Dusty plasmas

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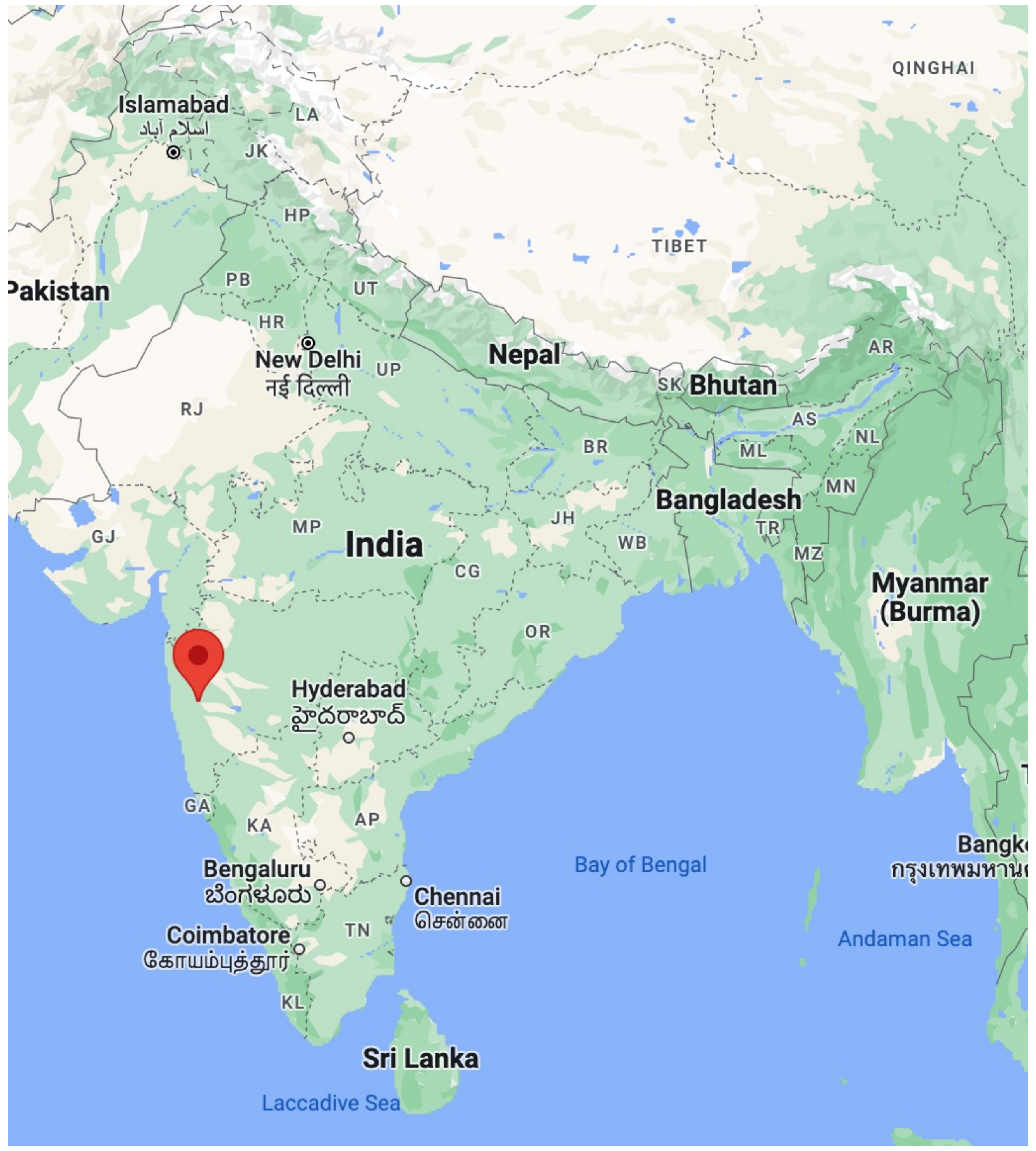


June 14th 2023, SULI Introduction to Fusion Energy and Plasma Physics Course

About me

Upto High School: Jawahar Navodaya Vidyalaya (JNV), Gauri Ganj

नवोदय विद्यालय समिति
प्रज्ञानं ब्रह्म

system of central schools for talented students predominantly from rural areas in India, targeting gifted students who lack access to accelerated learning due to financial, social and rural disadvantages.

Masters and PhD

इलाहाबाद विश्वविद्यालय
UNIVERSITY OF ALLAHABAD
(A Central University)

प्लाज़्मा अनुसंधान संस्थान
Institute for Plasma Research

German Aerospace Center, Postdoc

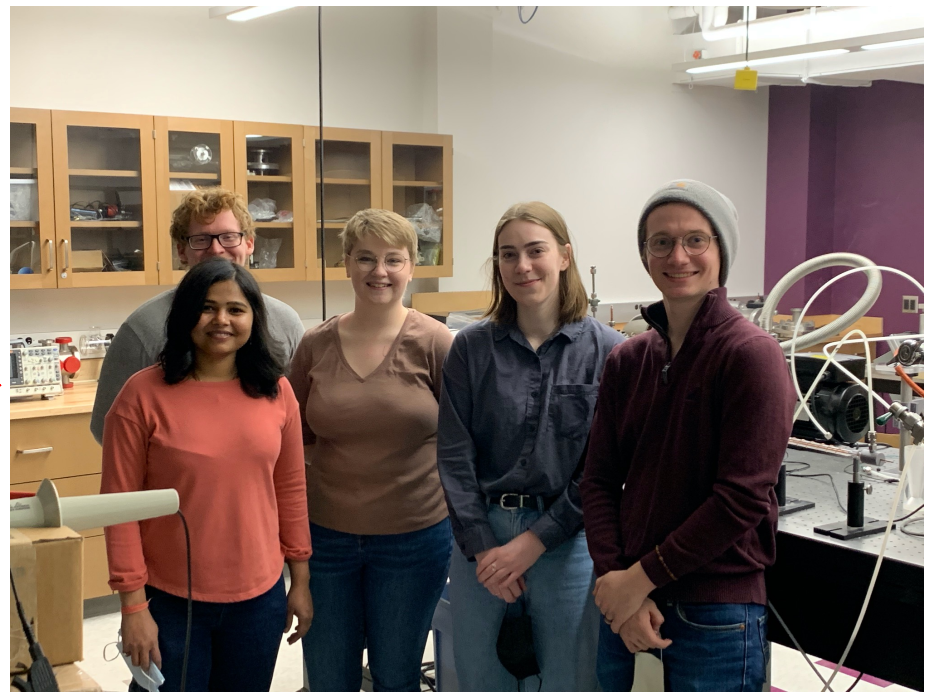
DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

DLR

Auburn University, Postdoc

Research associate, Department of Chemical and Biological Engineering

Assistant Professor, Eastern Michigan University



Adventures are the best way to learn

- The best thing about being researcher is that you become a global person
- Living on 3 continents made me more open towards different cultures and work environment.
- I have a strong interest in different cultures, as well as history of science
- I have learnt about education system in different part of the world and want to implement the best practices in learning

Collaborators

DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

DLR

ROGUE SPACE SYSTEMS CORPORATION

University of Saskatchewan

東京工業大学 Tokyo Institute of Technology

Princeton University

Eastern Michigan University

Abhijit Sen
IPR

- ***Dissertation and 6 papers published (1 PRE, 1 PSST, 1 RSI, 3 POP)***

- *Density waves in flowing complex plasma under microgravity condition.*
- *Data analysis, preparing script for campaigns.*
- *Outcome: Produce 4 papers (2 POP and 2 conf proc.)*

Magnetized Plasma Research Facility at Auburn University

Edward Thomas Jr.,
Auburn University

Uwe Konopka
Auburn University

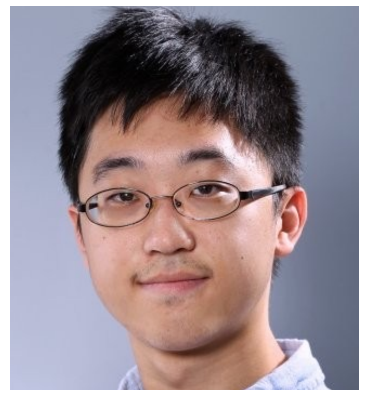
Bruce Koel
Princeton University

Connor Belt
EMU

Evan Aguirre
Rogue Space System

Lenaic Couedel
University of saskatchewan

Ahmed Diallo
Princeton University



Zhe Chen
PU

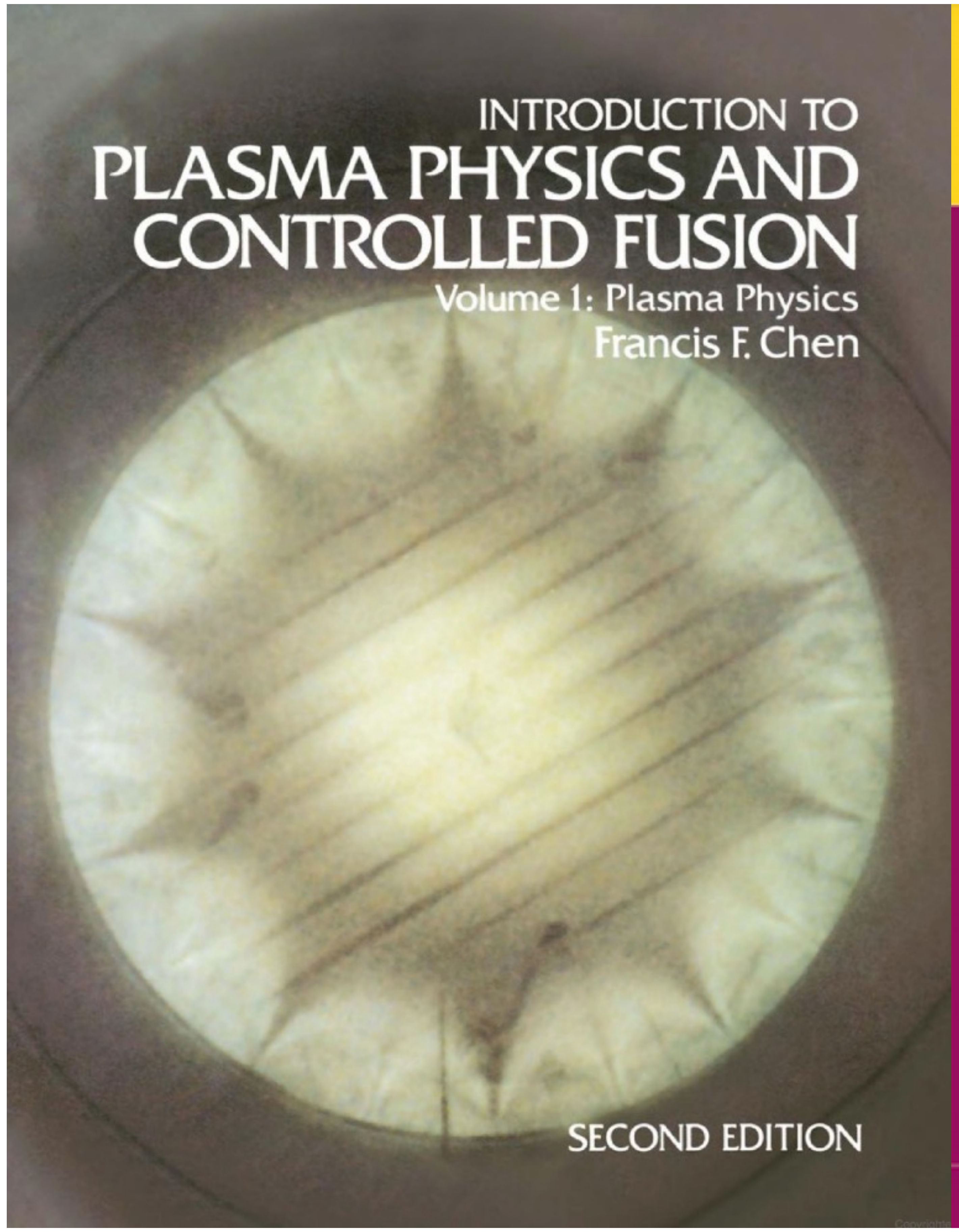
Masatoshi Hirabayashi
Auburn University

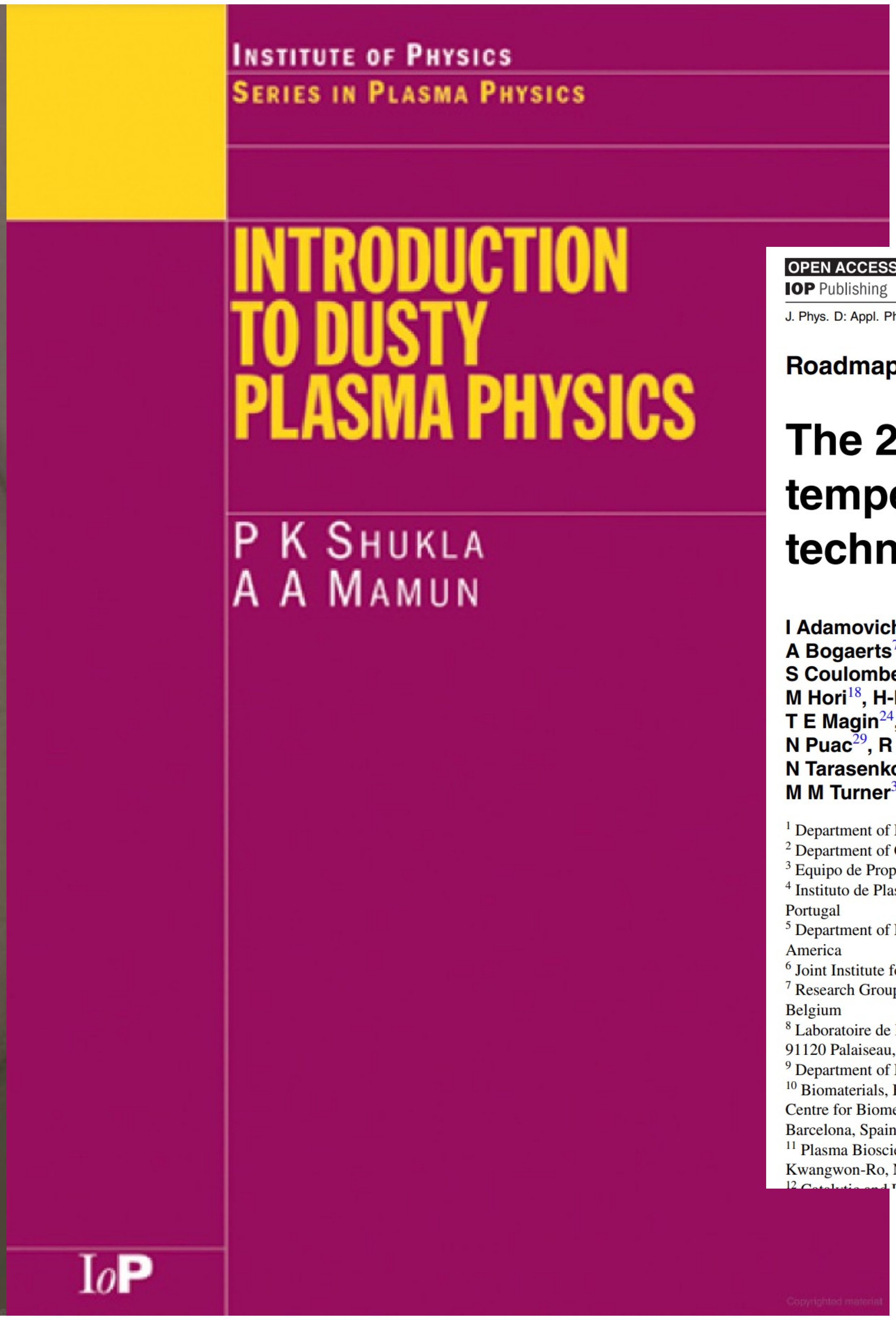
Anton kananovich
Appalachian State University

G Veda Prakash
IIT Delhi

- ***Independent project/ NSF seed funding for Atmospheric pressure plasma jet***
- ***3 external grant totaling $650K (DOD, DOE and NSF)***
- ***Mentored undergraduate projects***
- ***Outcome: 11paper published, 1 submitted***

Some references to consider





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Roadmap

The 2022 Plasma Roadmap: low temperature plasma science and technology

I Adamovich[1], S Agarwal[2], E Ahedo[3], L L Alves[4], S Baalrud[5], N Babaeva[6], A Bogaerts[7], A Bourdon[8], P J Bruggeman[9,*], C Canal[10], E H Choi[11], S Coulombe[12], Z Donkó[13], D B Graves[14,15], S Hamaguchi[16], D Hegemann[17], M Hori[18], H-H Kim[19], G M W Kroesen[20], M J Kushner[21], A Laricchiuta[22], X Li[23], T E Magin[24], S Mededovic Thagard[25], V Miller[26], A B Murphy[27], G S Oehrlein[28], N Puac[29], R M Sankaran[30], S Samukawa[31], M Shiratani[32], M Šimek[33], N Tarasenko[34], K Terashima[35], E Thomas Jr[36], J Trieschmann[37], S Tsikata[38], M M Turner[39], I J van der Walt[40], M C M van de Sanden[20,41] and T von Woedtke[42,43]

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[2] Department of Chemical and Biological Engineering, Colorado School of Mines, Golden, CO, 80401, United States of America
[3] Equipo de Propulsión Espacial y Plasmas (EP2), Universidad Carlos III de Madrid, Leganés, Spain
[4] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[5] Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109, United States of America
[6] Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow 125412, Russia
[7] Research Group PLASMANT, Department of Chemistry, University of Antwerp, Universiteitsplein 1, B-2610 Wilrijk-Antwerp, Belgium
[8] Laboratoire de Physique des Plasmas (LPP), CNRS, Sorbonne Université, Ecole Polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France
[9] Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN, United States of America
[10] Biomaterials, Biomechanics and Tissue Engineering Group, Department of Materials Science and Engineering, and Research Centre for Biomedical Engineering (CREB), Universitat Politècnica de Catalunya (UPC), Av. Eduard Maristany 10-14, 08019 Barcelona, Spain
[11] Plasma Bioscience Research Center, Department of Electrical and Biological Physics, Kwangwoon University, 20 Kwangwon-Ro, Nowon-Gu, Seoul 01897, Republic of Korea

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The Abdus Salam International Centre for Theoretical Physics

1856-39

2007 Summer College on Plasma Physics

30 July - 24 August, 2007

DUSTY PLASMA PHYSICS

Basic Theory and Experiments

R.L. Merlino
The University of Iowa
Department of Physics and Astronomy
Iowa City, IA, USA

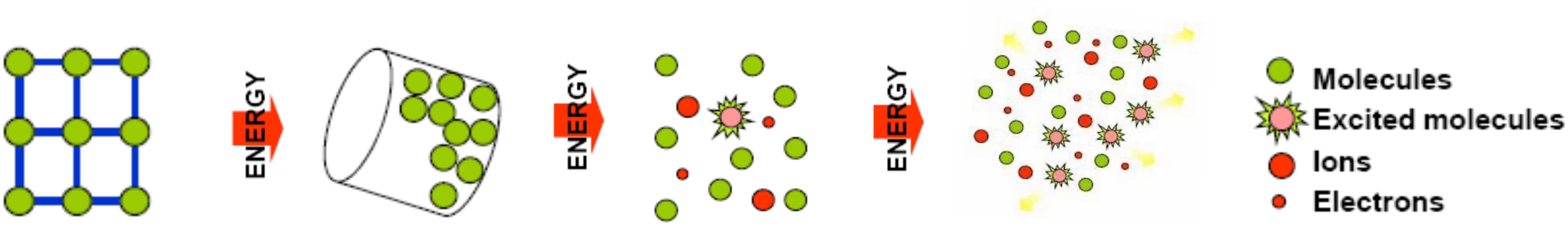
https://www.osti.gov/servlets/purl/972505

Outline

- ❑ Introduction to plasma
- ❑ Low temperature plasma and applications
- ❑ Complex (dusty) plasma : what is dusty plasma and where are they found
- ❑ Basics and applications of dusty plasma
    - ❑ Area 1: Particle level studies in plasmas, statistical behaviour
    - ❑ Area 2: Collective behavior of dust cloud, linear and nonlinear waves
- ❑ Dusty plasma under microgravity
- ❑ Magnetic field effect on plasma and dusty plasma
- ❑ Particle growth and processes using low temperature plasma
- ❑ Summary

Plasma ?

Solid, Liquid, Gas and ...Plasma -The 4th fundamental State of Matter : the highest energy state of the matter



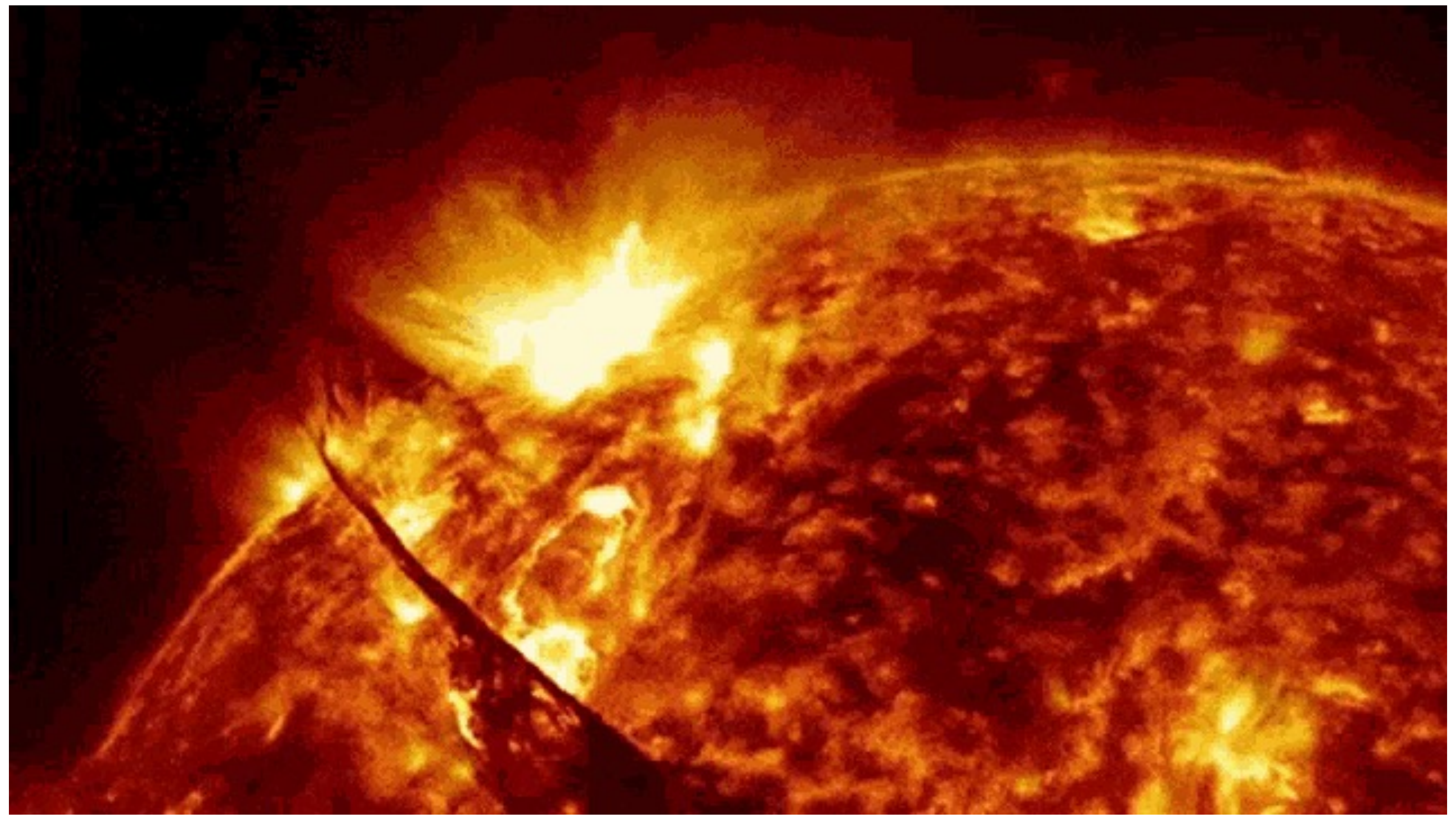



A plasma is a collection of neutrals, ions, and electrons characterized by a collective behavior

S. Eliezer and Y. Eliezer. The Fourth State of Matter: An Introduction to Plasma Science. Bristol, UK: IOP Publishing (2001)

Plasma in nature

99% of ordinary matter in the universe is in the plasma state: most stars are made up of plasma



Solar Flairs

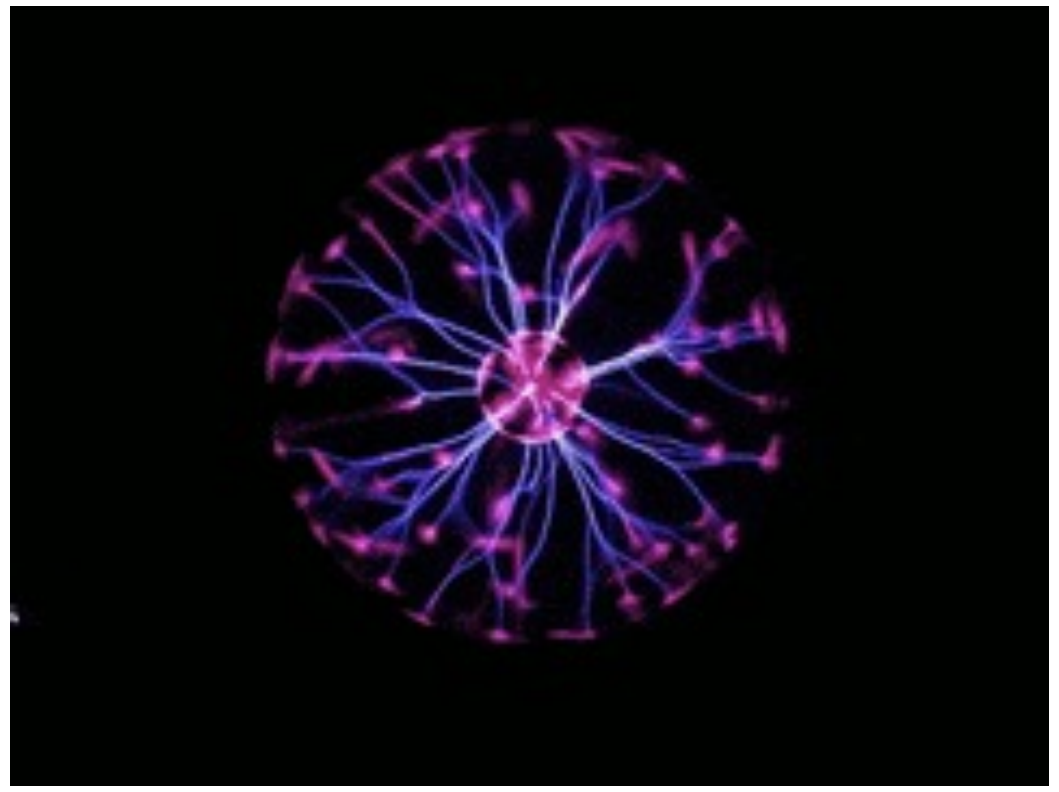
Aurora Borealis (Northern Lights)

Comet tail

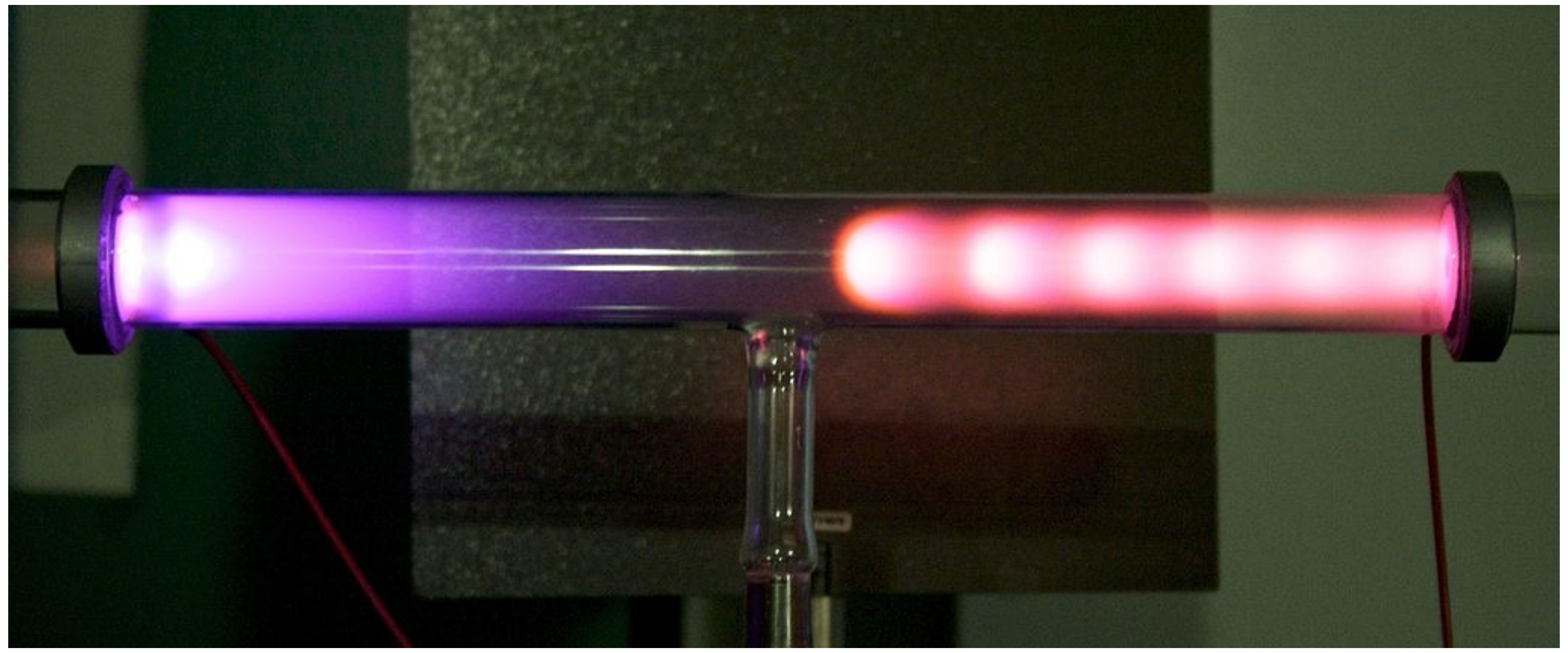
Lightening

Man made plasma

Neon light

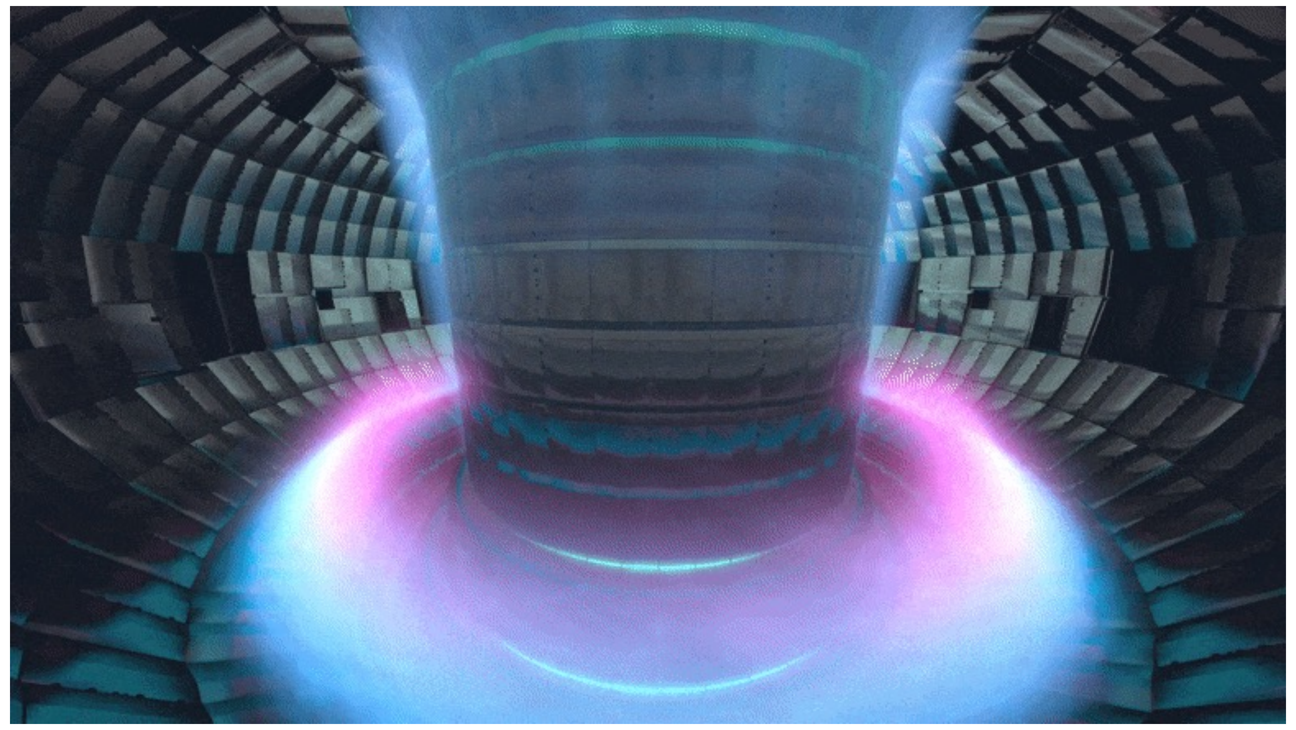


Plasma globe

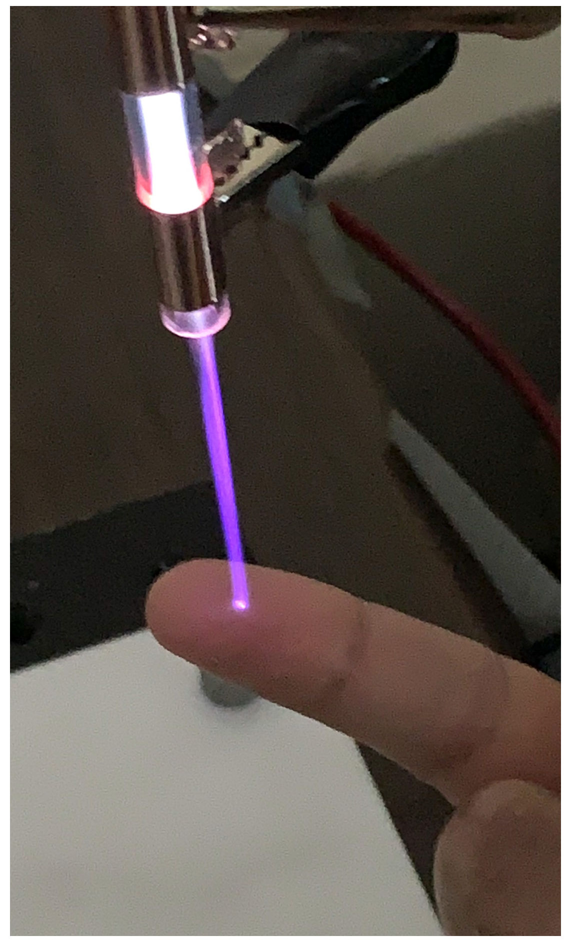


A classic glow discharge in a Crookes tube

6 kW Hall thruster in operation at the NASA Jet Propulsion Laboratory



Tokamak plasma

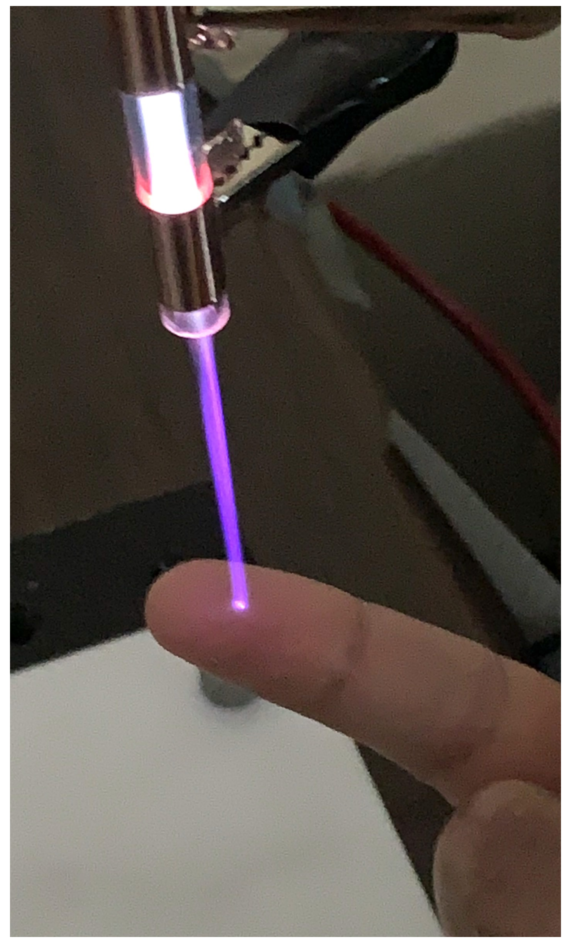


Plasma jet treatment

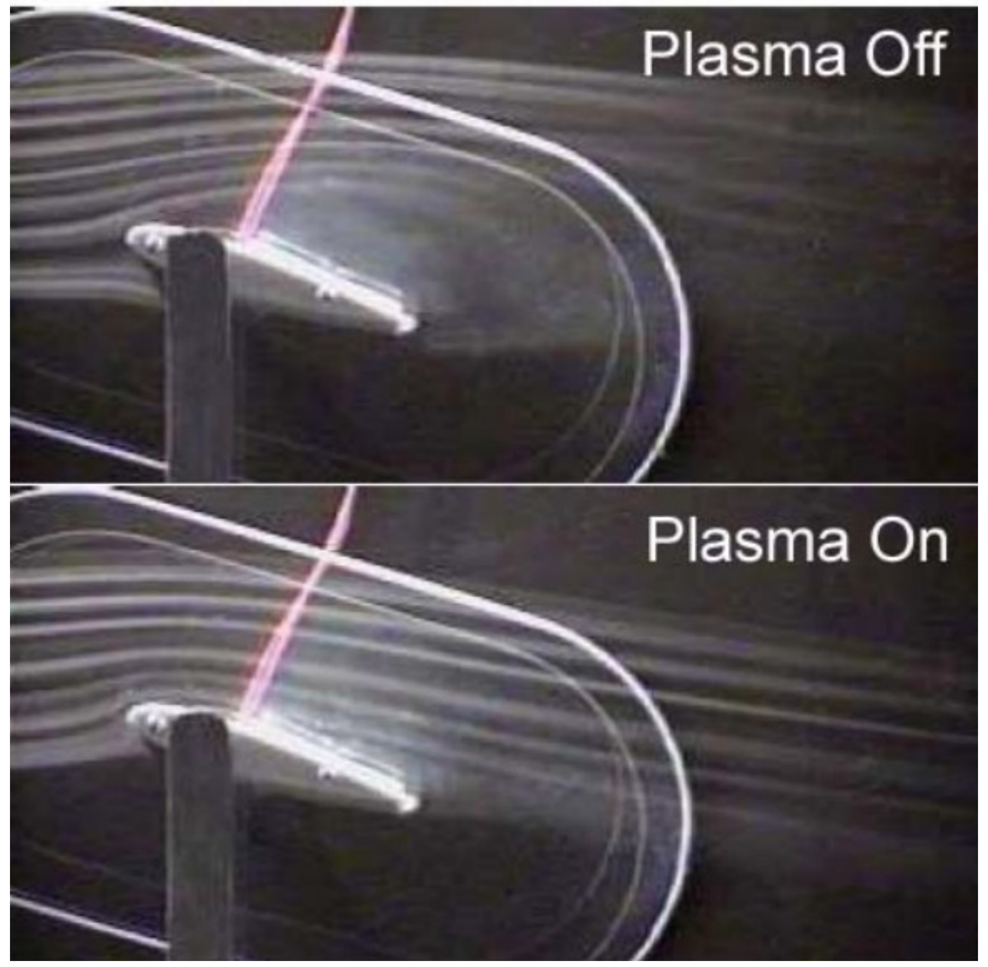
Fluorescent Lamps

Plasma Display Televisions

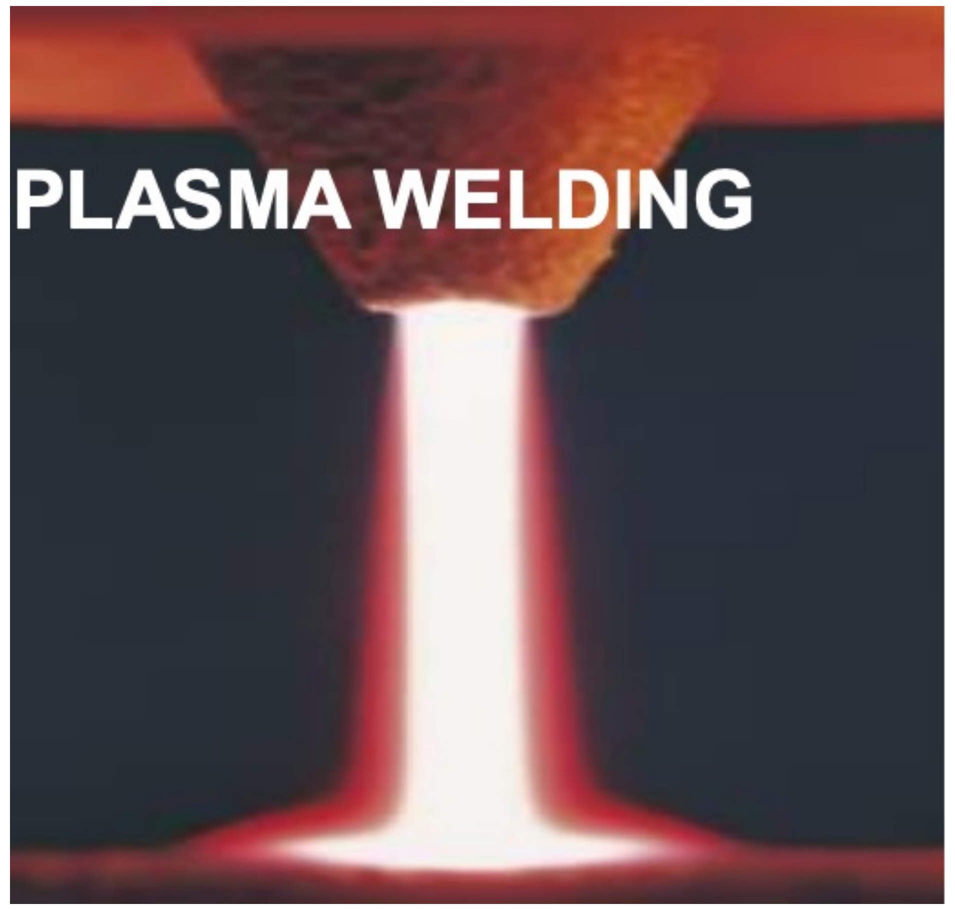
Plasma has applications

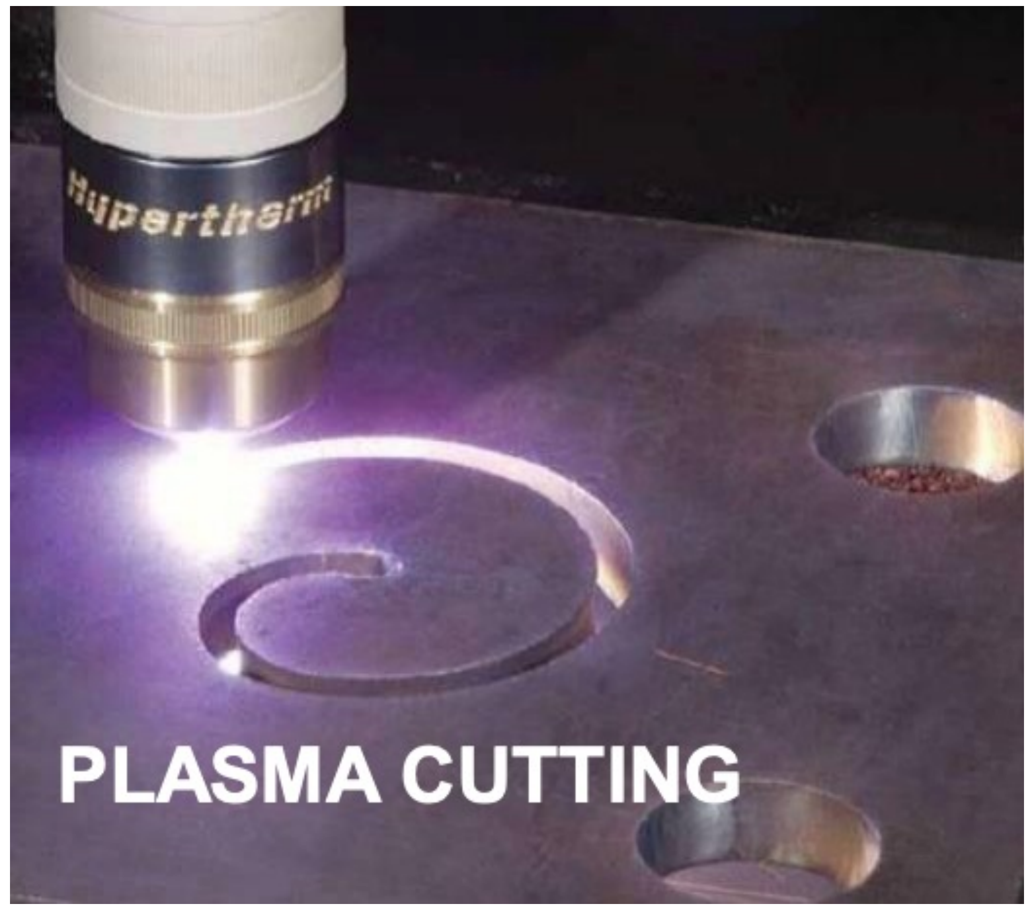


Plasma jet treatment

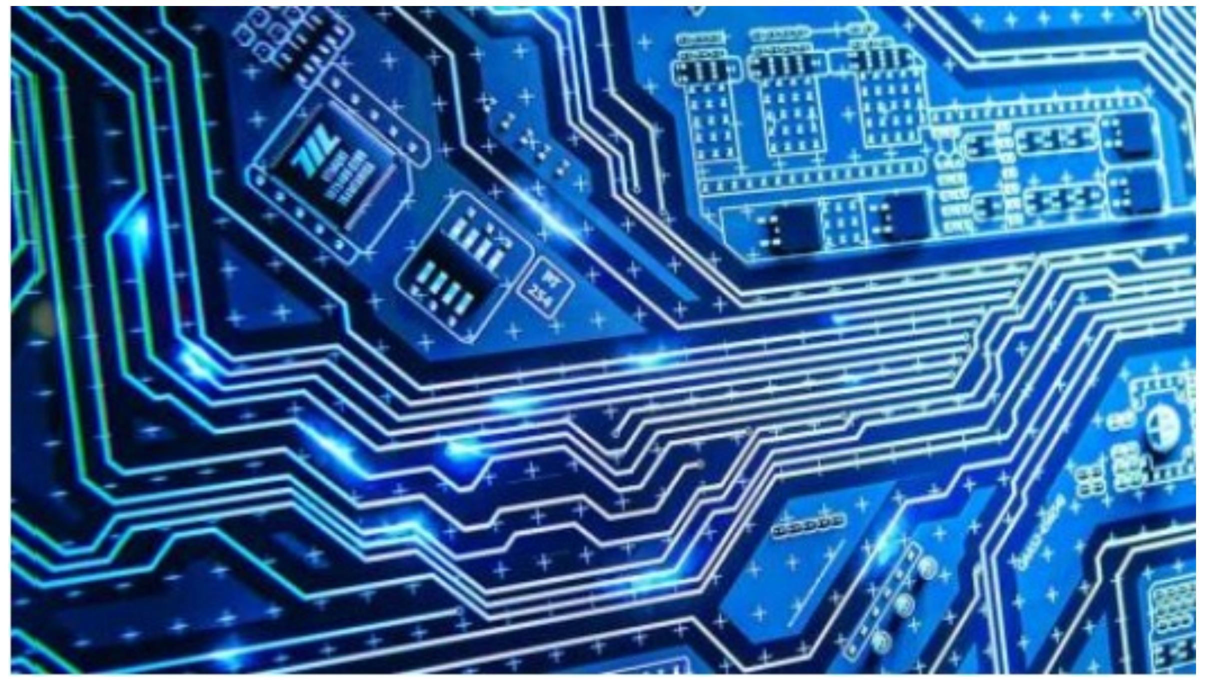


Control of aeronautical flows using plasmas

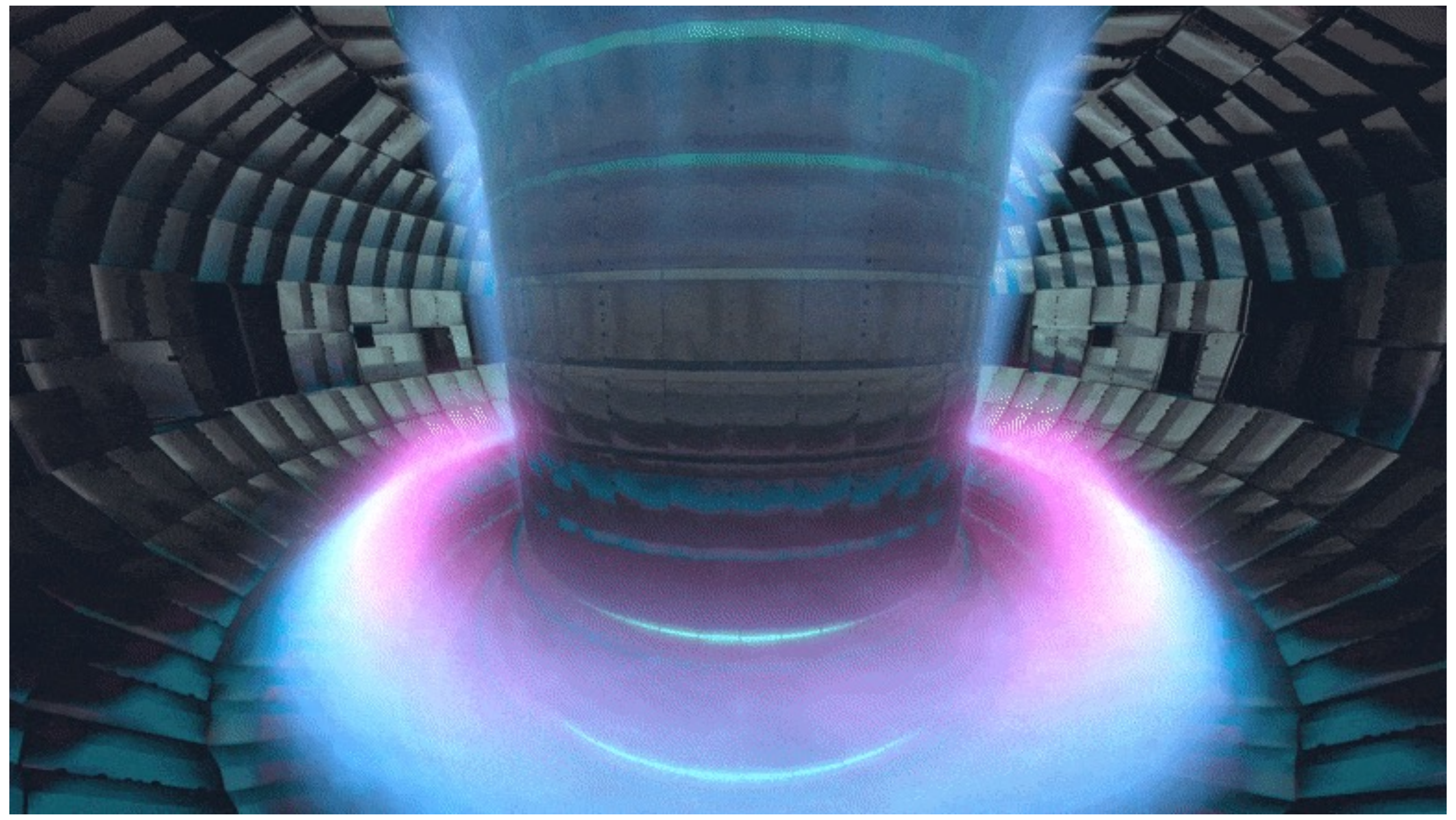




6 kW Hall thruster in operation at the NASA Jet Propulsion Laboratory

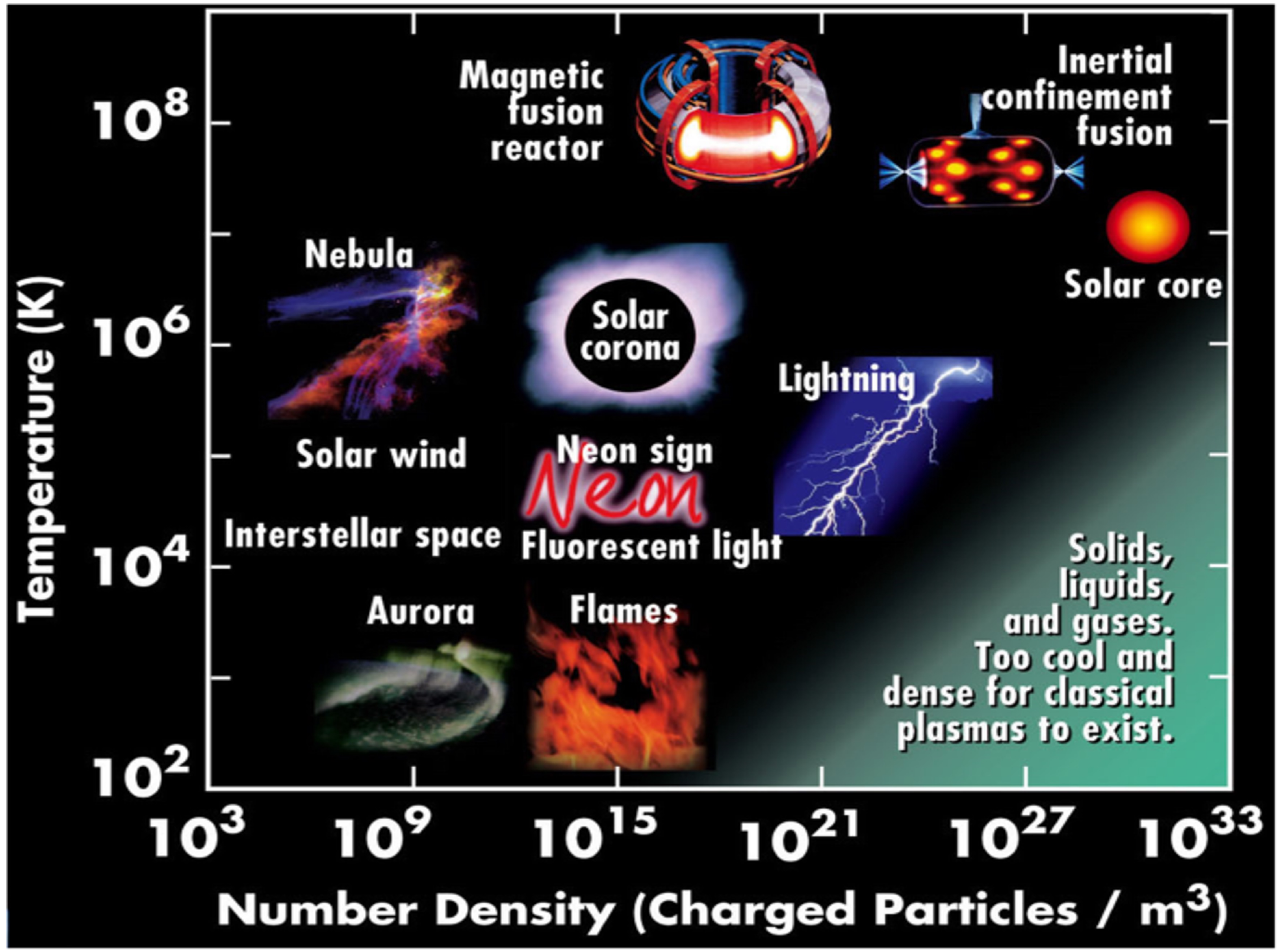


Plasma etching used for semiconductor industry



Tokamak plasma

Two types of plasmas



High-temperature plasmas or Hot (Thermal) plasmas
$T_i \approx T_e \geq 10^7$ K e.g., fusion plasmas
$T_i \approx T_e \approx T_g \leq 2x10^4$ K
e.g., arc plasma at normal pressure

Low-temperature plasmas or Cold (Non-thermal) Plasmas
Electron temperature can reach several eV, $T_e >> T_i$, T_g with $T_e \approx$ 0.5 to 5 eV
Ions and neutrals are near room temp., $T_i \approx T_g \approx 300 - 600$ K
e.g., low-pressure glow discharge, high-pressure cold plasma

Low temperature plasma application

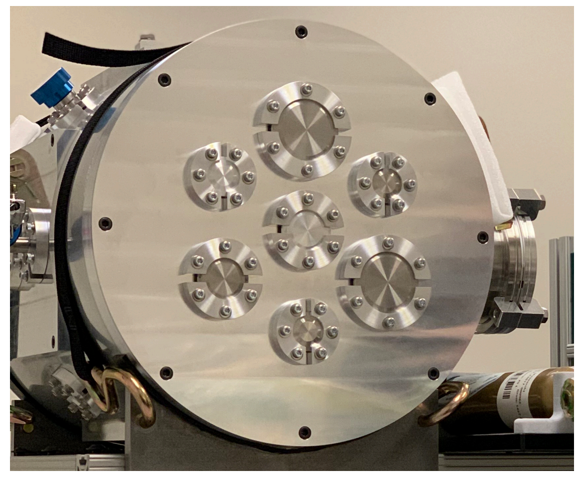
In the past decade, advancements of low-temperature plasma have demonstrated commercial and technical value in various areas

- Aerospace industry: space propulsion, plasma-based sterilization, plasma flow control, and plasma-assisted combustion
- Materials processing,
- Healthcare technologies (Immunotherapy, cancer treatment, wound healing and many more)
- Agriculture and food storage,
- Chemical processing techniques.

Generation of low temperature plasma

Low temperature Plasma

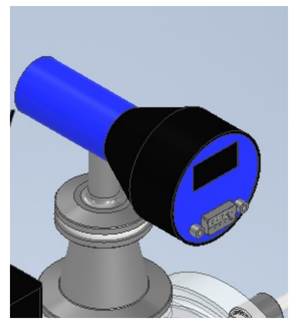
- Low pressure plasma (1 mTorr ~ a few Torr)
- Extensively Used to understand fundamental plasma physics (waves, instabilities), and application in plasma processing (e.g. in semiconductor industry for computer chips manufacturing)
- Requirements:



Vacuum chamber

pump

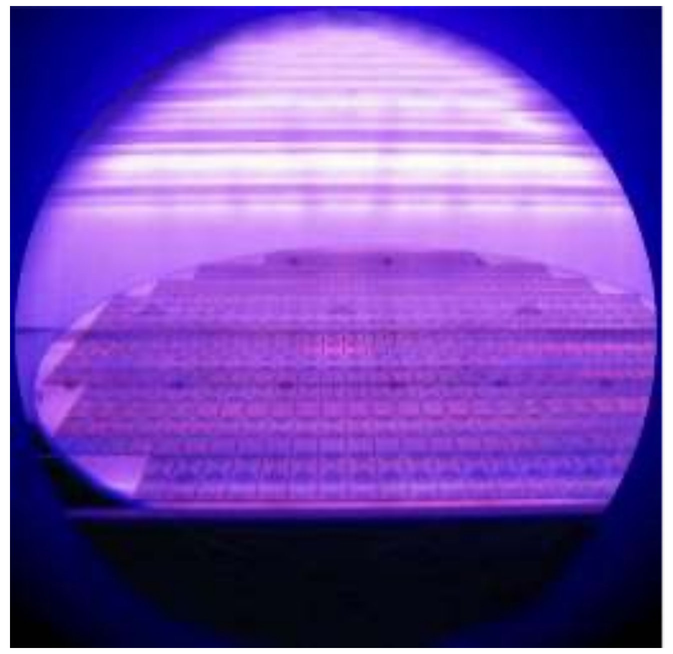
Mass flow controller



Pressure gauze

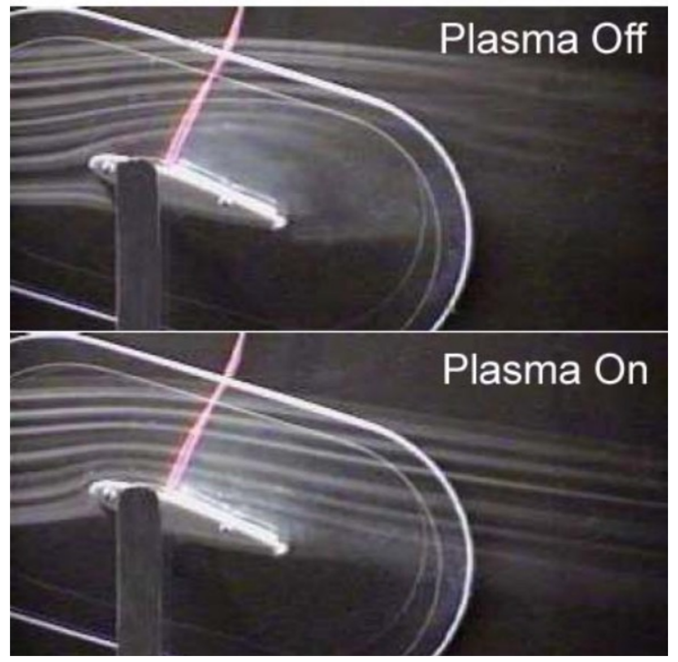
Gas

Plasma processing to harden or coat materials



Plasma processing of silicon for semiconductor manufacturing

- High pressure or Atmospheric pressure Plasma (a few Torr – few atm)
- Simple pumping system or no vacuum
- Easy handling, lower cost and numerous application. The interaction with atmosphere generate reactive species and radicals. An emerging area of research.



Control of aeronautical flows using plasmas

Surface treatment

Bio-application (wound healing, cancer treatment)

Ozone generation for water cleaning

Characteristic feature of plasma: formation of sheaths

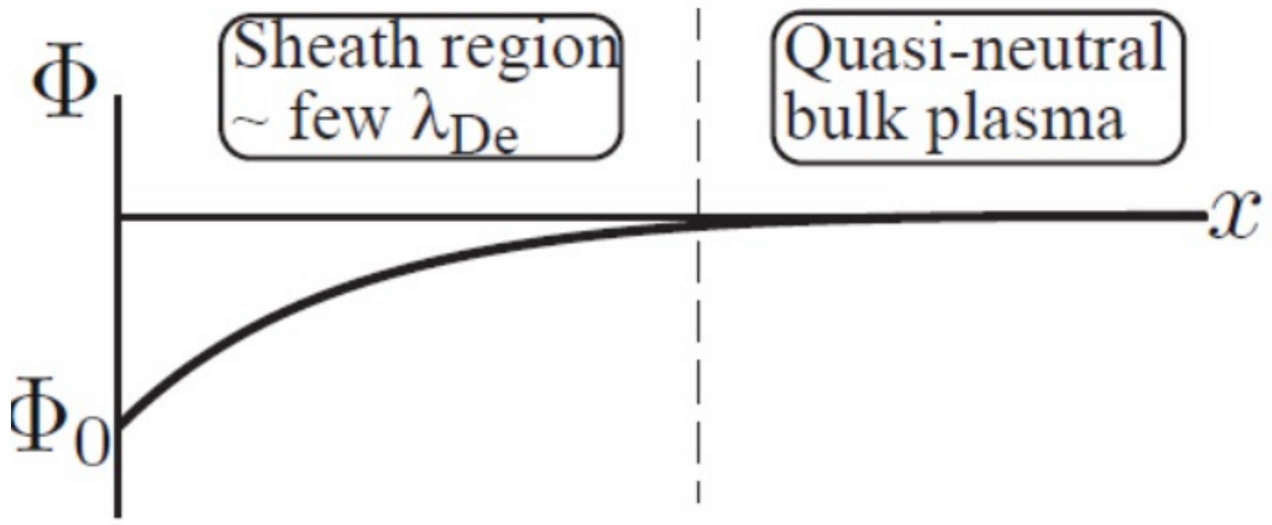
❖ Plasma are surrounded by sheath!

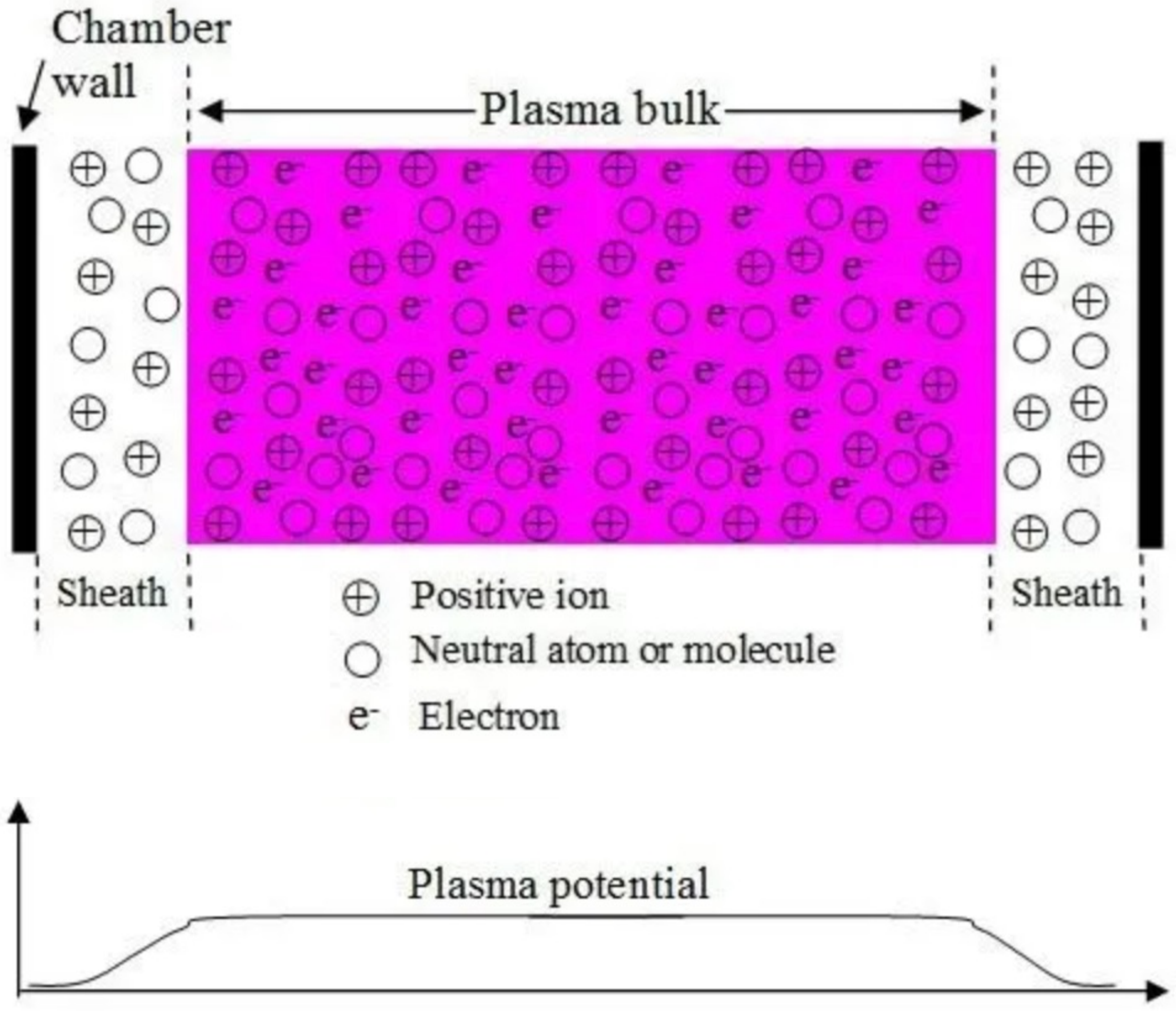
- The sheath is the boundary layer between a plasma and a solid surface (electrodes, substrate, container walls, …)
- It acts to balance electron and ion currents lost from a plasma
- Sheaths are characterized by a strong E-field, low electron density

The Debye length is the characteristic length scale of a plasma

$$\lambda_{De} = \left(\frac{\varepsilon_0 T_e}{e n_e}\right)^{\frac{1}{2}} \qquad \lambda_{De}(cm) = 740\sqrt{T_e/n_e}$$

T_e in eV and n_e in cm^{-3}





Plasma and plasma sheath

❖ Plasma frequency is the most fundamental time-scale in plasma physics.

$$\omega_p^2 = \frac{n e^2}{\epsilon_0 m}$$

It corresponds to typical electrostatic oscillation frequency of a given species in response to a small charge separation

Another interesting plasma: Dusty plasma

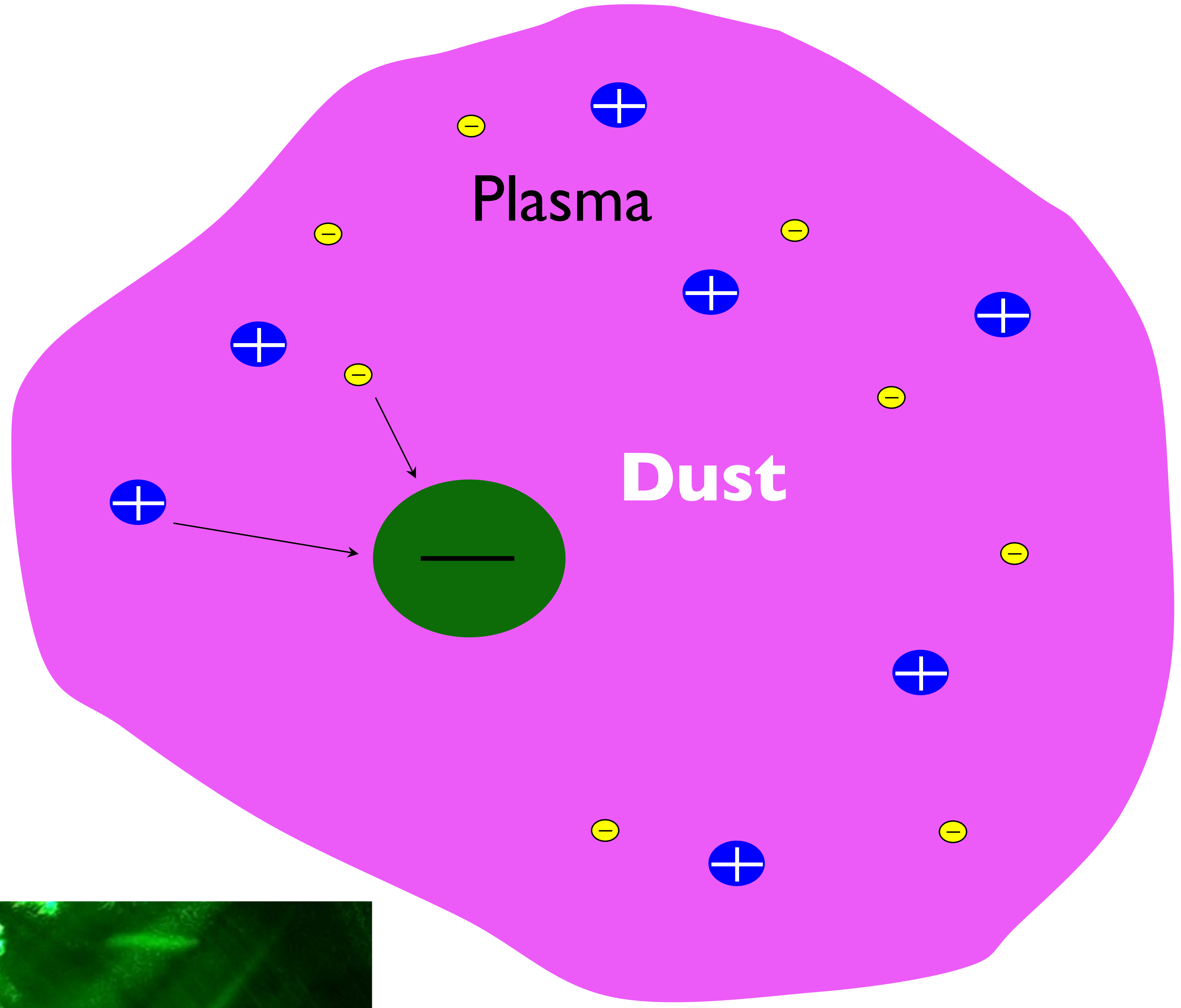
❖ Dusty plasma = electrons + ions + neutrals + charged dust particles (nanometer to micrometer)

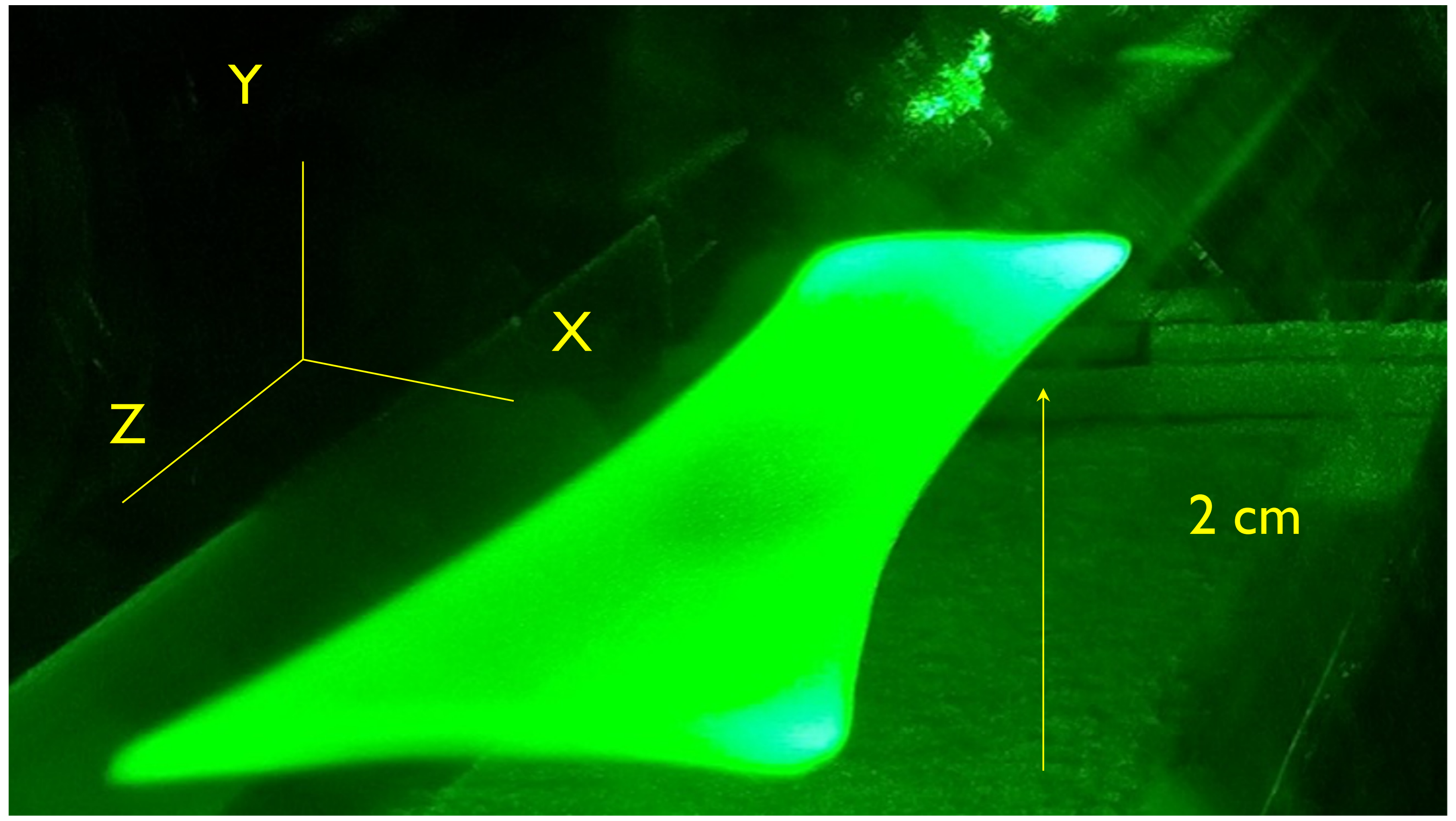
❖ Collect electron and ions

❖ Become Negatively charged

❖ Dust particles experience a net force due to gravity and the electric field

❖ Slow time scale phenomenon





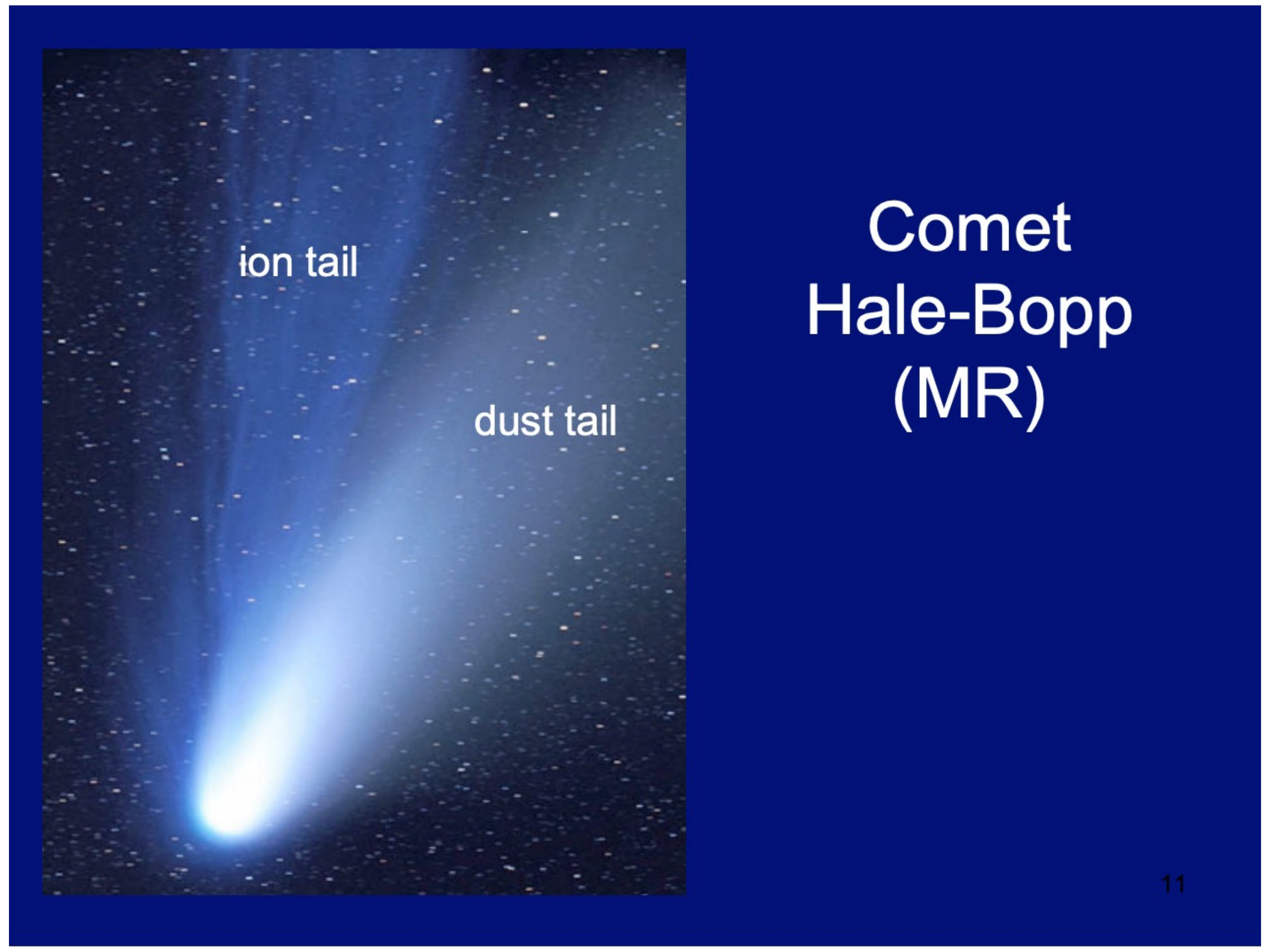
Dusty plasma in Nature

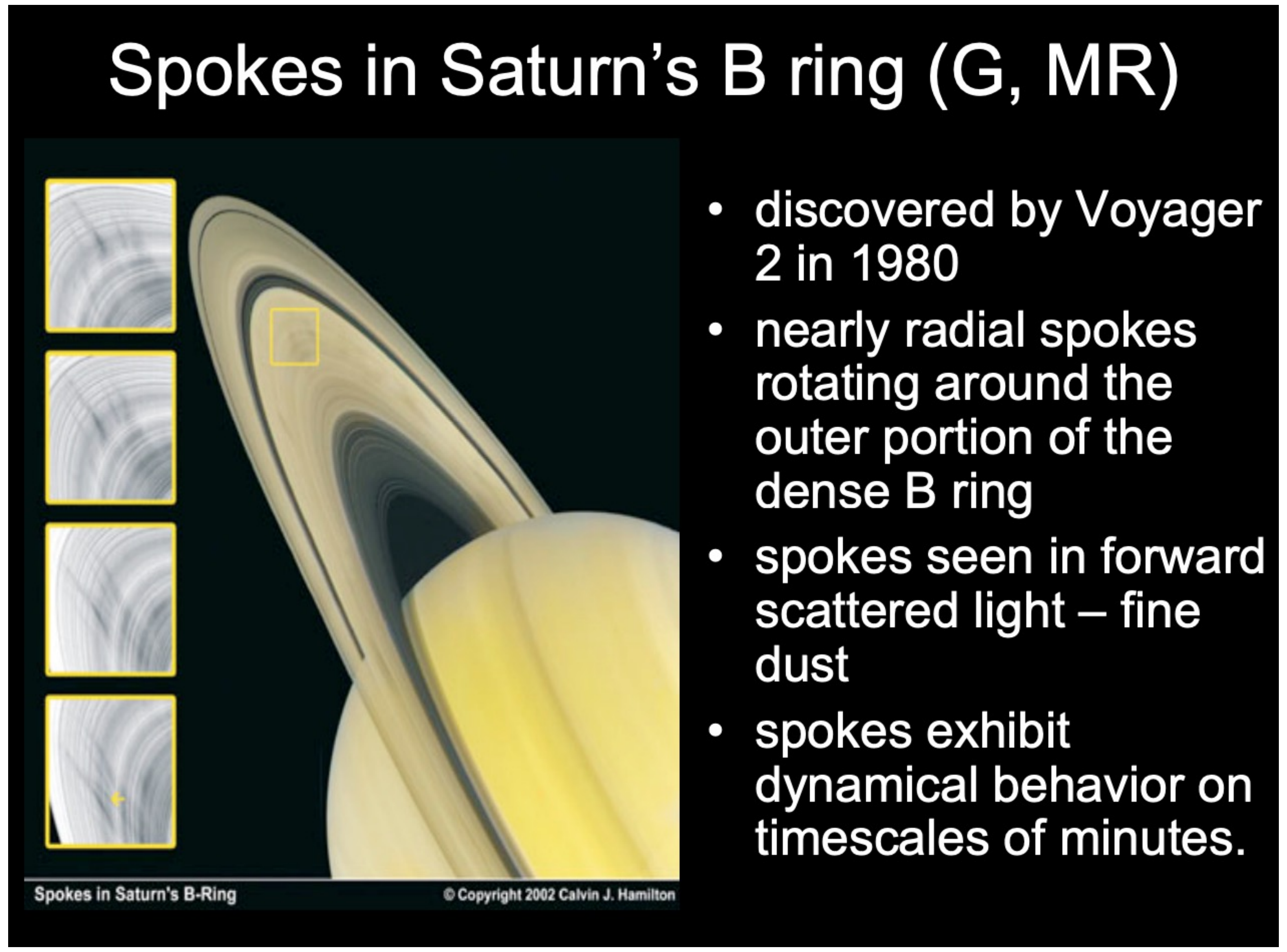
Dusty plasmas in the solar system

- Cometary tails
- Planetary ring systems – Saturn's rings
- Dust streams ejected from Jupiter
- Zodiacal light

Dusty plasmas on the earth

- Ordinary flames
- Atmospheric aerosols
- charged snow
- lightning on volcanoes





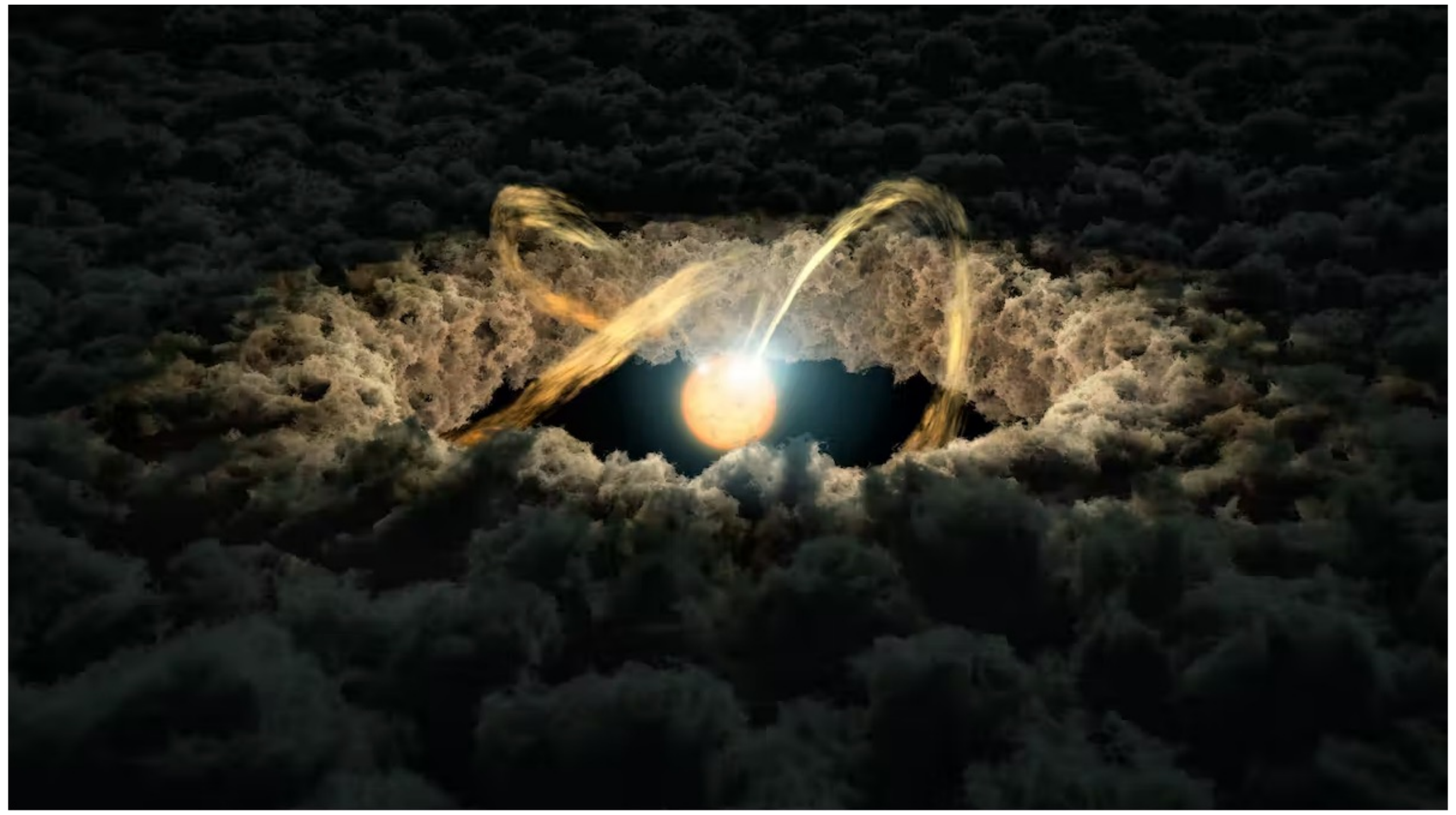
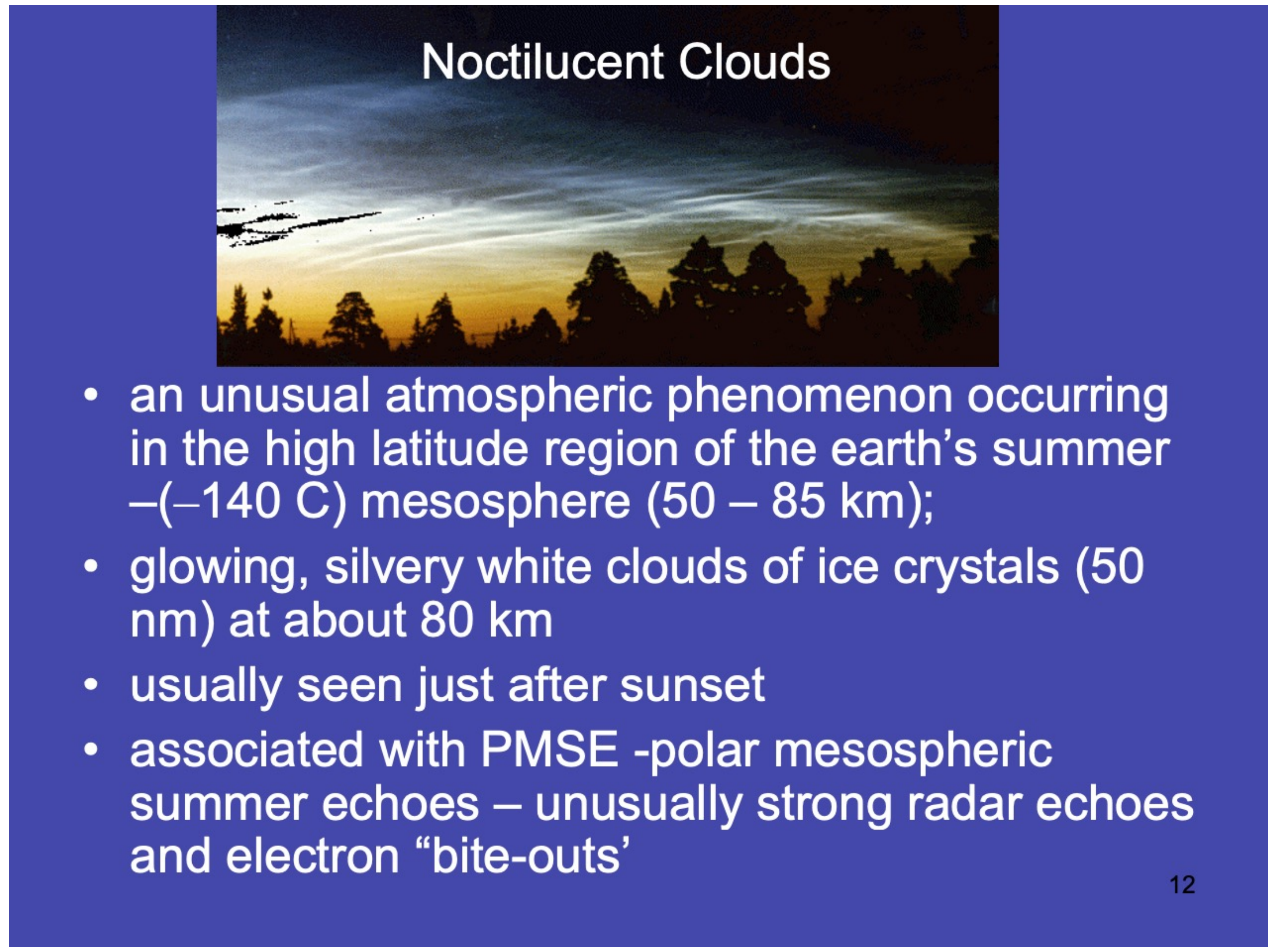
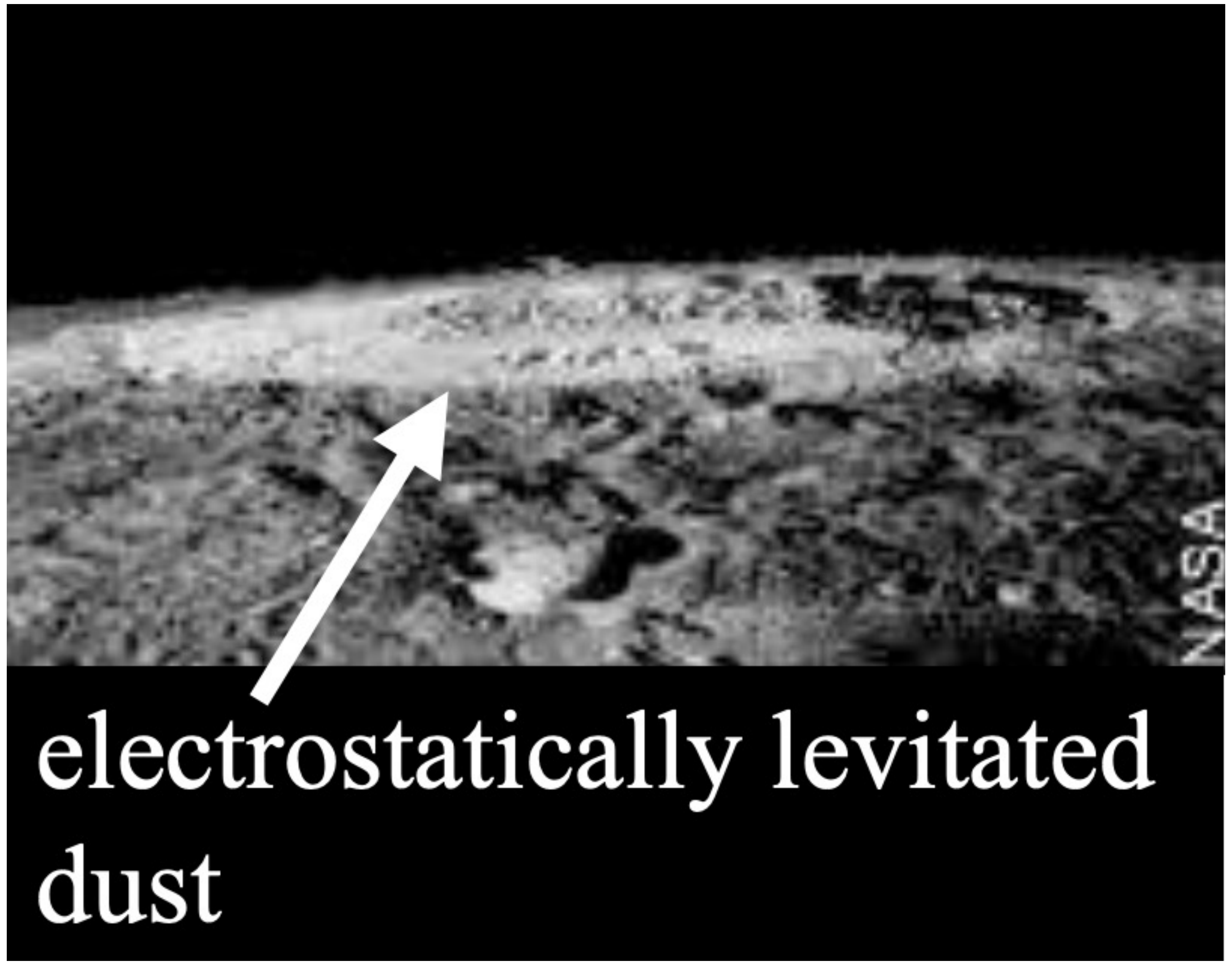


Illustration of a star surrounded by a protoplanetary disk. NASA/JPL-Caltech, CC BY-ND



Dusty plasma in Nature

Apollo astronauts see “moon clouds”

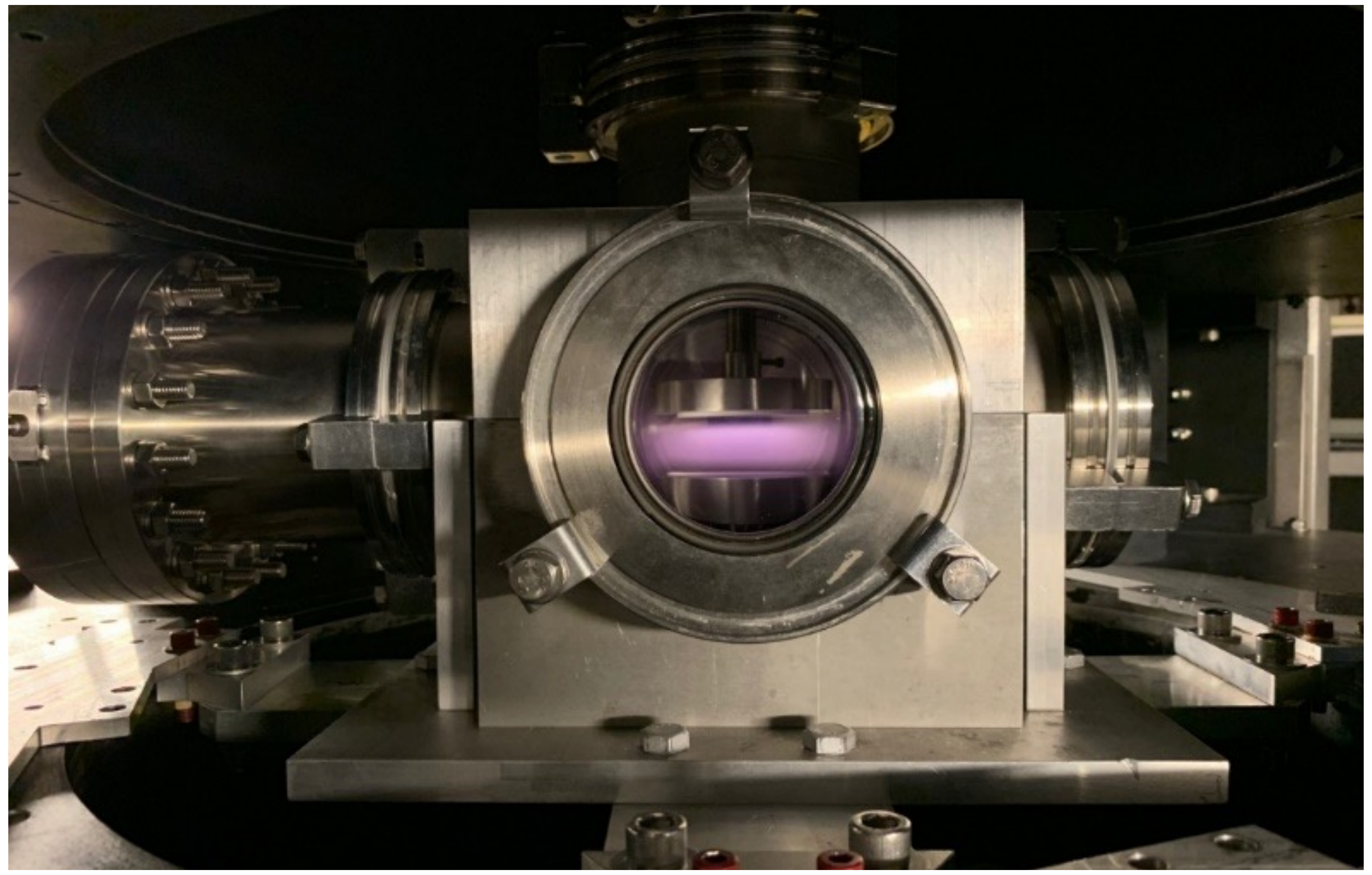


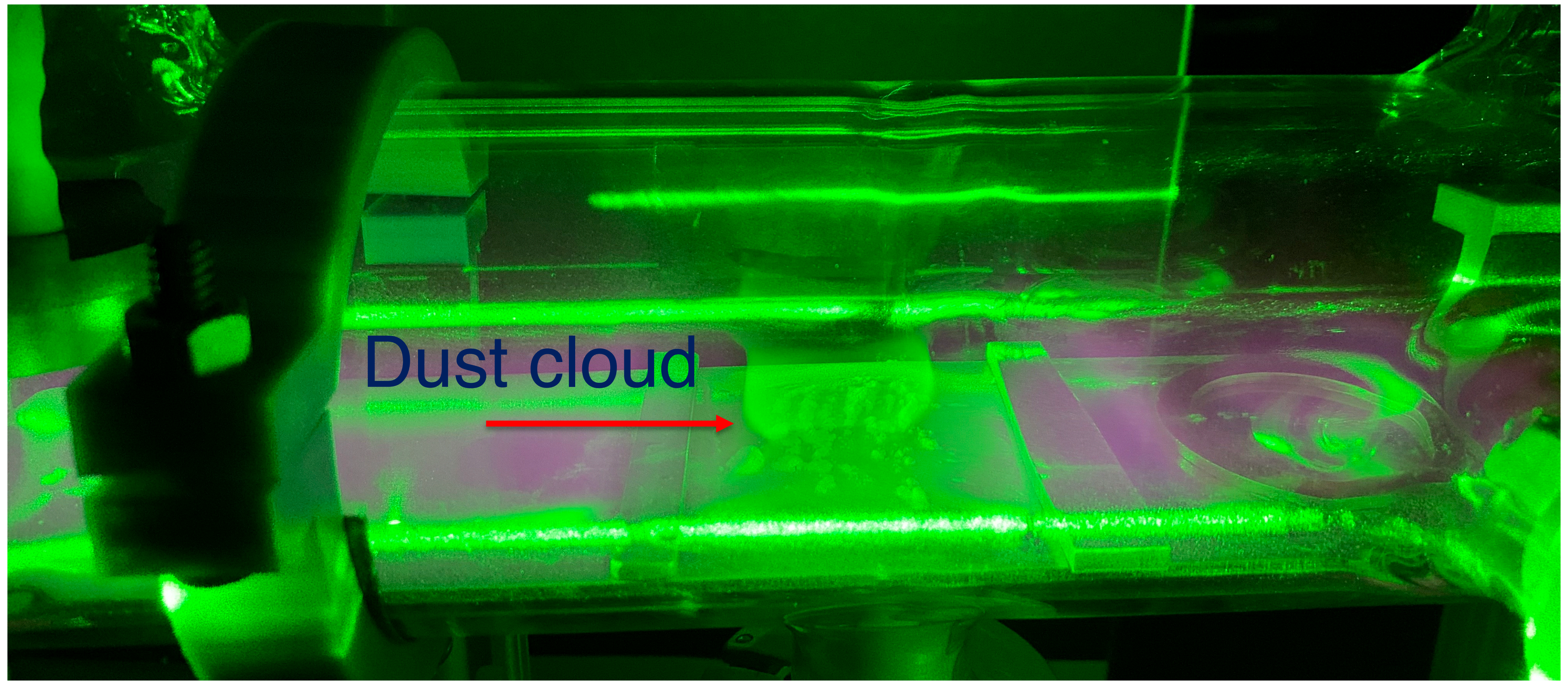
- dust acquires a positive charge due to solar UV
- Some grains are lifted off of the moon’s surface by the electrostatic force

http://www.space.com/scienceastronomy/061007_moon_dust.html

Man- made dusty plasmas

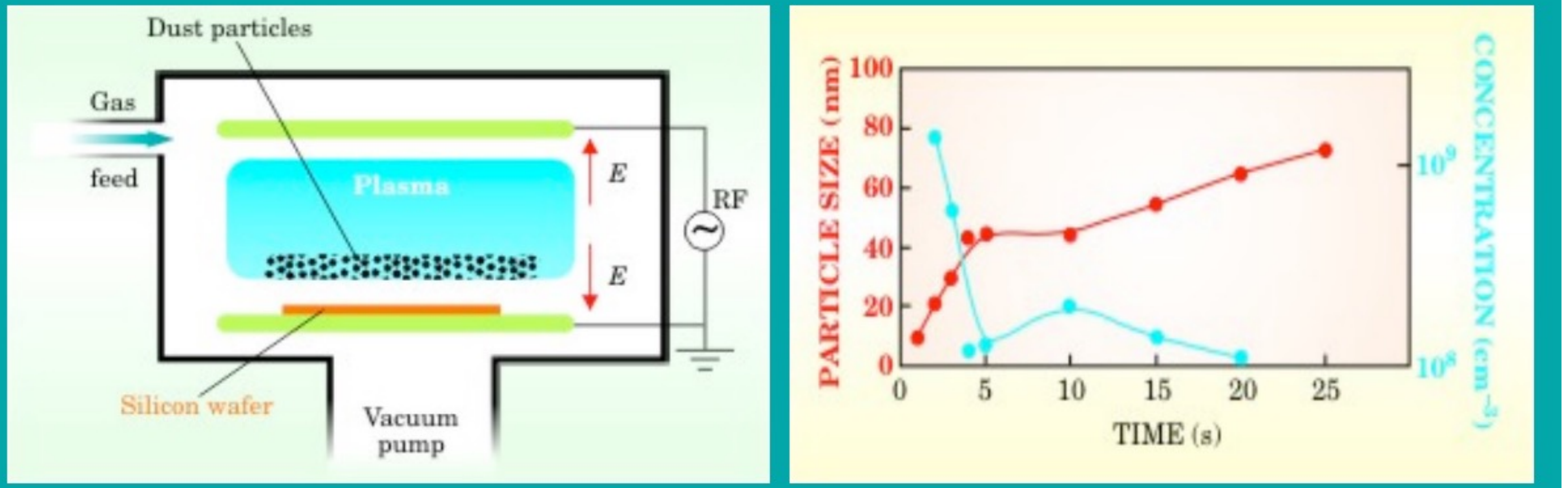
Dusty plasma can be made by introducing the particles or by growing within plasma





dusty plasma devices

Semiconductor processing

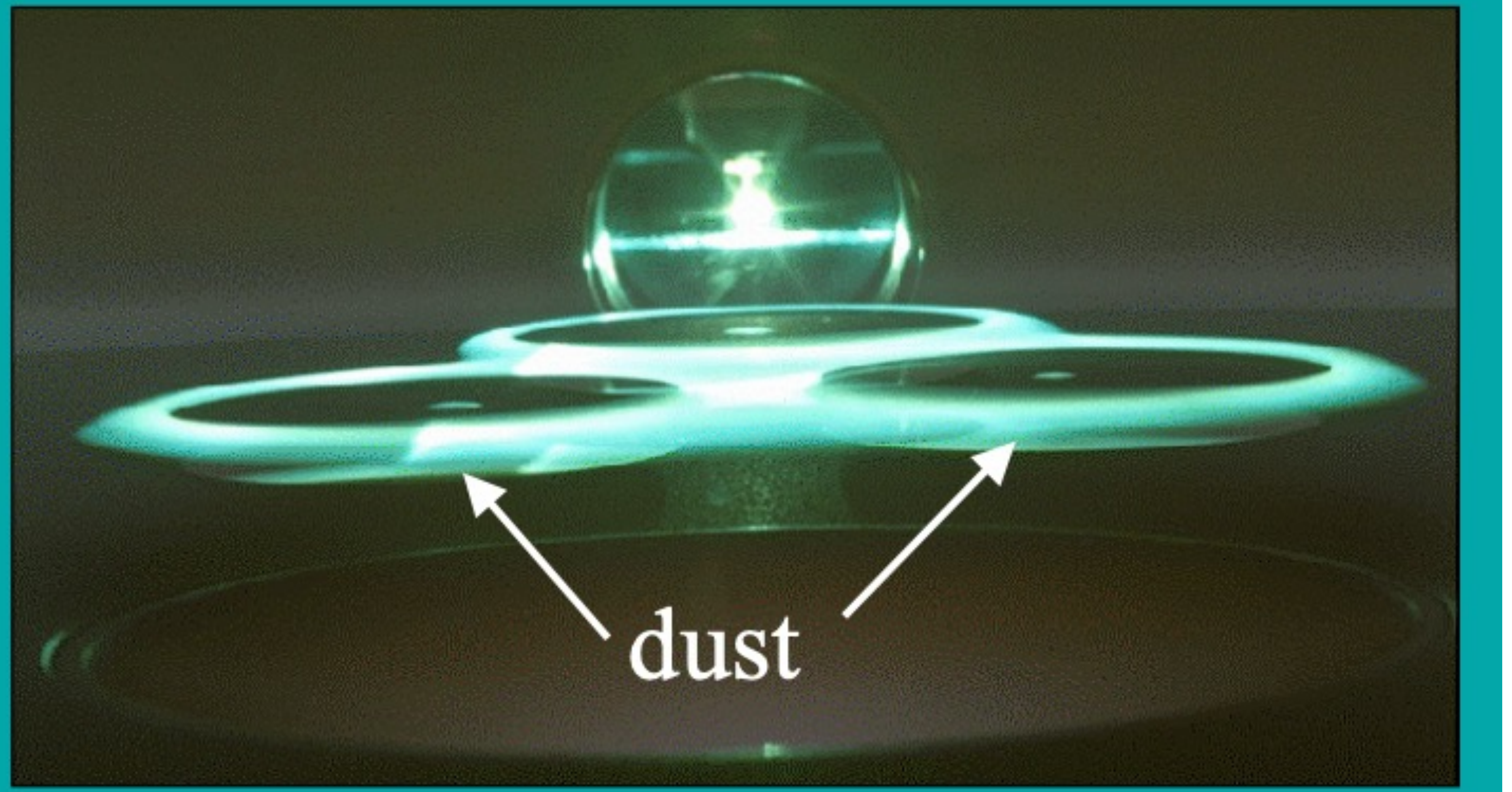


silane (SiH_4) + Ar + O_2 → SiO_2 particles

Man- made dusty plasmas

Dust is a bad thing?

Dust contamination in plasma processing devices



The formation of dust during the processing of semiconductor electronics is a serious problem for the industry. It has been estimated that up to one-half of all semiconductor chips were contaminated during processing.

Rocket Exhaust is a Dusty Plasma

- Exhaust plumes of solid propellant rocket motors are usually recognized as weakly ionized plasmas containing dusts of Al_2O_3.
- These charge dust may be trapped in earth's B field
- Reach high altitudes and contribute to Noctilucent clouds

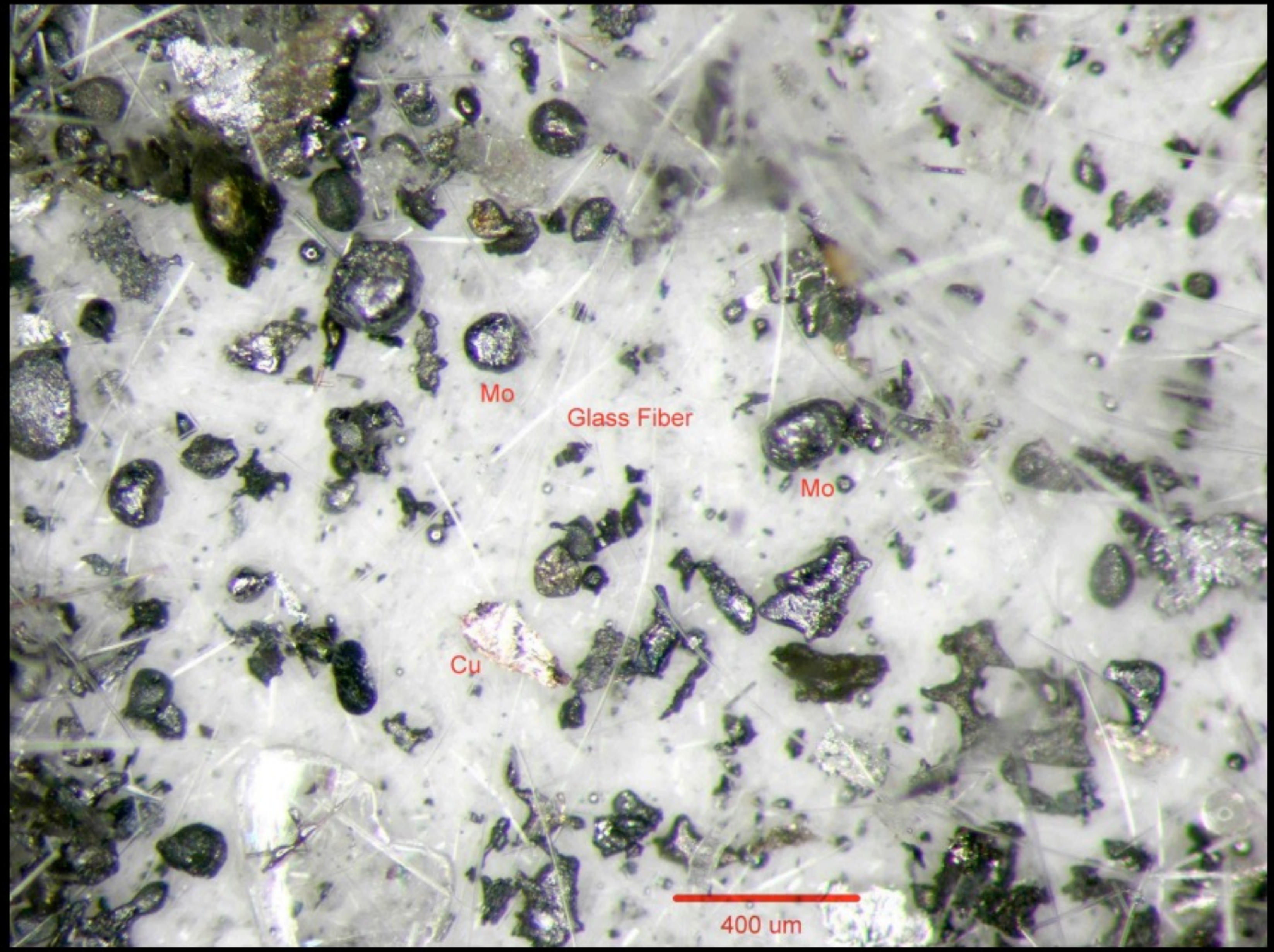
The Charged Aerosol Release Experiment takes off from Andoya Space Center in Norway, Sept. 16. Debris of polystyrene thermal cover of payloads rained particles on the launch pad. Credit NASA/Wallops Flight Facility,

https://www.dcmilitary.com/waterline/news/local/nrl-rocket-experiment-tests-effects-of-dusty-plasma-on-the-ionosphere/article_d510f12e-eb8e-515a-833d-e851afe80230.html

Man- made dusty plasmas

Dust in Fusion device

dust particles in tokamak C Mod



Man- made dusty plasmas

Dust in Fusion device

- The “dust” is a result of the strong interaction between the material walls and energetic plasma which causes flaking, blistering, arching and erosion of the carbon limiters or beryllium surfaces.
- Studies indicate that dust can be transported deep into the plasma causing a serious contamination problem.
- Dust poses a serious concern for ITER
- the discovery of the dust problem in fusion devices in1998 is become important factor that continues to drive dusty plasma research

Typical dusty plasma experiments in lab

- ❖ Dusty plasma = electrons + ions + neutrals
+ charged dust particles (nanometer to micrometer)
- ❖ Collect electron and ions
- ❖ Become charged
- ❖ Dust particles experience a net force due to gravity and the electric field

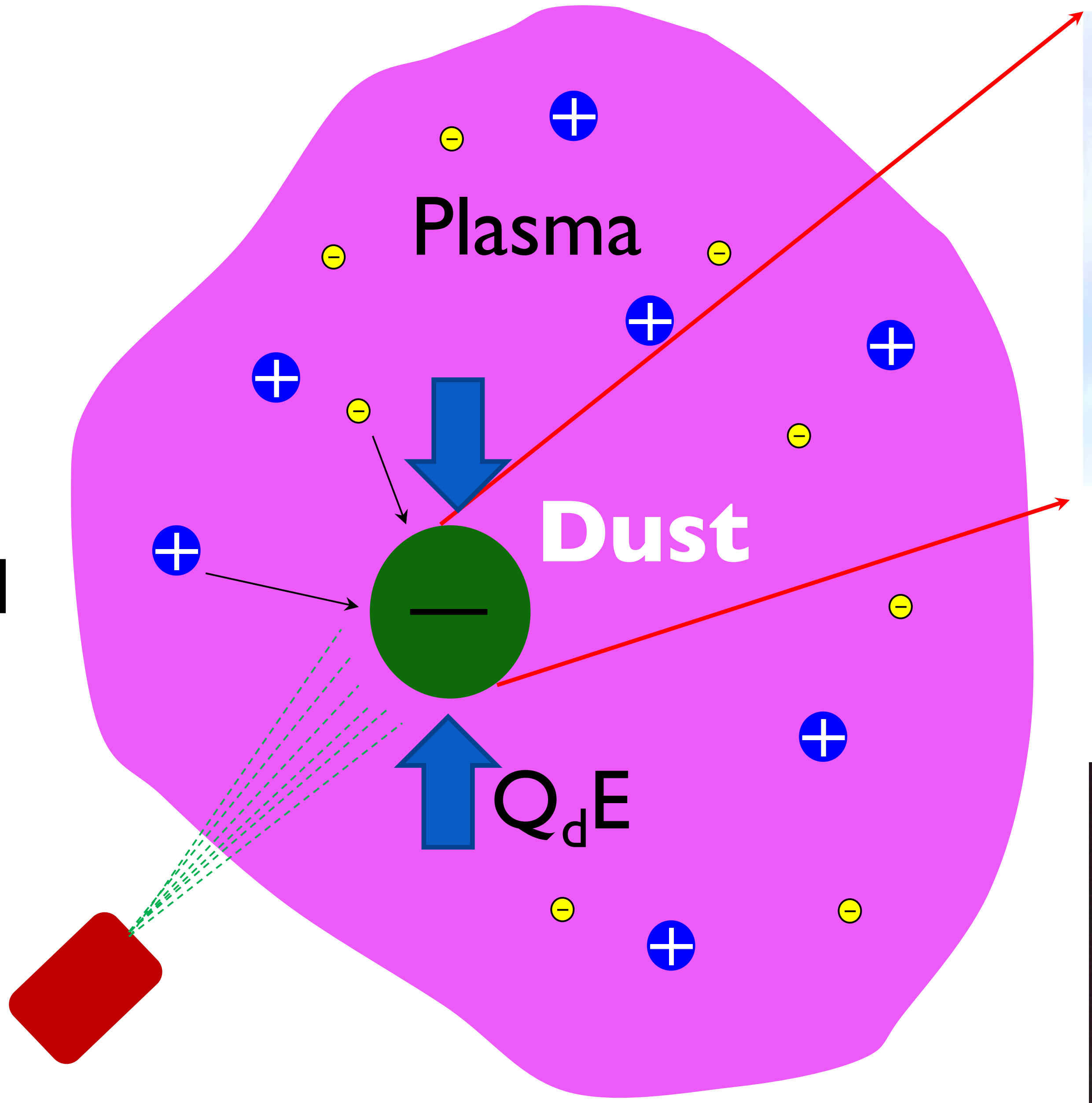
$F_g = m_d g = (4\pi/3)a^3 \rho_d g$

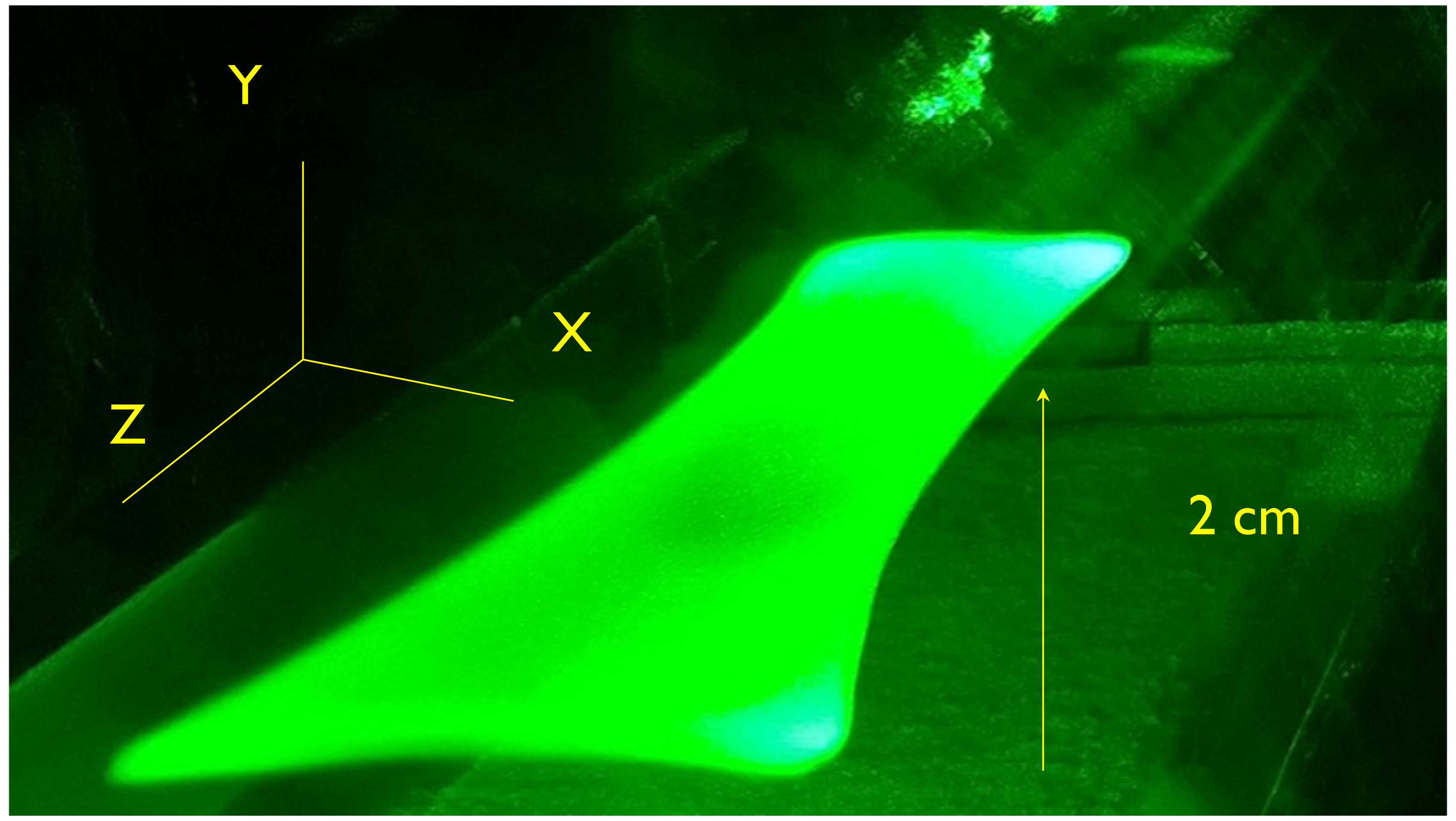
where ρ_d is the density of the dust material, typically ~ 1000 – 2000 kg/m^3
for thin-walled hollow microspheres of wall thickness t, $m_d \cong 4\pi a^2 t$

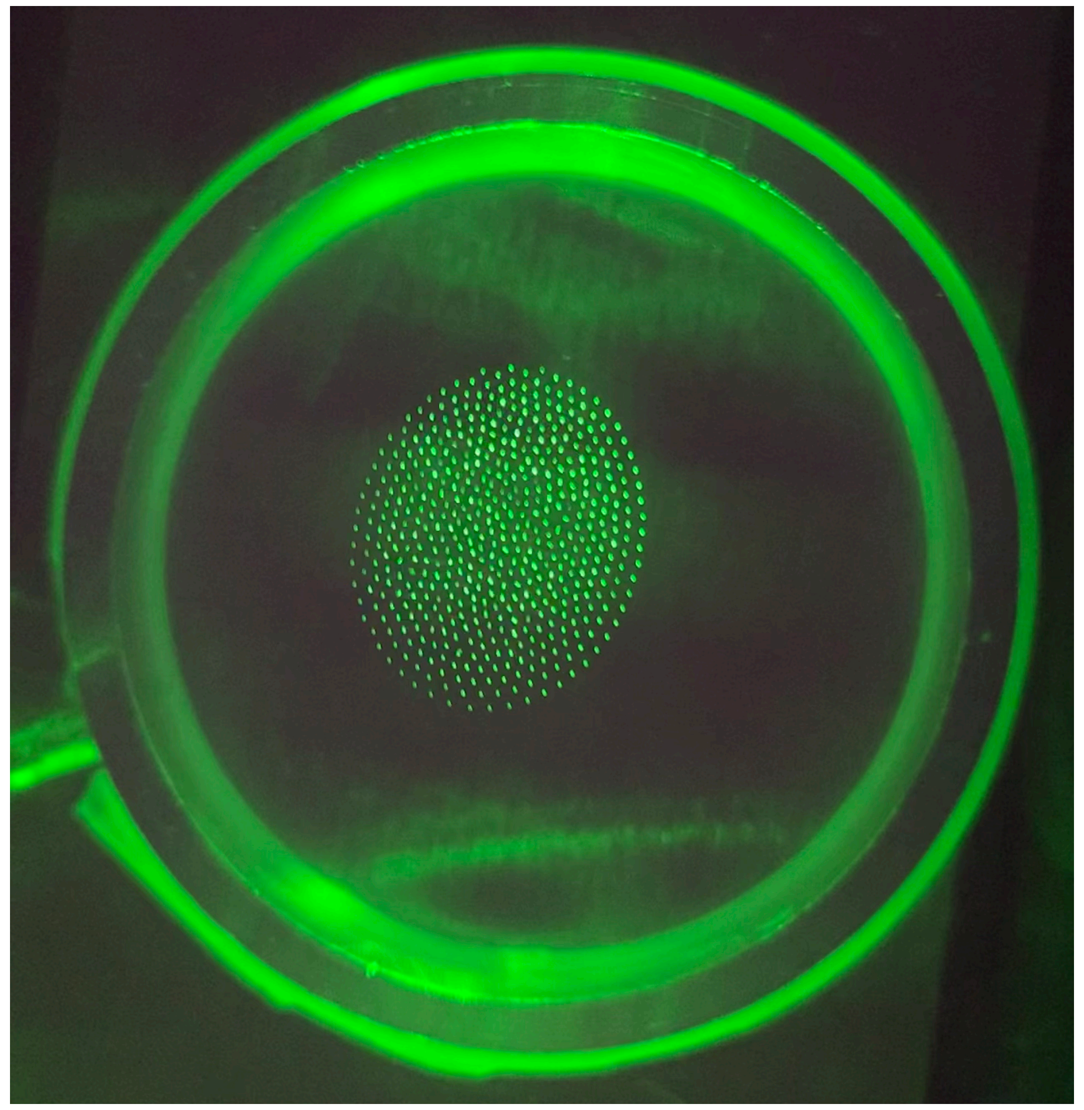
$F_e = Q_d E$

for a 1 micron particle
$m_d \sim 8\text{x}10^{-15}$ kg
Q ~ -2000e
$m_d g = Q_d E$

$E = m_d g/Q_d \sim 2.5$ V/cm







Dust cloud in Laboratory

Characteristics of many particle in plasma

The fundamental characteristics of a many-particle interacting system is the coupling constant

- $\Gamma = \dfrac{\text{potential energy of interation between particles}}{\text{average kinetic energy of the particles}}$
- $\Gamma = \dfrac{Q^2/4\pi\varepsilon_o\Delta}{kT} = \dfrac{Q^2}{4\pi\varepsilon_o kT\Delta}$

where Δ is the average interparticle spacing, usually taken to be the Wigner-Seitz radius $\Delta = \left(\dfrac{4\pi n}{3}\right)^{-1/3}$

where n is the particle density

Coupling parameter

Strongly coupled plasma

- Consider now a typical laboratory dusty plasma with a = 5 μm, $\Delta = 140\mu m$, $T_e = 2eV$, $T_d = 0.03eV$
- In this case $Q_d : 10^4 e$
- Now, $\Rightarrow \quad \Gamma : 10^4 >> 1$
- This is a strongly coupled dusty plasma

Factors that contribute to making dusty plasmas strongly coupled

- $Q_d = eZ_d$, with high Z_d ($\sim 10^3 - 10^4$), $\Gamma \sim Z^2$
- Dust grains are easily cooled to near room temperature by neutral gas interactions
- Dynamic time scales for microparticle relaxation in a plasmas are relatively short compared to colloidal systems.

- coupling constant $\Rightarrow \quad \Gamma \sim 10^{-4} << 1.$
- This is an example of a weakly coupled plasma.

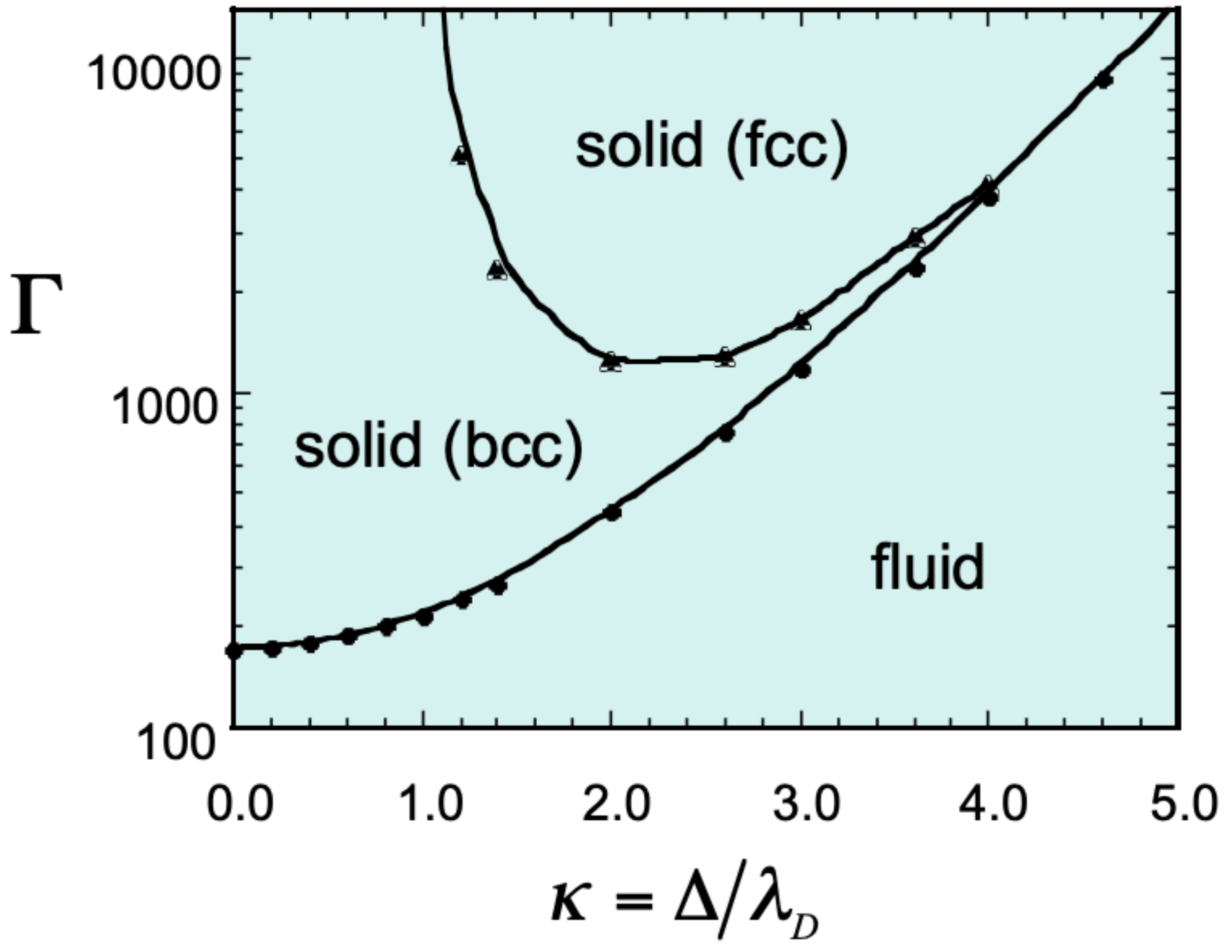
Coupling parameter

In laboratory plasma and other commonly observed plasmas, the interparticle potential between the two dust grains are screened by the background plasma and hence we can assume that the interaction potential between the dust particles as a screened Coulomb potential or the Yukawa potential

$$\phi_d = \frac{Q_d}{4\pi\epsilon_0 r} e^{-\frac{r}{\lambda_d}}$$

where r is the interparticle distance and λd is the Debye screening length.

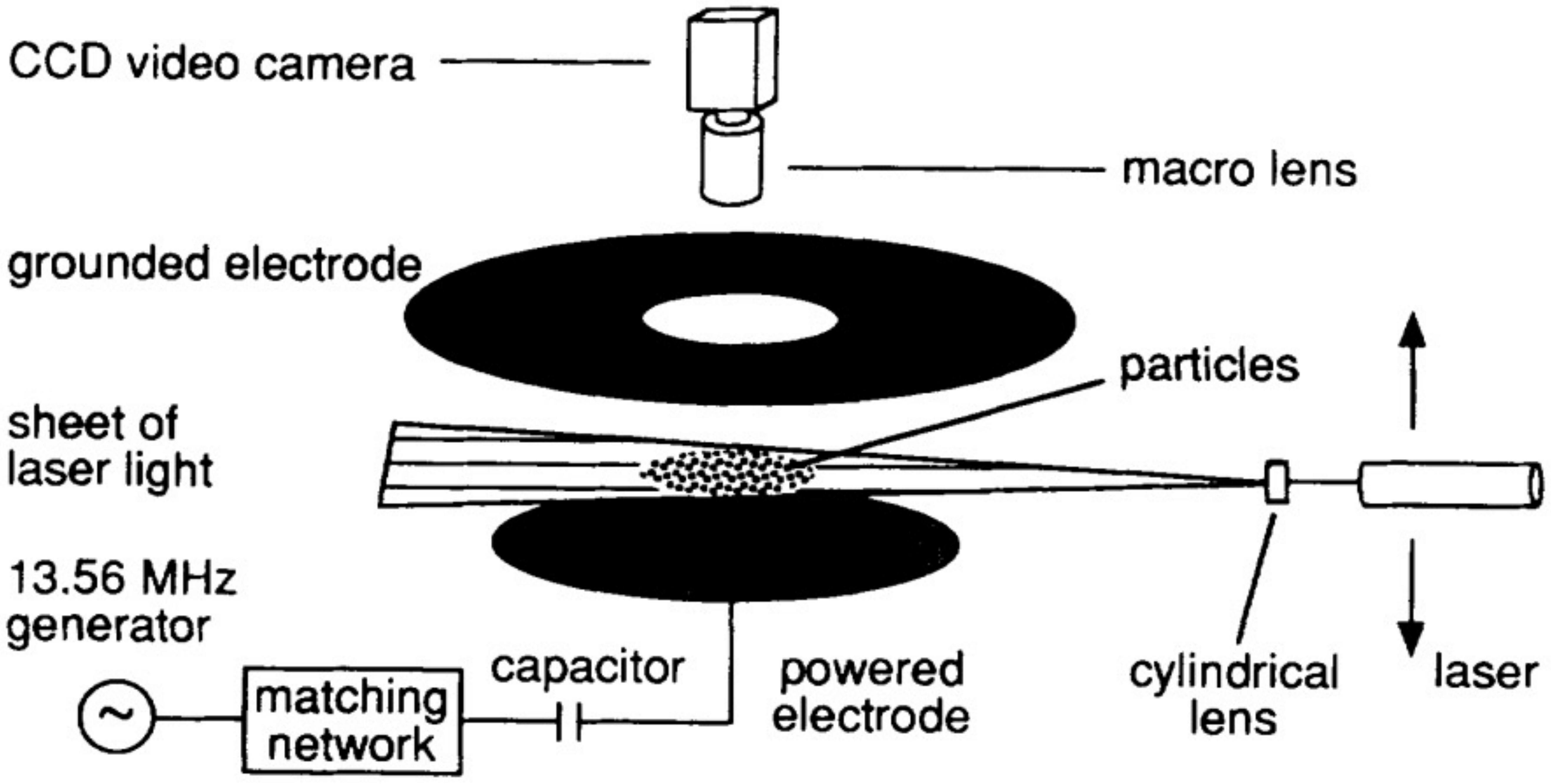
S. Hamaguchi and Farouki performed simulation to draw Phase Diagram of a Yukawa System



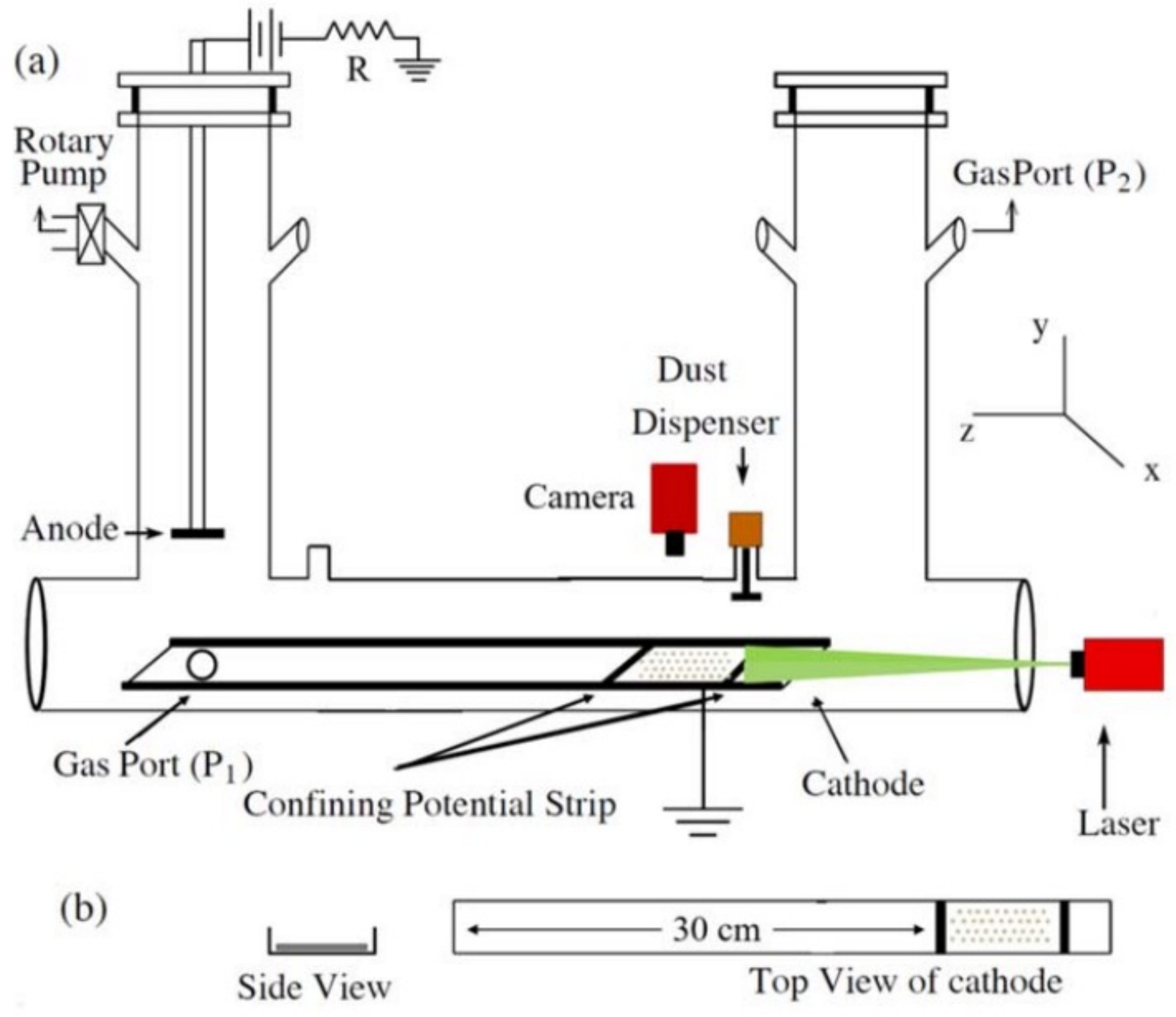
Condition for forming a dusty crystal is $\Gamma > \Gamma_c \sim 171$

https://journals.aps.org/pre/pdf/10.1103/PhysRevE.56.4671

RF and DC plasma device

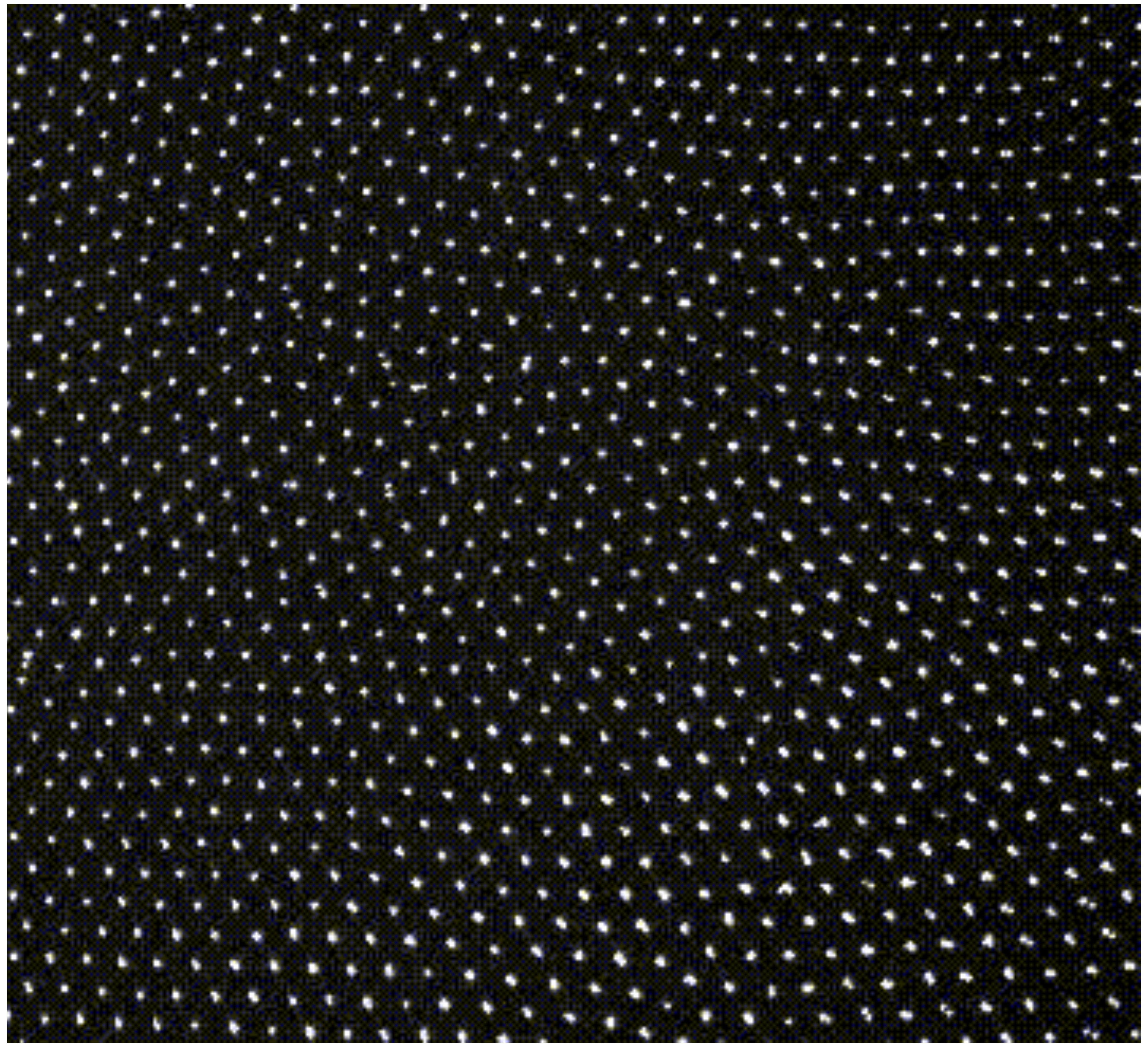


Thomas et al. Phys Rev L, 73 652 (1994)

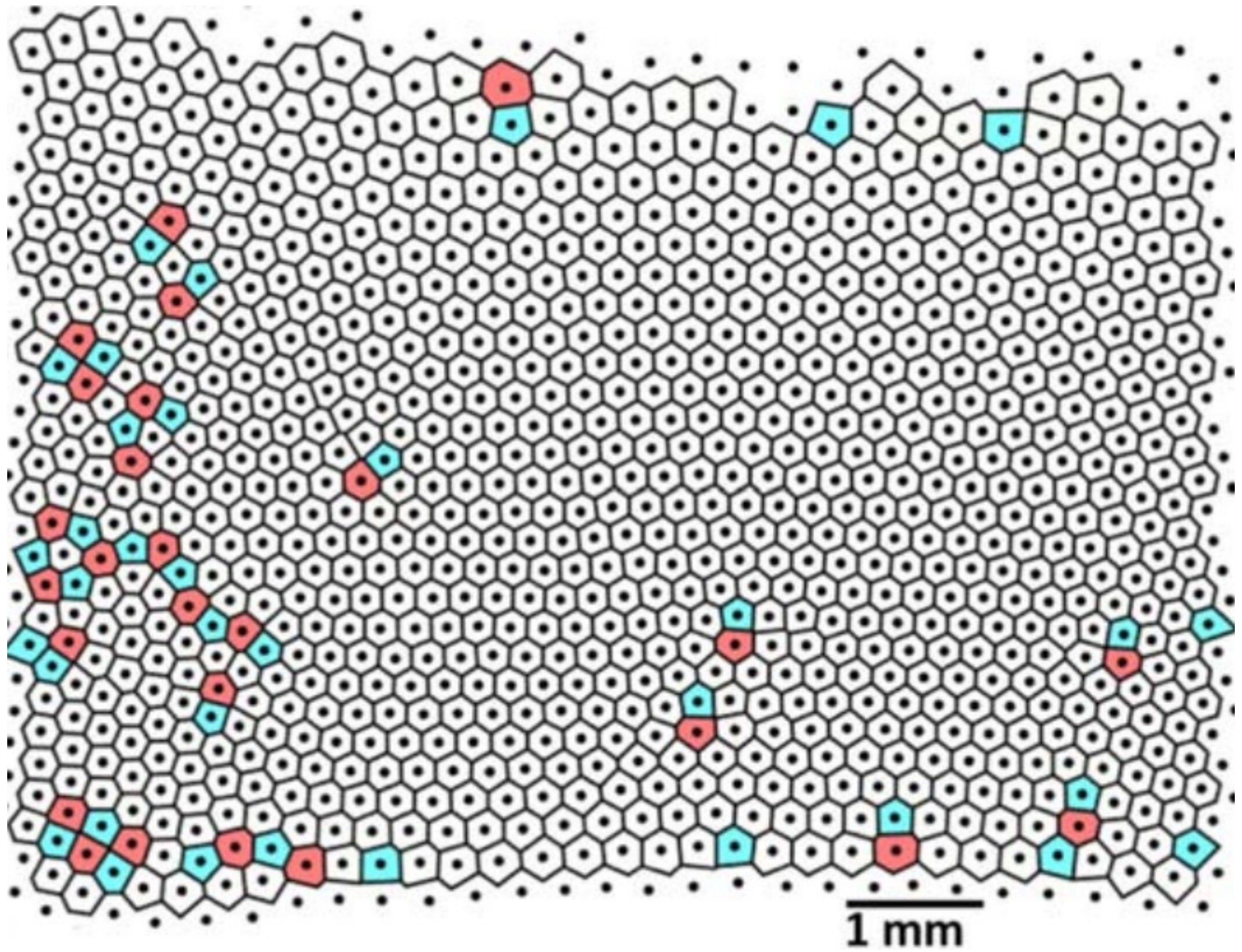


S. Jaiswal and E. Thomas Jr. Plasma Research Express, 1 (2019) 025014

Plasma crystal



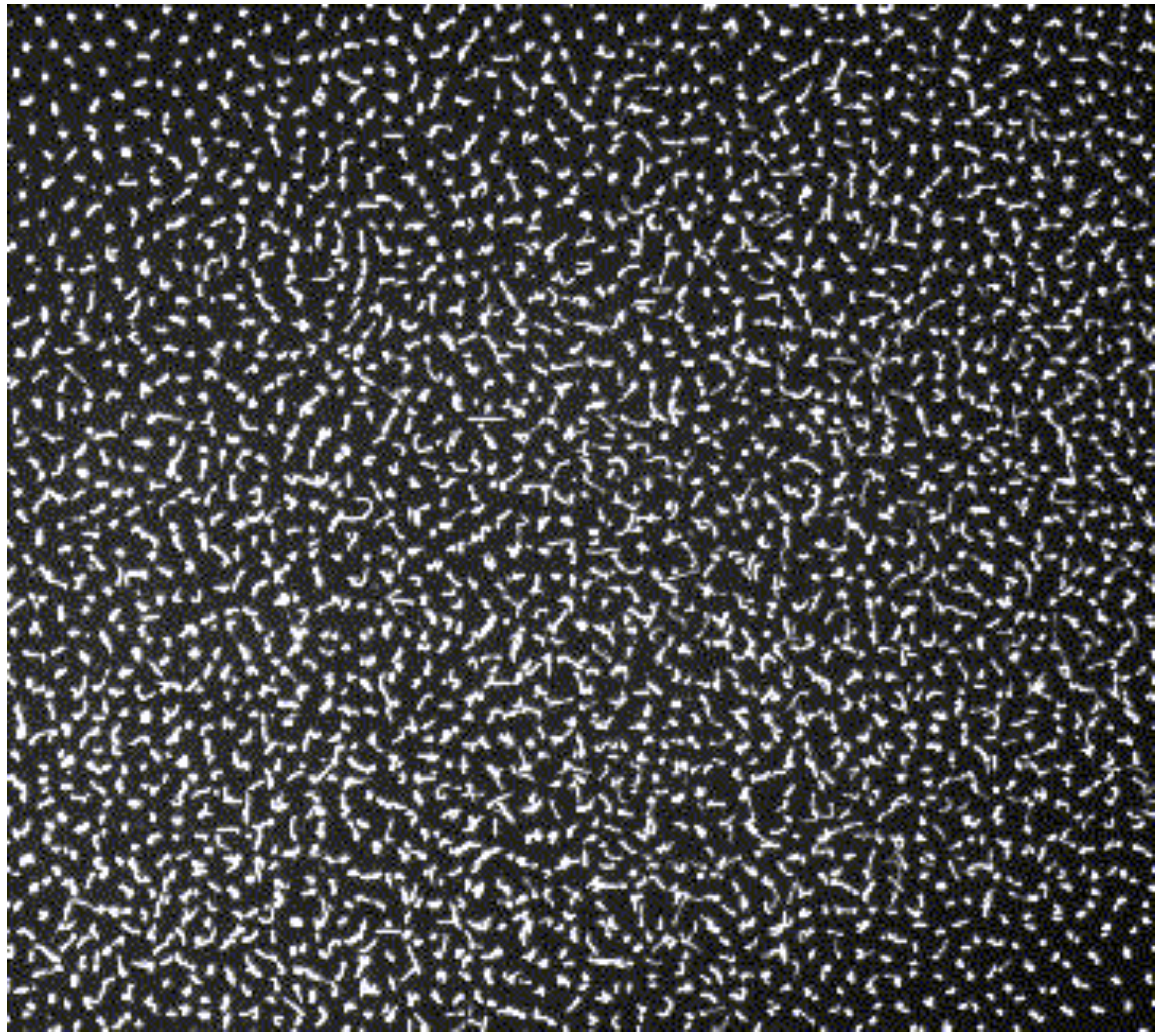
Plasma crystal observed in DC plasma



Voronoi diagram of the particle location

- Voronoi diagram is a useful tool to portray the amount of order or disorder in a particular configuration
- Partition of a plane into regions based on distances to each dust position.

Melting of plasma crystal



Melted state of particle cloud

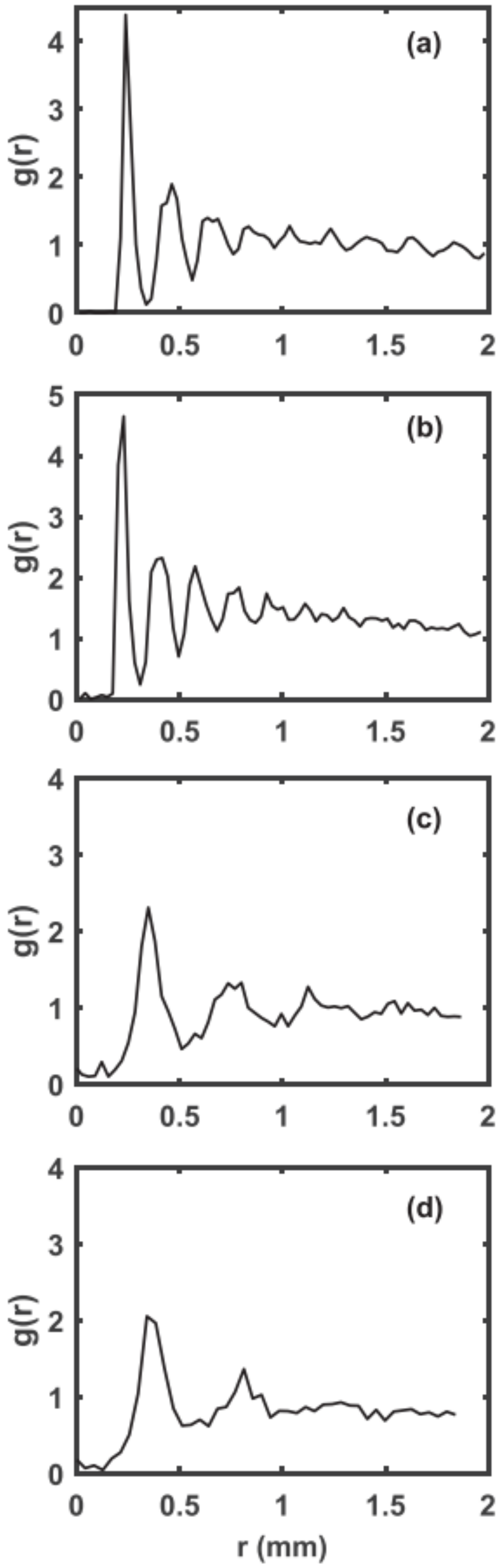
- The pair correlation function g(r)

$$g(r) = \left\langle \frac{1}{N} \sum_{i \neq j}^{N} \delta(r - r_i - r_j) \right\rangle,$$

$N = \#$ particles, r_i, r_j *positions*

represents the probability of finding 2 particles separated by a distance r.

- It is a measure of the translational order in structures.
- For a crystal at T = 0, g(r) is a series of equally spaced delta functions.



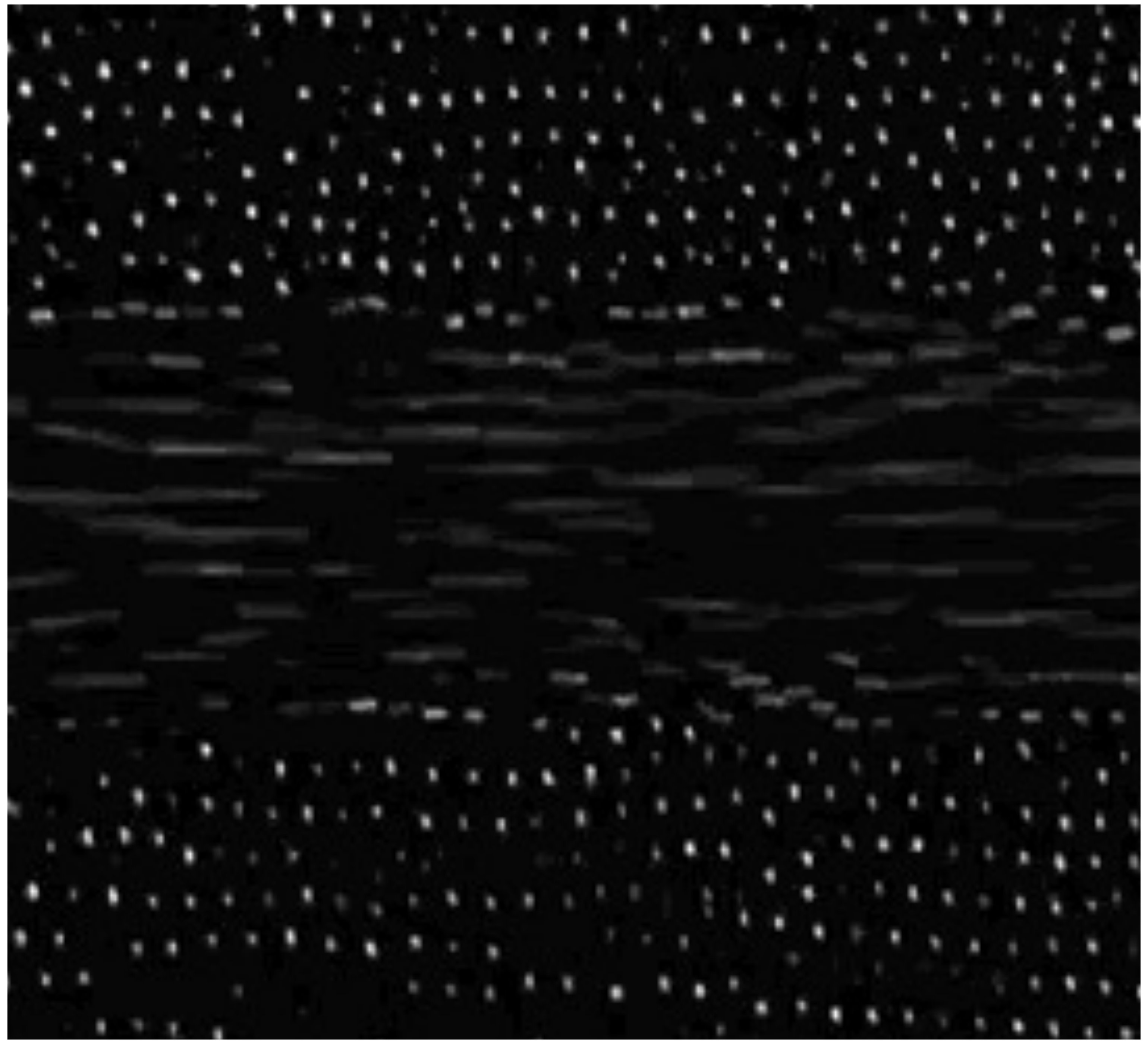
The pair correlation function g(r) of the particle clouds with the changing pressure (a) 14 Pa, (b) 13 Pa,(c) 12 Pa, and (d) 11 Pa.

S. Jaiswal and E. Thomas Jr. Plasma Research Express, 1 (2019) 025014

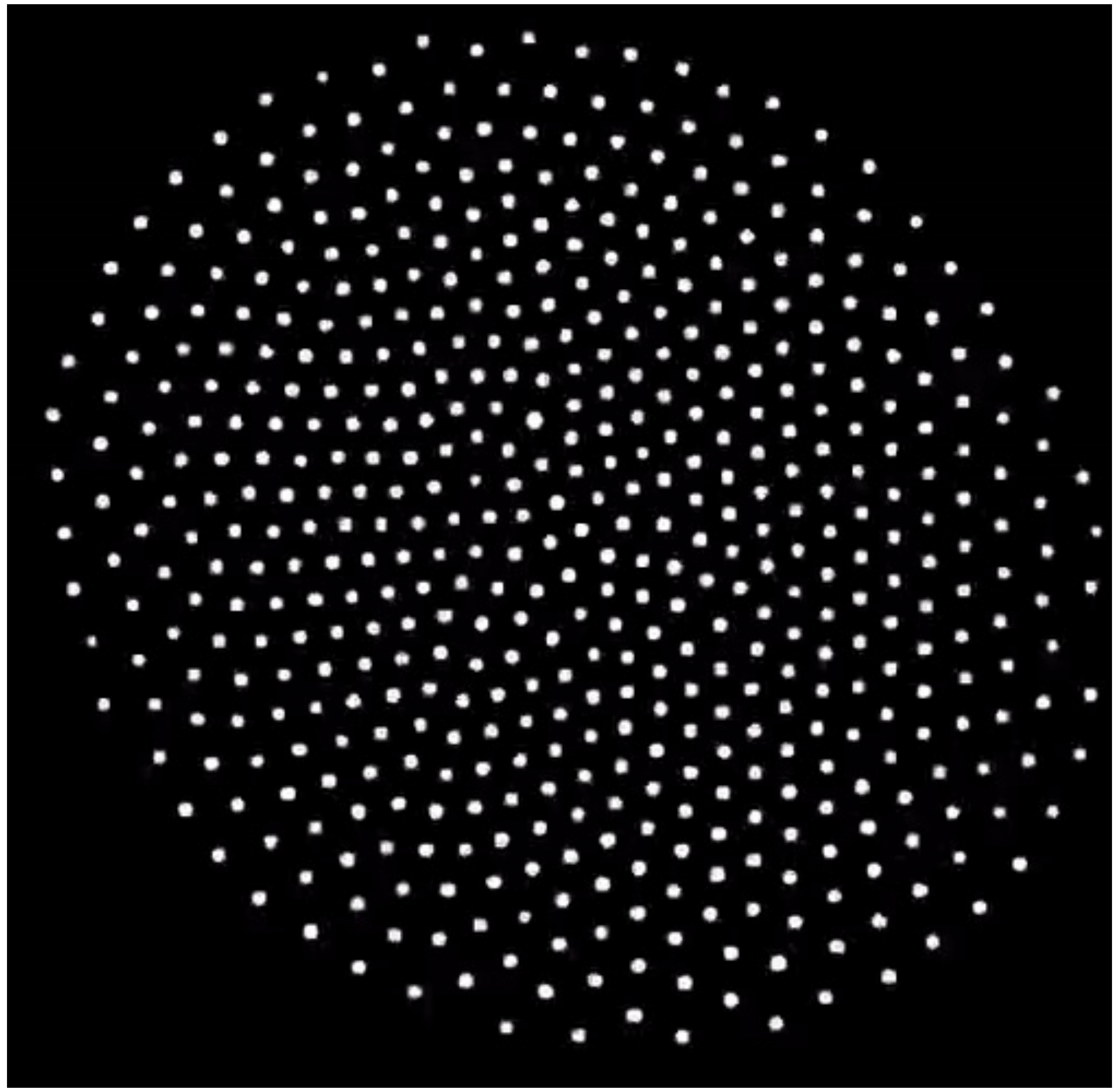
Fundamental physics using dusty plasma

❖ Means to study fundamental science of self –organization, pattern formation, phase transition and flows.

https://www.eoportal.org/other-space-activities/iss-plasma-kristall#iss-utilization-plasma-kristall-pk-the-longest-running-space-station-experiment



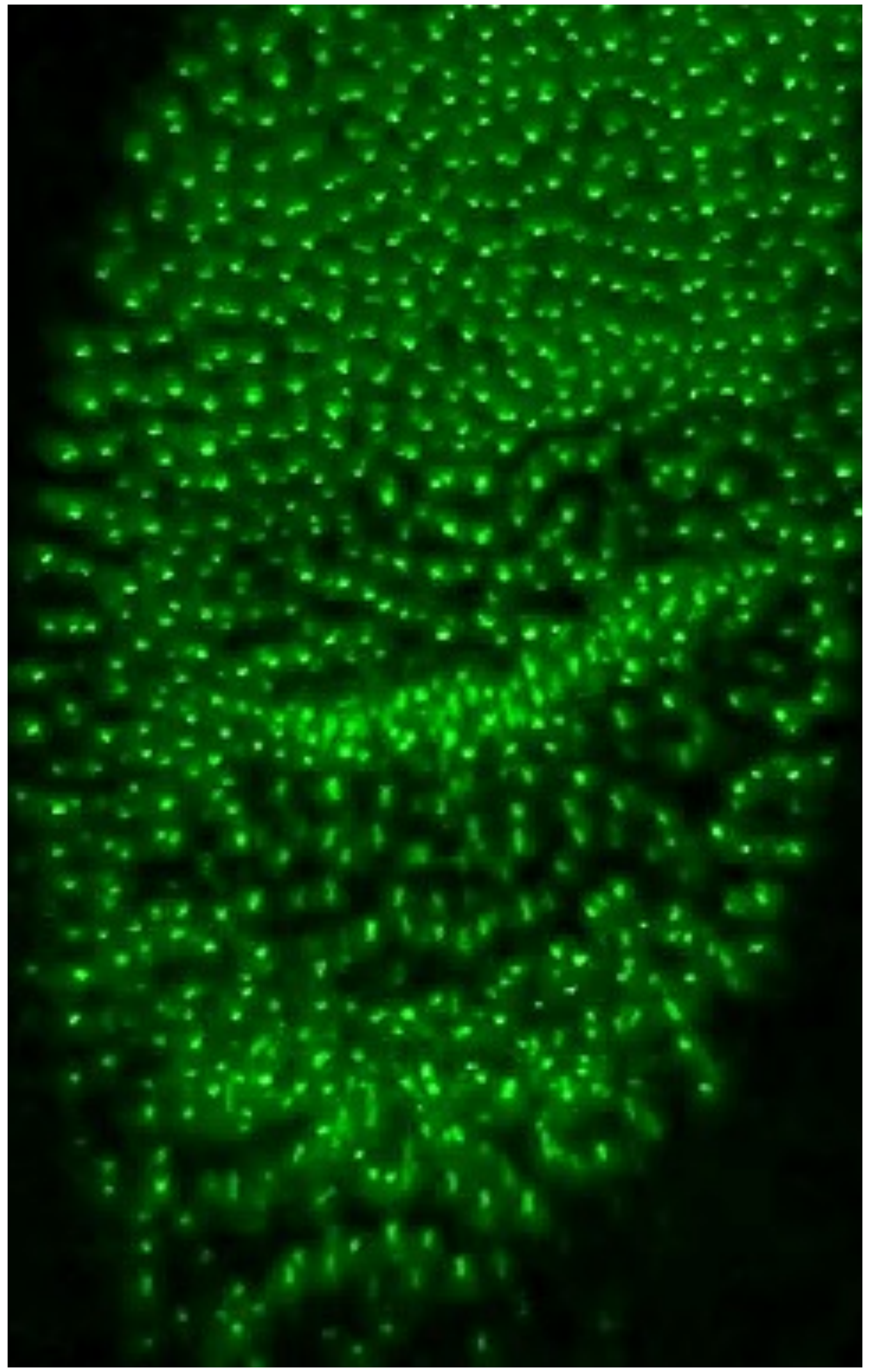
Shear flow motion in a complex plasma fluid in weightlessness on the International pace Station. Courtesy: Plasma Kristall-4 (PK-4) experiment.

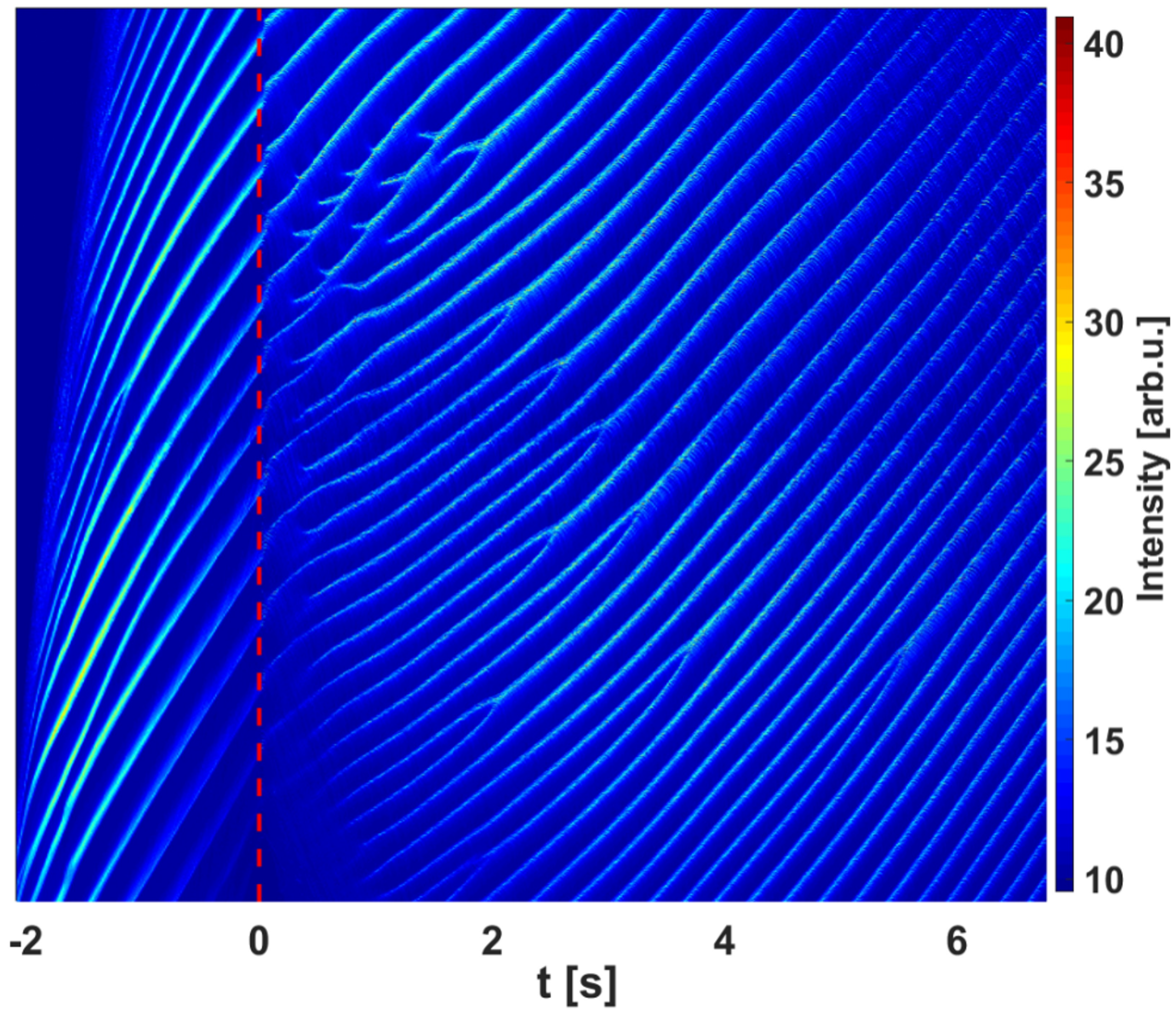


Guram Gogia and Justin C. Burton, Phys. Rev. Lett. **119**, 178004

Fundamental physics using dusty plasma

❖ Fluid nature can also be utilized for the formation of linear and Nonlinear waves and structure excitations in laboratory plasma

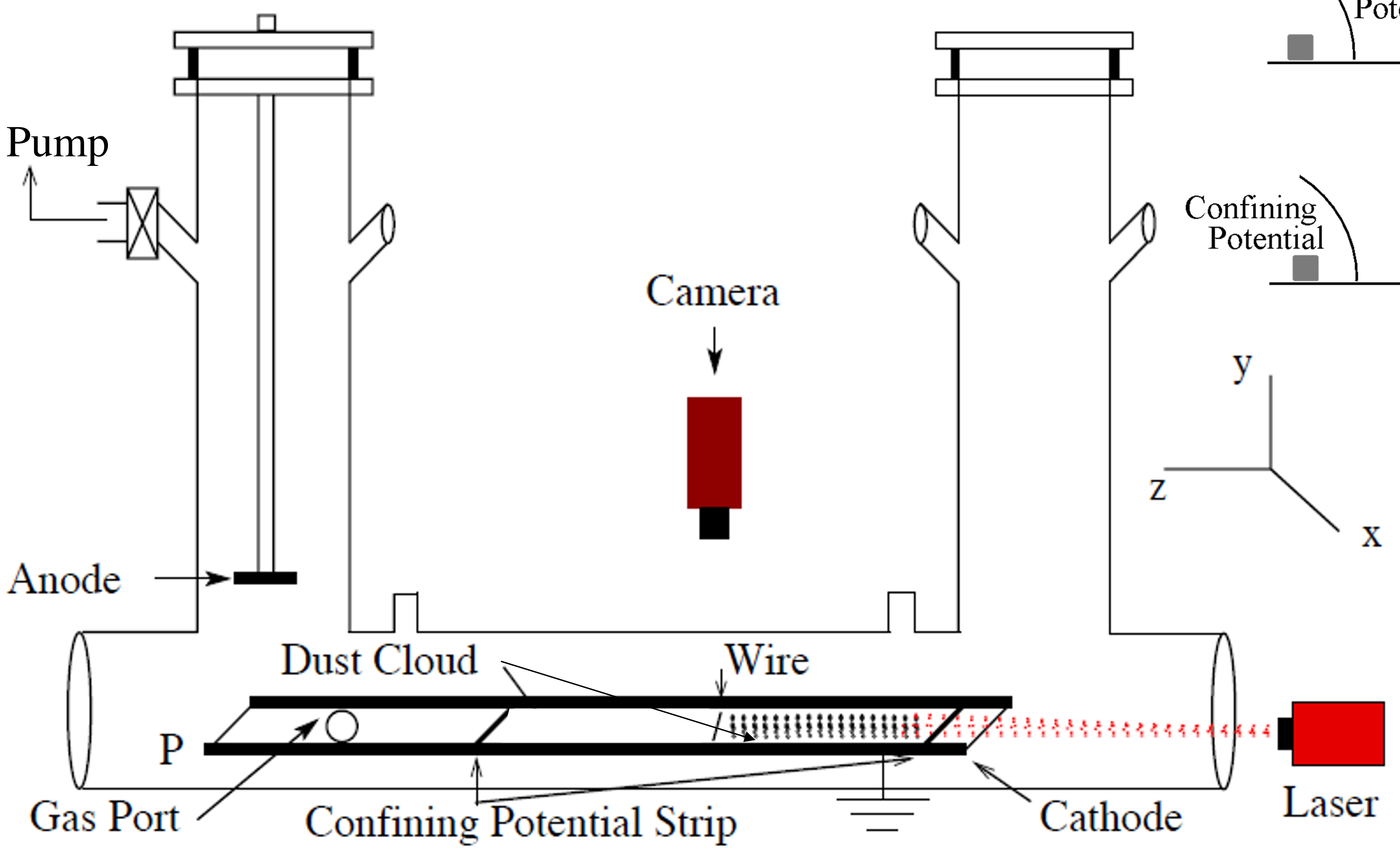




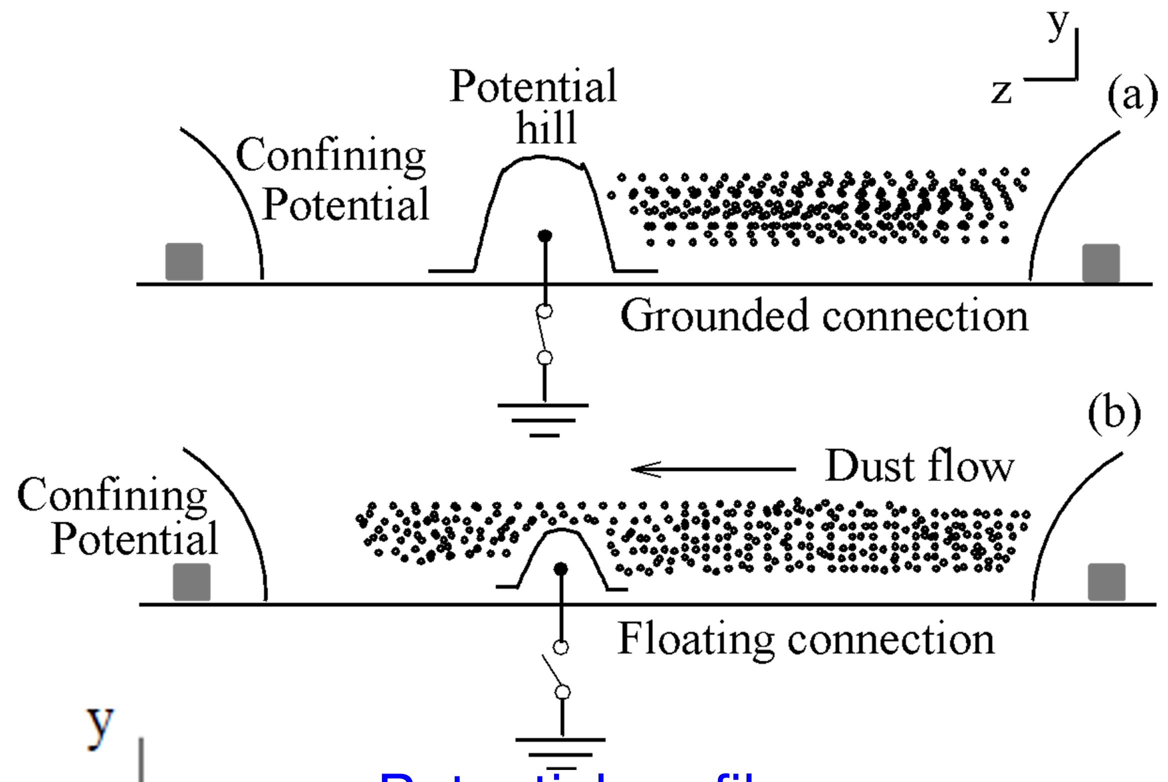
S. Jaiswal, P. Bandyopadhyay, A. Sen, ***Phys. Rev. E*, 93, 041201(R) (2016).**

S. Jaiswal *et al.Phys. Plasmas 25, 083705 (2018)*

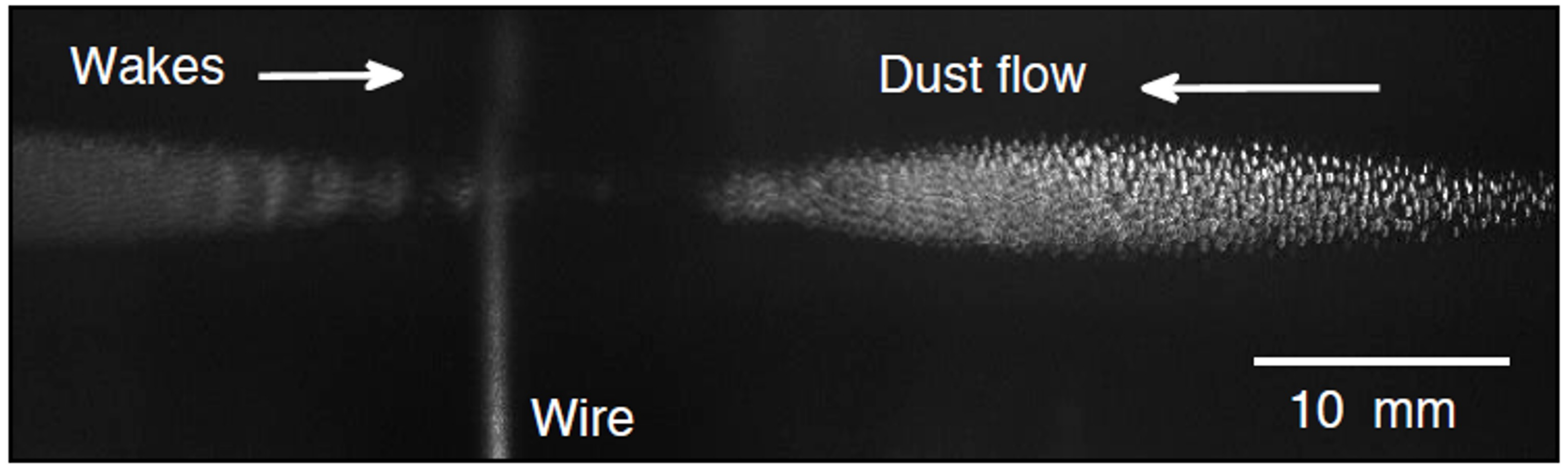
Observation of precursor soliton



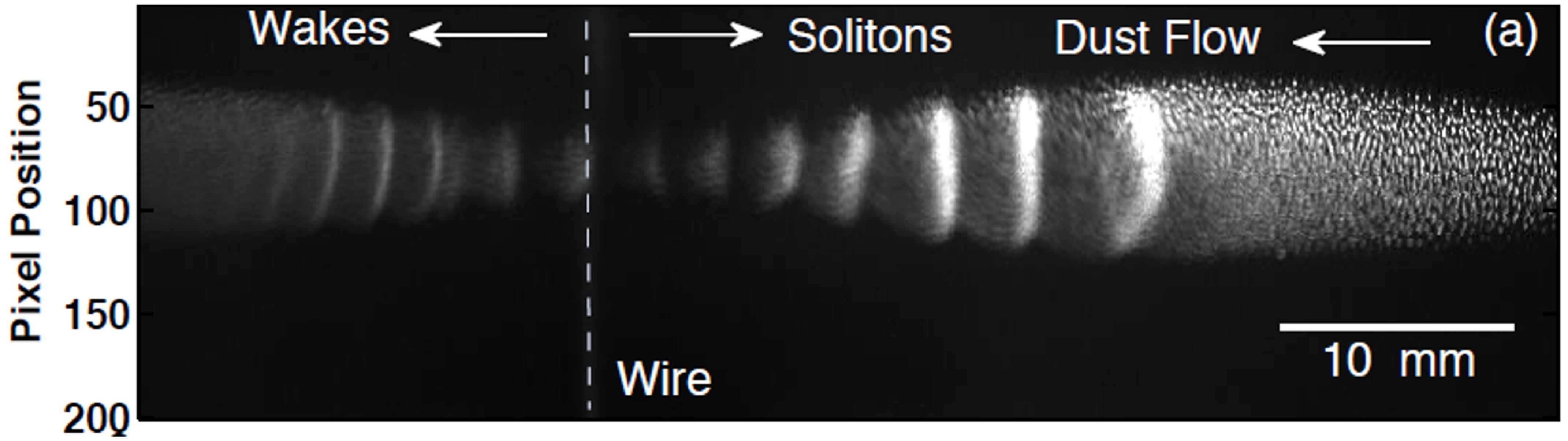
Experimental arrangement



Potential profile across a grounded and floating wire



Generation of wakes due to the subsonic flow of the dust fluid over the wire.



Generation of Soliton for supersonic flow.

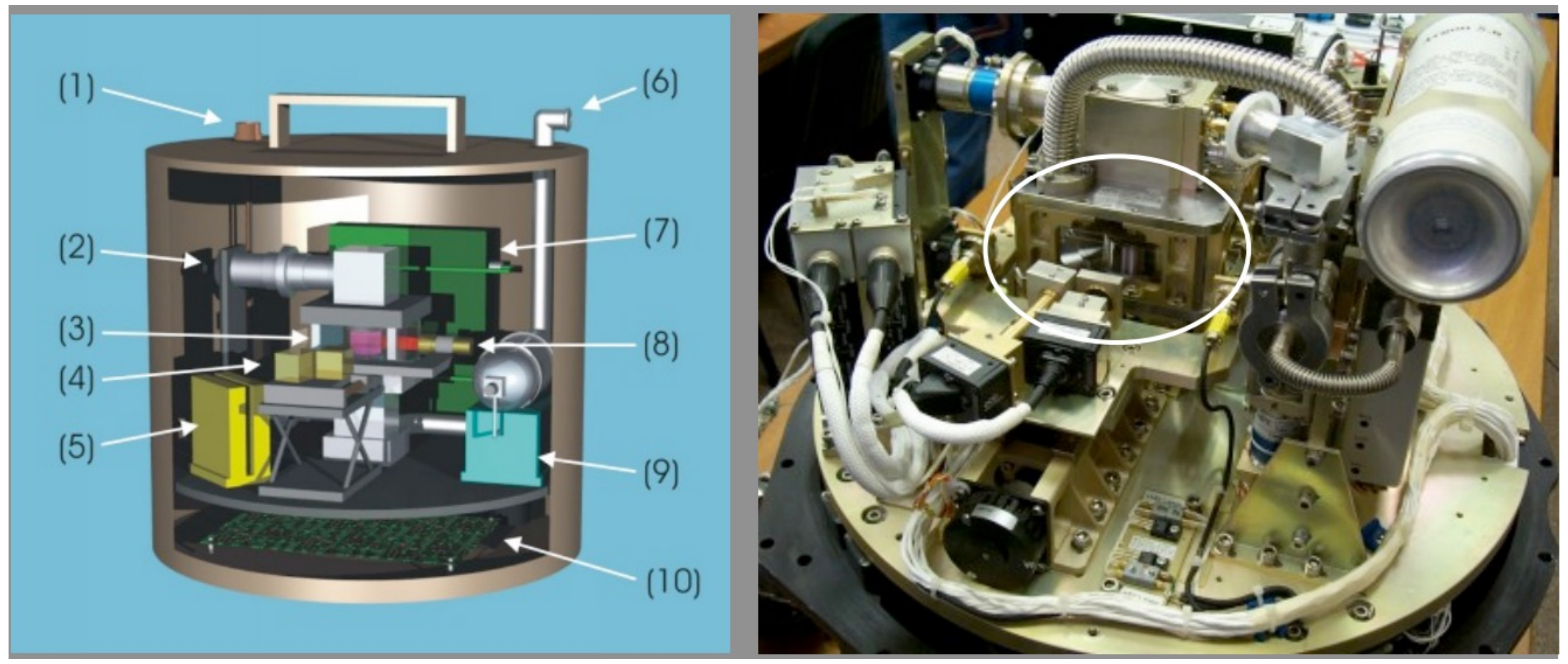
- ❑The height of the potential hill and hence the speed of flow of the particles, can be precisely controlled by biasing the wire or applying the external resistance.
- ❑ The flow velocity is calculated by tracing the particles over time.
- ❑ Excitation of soliton in the case of flow velocity greater than dust acoustic velocity (Mach number ~1.6).

S. Jaiswal, P. Bandyopadhyay, A. Sen, ***Phys. Rev. E*, 93, 041201(R) (2016).**

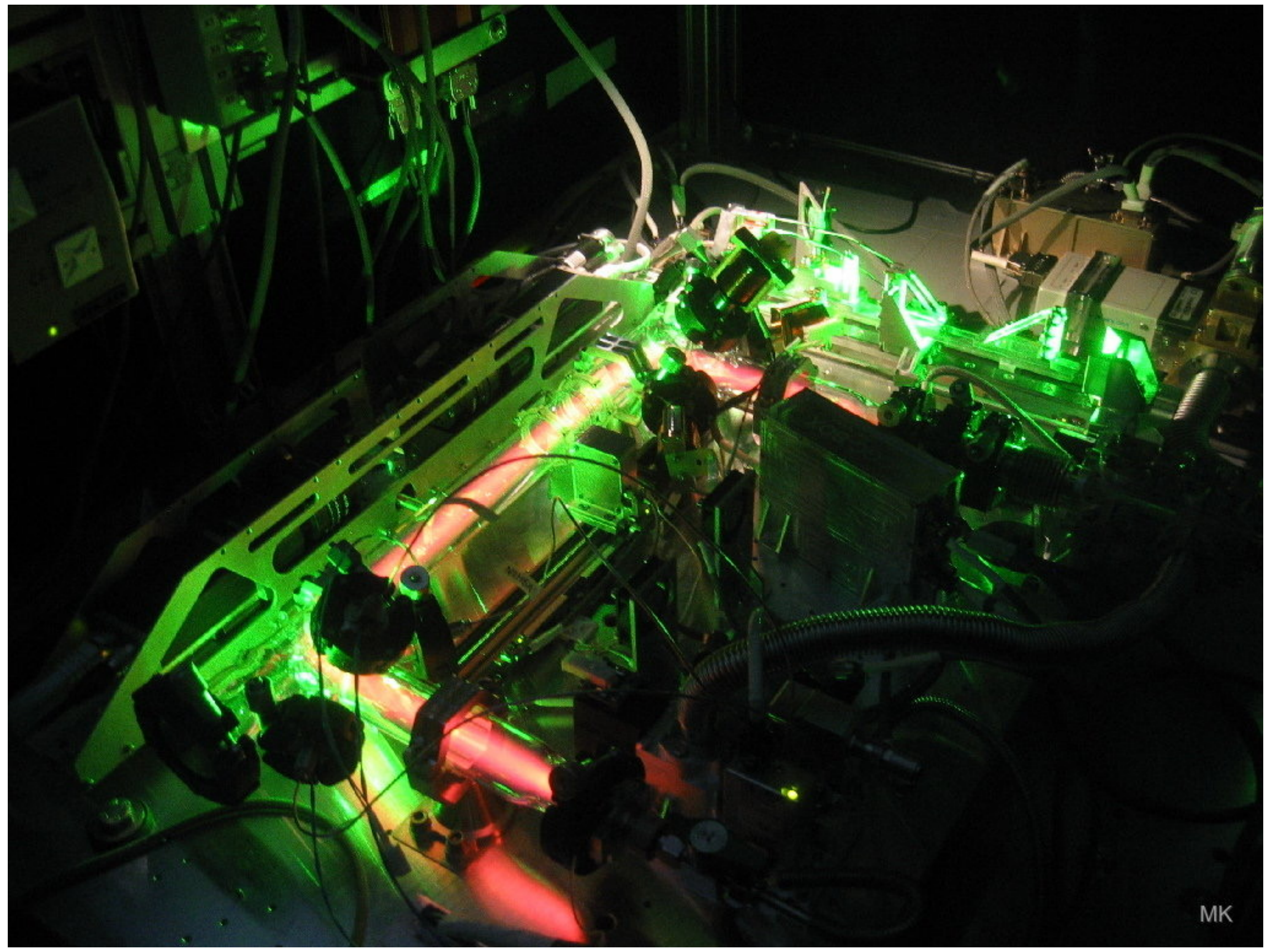
S. Jaiswal, P. Bandyopadhyay and A. Sen, ***PSST, 25, 065021, 2016.***

Dusty plasma under microgravity

- In the earth-based laboratory, it is necessary to use a levitation method to keep microparticles from falling.
- In the laboratory dusty plasma devices, the particles always reside in the sheath region and usually in 2D structures.
- The PKE Nefedov device is an RF plasma system operating in the microgravity environment on the International Space Station (ISS)



❖ Recent microgravity laboratory: PlasmaKristall Experiment 4

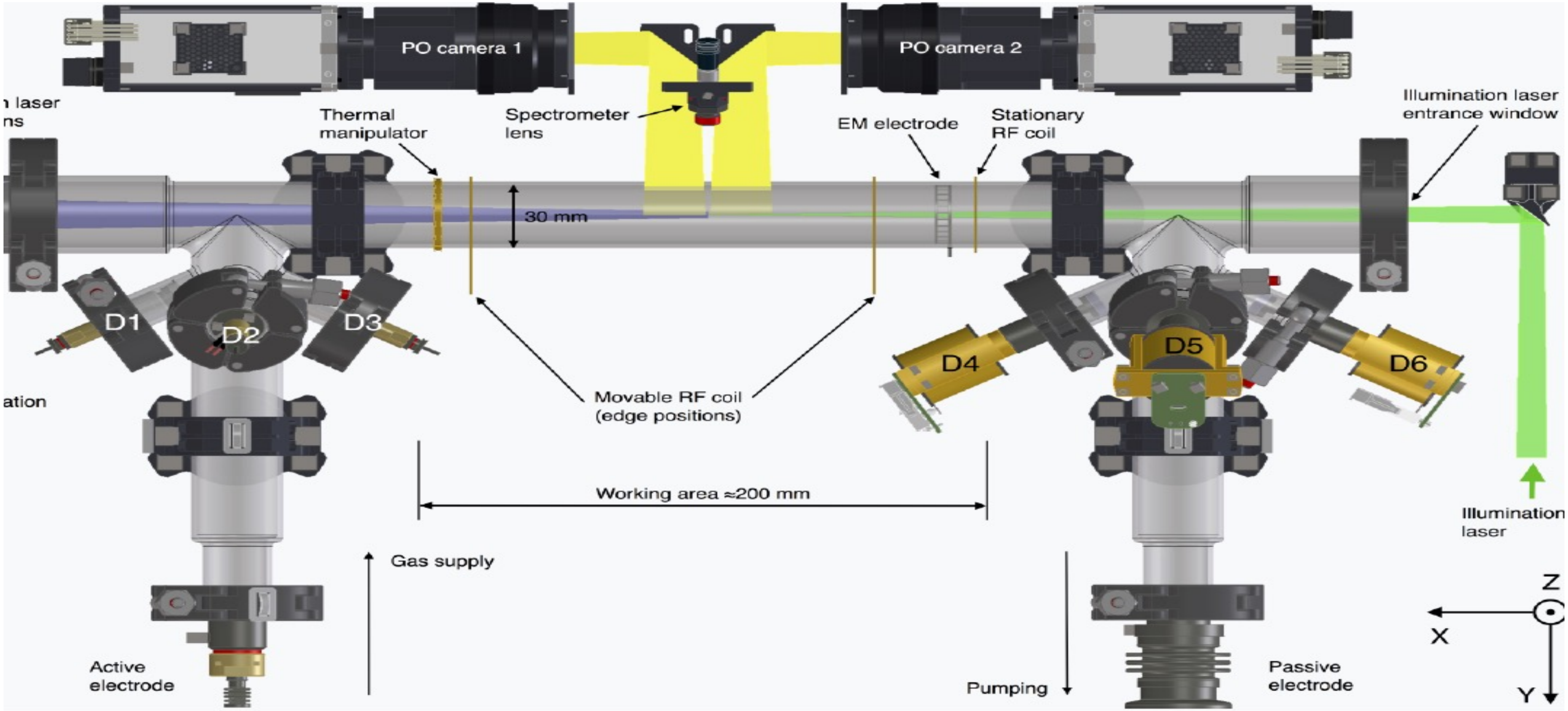


https://www.esa.int/

NASA Image: ISS057E074488 - Russian cosmonaut Sergei Prokopev, during the Plasma Kristall-4 (PK-4) investigation

https://www.esa.int/, NASA.gov

Dusty plasma under microgravity

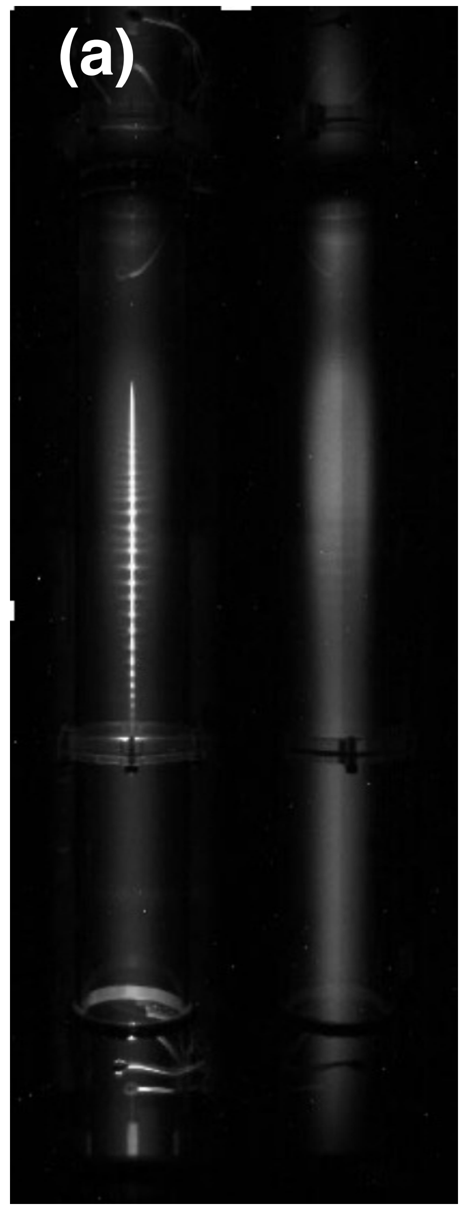


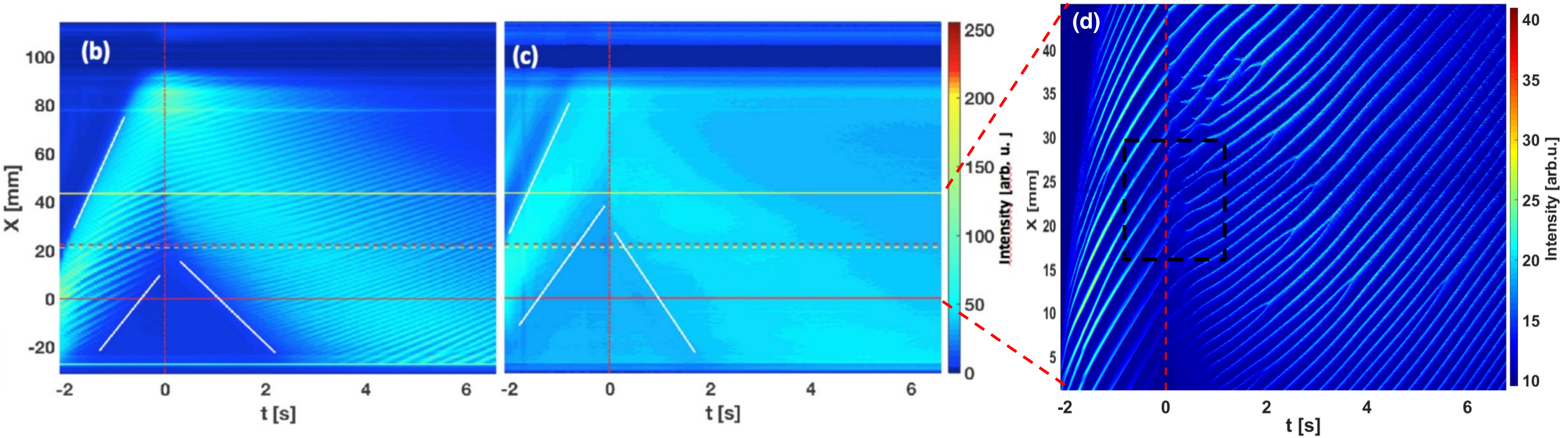
Schematic of the PK-4 experimental setup

M. Y. Pustylnik *et al.* RSI, **87**, 093505 (2016).

Wave studies on PK-4 laboratory

Typical image of a neon plasma discharge





Spatiotemporal pattern of microparticle cloud and plasma emission dynamics

Dust density waves in a dc flowing complex plasma with discharge polarity reversal F

Cite as: Phys. Plasmas **25**, 083705 (2018); https://doi.org/10.1063/1.5040417
Submitted: 17 May 2018 . Accepted: 10 July 2018 . Published Online: 07 August 2018

S. Jaiswal, M. Y. Pustylnik, S. Zhdanov, H. M. Thomas, A. M. Lipaev, A. D. Usachev, V. I. Molotkov, V. E. Fortov, M. H. Thoma, and O. V. Novitskii

COLLECTIONS

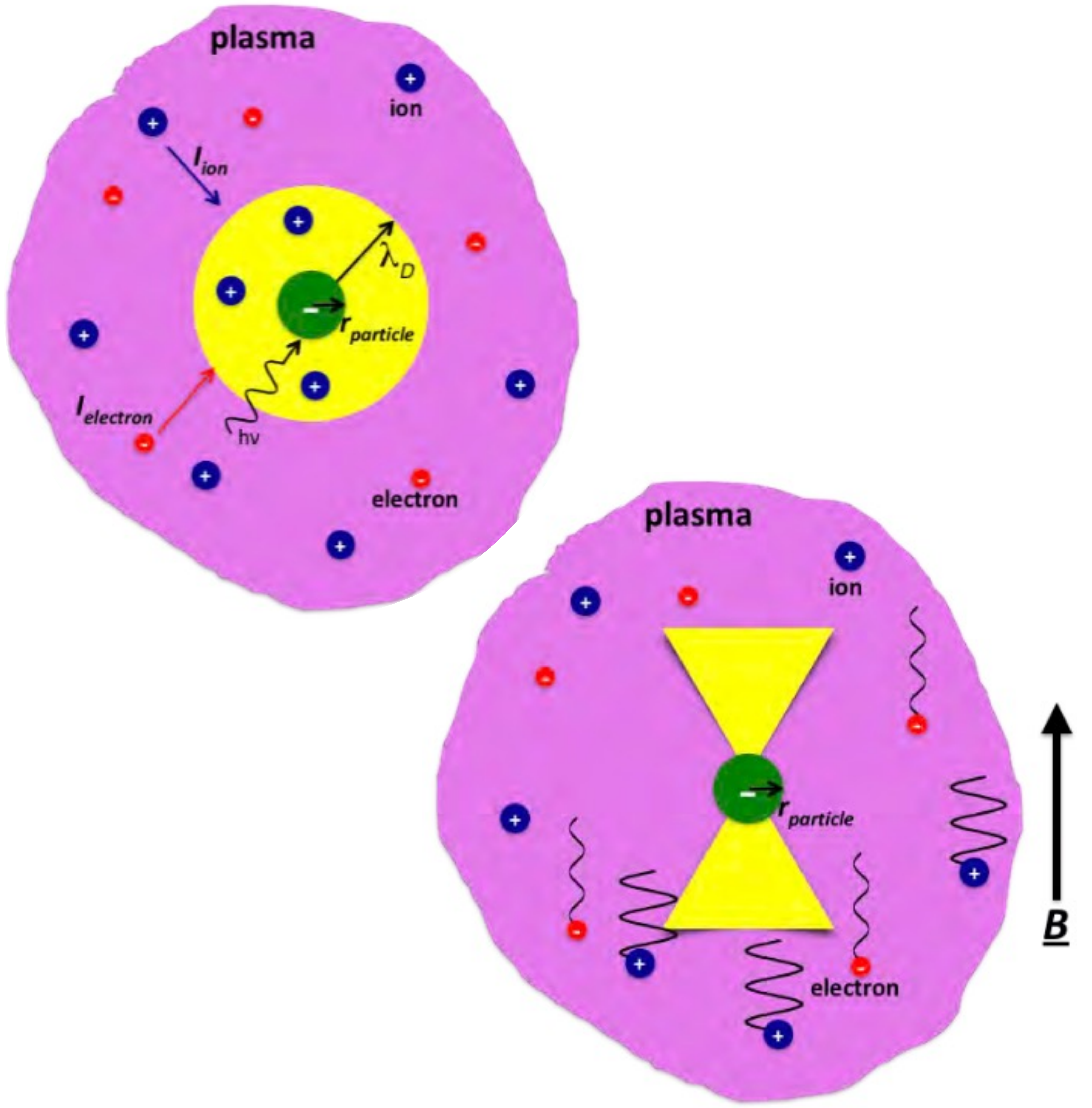
F This paper was selected as Featured

The presence of a magnetic field modifies dusty plasma

- ❖ Electric field directly affect the plasma and microparticles and leads to various phenomena

- ❖ The presence of an externally applied magnetic field modifies the behavior of all of the charged species in the plasma. True for even for magnetic fields as low as Earth's magnetic field

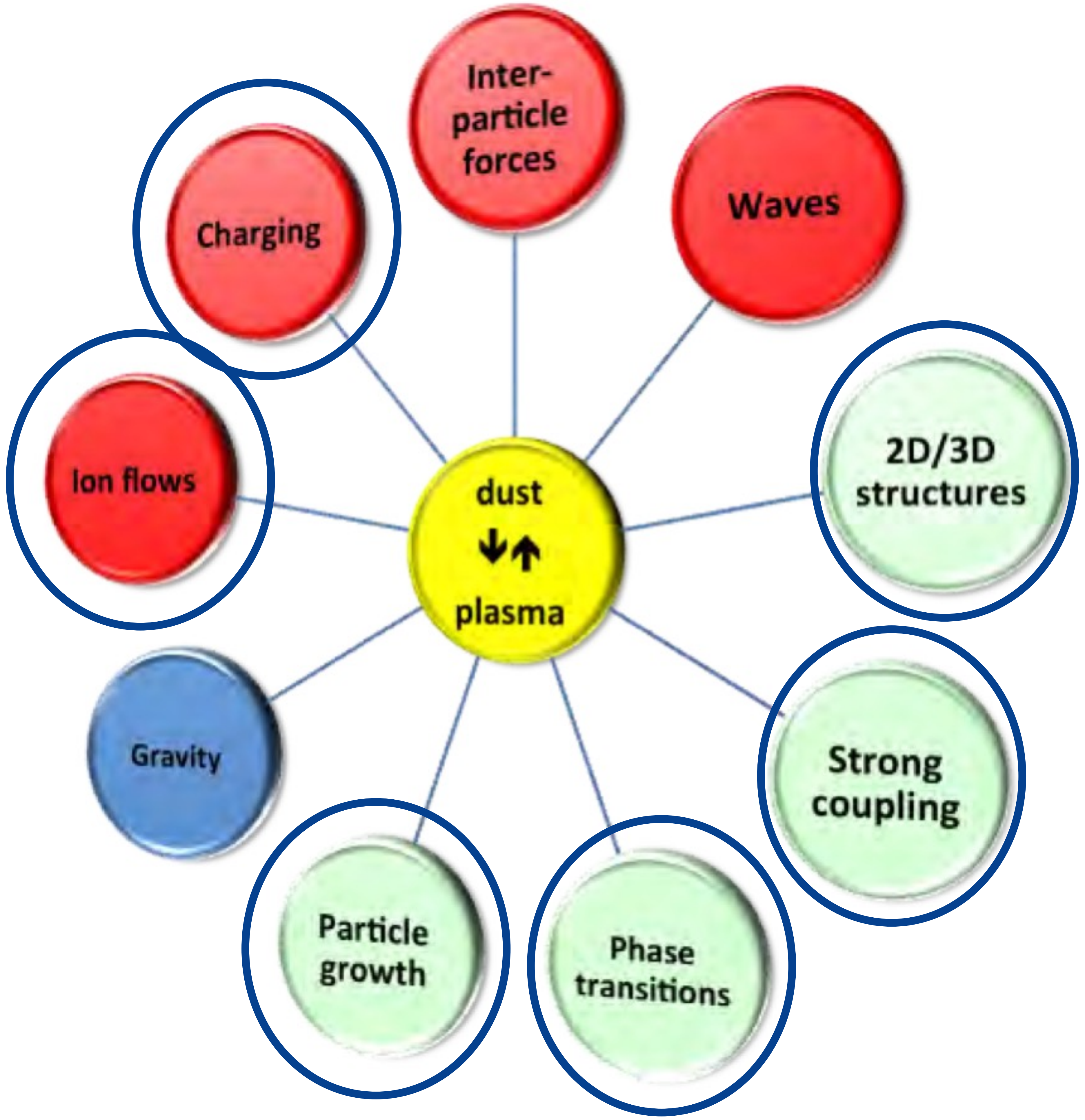
- ❖ Research on *magnetized dusty plasmas* seeks to understand plasma systems in which the dynamics of all the charged species (electrons, ion, and dust) is dominated by the magnetic field.



The presence of a magnetic field modifies dusty plasma

Increasing magnetic field strength alters the overall dynamics of plasma,

- Modifies ions and electron collection and change the net force on the dust grains
- Alters plasma confinement and initiate rotation
- Modifies waves and introduces new wave modes
- Dust charging and screening mechanisms, and thus the properties responsible for the dust-dust interaction
- Melting transition of a plasma crystal
- Modifies formation of 2D and 3D structures
- Affects particle growth



The presence of a magnetic field modifies dusty plasma: examples

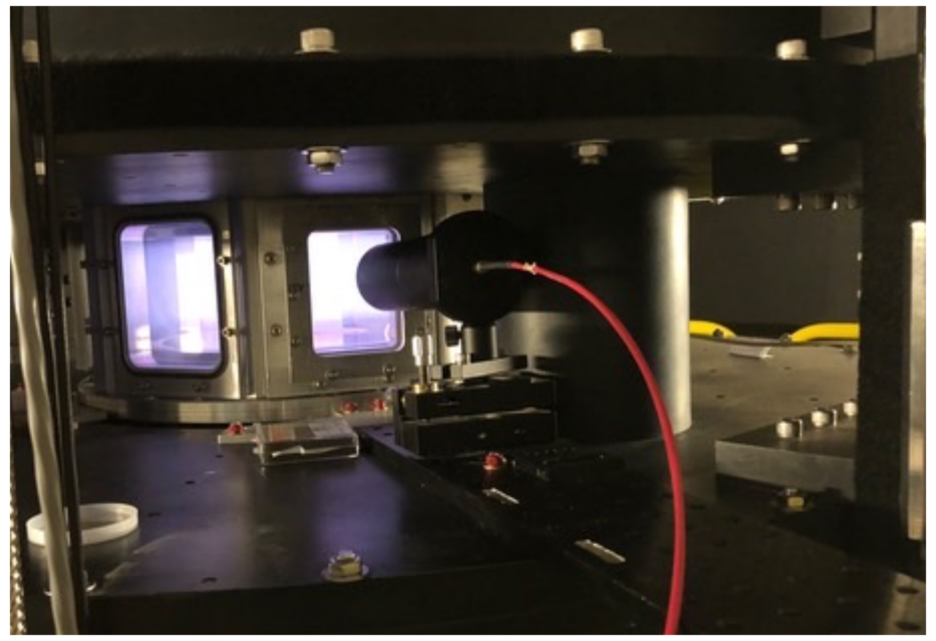
Using MDPX chamber at MPRL facility B_{max}: 3.3 T (to date)
dB/dz: 1 - 2 T /m
Warm bore: 50 cm ID
127 cm OD
158 cm axial

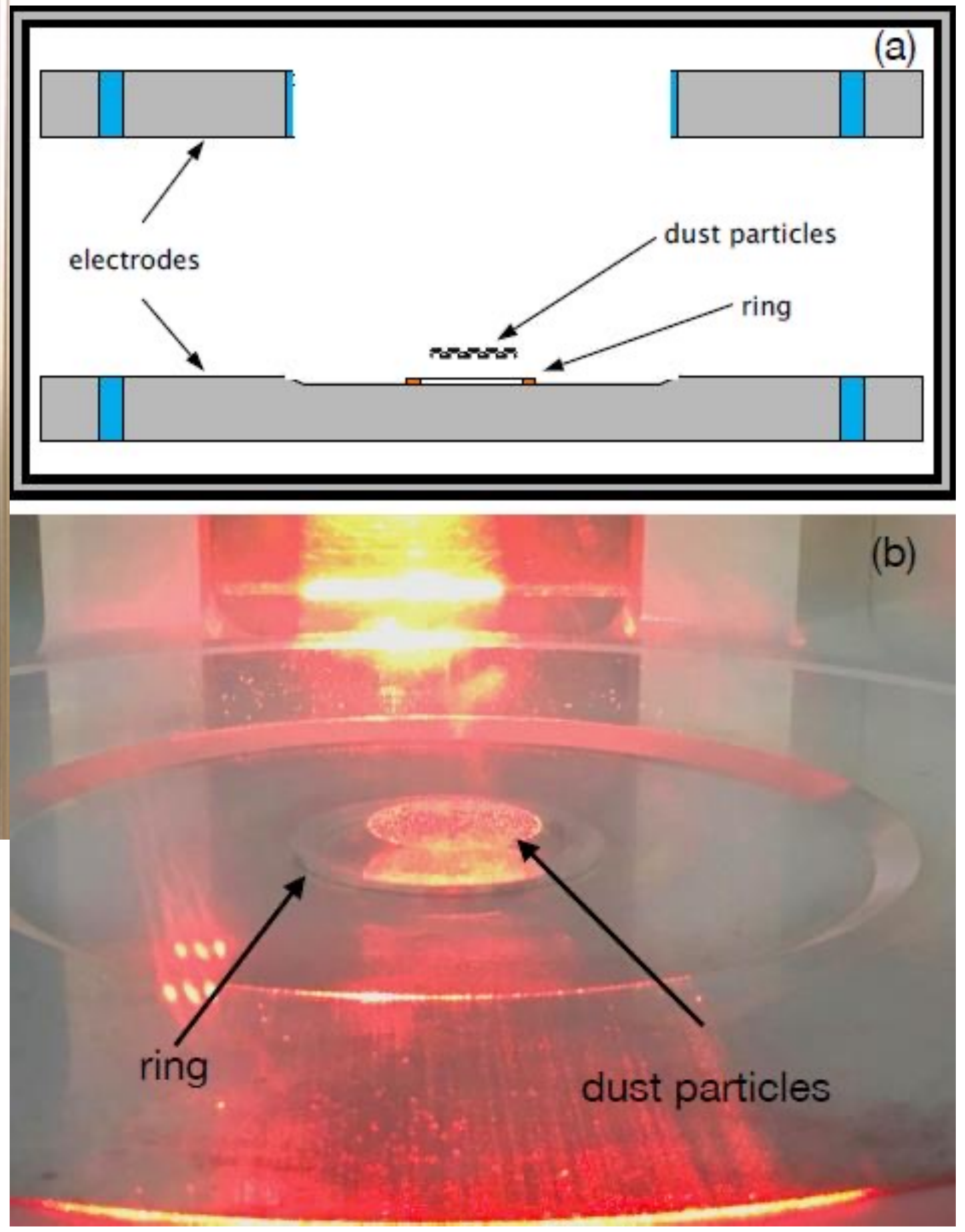
•Octagon Vacuum chamber: 35.5 cm ID x 17.8 cm tall

•An external ring of 50 mm OD is used for extra confinement.

Operating Parameters

- Gas: Argon
- Pressure: 221±0.5 mTorr (29.4±0.1Pa)
- capacitively coupled, glow discharge argon plasma at 13.56 MHz, radio-frequency, 3.5 W
- Electron temp (Te) 2.5 –3.5 eV
- Electron density $10^{15} m^{-3}$
- Dust particles 7.17±0.08 µm diameter silica microspheres

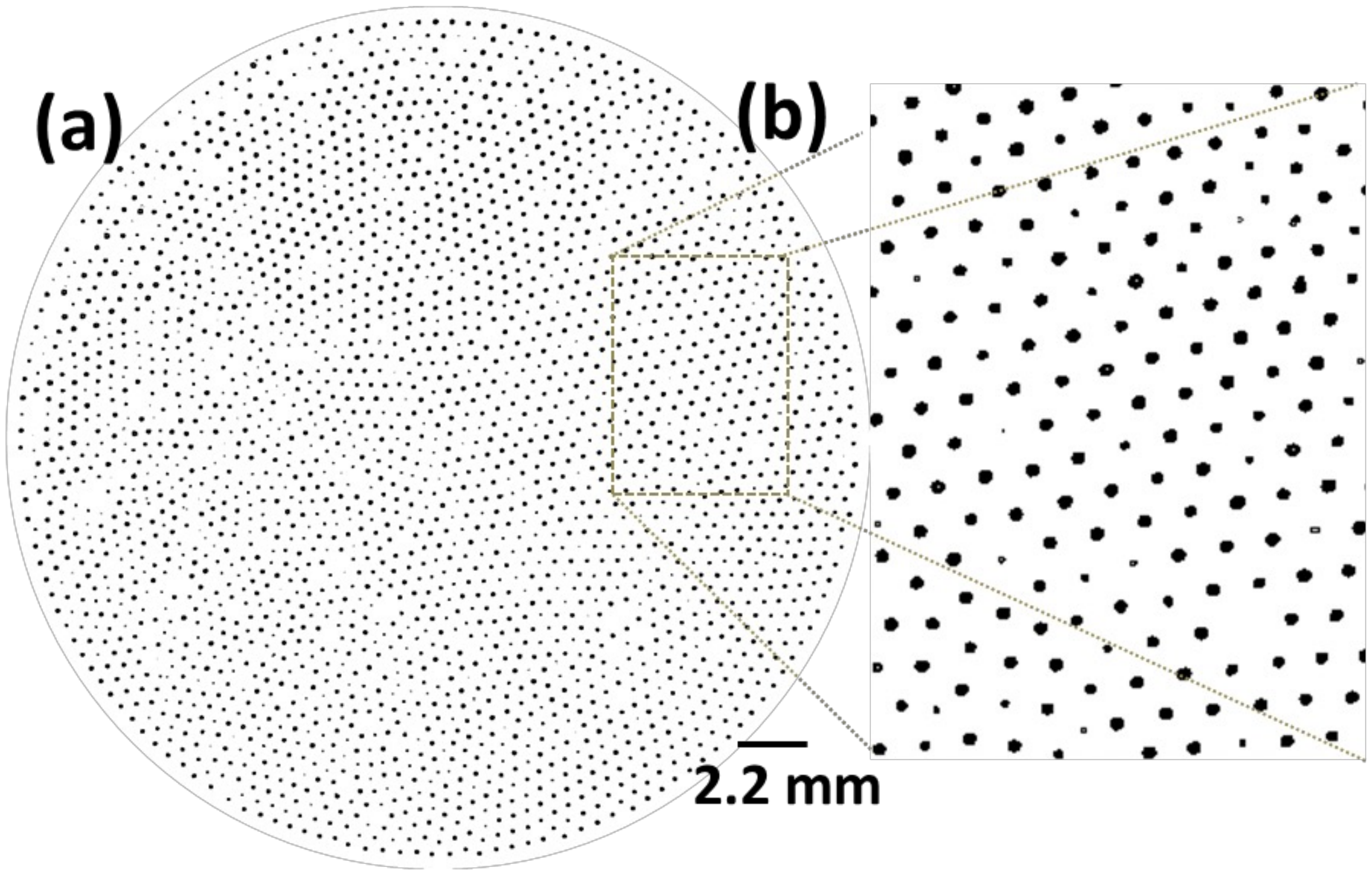




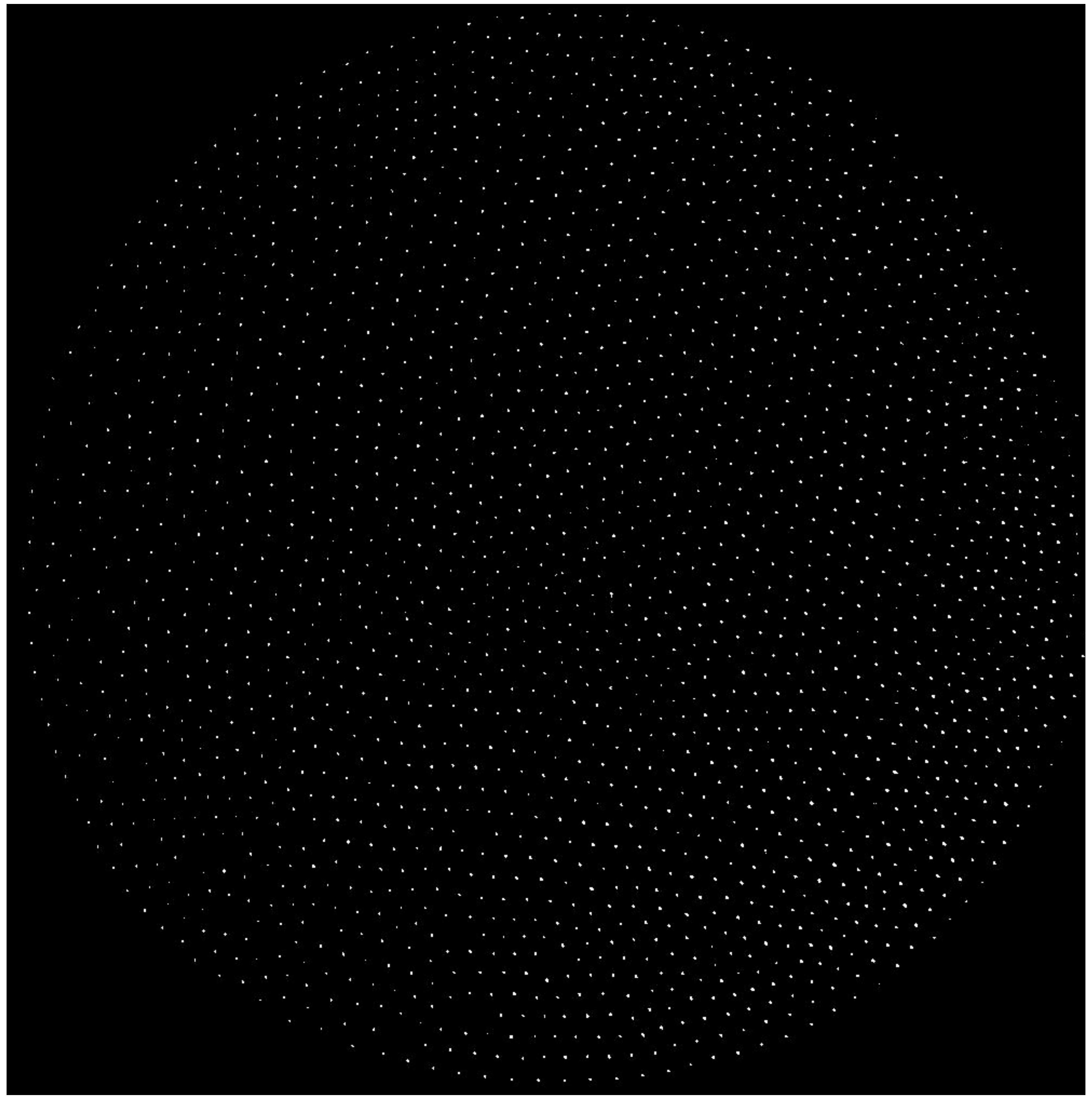
S. Jaiswal, et al., Phys. Plasmas, **24**, 113703 (2017)

The presence of a magnetic field modifies dusty plasma: examples

- At higher pressures (p > 220 mTorr / 30 Pa), a plasma crystal is formed.
- With increasing magnetic field, a rotation is induced in the crystal due to ion E x B drift.

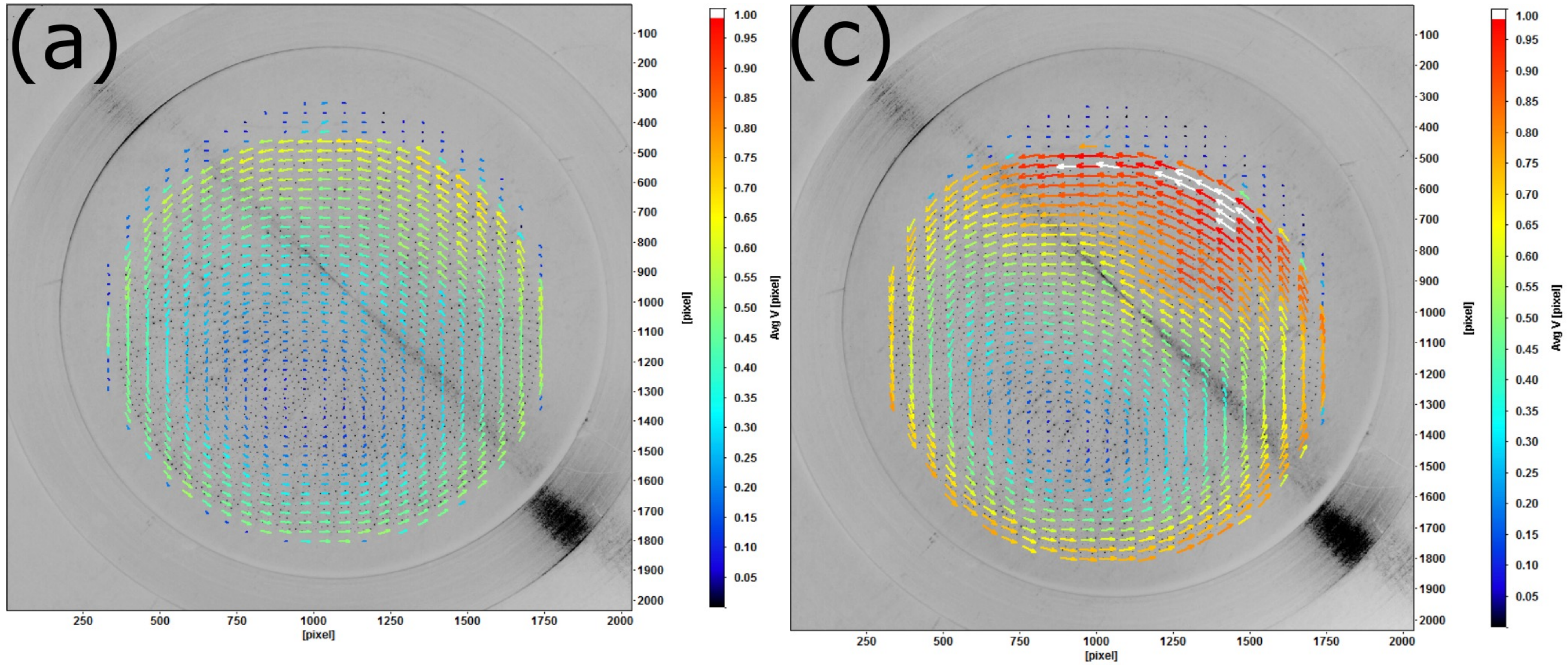


Formation of coulomb crystal and its b) zoomed view, formed at B = 0, P = 221 mTorr, rf power = 3.5 Watt

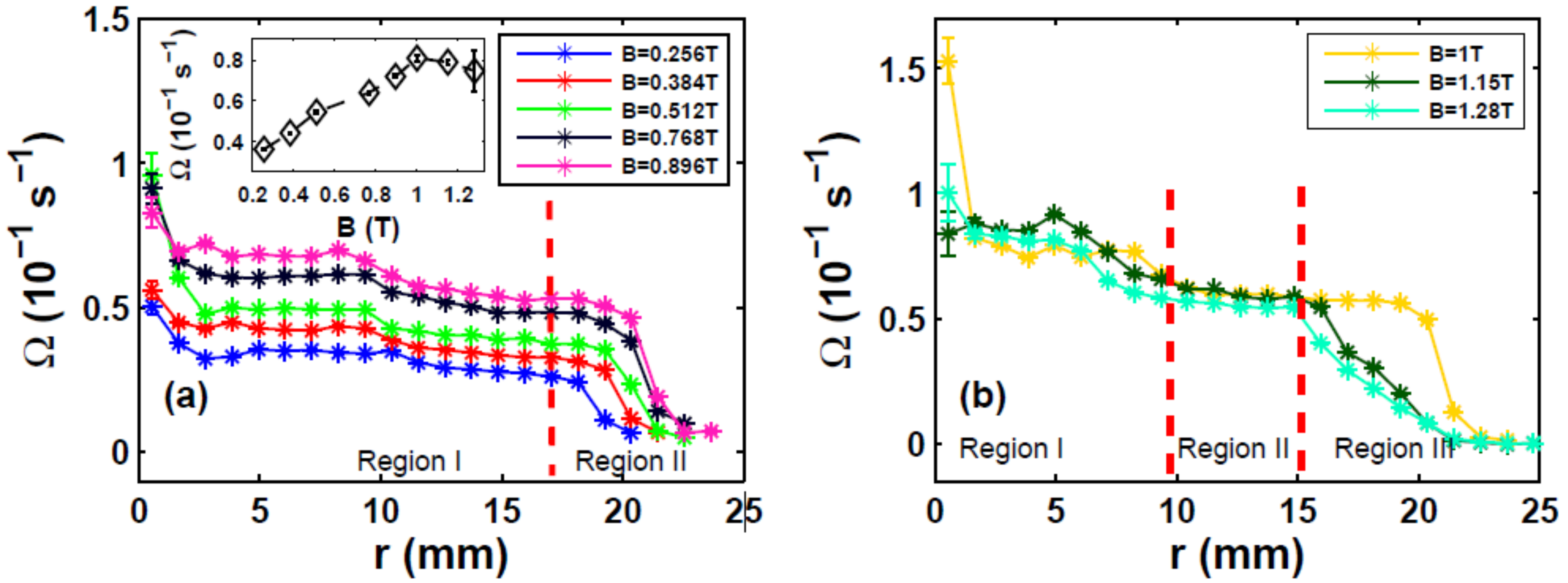


S. Jaiswal, et al., Phys. Plasmas, ***24****, 113703 (2017)*

The presence of a magnetic field modifies dusty plasma: examples



Velocity vector field along with the magnitude of the velocity component v_θ at a) 0.512 T and, e) 1 T.



Angular velocity Ω of the particles cloud rotating in the magnetic field vs distance from the center of rotation

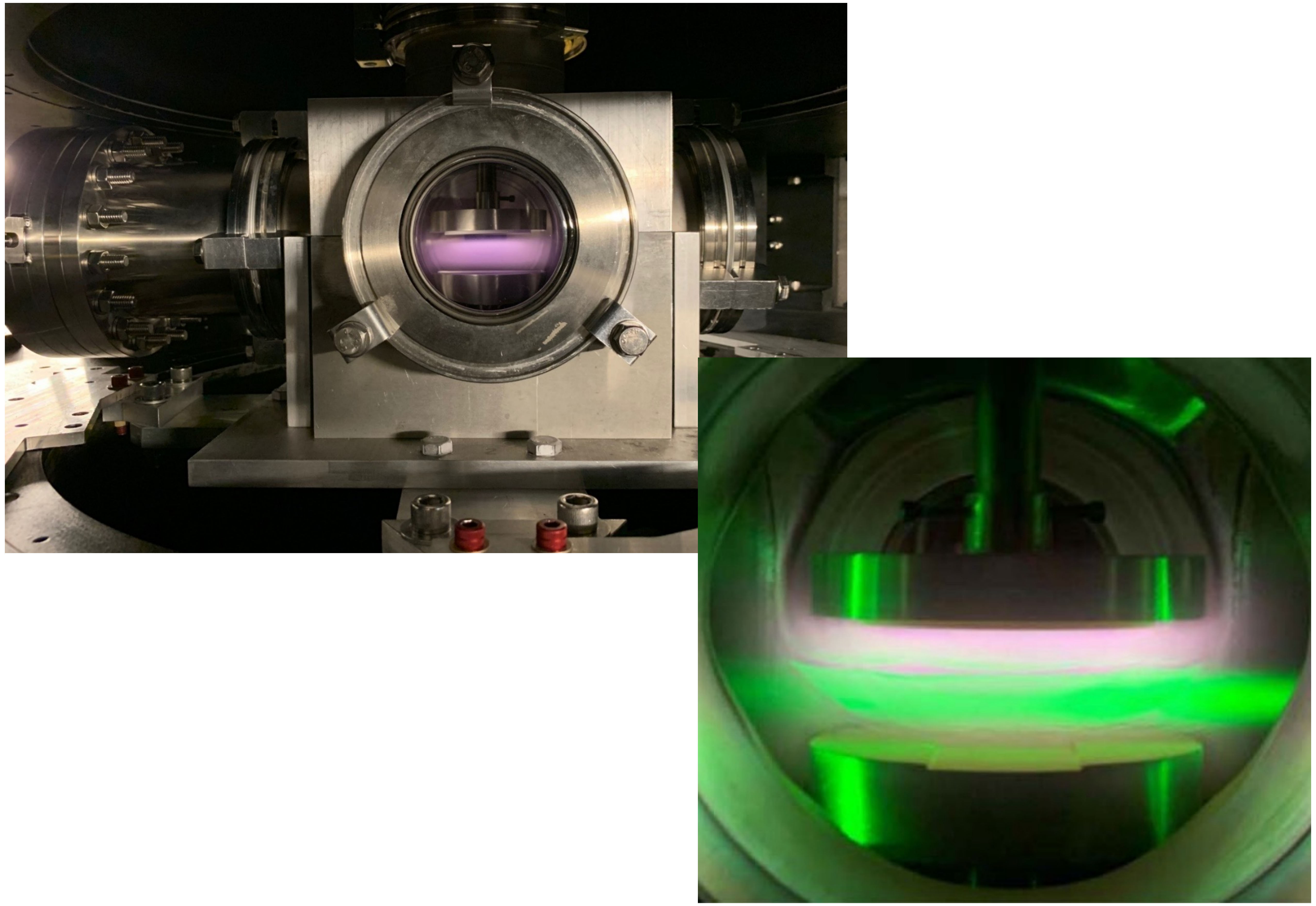
- slight shift in the rotation center with increasing magnetic field strength that means crystal are not symmetric about the center of confinement ring.
- differential rotation is established between the inner and outer regions of the plasma crystal.
- This leads to a flow shear that heats, and eventually melts the crystal.

S. Jaiswal, et al., Phys. Plasmas, ***24****, 113703 (2017)*

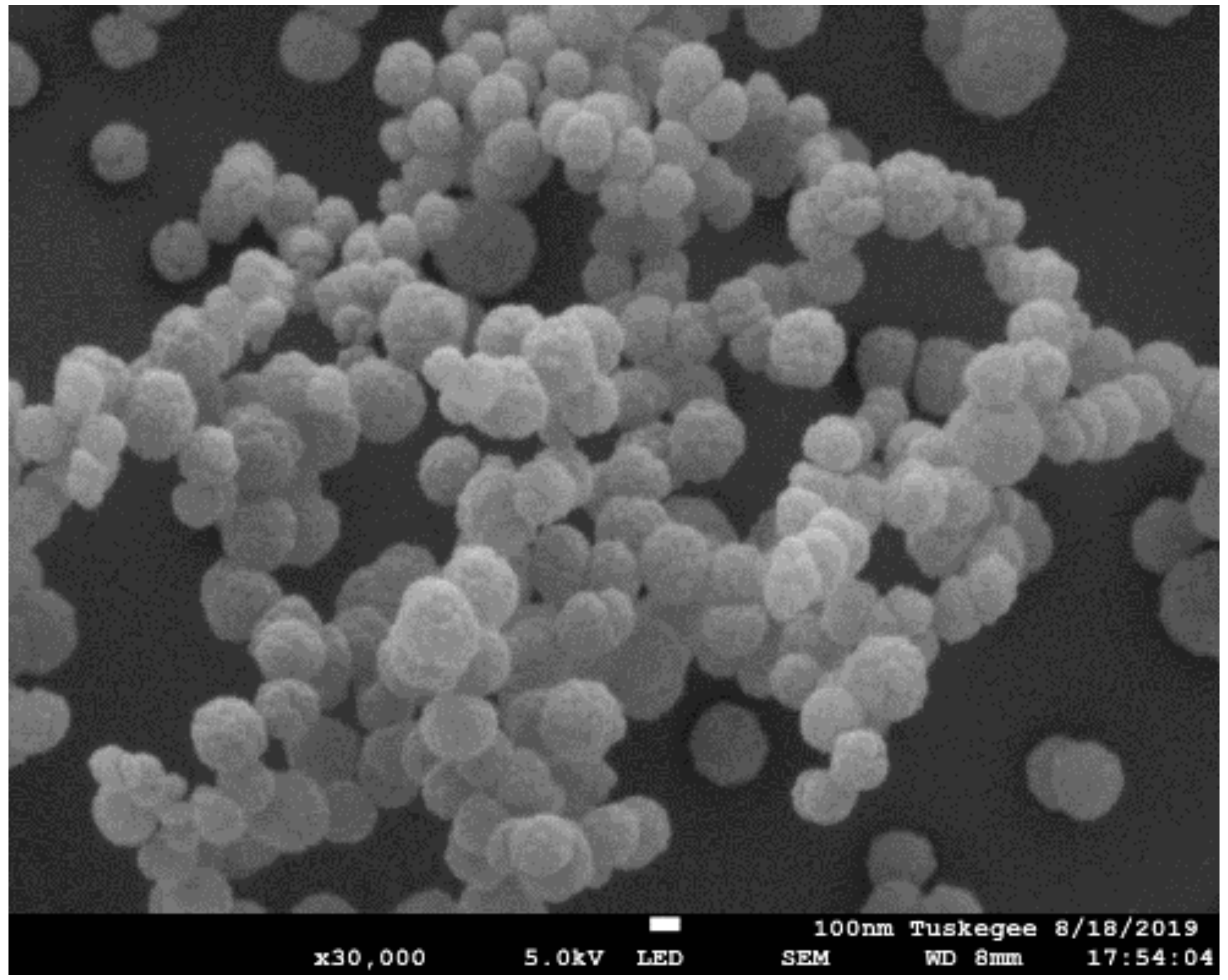
Particle growth in plasma

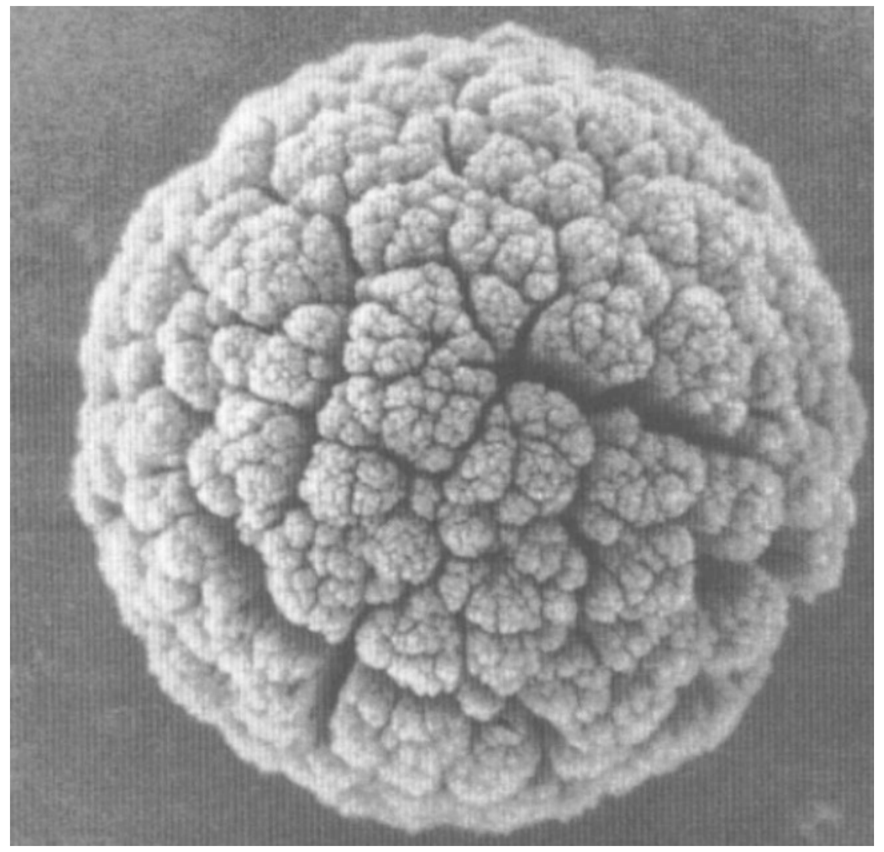
- Nanoparticles and microparticles can be grown in a plasma.
- This can occur in plasma reactors used in semiconductor etching and deposition systems using reactive chemical species like silane, SiH_4:
- $e^- + SiH_4 \rightarrow (SiH_4)^* \rightarrow SiH_2 + 2\,H$

Particle growth in plasma



(a) Particle growth chamber (b) snapshot of particle growth





A 650 nm particle grown in an helium rf plasma with carbon electrodes

Summary

- ✓ Dusty plasma is an interesting and important area to study: fundamentals and industrial applications
- ✓ There are number of scientific topics - from dust grain screening to collective effects to dust particle growth in strongly magnetized plasmas and there are plethora of topics to study under microgravity condition.
- ✓ Detailed investigation is required to understand the fundamentals and control mechanism
- ✓ Many industries require the understanding of dusty plasma including material processing industries and aerospace. Lots of job opportunities.
- ✓ Ongoing work involves experimental, theory, and modelling efforts
- ✓ Come join us!

THANK YOU