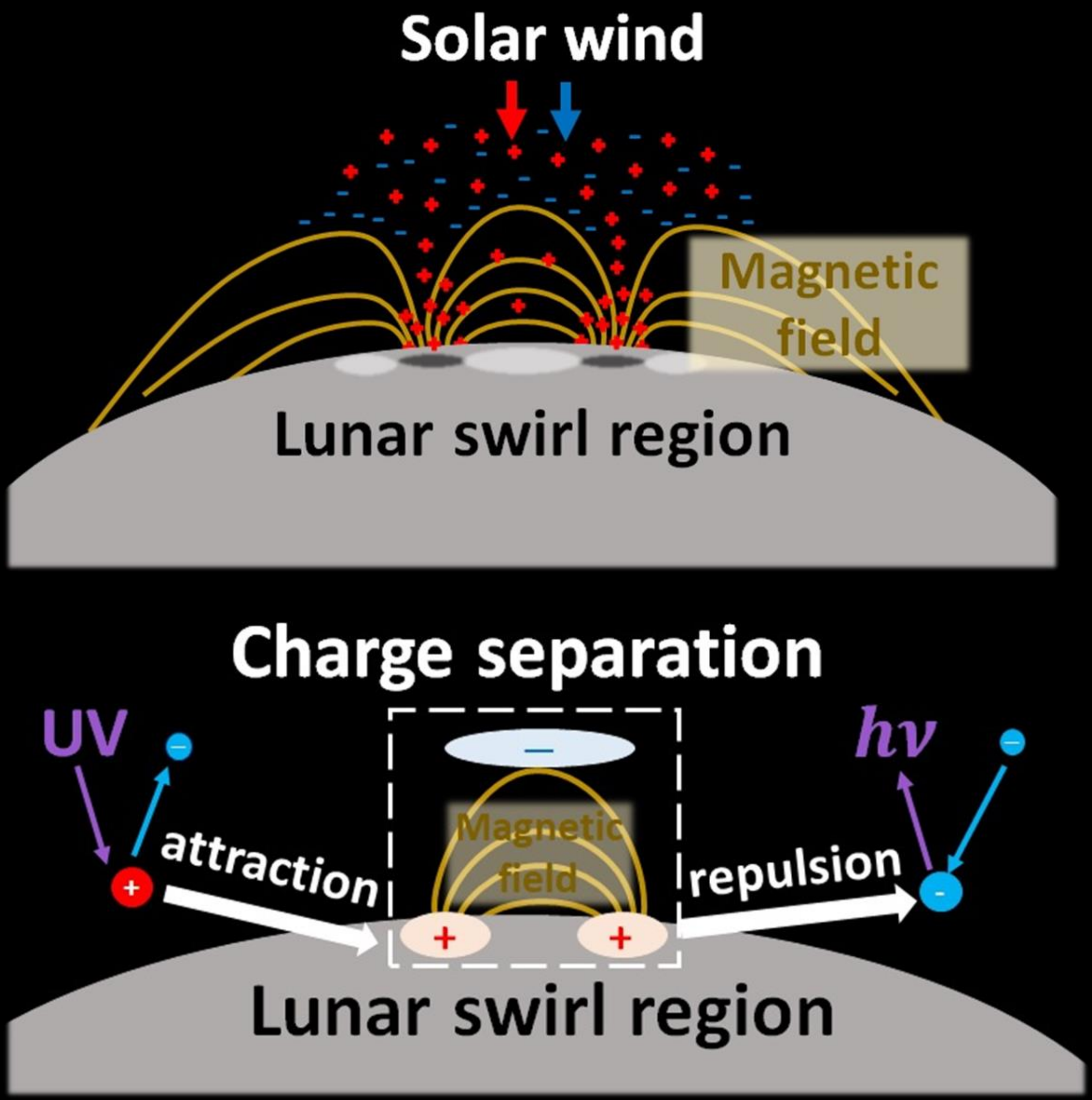
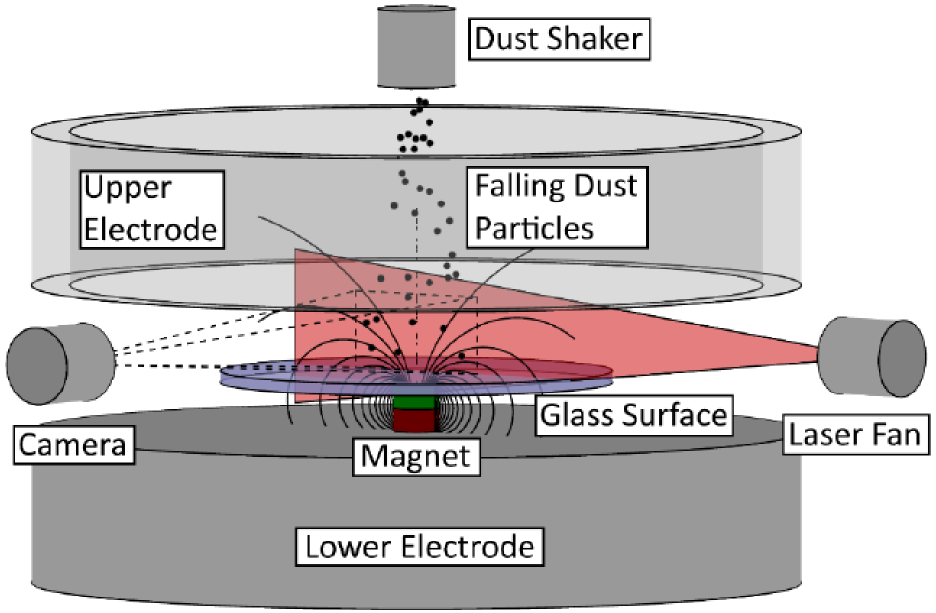
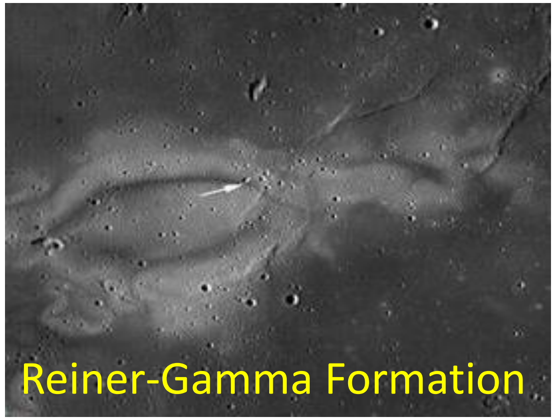
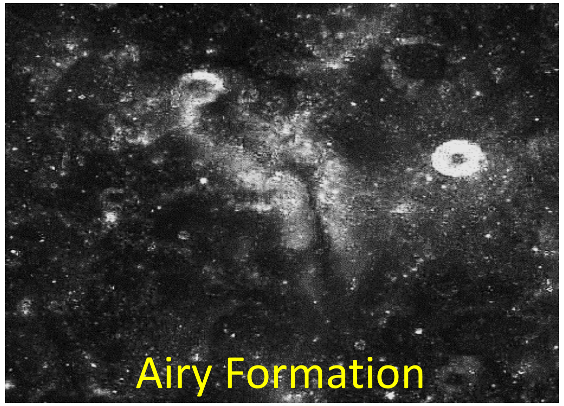
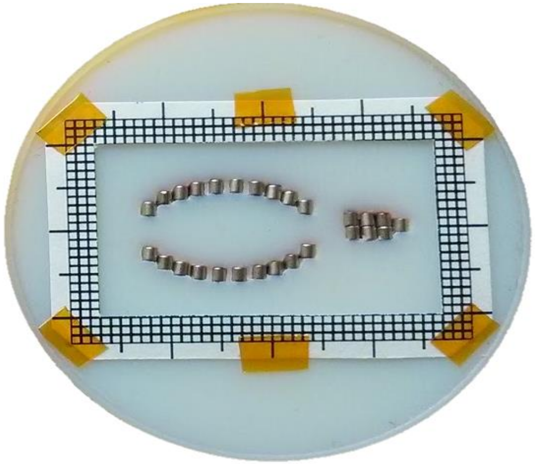


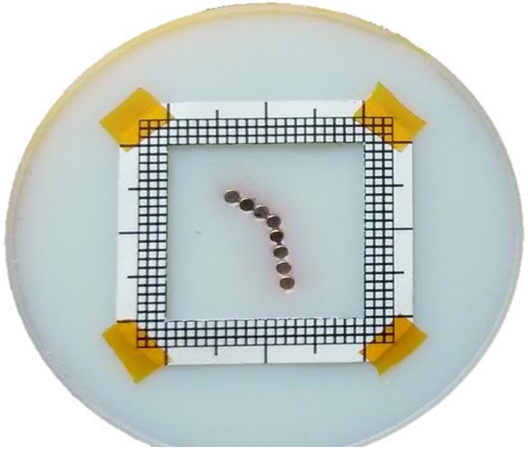
Scaling of Lunar Swirls



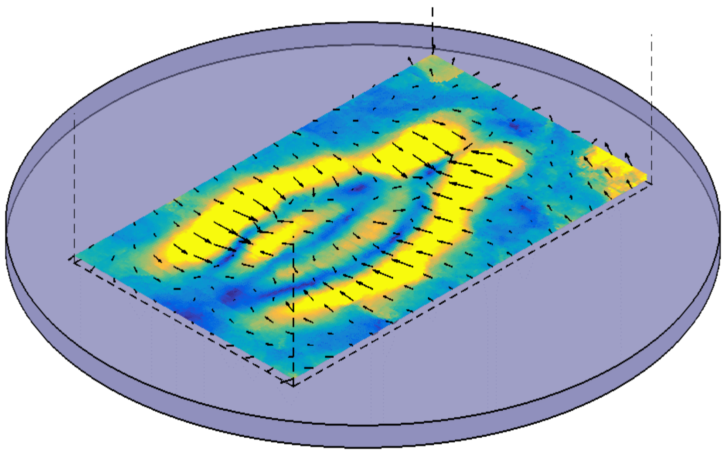


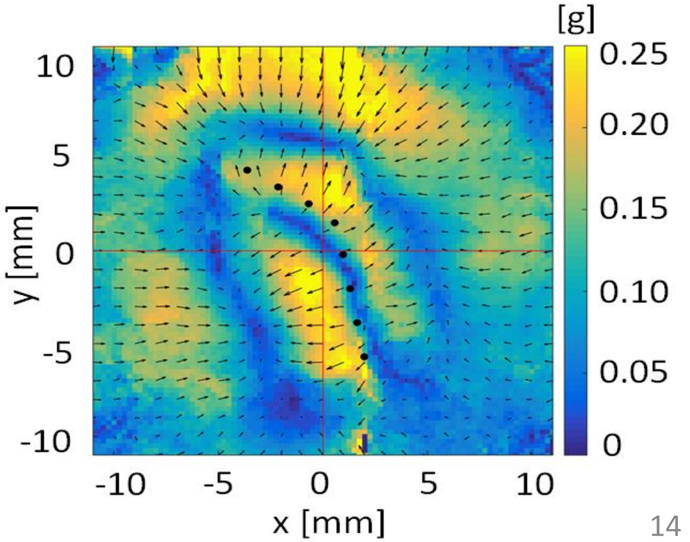






- Interaction b/w the solar wind and weak B-field in the lunar crust yields lunar dust transport and formation of lunar swirls $\sim 100\ km$ in size.
- Similar processes seem to guide dust transport in laboratory plasmas and the formation of dusty plasma swirls $\sim 20\ mm$ in size.

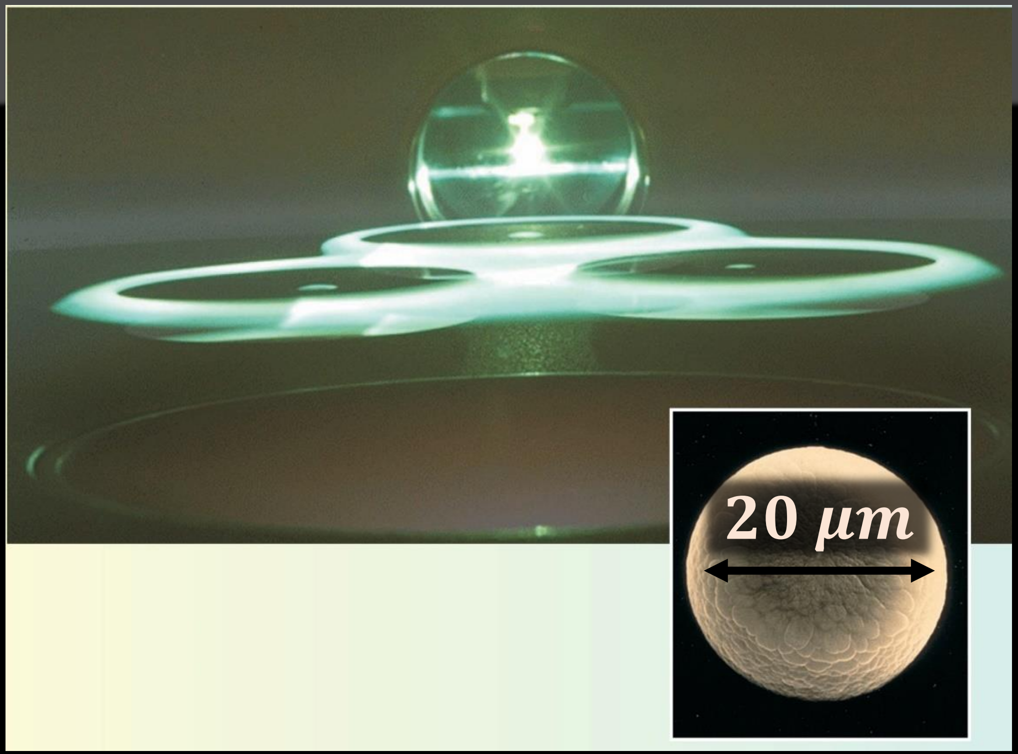


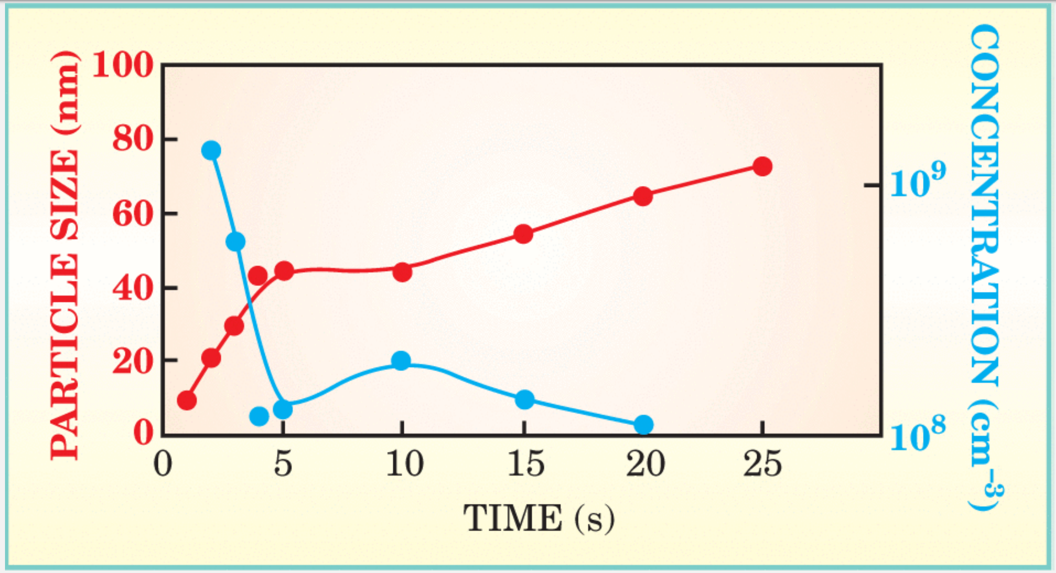


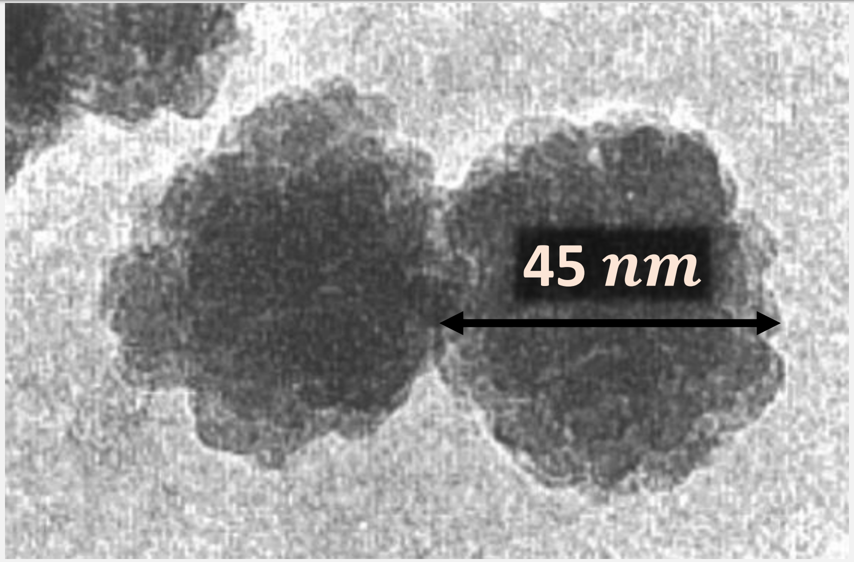
Credit: CASPER lab, Baylor

Dusty plasmas in industry

- Up to **50%** of all semiconductor chips are contaminated during processing due to dust formation.
- **“Killer Defects”** are caused by dust larger than half the width of an etched feature on the wafer
- The U.S. semiconductor industry generated global sales of **$166 billion** out of a $335 billion total market in 2015





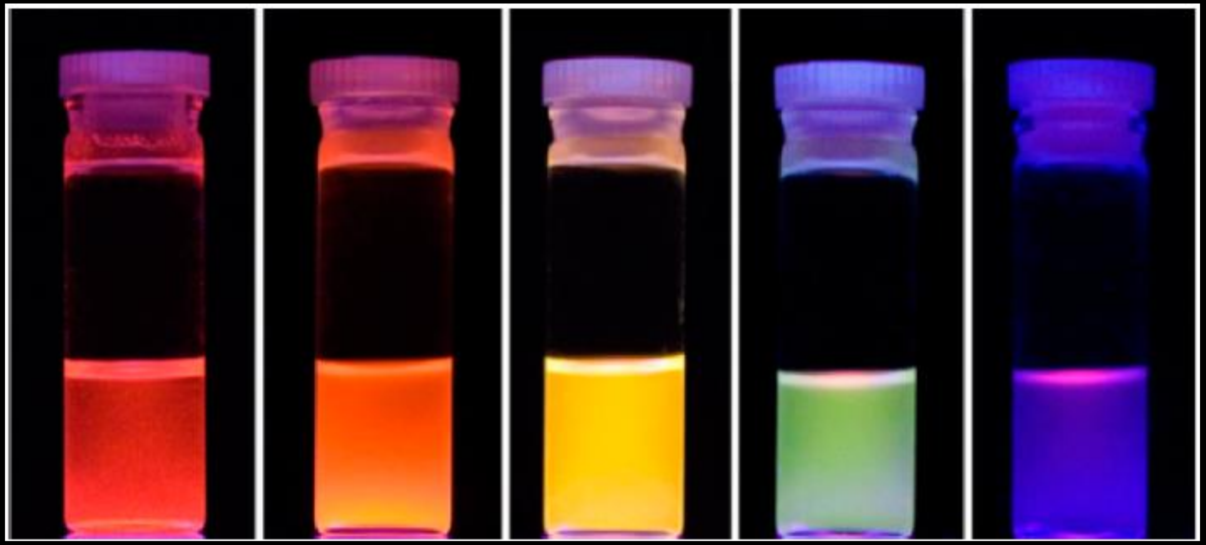


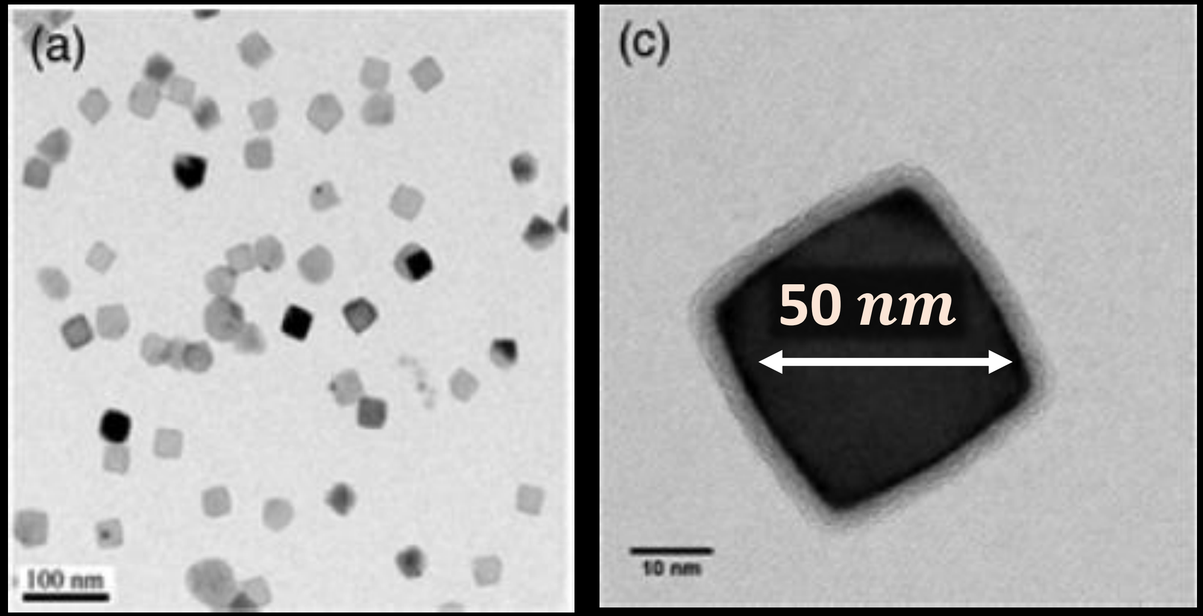
Merlino, R. L., and J. A. Goree. *PHYSICS TODAY.* 57.7 (2004)

Dusty plasmas in industry

Nonthermal plasma synthesis of nanocrystals

- Nanoparticles are intensely heated by surface reactions → **high melting point materials** can be synthesized
- Charging of nanoparticles reduces agglomeration → synthesis of **very small nanocrystals** with diameters 2 - 10 nm
- In 2017, US nanotechnology industry had market value of ≈$49 billion and is projected to have **$76 billion by 2020**





Kortshagen, Uwe R., et al. Chemical reviews 116.18 (2016).

Particulates in Edge Plasma → Interfacial Plasma Physics

"Dust" Particulates

- **wall material** — ***Natural***
- **pellets / powders** — ***Introduced***

Topics in interfacial plasmas

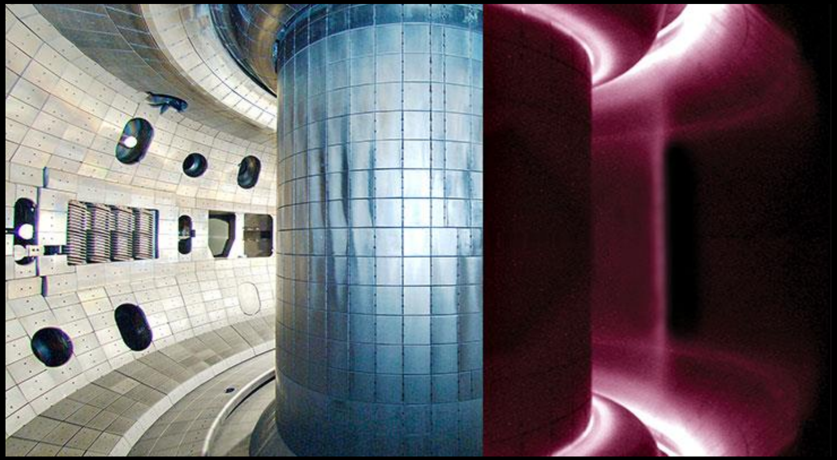
- ***Charge & dynamics:*** strong B-field, thermionic emission, fast flows of ions
- ***Cooling mechanisms:*** radiation vs. ablation at the plasma-dust interface
- ***Diagnostics:*** real-time detection and measurement of dust dynamics and properties

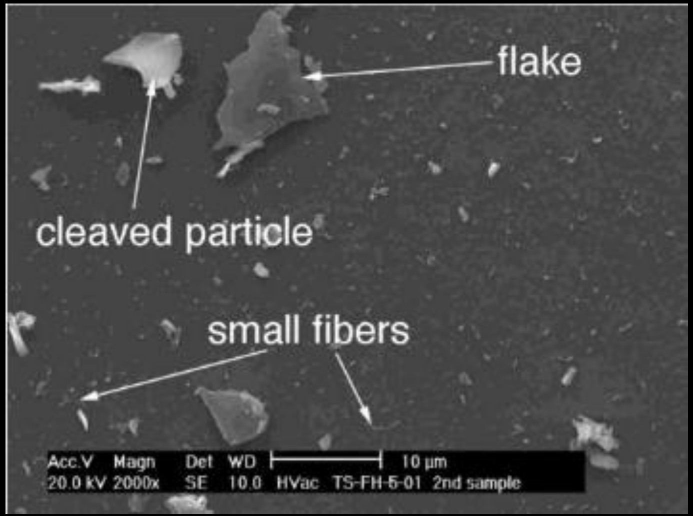
Plasma Parameters

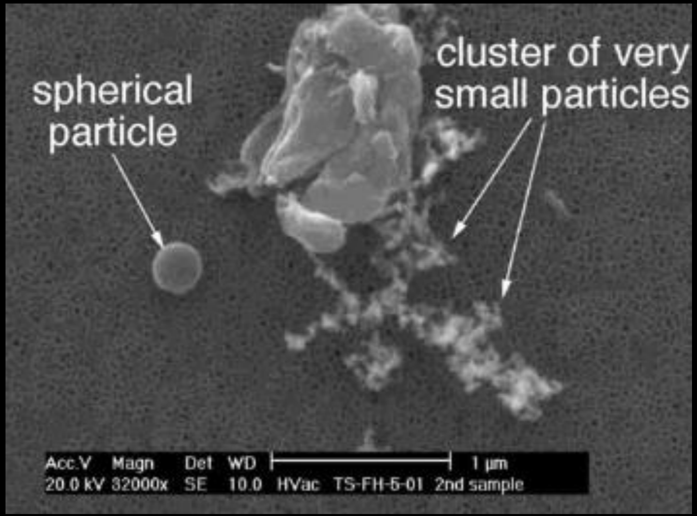
$$n = 10^{17} - 10^{20} m^{-3}$$
$$T_e = 1 - 100 eV$$
$$B = 1 - 10\ T$$

Grain Parameters

$$r_d = nm - cm$$
Material: Be, C, W
$$v_d = 10 - 60\ m/s$$







Sharpe, J. P., Petti, D. A., & Bartels, H. W. (2002). *Fusion Eng & Design*, *63*, 153-163.

Particulates in Edge Plasma → Interfacial Plasma Physics

“Dust” Particulates

wall material — ***Natural***

pellets / powders — ***Introduced***

Frontier Science in Tokamaks

- ❑ Expose material samples to edge or scrape-off layer regions, where high plasma velocities result in high heat fluxes
- ❑ Simulate hypervelocity entry of solid projectiles, meteorites and probes, into high density atmosphere
- ❑ Study materials for thermal shields

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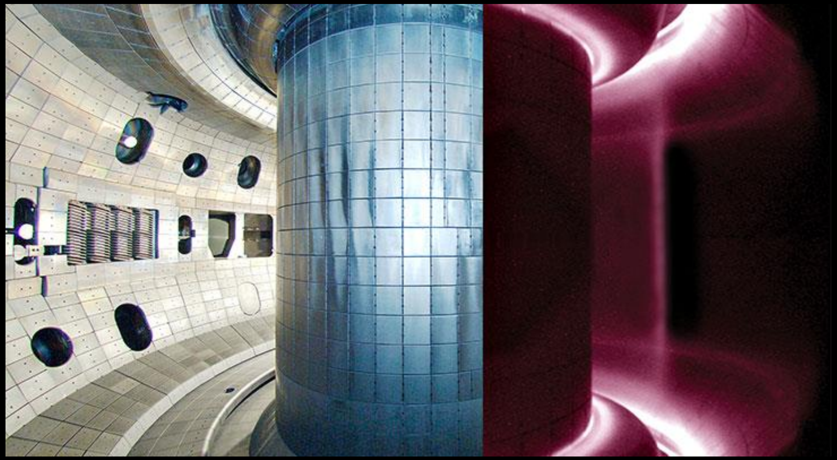

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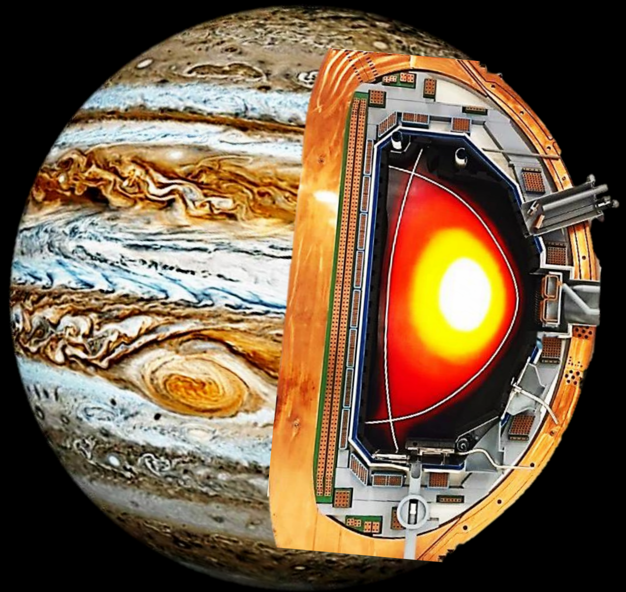

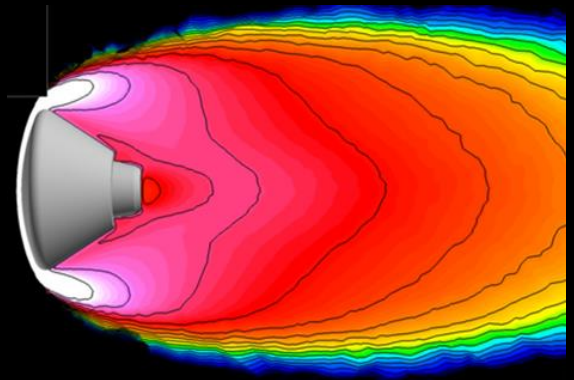

Why Dusty Plasma Physics is a separate field?

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Has been around longer than you think

Early temperature
measurement in a dusty plasma

R. Marlino, 2007 Summer College on Plasma Physics, Abdus Salam International Center for Theoretical Physics

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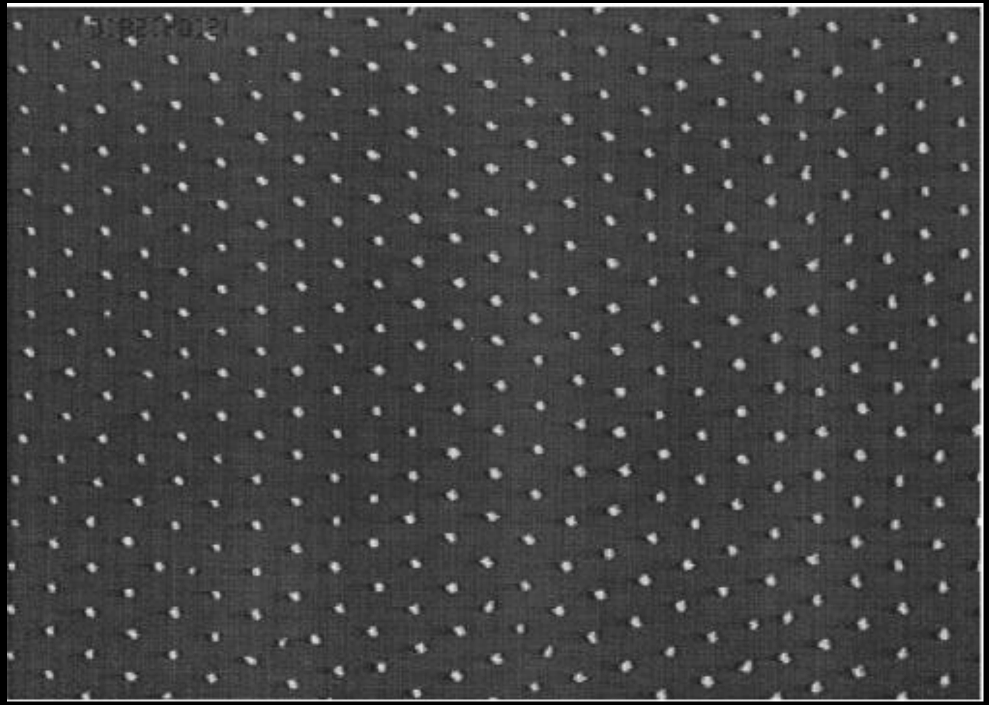
More fundamental than you think

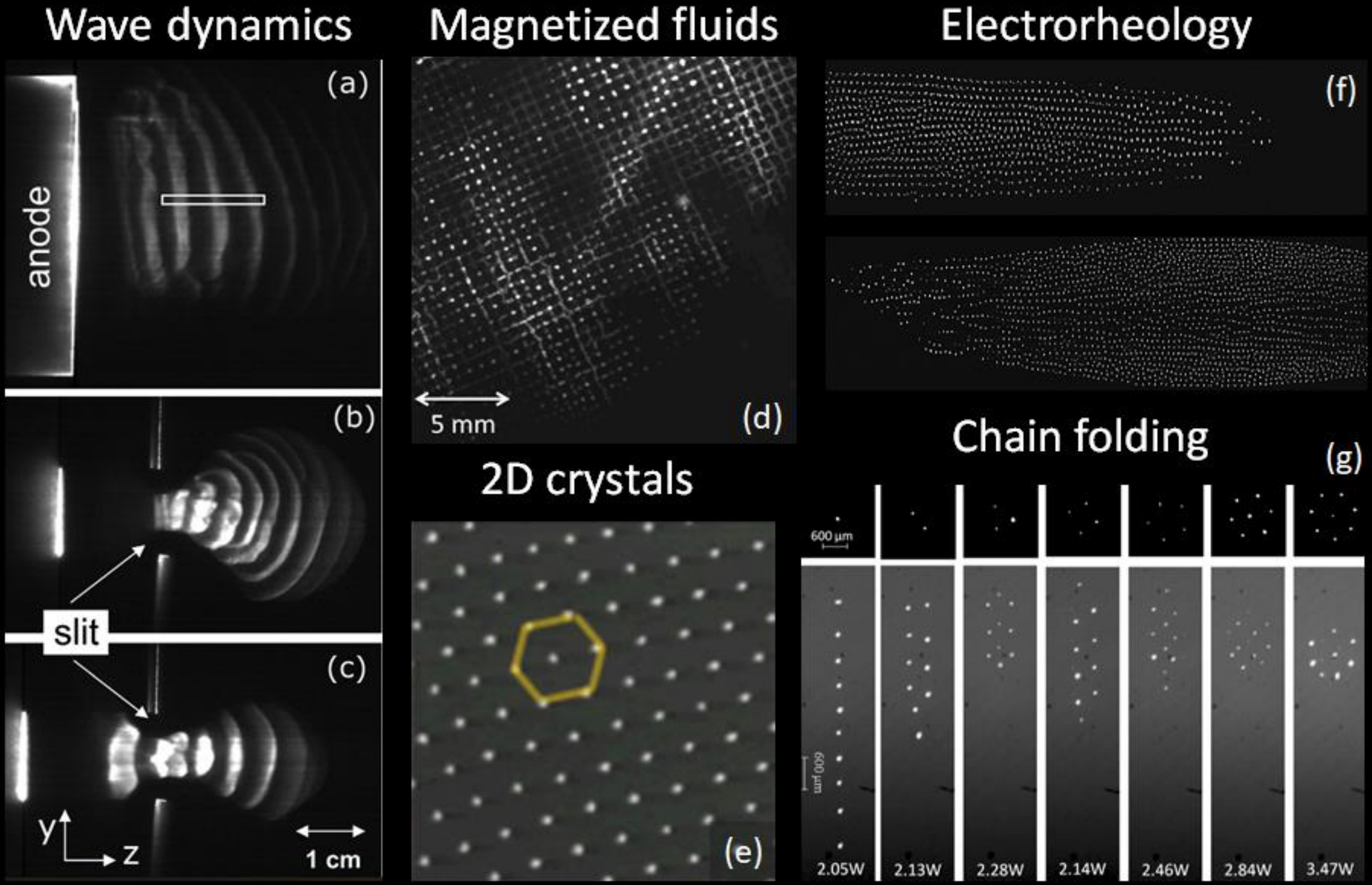


The discovery of the world's
first 2D dusty plasma crystal

Morfill, G. E., and H. Thomas. "Plasma crystal." Journal of Vacuum Science & Technology A, 14.2 (1996): 490-495.

Part II: Experiments and phenomena

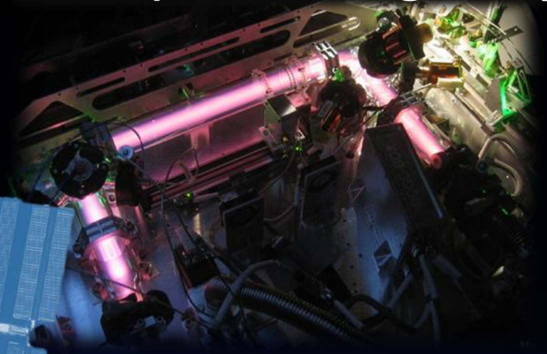
Outline

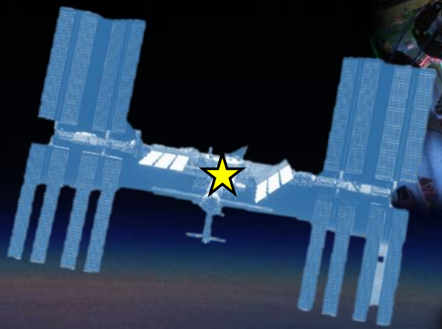

Wave dynamics
Magnetized fluids
Electrorheology
(a)
anode
(b)
slit
(c)
y
z
1 cm
5 mm
(d)
2D crystals
(e)
(f)
Chain folding
(g)
600 µm
600 µm
2.05W
2.13W
2.28W
2.14W
2.46W
2.84W
3.47W

International Collaborations in Dusty Plasmas

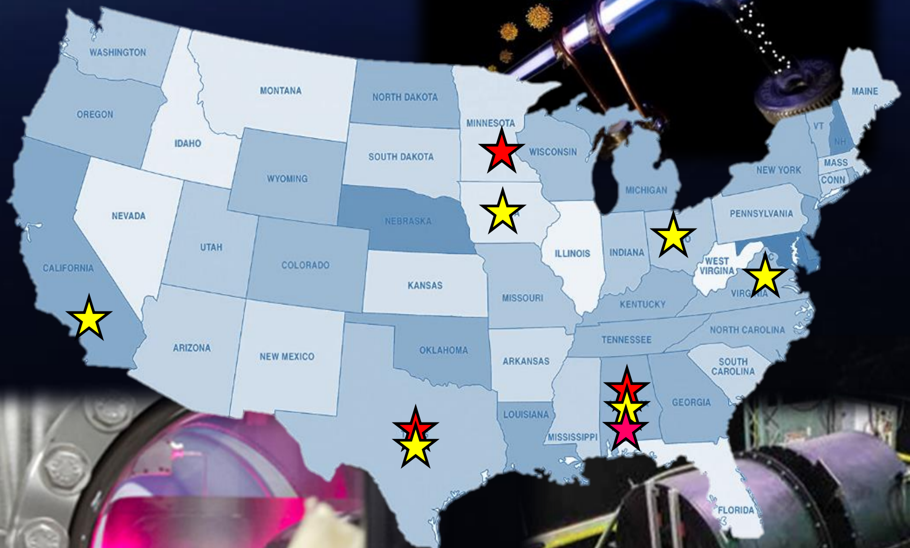
- ❑ **Expand and explore large parameter space**
- ❑ **Evaluate techniques in various conditions**
- ❑ **Develop advanced numerical simulations**

PK-4 (DC, microgravity)

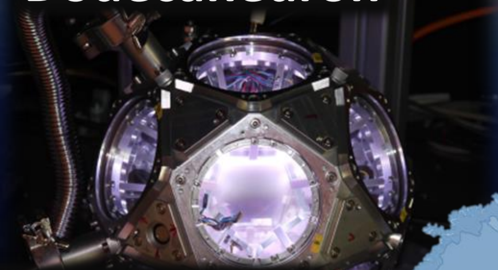




Reactive Plasma

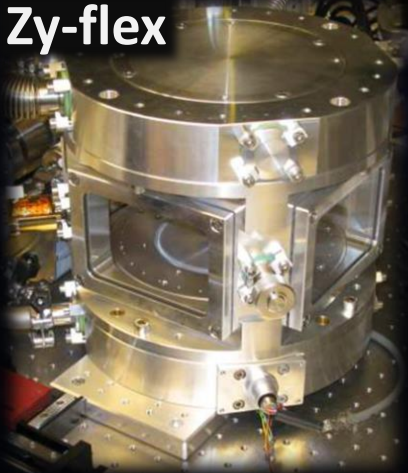


Dodecahedron



(tailored electric fields)

Zy-flex

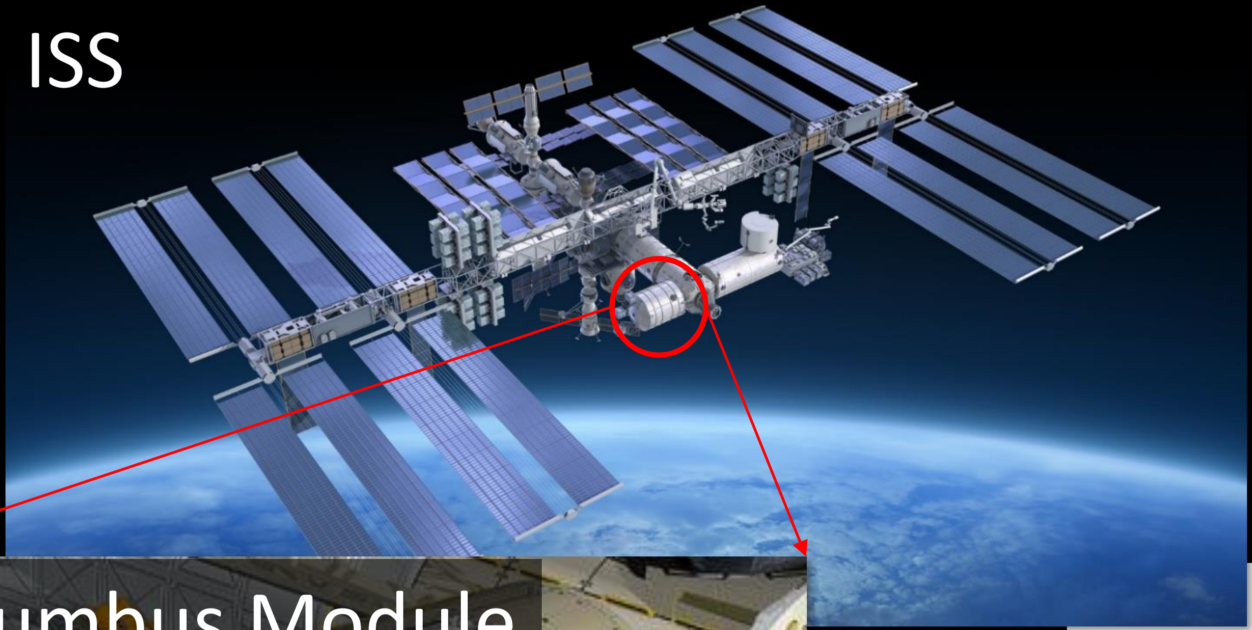


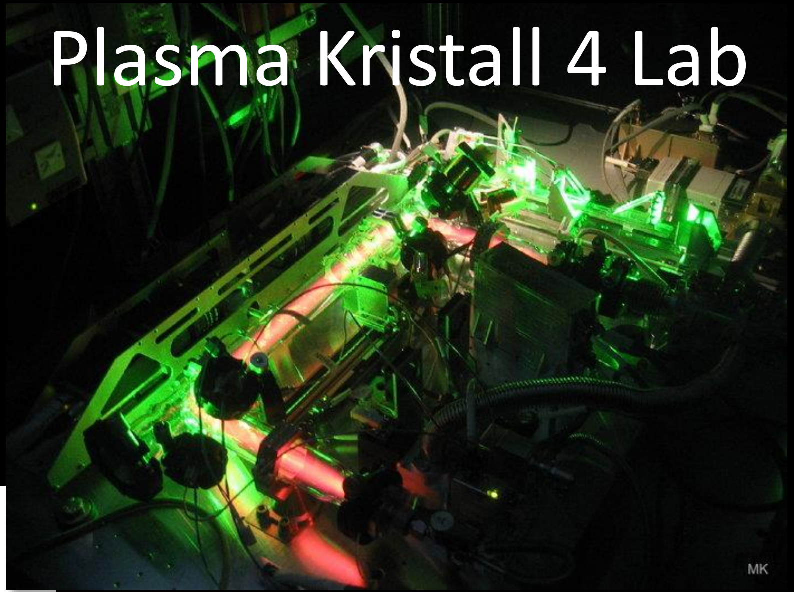
RF (electrostatic)

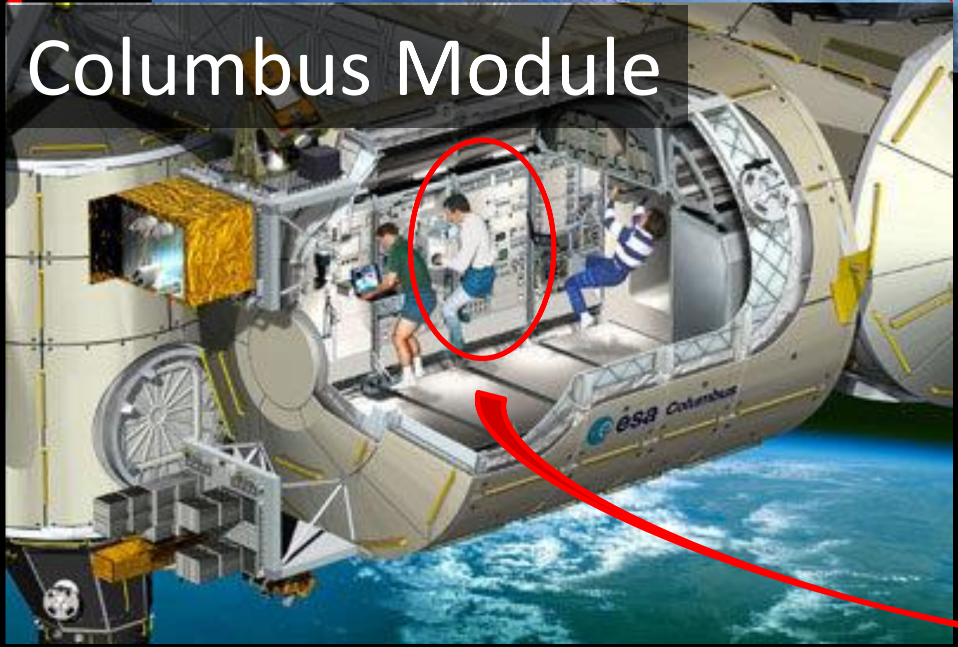
MDPX (magnetized)

Dusty plasma experiments on the ISS

Images credit: German Aerospace Center (DLR)

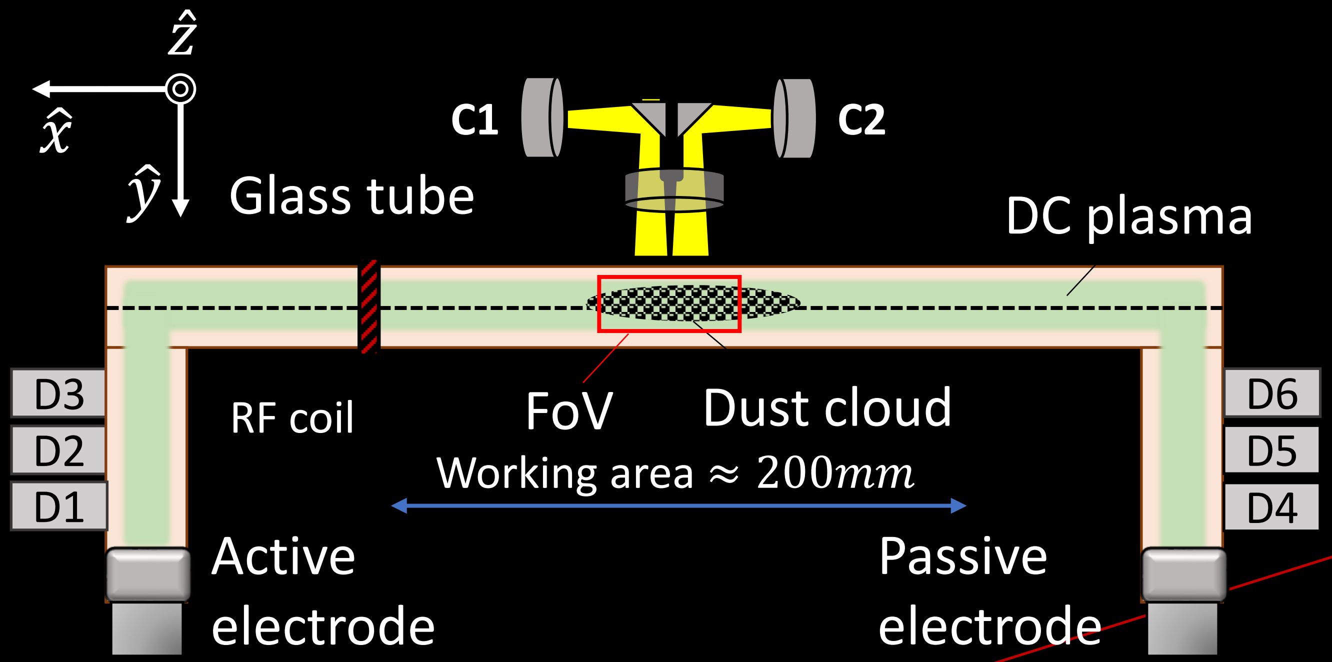


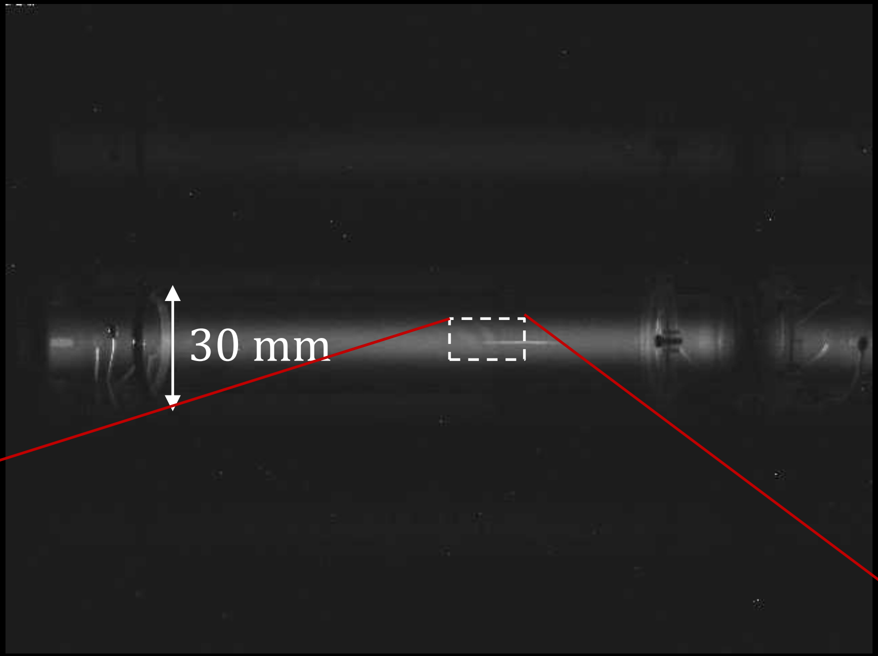


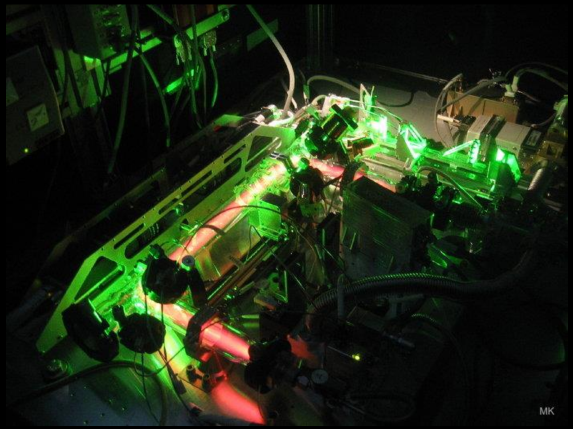


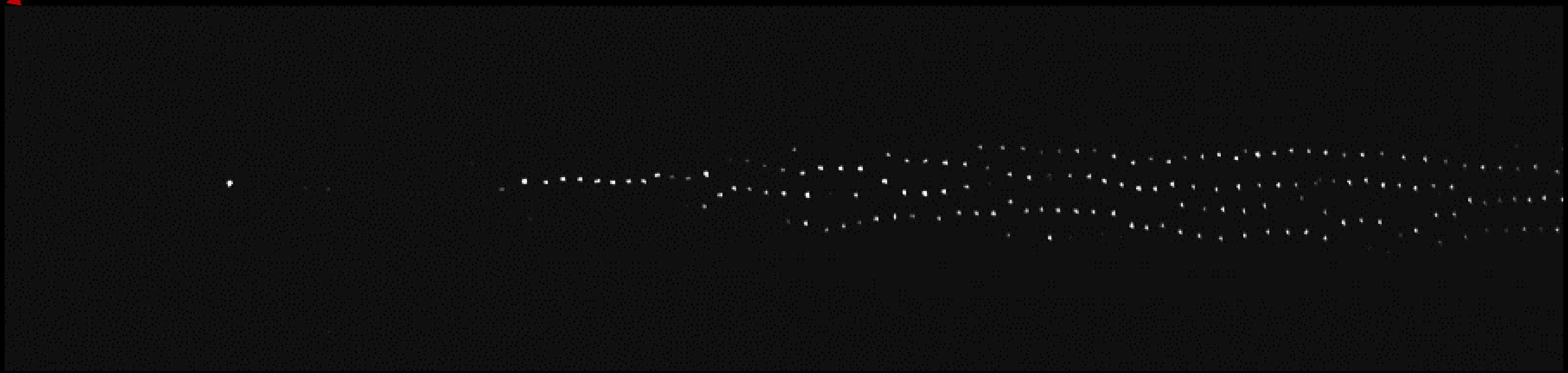
Laboratory cabinet with drawers for the instruments of the experiment

Plasma Kristall – 4 (PK-4) Experiment on the ISS







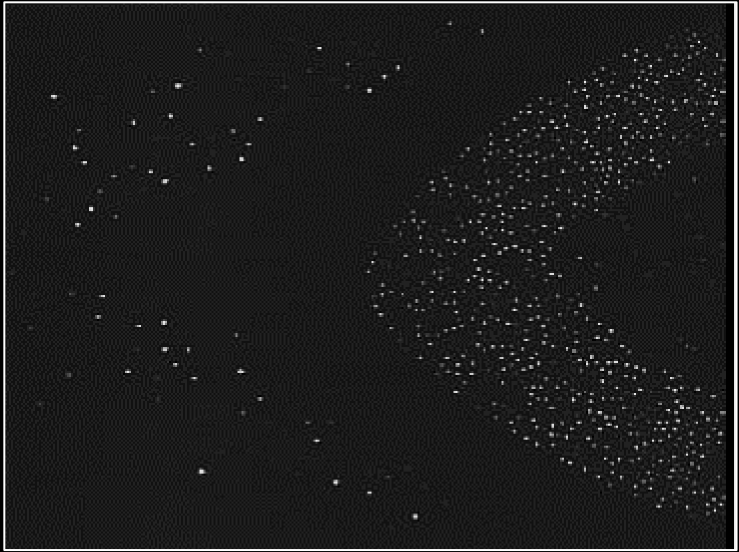


Fink, Martin A., Markus H. Thoma, and Gregor E. Morfill., Microgravity Science and Technology 23.2 (2011): 169-171.

PK-4 ISS Observed Phenomena

Microgravity dusty plasmas are ideal for studying fundamental processes in fluid dynamics at the individual particle level.

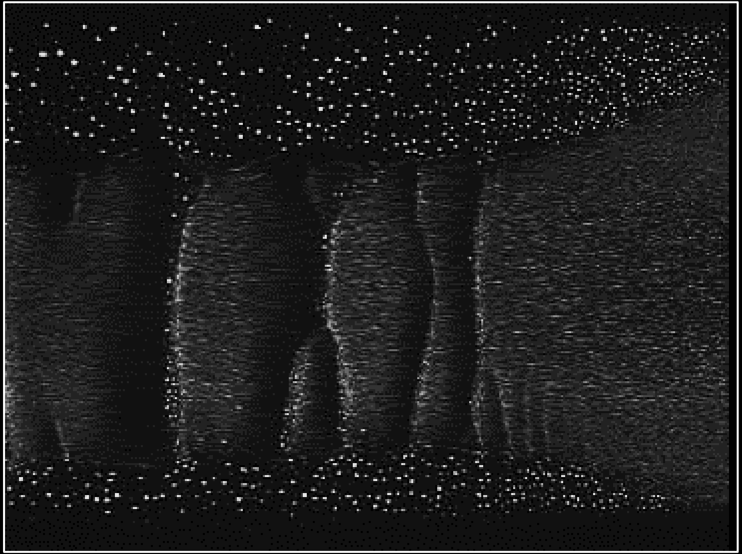
Dust ordering around RF glow



Dust jets

Dust ordering by size

Solitons



Usachev, A., et al. Czechoslovak Journal of Physics 54.3 (2004): C639.

PK-4 ISS Observed Phenomena

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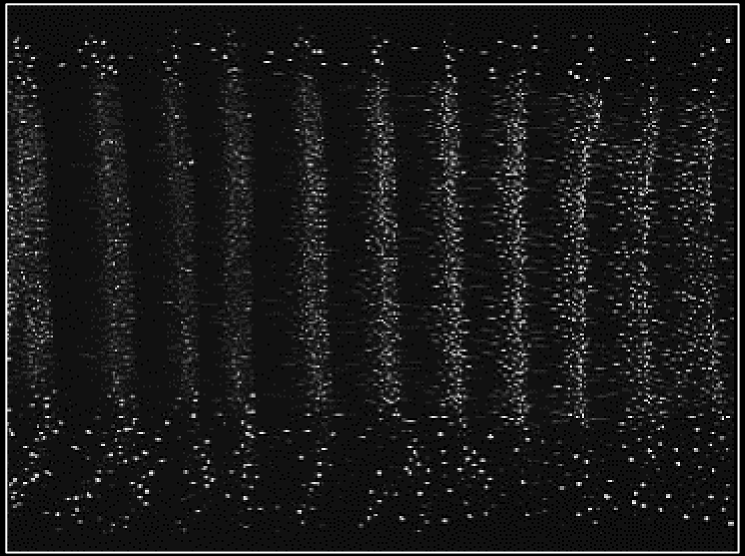
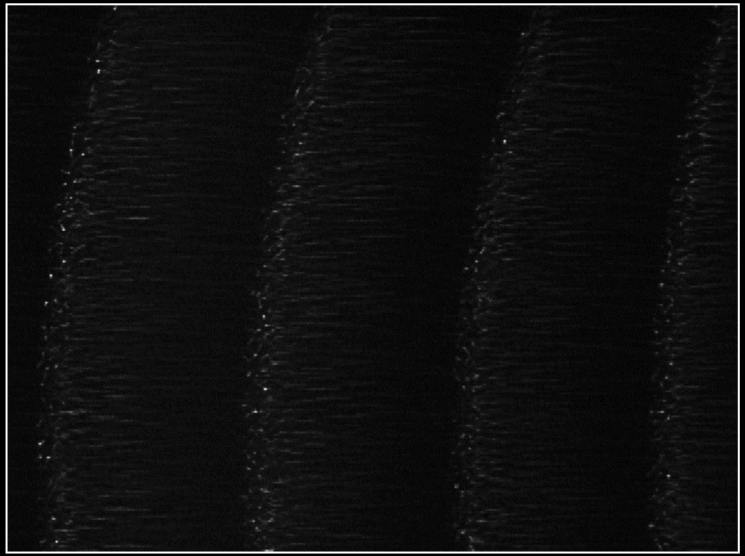
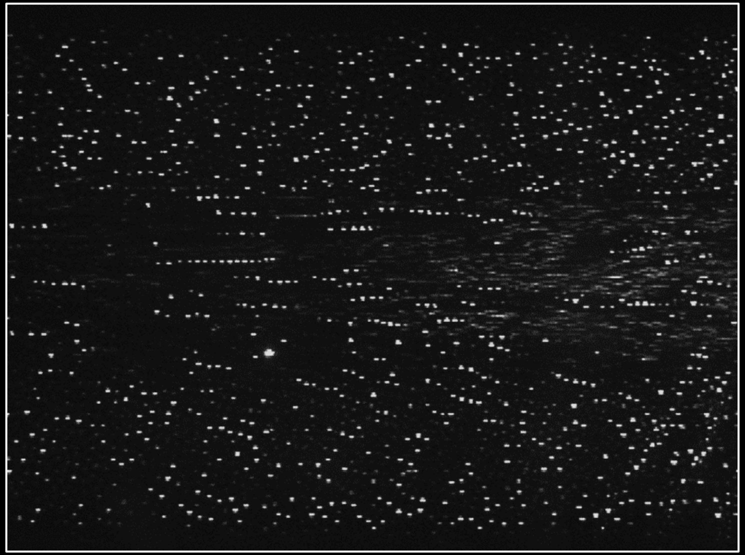
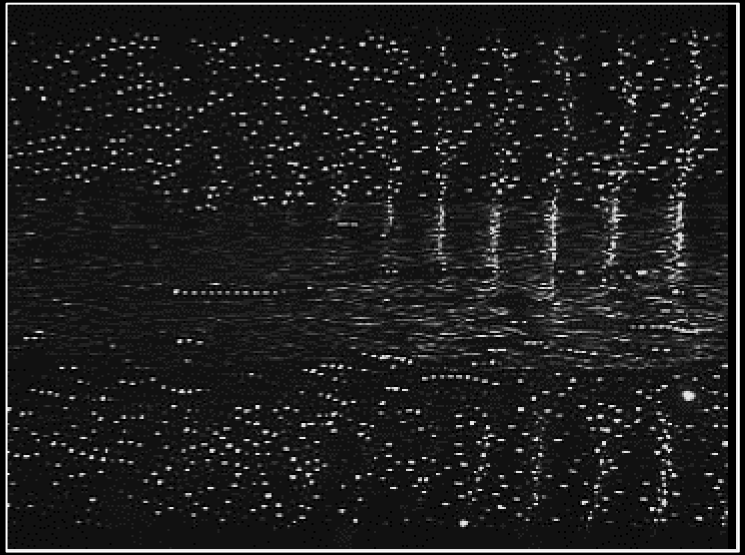
Dust acoustic waves





Dust lane formation





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Part III: Dusty plasma theory

Outline

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- ❖ **Part IV:** Order and disorder

Fundamental parameters

$\alpha =$ electrons (e), ions (i), dust (d), neutrals (n)

n_α – Plasma density of species α

T_α – Temperature *(often assumed room temp. for neutrals/ions/dust)*

$v_{th,\alpha}$ – Thermal velocity

$\lambda_{D,\alpha}$ - Debye length

$\omega_{p,\alpha}$ - Plasma frequency

η_{ij} - Collision frequency b/w species

All these are needed to calculate the dynamics of each species α.

Fundamental parameters

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can measure

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All these are needed to calculate the dynamics of each species α.

Expressions

$$v_{th,\alpha} = \sqrt{\frac{T_\alpha}{m_\alpha}}, \quad \lambda_{D,\alpha} = \sqrt{\frac{(T_\alpha \epsilon_0)}{(n_\alpha Z_\alpha^2)}}$$

$$\omega_{p,\alpha} = \sqrt{\frac{4\pi n_\alpha Z_\alpha^2 e^2}{m_\alpha}}$$

Can't measure dust charge directly

$$\eta_{e,i} \sim \sigma_{e,i} n_n v_{n,th}$$

$$\eta_d = \frac{8\sqrt{2\pi} r_d^2 n_n v_{n,th} m_n}{3 m_d}$$

Preliminaries

α = electron or ion

Number density

$$n_\alpha = \int_{-\infty}^{\infty} f_\alpha(\bar{v}) d^3\bar{v}$$

$$d^3\bar{v} = v^2 \sin\theta \, dv d\theta d\phi$$

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Thermalized plasma →

Maxwellian velocity distributions

$$f_\alpha(\bar{v}) = n_\alpha \left(\frac{m_\alpha}{2\pi k T_\alpha}\right)^{3/2} \mathrm{e}^{-\frac{m_\alpha v^2}{2kT_\alpha}}$$

Preliminaries

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$$n_\alpha = \int_{-\infty}^{\infty} f_\alpha(\bar{v})\, d^3\bar{v}$$

$$d^3\bar{v} = v^2 \sin\theta \, dv d\theta d\phi$$

Temperature

$$\left\langle \frac{1}{2} m_\alpha v^2 \right\rangle = \frac{3}{2} k T_\alpha; \quad \langle v^2 \rangle = \frac{\int_{-\infty}^{\infty} v^2 f_\alpha(\bar{v}) d^3\bar{v}}{\int_{-\infty}^{\infty} f_\alpha(\bar{v}) d^3\bar{v}}$$

$$v_{rms} = \sqrt{\frac{3kT_\alpha}{m_\alpha}}$$

Thermalized plasma →

Maxwellian velocity distributions

$$f_\alpha(\bar{v}) = n_\alpha \left(\frac{m_\alpha}{2\pi k T_\alpha} \right)^{3/2} \mathrm{e}^{-\frac{m_\alpha v^2}{2kT_\alpha}}$$

Preliminaries

α = electron or ion

Number density

$$n_\alpha = \int_{-\infty}^{\infty} f_\alpha(\bar{v})\, d^3\bar{v}$$

$$d^3\bar{v} = v^2 \sin\theta \, dv d\theta d\phi$$

Temperature

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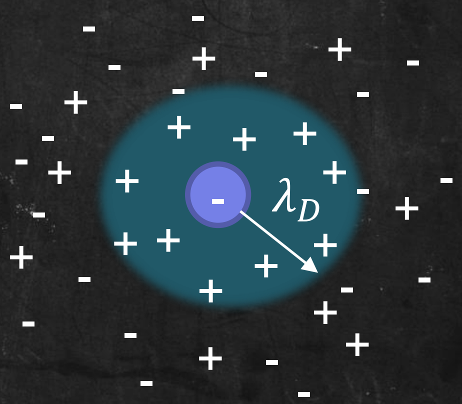
Yukawa Shielding potential

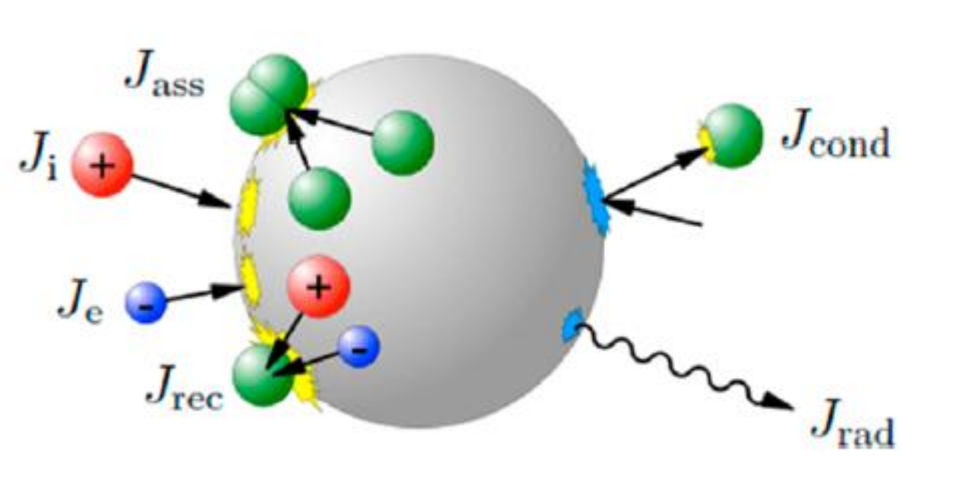
Can't measure dust charge directly

$$\Phi(r) = \frac{Ze}{4\pi\epsilon_0 r} e^{\frac{-r}{\lambda_D}}$$



Finding dust charge: Equilibrium condition

Kortshagen, Uwe R., et al. Chemical reviews 116.18 (2016).



- Assume dust particles float to a potential at which total current to its surface is zero

$$\frac{dQ}{dt} = \sum_i J_i(\phi_s) = 0$$

- Charge related to surface potential

$$Q = C\phi_s$$

Capacitance C depends on dust properties (material, size, shape)

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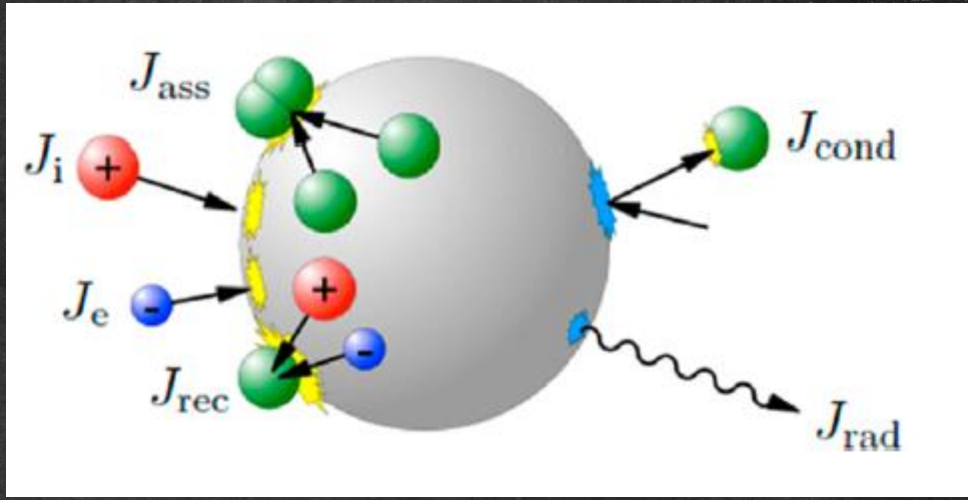

- The particle gains energy from capturing electrons and ions and from their recombination at the particle surface.
- It loses energy from impacts with energetic particles (secondary electron emission) and thermionic emission or photoemission of electrons.

Finding dust charge: OML theory of charging

- For lab studies, ions and electrons are the dominant charging mechanisms.

- Estimate the flux to the grain surface using orbit motion limited (OML) theory.

$$I_e = -4\pi r_d^2 e n_e \left(\frac{8kT_e}{\pi m_e}\right)^{\frac{1}{2}} \exp\left(\frac{e\phi_s}{kT_e}\right)$$

$$I_i = 4\pi r_d^2 e n_i \left(\frac{8kT_i}{\pi m_i}\right)^{\frac{1}{2}} \left(1 - \frac{e\phi_s}{kT_i}\right)$$

- Steady state: $I_e + I_i = 0$

Allen, Physica Scripta, 45(5) p. 496, 1992
V. E. Fortov, et al., Rev. of Topical Problems: Dusty plasmas. Phys. Usp., 47:447–492, 2004.

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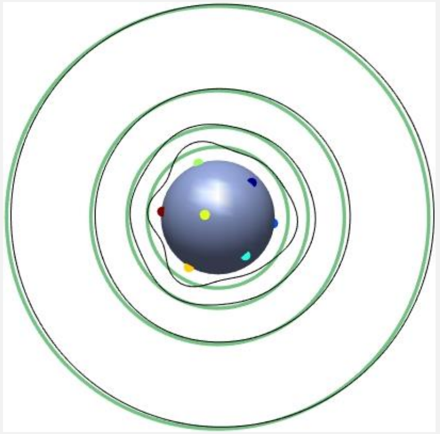
OML Theory assumes

- Homogeneous, isotropic plasma
- Conservation of energy and angular momentum
- Plasma particles which 'orbit' the charged grain are assumed to be collected.



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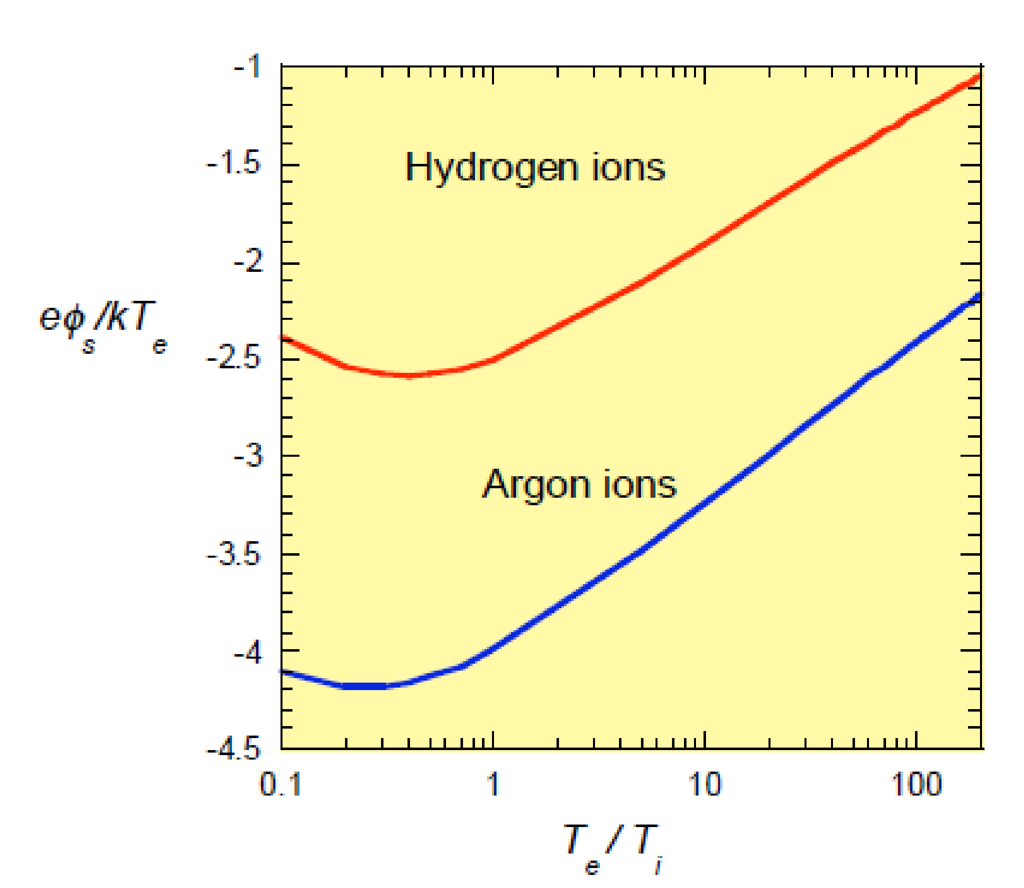
- Steady state: $I_e + I_i = 0$

Solve numerically to for ϕ_s to get the charge $Q = C\phi_s$



R. Marlino, 2007 Summer College on Plasma Physics, Abdus Salam International Center for Theoretical Physics

Allen, Physica Scripta, 45(5) p. 496, 1992
V. E. Fortov, et al., Rev. of Topical Problems: Dusty plasmas. Phys. Usp., 47:447–492, 2004.

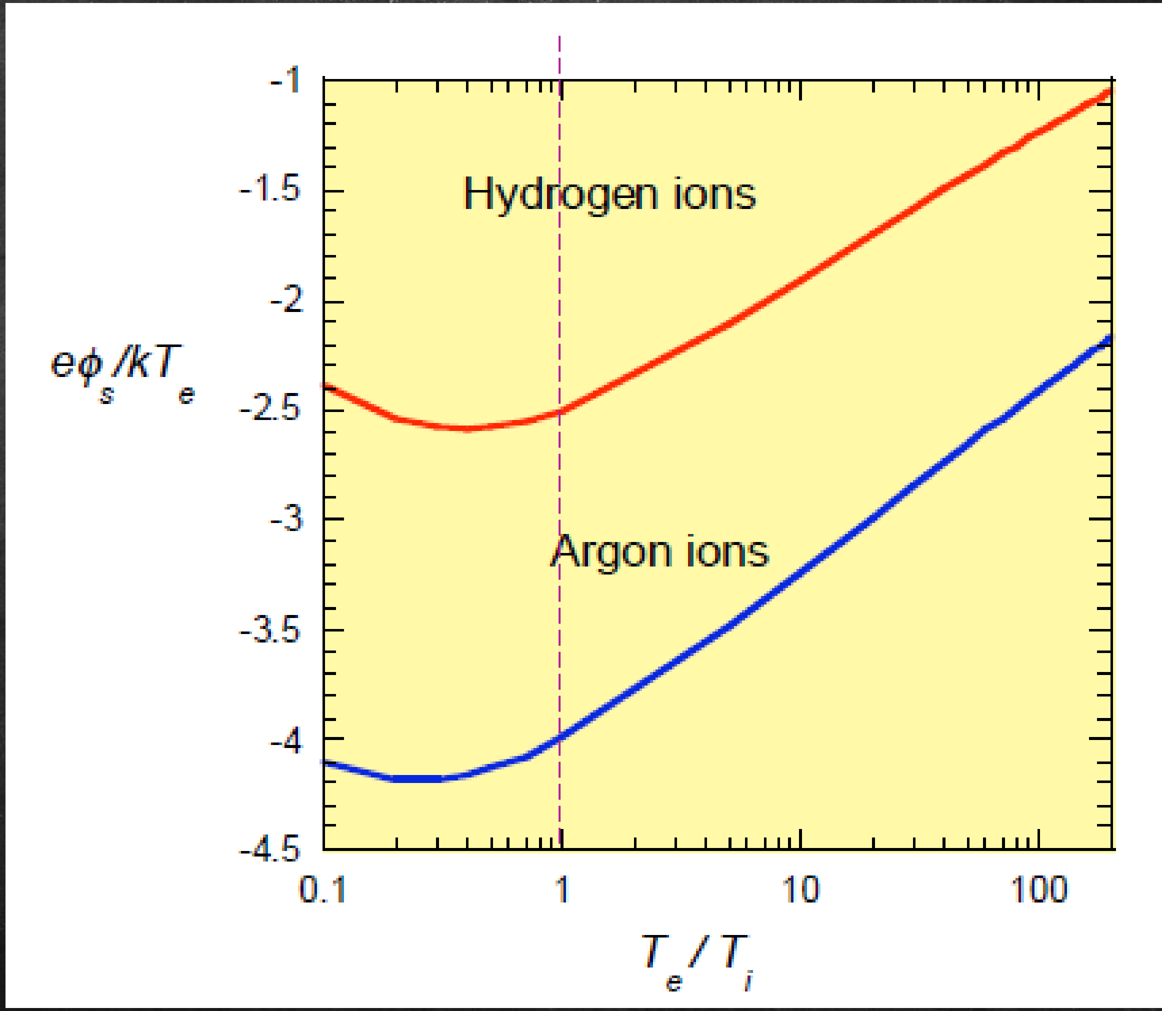
Finding dust charge: Numerical solution

<u>*Example conditions:*</u>

- Spherical grains $1\mu m$ radius
- Hydrogen plasma

$$T_e = T_i \approx 1eV$$

$$\boxed{\begin{aligned} \phi_s &= -2.5\, kT/e \\ Q_d = C\phi_s &= -2000e \end{aligned}}$$



R. Marlino, 2007 Summer College on Plasma Physics, Abdus Salam International Center for Theoretical Physics

Part IV: Order and Disorder

Electrorheology

Outline

- **Part I:** It's a dusty Universe
- **Part II:** Experiments and phenomena
- **Part III:** Dusty plasma theory
- **Part IV: Order and disorder**

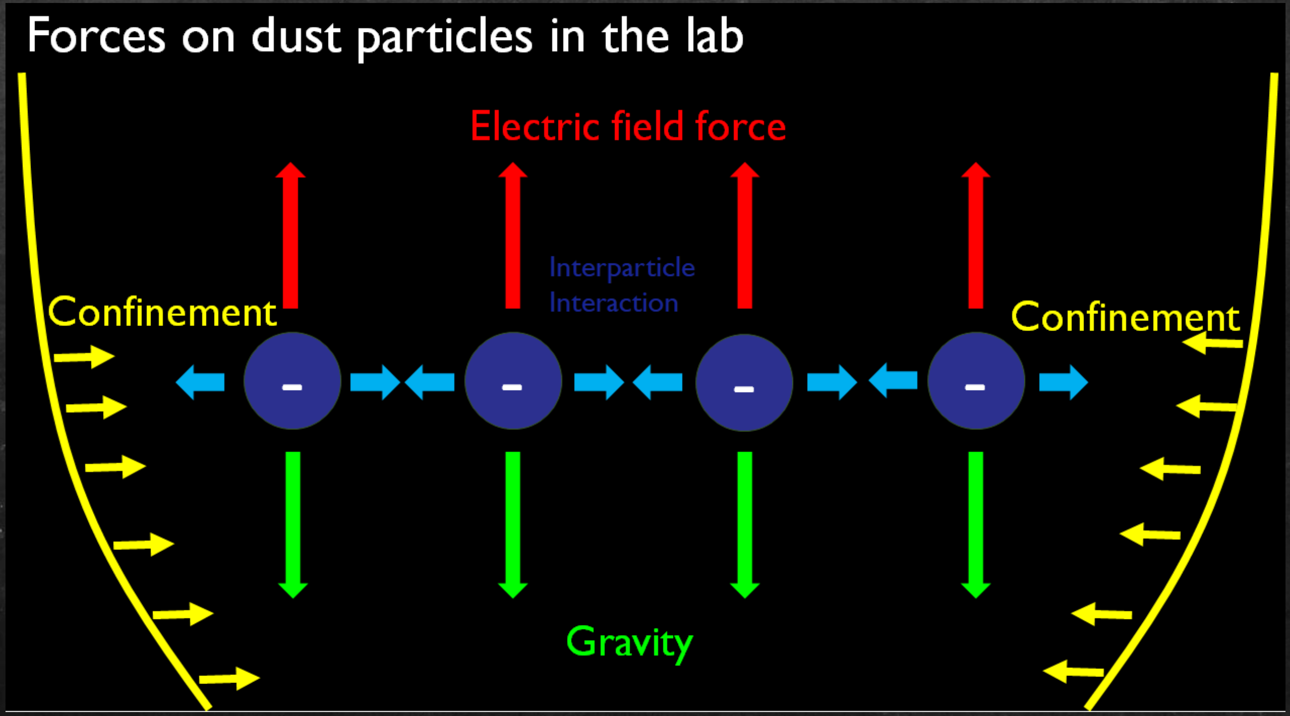
Turbulence

Forces acting on the dust particles

$$m_d \frac{dv}{dt} = F_L + F_G + F_D + F_T + F_P$$

- F_L – Lorentz force = $F_E + F_M$ $(F_E \gg F_M)$
- F_G – Gravitational force
- F_D – Drag Forces
  - *Ion Drag Force*
  - *Neutral Drag Force*
- F_T – Thermophoretic Force
- F_P – Radiation Pressure

*In addition, the dusty plasma dynamics is affected by **dust-dust** and **dust-plasma** interactions.*



Self-organization in dusty plasma

- The coupling parameter Γ is a measure for self-organization (ordering)

$$\Gamma = \frac{\text{electrostatic potential}}{\text{thermal energy}} = \frac{Q_d^2}{4\pi\varepsilon_0 k T_d \Delta}$$

Dust charge

Wigner-Seitz radius

- Dusty plasmas exhibit states of matter and structural transitions like materials in condensed and soft-matter physics
- Plasma-shielded dust particles behave as "proxy atoms"

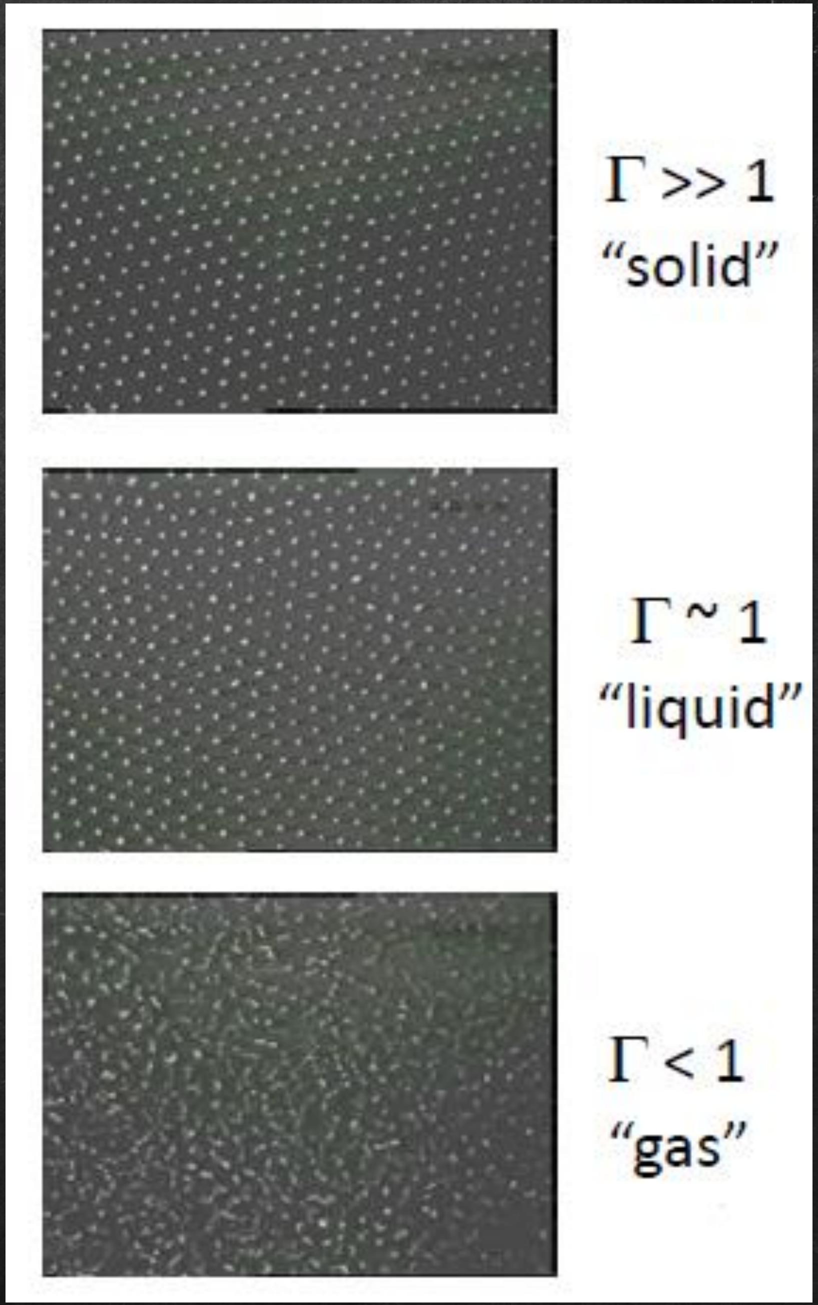
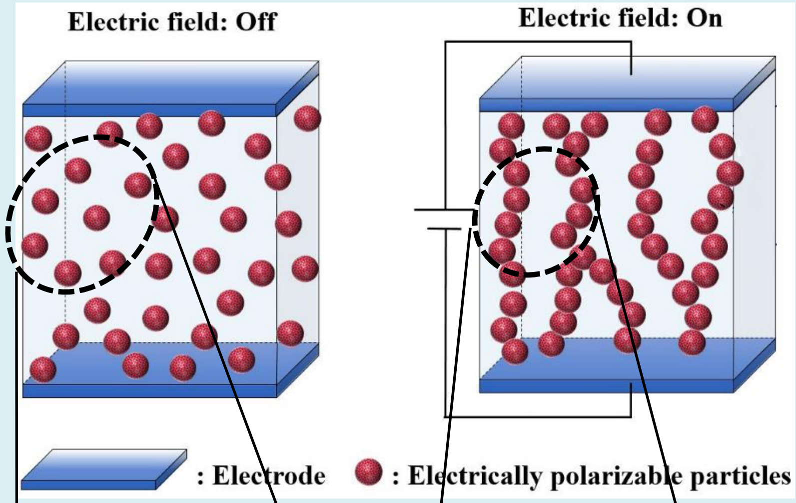


Image source: Introduction to the physics of complex/dusty plasmas, E. Thomas, Auburn University

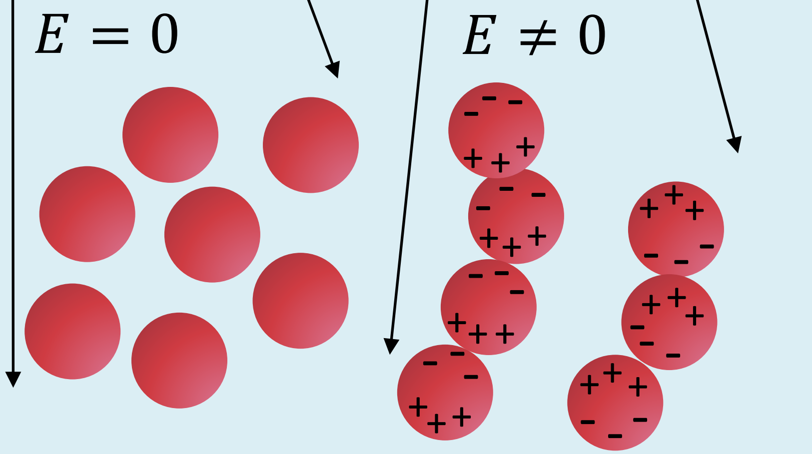
Part IV: Order and Disorder

Electrorheological (ER) Dusty Plasma

Electrorheology: isotropic-to-string transition due to applied $\boldsymbol{E}$-field



Polarization Dipole-Dipole Mechanism



Kwon, S.,, et al. 2015. *Nanomaterials*, *5*(4), p.2249.

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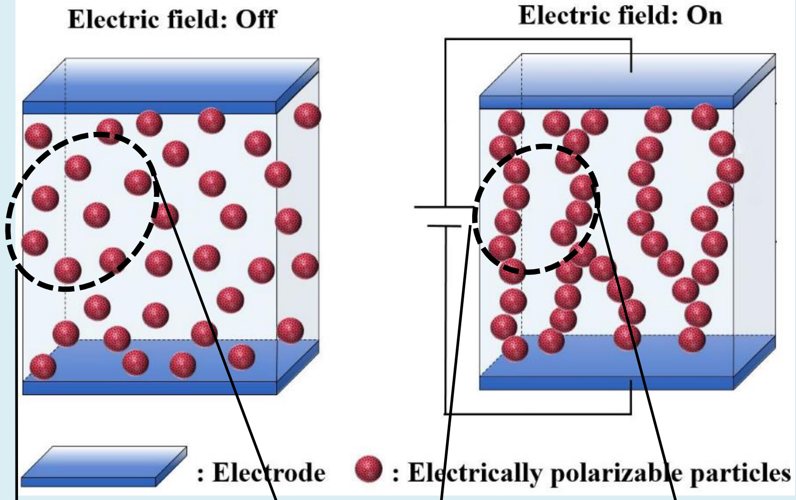

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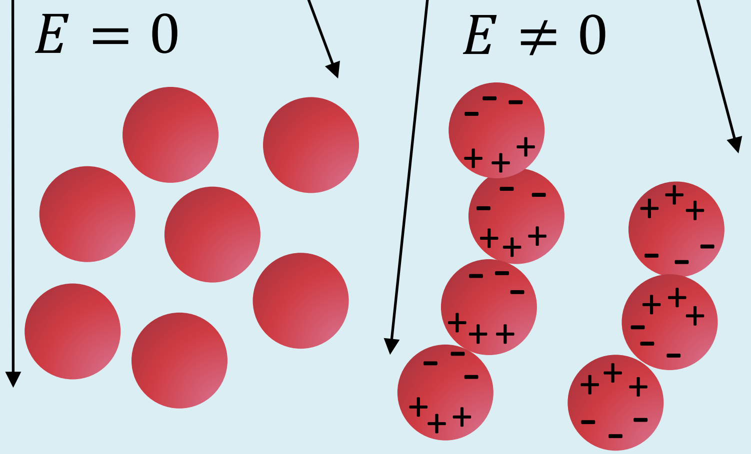

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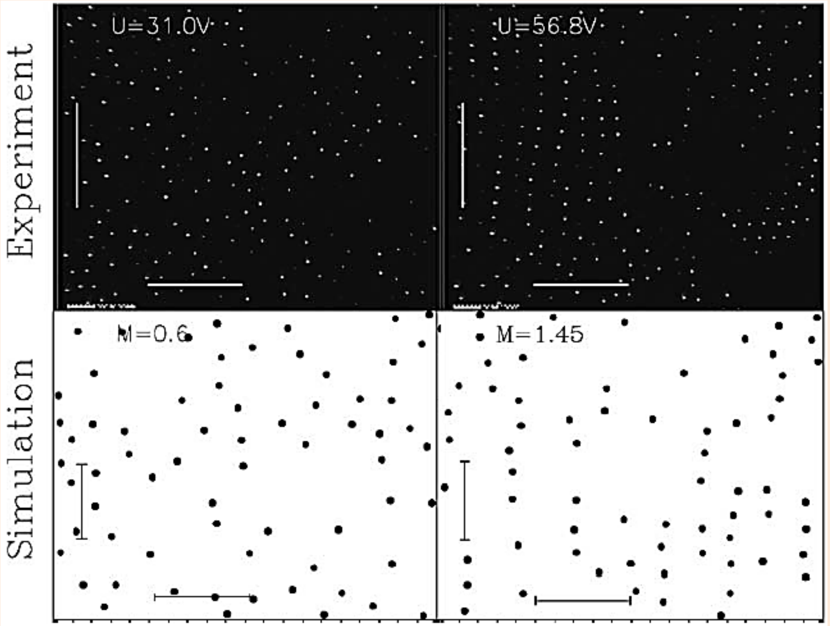
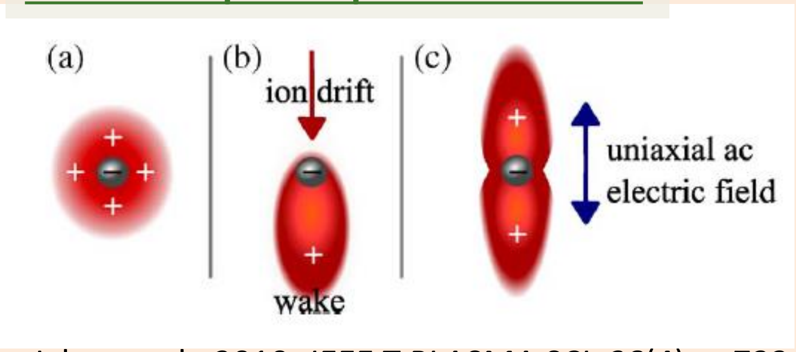
PK-3: first observation of ER dusty plasma, RF argon discharge



Dust-Ion Dipole-Dipole Mechanism



Ivlev, et al., 2010. *IEEE T PLASMA SCI*, *38*(4), p.733

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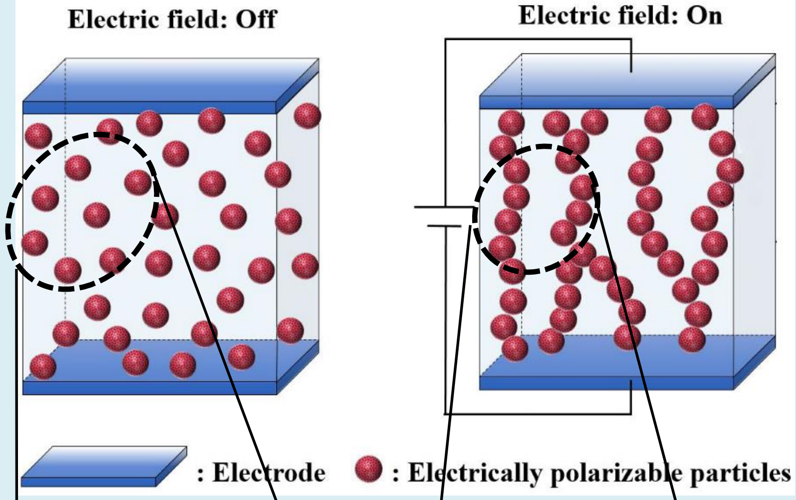
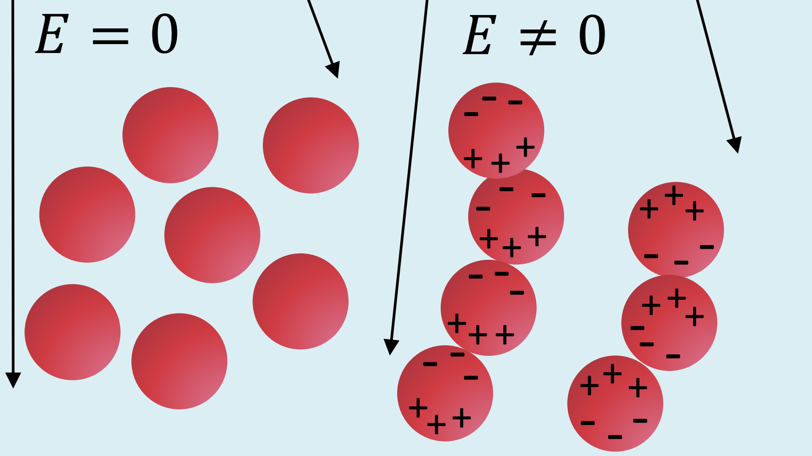


***Polarization* Dipole-Dipole Mechanism**



Kwon, S.,, et al. 2015. *Nanomaterials*, *5*(4), p.2249.

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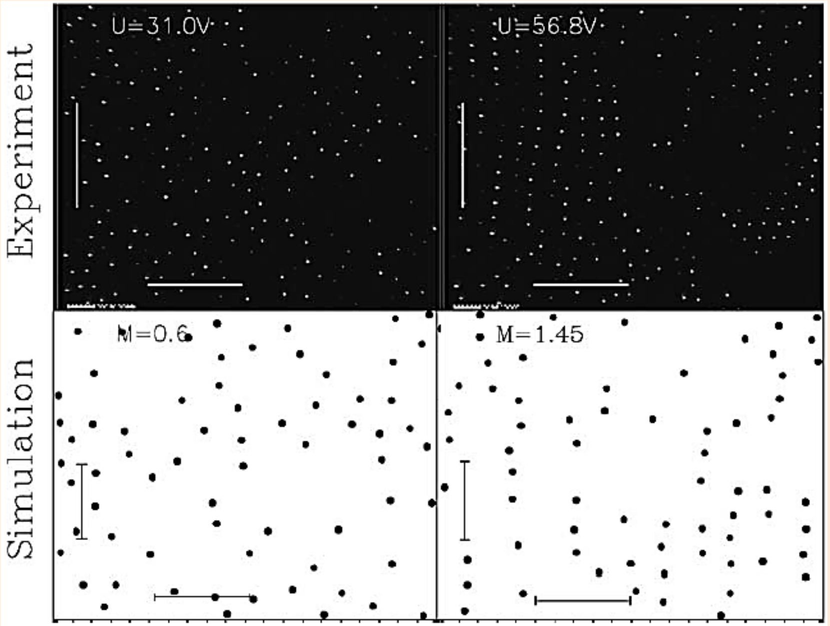
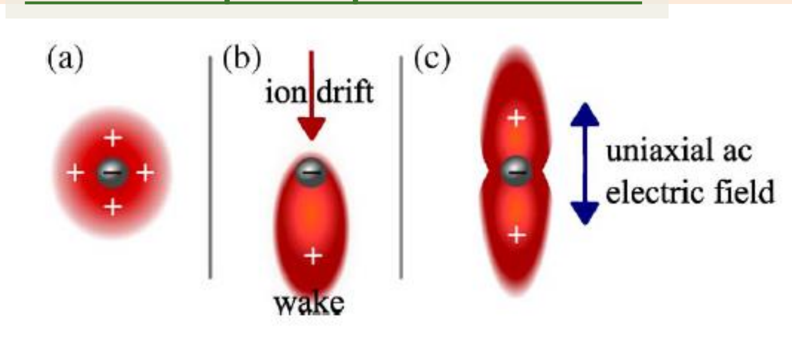
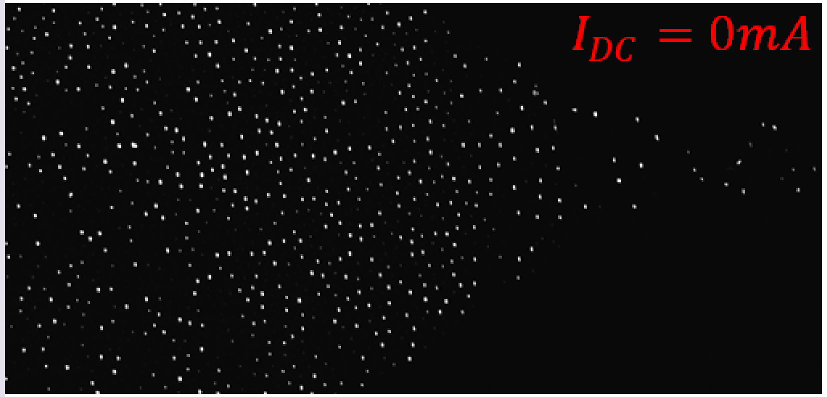


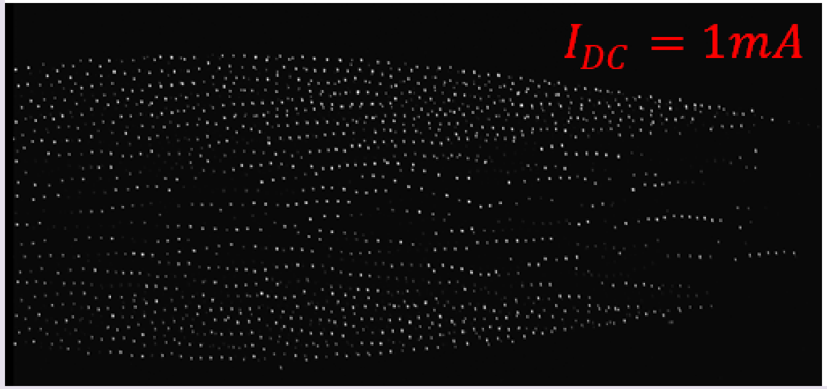
***Dust-Ion* Dipole-Dipole Mechanism**



Ivlev, et al., 2010. *IEEE T PLASMA SCI*, *38*(4), p.733

PK-4: isotropic-to-string transition, DC neon discharge





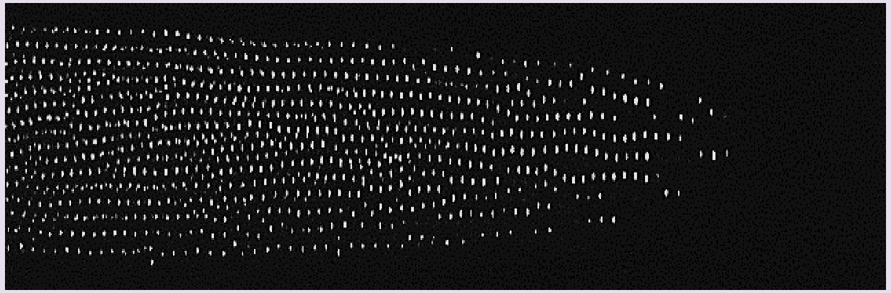
Mechanism under investigation

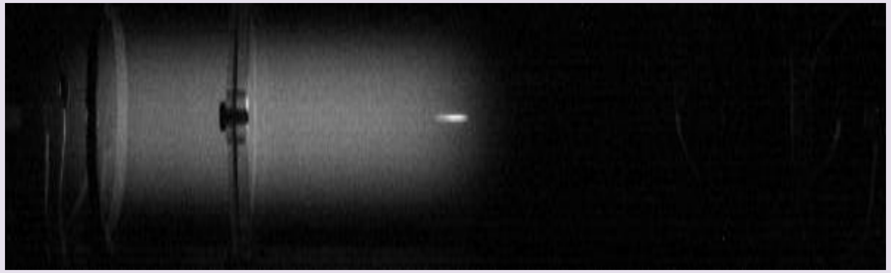
Credit: PK-4 lab, Video VM2-AVI-151028-134729

Connecting experiment and theory

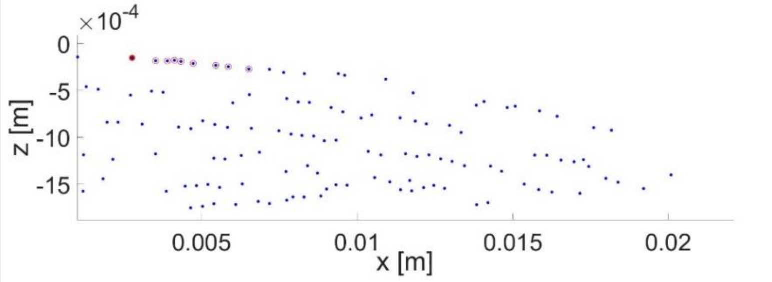
PK-4 EXPERIMENT:

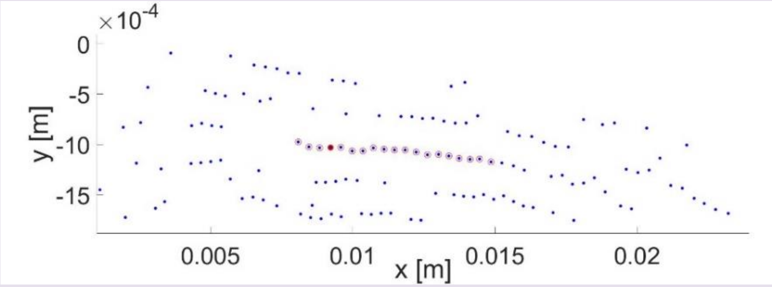
DC Ne, 16 Pa, 0.5 mA, 50% Duty Cycle, 500 Hz switching



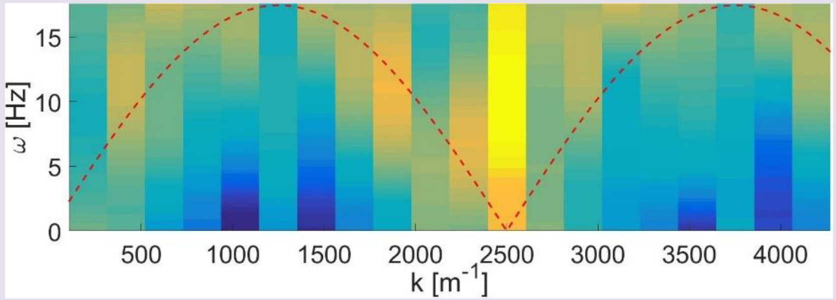


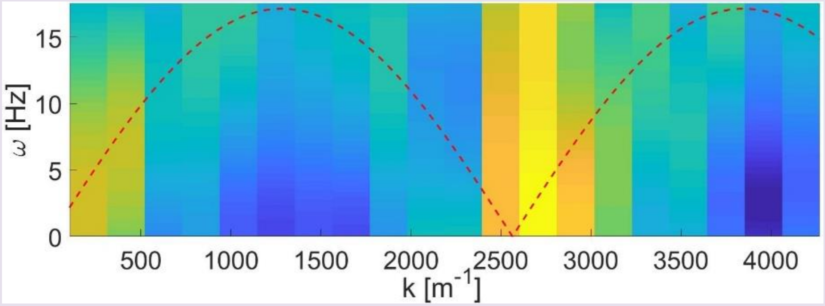
Particle tracking of grains





Experimental dispersion relation



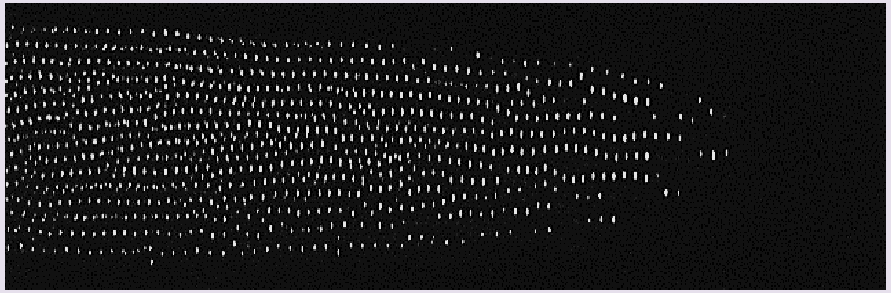


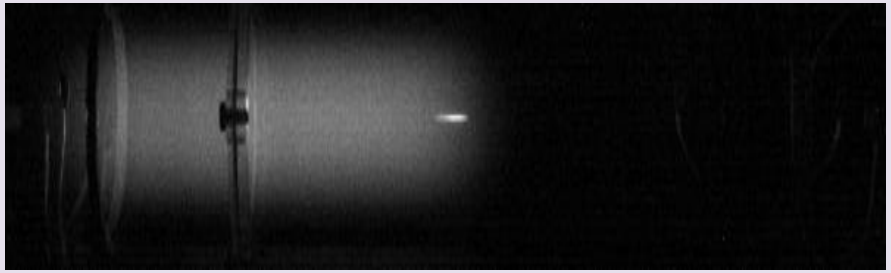
Connecting experiment and theory

www.baylor.edu/CASPER

EXPERIMENT:

DC Ne, 16 Pa, 0.5 mA, 50% Duty Cycle, 500 Hz switching





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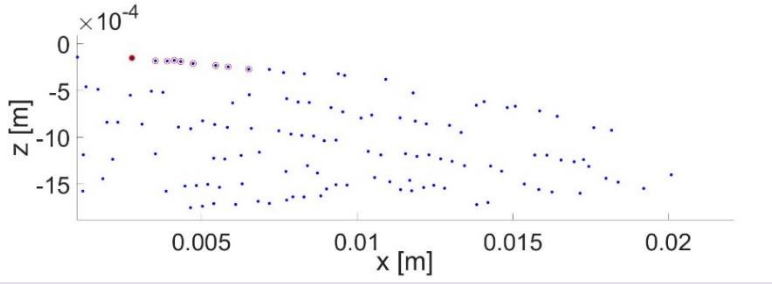

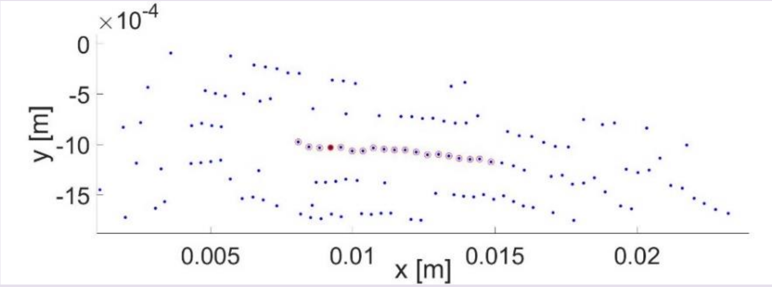

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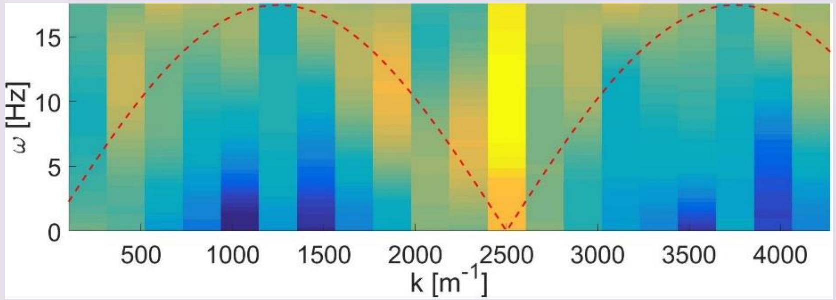
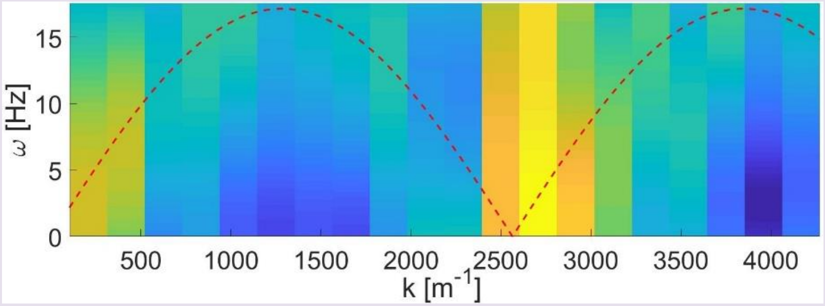




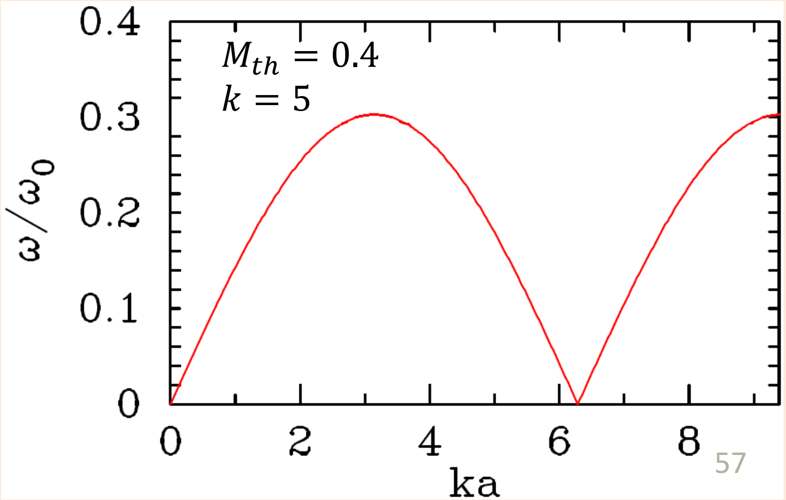
THEORY: For given potential ϕ, the dispersion relation can be derived:

$$\omega = 2\left(\frac{1}{m_d}\frac{d^2\phi_{total}(a)}{dx^2}\right)^{1/2}\left|\sin\frac{ka}{2}\right|$$

Rosenberg, M., 2015.. *J Plasma Phys*, *81*(4).

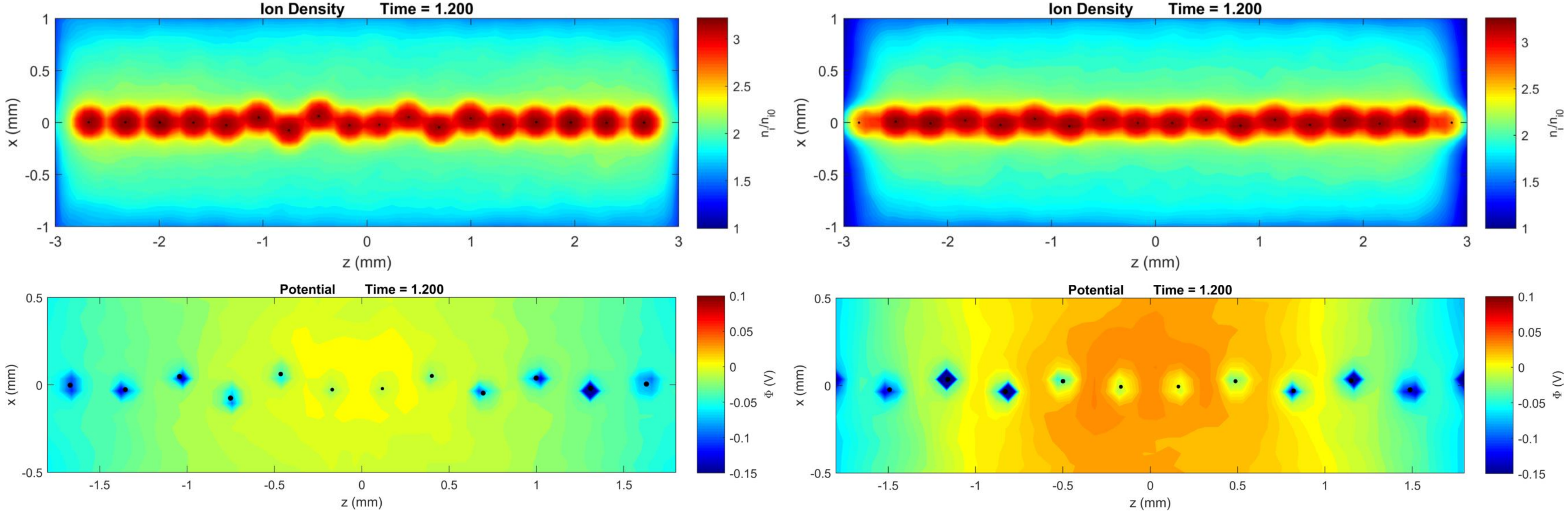
Assume Dust-Ion Dipole

$$\phi_Y + \phi_D = \phi_{total}$$



How to verify the assumed mechanism?

E = 100 V/m   E = 1000 V/m



Stable chains form at higher $\mathrm{M_T}$ → **higher ion speed** → **Large E-field needed to accelerate ions and induce the ER transition in DC.**

Matthews, Lorin, et al. "Dust chains in the strongly coupled liquid regime." *Bulletin of the American Physical Society*(2018).

What can cause Dust-Ion Dipoles in DC?

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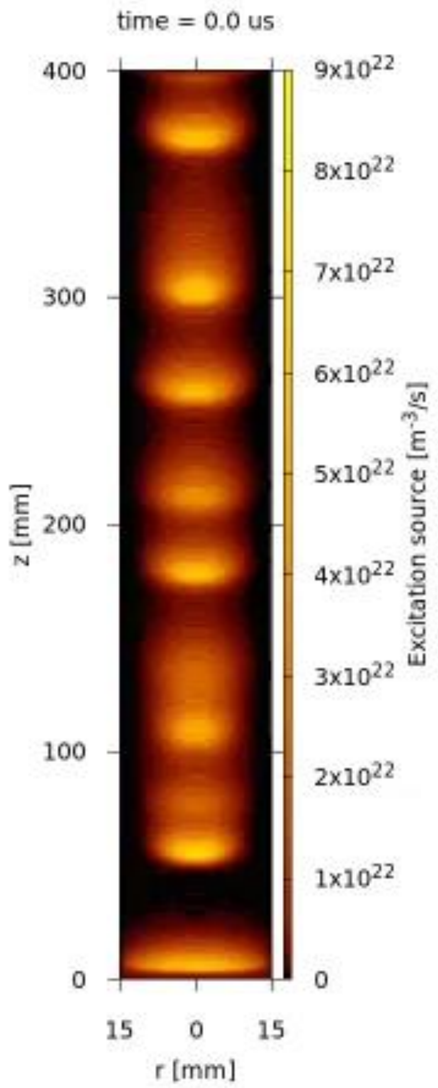

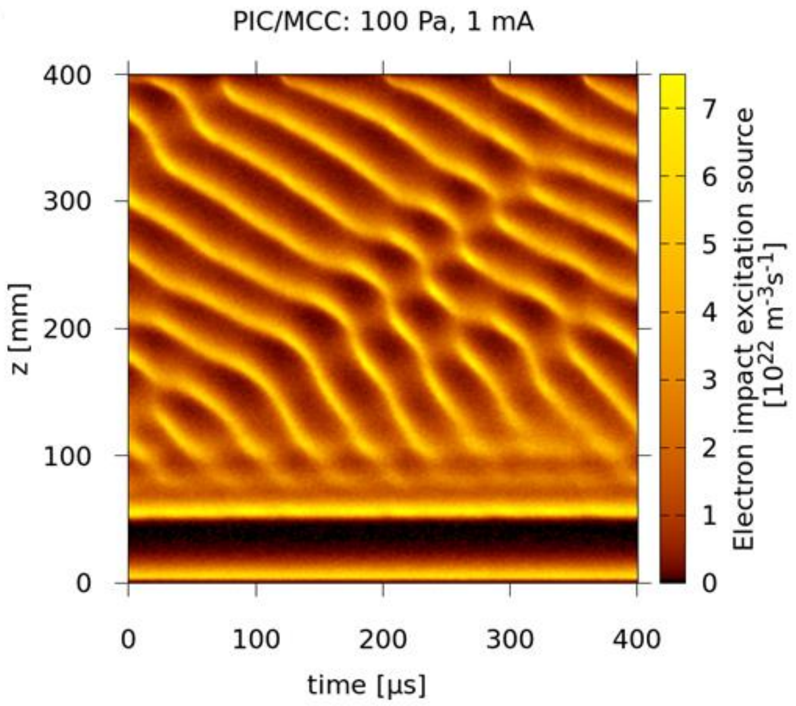

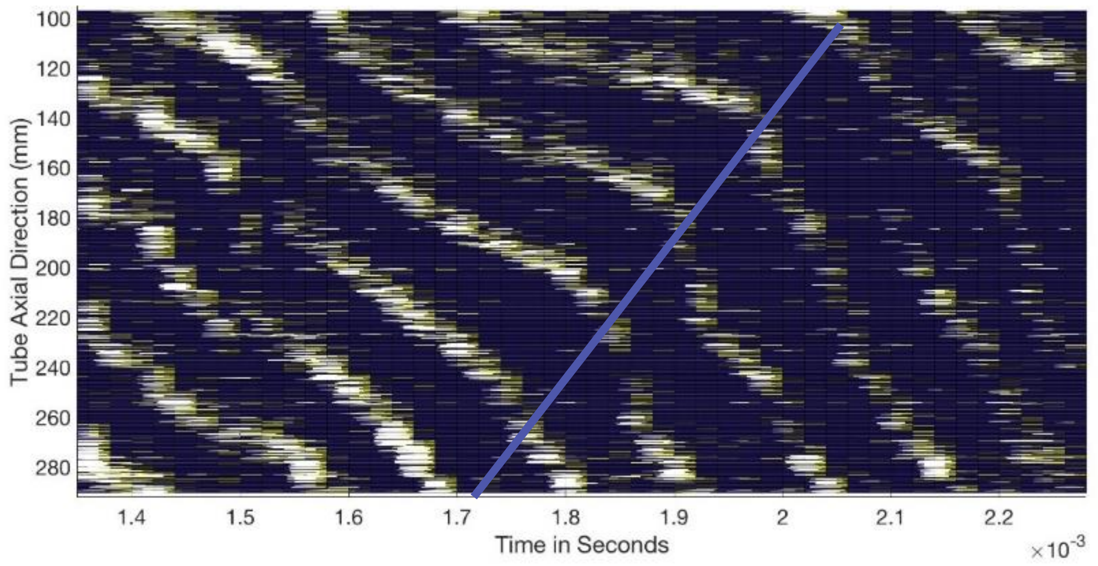

Discharge striations and Ionization waves, PIC/MCC simulation

DC neon, 100 Pa, 1 mA, 50% Duty Cycle, 500 Hz switching

Experimental confirmation from PK-4 BU

DC neon, 100 Pa, 3 mA, 50% Duty Cycle, 500 Hz switching, **50k fps**

Hartmann, P., Rosenberg, M., Matthews, L., Sanford, D., Reyes, J., & Hyde, T. (2018). Ionization waves in the PK-4 direct current neon discharge. *Bulletin of the American Physical Society*.

Part IV: Order and Disorder

Turbulence

Definition of Turbulence

Classical Turbulence

Navier Stokes Equation for the velocity vector:

$$\boldsymbol{u_t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla u}) = \Delta \boldsymbol{u} - \boldsymbol{\nabla p}$$

Describes the flow of an incompressible viscous fluid.

Definition of Turbulence

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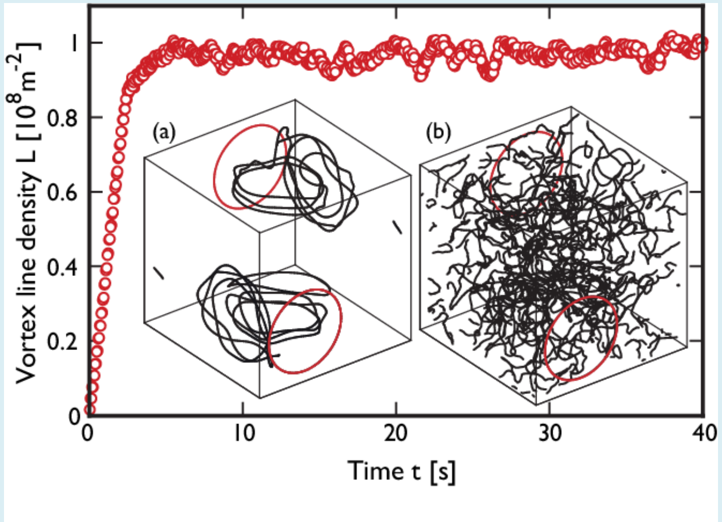
(Royal Collection Trust/© Her Majesty Queen Elizabeth II 2019)

Quantum Turbulence

Differs from classical turbulence in three ways:

i. Two-fluid behavior
ii. Fluids can be inviscid
iii. **Discrete vortices .**



Tsepelin, Viktor, et al., *Phys Rev B* 96.5 (2017)

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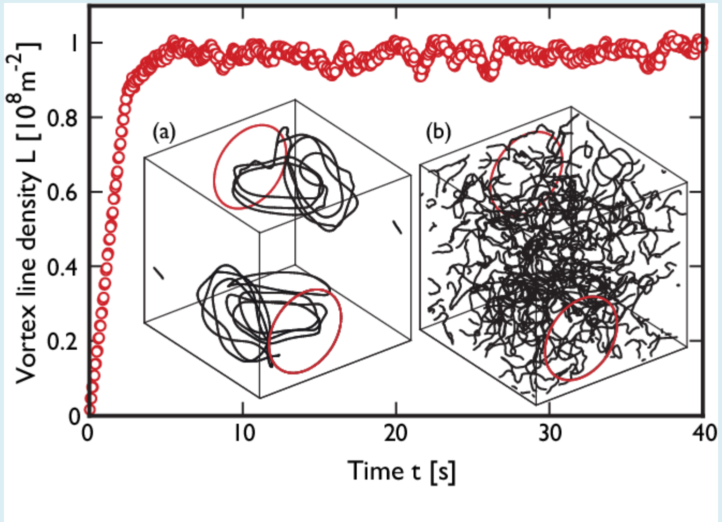


Tsepelin, Viktor, et al., *Phys Rev B* 96.5 (2017)

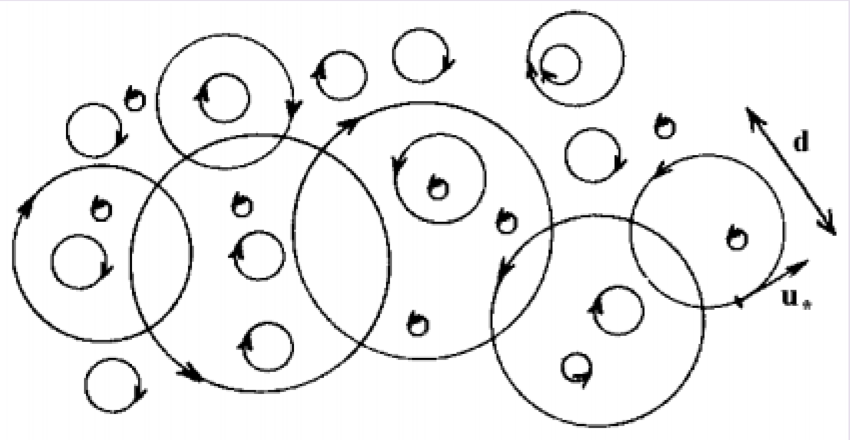
Semi-Classical Turbulence

Dissipationless transfer of energy from large to small scales.

Kolmogorov energy spectrum:

$$E(k) \sim k^{-5/3}$$

Can be associated with the presence of metastable bundles of polarized quantized vortices.

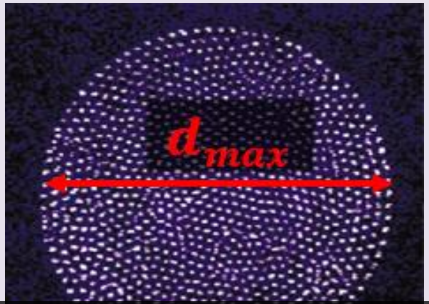


(dartmouth.edu/~cushman/courses/engs250/Kolmogorov.pdf)

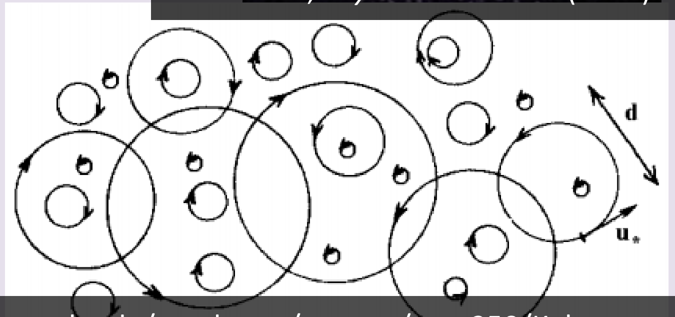
Turbulence in Dusty Plasma

1. Consider **2D dust fluid** close to crystallization.
2. At $t = 0$ **import energy E** at the largest scale.
3. Resulting **vortex scales are discretized** by the # of participating dust particles.

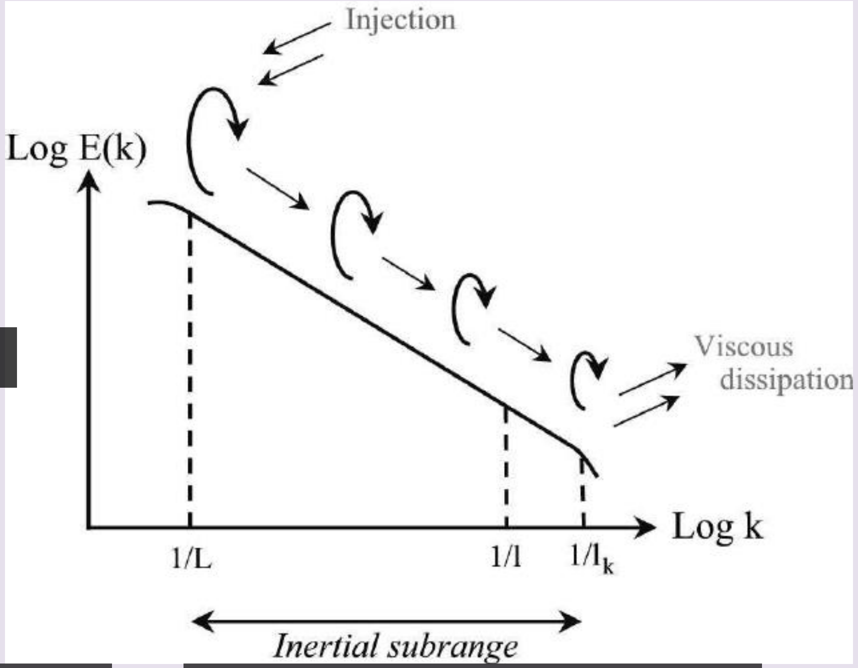
- d_{max} ~ spatial size of crystal
- d_{min} ~ dust particle diameter



M. Murillo, *Phys Plasmas* 11.5 (2004).



(dartmouth.edu/~cushman/courses/engs250/Kolmogorov.pdf)



(*Image Source*: Aakash30jan, Wikimedia)

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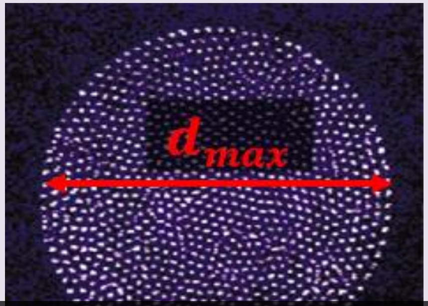
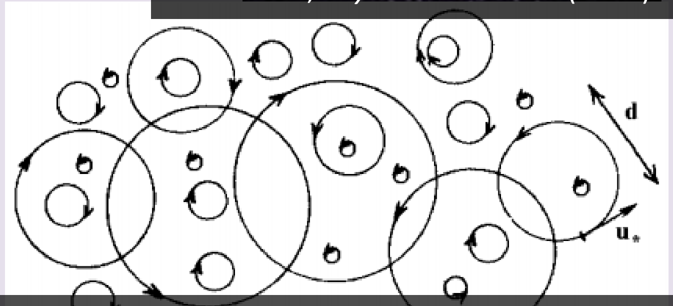
1. Consider **2D dust fluid** close to crystallization.
2. At $t = 0$ **import energy E** at the largest scale.
3. Resulting **vortex scales are discretized** by the # of participating dust particles.

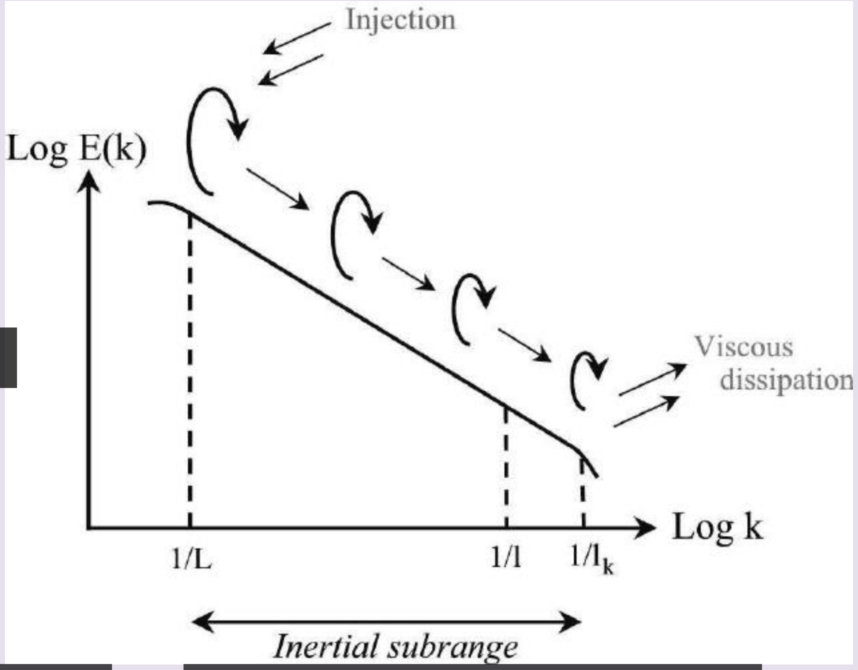
- d_{max} ~ spatial size of crystal
- d_{min} ~ dust particle diameter



M. Murillo, *Phys Plasmas* 11.5 (2004).



(dartmouth.edu/~cushman/courses/engs250/Kolmogorov.pdf)



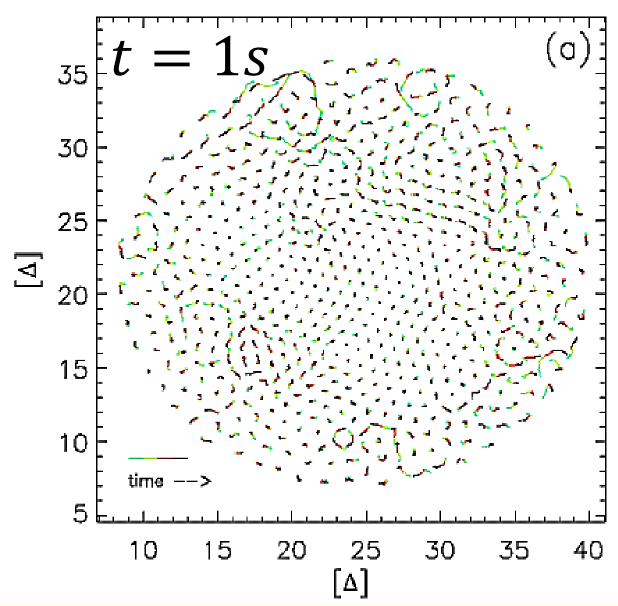
(*Image Source*: Aakash30jan, Wikimedia)

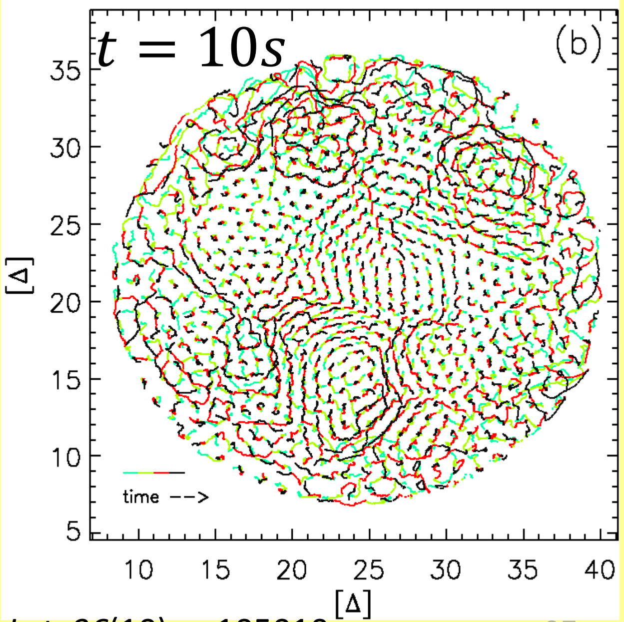
$$k \sim \frac{1}{d}$$

1. Consider **discrete k-space** of simple wave modes
2. At $t = 0$ **import energy E** at the largest scale.
3. **Vortex scales** are combinations of wave modes in k-space with:

- $k_{min} \equiv \delta_0$ (single delta function)
- $k_{max} \equiv$ simulation size

The largest k corresponds to the dissipation space scale.





Ratynskaia, et al., 2006. " *Phys Rev Let*, *96*(10), p.105010.

Summary

- Dusty plasma physics spans topics across astrophysics, fusion, materials research, space exploration, mathematics, etc.
- Plasma – dust interactions are key to laboratory plasma physics → crucial for fusion
- Dusty plasmas exhibit states of matter and structural transitions like materials in condensed and soft-matter physics
- Dusty plasma physics has applications to multi-billion industries, including semi-conductors and nanotechnology.