Introduction to the physics of dusty plasmas

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2021 SULI Introductory Course in Plasma Physics

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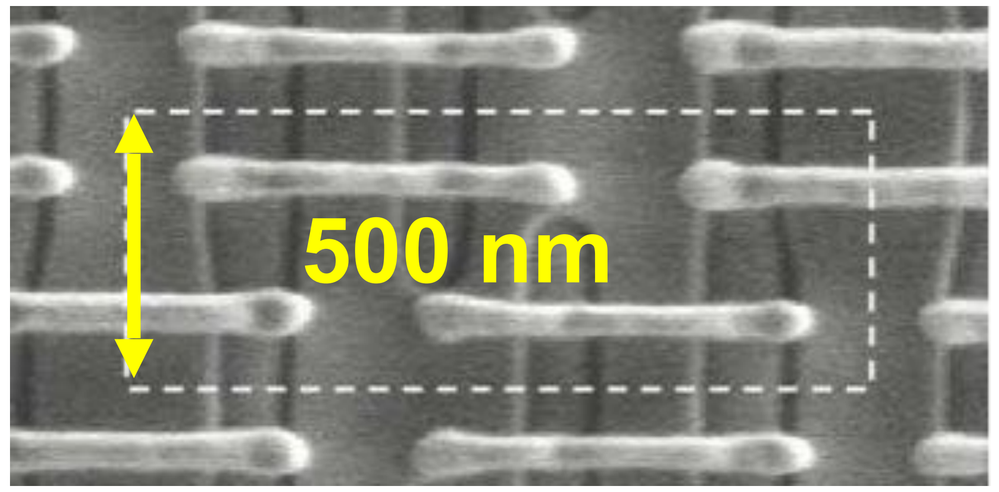
Outline

- Why dusty plasmas?
- Dust in fusion devices
- Basic properties
  - Fundamental parameters
  - Charging
  - Forces and transport
- Outlook

Plasmas: natural and man-made occur at all scales (nm to light years)

Man-made



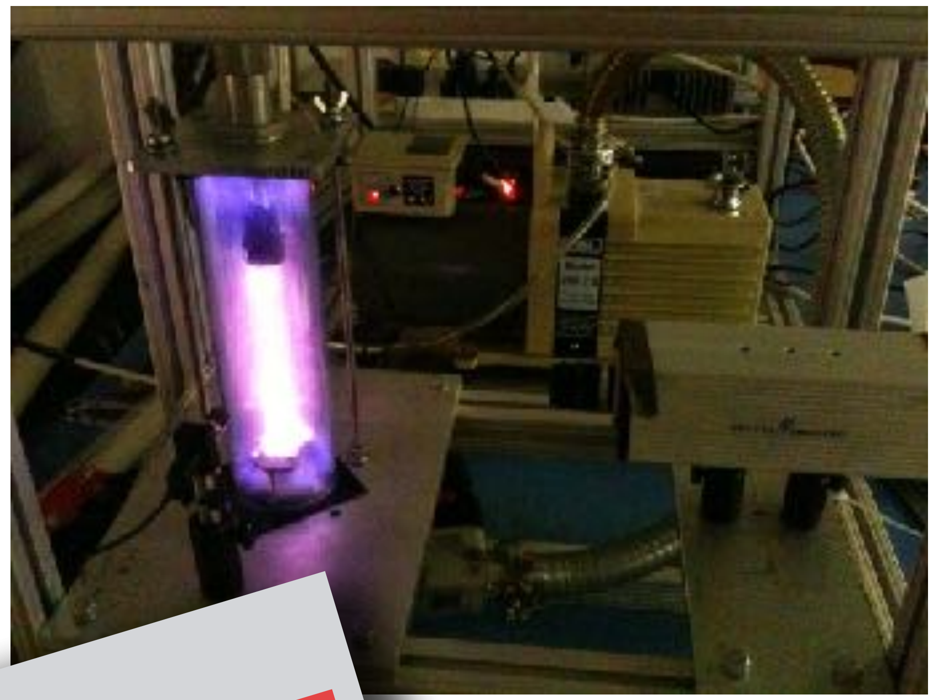
Manufacturing

Plasma medicine

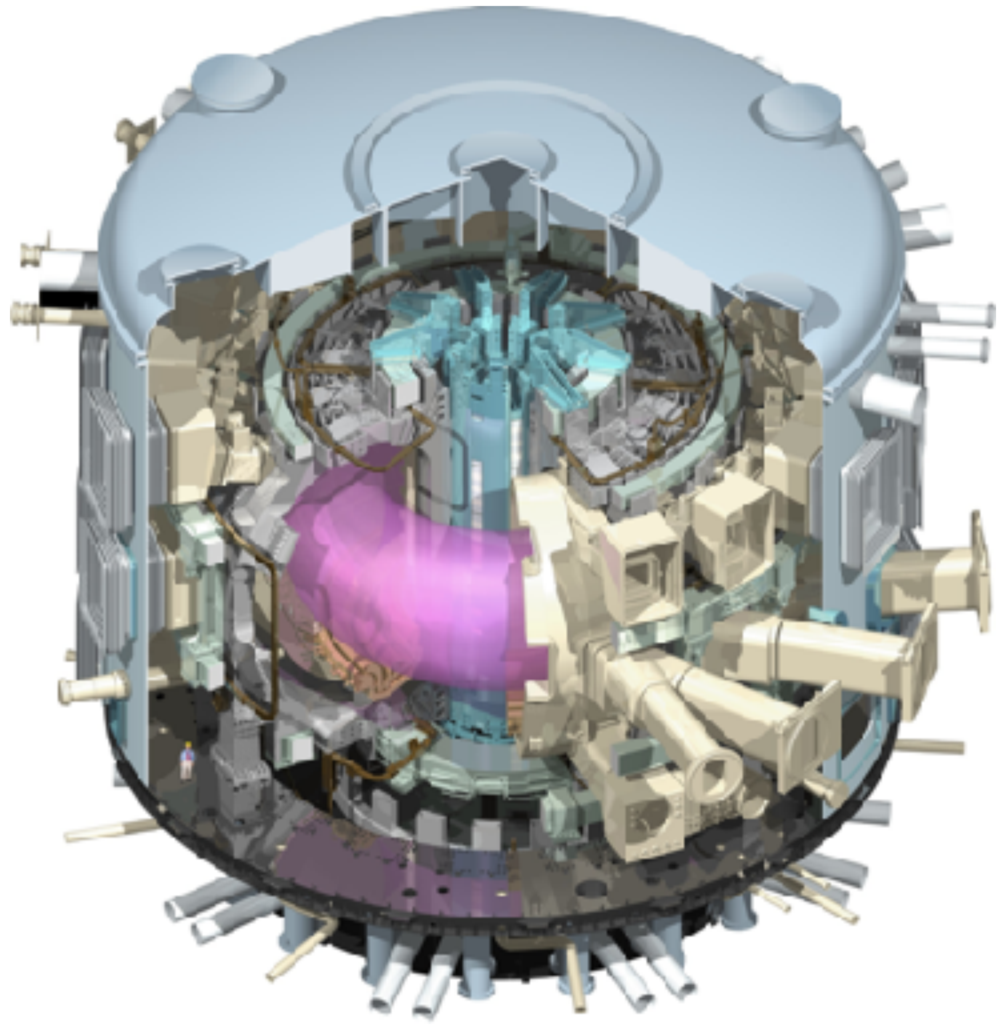
Lighting

Plasma ag

DUST



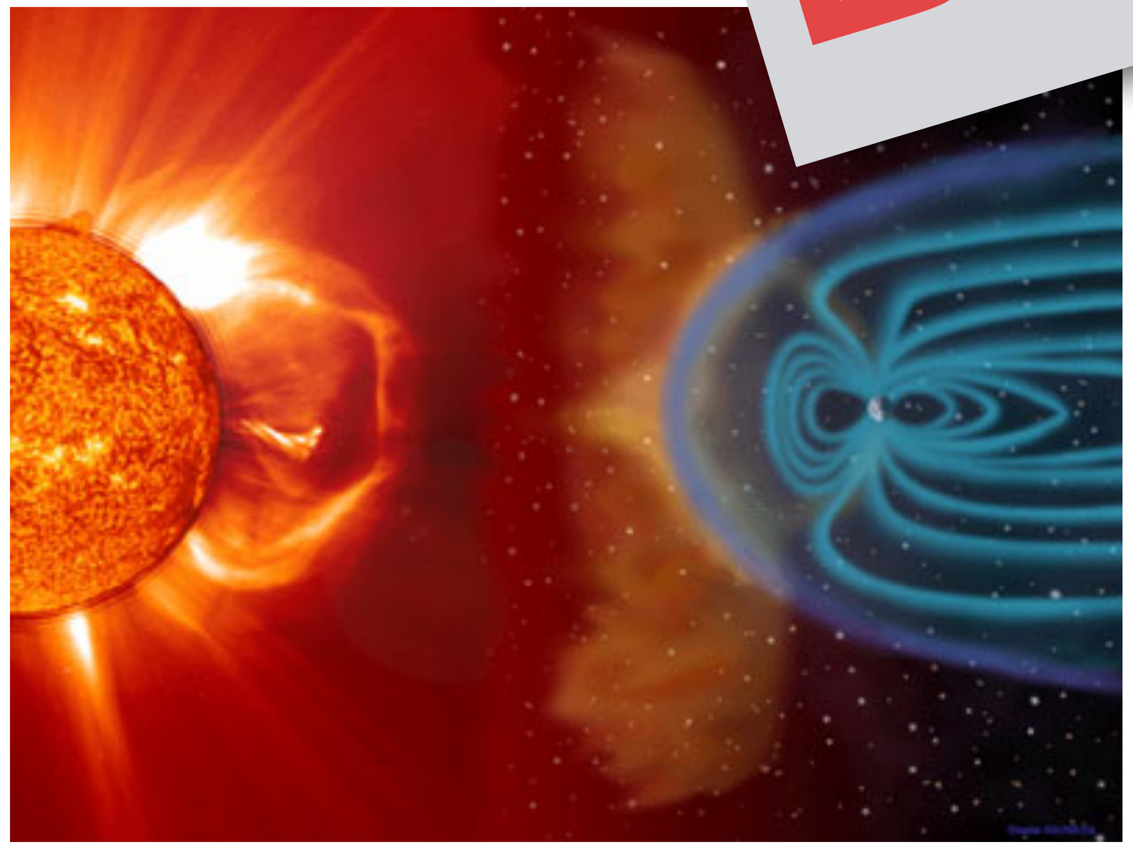
periments



Fusion energy

Naturally-Occurring

Lightning



Sun-Earth connection
"space weather"

Astrophysical jets powered by black holes

Eta Carina nebula
"star and planet formation"

WHY DUSTY PLASMAS?

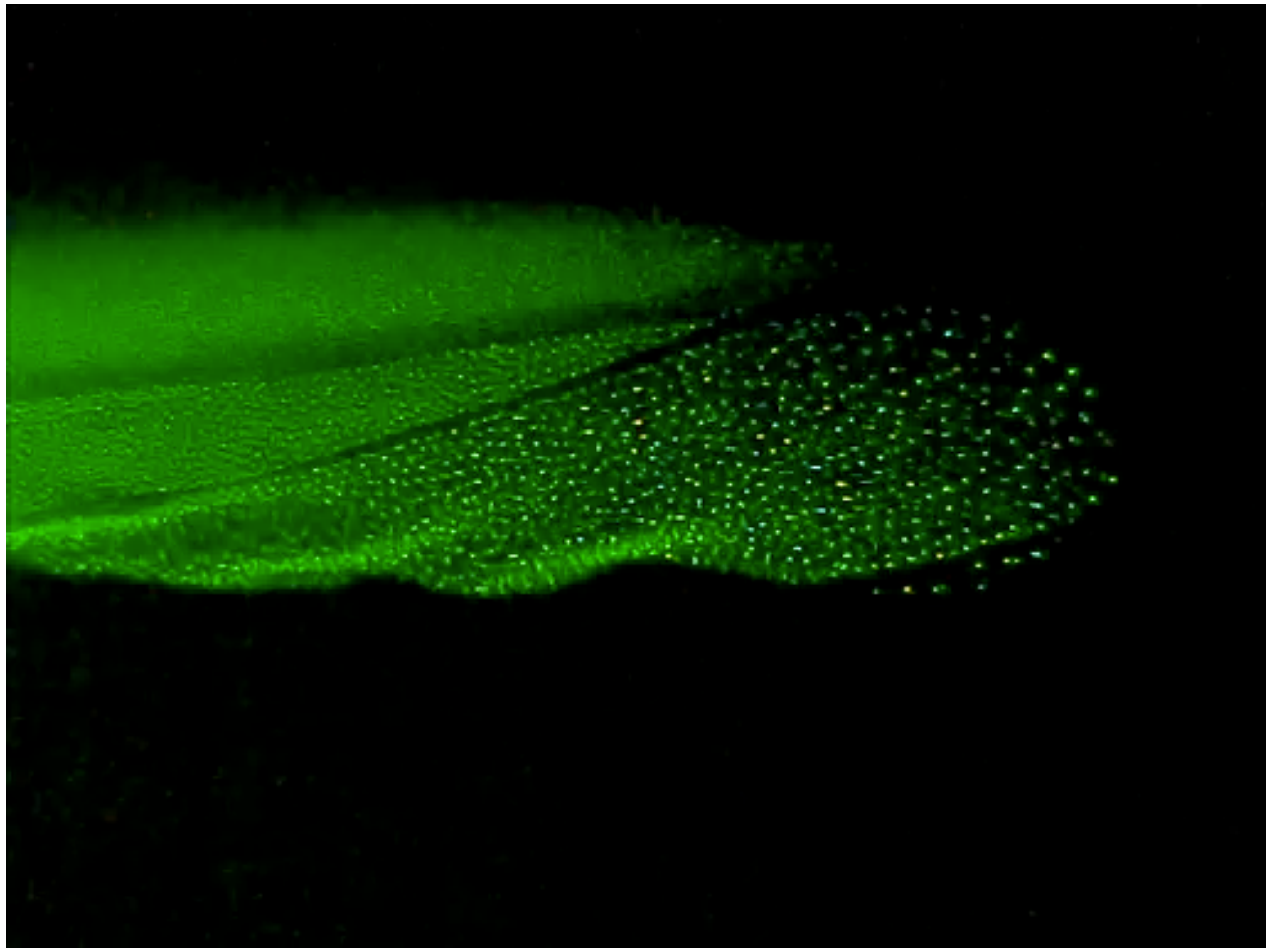
Dusty (complex, fine particle, colloidal) plasmas

- Complex plasmas - four component plasma system
  - Ions
  - Electrons
  - Neutral atoms
  - Charged microparticles

- Plasma and charged microparticles - coupled via collection of ions and electrons from the background plasma.

- Presence of microparticles:
  - Modifies density and charge distribution
  - Modifies plasma instabilities
  - Introduces new dust-driven waves
  - Ubiquitous in natural and man-made plasmas

- **<u>Direct visualization</u>** of plasma phenomena at the particle scale



3 micron diameter silica particles in an argon dc glow discharge plasma recorded at 300 fps [Auburn University]

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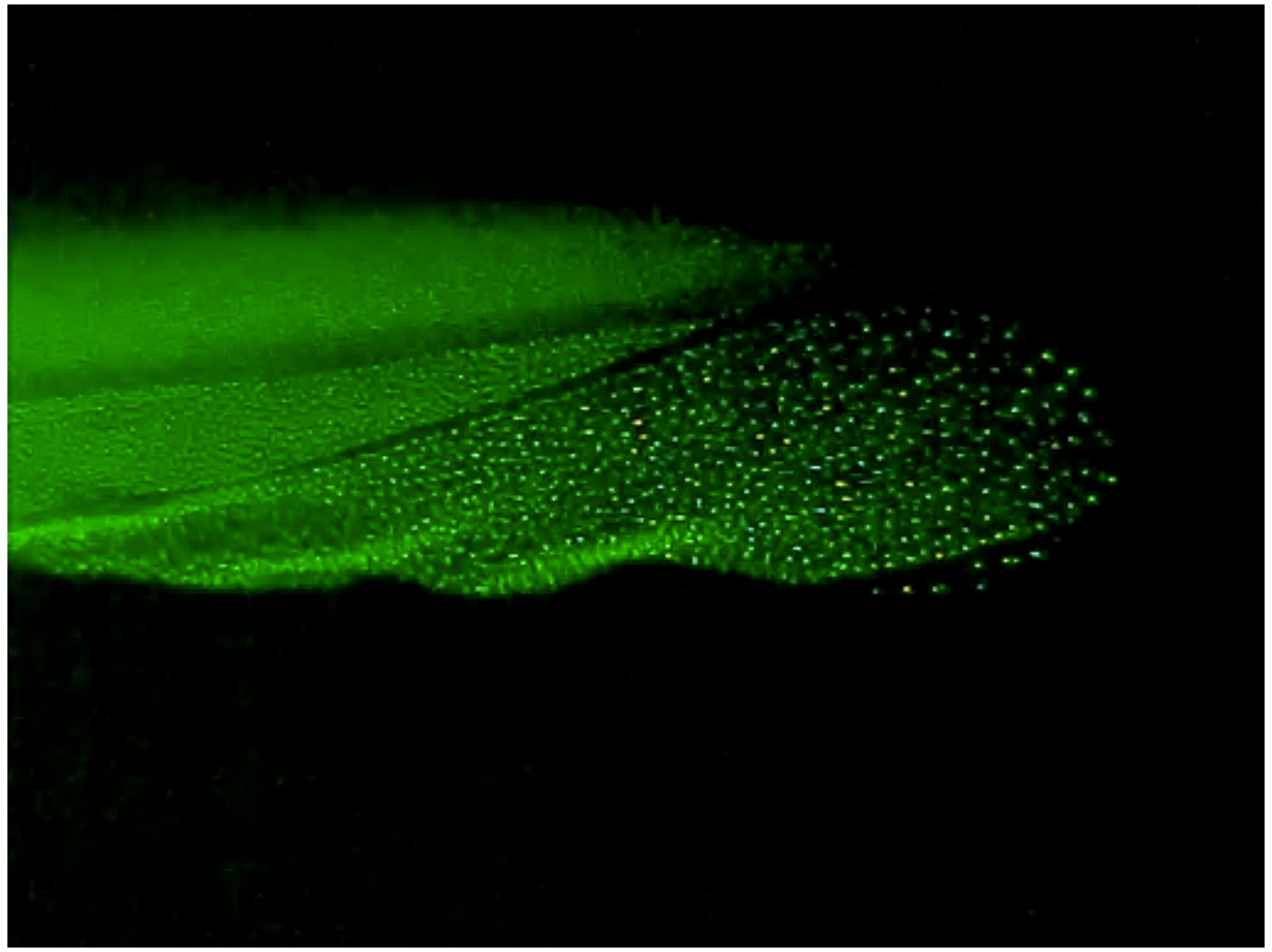
What is the scientific motivation for studying the physics of dusty plasmas?

- **Scientific questions:**
  - What are the microscopic processes that lead to the dust particles become charged?
  - What are the forces that act upon the dust particles in the plasma?
  - What are the microscopic processes that drive particle flows and instabilities?
- <u>Scientific goal</u>: Use the ability to study the "atomic-like" resolution of a dusty plasma to properties of understand the transport of particles, energy, and waves in all plasmas.

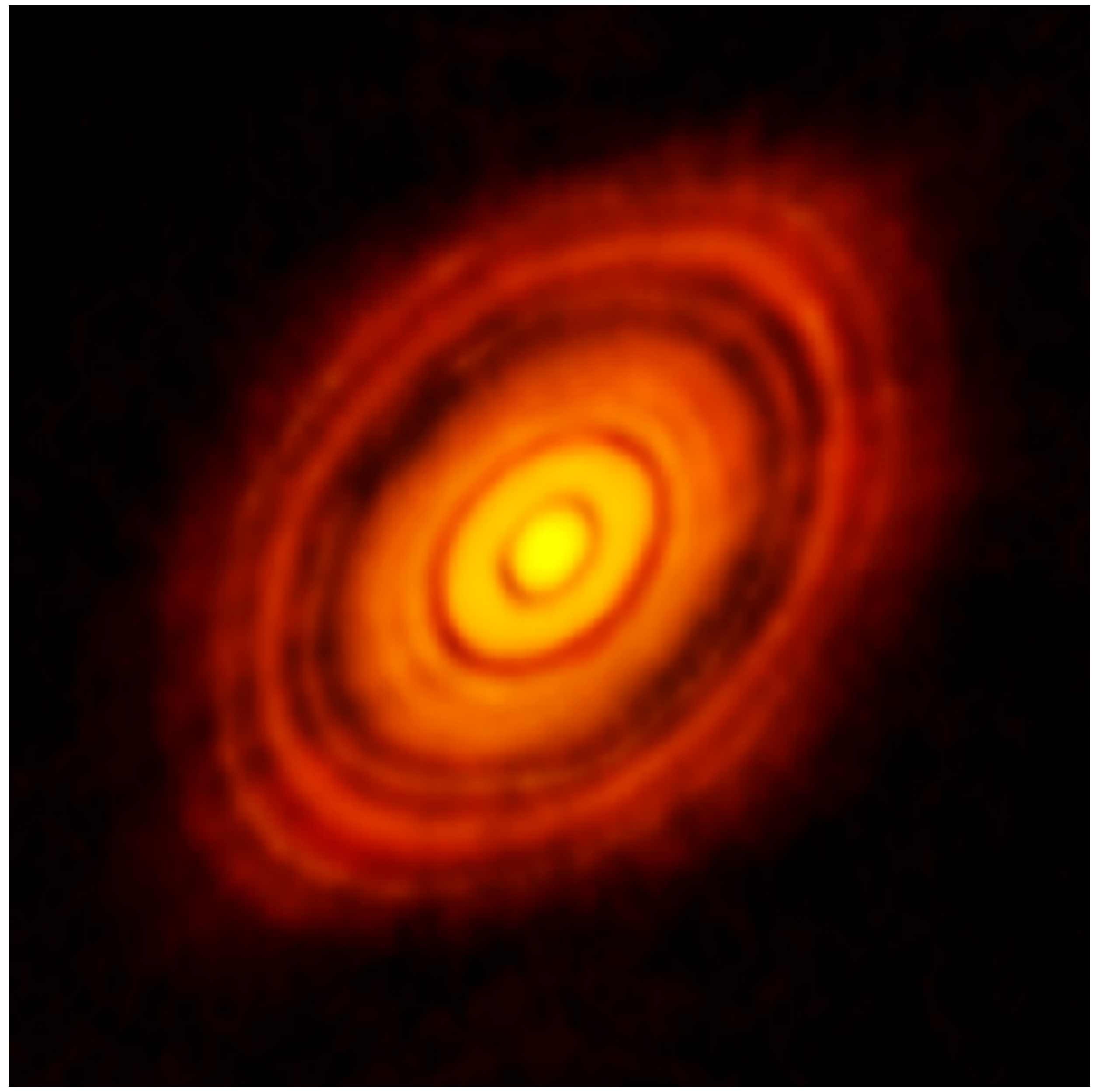


Approach: measure the **position**, **velocity**, and **acceleration** of the particles — to obtain the **forces**, **energy**, and **thermal properties**

Dusty plasmas in astrophysical environments

http://hubblesite.org/newscenter/archive/releases/2007/16/image/f/format/large_web/

Image: Star formation in Carina Nebula



http://www.almaobservatory.org/en/press-room/press-releases/771-revolutionary-alma-image-reveals-planetary-genesis

Image: HL Tau (2014)

Photoionization from stellar material charges the dust in the nebula. The presence of charged dust may lead to enhanced coagulation of small particles AND to repulsion between larger particles. [F. Verheest, PPCF, **41**, A445 (1999)]

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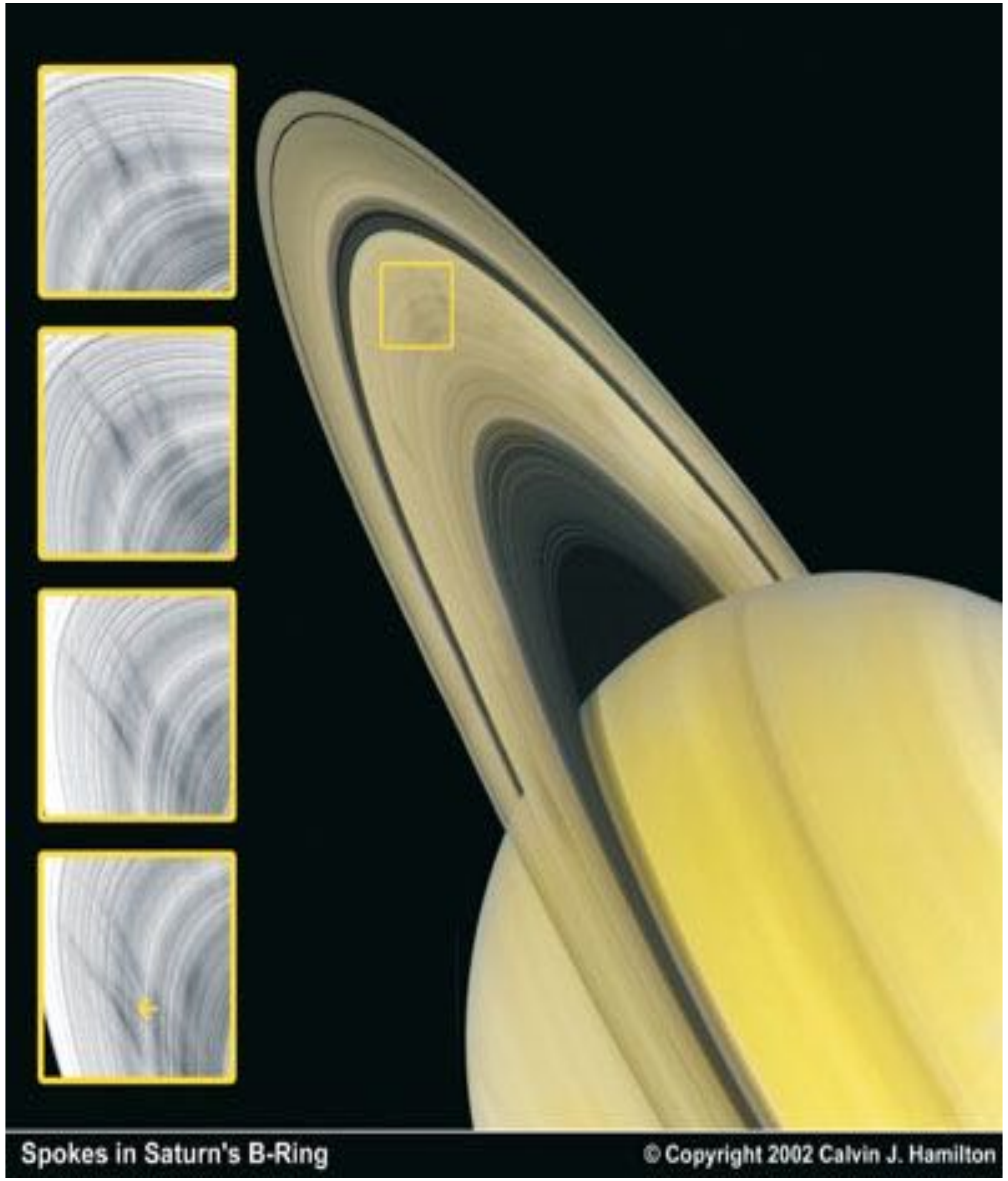
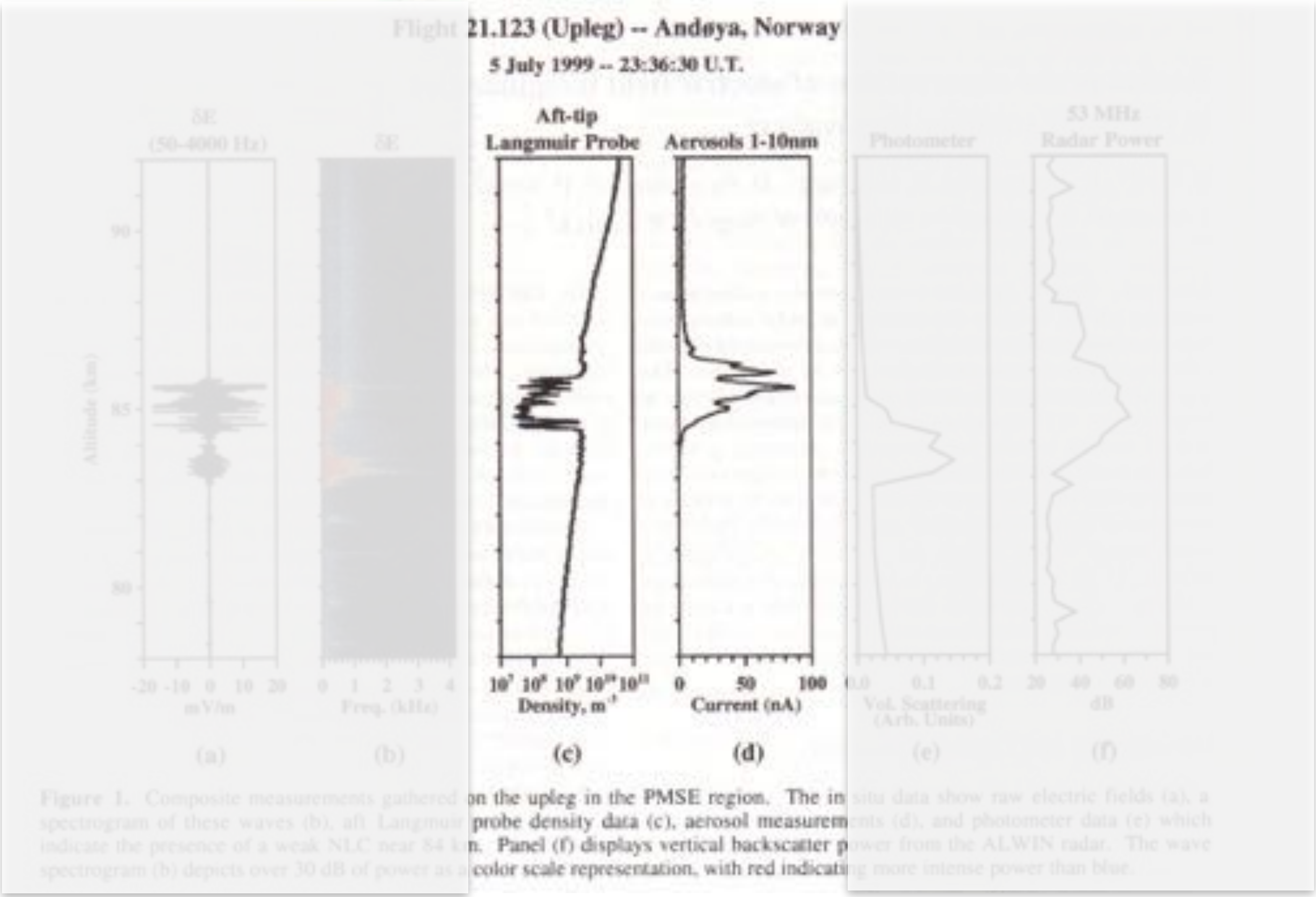
Dusty plasmas in the solar system



- Discovered by Voyager 2 in 1980
- Spokes seen in forward scattered light –> composed of micron-sized dust and ice
- Spokes exhibit dynamical behavior on timescales of minutes.

Dusty plasmas in terrestrial environments

- Noctilucent clouds (NLC’s) form at extremely high altitudes, about 85 km, that “shine at night”.
- They form in the cold, summer polar mesopause and are believed to be charged ice crystals.
- They are believed to be associated with radar backscatter phenomena (PSME’s) observed during the northern summers.



From: http://lasp.colorado.edu/noctilucent_clouds/

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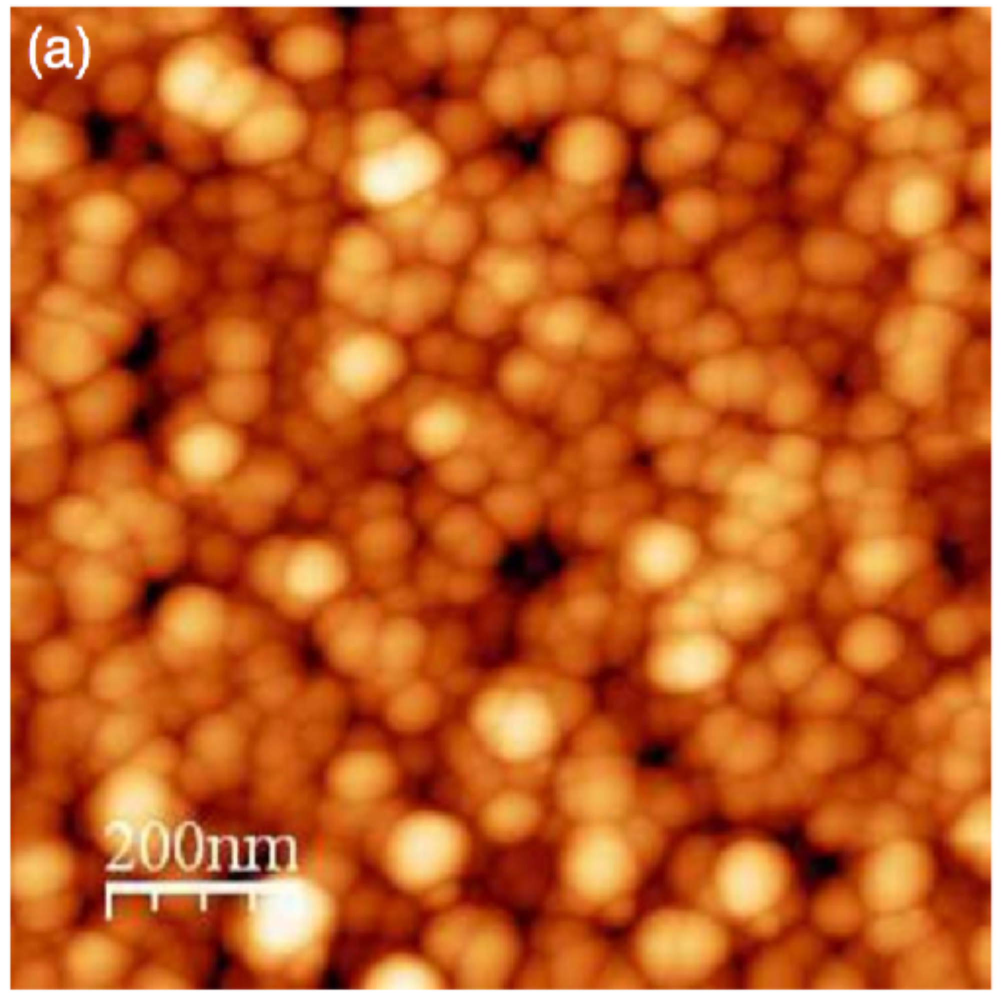
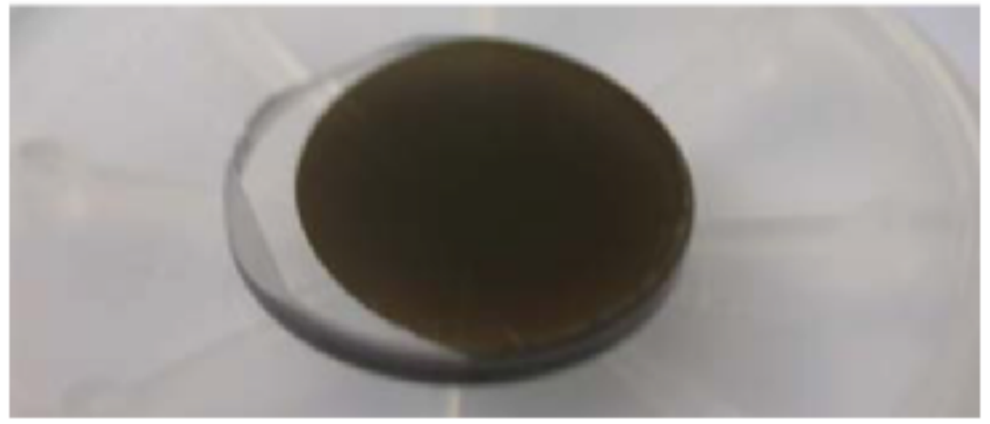
The presence of "dust" in industrial applications has matured from contamination to a commodity

- During the 1990s research was driven by the formation of microparticles in plasma processing reactors.
- Here, microparticles up to several microns in diameter can be grown in the plasma.
- "Killer" particle size has diameter, d ≤ 20 nm.

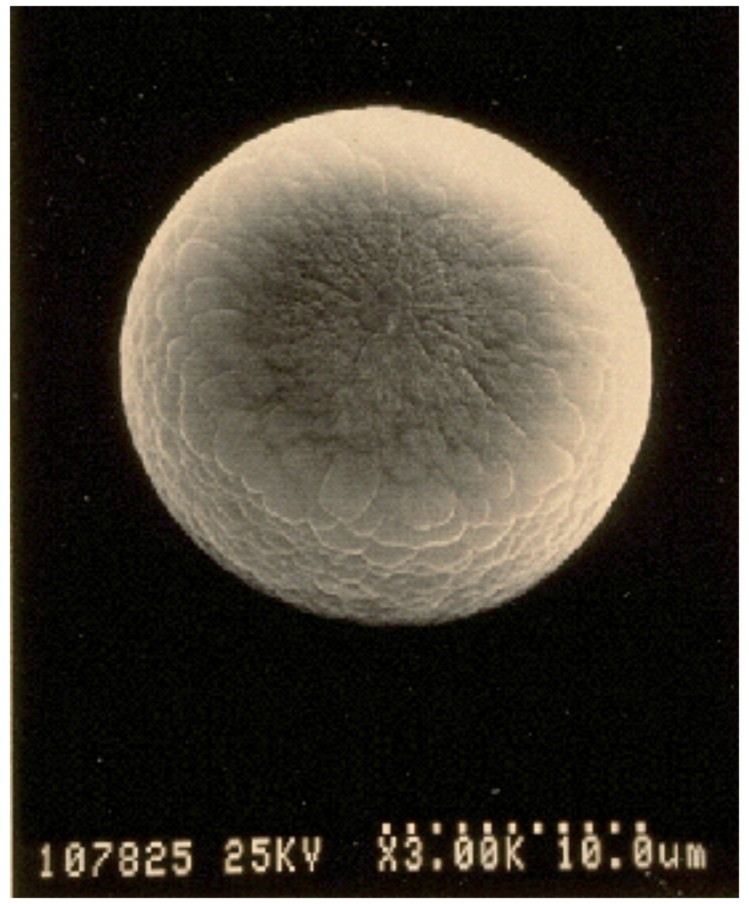


(c)



Copper nanoparticles grown on a substrate to modify the optical properties

E. Quesnel, et al., J. Appl. Phys., **107**, 054309 (2010)



From: http://fjwsys.lanl.gov/bpw/contamination.html - G. Selwyn, LANL

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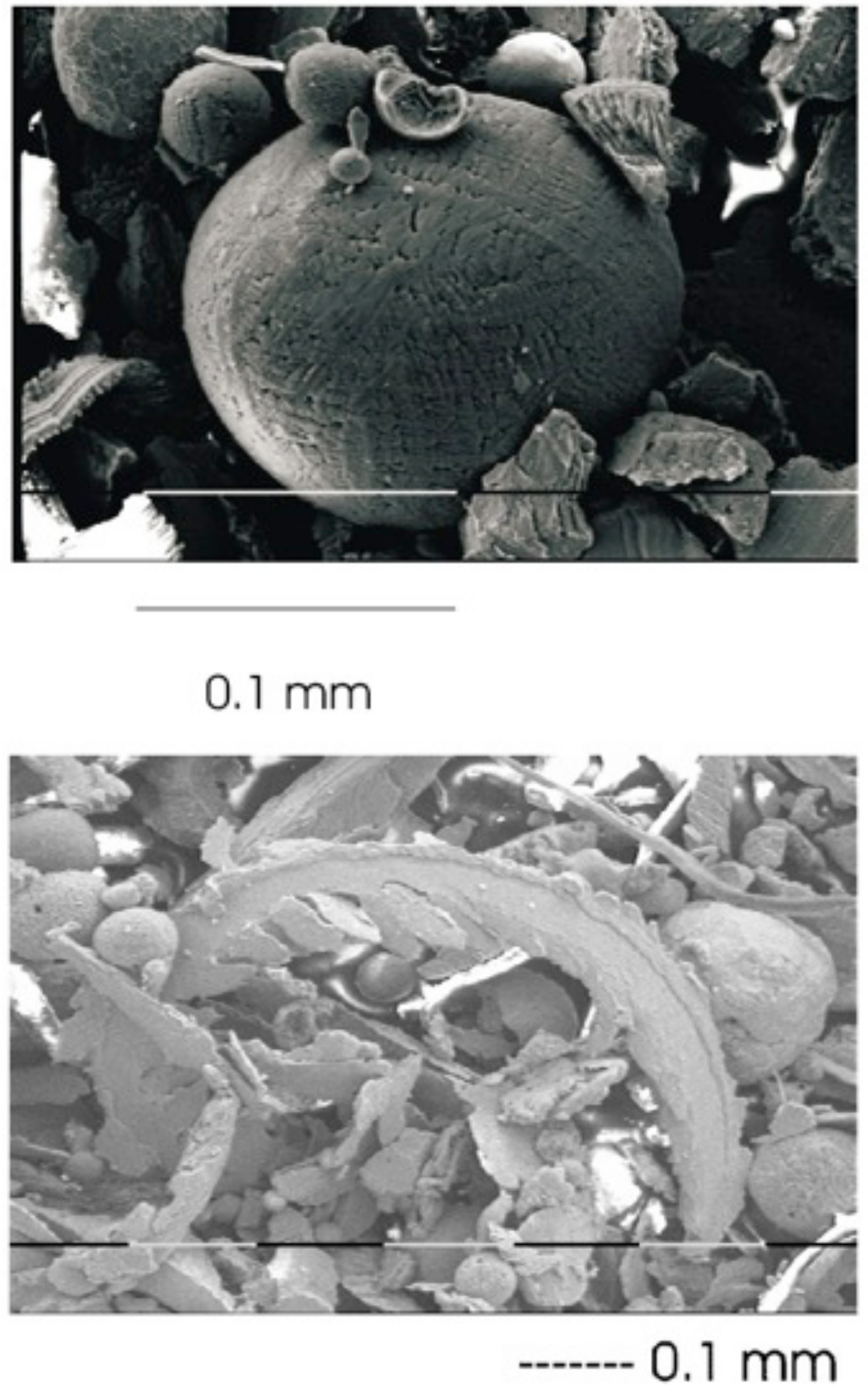
DUST IN FUSION DEVICES

Dust is produced in fusion plasmas by plasma-wall interactions

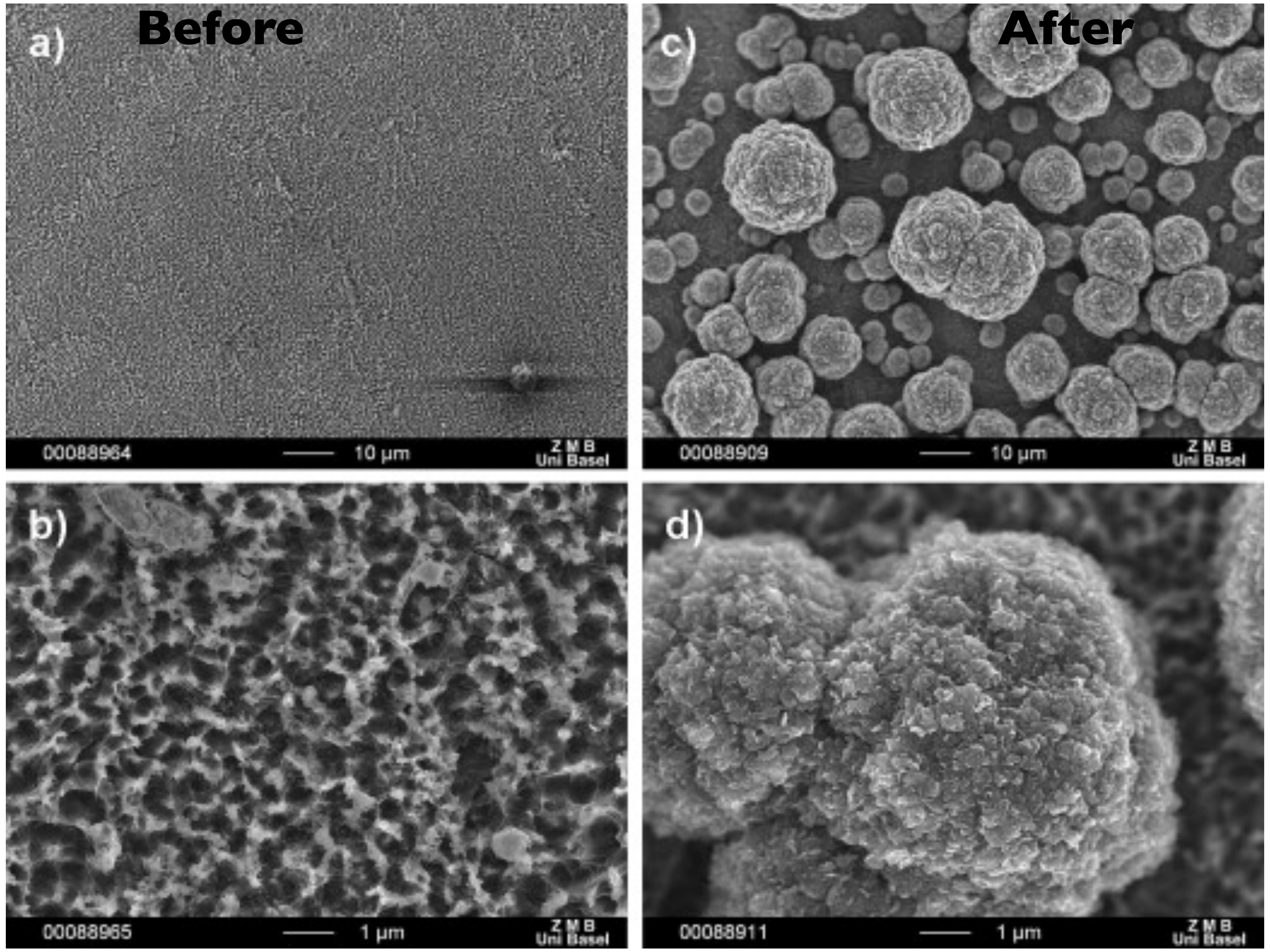
- Plasma-wall interactions lead to material sputtering and localized melting of the first wall.
- Tungsten dust production of **up to 1 g/s** could occur in ITER. [R. D. Smirnov, et al., Phys. Plasmas, **22**, 012506 (2015)]
- Recognized as a possible major issue for fusion devices

Micron-sized dust particles formed in TEXTOR-94



J. Winter, PPCF, **40**, 1201 (1998)
S. I. Krasheninnikov, et al., PPCF, **53**, 083001 (2011)

Modification of carbon surface by hydrogen plasma



From: Dutch Institute for Fundamental Energy Research (www.differ.nl/node/2921)
Ref: K. Bystrov, et al., J. Nucl. Materials, 415, S149 (2011)

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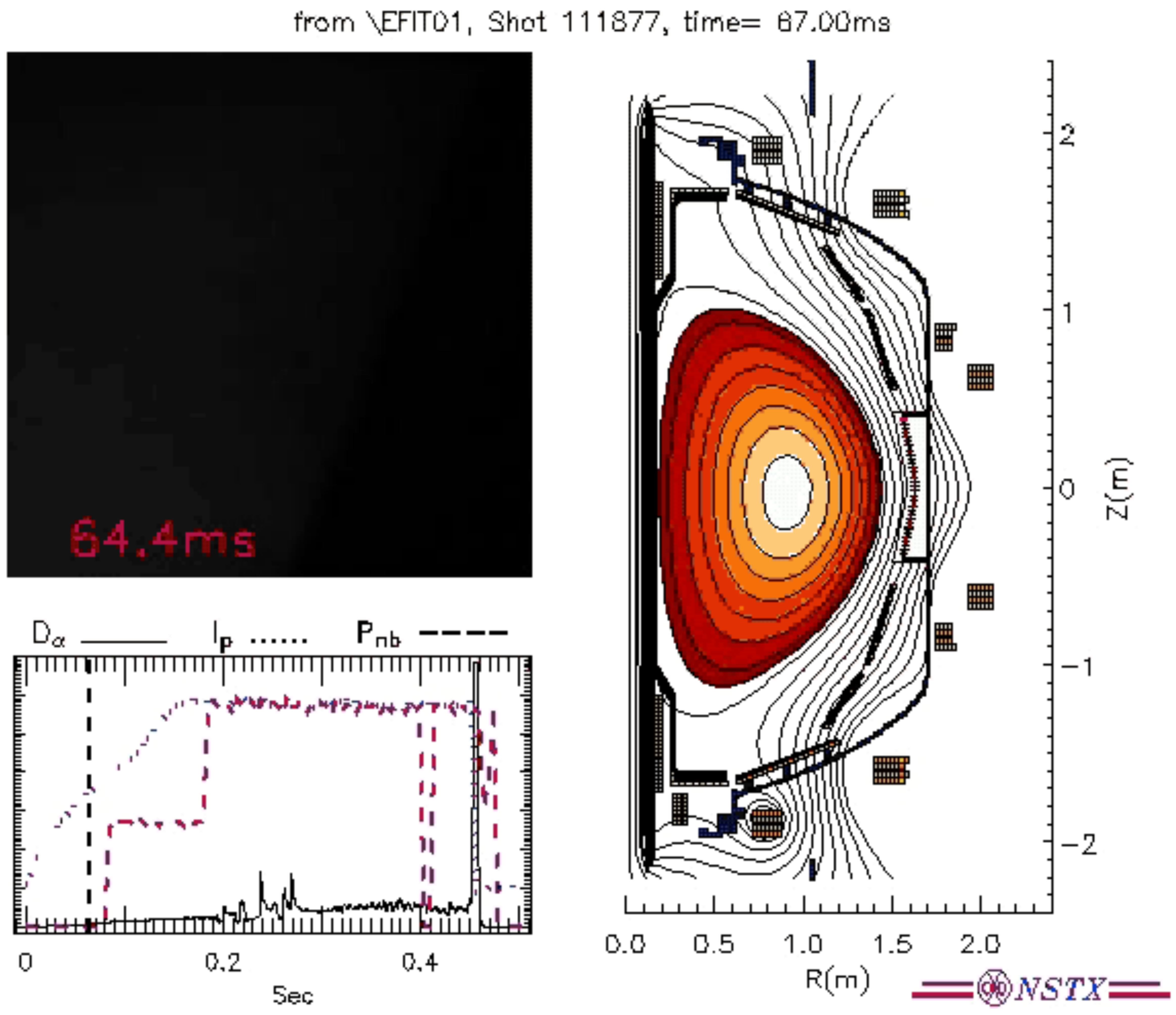
Evidence of dust particles in fusion plasmas



Transport of "hot" dust particles in the diverter of NSTX
Courtesy: PPPL

- Experiments on tokamaks and stellarators have shown evidence of the formation and transport of dust particles.
- As particles move through the plasma, they are subject to a variety of processes: charging, heating, and ablation.
- These processes contribute to the modification of the background plasma.

Impact of dust injection/production on the plasma

- On the assumption of 1.0 g of tungsten dust production.
- ITER parameters (iter.org):
  - Density: ~10^{20} m^{-3}
  - Plasma volume: 840 m^3

- 1 gram tungsten = 3.3 x 10^{21} atoms
- Assume these atoms fill the plasma volume uniformly (not accurate!)
- Further, assume all atoms are singly ionized (not accurate!)

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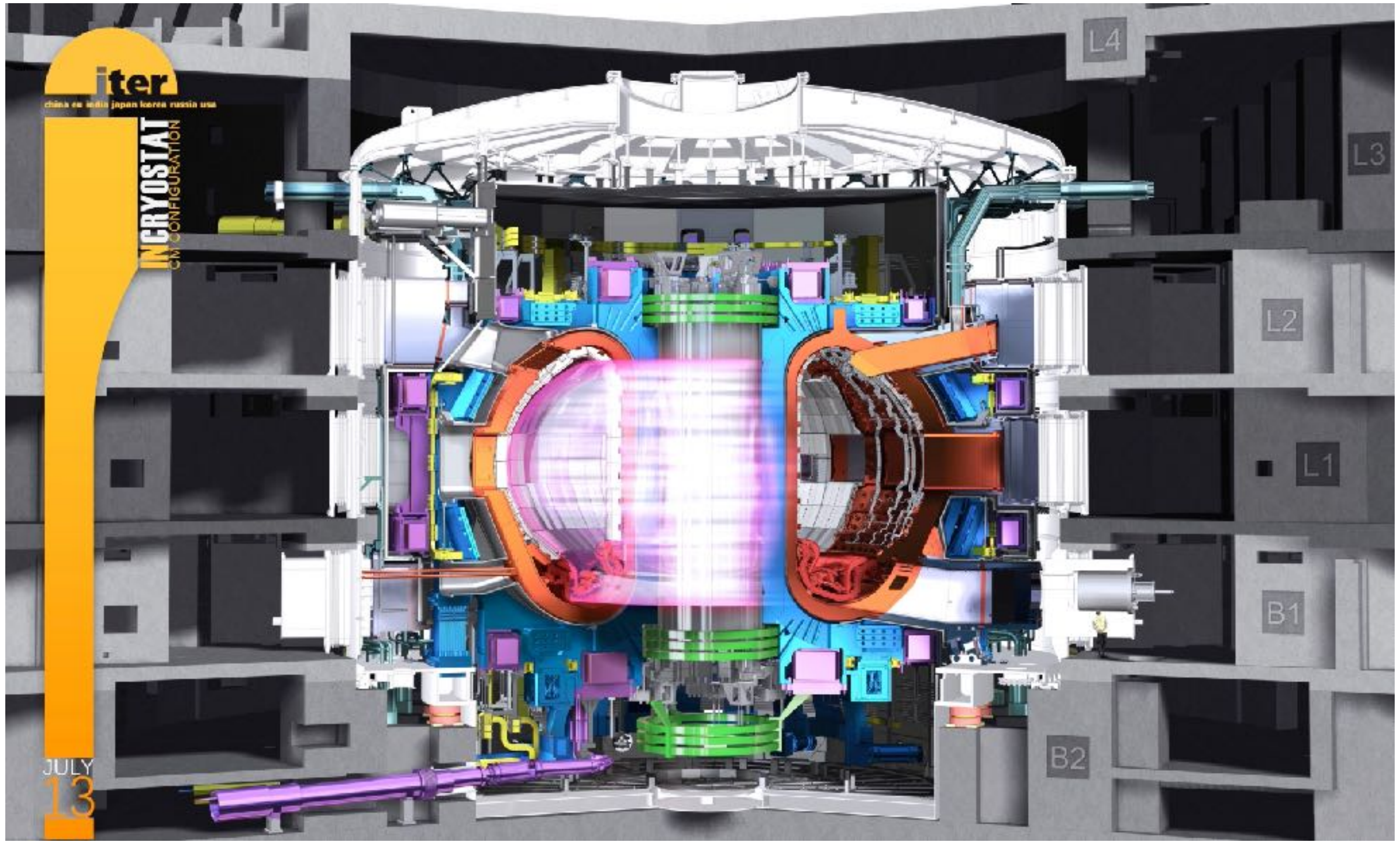
- Assume these atoms fill the plasma volume uniformly (not accurate!)
- Further, assume all atoms are singly ionized (not accurate!)
- n(tungsten) ≈ 4 x 10^{18} m^{-3}
- 4% of plasma density would be impurity atoms
- Since particles would generally be trapped near edges, relative density could be higher.

Consequences of dust contamination in ITER

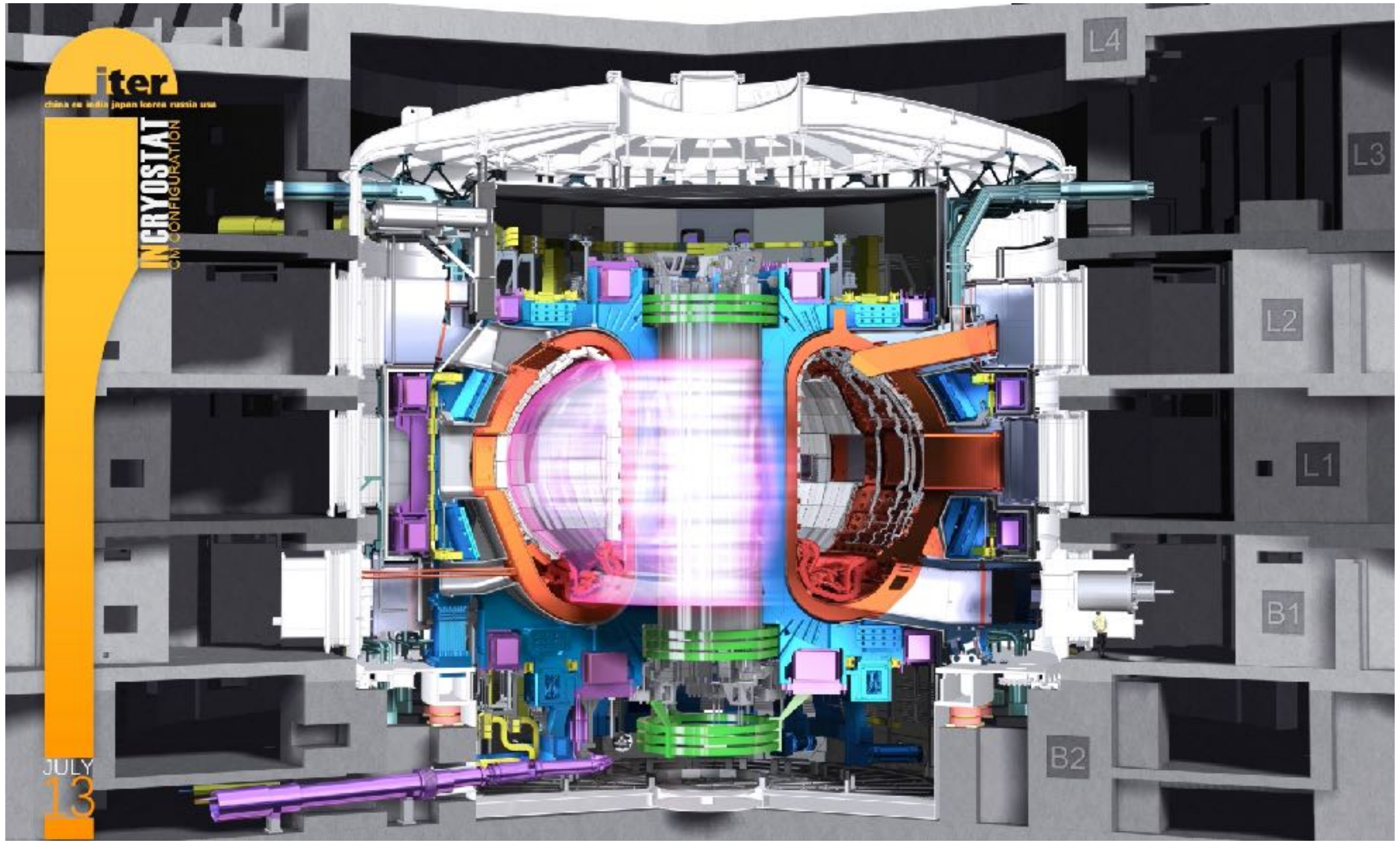


From: http://www.iter.org

There are a number of operational and safety issues associated with the formation of dust in ITER.

- Tritium retention in "dust"
- Reduction of density control
- Degradation of first wall material
- Radiated power losses
- Health and safety hazards
  - fire hazard
  - radiation safety limits
  - safe removal

Consequences of dust contamination in ITER



From: http://www.iter.org

[1] N. K. Bastykova, R. I. Golyatina, S. K. Kodanova, et al., Investigation of the Evolution of Be, Ni, Mo, and W Dust Grains in Fusion Plasma. *Plasma Phys. Rep.* **47,** 92–95 (2021).

[2] J. Sharma, S. C. Sharma, and A. Gahlot , "Kinetic theory of effect of dust charge fluctuations on the parametric decay of lower hybrid wave instability by relativistic runaway electrons in tokamak", *Physics of Plasmas* **28**, 043701 (2021).

[3] A. Makar, "An Audit of Occurrence of Dust in Tokamak and Stability of Fusion Plasmas", *Plasma and Fusion Res.*, **15**, 1405019 (2020).

[4] S. Krasheninnikov, A. Smolyakov. A. Kukushkin, (2020) Dust in Fusion Plasmas. In: *On the Edge of Magnetic Fusion Devices*. Springer Series in Plasma Science and Technology. (Book Chapter)

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[7] M. Rubel, A. Widdowson, J. Grzonka, E. Fortuna-Zaleśna, S. Moon, P. Petersson, N. Ashikawa, N. Asakura, D. Hamaguchi, Y. Hatano, K. Isobe, S. Masuzaki, H. Kurotaki, Y. Oya, M. Oyaidzu, M. Tokitani, and J. Contributors, "Dust generation in tokamaks_ Overview of beryllium and tungsten dust characterisation in JET with the ITER-like wall," *Fusion Engineering and Design*, pp. 1–8, Mar. 2018.

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[10] S. Ratynskaia, P. Tolias, M. De Angeli, V. Weinzettl, J. Matejicek, I. Bykov, D. L. Rudakov, L. Vignitchouk, E. Thorén, G. Riva, D. Ripamonti, T. Morgan, R. Panek, and G. De Temmerman, "Tungsten dust remobilization under steady-state and transient plasma conditions," pp. 1–6, Oct. 2017.

80+ papers from 2016-2021

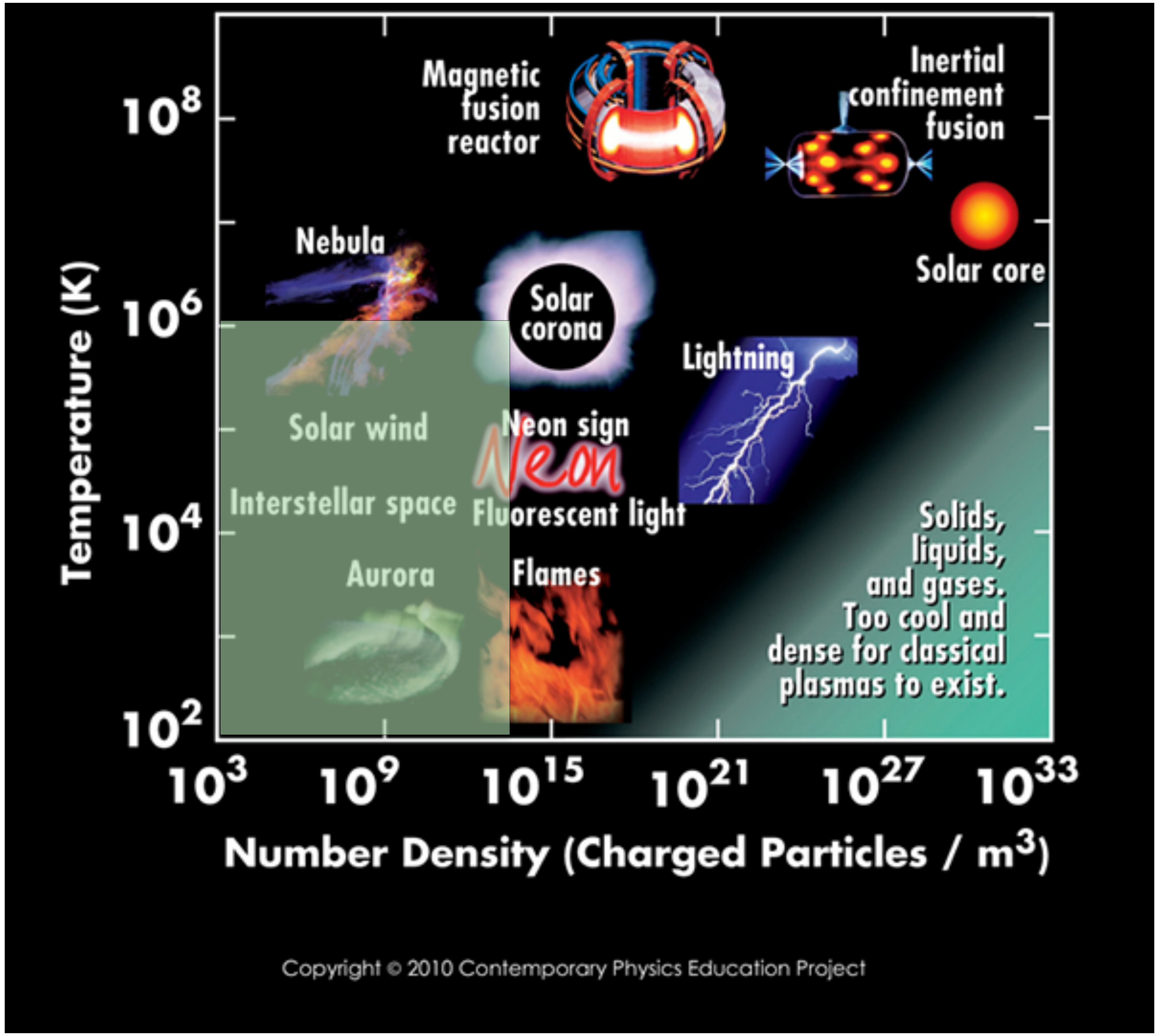
BASIC PROPERTIES

Basic properties of dusty plasmas

- Fundamental parameters
- Charging
- Forces

Where do we find dusty plasmas?

Typical regimes in the laboratory and in space where dusty plasmas are found.



Fundamental Parameters (1): The basic equations

- Define: Relevant scales for a dusty plasma

- Use continuity and momentum equations
  - Assume no zero-order gradients or flows
  - Assume only electrostatic oscillations
  - Close set of equations using Poisson's equation

Parameters:
s – ion, elec, dust
a – dust radius
q_s – charge; $q_d = -Z_d e$
n_s – density
m_s – mass
v_s – velocity
ϕ - potential

- Continuity: $$\frac{\partial n_s}{\partial t} + \nabla \bullet \left(n_s \vec{v}_s \right) = 0$$
- Momentum: $$\frac{\partial \vec{v}_s}{\partial t} + \left(\vec{v}_s \bullet \nabla \right) \vec{v}_s = -\frac{q_s}{m_s} \nabla \phi$$
- Poisson's: $$\nabla^2 \phi = -\frac{1}{\varepsilon_0} \sum q_s n_s$$

Fundamental Parameters (2): Large mass extends the time scales

- Linearize the equations using: $a = a_0 + a_1 \exp[i(kx-\omega t)]$

- Derive a result that gives the time scales of plasma oscillations:

$$\omega^2 = \sum \omega_{ps}^2 = \omega_{pe}^2 + \omega_{pi}^2 + \omega_{pd}^2$$

$$where:\ \omega_{ps}^2 = \frac{q_s^2 n_{0s}}{\epsilon_0 m_s}$$

- For typical lab plasma parameters: $f_{ps} = \omega_{ps}/2\pi$
  $n_{i0} = n_{e0} \sim 10^{14}$ m^{-3}, $n_{d0} \sim 10^{10}$ m^{-3}, argon plasma, $Z_d \sim 4600$, a ~ 1.5 μm

- f_{pe} = 90 MHz, f_{pi} = 330 kHz, f_{pd} = 23 Hz

Fundamental Parameters (3): Spatial scales

- Start again with Poisson's equation: $$\nabla^2\phi = -\frac{1}{\epsilon_0}[en_i - en_e - q_d n_d]$$
- Model the electron and ion densities using Boltzmann distributions

$$n_e = n_{e0} exp\left(\frac{e\phi}{kT_e}\right) \approx n_{e0}\left(1 + \frac{e\phi}{kT_e}\right)$$

$$n_i = n_{i0} exp\left(-\frac{e\phi}{kT_i}\right) \approx n_{i0}\left(1 - \frac{e\phi}{kT_i}\right)$$

- Assume quasi-neutrality: $en_{i0} = en_{e0} + eZ_d n_{d0}$
- Solve for the 1-D potential

$$\phi = \phi_0 exp\left[-{}^{x}/_{\lambda_D}\right]$$

where: $\underbrace{\lambda_D = \left[\lambda_{De}^{-2} + \lambda_{Di}^{-2}\right]^{-1/2}}_{\text{Debye length}}$ and $\lambda_{Ds} = \left(\frac{\varepsilon_0 kT_s}{q_s n_{s0}}\right)^{1/2}$

λ_{De} = 204 μm

λ_{Di} = 19 μm

$\lambda_D \sim \lambda_{Di} \approx 19$ μm

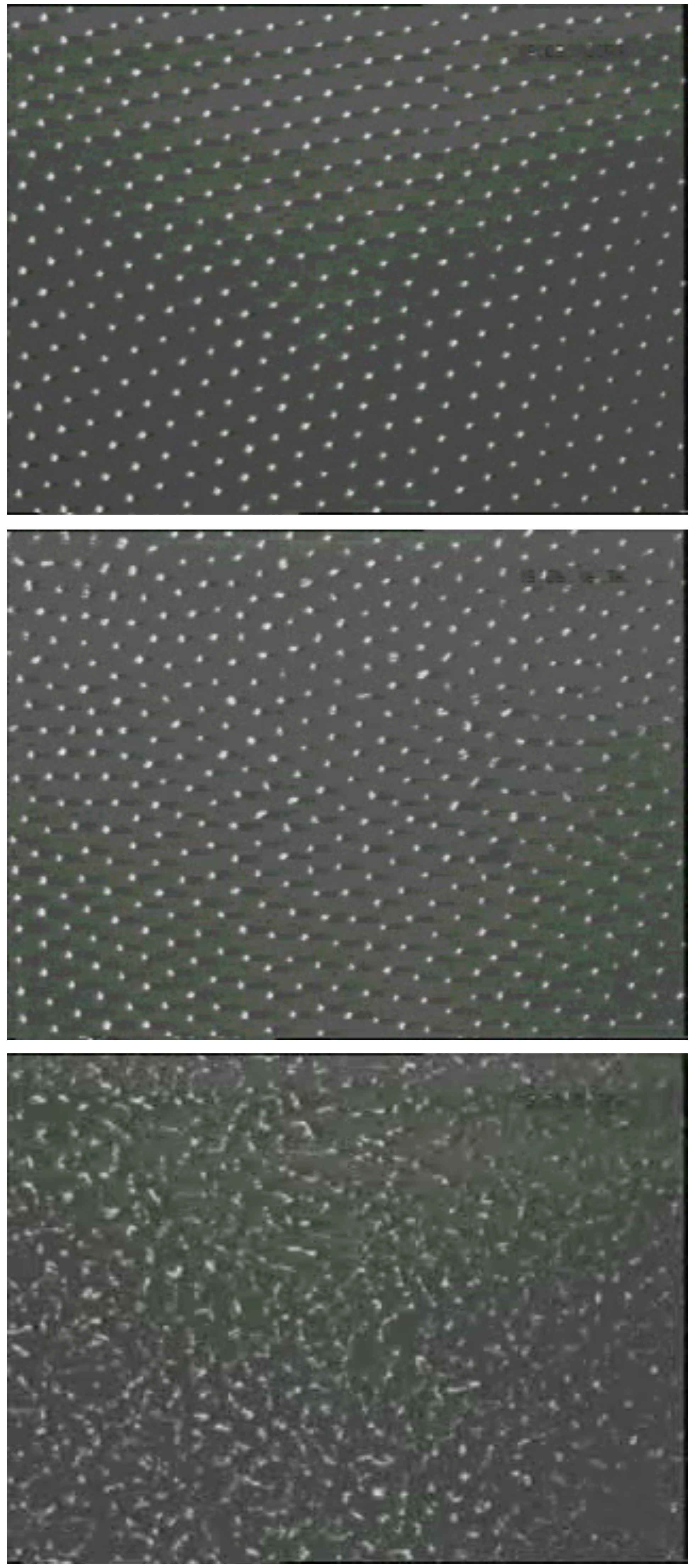
Fundamental Parameters (4): Coupling parameter is a measure of self-organization

- Γ (coupling parameter) is indicative of the self-organizing, emergent properties of dusty plasmas.
- A dusty plasma can be used as a model system to investigate problems in soft-matter physics.
- Assume dust particles interact via a screened Coulomb interaction

Yukawa, Debye-Hückel: $$\varphi \sim \frac{\exp\left(-r/\lambda_D\right)}{r}$$

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

$$\Delta = \text{Wigner-Seitz radius} = \left(\frac{4\pi n_d}{3}\right)^{-1/3}$$



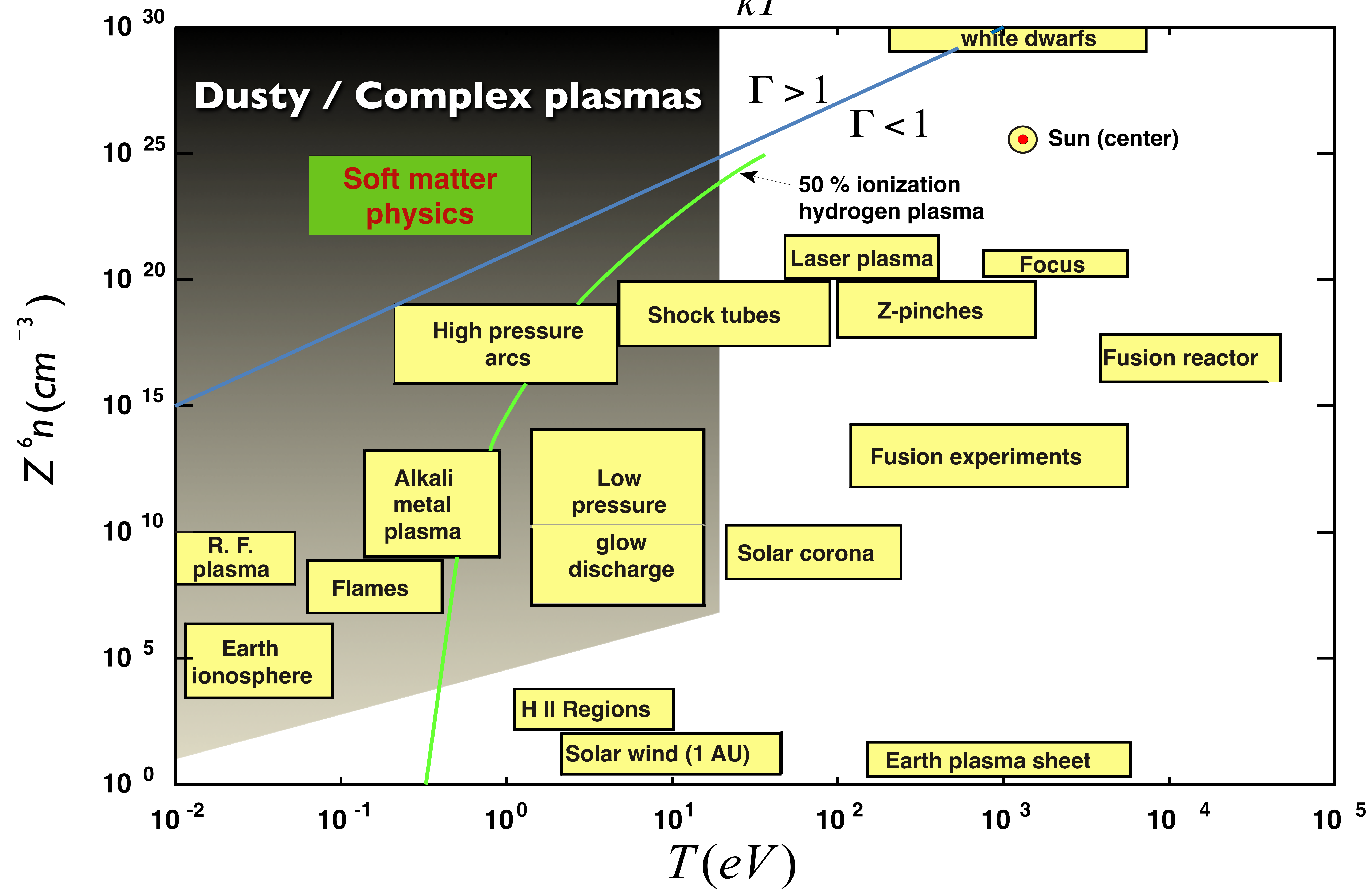
$\Gamma >> 1$
"solid"

$\Gamma \sim 1$
"liquid"

$\Gamma < 1$
"gas"

Redefining the parameters of a dusty plasma

$$\Gamma \equiv \frac{(Ze)^2}{kT} n^{1/3}$$



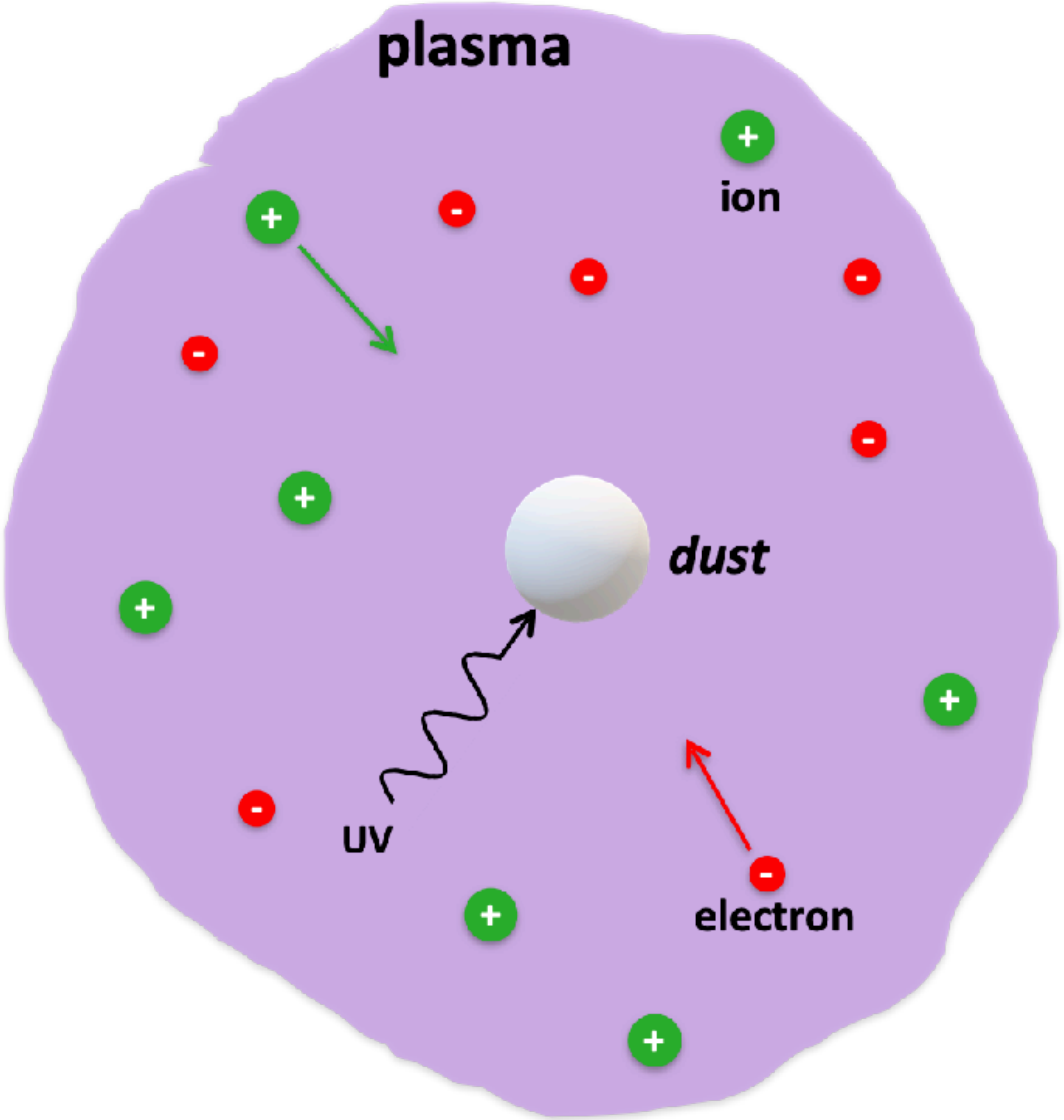
G. Morfill, et al., PoP, **6**, 1769 (1999).

Basic properties of dusty plasmas

- Fundamental parameters
- Charging
- Forces

Dust grain charge is a dynamic variable

- A dynamic equilibrium is established as the grain electrically floats in the plasma:
- $I_{total} = I_{electron} + I_{ion} + I_{see} + I_{thermionic} + I_{h\nu} = f(n_j, T_j, \varphi; \underline{r}, t)$
- Implication: $Q_d(t) \neq$ constant;
- Grain charge ($Q_d = Z_d e$) is a new dynamic variable



Estimating dust grain charge (1)

- For laboratory studies, ions and electrons are the dominant charging mechanisms.
- We assume dust behaves as an electrically floating probe and estimate the flux to the grain surface using orbit motion limited (OML) theory.

$$I_e = 4\pi a^2 \left(\frac{e n_e}{4}\right)\left(\frac{8kT_e}{\pi m_e}\right)^{1/2} \exp\left(\frac{eU}{kT_e}\right)$$ **electron**

a – grain radius
T_s – temperature
k – Boltzmann's constant
U – grain surface potential

$$I_i = 4\pi a^2 \left(\frac{e n_i}{4}\right)\left(\frac{8kT_i}{\pi m_i}\right)^{1/2} \left(1 - \frac{eU}{kT_i}\right)$$ **ion**

Estimating dust grain charge (2)

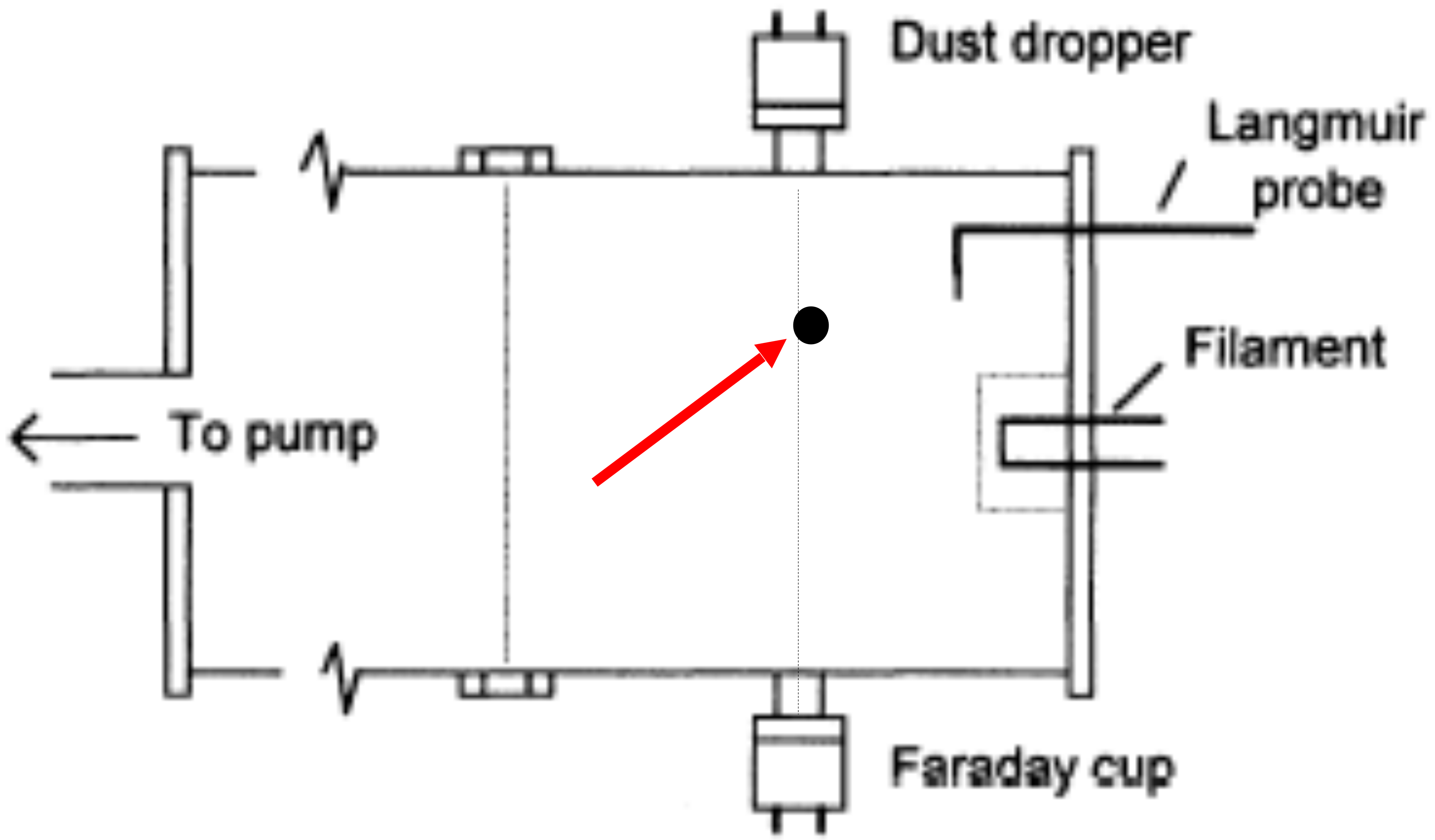
- Assume grains are conducting.
- Assume grains are spherical capacitors: $Q_d = \pm eZ_d = 4\pi\varepsilon_0 aU$
- Assume quasineutrality: $en_i = en_e + Q_d n_d$
- Solve the balance equation: $I_e + I_i = 0$

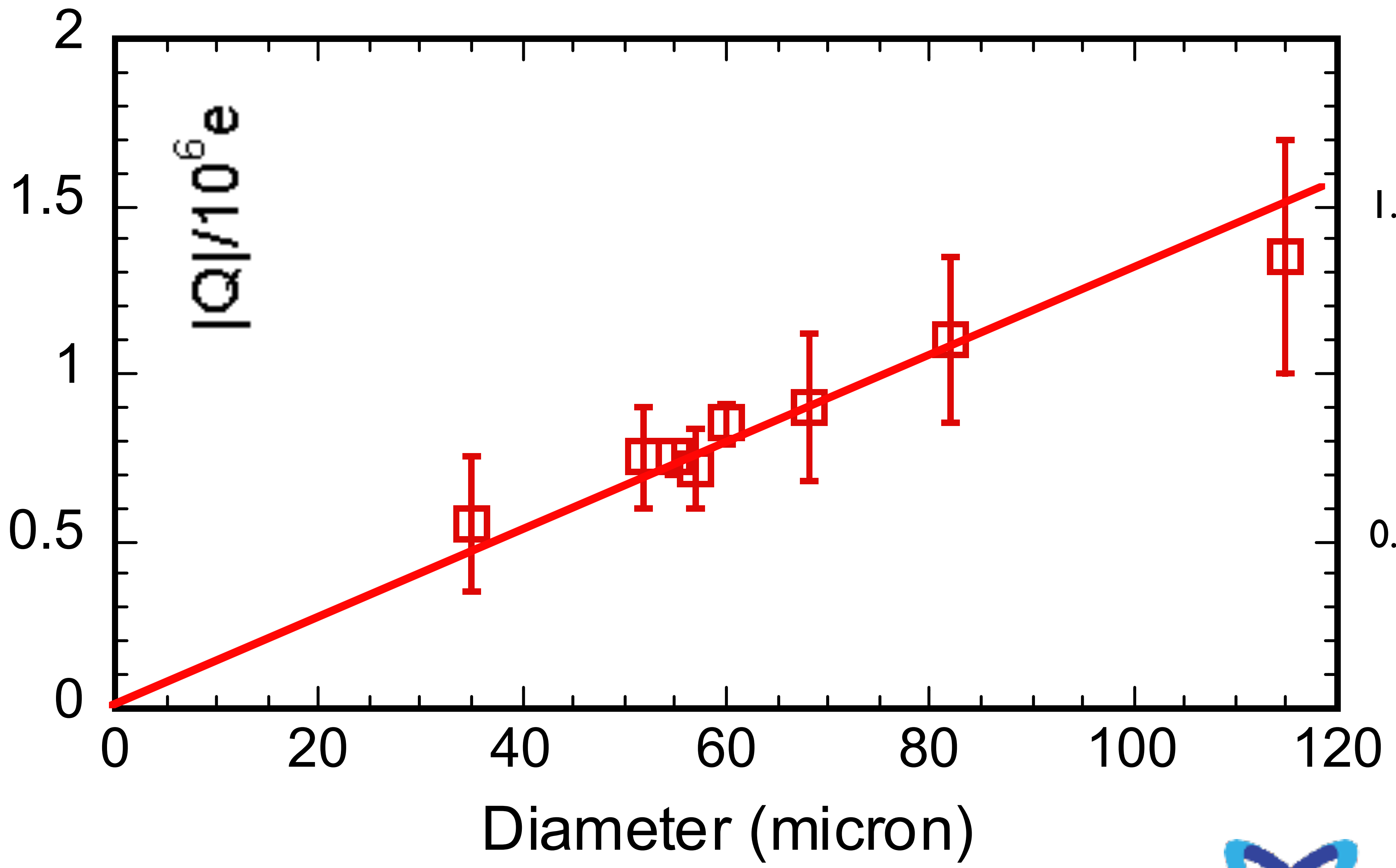
$$\left(1+\frac{Q_d n_d}{en_0}\right)\left(\frac{m_i T_e}{m_e T_i}\right)^{1/2}\exp\left(\frac{eU}{kT_e}\right)=1-\left(\frac{eU}{kT_i}\right)$$

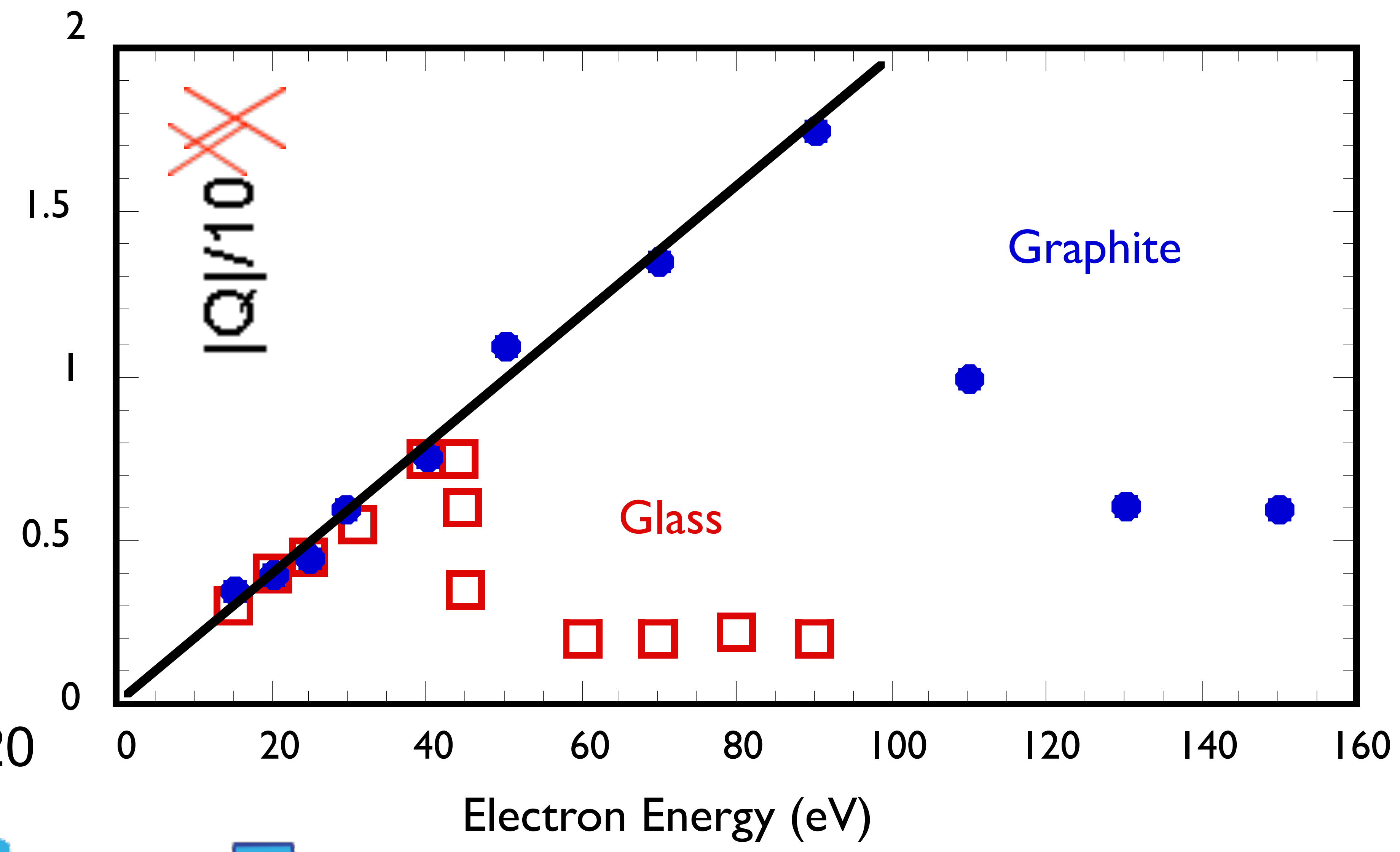
- Solve numerically for the grain surface potential U to get the charge, Q_d.

Charging experiments (1)

- Individual grains are dropped through a hot filament plasma.
- Grains are captured in a Faraday cup.







Walch, et al., Phys. Rev. Lett. 75, 838 (1995)

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Charging experiments (2)

Barkan experiment uses a Q-machine to generate the plasma

-> Here, $T_i \approx T_e \sim 0.2$ eV

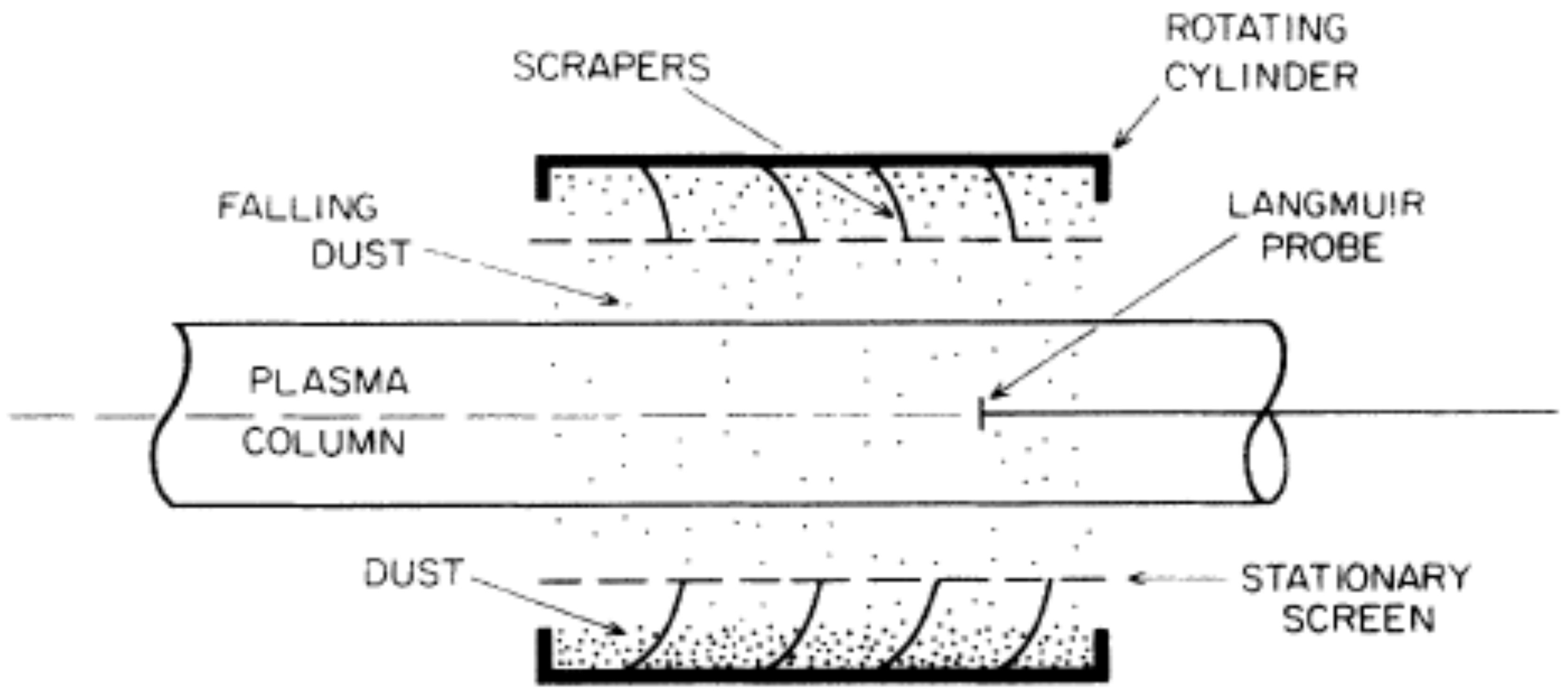

FIG. 2. Schematic diagram of the device used to disperse dust into the plasma column.

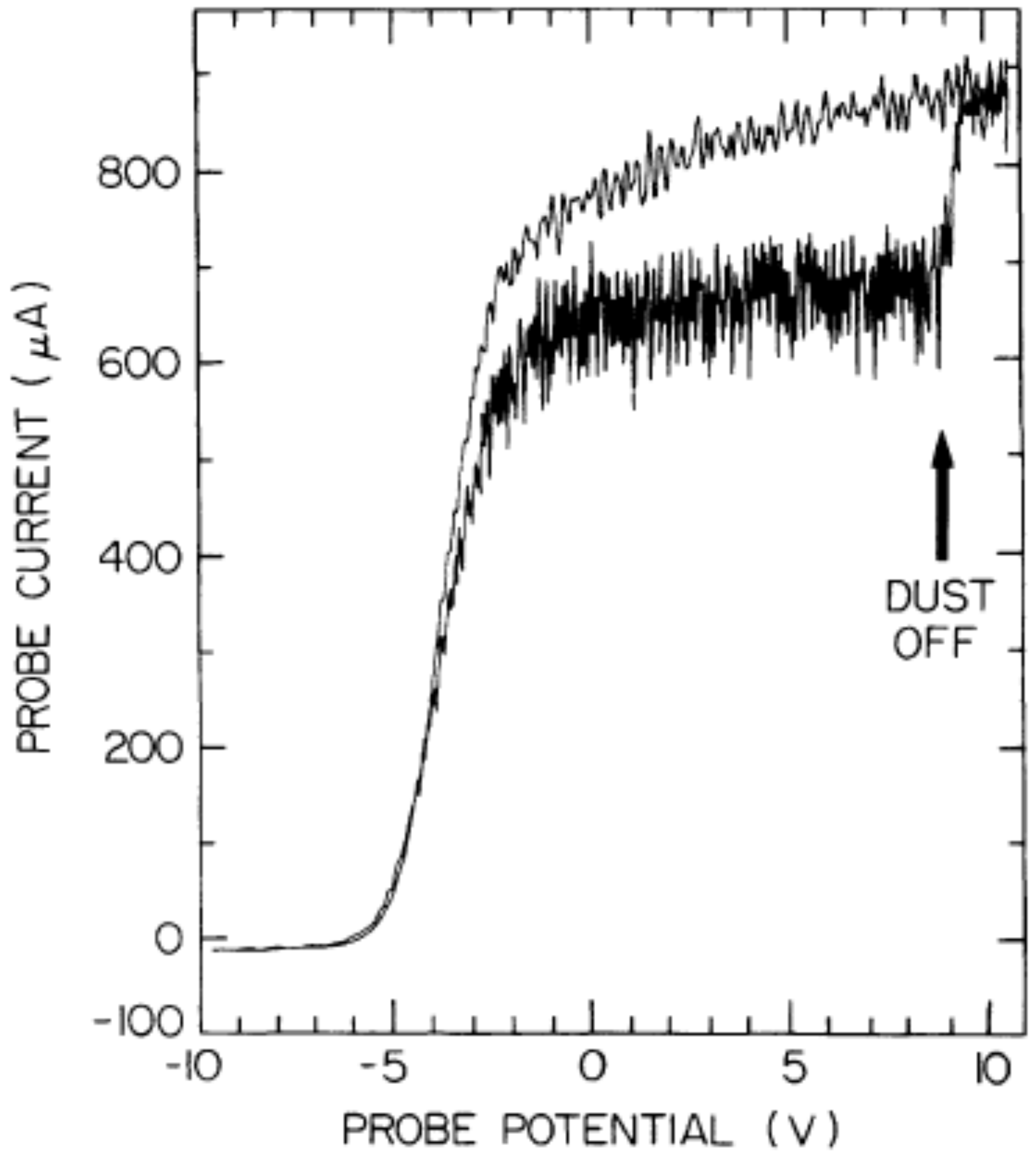

FIG. 3. Langmuir probe characteristics obtained under identical conditions, except for the absence (upper plot) or presence (lower plot) of kaolin dust. In the lower characteristic, the dust dispenser is abruptly turned off near the end of the trace to check that the electron current returns to the no-dust value.

A. Barkan, et. al., Phys. Rev. Lett., **73**, 3093 (1994)

Basic properties of dusty plasmas

- Fundamental parameters
- Charging
- Forces

Summary of the dominant forces in dusty plasmas

Force	**Origin**	**Size dependence**
Weight	Gravity	a^3
Neutral drag	Streaming neutrals	a^2
Ion drag	Streaming ions	a^2
Thermophoretic	Temperature gradient	a^2
Electric	Electric field	a^1
Magnetic	Magnetic field	a^1

These forces give rise to the majority of the phenomena observed in laboratory and microgravity dusty plasma experiments

a = dust grain radius

Adapted from textbook *Plasma Physics* by A. Piel, Table 10.2 (Springer-Verlag, 2010)

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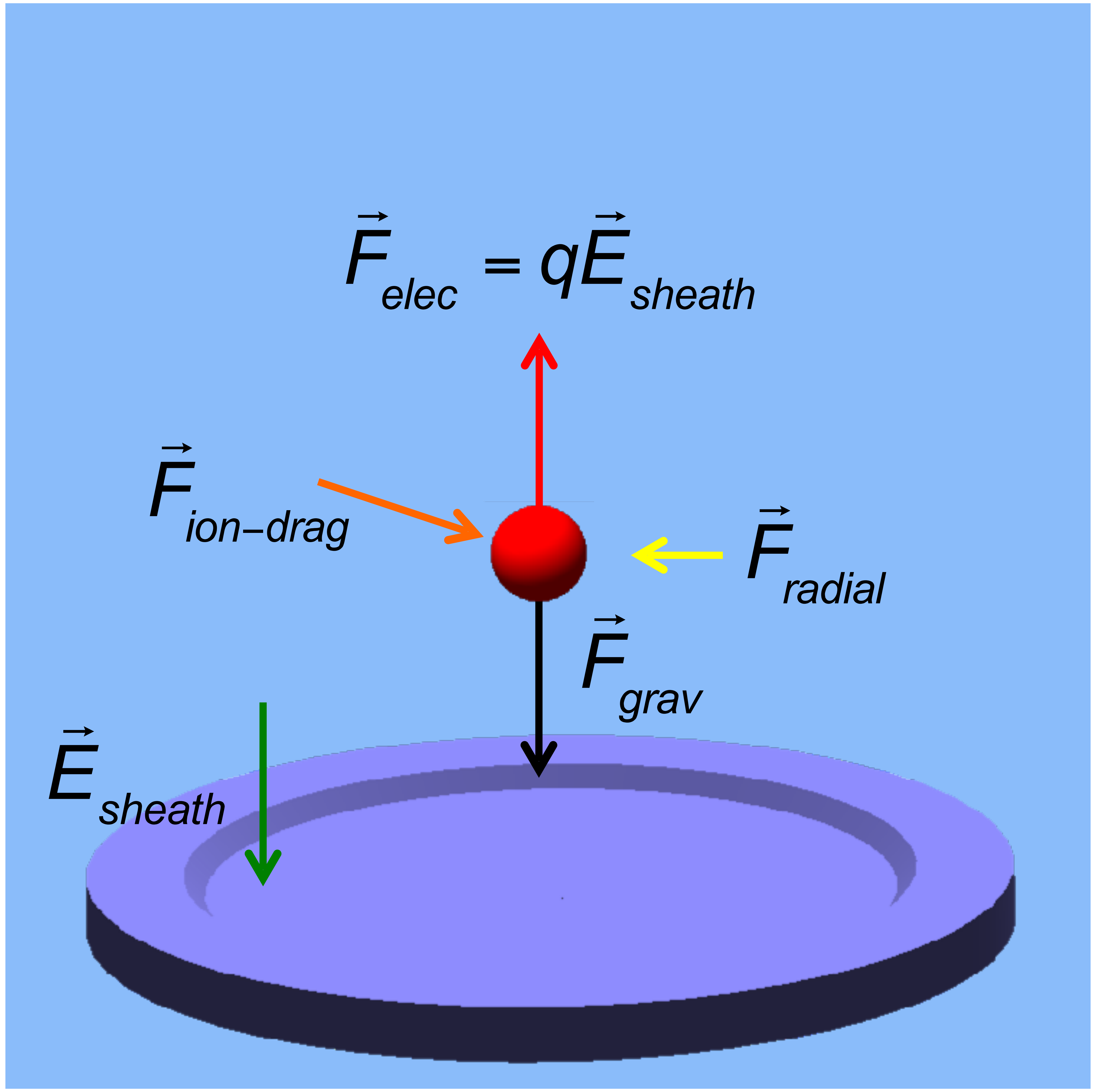
Summary of the dominant forces in dusty plasmas

- In ground-based experiments, the charged microparticles in the dusty plasma must be suspended against gravity.
- This occurs in the plasma sheath where there can exist a significant electric field.
- There is also a radial electrical field that provides horizontal confinement of the particles.
- Ions flowing along the electric fields can give rise to a "ion drag" or "ion wind" force on the particles.



Gravitational force

- Relevant for dusty / complex plasmas since the particles need to be suspended in the plasma.

- $\vec{F}_{\mathrm{g}} = m_{\mathrm{d}}\vec{g} = \frac{4}{3}\pi a^3 \rho_{\mathrm{d}}\vec{g}$

- Gravitational force can also play an important role in astrophysical environments (e.g., Saturn's rings).

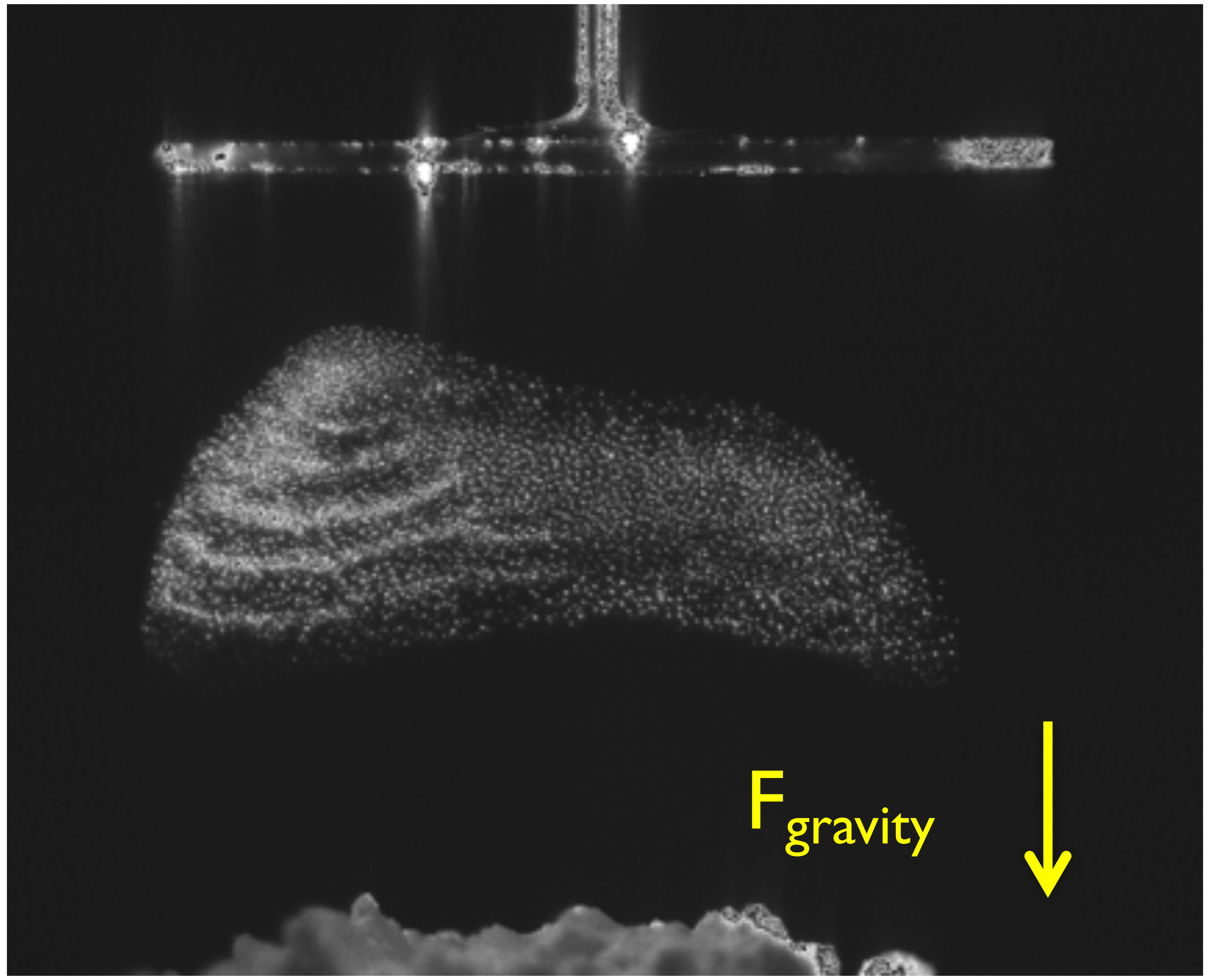


Image from Auburn University

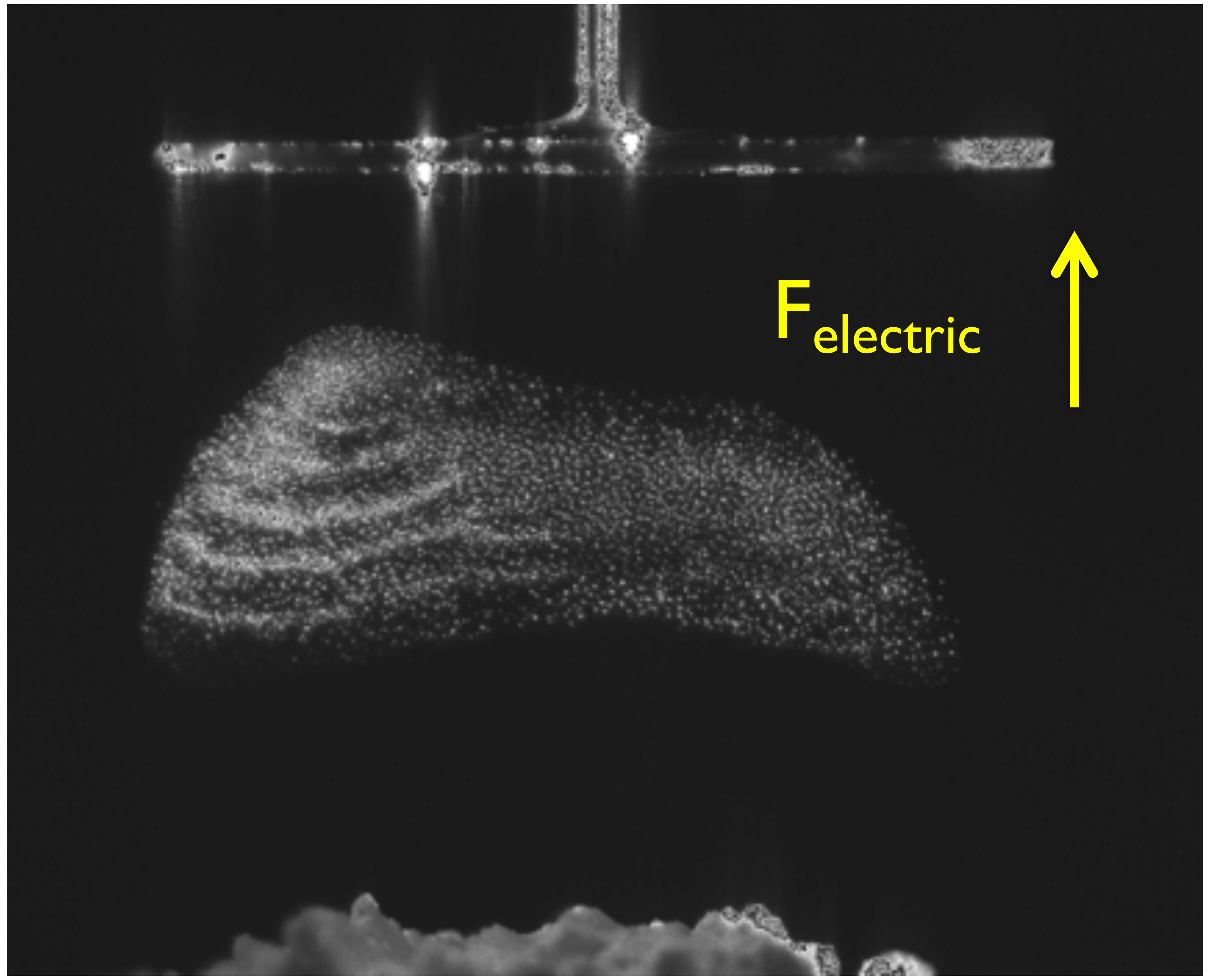
Electric force

- Because the dust grains are charged, they respond to the internal electric fields within the plasma.

- $\vec{F}_{\mathrm{E}} = Q_{\mathrm{d}}\vec{E} = 4\pi\epsilon_0 a\phi_{\mathrm{fl}}\vec{E}$

- Ion flows can cause the shielding cloud around dust grains to become distorted, leading to a dipole-like charge distributions.

- $\vec{F}_{\mathrm{dip}} = \vec{\nabla}(\vec{p}\cdot\vec{E})$



Ion flows can lead to a downstream positive wake below a dust grain

Image from Auburn University

Balancing gravitational and electric forces: the zero-order equilibrium in laboratory dusty plasmas

- For most ground-based experiments: $F_{gravity} \sim F_{electric}$
- Defines zero-order equilibrium
- Typical values:
  - ➡ $a = 1.5\ \mu m$
  - ➡ $m_d = 2.8 \times 10^{-14}$ kg
  - ➡ $Z_d = 4600$ electrons
  - ➡ **$E = 3.8$ V/cm**

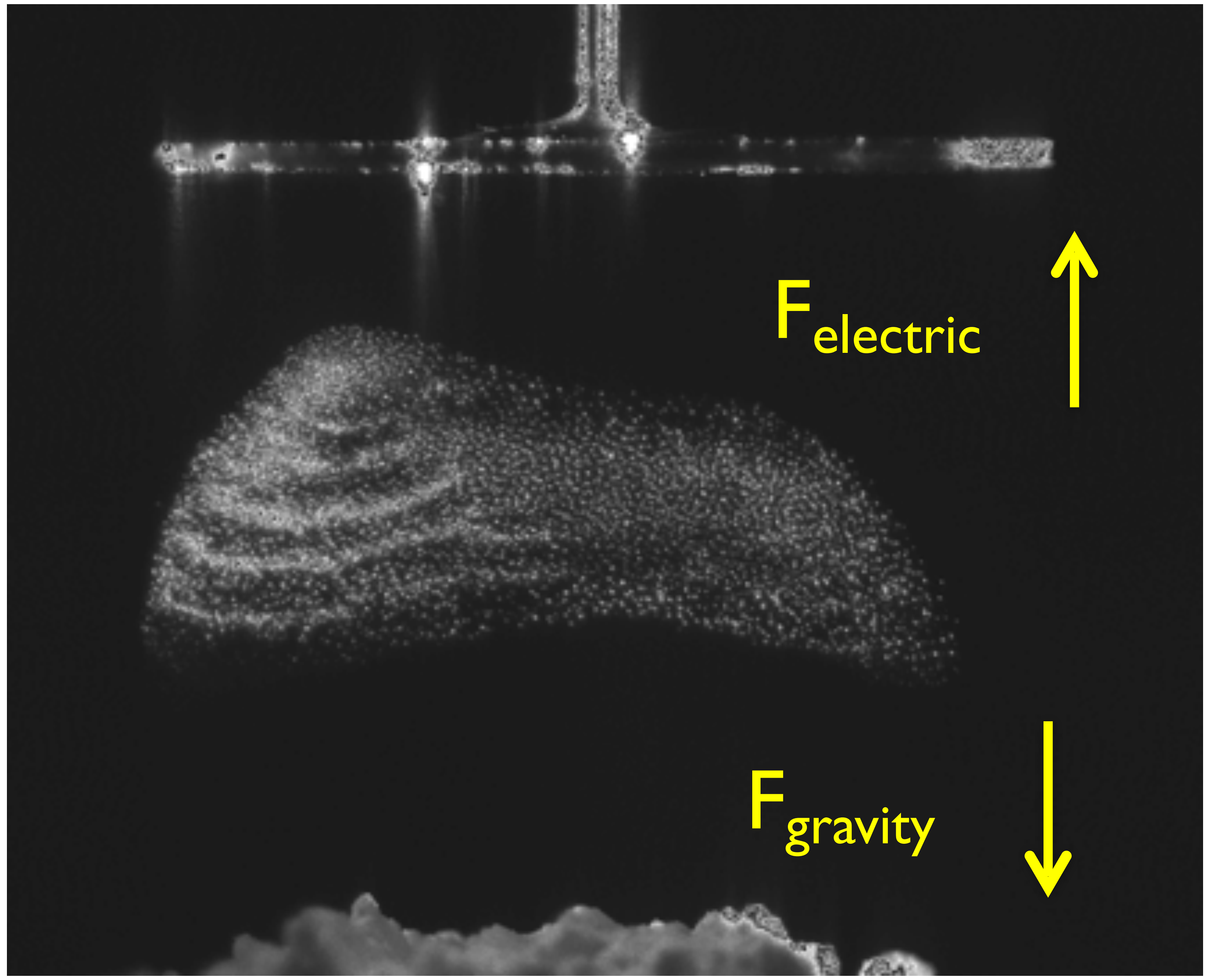
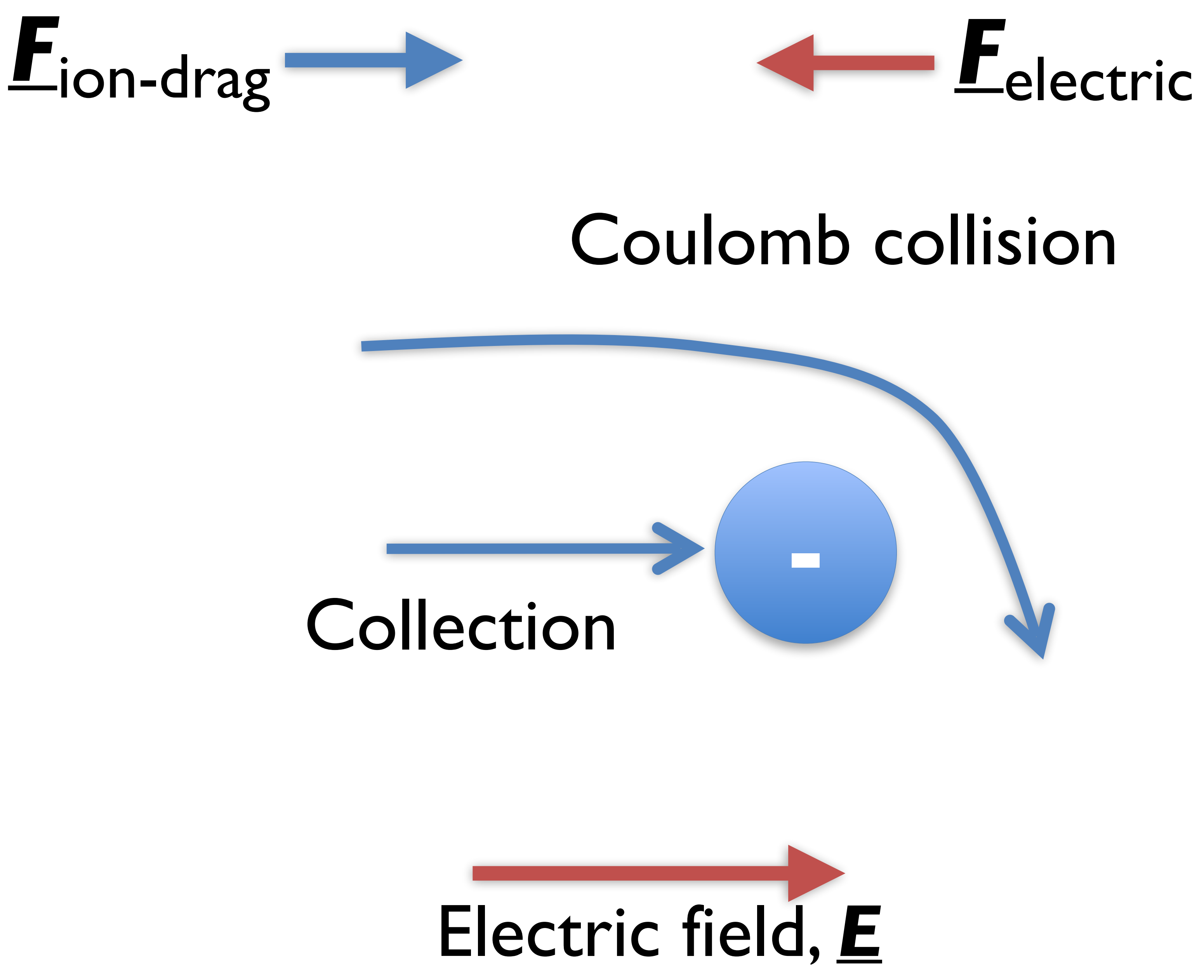


Image from Auburn University

Ion drag force - origins

- Positive ions can flow in a plasma in the direction of the electric field.
- Arises from the momentum transfer from ion-dust interactions: the collection of ions and Coulomb collisions.
- $F_{\text{ion-drag}} = F_{\text{collection}} + F_{\text{collision}}$
- Critically depends upon the screening length of the dust particle.



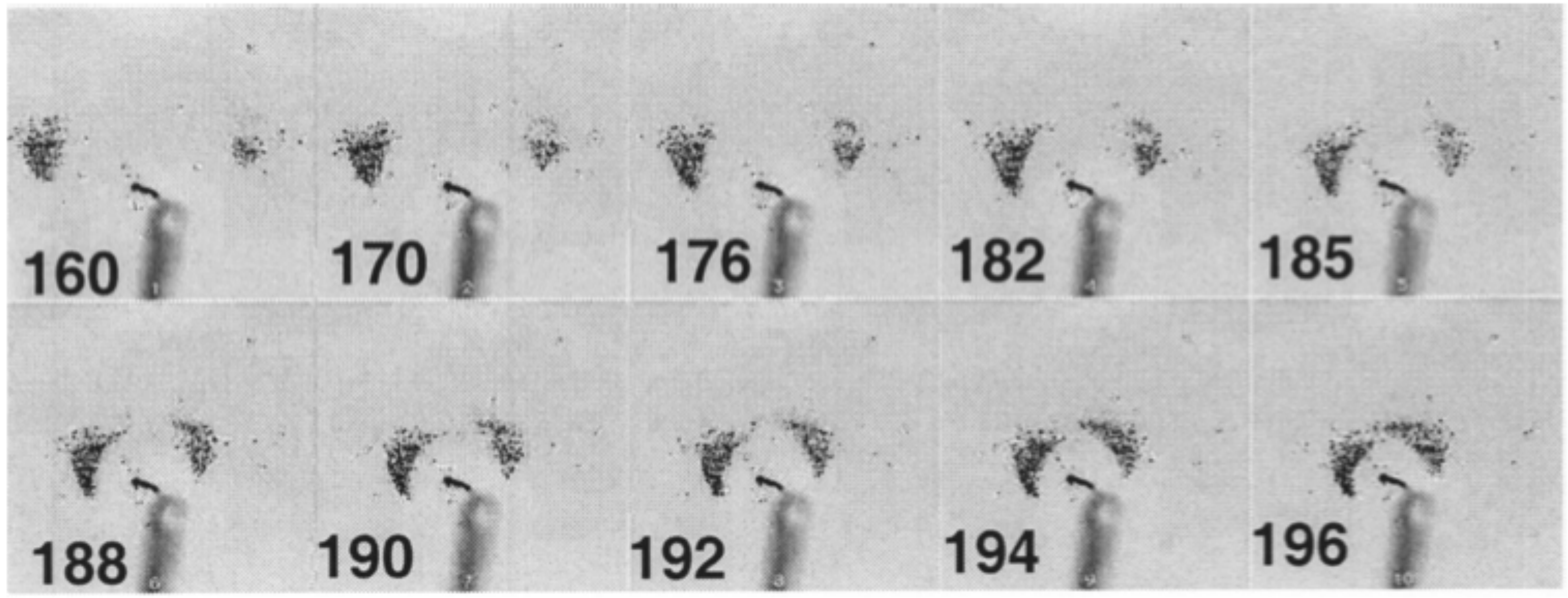
Refs: M. Barnes, et al., PRL, **68**, 313 (1992)
S. Khrapak, et al., PRE, **66**, 046414 (2002)
A. Ivlev, et al., PRE, **71**, 016405 (2004)
I. Hutchinson, et al., PPCF, **48** 185 (2006)
S. Khrapak, et al., IEEE TPS, **37**, 487 (2009)

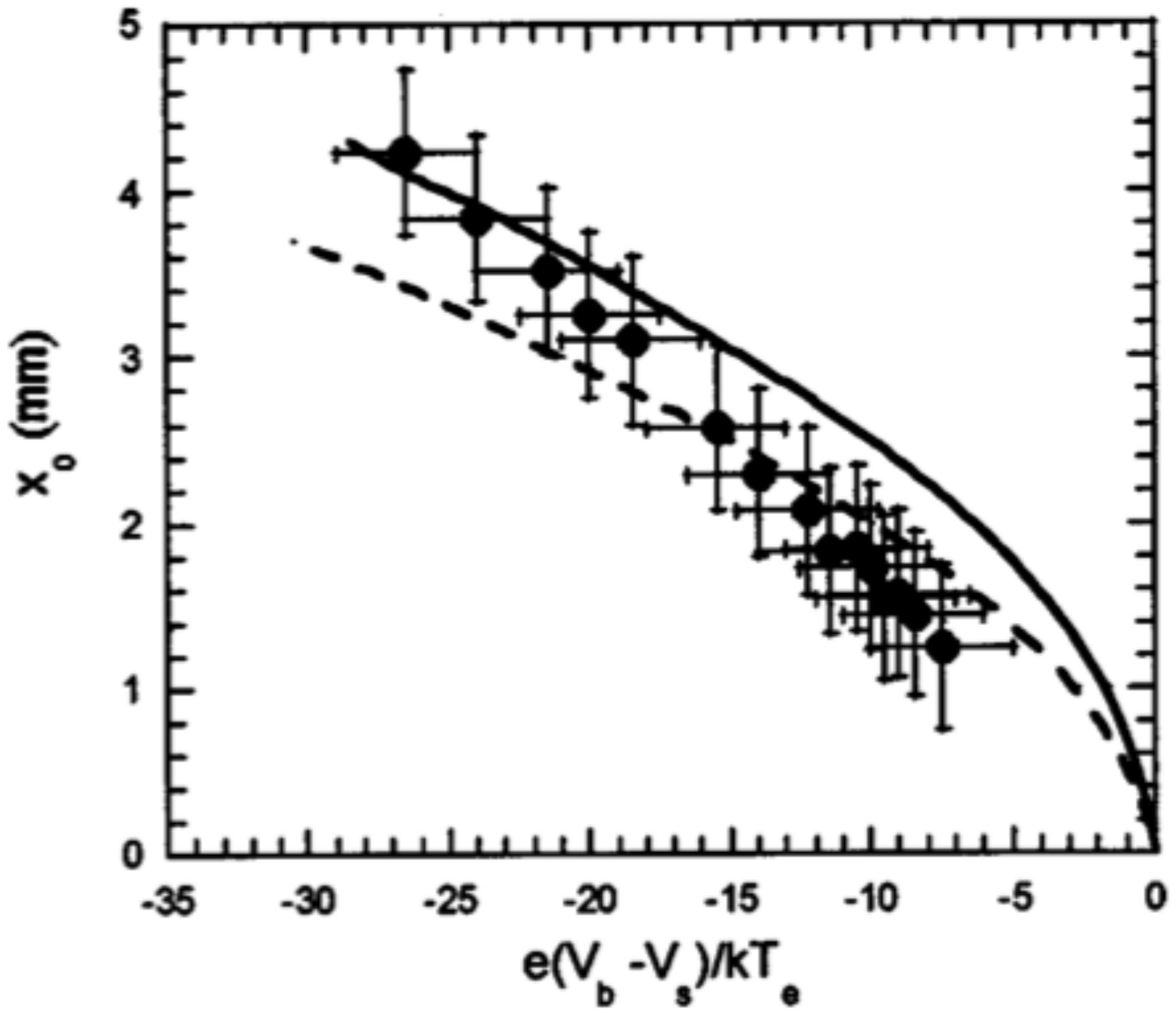
Evidence for ion drag force: voids in the lab

- Control size of the void region using different potentials on a probe tip.

- Estimate the void size, x_0, using different electric field estimates.

  Dashed: 25 V/cm
  Solid: 17 V/cm





E. Thomas, Jr., et al., PoP, 11, 1770 (2004)

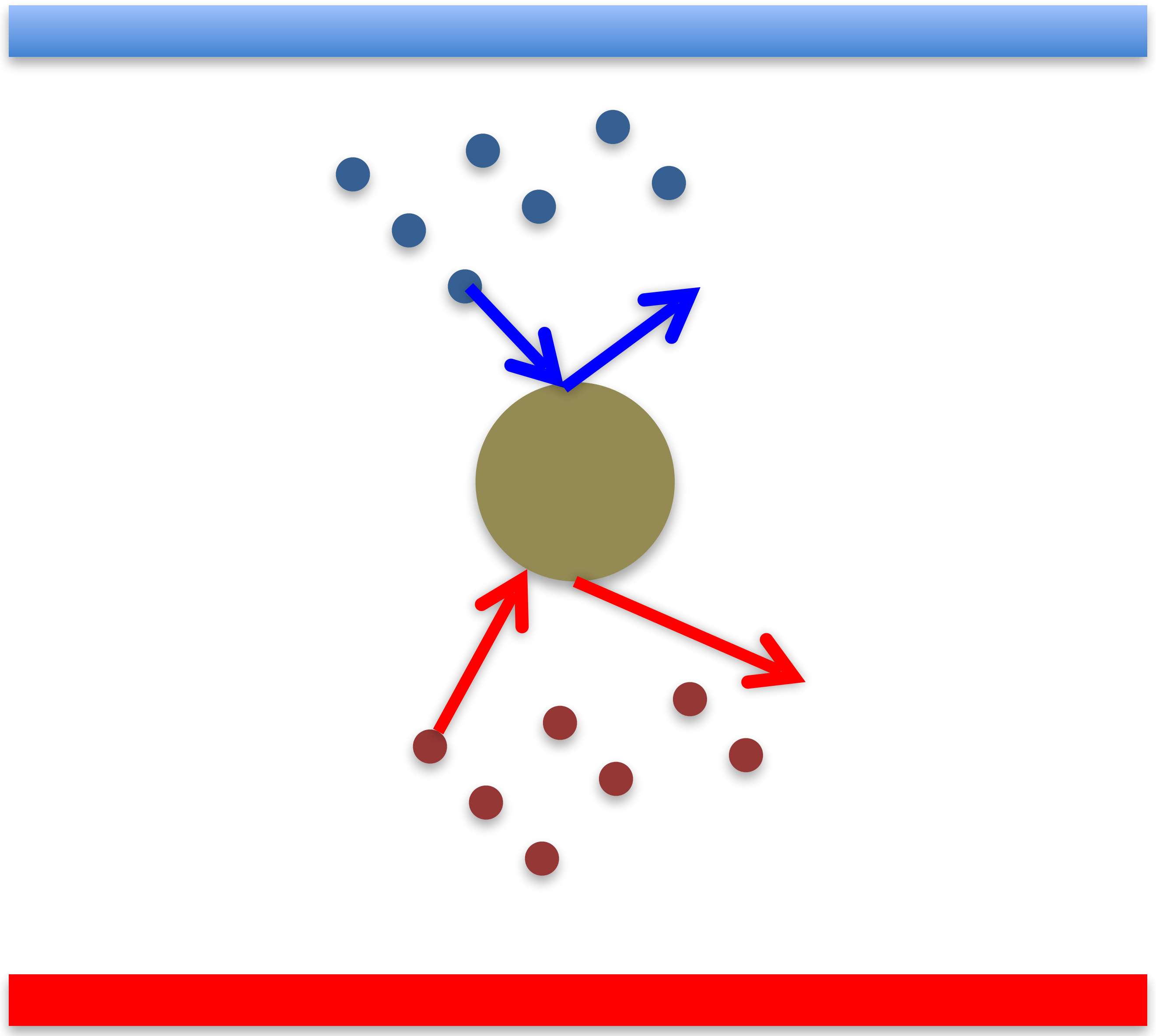
Thermophoretic force

- Arises from the momentum transfer from neutral-dust interactions.

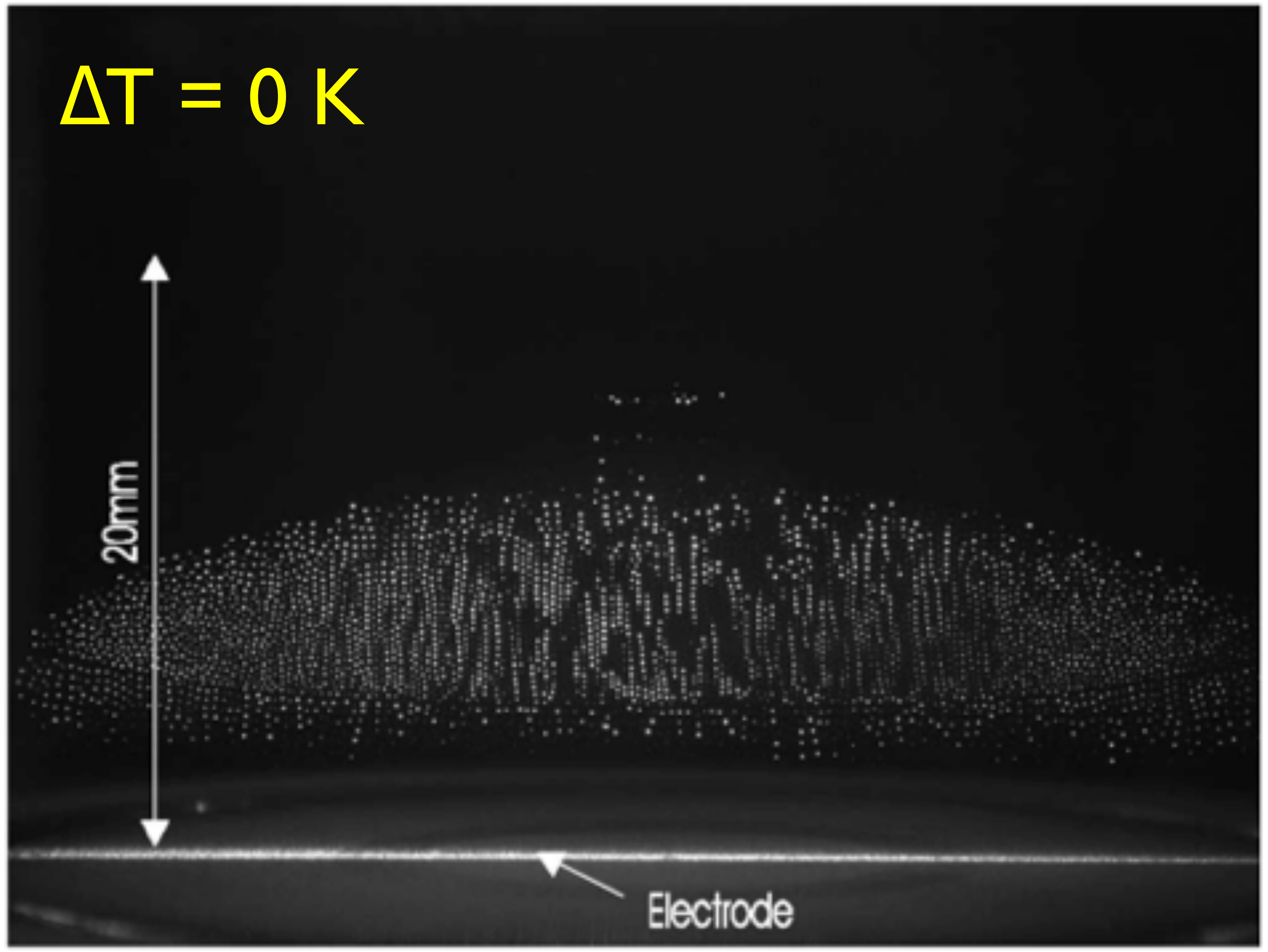
- Neutral atoms from "hot" side provide more momentum than those from "cold" side.

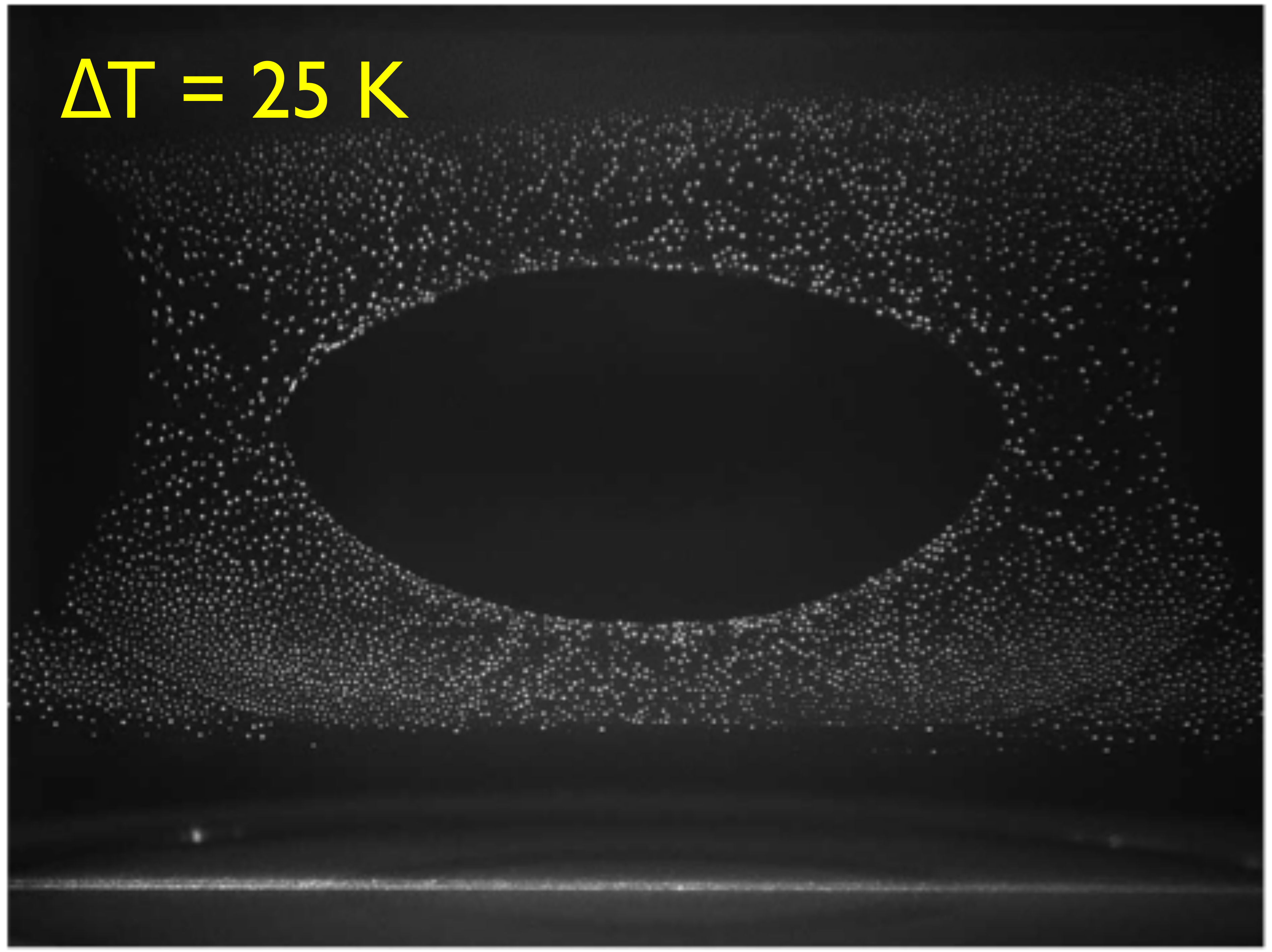
- $$F_{thermo} = -\frac{8}{3}\frac{a^2}{v_{tn}}\Lambda\frac{dT_n}{dz}$$

v_{tn} – neutral thermal velocity
T_n – neutral gas temperature
Λ – thermal conductivity



Evidence for thermophoretic force: simulated voids

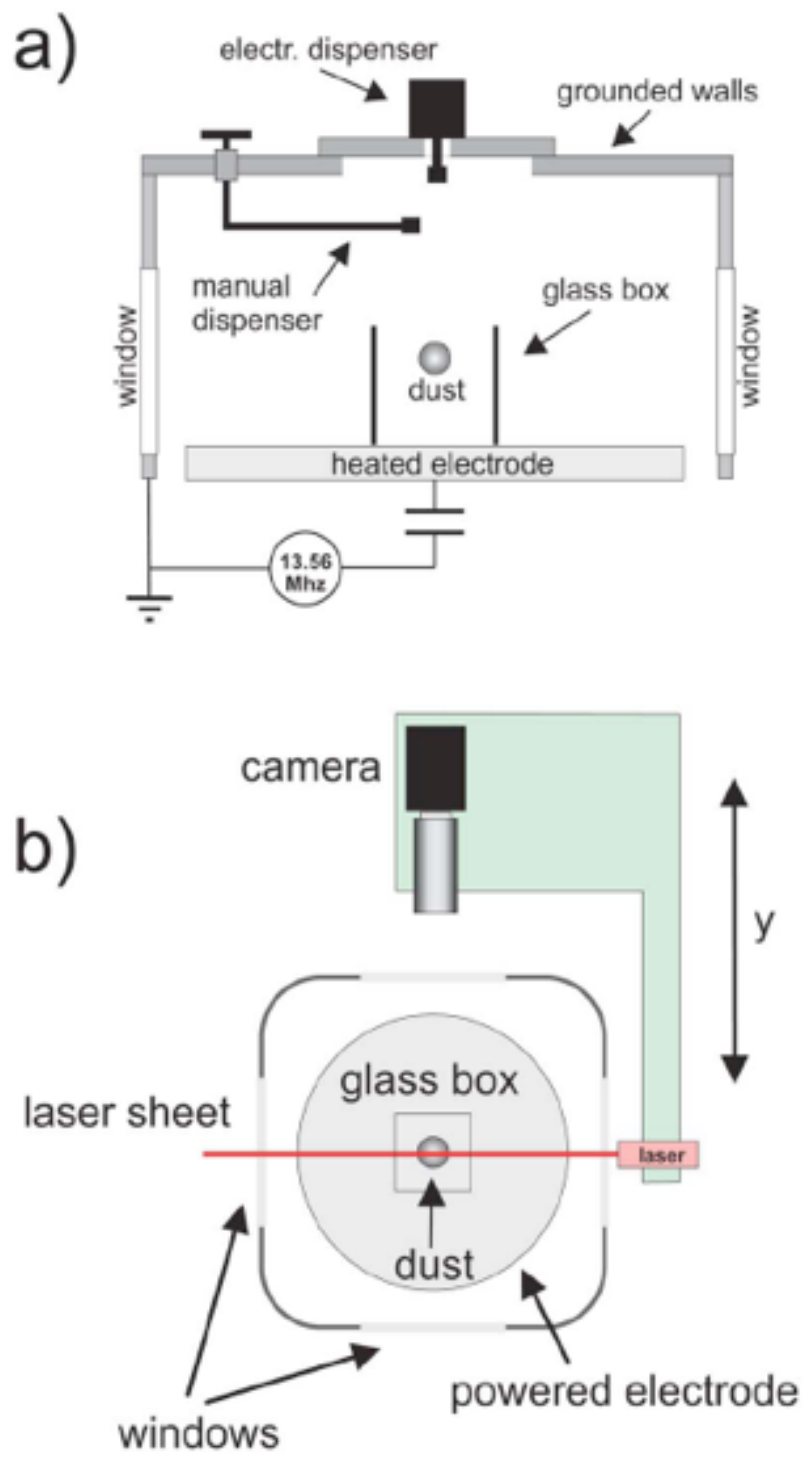


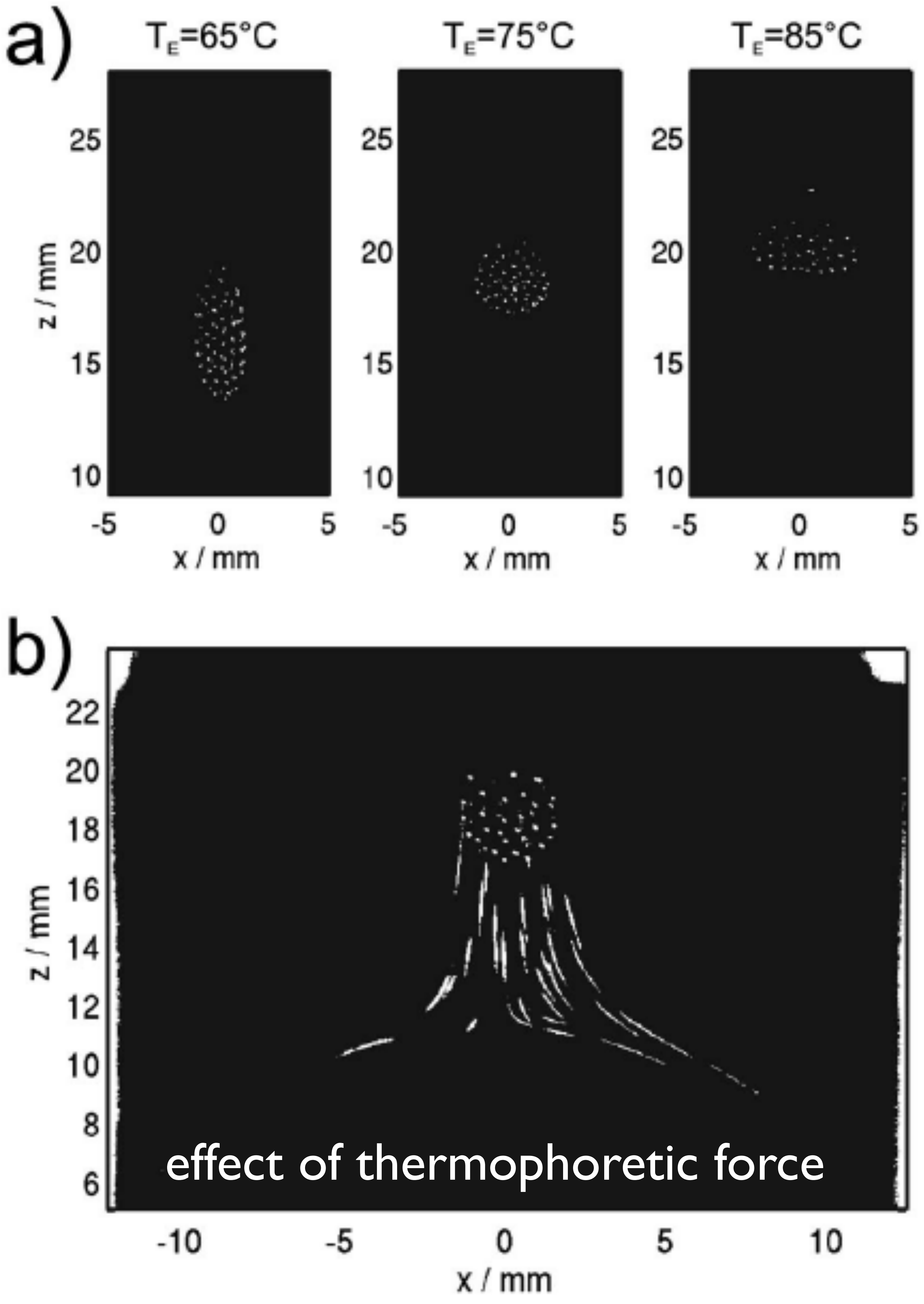


- Dusty plasma of 3.4 μm melamine formaldehyde particles
- Applied temperature gradient of ~1200 K/m
- ΔT = 25 K over 20 mm
- Lower electrode is heated using a Peltier element

H. Rothermel, et al., PRL, **89**, 175001 (2002)

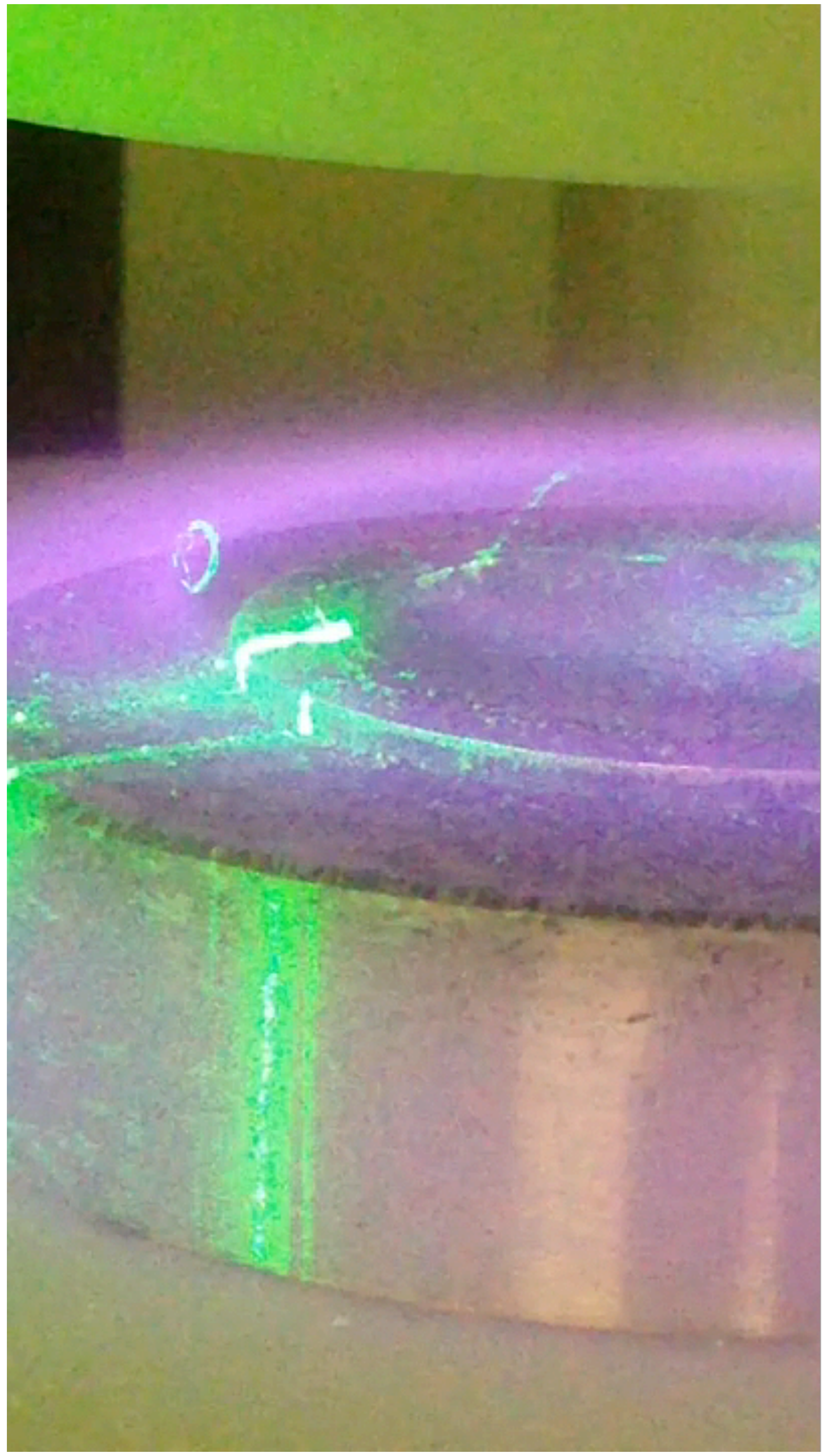
Evidence for thermophoretic force:

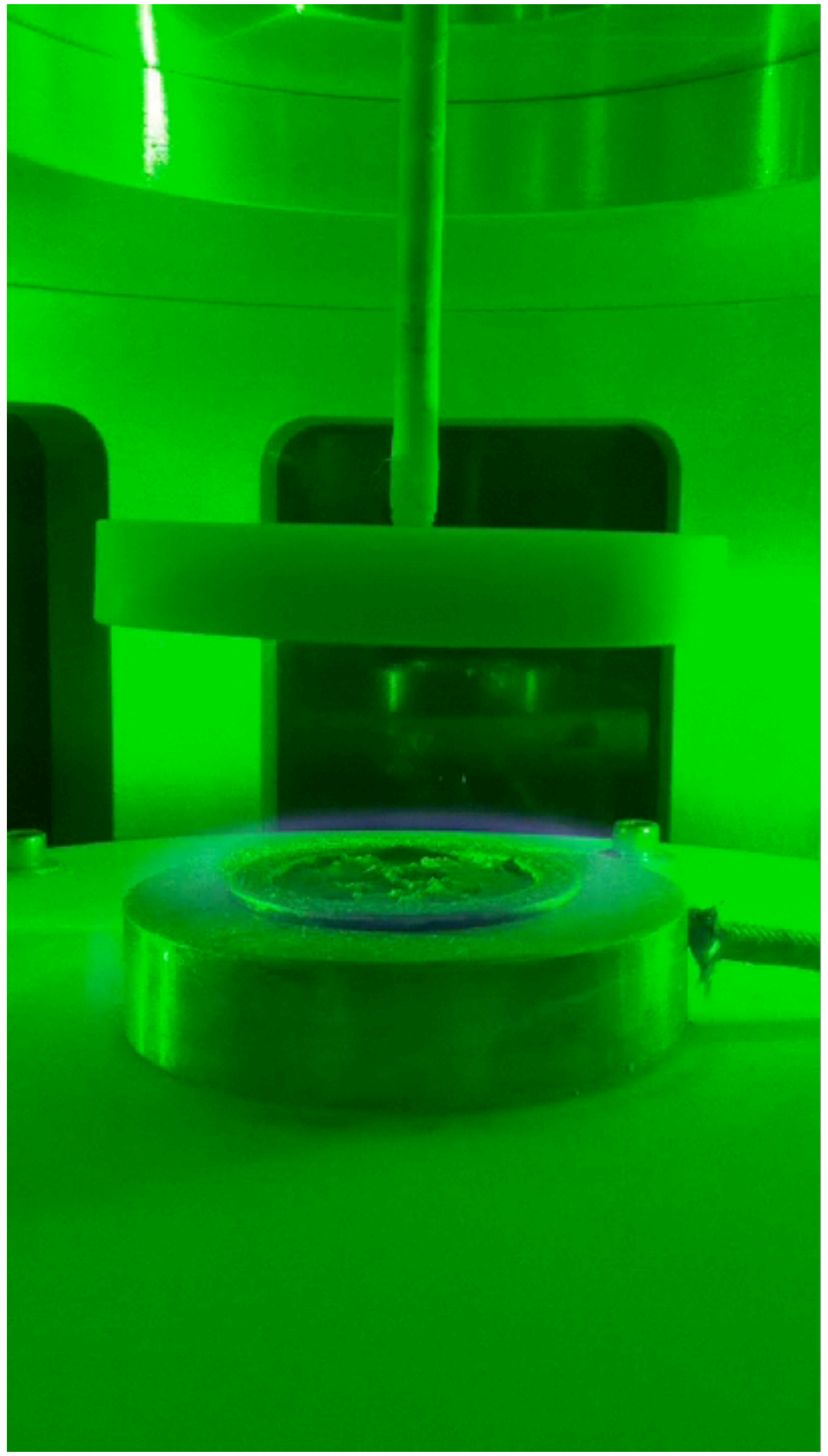


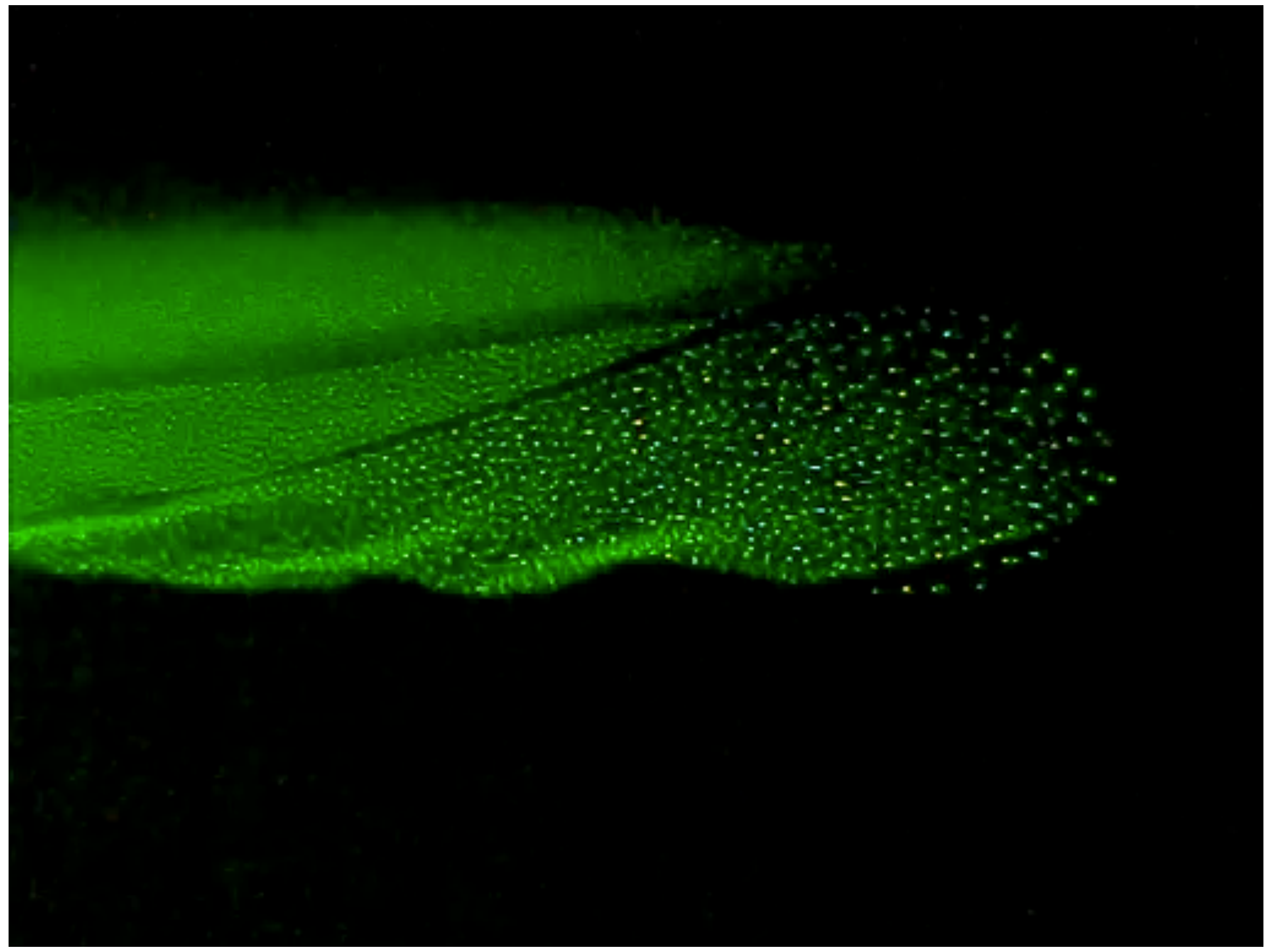


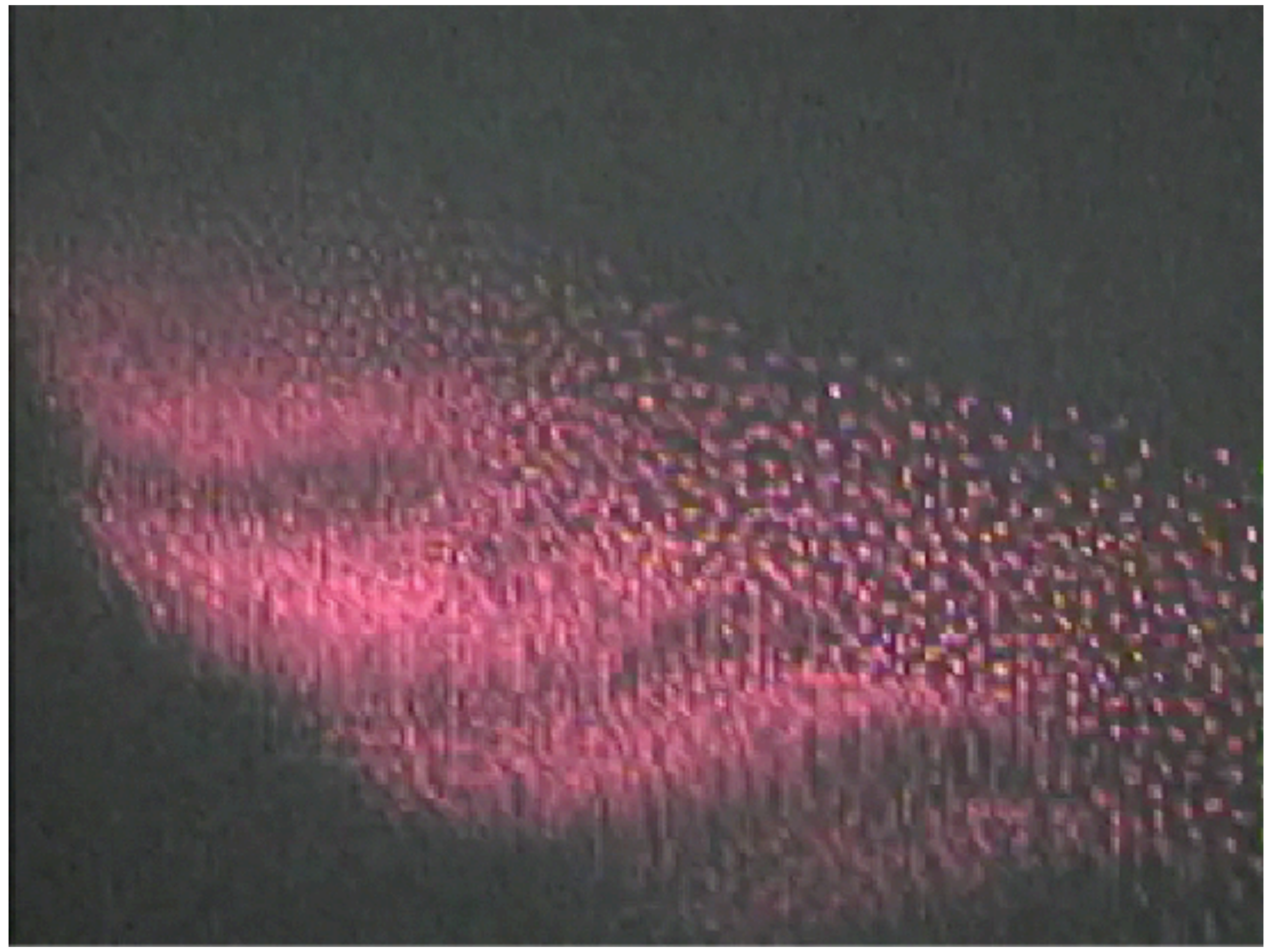
O. Arp, et al, Phys. Plasmas, **12**, 122102 (2005)

Combinations of these forces give rise to the complex behavior in dusty plasmas









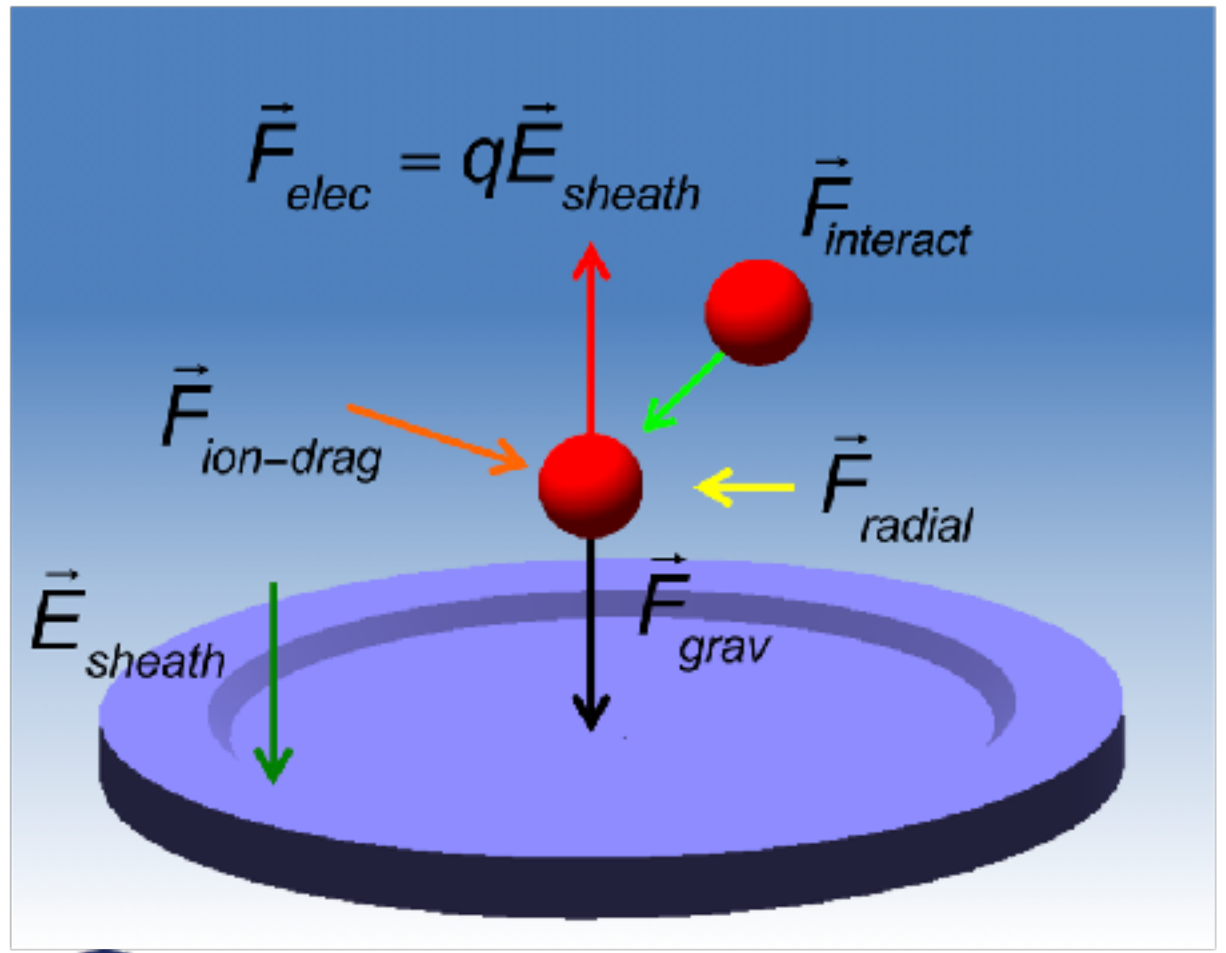
OUTLOOK FOR
DUSTY PLASMA RESEACH

How do the thermal, charging, and transport properties of a dusty/complex plasma evolve beyond "laboratory" conditions?

Laboratory dusty plasma

electrostatic balance
m**g** = q***E***

Ion-dust interactions



Magnetic field effects
(q/m → small)

Microgravity and polarity switching
(g → 0)

Modified ion transport

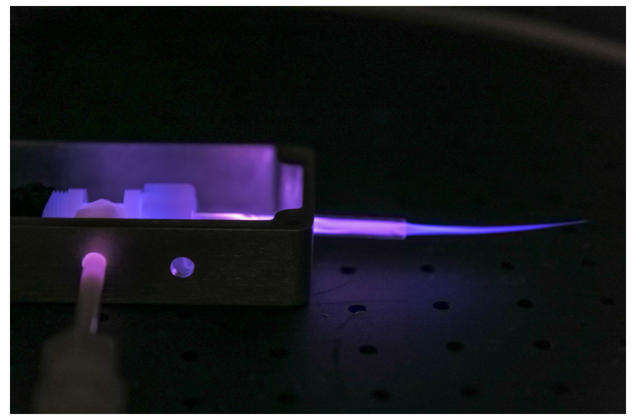
$m_d >> m_i, m_e$

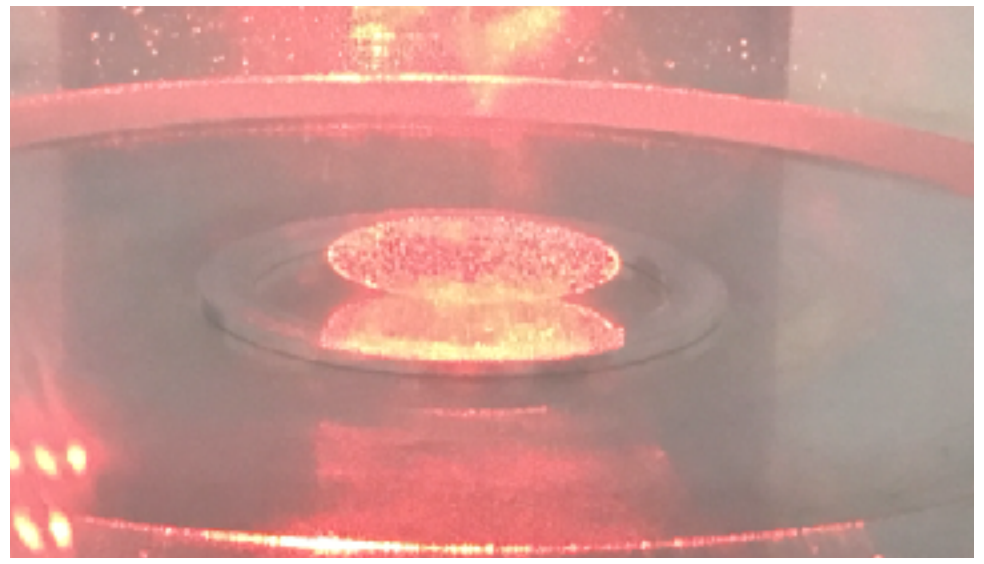
$$\frac{q_d}{m_d} << \frac{e}{m_i} << \frac{e}{m_e}$$

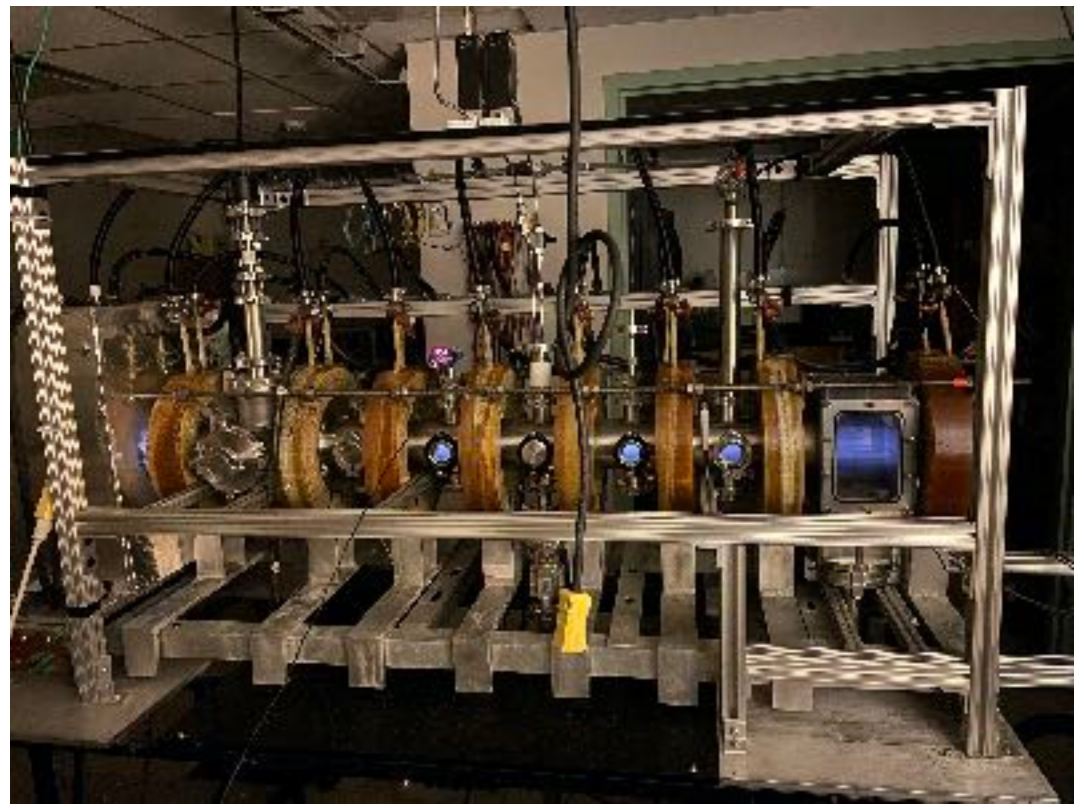
Large mass
Small charge-to-mass ratio
Coulomb coupling, Γ

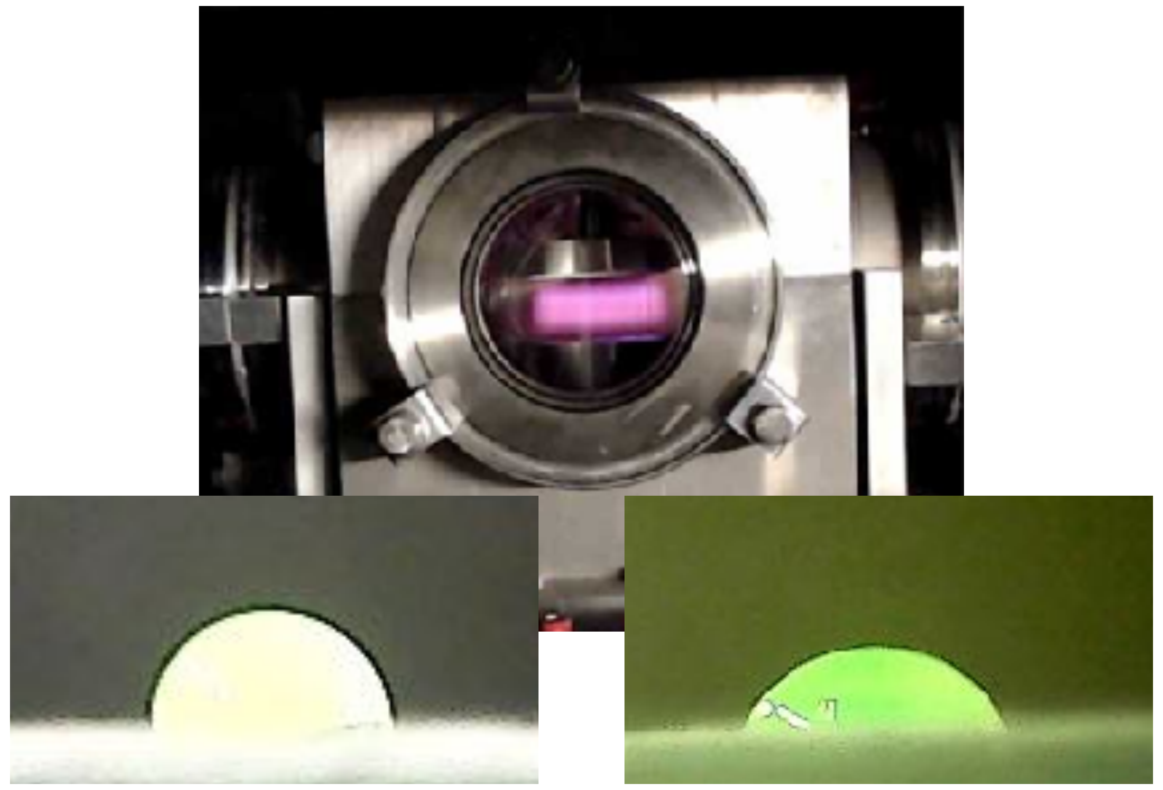
Magnetized Plasma Research Laboratory (MPRL)

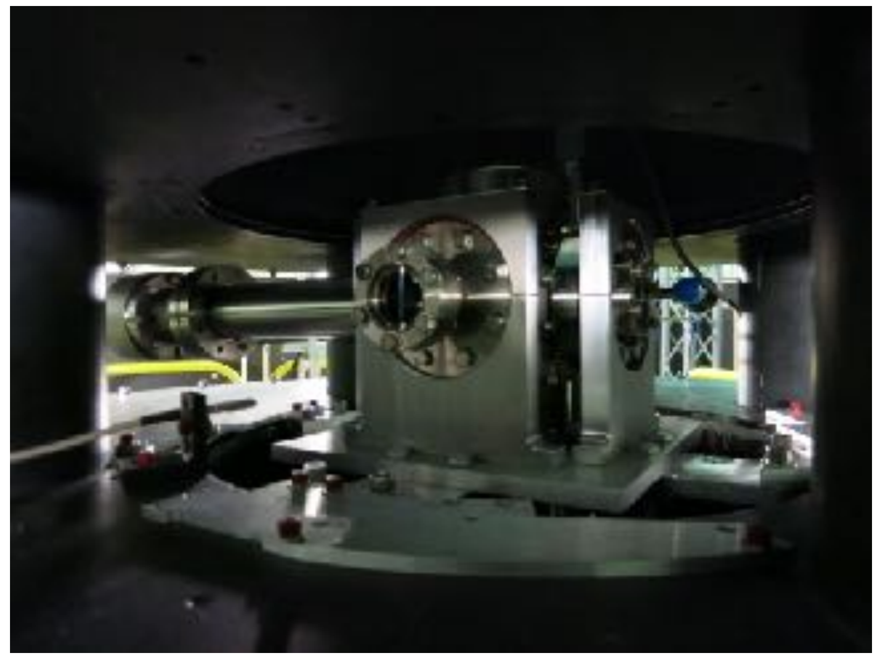
A Department of Energy Shared User Facility - Major equipment funded by the NSF, DOE, and NASA











External Users/Collaborations

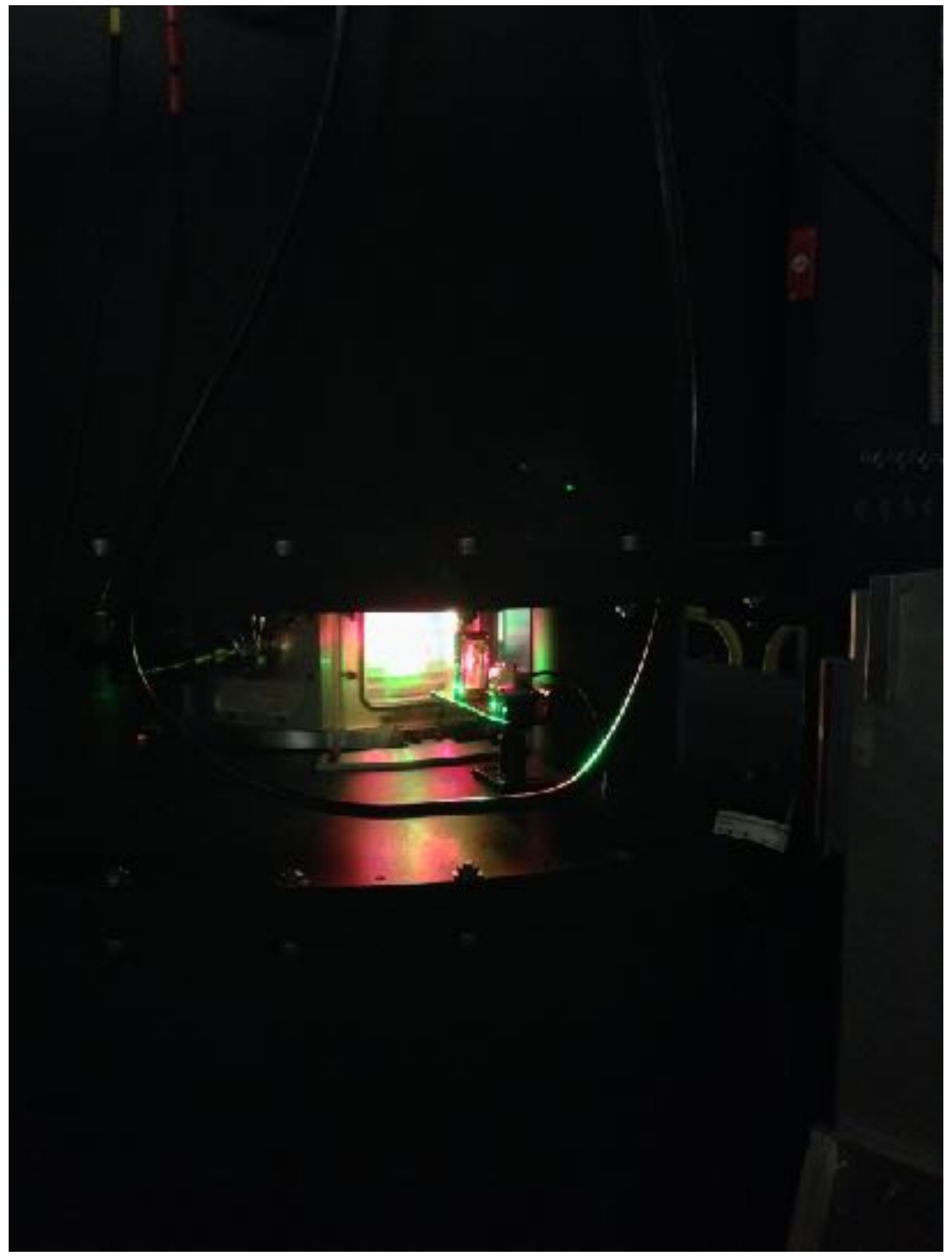
Univ. Greifwald*
IPR, India*
German Aerospace Center (DLR)+

Baylor Univ.
Emory Univ.*
Mississippi State Univ.*
Univ. Alabama - Birmingham (UAB)+
Univ. Alabama - Huntsville* +
UCSD
Univ. Iowa
Univ. Maryland - Baltimore (UMBC)*
Univ. Wisconsin*
West Virginia Univ.*
Wittenberg Univ.*

* DOE +NSF-EPSCoR

MDPX: A cryogen-free, superconducting, multi-configuration magnetic field system

- Radial and axial diagnostic access
- RF generated plasmas:
  f = 13.56 MHz, P_{RF} = 1 to 10 W
- Argon:
  P = 5 to 300 mTorr (0.6 to 40 Pa)
- Silica microspheres
  <dia> = 0.1 μm to 8 μm
- Diagnostics:
  Langmuir probes
  Triple probe (n_e, T_e, V_p)
  DPSS lasers
  High-speed video cameras (300 fps)
- Plasma parameters (@ B = 0 T):
  T_e = 1- 5 eV, T_i = 1/40 eV
  $n_e \sim n_i \sim$ 2 to 8 x 10^{15} m^{-3}



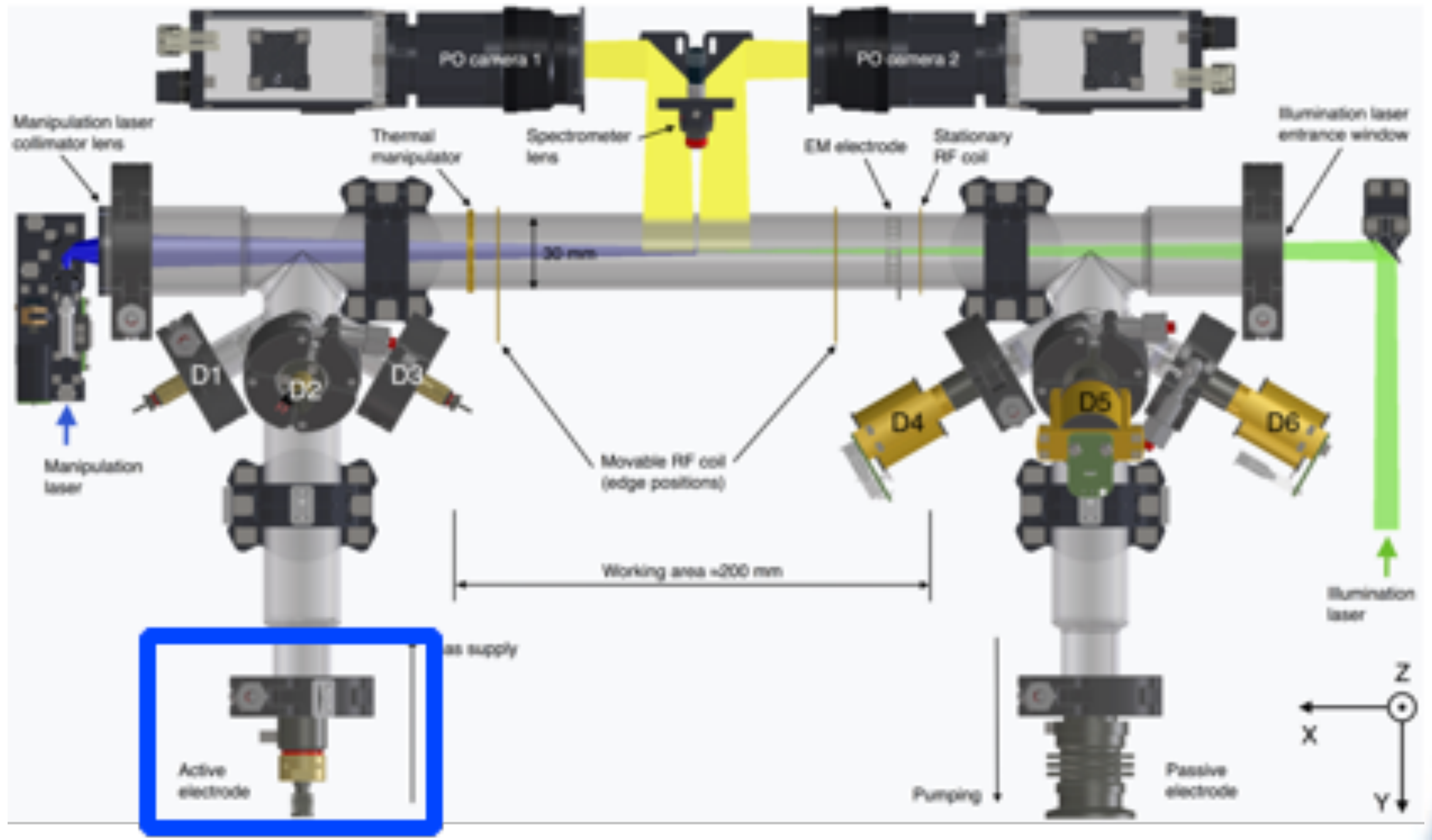
Magnetic field:	3.5 T (to date); 4 T (max)
Magnetic field gradient:	1 - 2 T /m
Magnet cryostat:	50 cm ID / 127 cm OD / 158 cm axial
Magnet material:	NbTi superconductor; cryogen-free

C. E. Miller, et al., *IEEE Trans. Appl. Supercond.*, **24**, 1 (2014)
E. Thomas, et al., *J. Plasma Phys.*, **81**, 345810206 (2015)

PK-4 is a multi-purpose, multi-user facility on the ISS

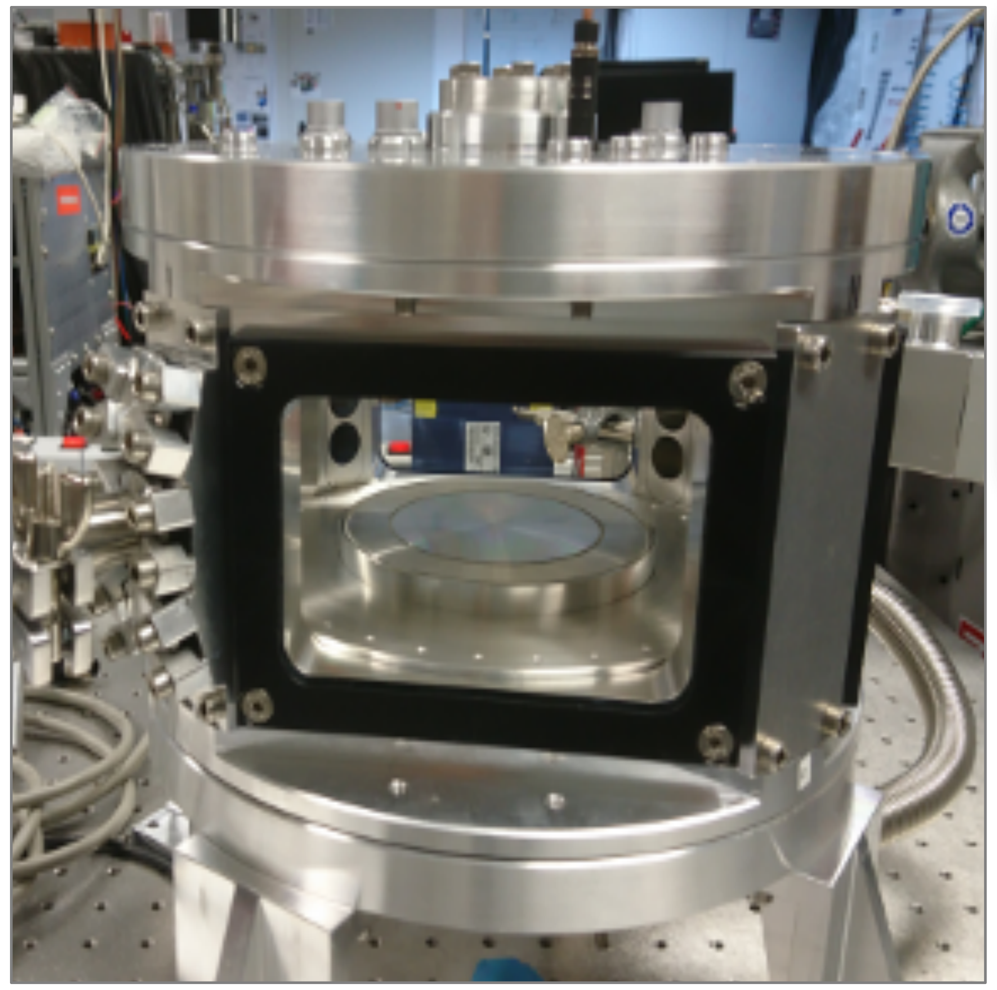
- Long list of interdisciplinary experiments in the Experiment Science Requirement Document → all can be performed with one setup
- New ideas will appear while performing experiments under μg

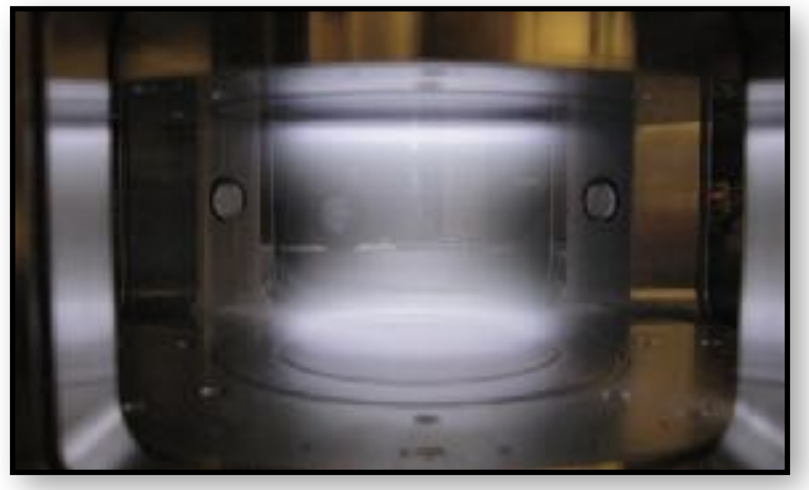
→ Science Team: 60 members from all over the world

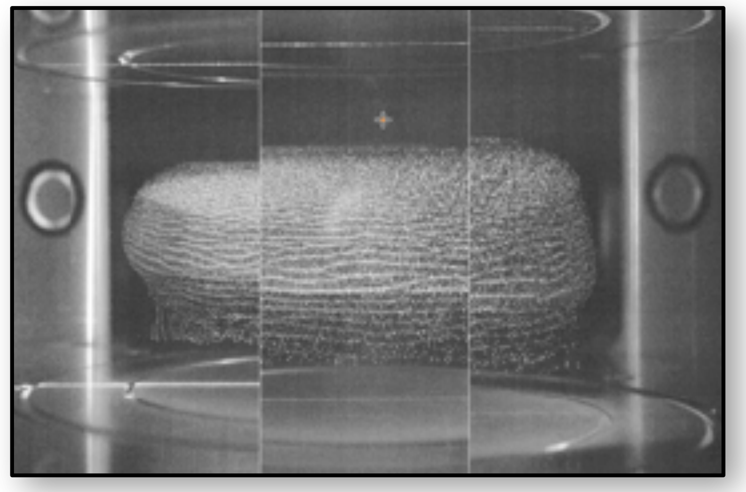


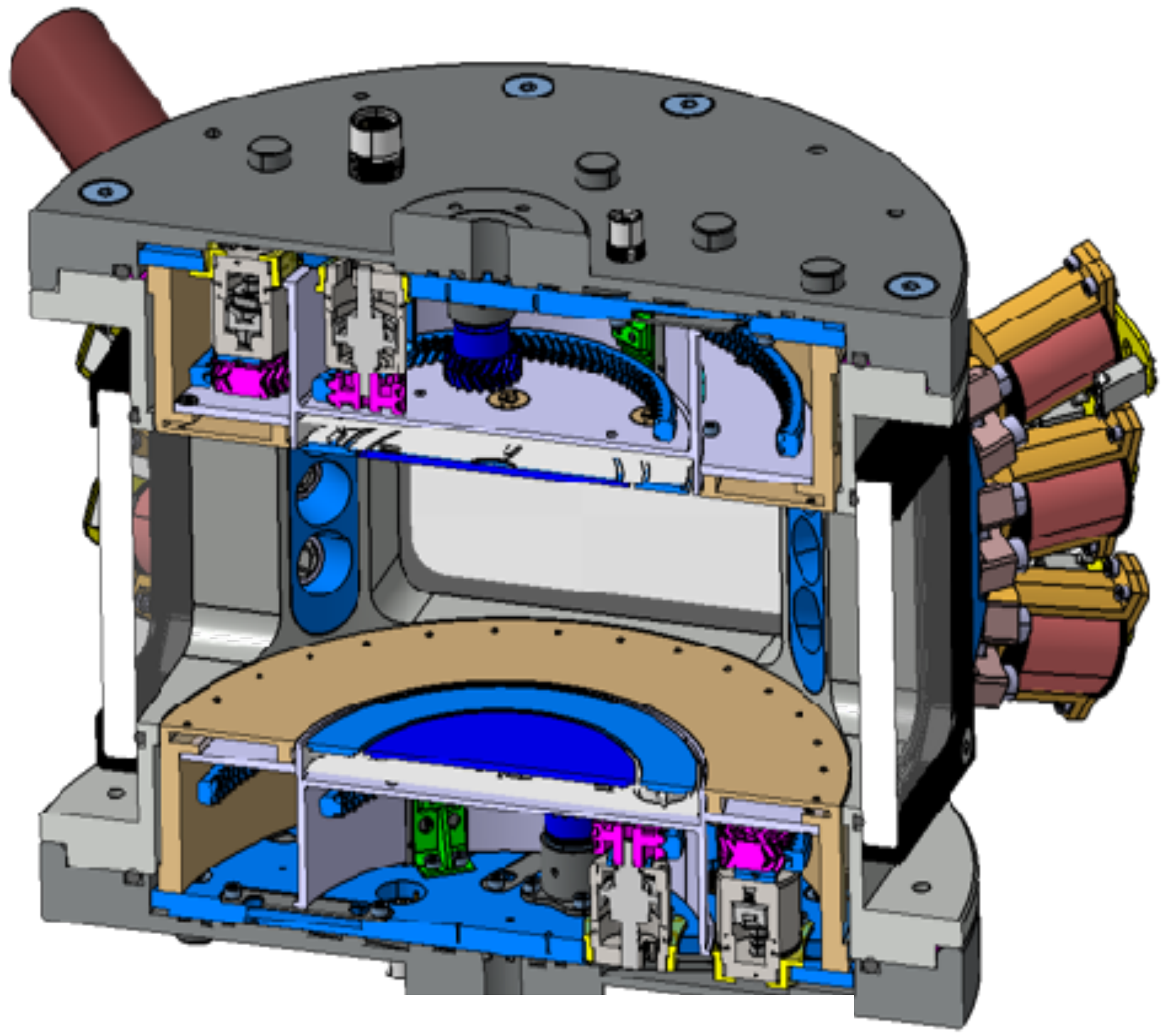
Auburn Univ.
Baylor Univ.
Wittenberg Univ.

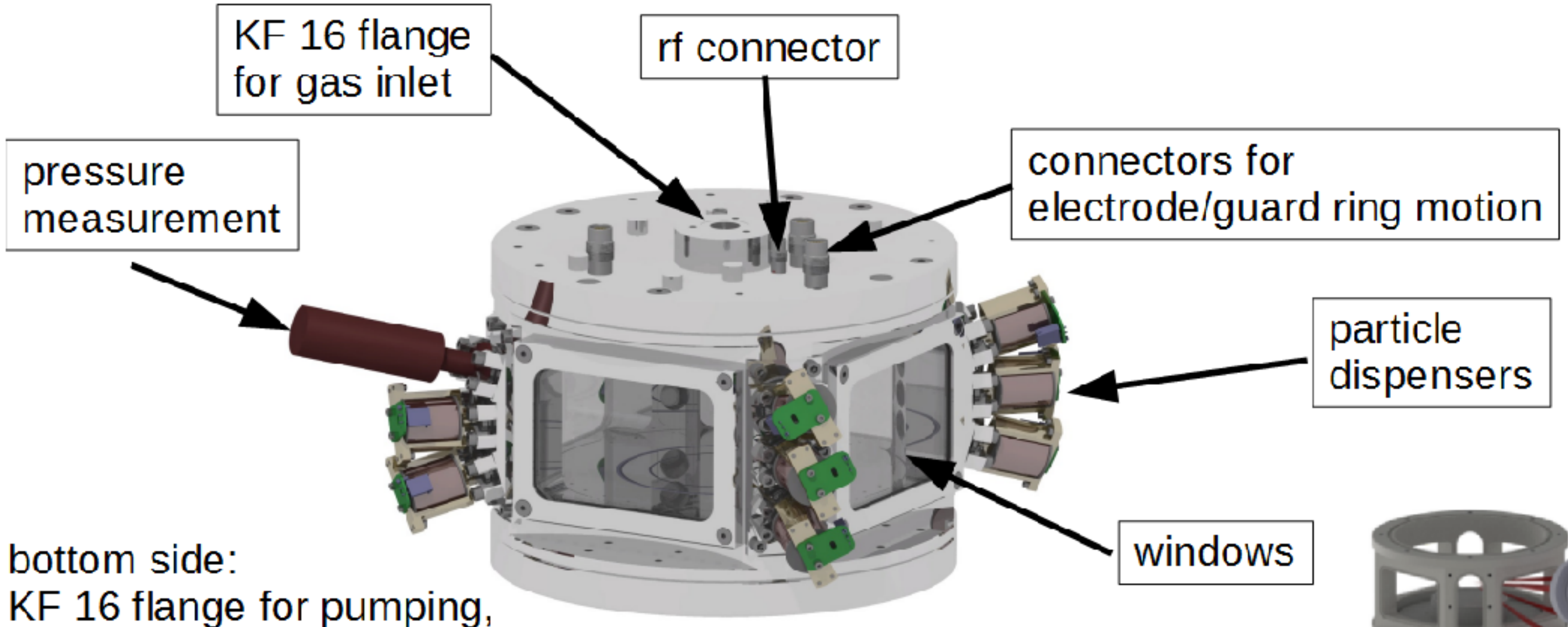
Beyond PK-4: COMPACT – A next generation space experiment to study multi particle systems on their "atomic" level



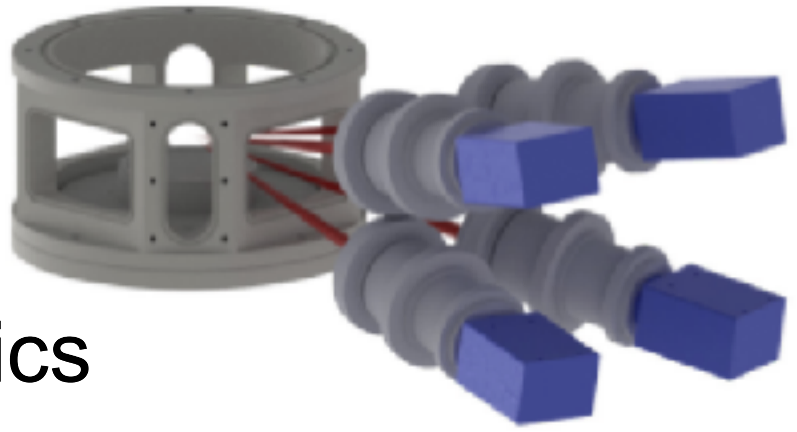




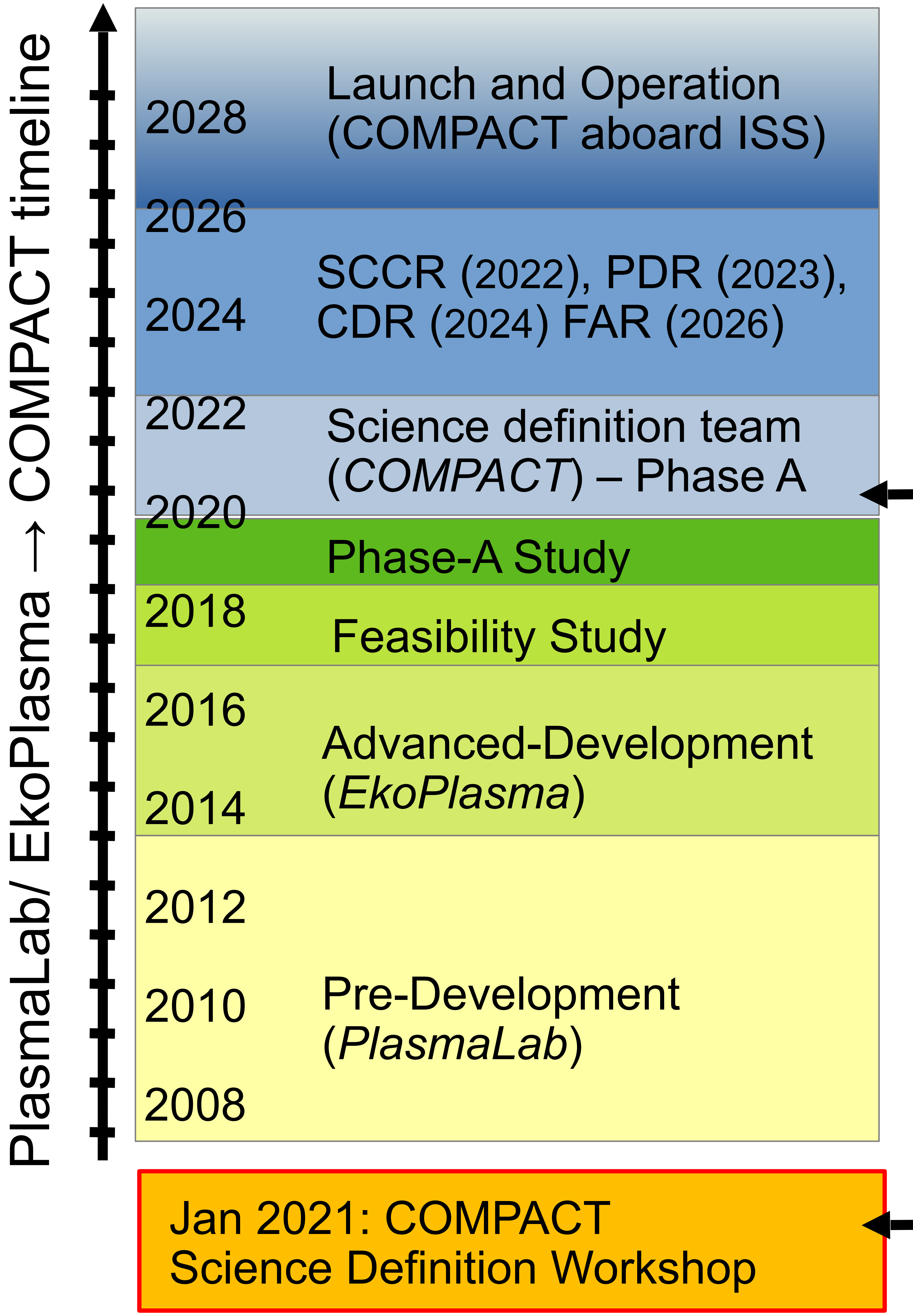




bottom side:
KF 16 flange for pumping,
electrical connections as on top side



3D diagnostics



Beyond PK-4: Preparing for Lunar and Martian exploration

- Electrostatic forces on surface dust may be significant on microgravity bodies, like the Moon, asteroids and planetary rings
- Dust-plasma interactions may also be exploited to remove hazardous dust from mechanical components and spacesuits
- Dust-plasma interactions on/near planetary surfaces is of interest to a variety of NASA stakeholders
- In January 2020, JPL stood up a science definition team to identify payloads for a multi-user facility on the Moon to study dust-plasma interactions
- Top three science objectives:
  1. Measure the plasma properties near the lunar surface.
  2. Determine whether or not electrostatic lofting occurs naturally.
  3. Determine whether or not electrostatic levitation occurs.

ARTEMIS

Dusty plasmas: an interdisciplinary field that links fundamental physics, space phenomena, and societal benefits

	Fundamental Physics	Space	Application
Charging	Plasma and UV fluxes to surfaces	Planetary rings	Spacecraft charging
Levitation and transport	Inter-particle forces	Lunar horizon glow	Mitigating dust contamination
Particle growth	Atomic processes in plasmas	Solar system formation	Microelectronics fabrication

Outlook for dusty plasma research: basic and astrophysical studies

- Upcoming space missions to Jupiter, comets, Moon, Mars will involve study of charged dust or charged ice in solar system environment - need a new generation of lab studies to support these missions.

- Dusty plasma can be "model systems" for soft condensed matter, fluid systems and statistical mechanics - need new insights and people to help make these connections.
- A unified model of dust grain charging in plasmas still remains elusive - can a model be developed that works for lab, fusion, and space plasmas?
- Several groups around the world are studying magnetic field effects - need new models, theories, and diagnostic tools to understand experimental observations.
- New "multi-user" dusty plasma lab facilities for ground- and space-based research are coming online.

Outlook for dusty plasma research: fusion and industrial applications

- Dust formation and control in fusion remains a major issue.
- The dust is a contaminant, but can it be used to control and fuel the plasma or for disruption mitigation?

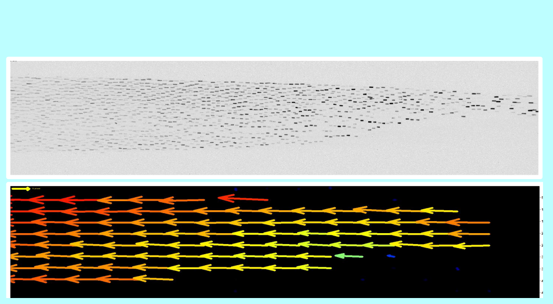
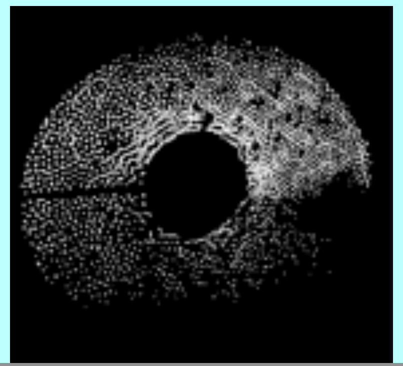
- For processing plasmas, the formation of nanometer-sized particles in reactive plasmas is also an important source of contamination.
- These particles are comparable in size to the etched features on modern microelectronic devices.
- But, the controlled formation and deposition of nanoparticles can also be used to beneficially modify the electrical, structural and optical properties of materials.

Selected list of institutions involved in dusty plasma research

- US
  - Auburn University (Physics)
  - Baylor University (Physics)
  - Caltech (Physics)
  - University of Alabama at Huntsville (Mech. Eng.)
  - University of California - San Diego (Elec. Eng.)
  - University of Colorado (Physics)
  - University of Iowa (Physics)
  - University of Maryland - Baltimore County (Mech. Eng.)
  - University of Michigan (Elec. Eng.)
  - University of Minnesota (Mech. Eng.)
  - MIT (Nucl. Eng.)
  - Virginia Tech (Elec. Eng)
  - Wittenberg University (Physics)
  - Los Alamos National Lab
  - Princeton Plasma Physics Lab
  - Naval Research Lab

- International
  - Canada: *U. Saskatchewan*
  - China: *Donghua Univ.,*
  - Germany: *U. Kiel, U. Giessen, U. Greifswald, U. Bochum, Germany Aerospace Center (DLR)*
  - France: *CNRS - Marseilles, U. Orleans*
  - Sweden: *Royal Institute of Technology, Univ. of Stockholm*
  - Japan: *U. Kyoto*
  - *Netherlands: U. Eindhoven*
  - India: *Inst. Plasma Research (IPR), U. Delhi*

Magnetized Plasma Research Laboratory

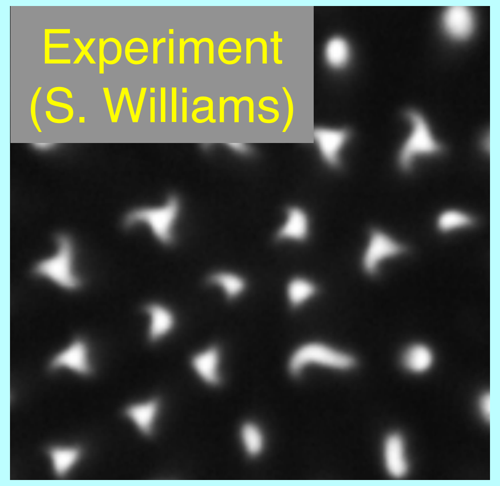
Fluid-like in μ-gravity (L. Scott)

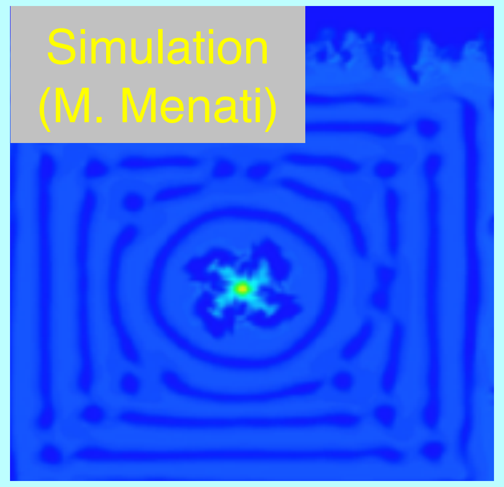
Solid-like in B-field (S. LeBlanc)

Thermal properties in dusty plasmas

Studying strongly vs. weakly coupled plasmas in lab, magnetized, and microgravity plasmas.

Collaborations: Baylor, UCSD, ESA, Roscosmos



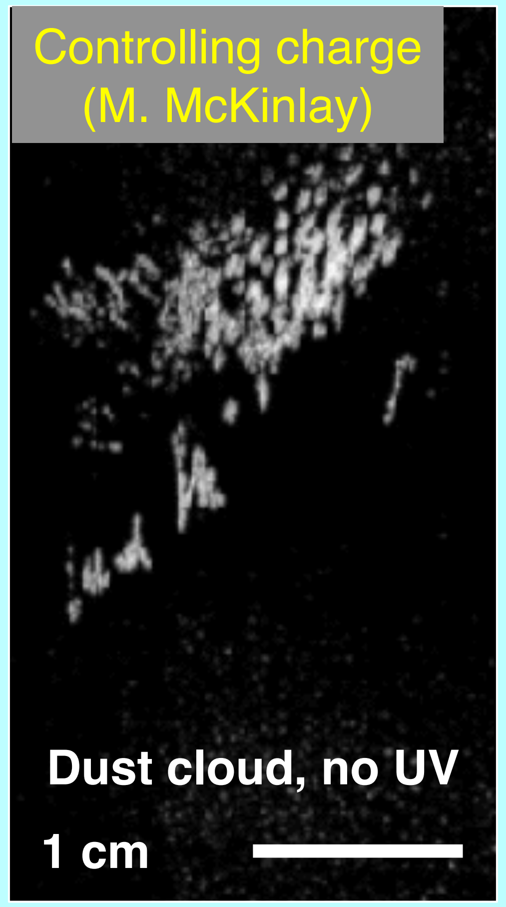


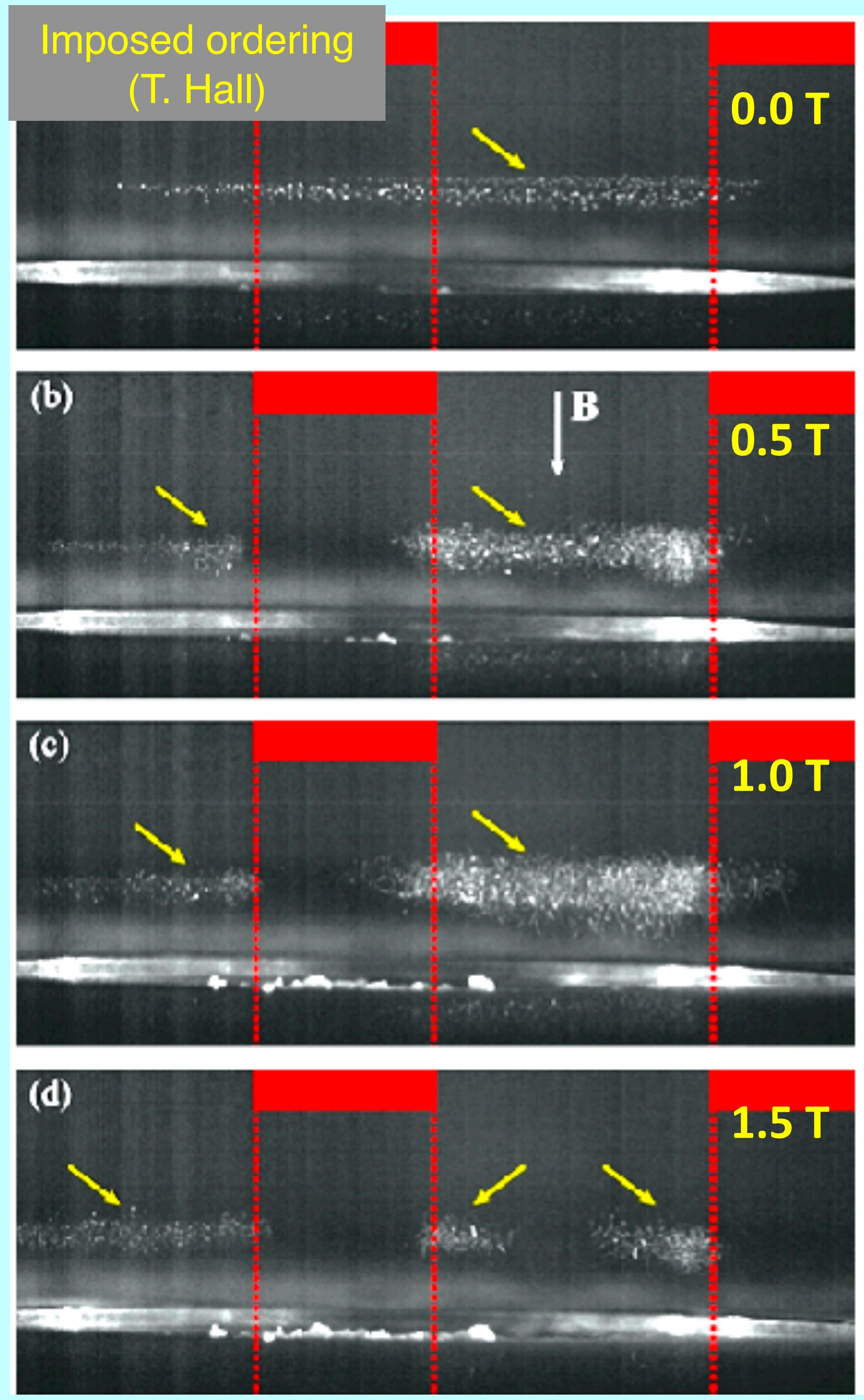
Plasma filaments and plasma self-organization

Experiments and modeling of plasma pattern formation show good qualitative agreement.

Controlling charge

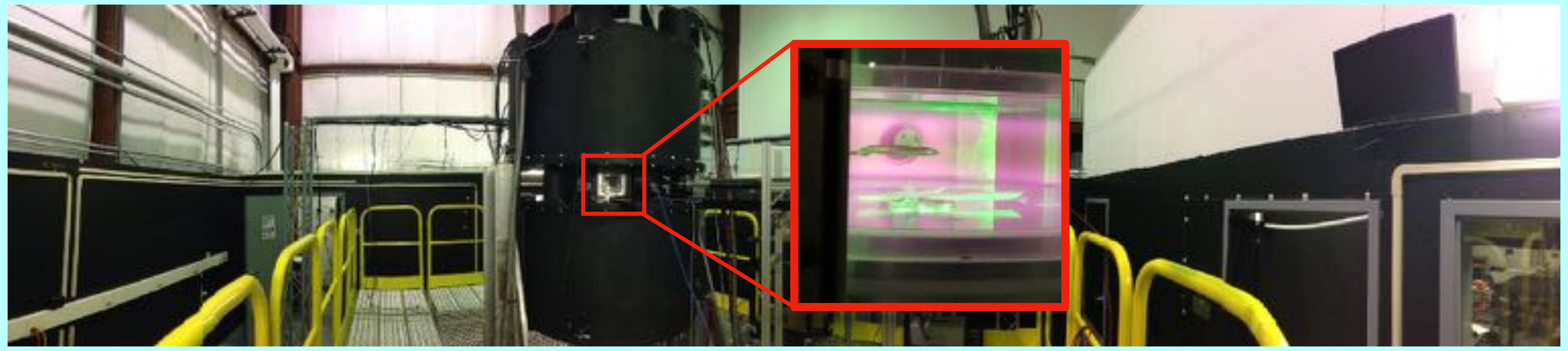
Using UV to control dust without modifying background plasma.



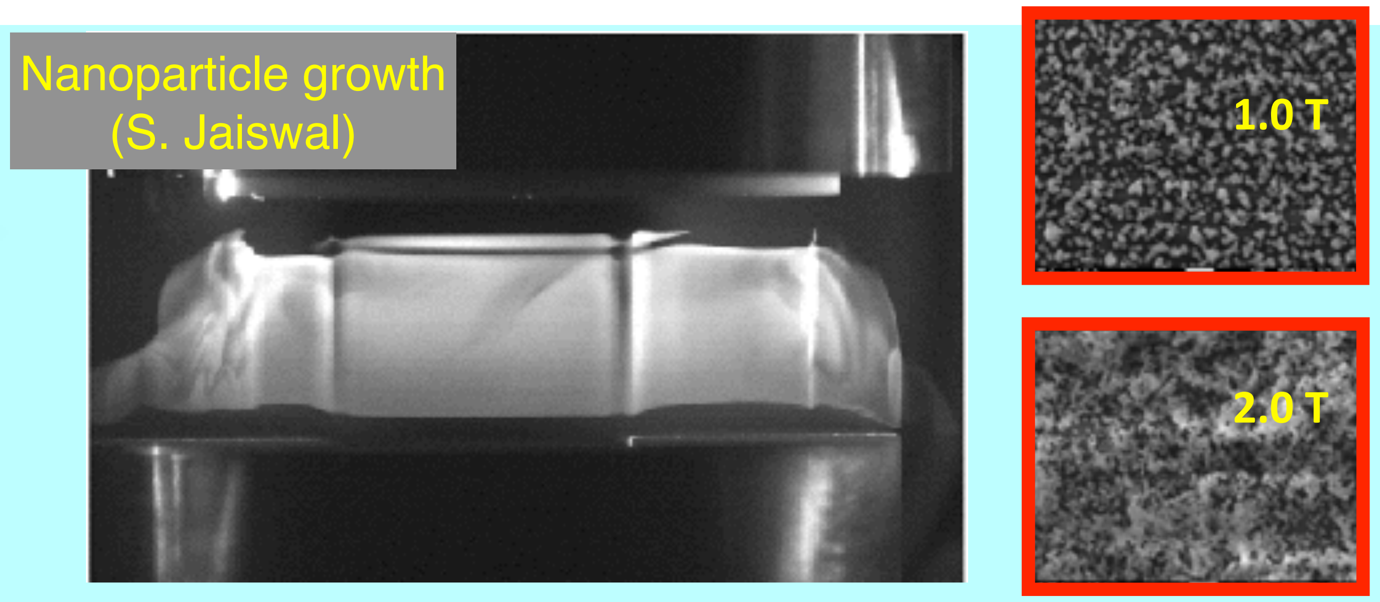


Imposed ordering

Using dust particles as a diagnostic for sheath and filament formation in magnetized plasmas.



Panoramic view of the Magnetized Dusty Plasma Experiment (MDPX) device. Insert of plasma and dust cloud.



Particle growth

Nanoparticle growth in magnetized plasmas filaments leads to control over morphology.

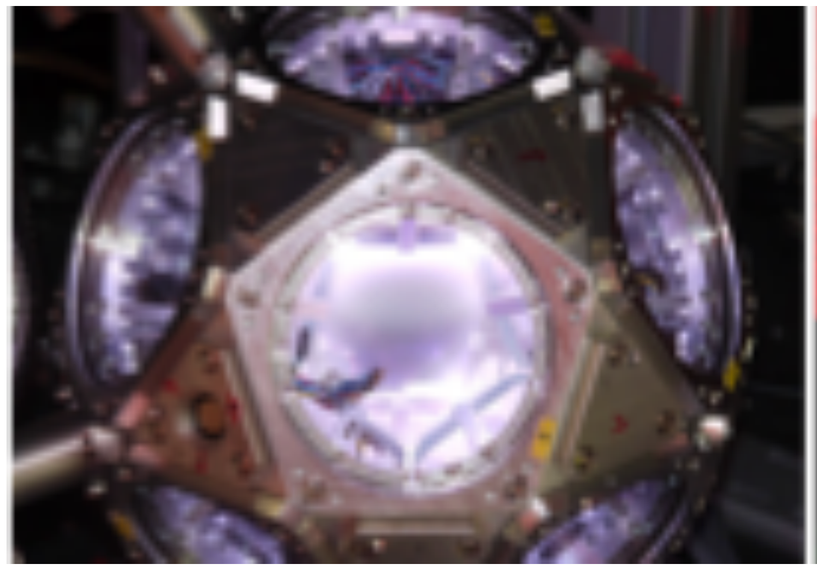
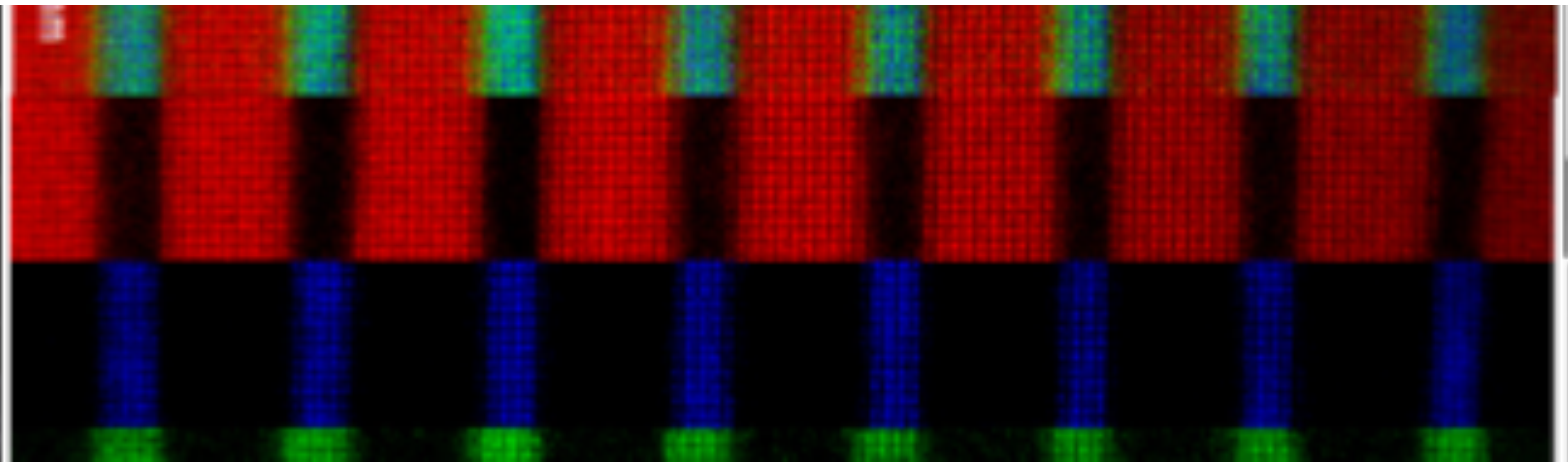
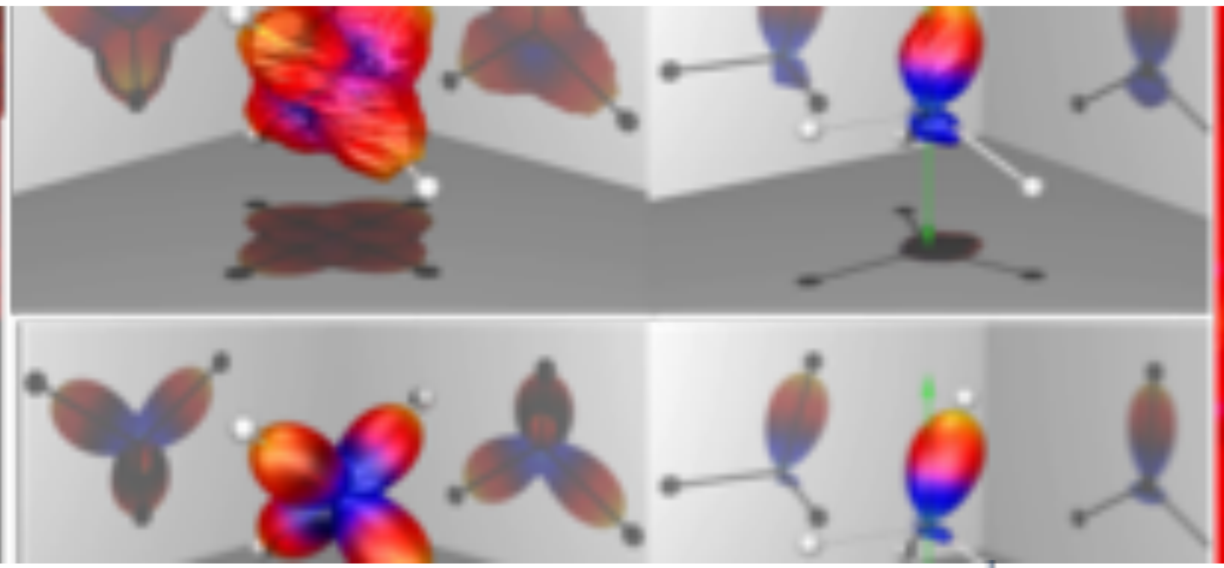
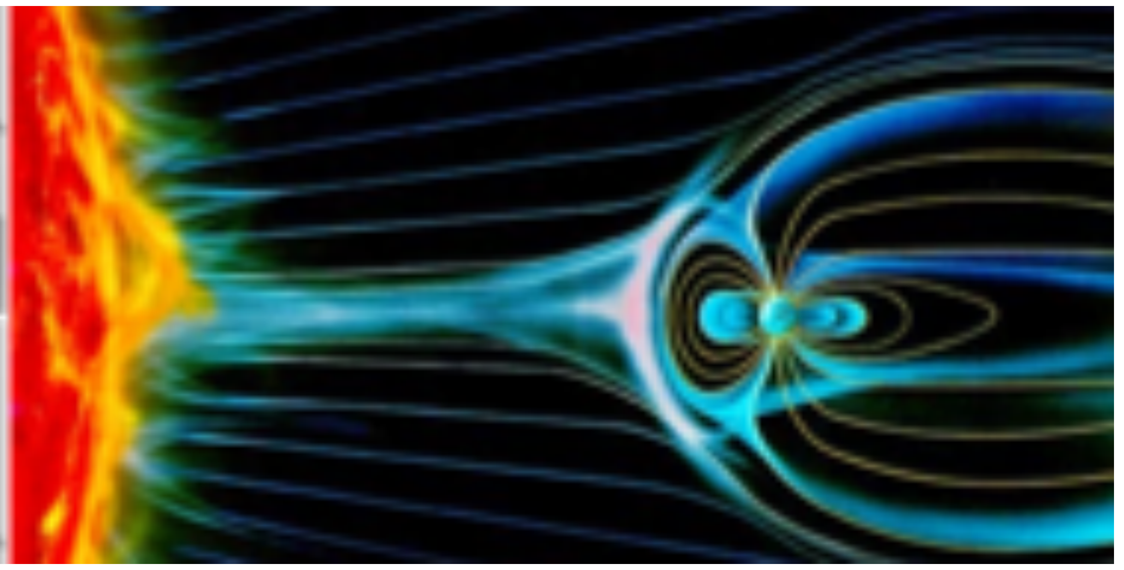
Collaborations: CPU2AL, Tuskegee Univ., U. Saskatchewan, Univ. of Alabama - Birmingham

MPRL Magnetized Plasma Research Laboratory

http://aub.ie/mprl

CPU2AL

AUBURN UNIVERSITY

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AUBURN UNIVERSITY

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- Collision dynamics
- Spectroscopy

Biophysics
- Intracellular transport
- Neuroscience
- Computational modeling

Space Physics
- Magnetosphere
- Solar emissions
- Satellite observations

Condensed Matter Physics
- Molecular beam epitaxy
- Wide bandgap devices
- 2D materials
- Electronic structure calculations

Plasma Physics
- 3D magnetic confinement
- Complex plasmas
- Plasma computational modeling

Quick Facts

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QUESTIONS???