# Introduction to the physics of dusty plasmas

Prof. Edward Thomas, Jr.
Physics Department
Auburn University
Auburn, Alabama

etjr@auburn.edu
http://aub.ie/mprl

2019 SULI Introductory Course in Plasma Physics

# Outline

- Why dusty plasmas?
- Dusty in fusion devices
- Basic properties
  - Fundamental parameters
  - Charging
  - Forces and transport
- Recent advances in dusty plasma research
  - Microgravity research on the ISS
  - Magnetic field effects
- Outlook

# WHY DUSTY PLASMAS?

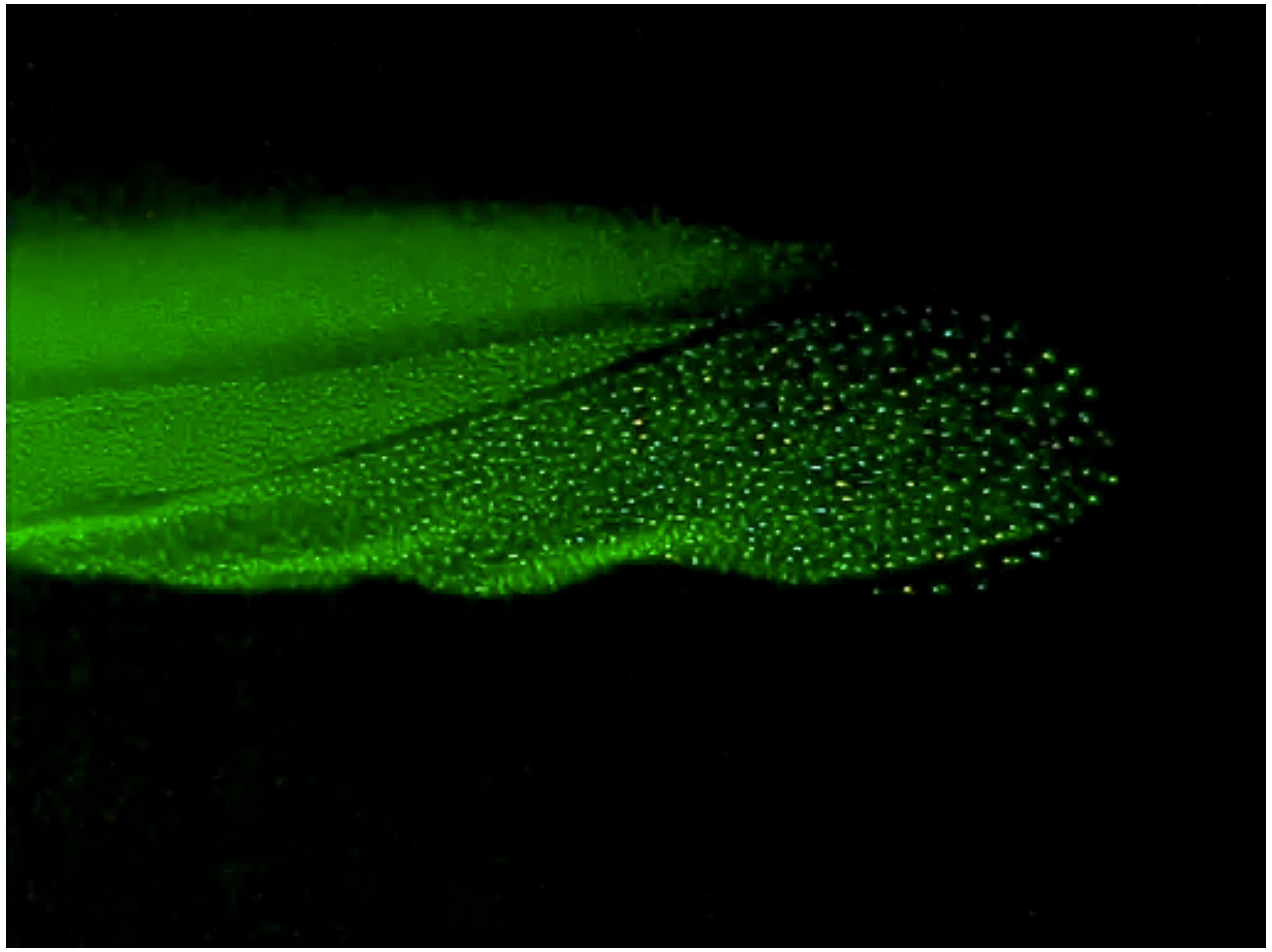
# Dusty (complex, fine particle, colloidal) plasmas

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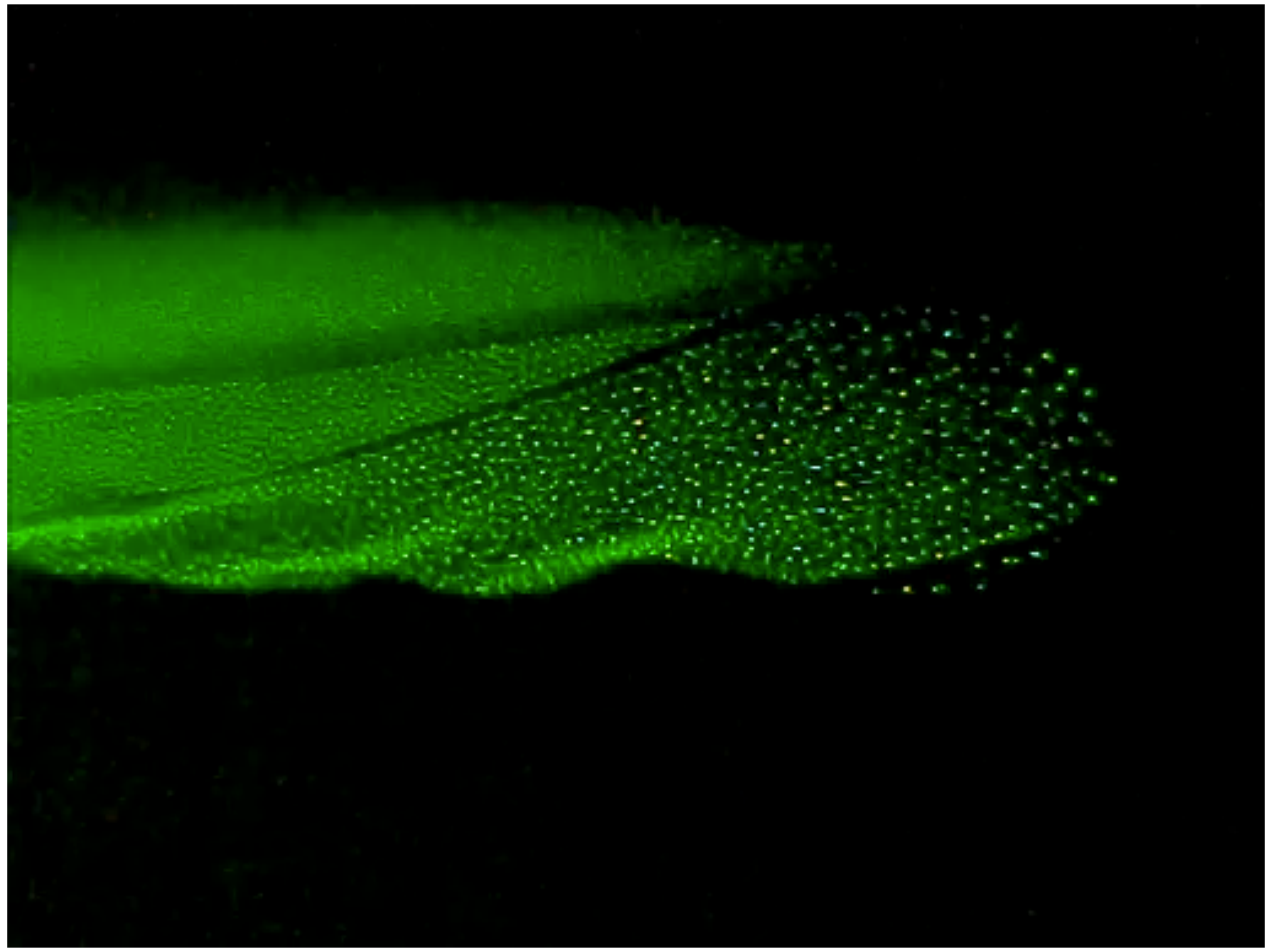
# What is the scientific motivation for studying the physics of dusty plasmas?

- **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?
- Scientific goal: 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

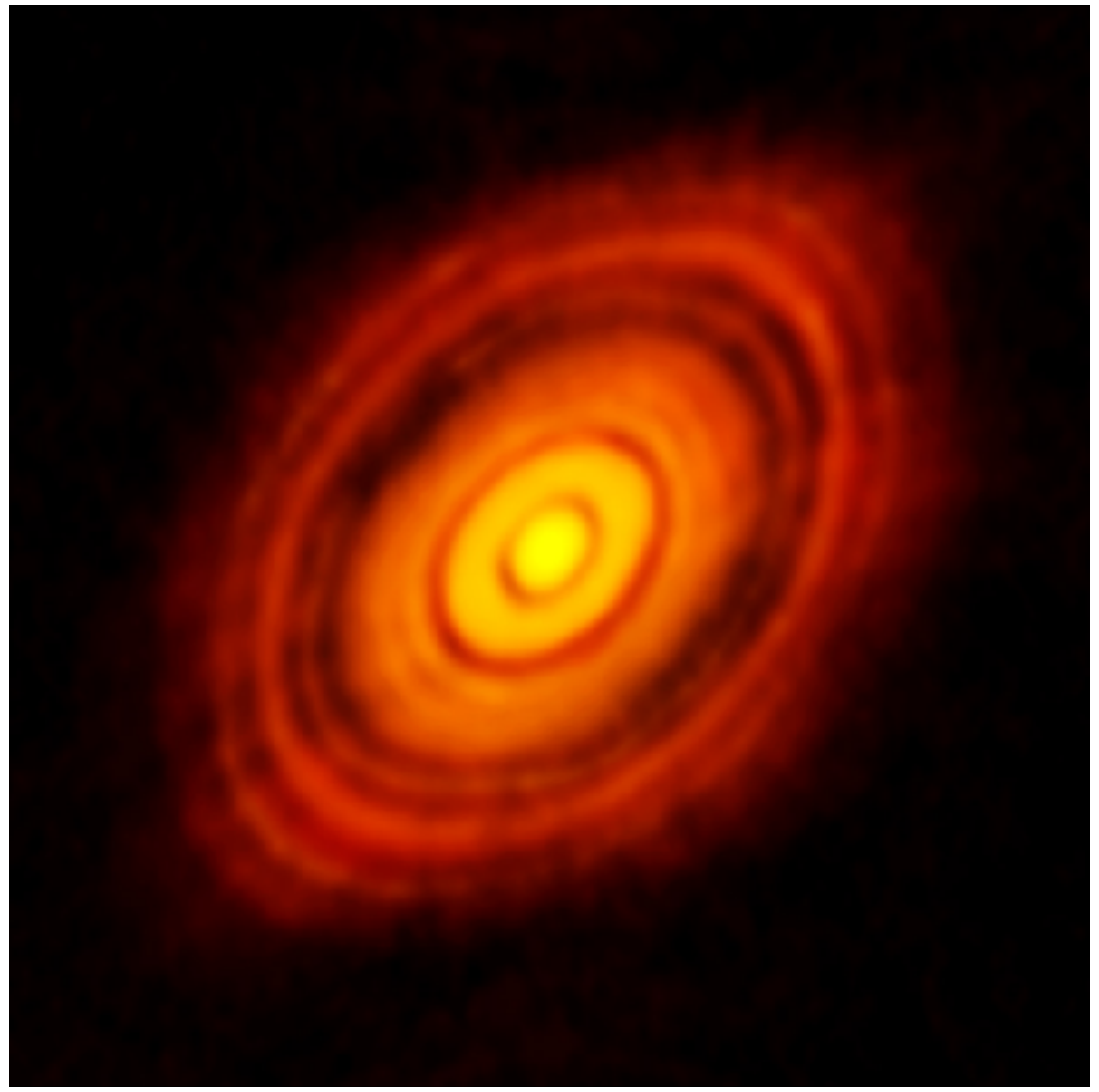


**Approach:** measure the **position**, **velocity**, and **acceleration** of the particles — to obtain the **forces**, **energy**, and **thermal properties**

# Dusty plasmas in astrophysical environments

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

Image: Star formation in Carina Nebula

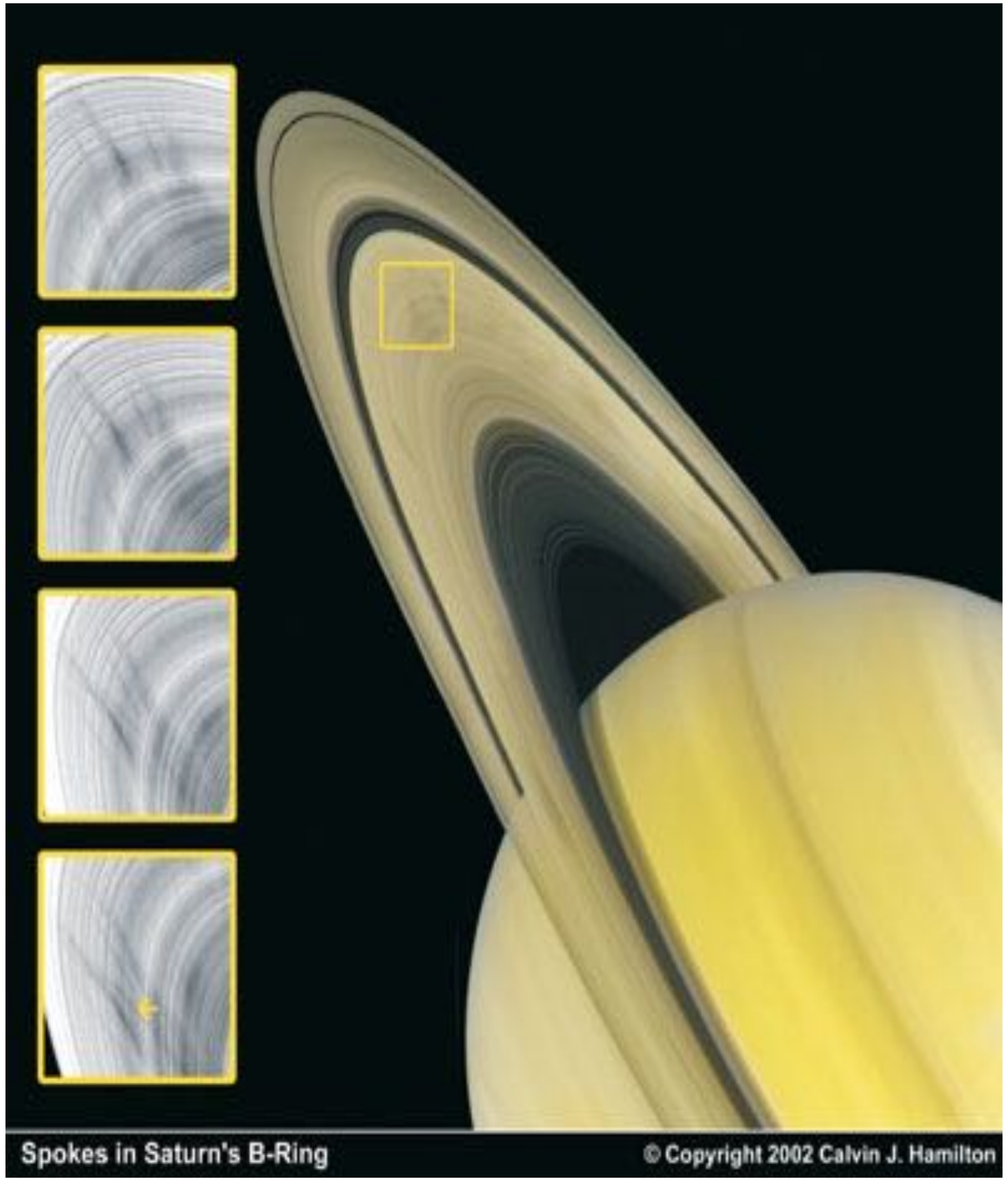


http://www.almaobservatory.org/en/press-room/press-releases/771-revolutionary-alma-image-reveals-planetary-genesis

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)]

# 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.

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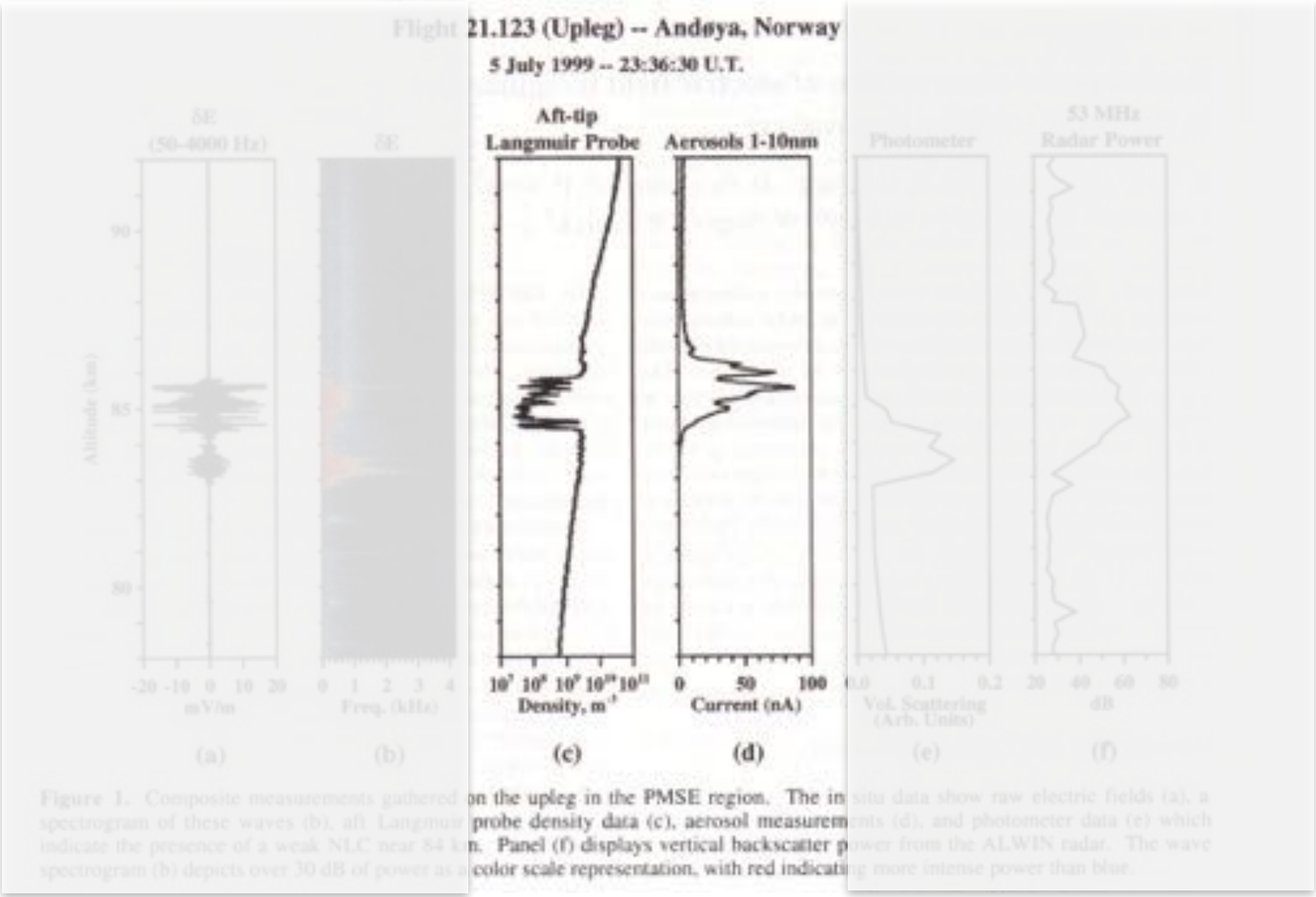
# Dusty plasmas in terrestrial environments

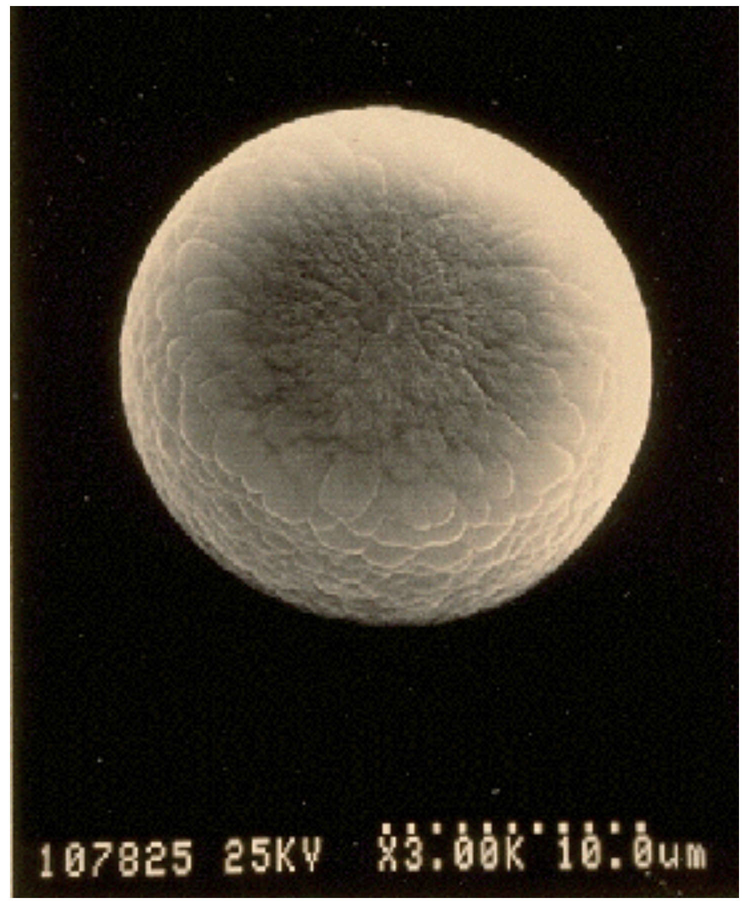
- Noctilucent clouds (NLC's) form at extremely high altitudes, about 85 km, that "shine at night".
- They form in the cold, summer polar mesopause and are believed to be charged ice crystals.
- They are believed to be associated with radar backscatter phenomena (PSME's) observed during the northern summers.




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

# 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, $d \leq 20$ nm.




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

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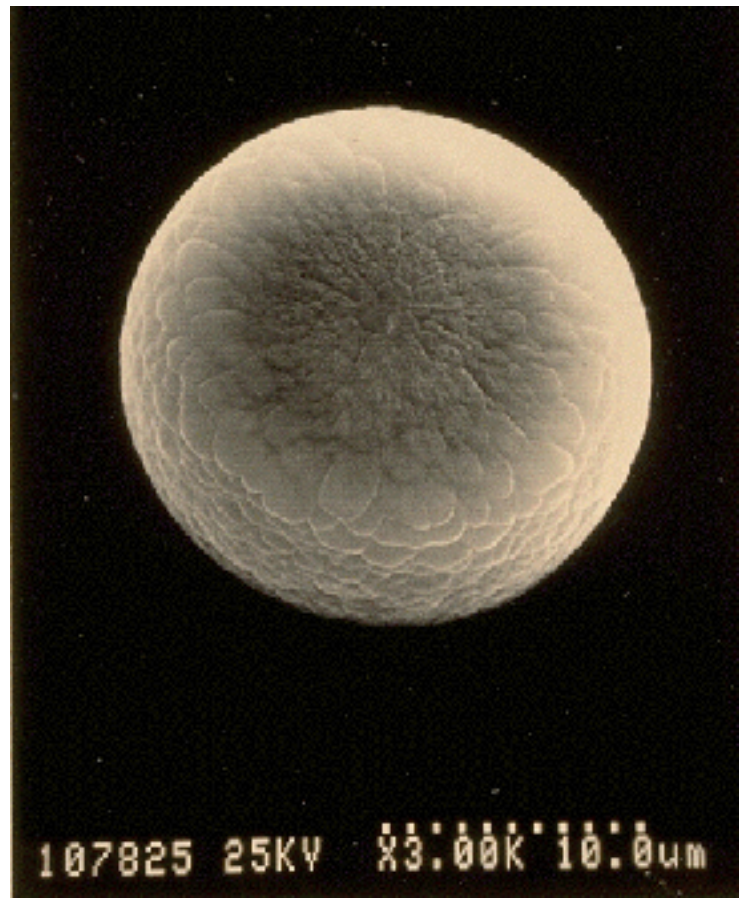


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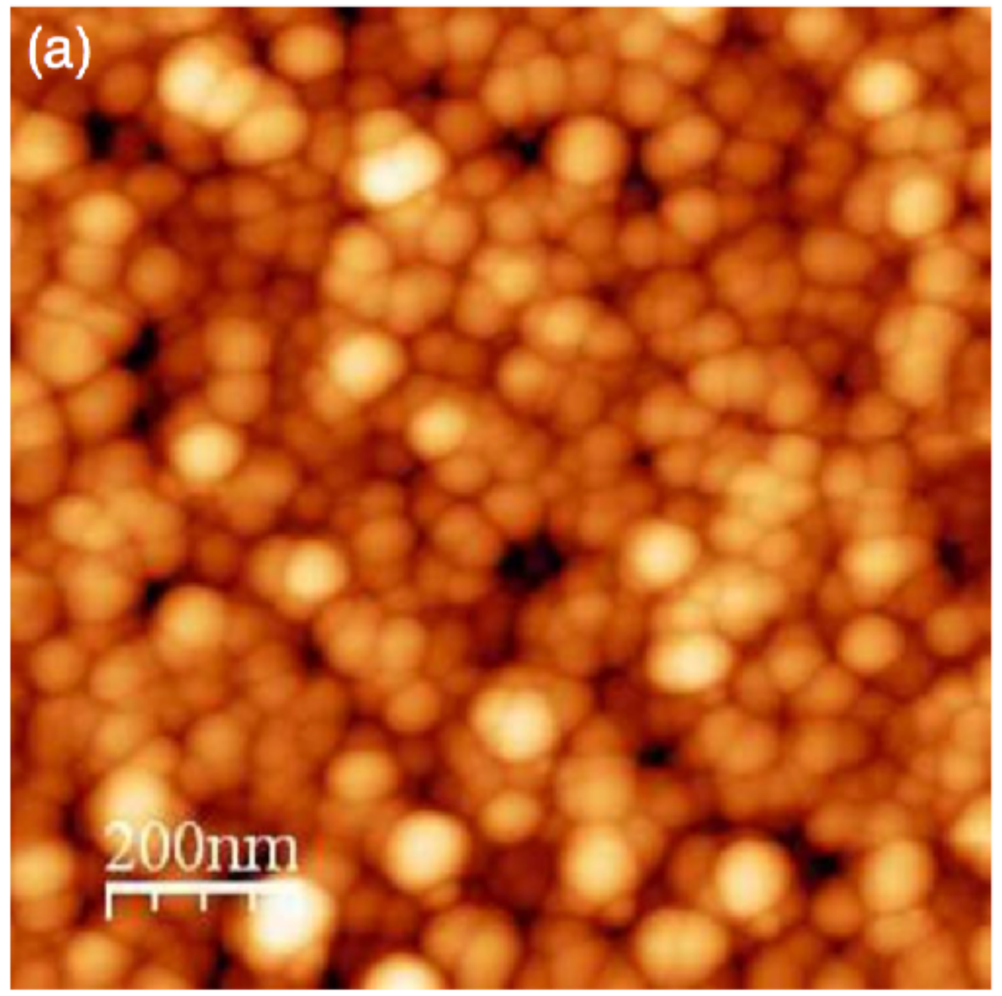


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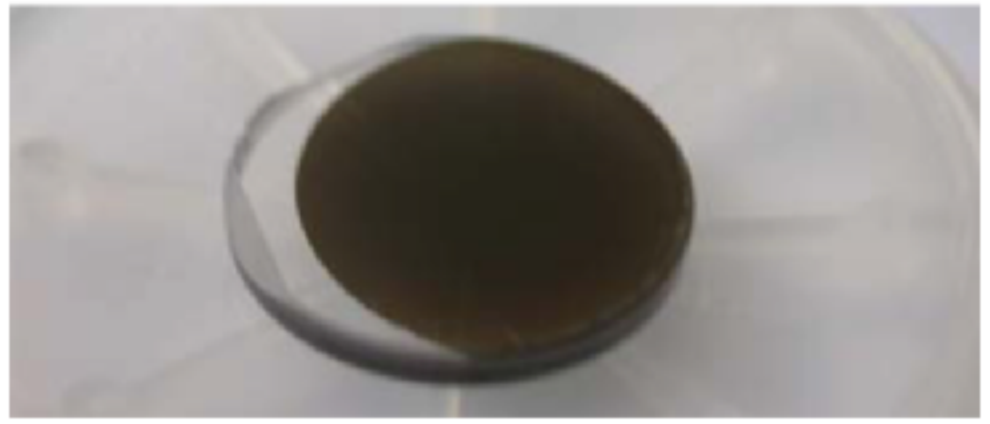

Copper nanoparticles grown on a substrate to modify the optical properties

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

# 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.

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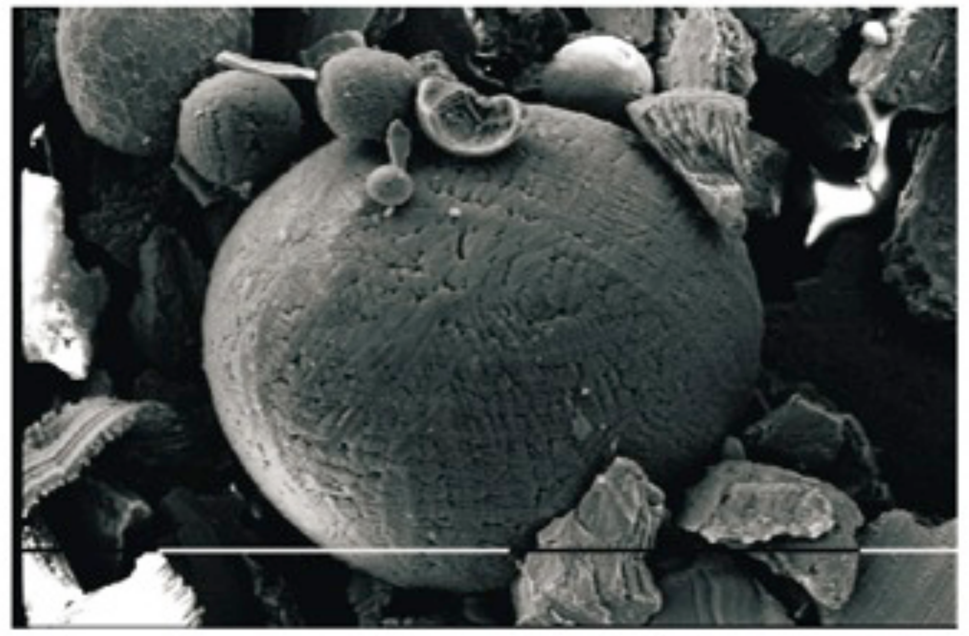
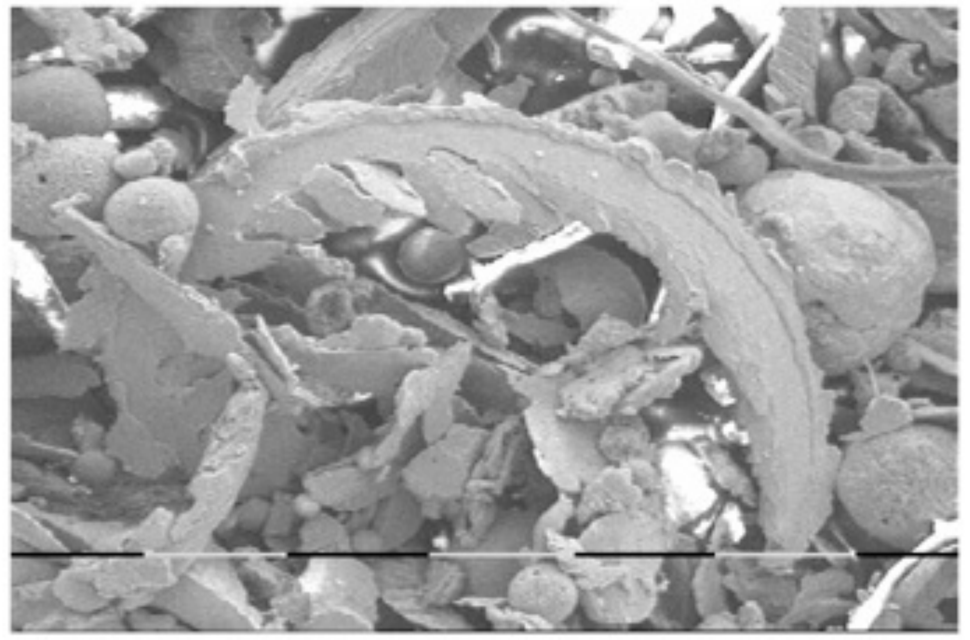
**Micron-sized dust particles formed in TEXTOR-94**



0.1 mm



------- 0.1 mm

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

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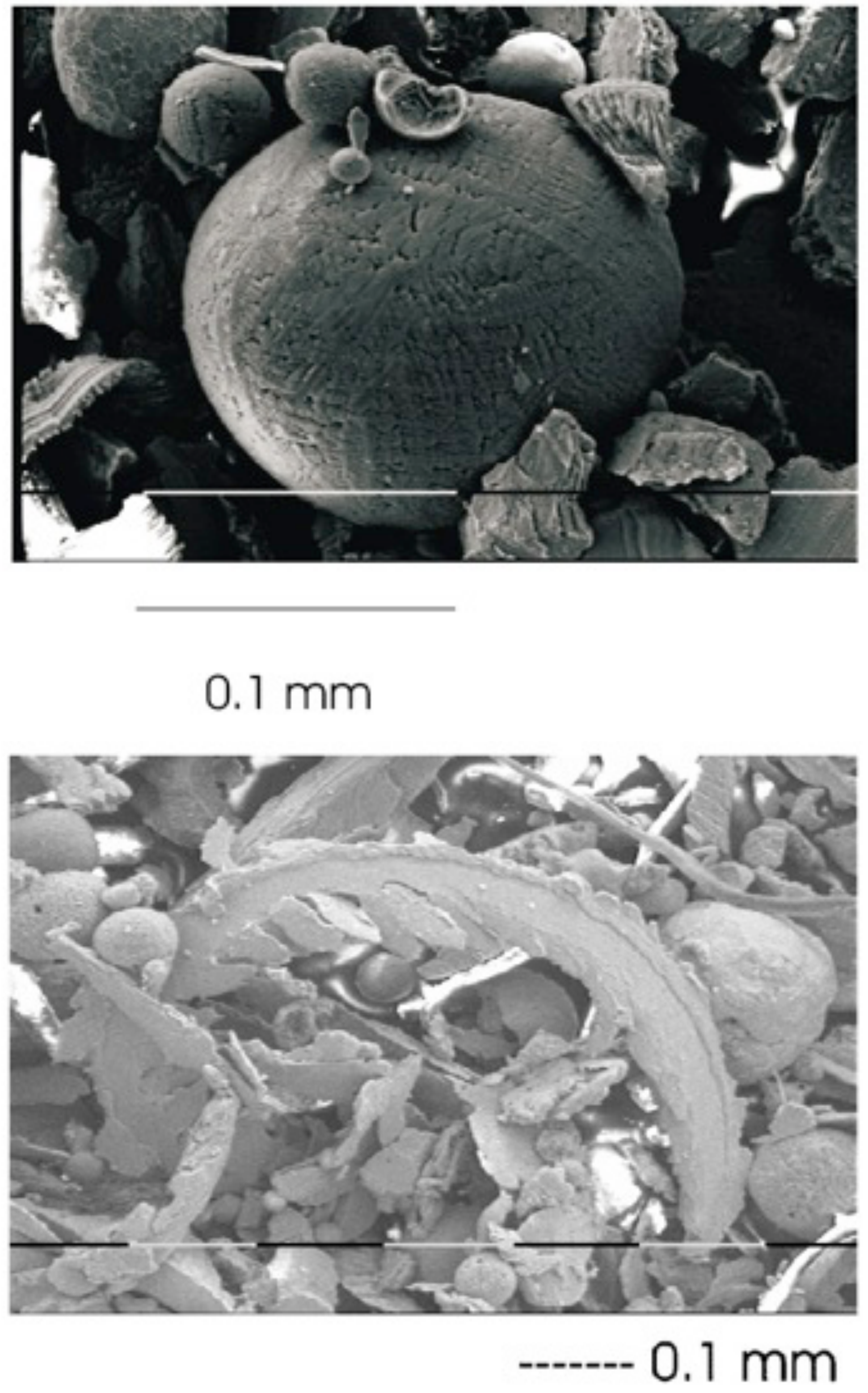
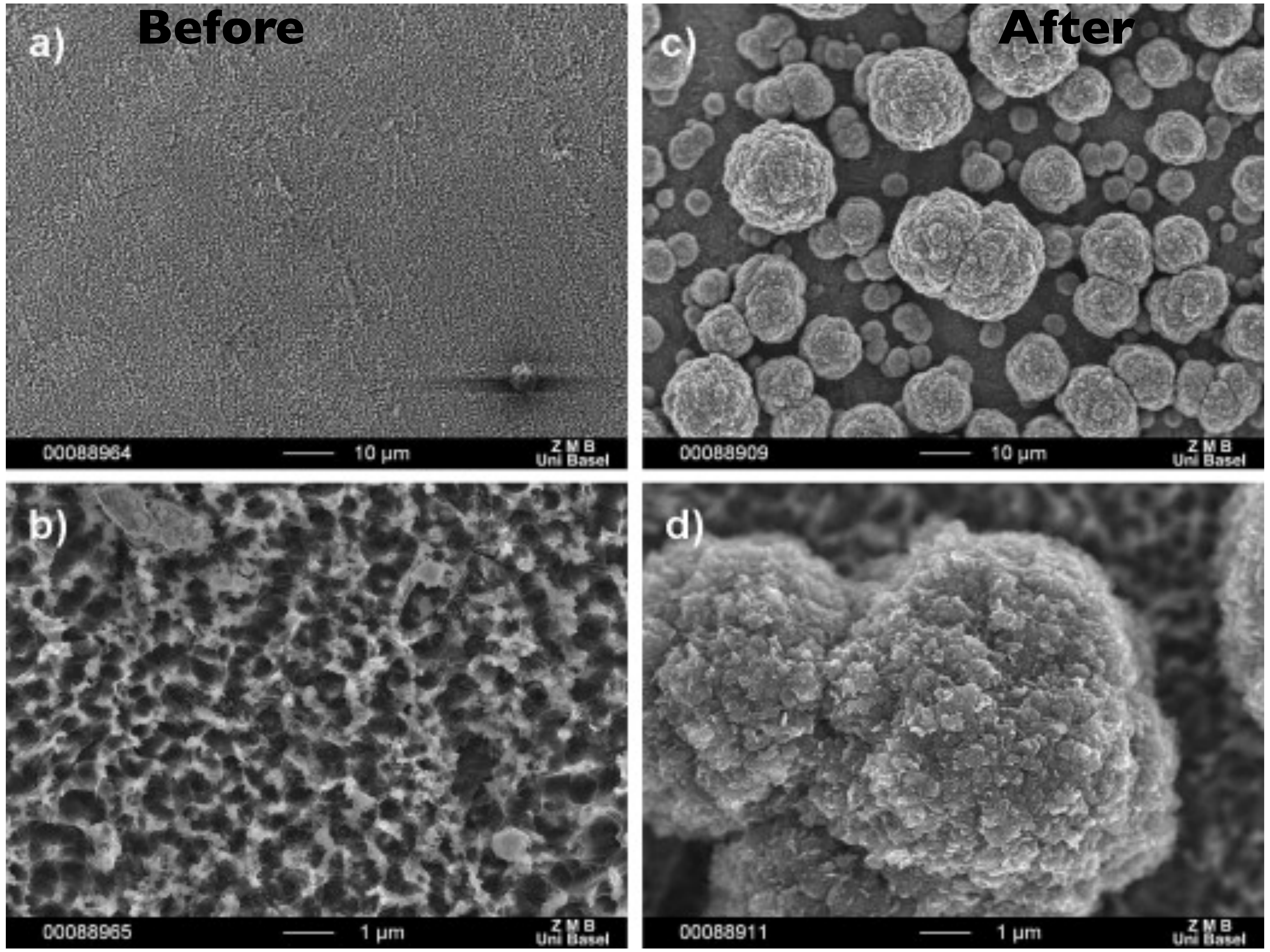


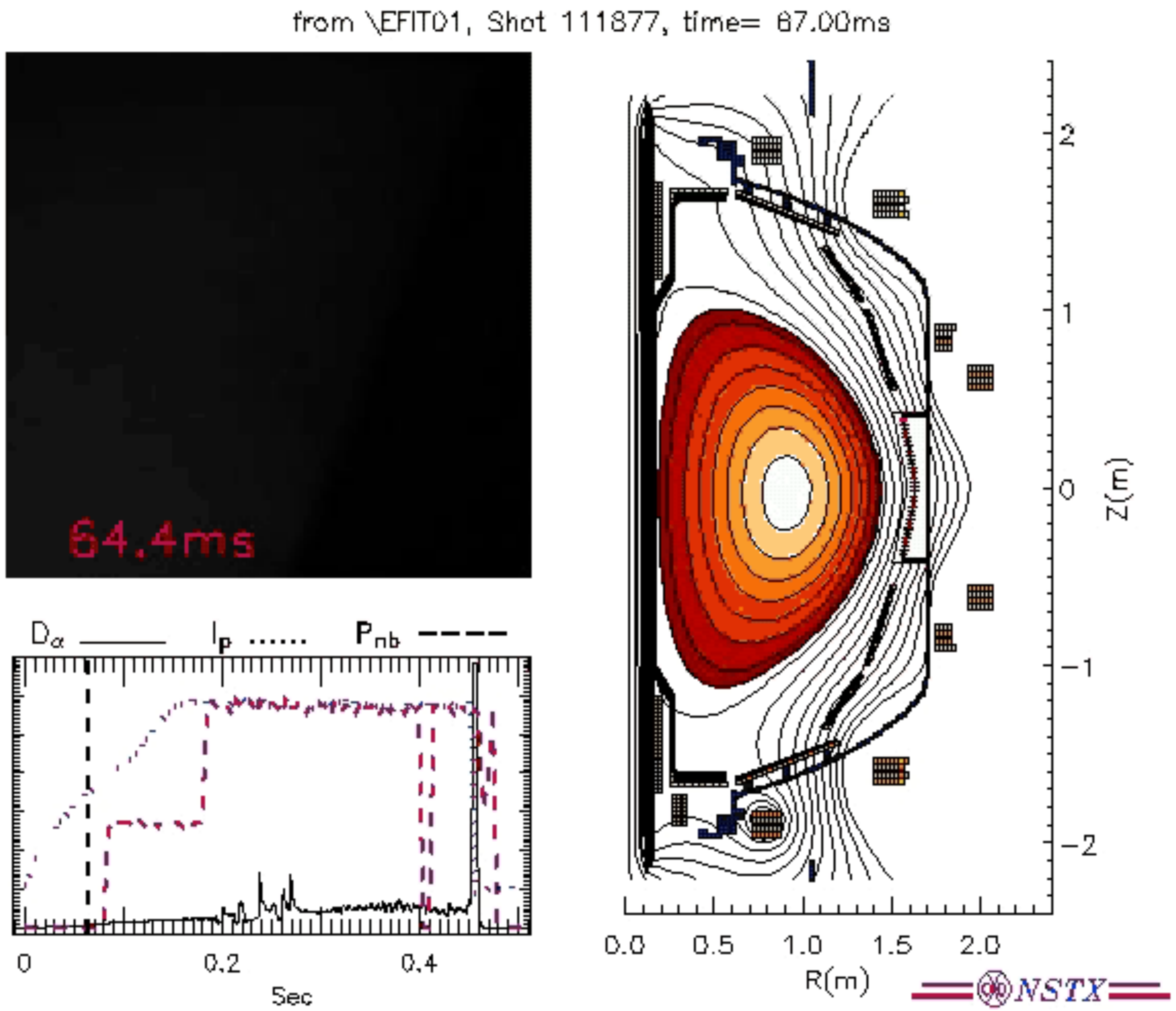

J. Winter, PPCF, **40**, 1201 (1998)
S. I. Krasheninnikov, et al., PPCF, **53**, 083001 (2011)

**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)

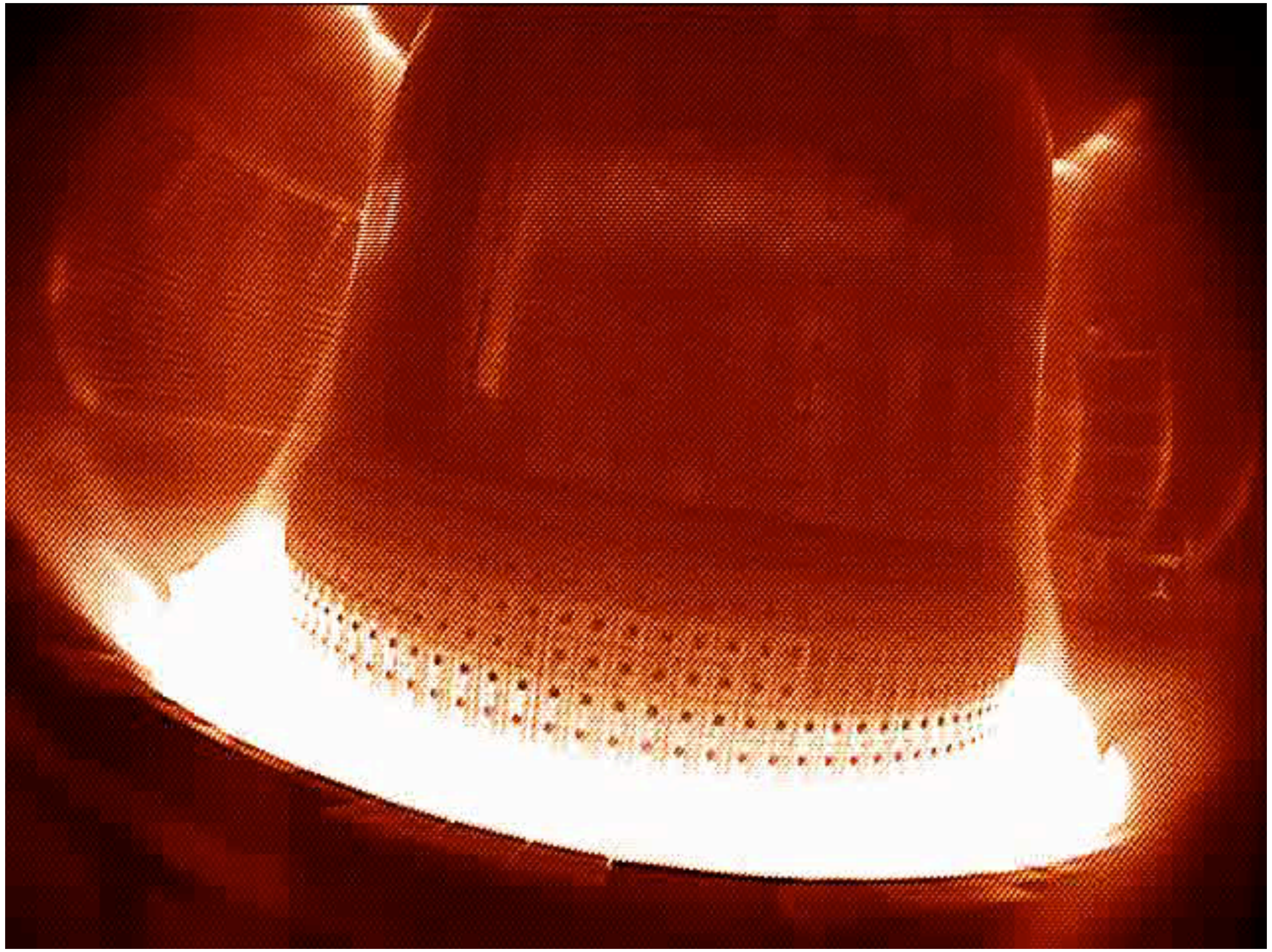
# Evidence of dust particles in fusion plasmas




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.

# Evidence of dust particles in fusion plasmas



Injection of "hot" dust particles in Alcator C-Mod after a disruption
Courtesy: MIT

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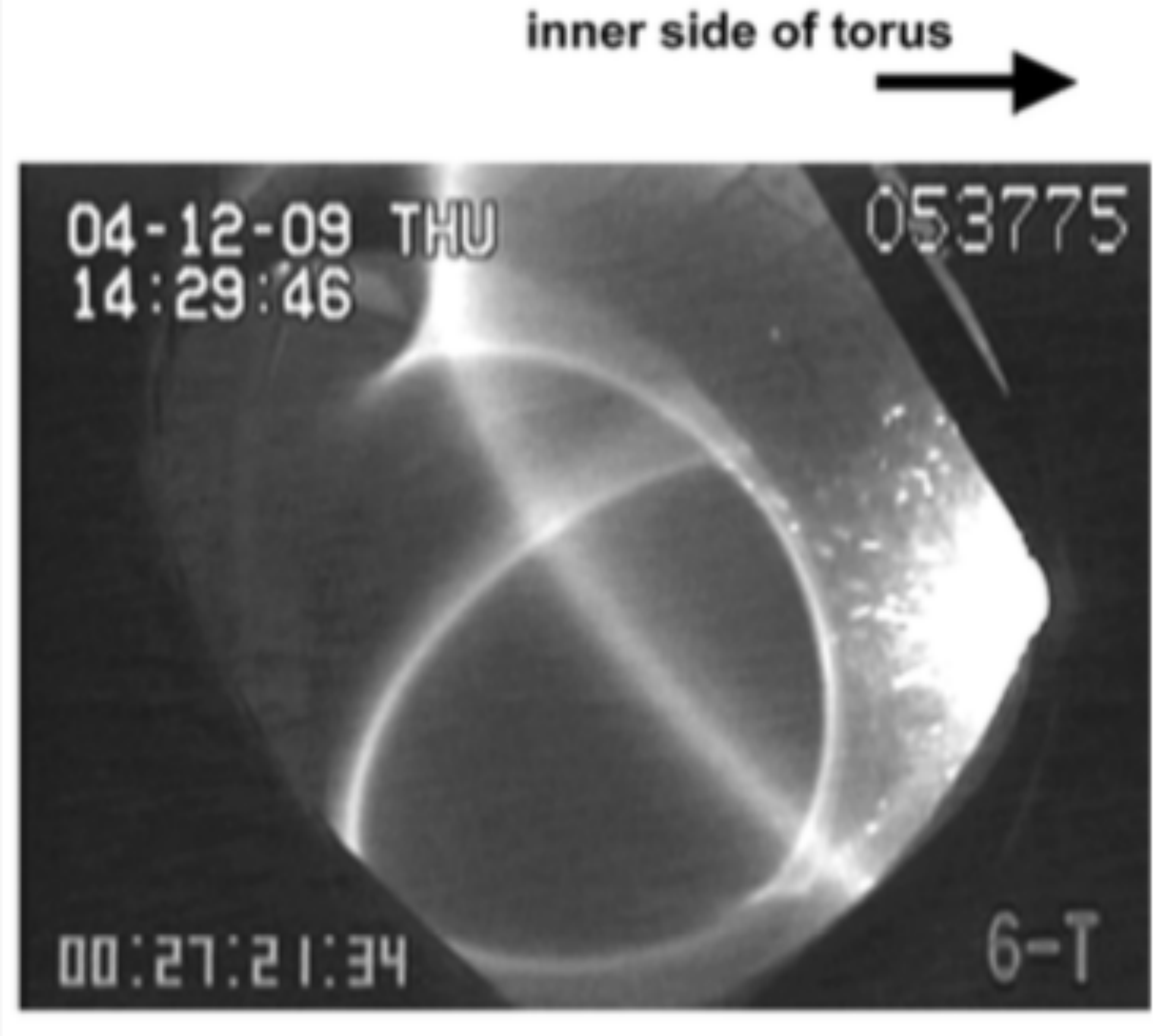


Dust injection in LHD stellarator
K. Saito, et al., J. Nucl. Mat., 363-365, 1323 (2007)

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- 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: $\sim 10^{20}$ $m^{-3}$
  - Plasma volume: 840 $m^3$

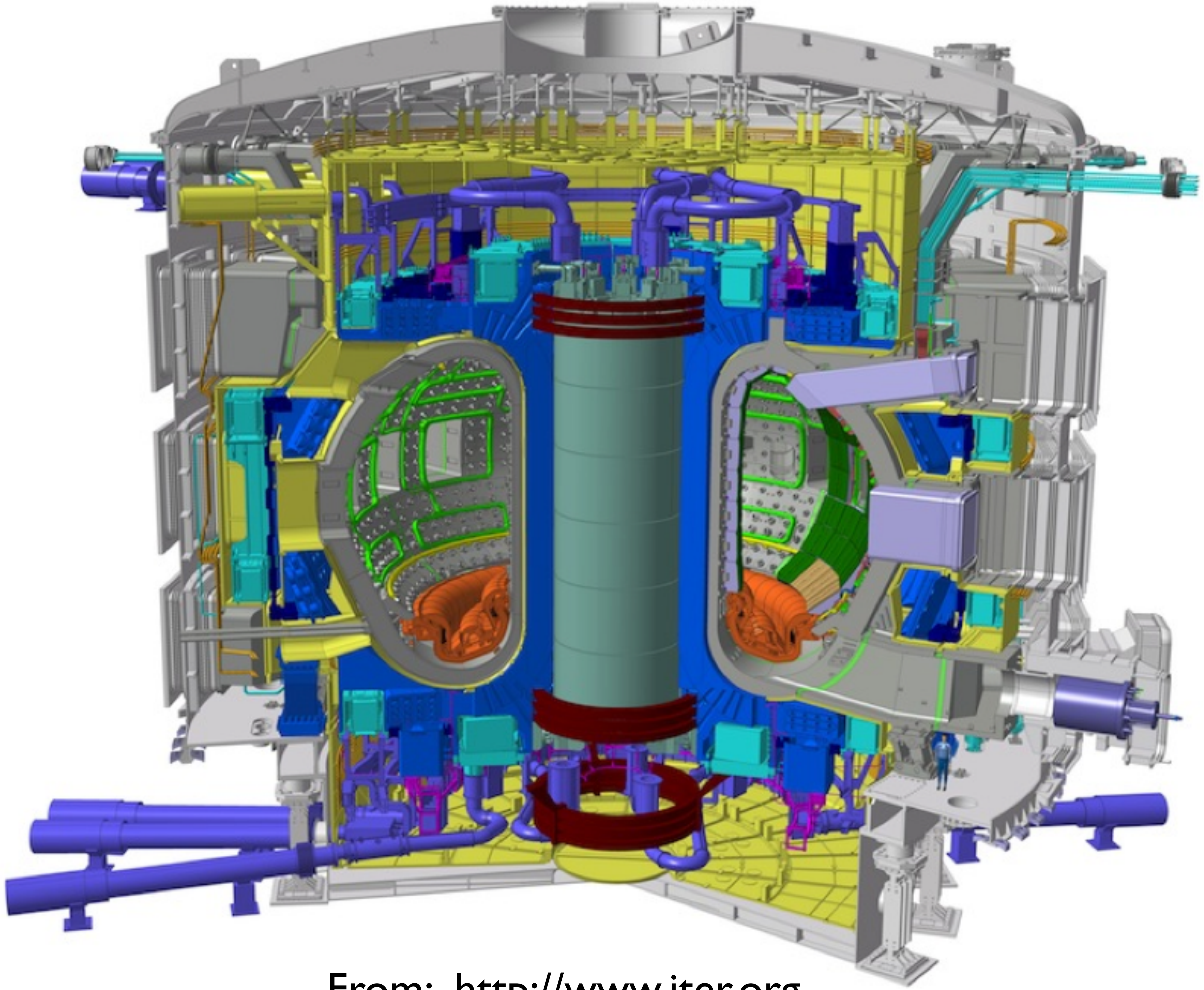
- 1 gram tungsten = $3.3 \times 10^{21}$ atoms
- Assume these atoms fill the plasma volume uniformly (not accurate!)
- Further, assume all atoms are singly ionized (not accurate!)

# 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!)
- 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

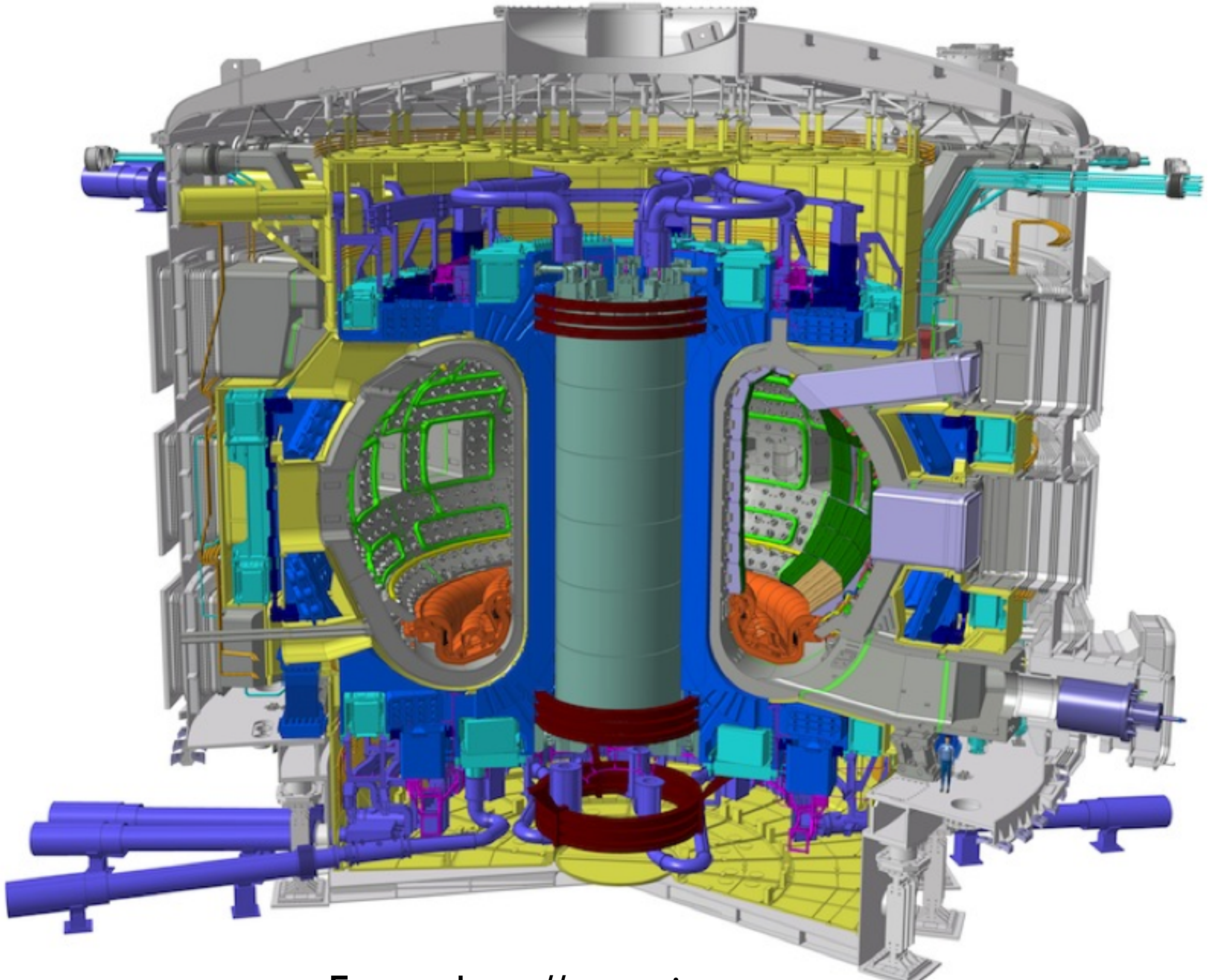


From: http://www.iter.org

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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[7] Z. Liu, D. Wang, and G. Miloshevsky, "Simulation of dust grain charging under tokamak plasma conditions," *Nuclear Materials and Energy*, vol. 12, pp. 530–535, Aug. 2017.

[8] A. Autricque, S. H. Hong, N. Fedorczak, S. H. Son, H. Y. Lee, I. Song, W. Choe, and C. Grisolia, "Simulation of W dust transport in the KSTAR tokamak, comparison with fast camera data," *Nuclear Materials and Energy*, vol. 12, pp. 599–604, Aug. 2017.

[9] R. D. Smirnov and S. I. Krasheninnikov, "Impact of cross-field motion on ablation of high-Z dust in fusion edge plasmas," *Phys. Plasmas*, vol. 24, no. 7, pp. 072505–6, Jul. 2017.

[10] F. Brochard, et al., "Video analysis of dust events in full-tungsten ASDEX Upgrade," Nuclear Fusion, 57, 036002 (2017).


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50+ papers from 2016-2019

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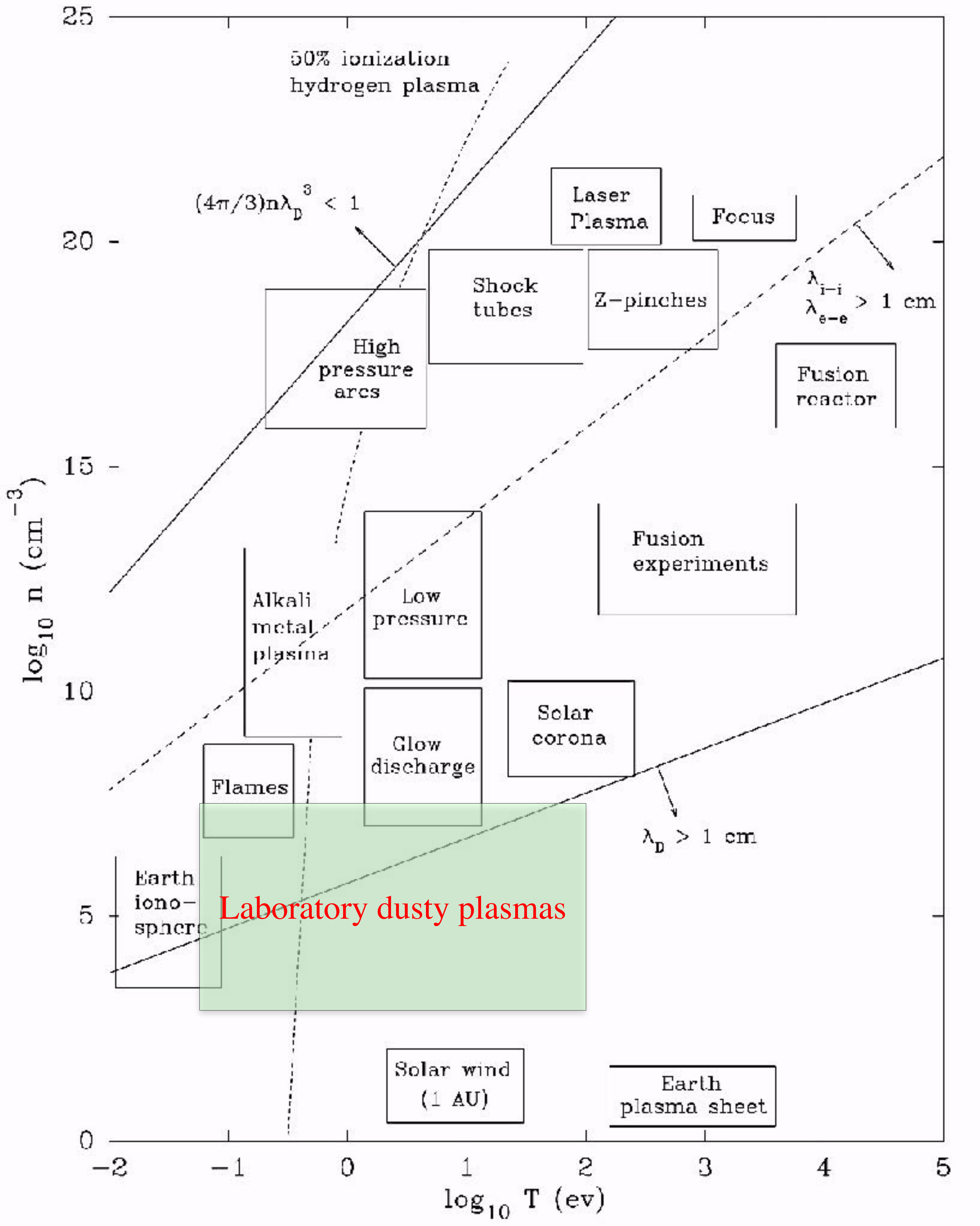
# BASIC PROPERTIES

# Basic properties of dusty plasmas

- Fundamental parameters
- Charging
- Forces

# What are the parameters of a dusty plasma?

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# 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
$\phi$ - 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: $\lambda_D = \left[\lambda_{De}^{-2} + \lambda_{Di}^{-2}\right]^{-1/2}$ and $\lambda_{Ds} = \left(\frac{\varepsilon_0 kT_s}{q_s n_{s0}}\right)^{1/2}$

Debye length

$\lambda_{De}$ = 204 μm

$\lambda_{Di}$ = 19 μm

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

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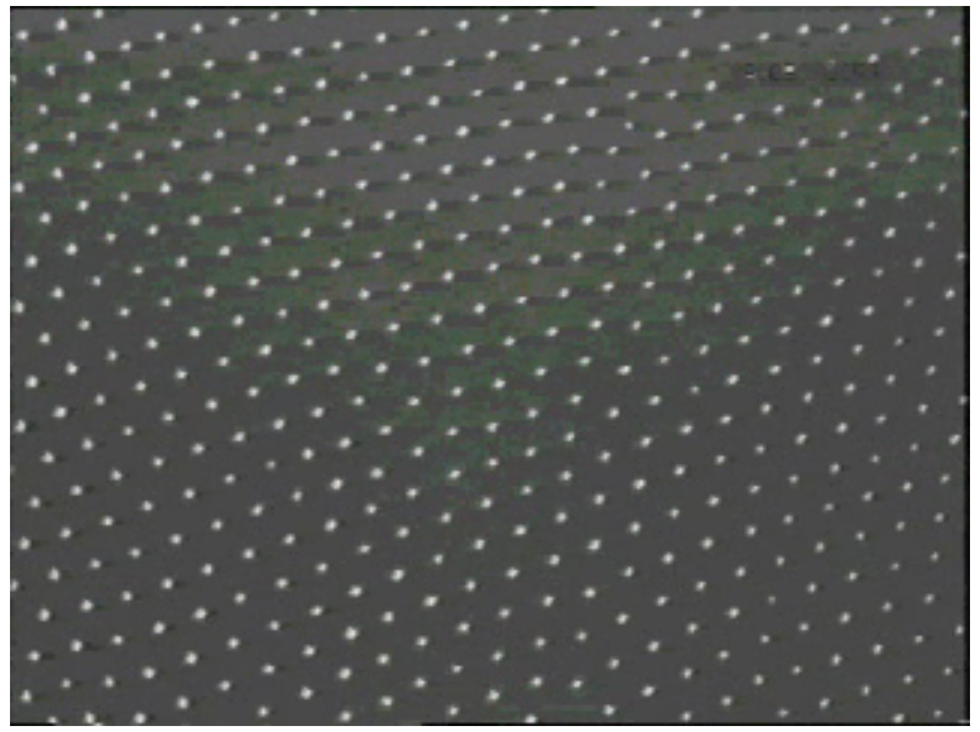
# Fundamental Parameters (4): Coupling parameter is a measure of self-organization

- $\Gamma$ (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

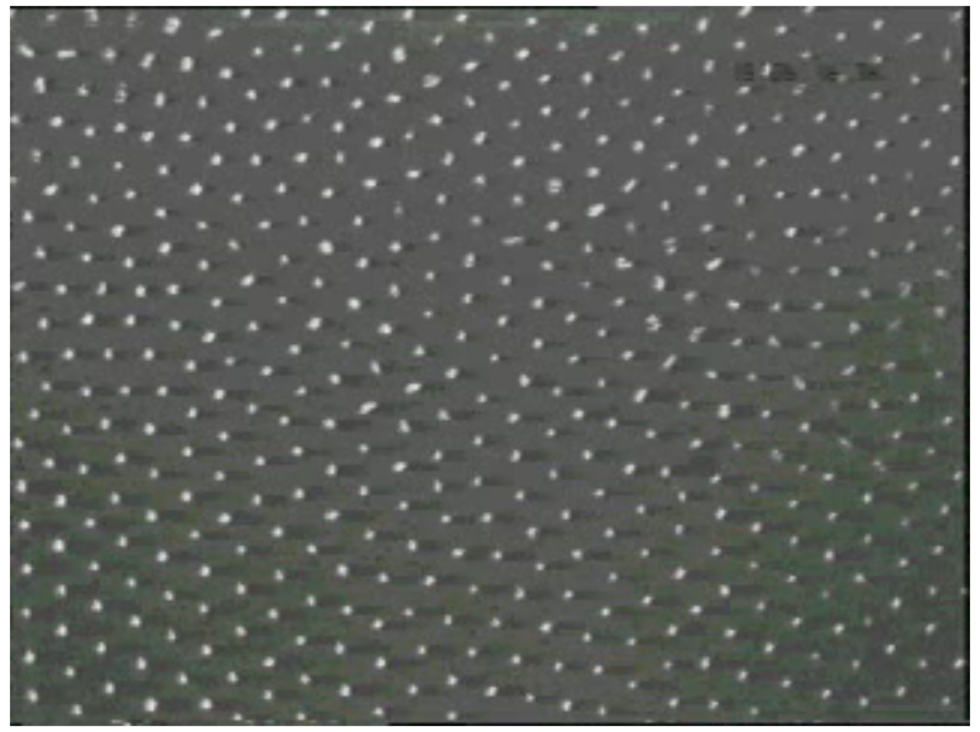
Yukawa, Debye-Hückel: $\varphi \sim \frac{\exp\left(-r/\lambda_D\right)}{r}$

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

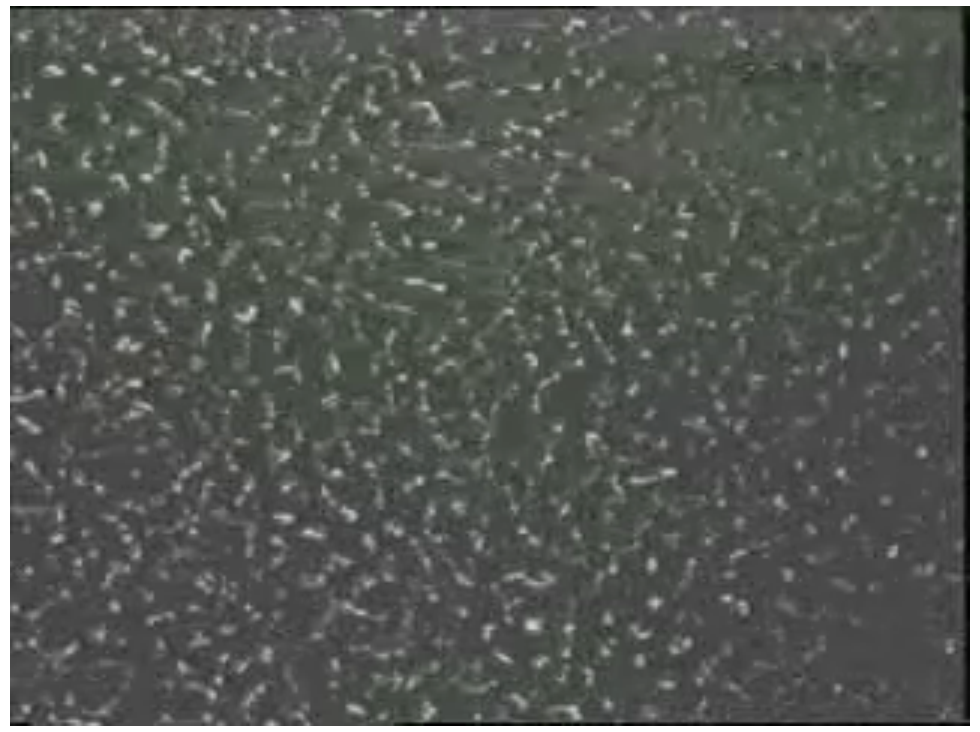
$$\Delta = \text{Wigner-Seitz radius} = \left(\frac{4\pi n_d}{3}\right)^{-1/3}$$



$\Gamma >> 1$
"solid"



$\Gamma \sim 1$
"liquid"



$\Gamma < 1$
"gas"

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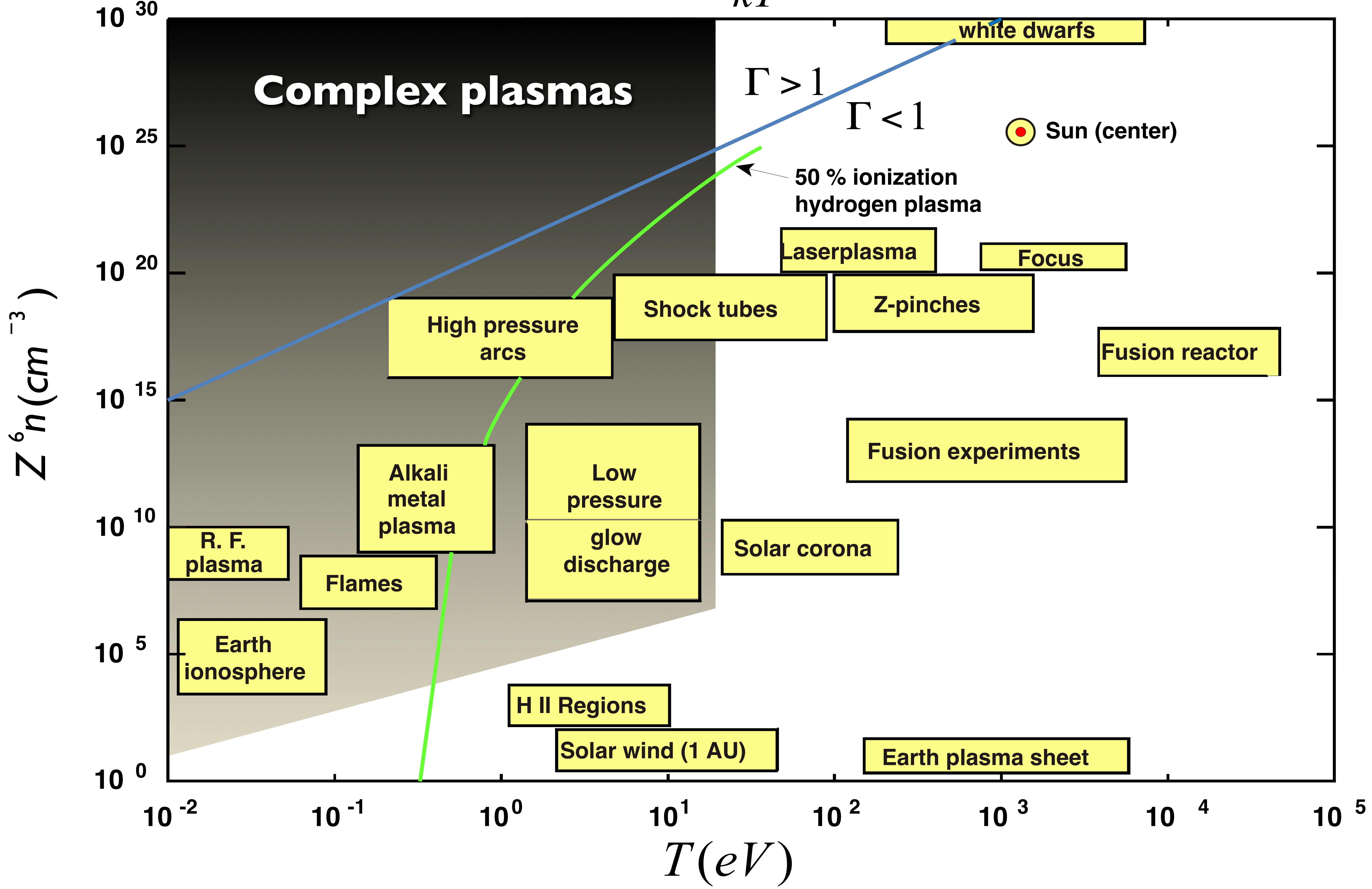
# Redefining the parameters of a dusty plasma

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




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

# Basic properties of dusty plasmas

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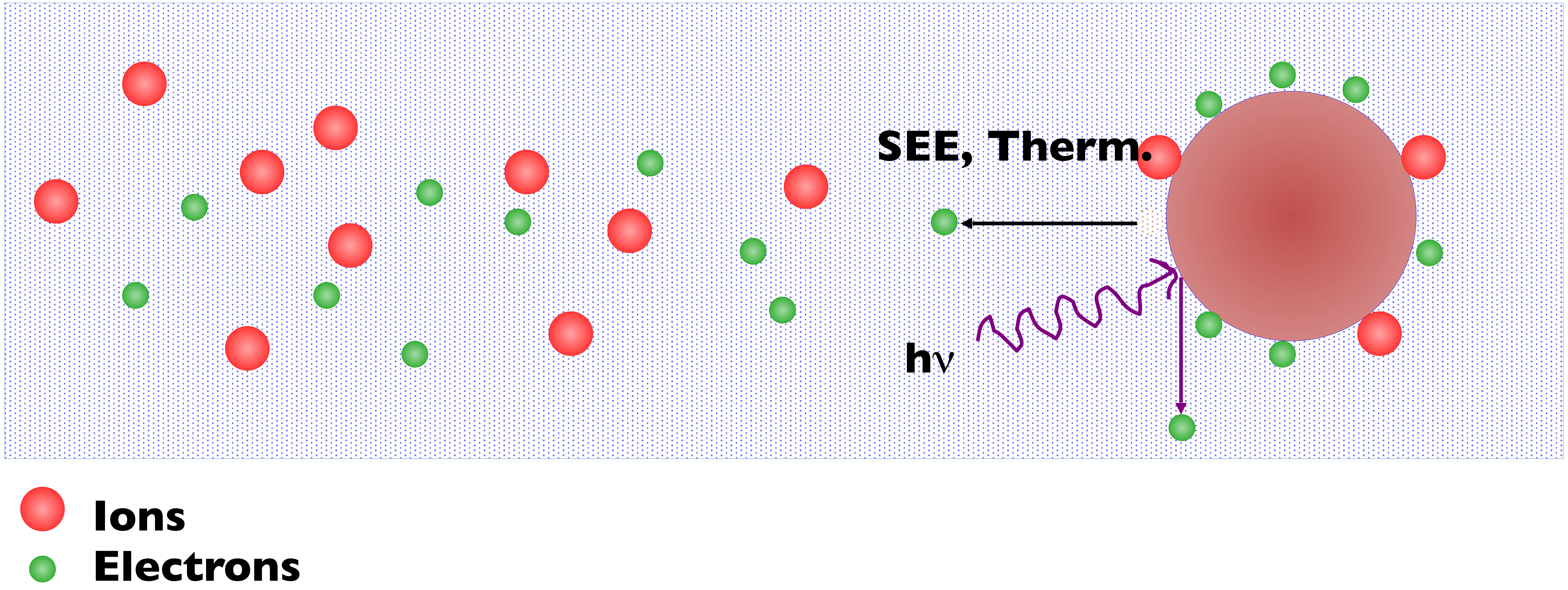
# Dust grain charge is a dynamic variable




- 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)

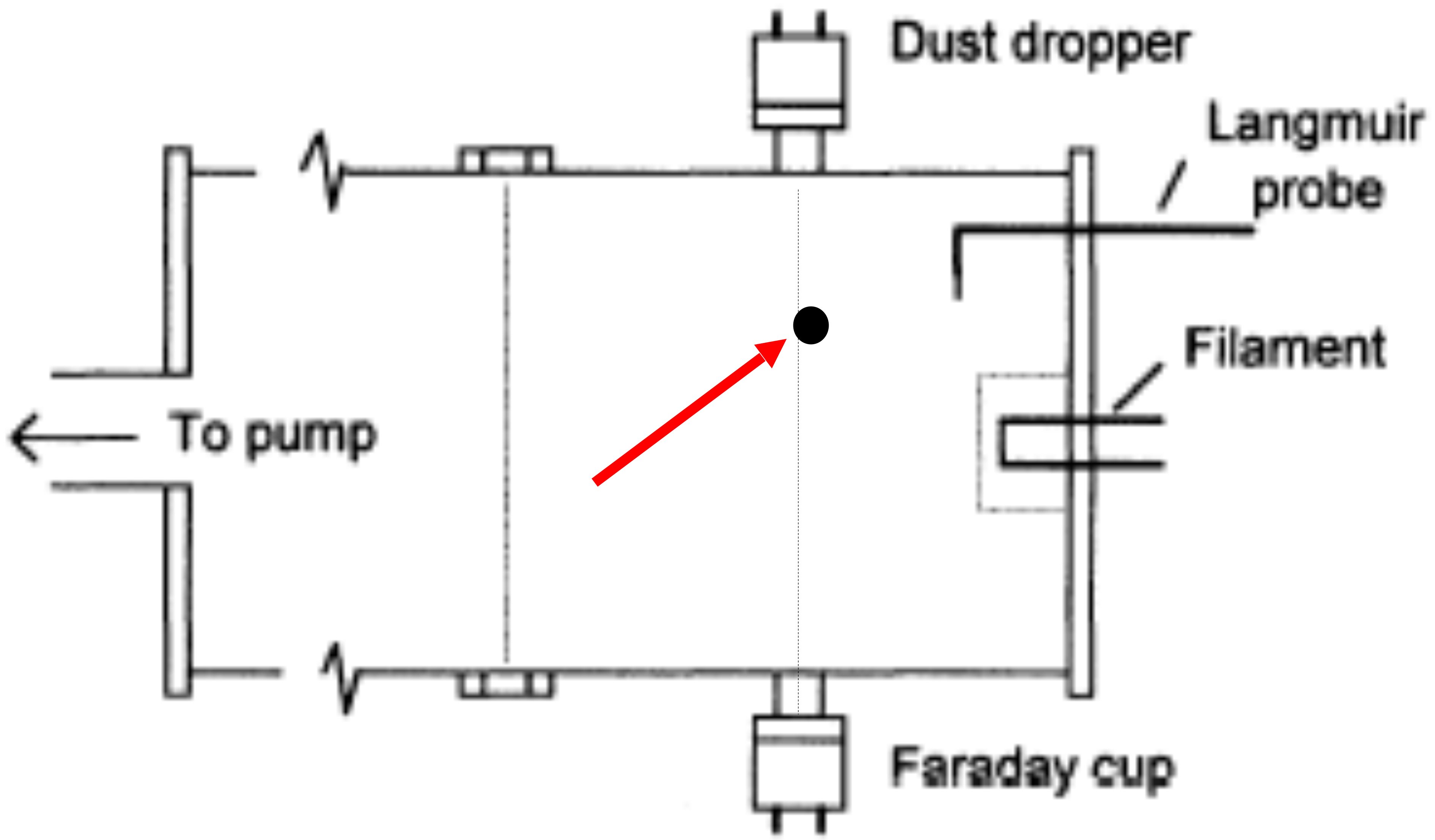
- Assume grains are conducting.
- Assume grains are spherical capacitors: $Q_d = \pm eZ_d = 4\pi\varepsilon_0 aU$
- Assume quasineutrality: $en_i = en_e + Q_d n_d$
- Solve the balance equation: $I_e + I_i = 0$

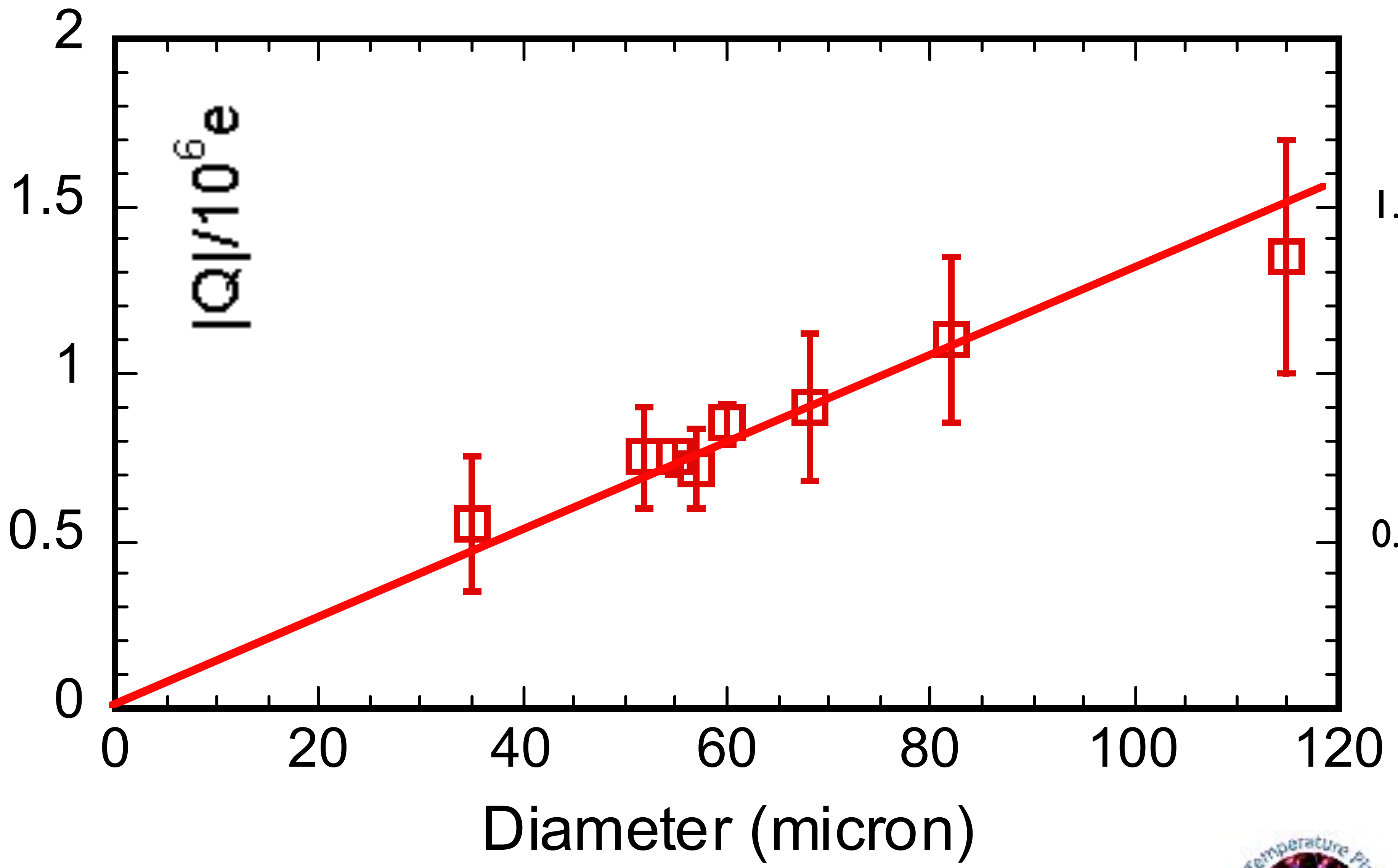
$$\left(1+\frac{Q_d n_d}{e n_0}\right)\left(\frac{m_i T_e}{m_e T_i}\right)^{1/2} \exp\left(\frac{eU}{kT_e}\right) = 1-\left(\frac{eU}{kT_i}\right)$$

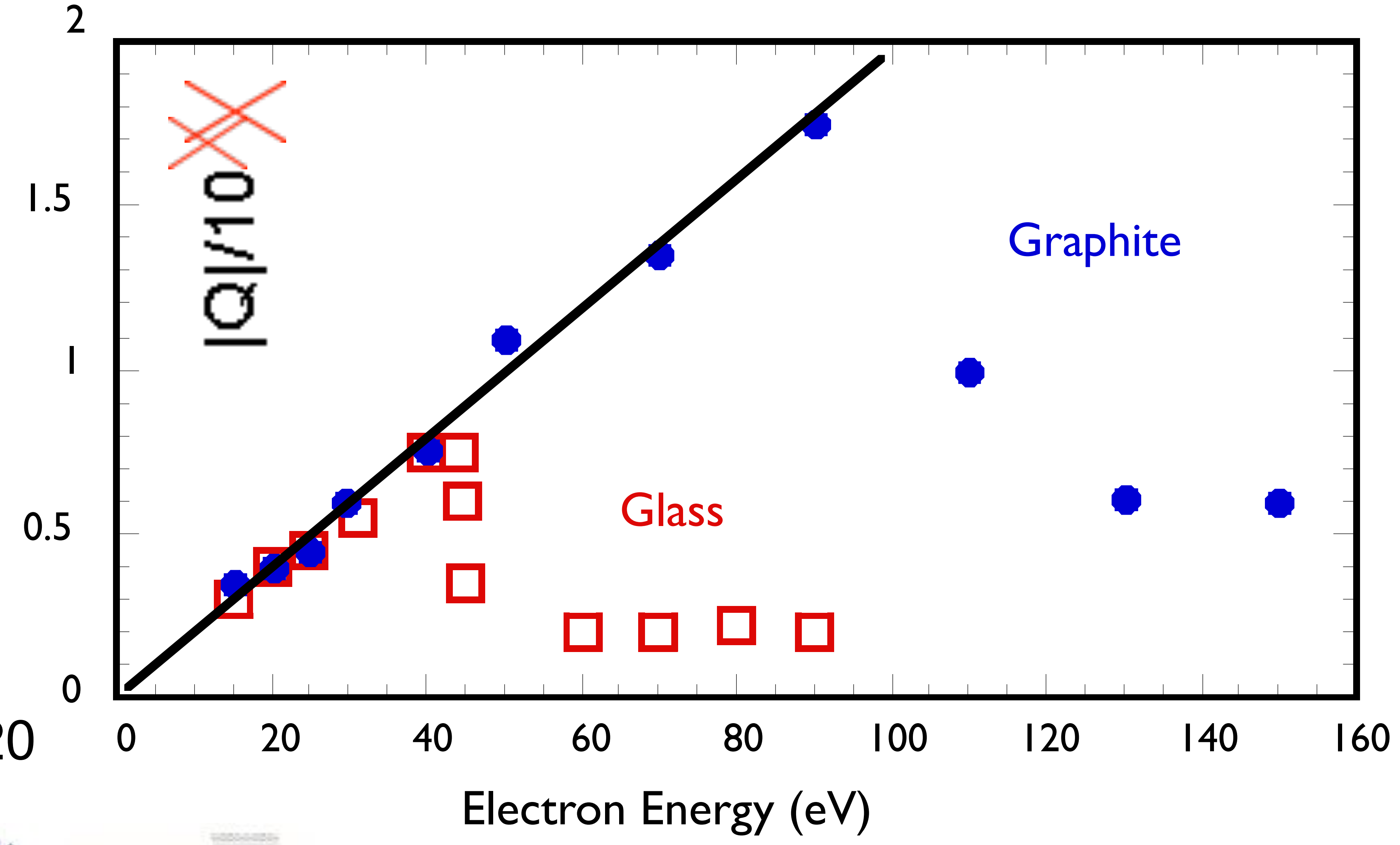
- Solve numerically for the grain surface potential U to get the charge, $Q_d$.

# 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

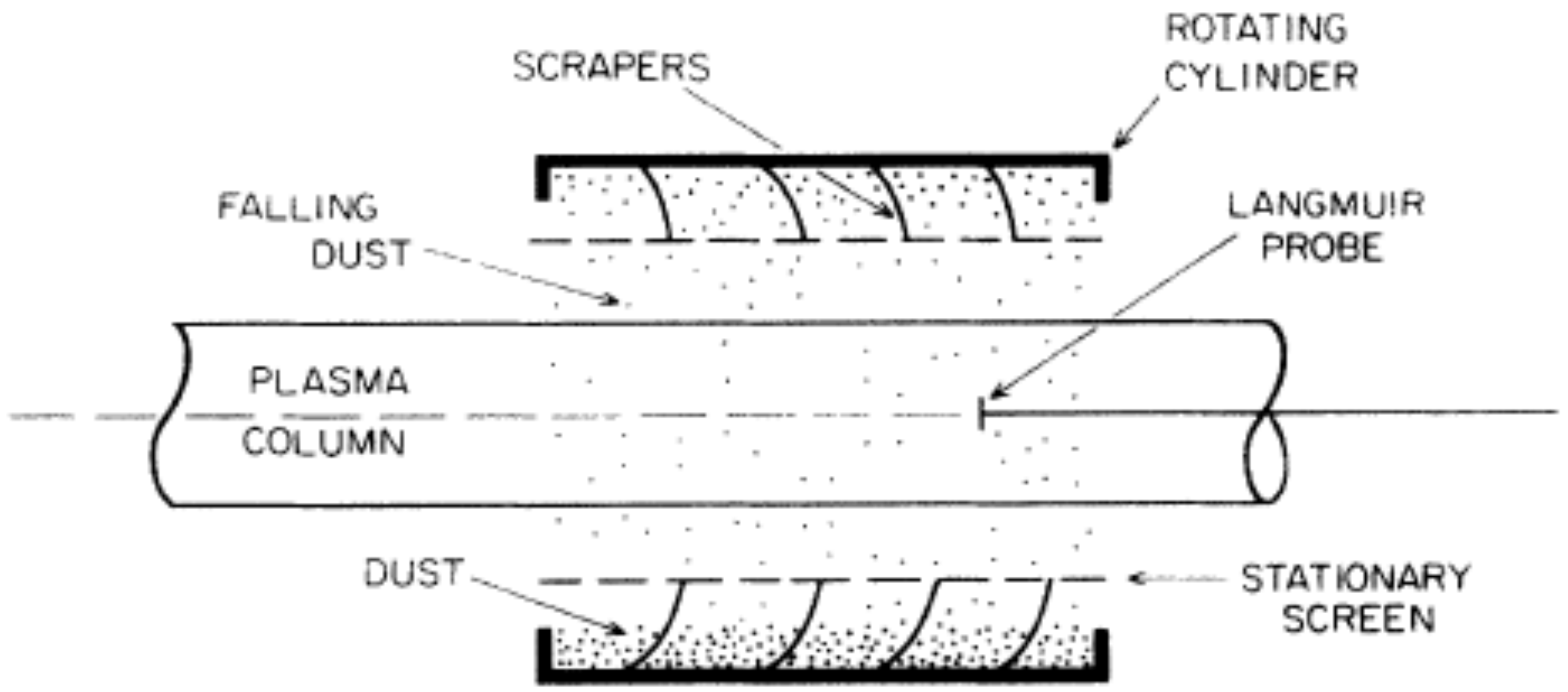



FIG. 2. Schematic diagram of the device used to disperse dust into the plasma column.

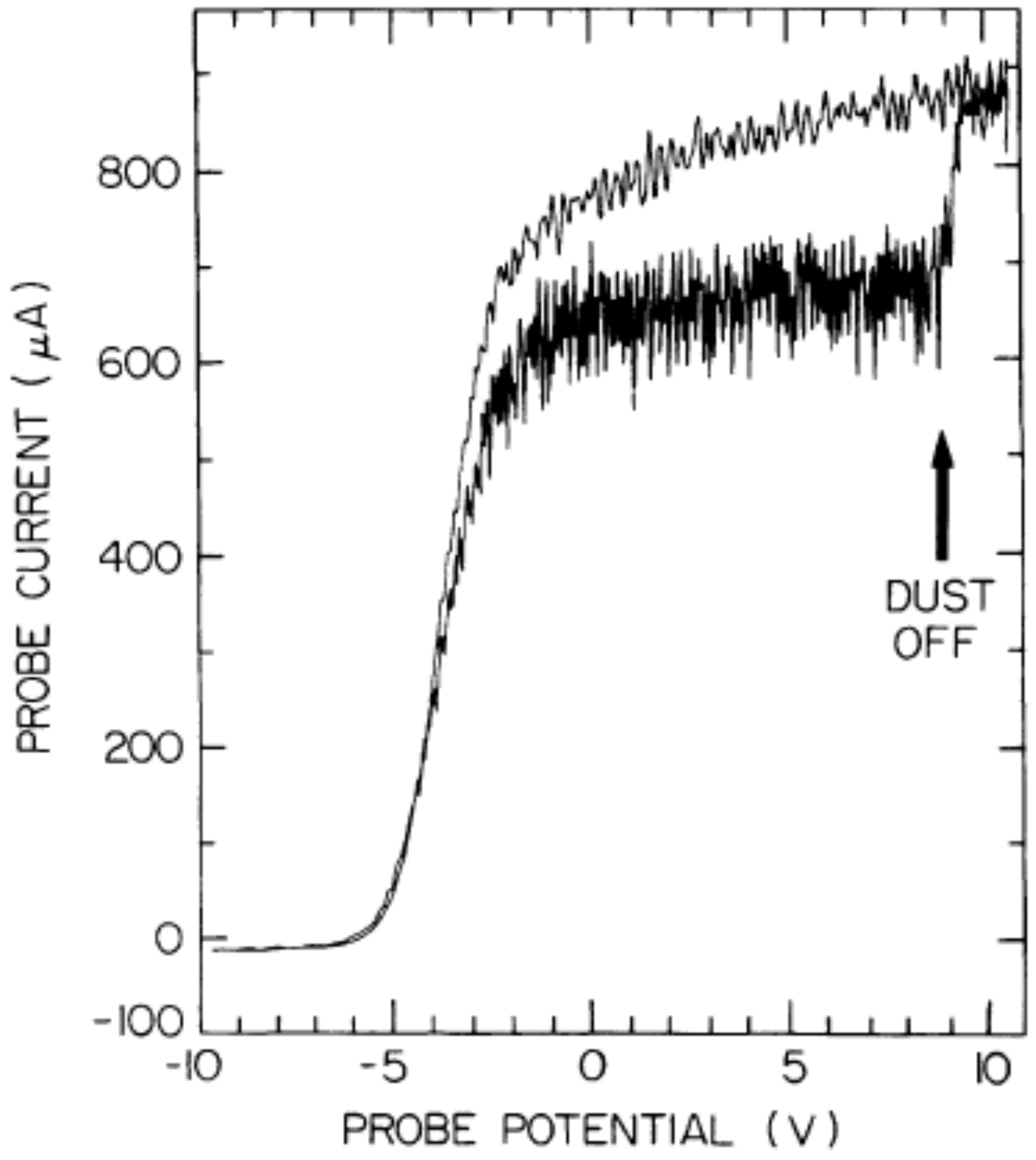
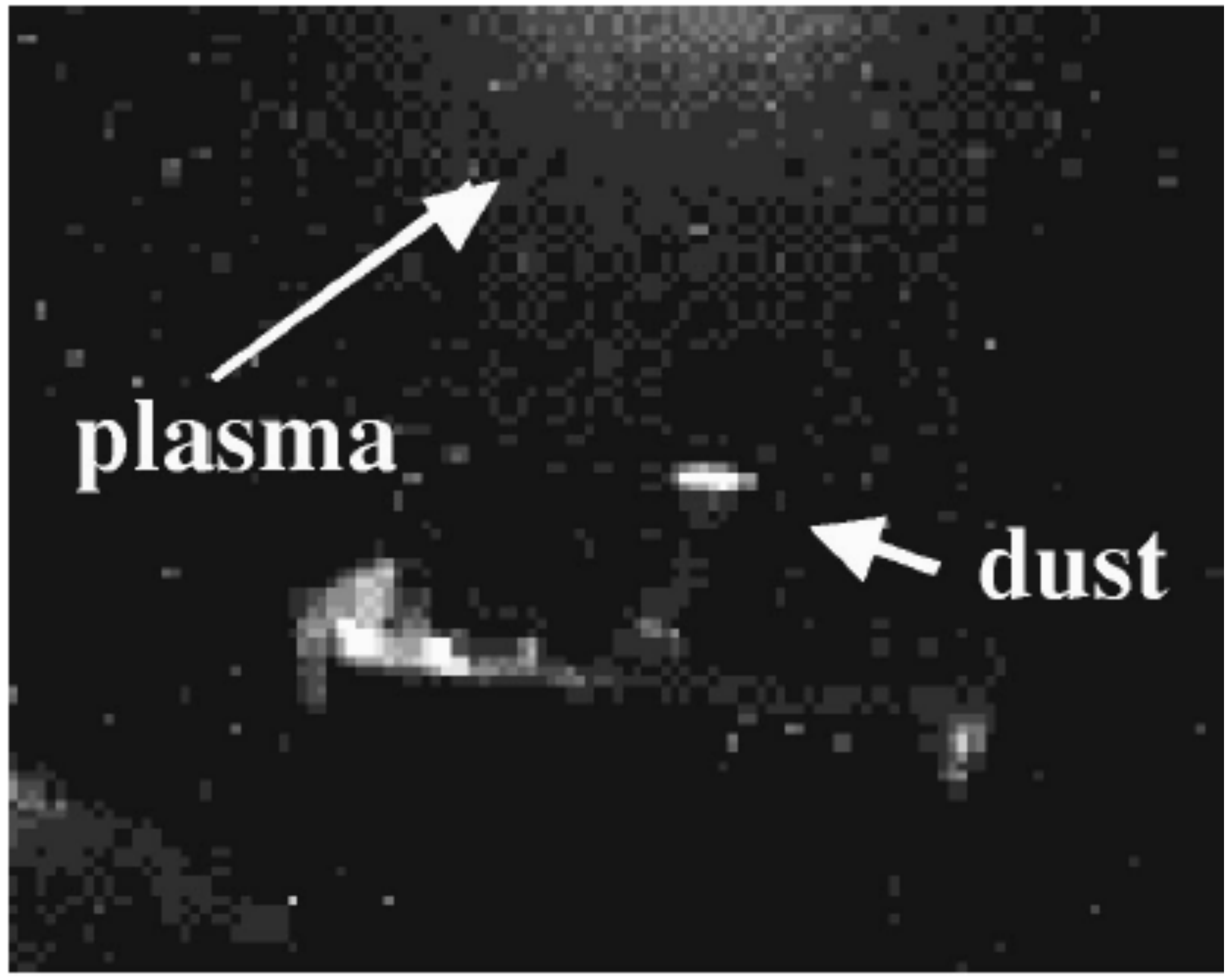



FIG. 3. Langmuir probe characteristics obtained under identical conditions, except for the absence (upper plot) or presence (lower plot) of kaolin dust. In the lower characteristic, the dust dispenser is abruptly turned off near the end of the trace to check that the electron current returns to the no-dust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

# Charging experiments (3)

Grain charging in a dc glow discharge pla
-> Here, $T_i << T_e$



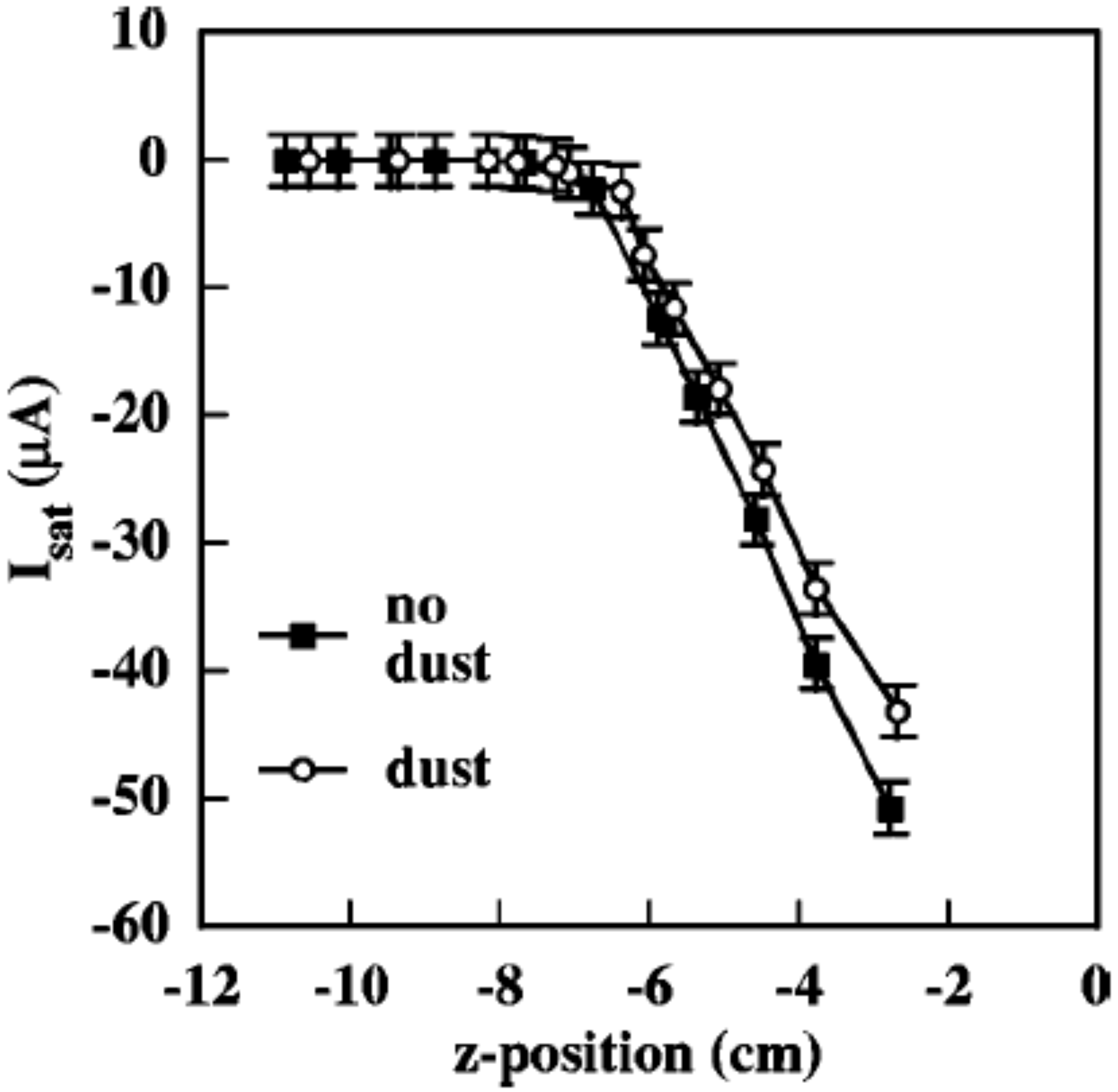




FIG. 3. Electron saturation current measurement as a function of axial position in the FPS device. The open circles indicate measurements of the electron saturation current in the absence of the silica dust and the closed squares indicate measurements of the electron saturation current in the presence of the silica dust particles.

E. Thomas and M. Watson, Phys. Plasmas, **7**, 3194 (2002)

# Basic properties of dusty plasmas

- Fundamental parameters
- Charging
- Forces

# Summary of the dominant forces in dusty plasmas

| **Force** | **Origin** | **Size dependence** |
|---|---|---|
| Weight | Gravity | $\boldsymbol{a}^3$ |
| Neutral drag | Streaming neutrals | $\boldsymbol{a}^2$ |
| Ion drag | Streaming ions | $\boldsymbol{a}^2$ |
| Thermophoretic | Temperature gradient | $\boldsymbol{a}^2$ |
| Electric | Electric field | $\boldsymbol{a}^1$ |
| Magnetic | Magnetic field | $\boldsymbol{a}^1$ |

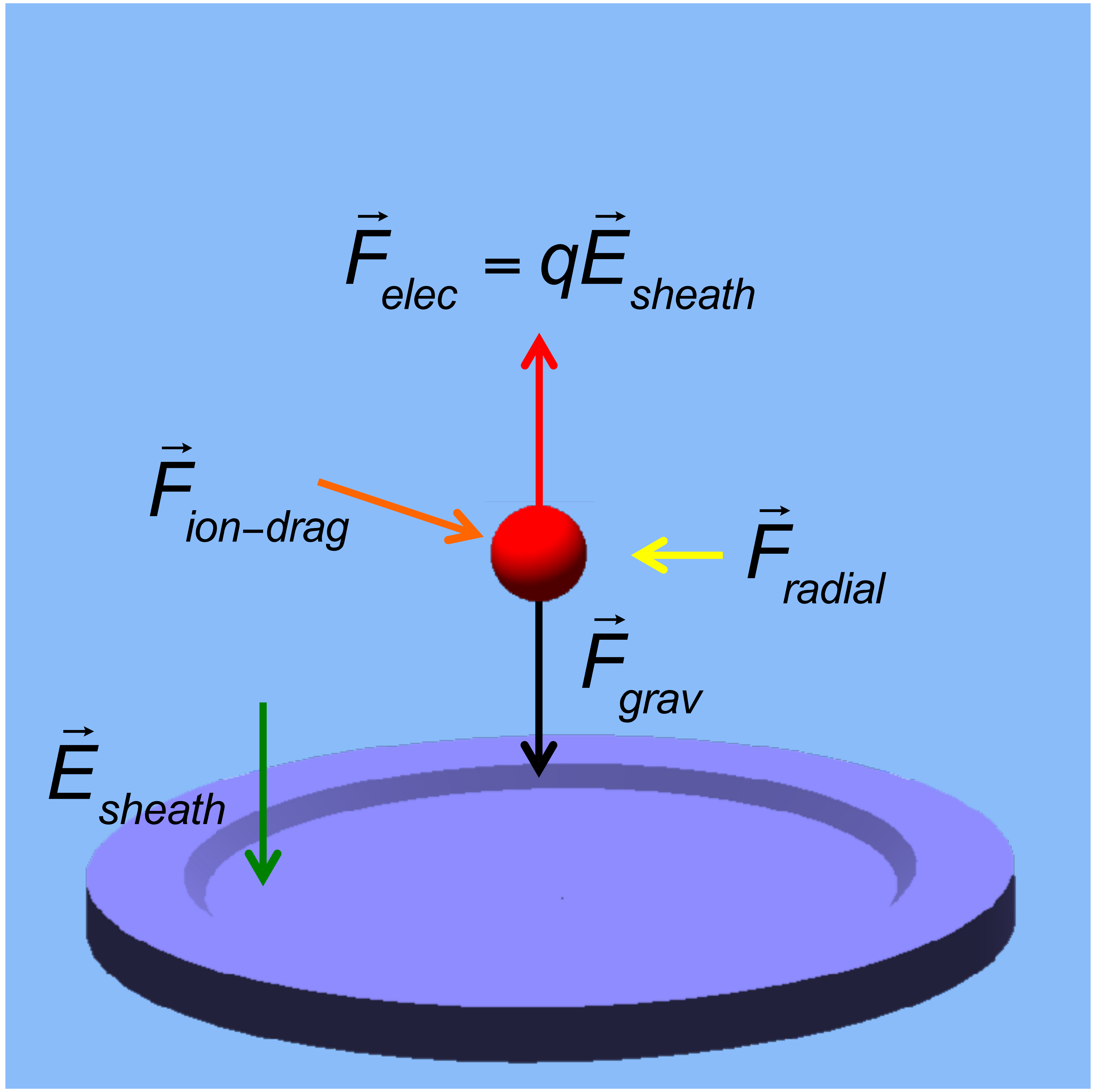
These forces give rise to the majority of the phenomena observed in laboratory and microgravity dusty plasma experiments

$\boldsymbol{a}$ = dust grain radius

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

# 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).

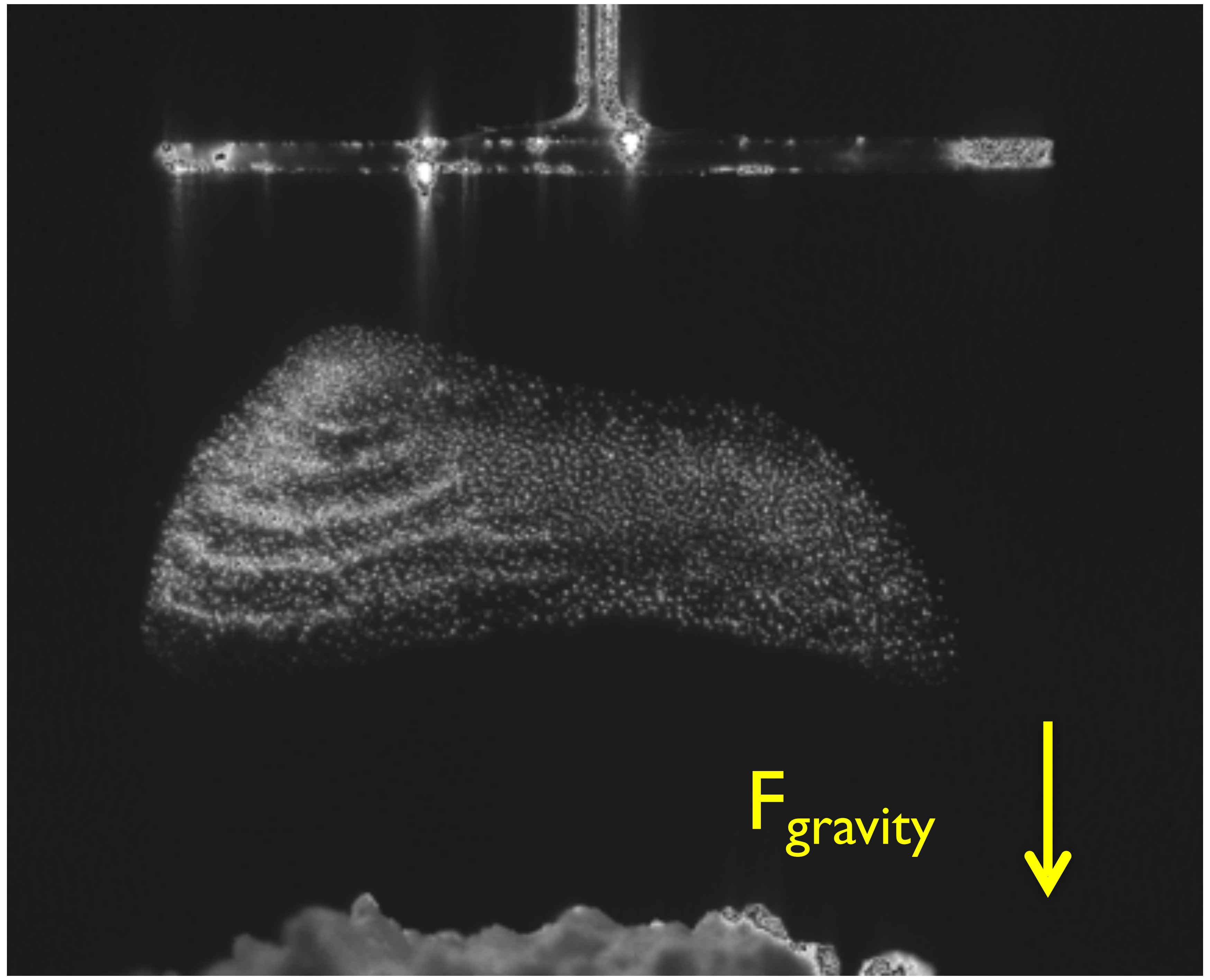



Image from Auburn University

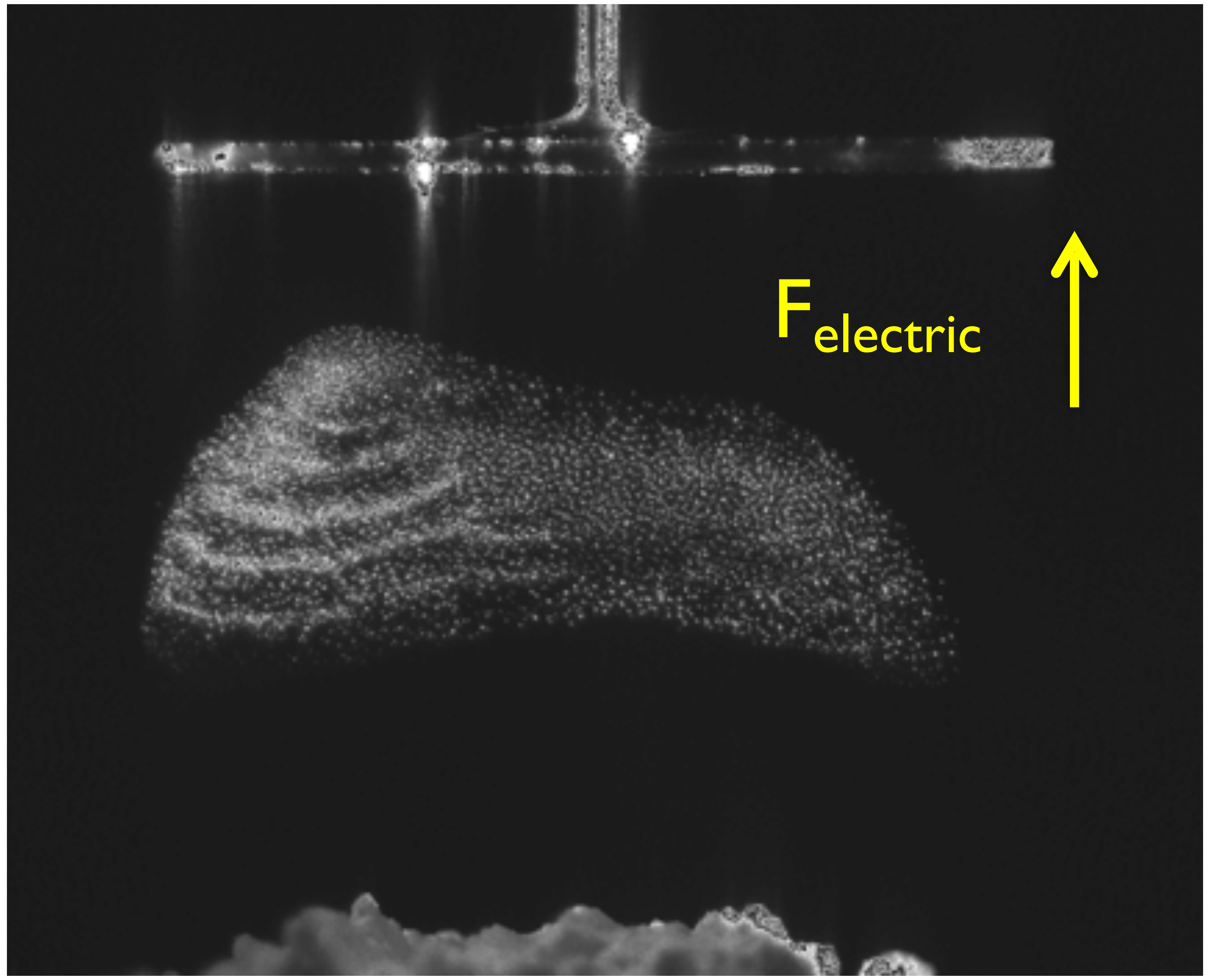
# Electric force

- 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.

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



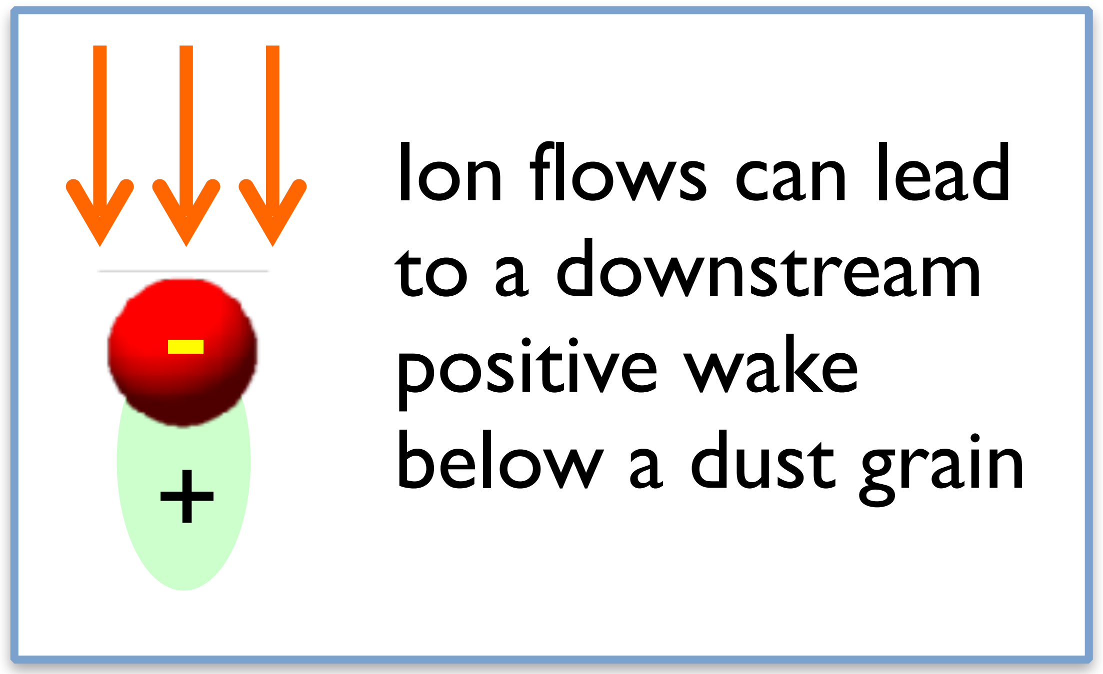




Image from Auburn University

# 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 μm
  - ➡ $m_d = 2.8 \times 10^{-14}$ kg
  - ➡ $Z_d$ = 4600 electrons
  - ➡ **E = 3.8 V/cm**

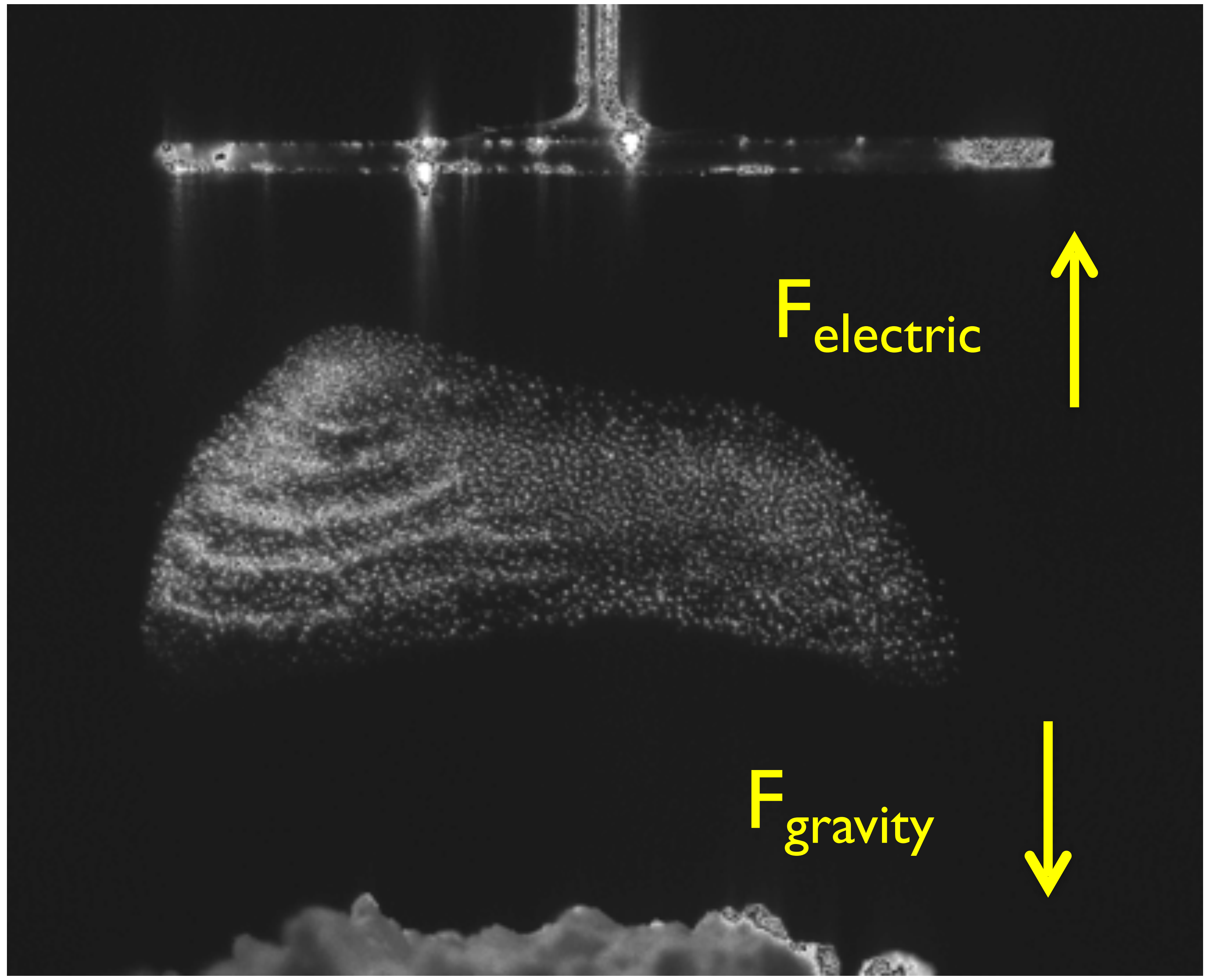
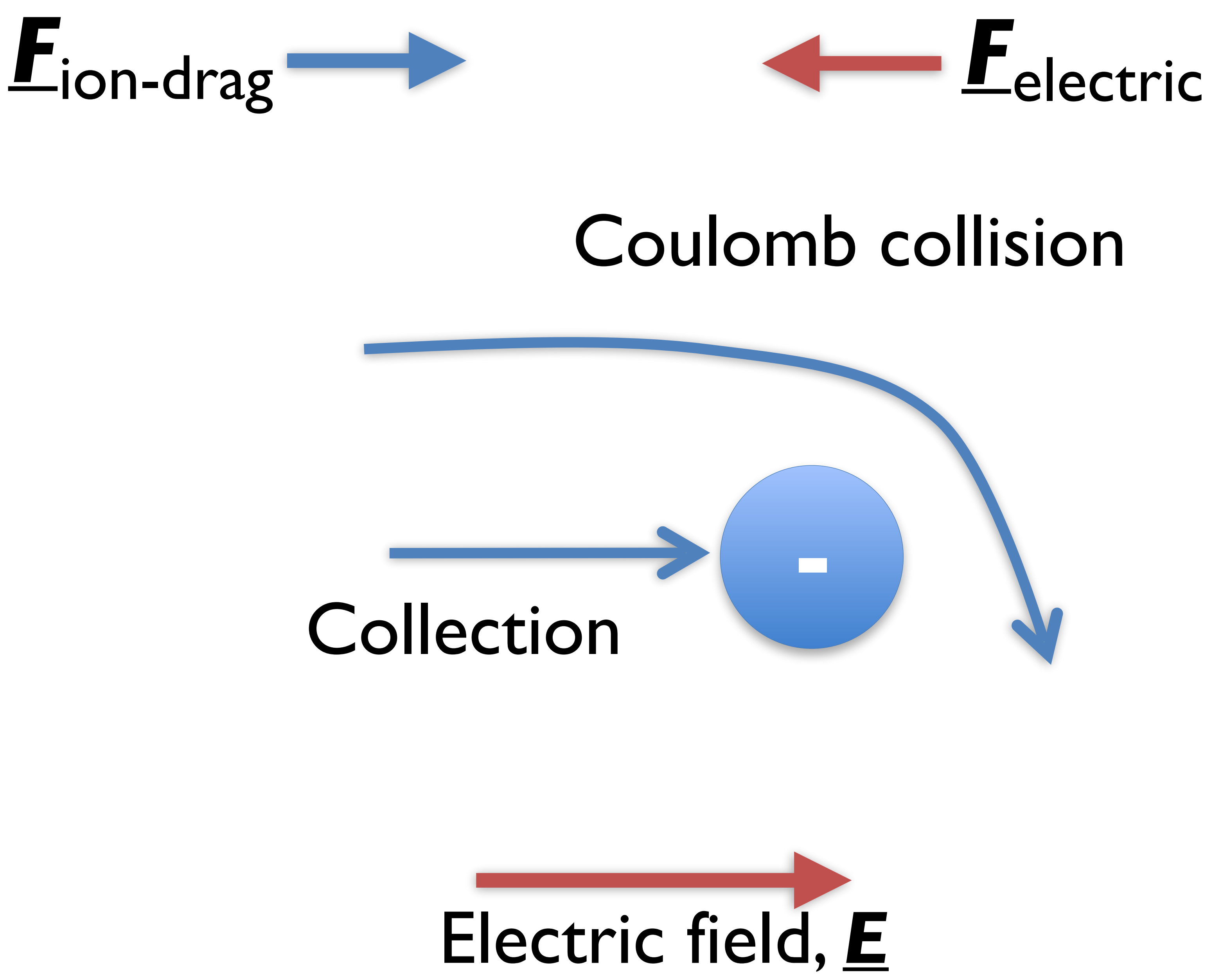



Image from Auburn University

# 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.
- $F_{ion\text{-}drag} = F_{collection} + F_{collision}$
- Critically depends upon the screening length of the dust particle.

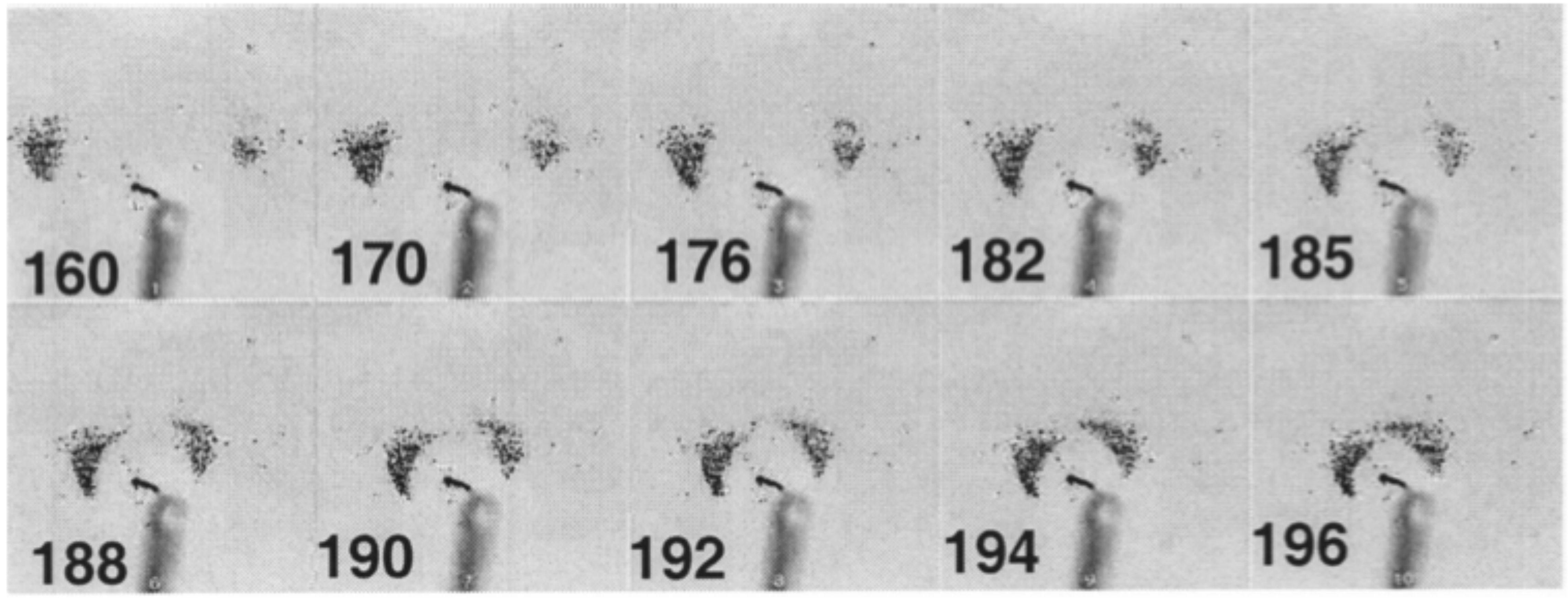


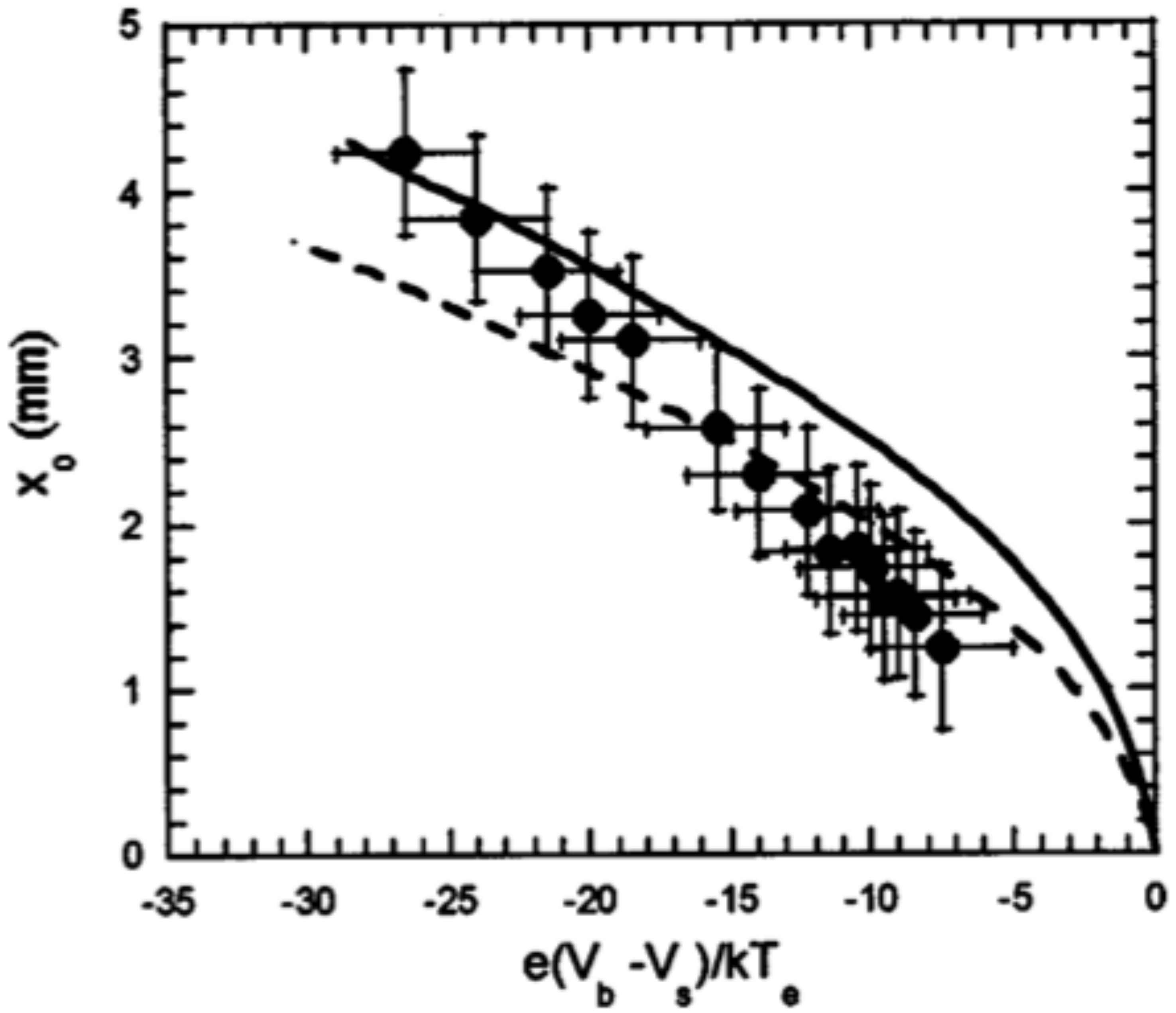

Refs: M. Barnes, et al., PRL, **68**, 313 (1992)
S. Khrapak, et al., PRE, **66**, 046414 (2002)
A. Ivlev, et al., PRE, **71**, 016405 (2004)
I. Hutchinson, et al., PPCF, **48** 185 (2006)
S. Khrapak, et al., IEEE TPS, **37**, 487 (2009)

# 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)

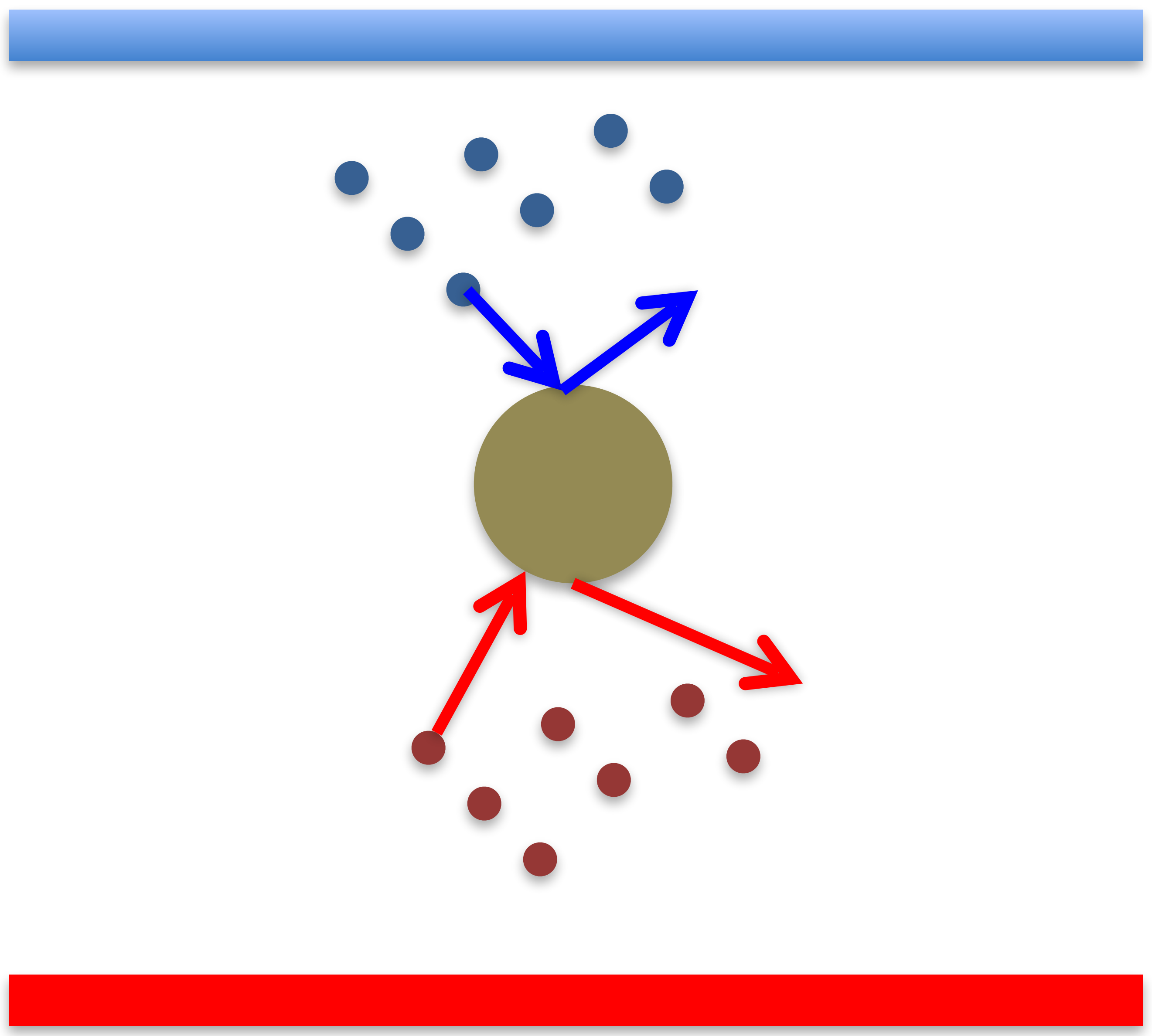
# Thermophoretic force

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

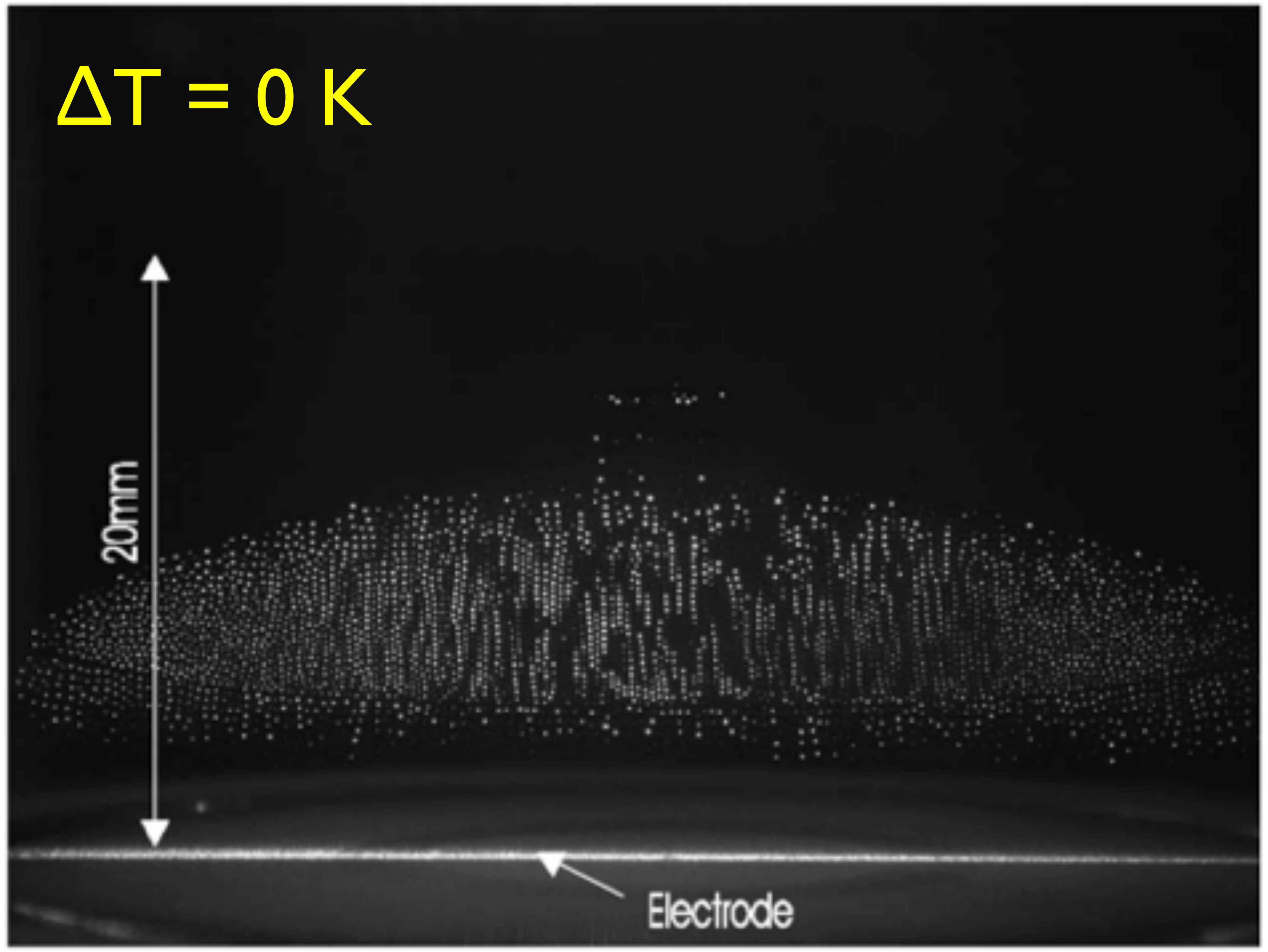
- Neutral atoms from "hot" side provide more momentum than those from "cold" side.

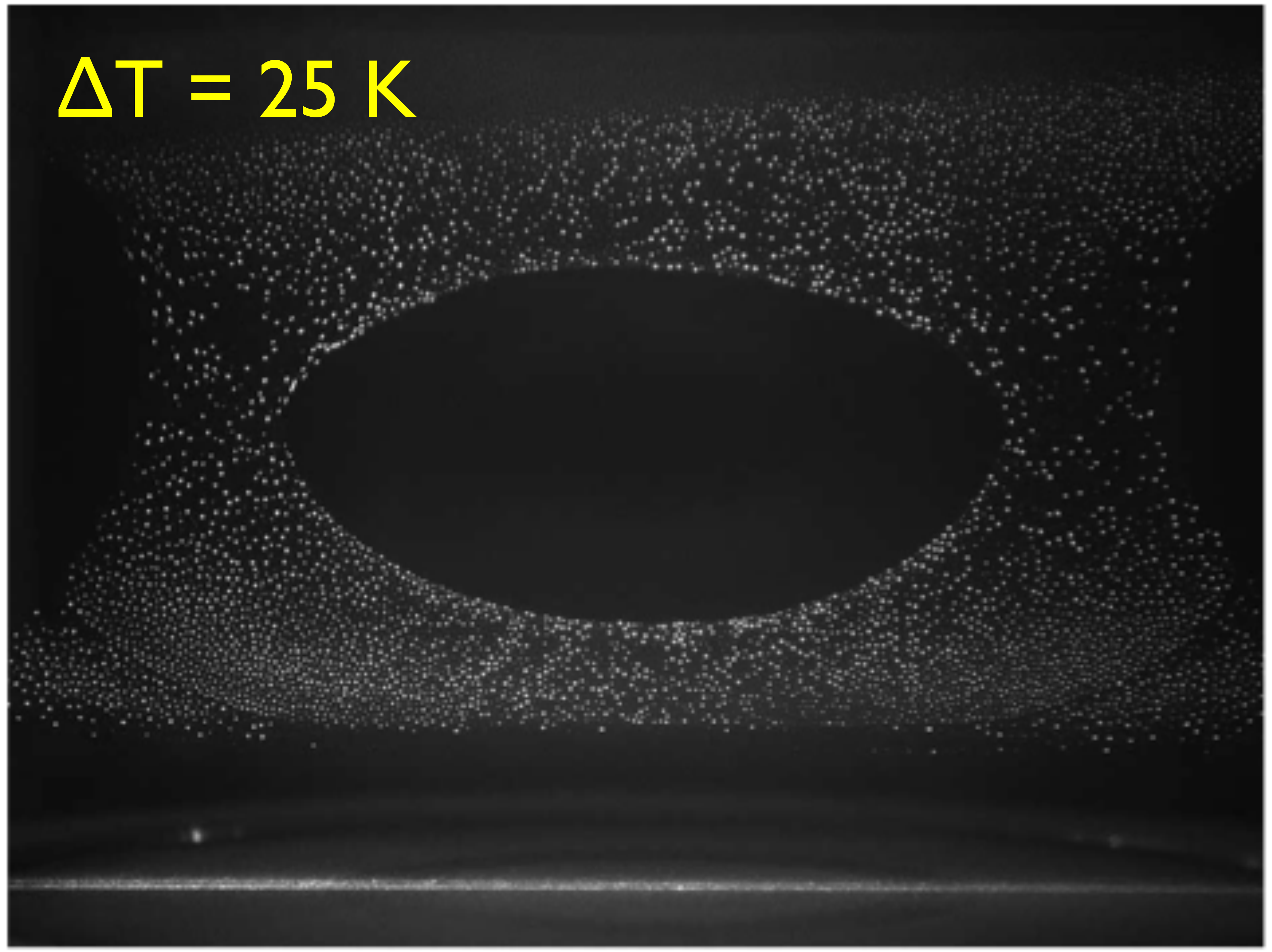
- $$F_{thermo} = -\frac{8}{3}\frac{a^2}{v_{tn}}\Lambda\frac{dT_n}{dz}$$

$v_{tn}$ – neutral thermal velocity
$T_n$ – neutral gas temperature
$\Lambda$ – thermal conductivity



# Evidence for thermophoretic force: simulated voids

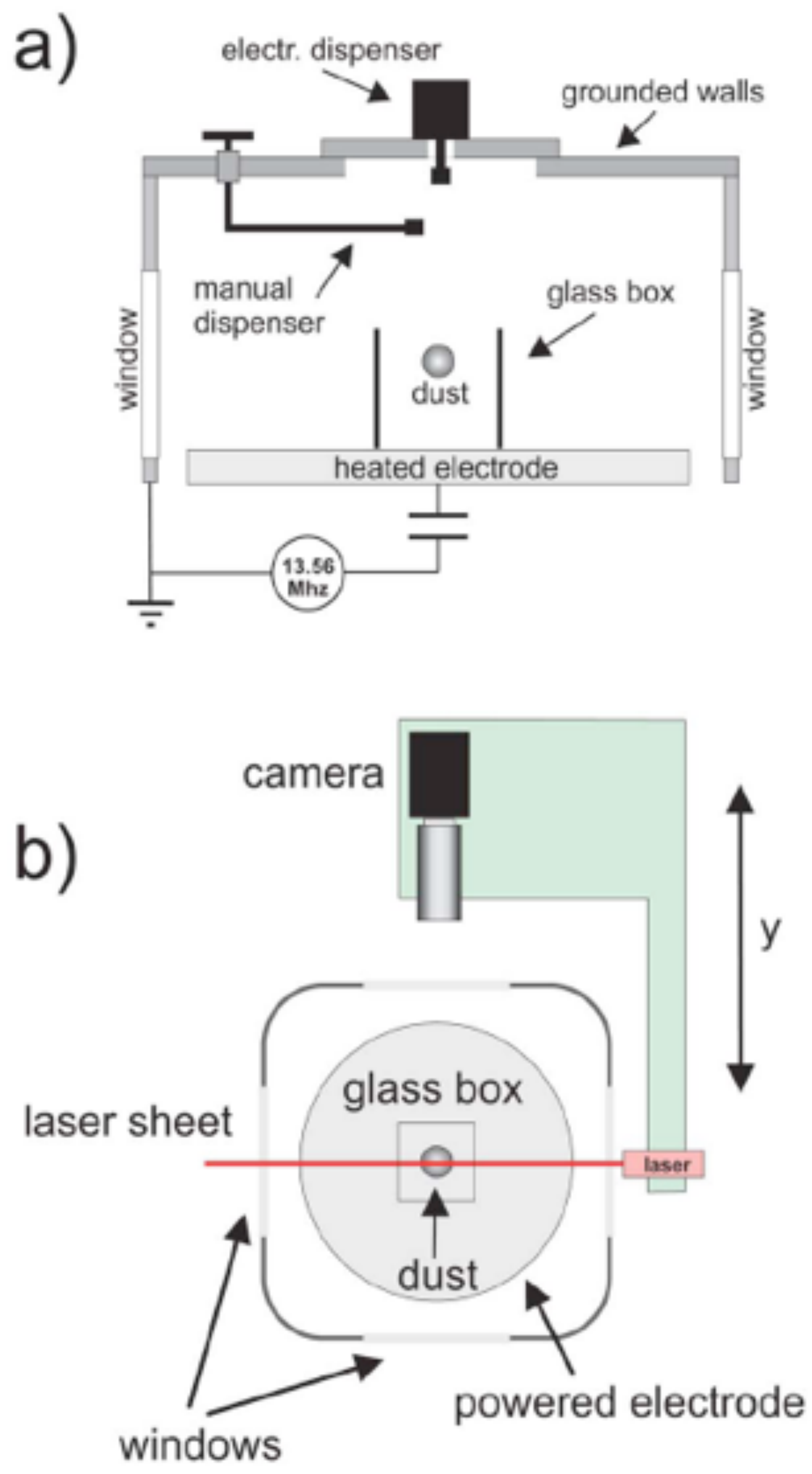


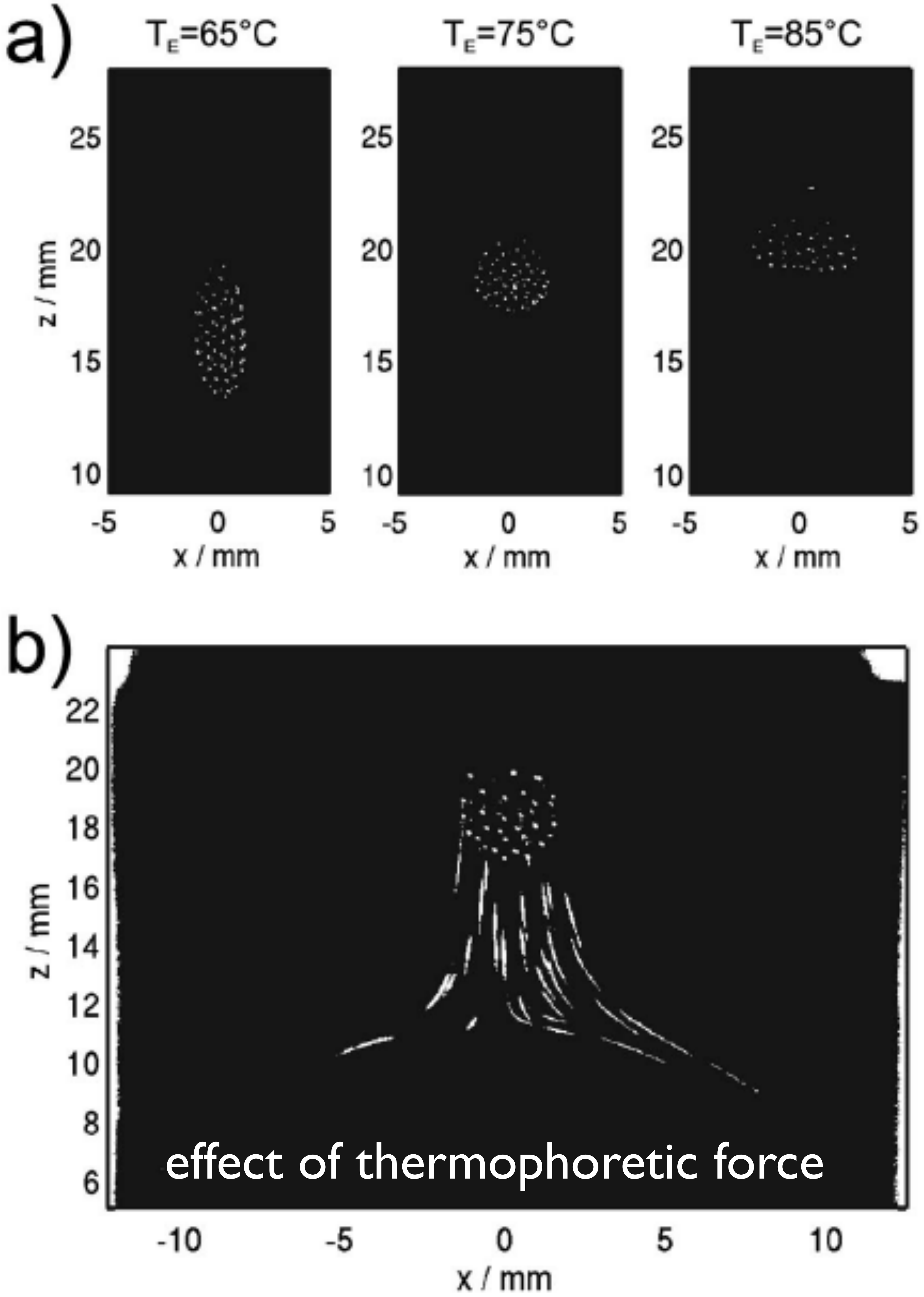




- Dusty plasma of 3.4 μm melamine formaldehyde particles
- Applied temperature gradient of ~1200 K/m
- ΔT = 25 K over 20 mm
- Lower electrode is heated using a Peltier element

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

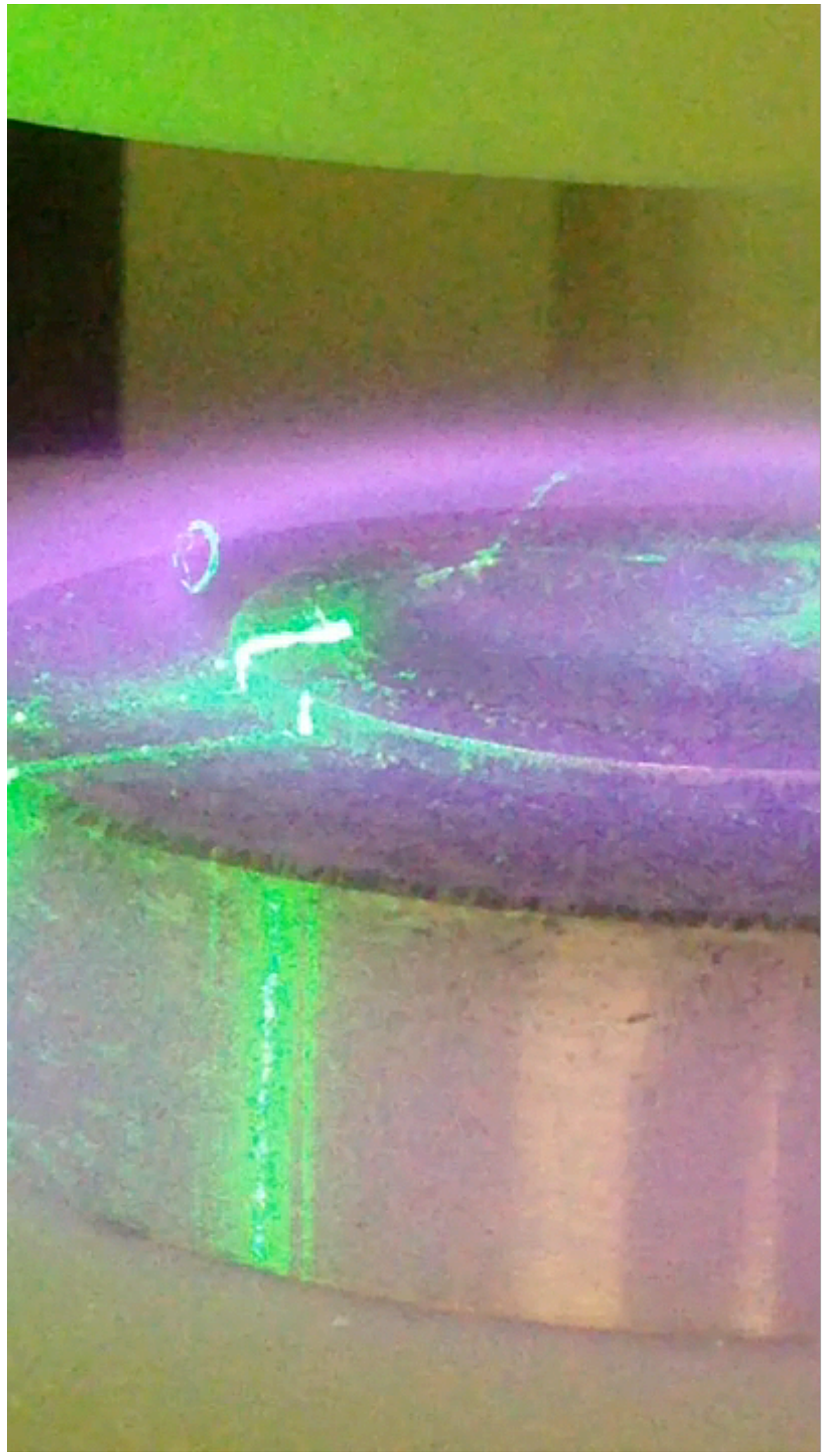
# Evidence for thermophoretic force:

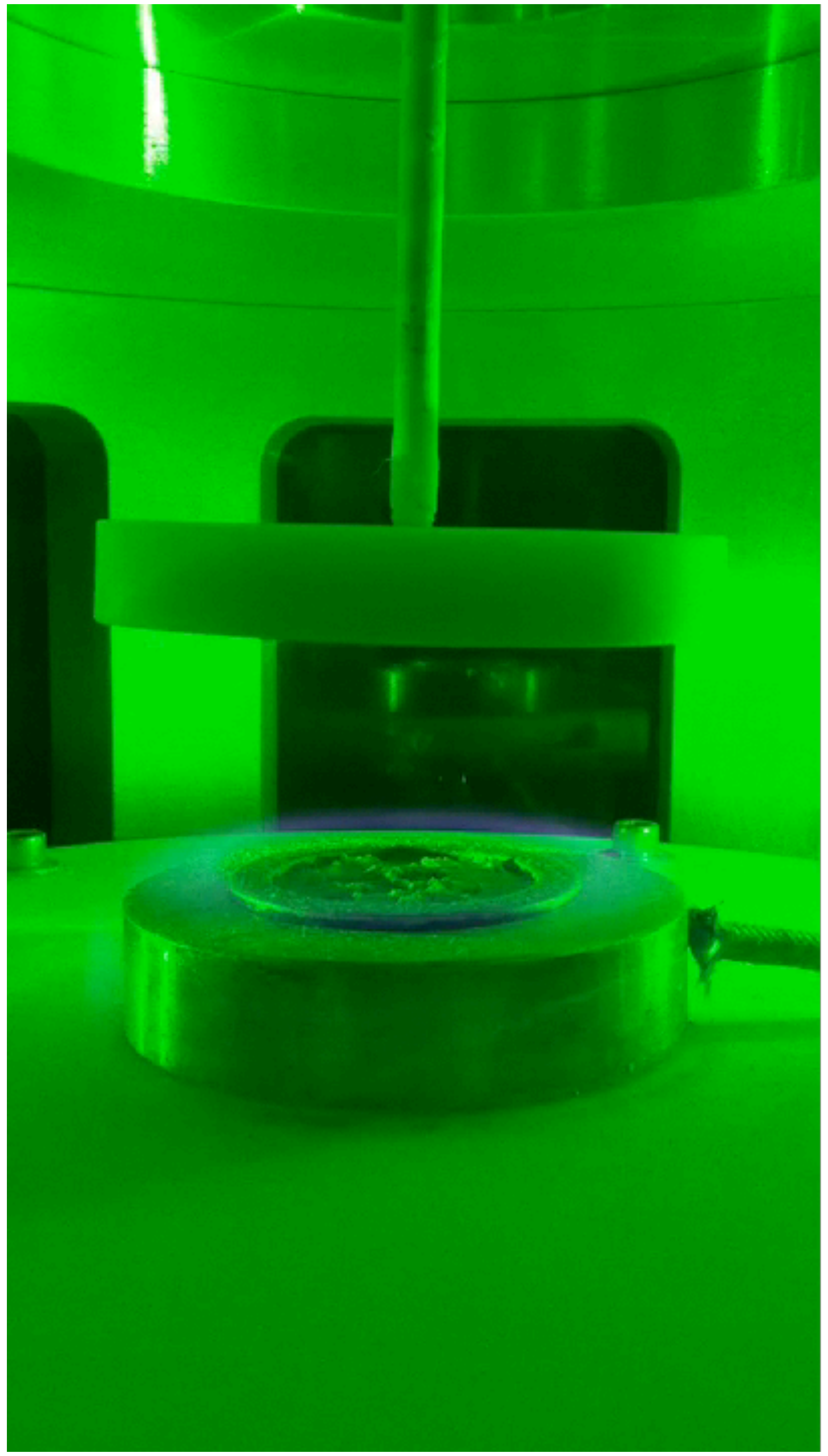


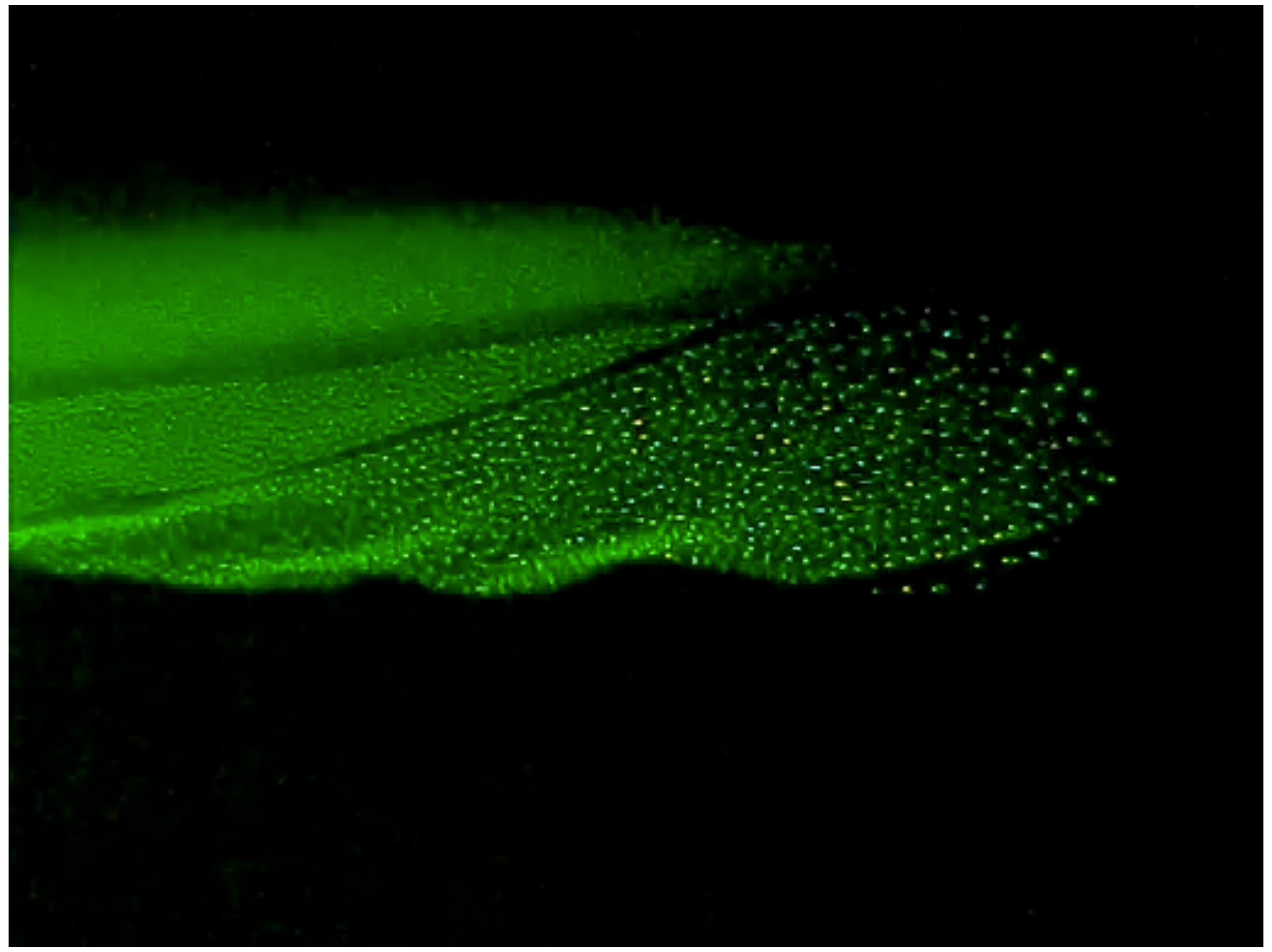



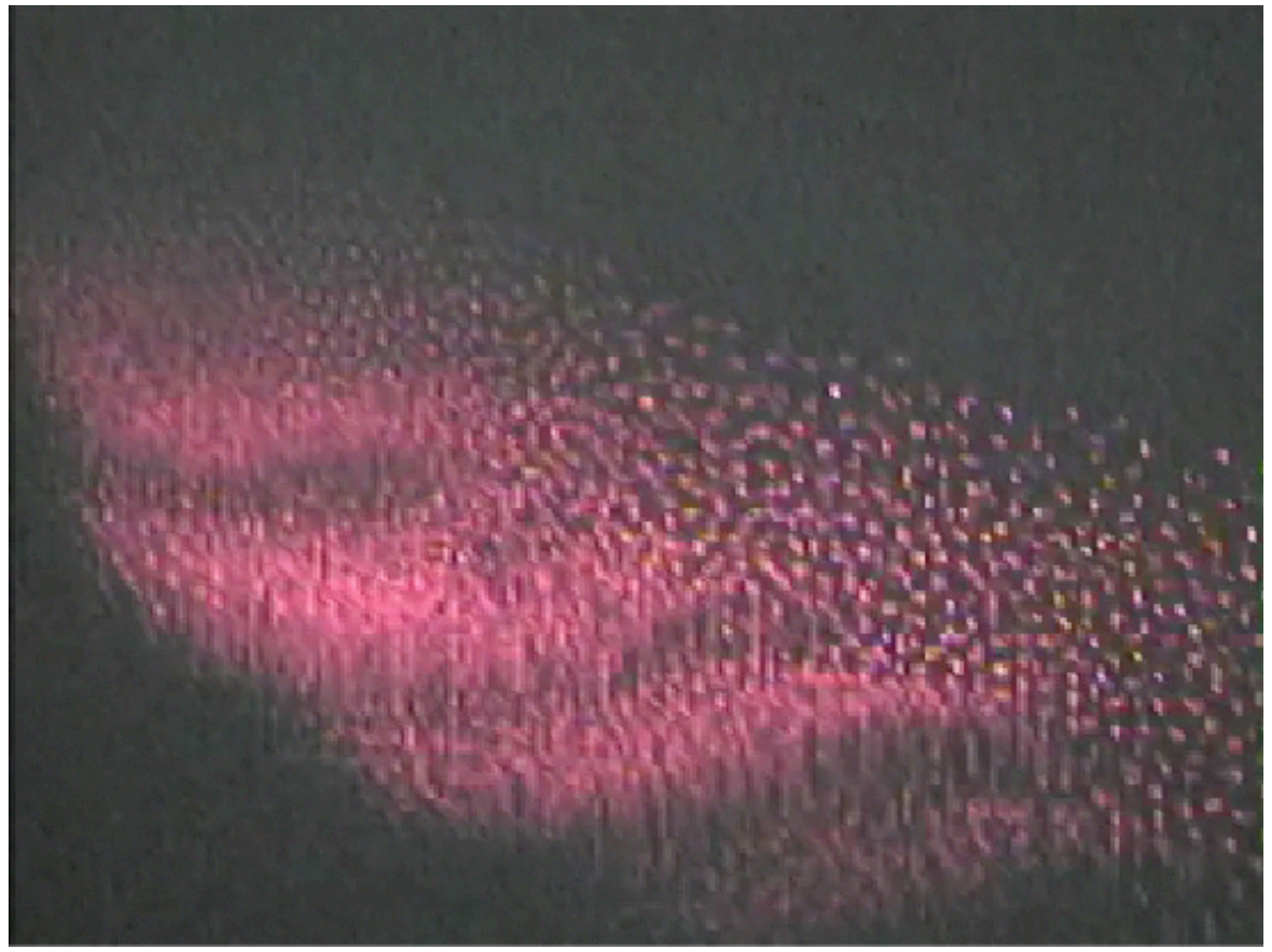

O. Arp, et al, Phys. Plasmas, **12**, 122102 (2005)

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





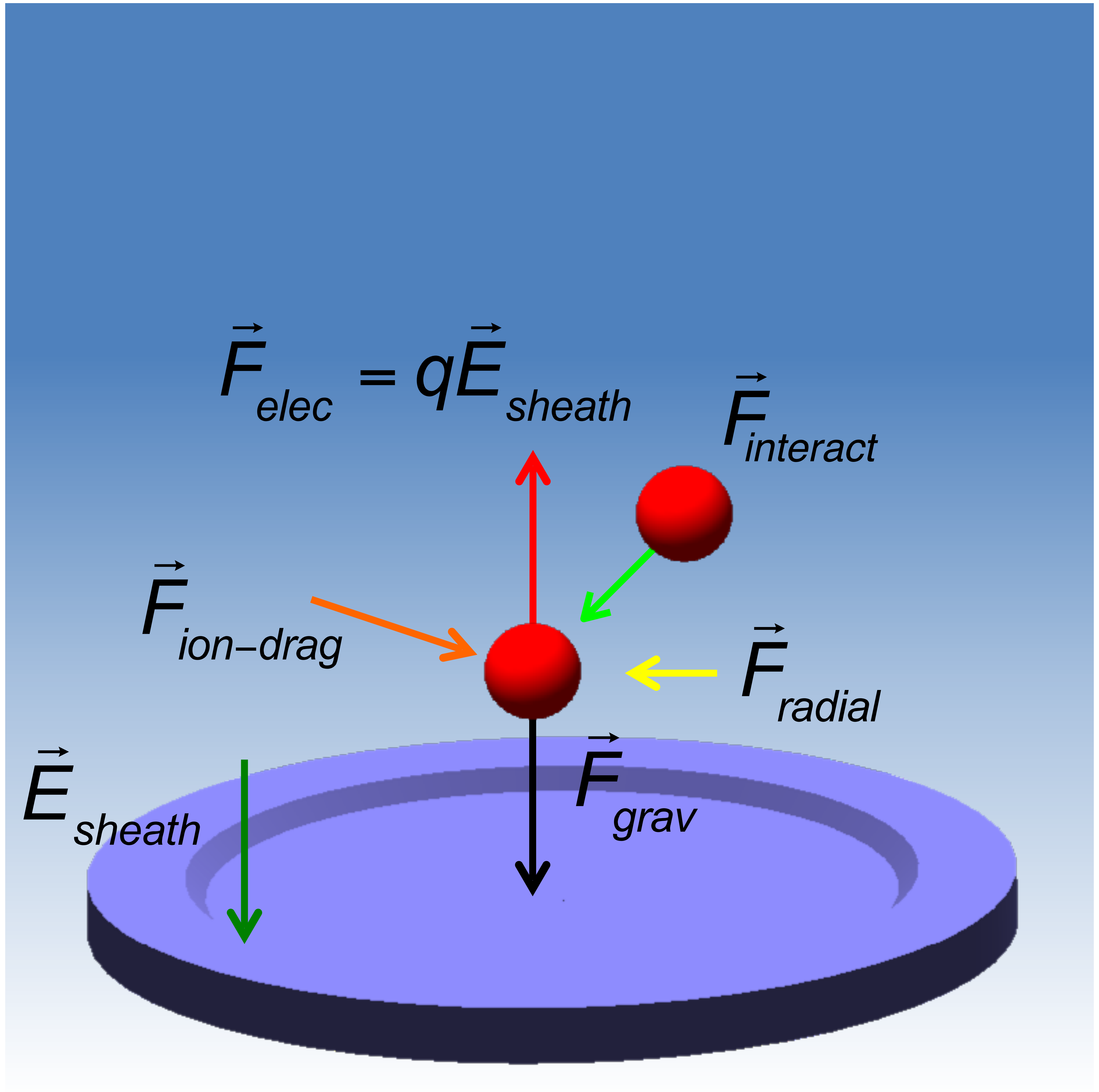




# RECENT ADVANCES IN DUSTY PLASMA RESEARCH:
## MICROGRAVITY RESEARCH ON THE SPACE STATION

# Gravity acts to compress the dust particles to the plasma sheath region

- On the ground, particles are suspended in a plasma due to a balance of forces that counteract gravity; this compresses the system.
- Without the influence of gravity, it is possible to study the detailed physics of how the particles interact with the plasma and with each other – without the need to suspend the particles against gravity.
- Studying complex plasmas under microgravity gives new insights into fundamental plasma physics, fluid mechanics, and soft condensed matter.



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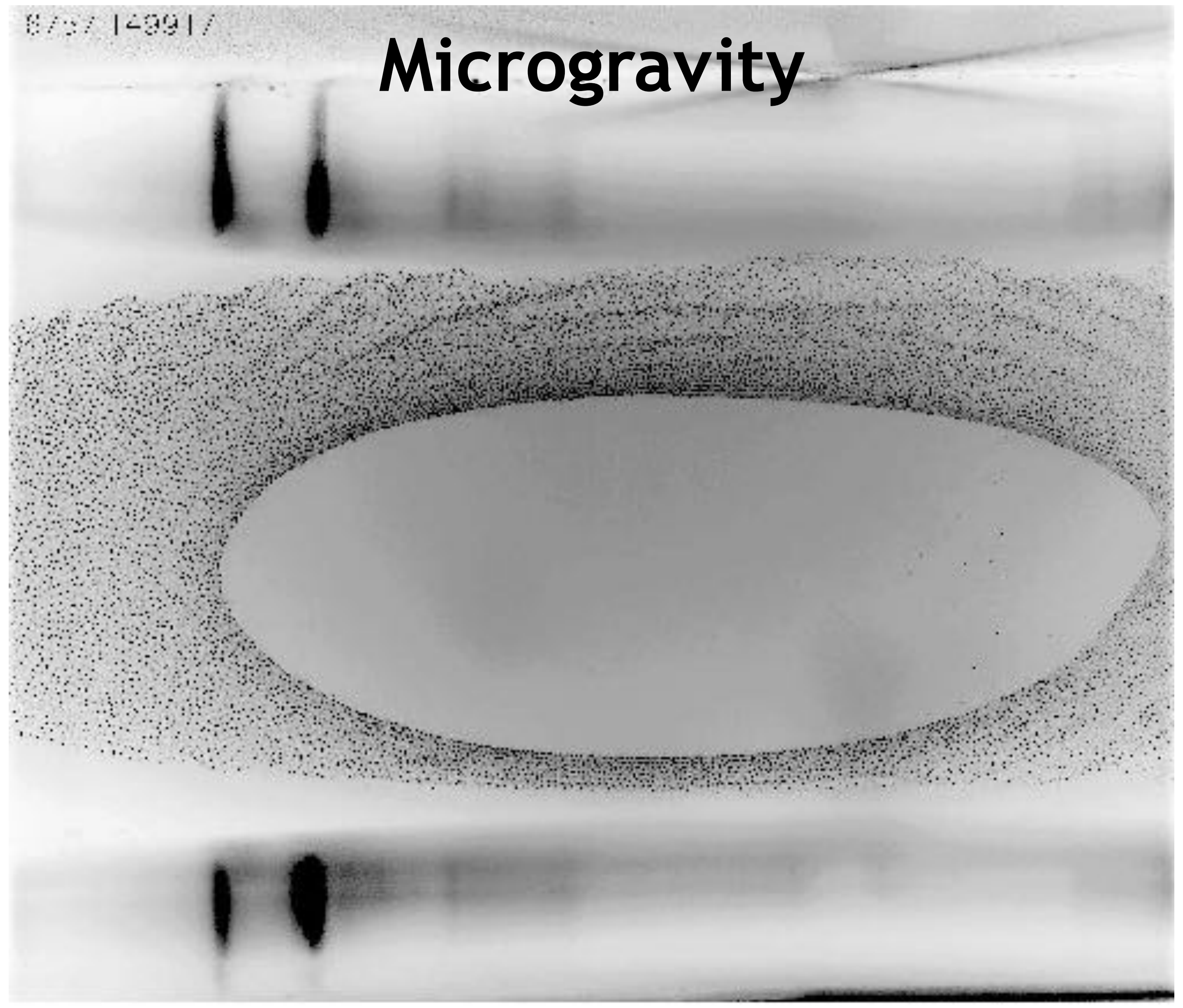
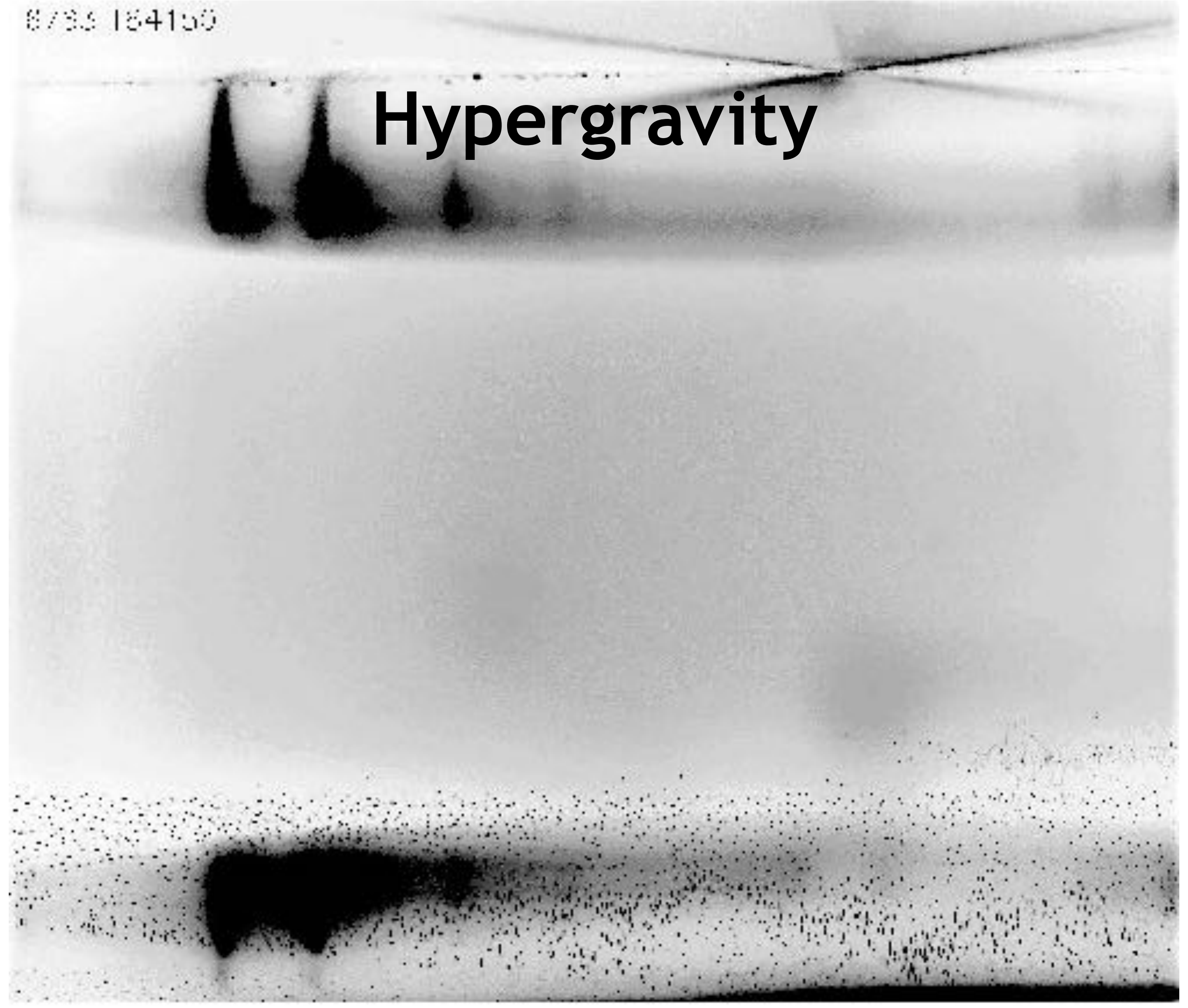
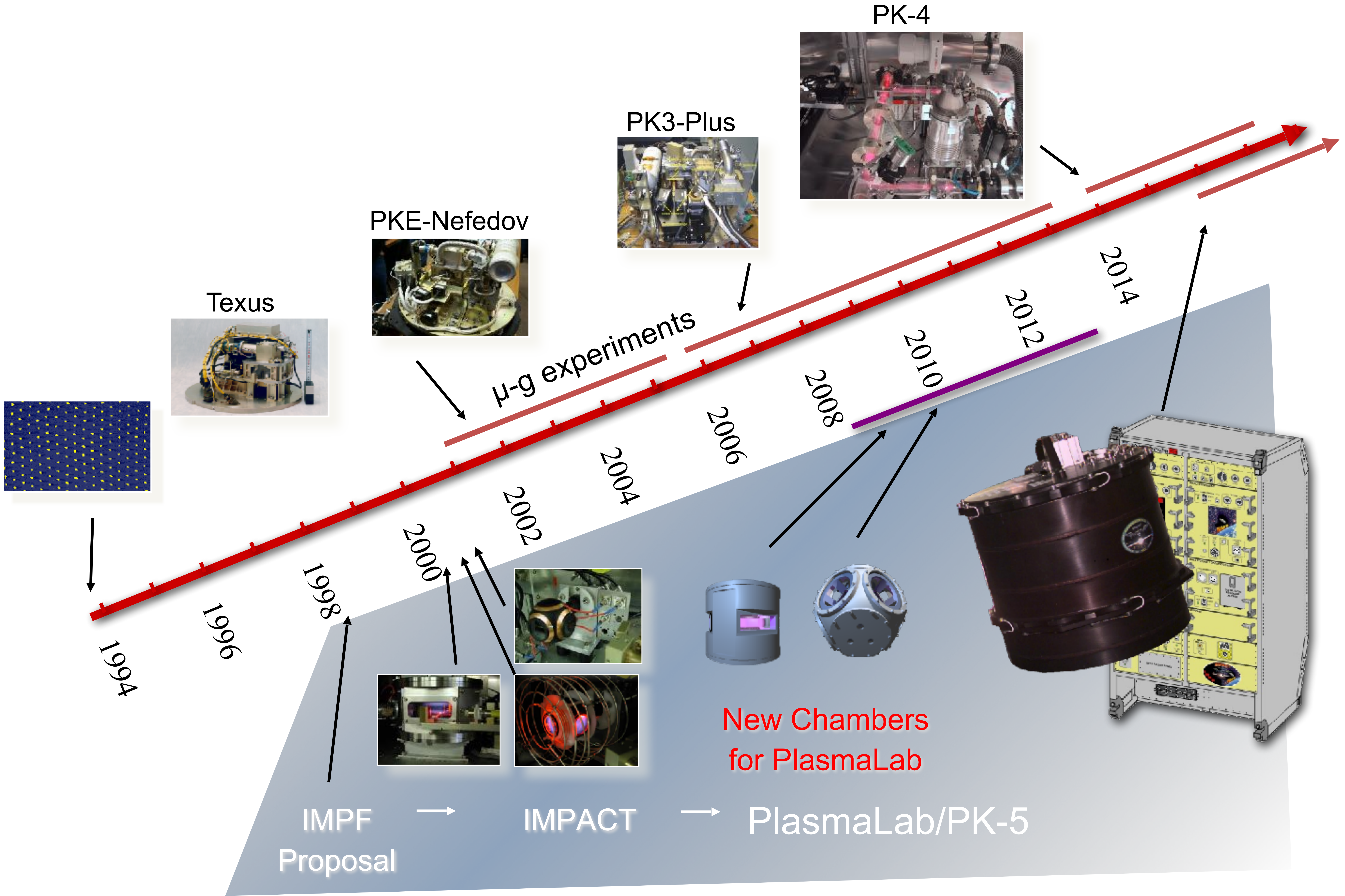
Parabolic flight data from PlasmaLab



# Progress in the study of complex plasmas in microgravity and on the ISS



# Evidence for ion drag force: voids in space

- In rf plasmas in microgravity experiments, a void appears.
- Enhanced ionization at the center: provides a source of ions and outward electric field.
- Boundary determined by the force balance: $F_{elec} = F_{ion\text{-}drag}$

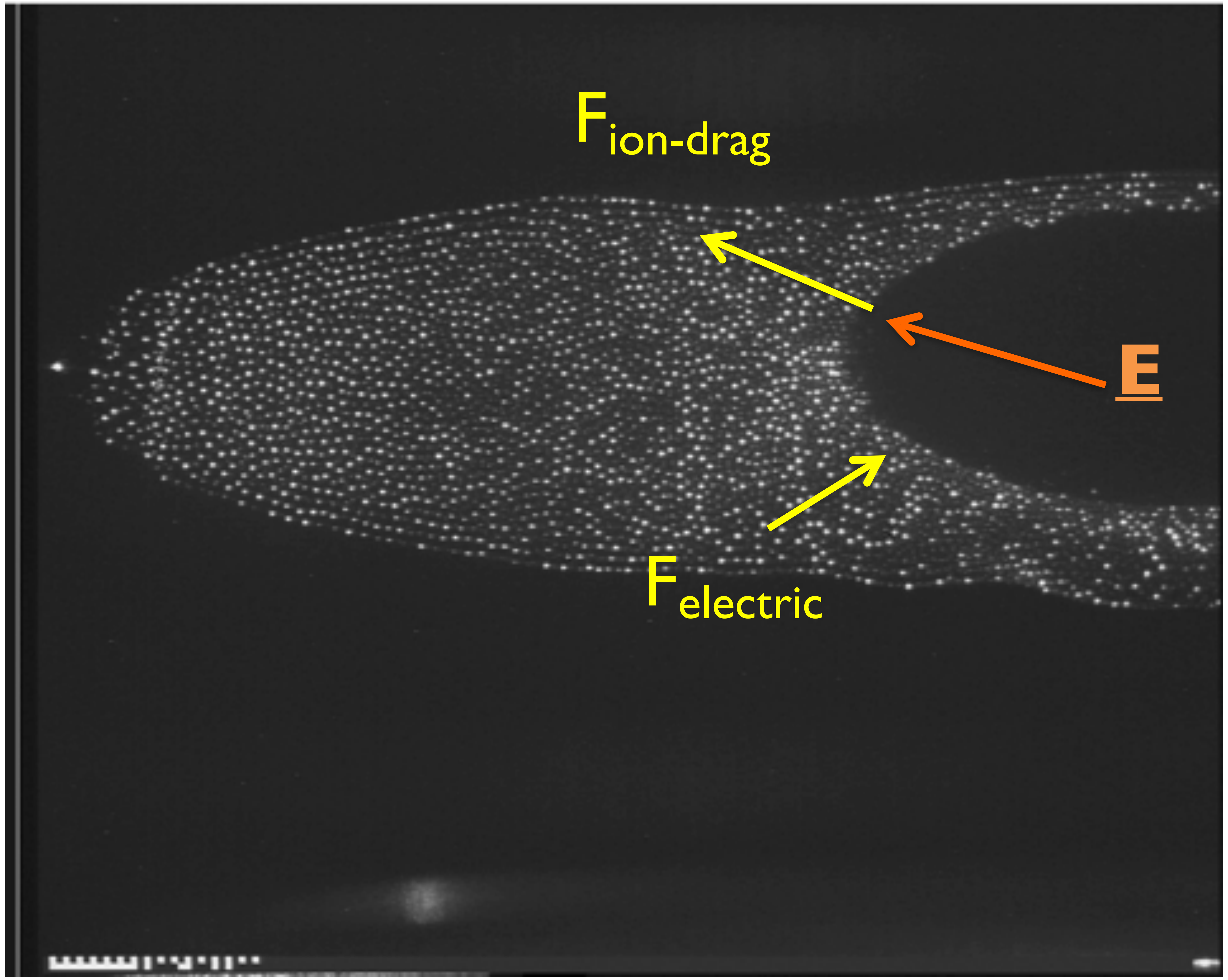
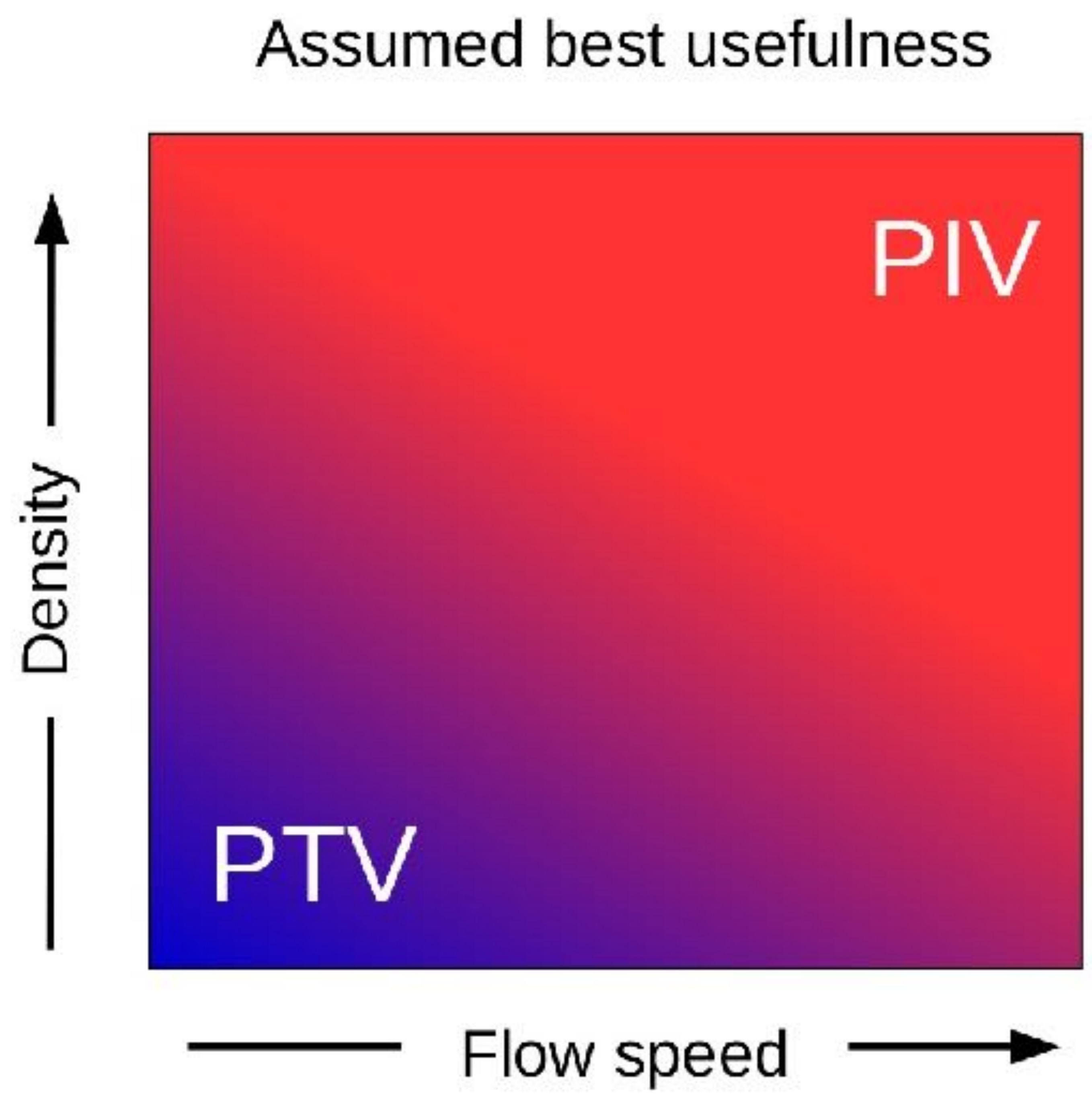
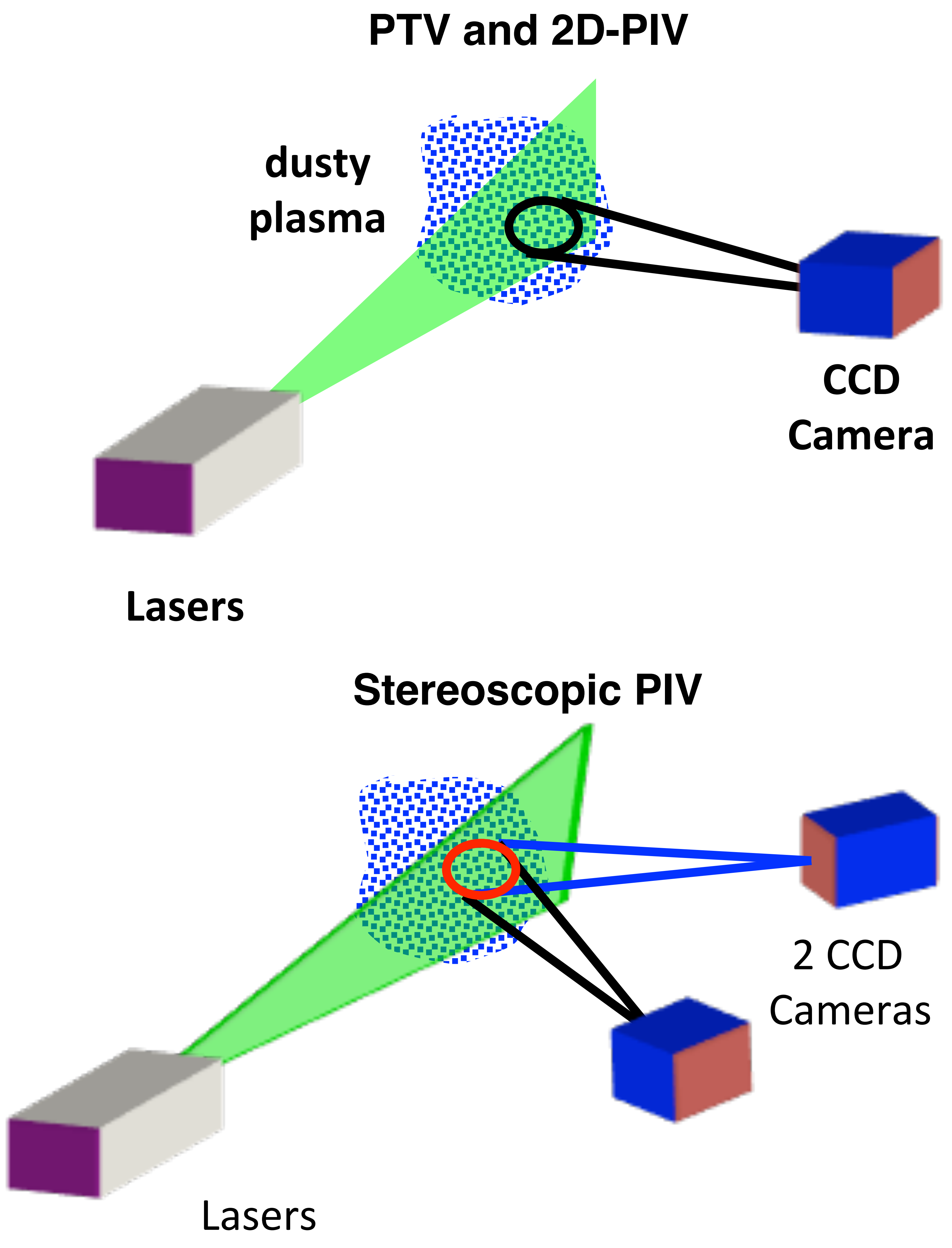



Image from Max Planck Institute, PK-3 Plus

# Measurements: particle tracking velocimetry (PTV) and particle image velocimetry (PIV)




**PTV:** Follows the motion of individual particles from one image to another

**PIV:** Uses a pair of images to reconstruct 2D-velocity profiles of groups of particles

E. Thomas, et al.,. Phys. Plasmas (1999-2007)

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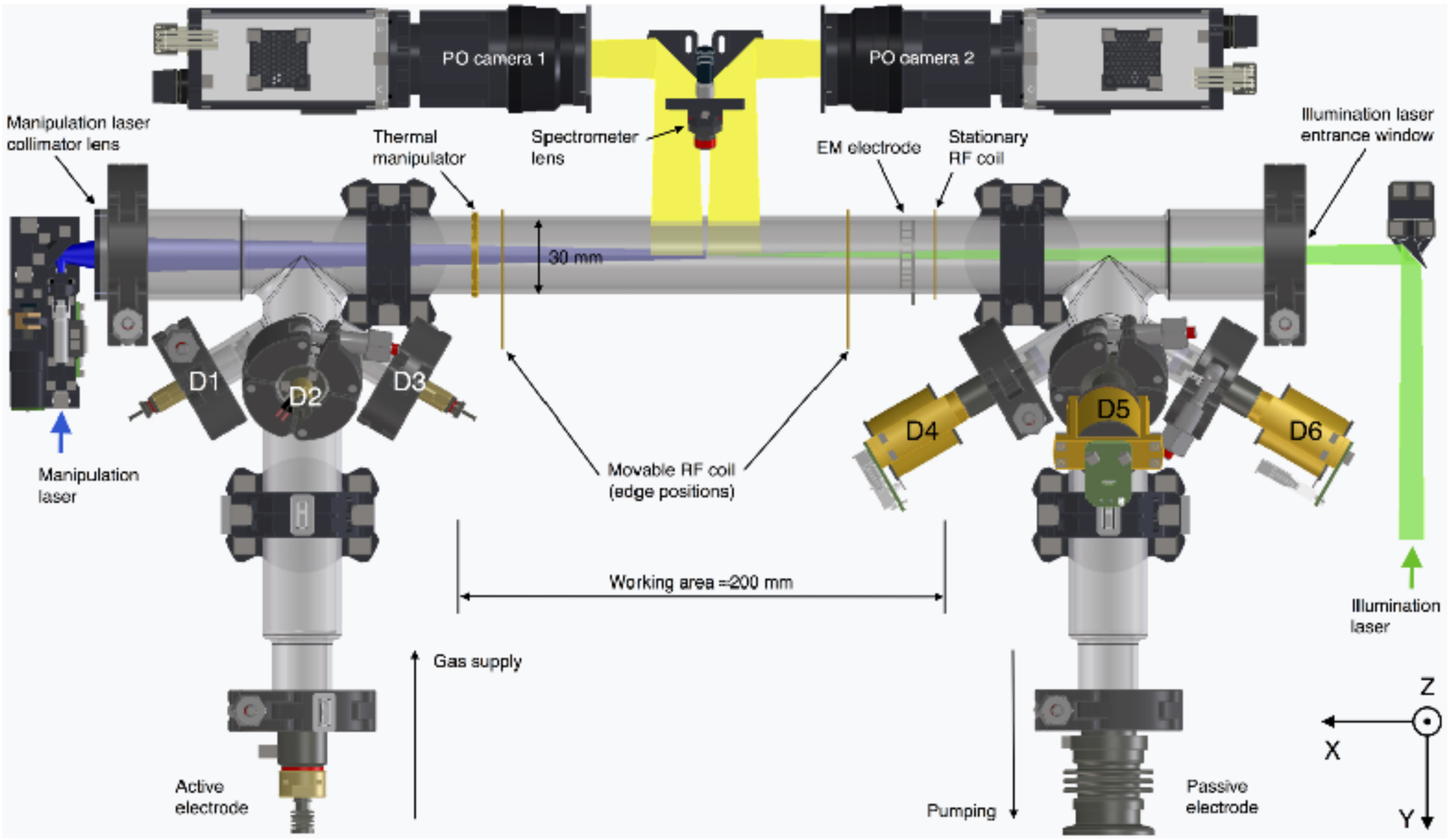
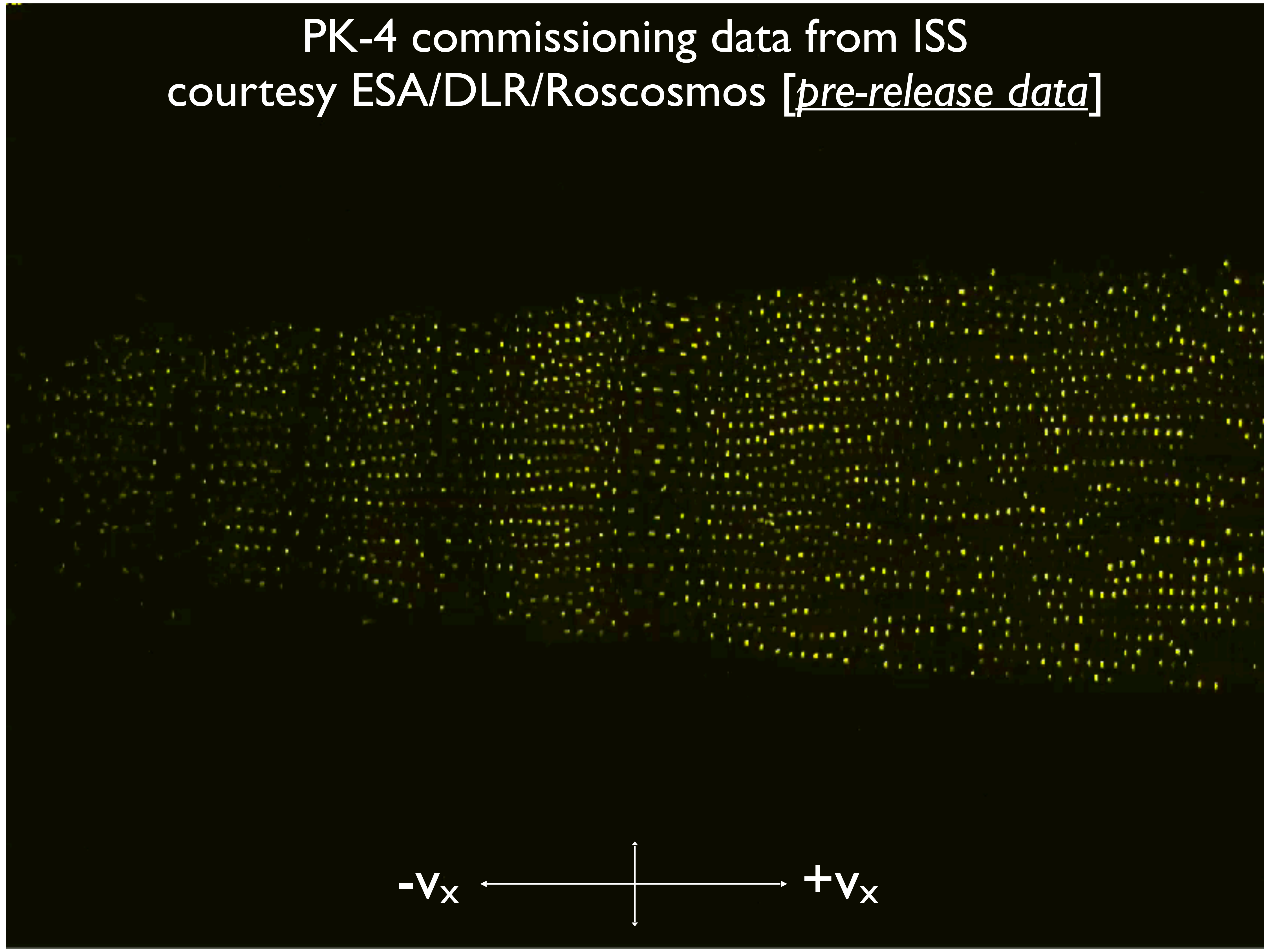
# Fluid-like dusty plasmas in microgravity




M. Pustylnik, et al., Rev. Sci. Instrum., **87**, 093505 (2016)

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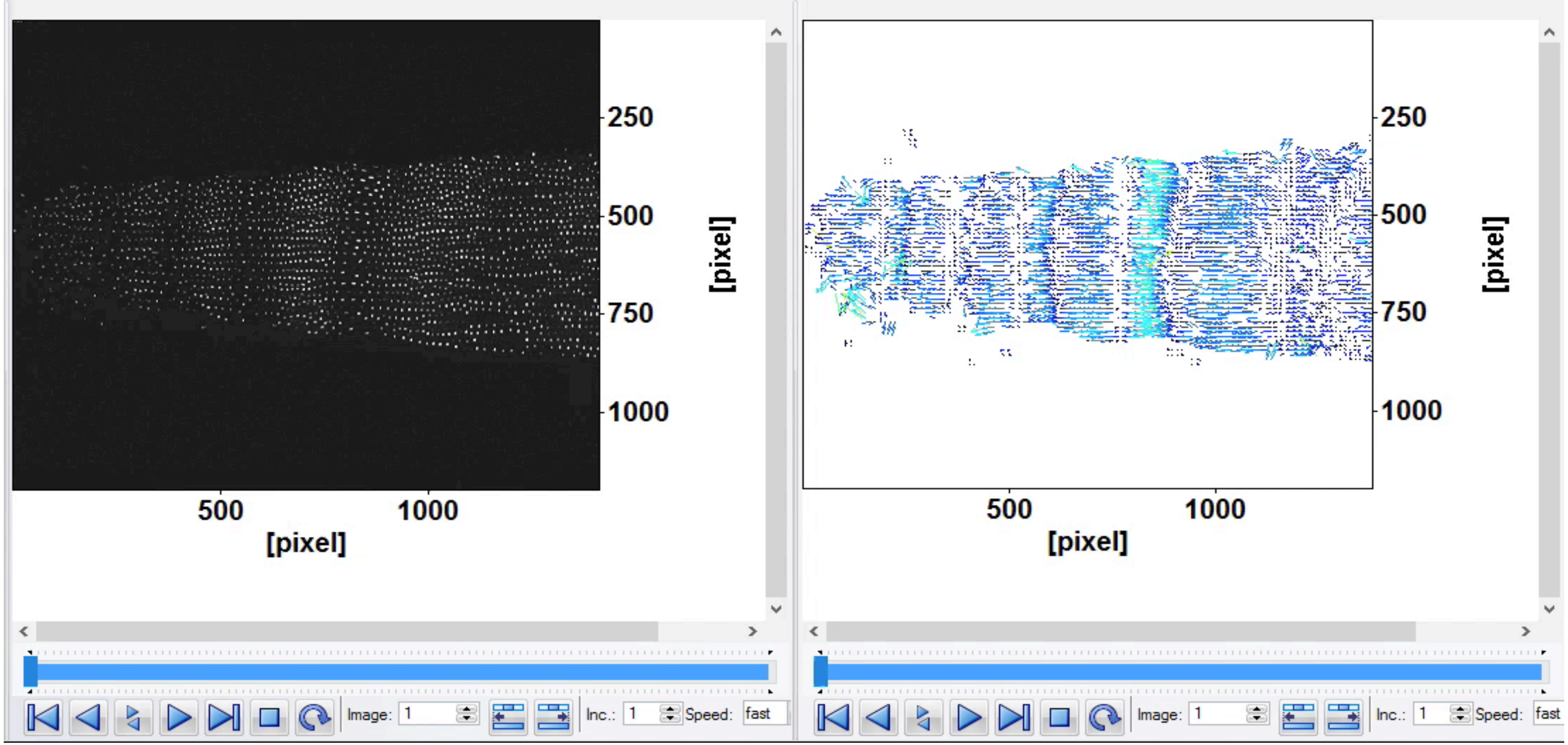
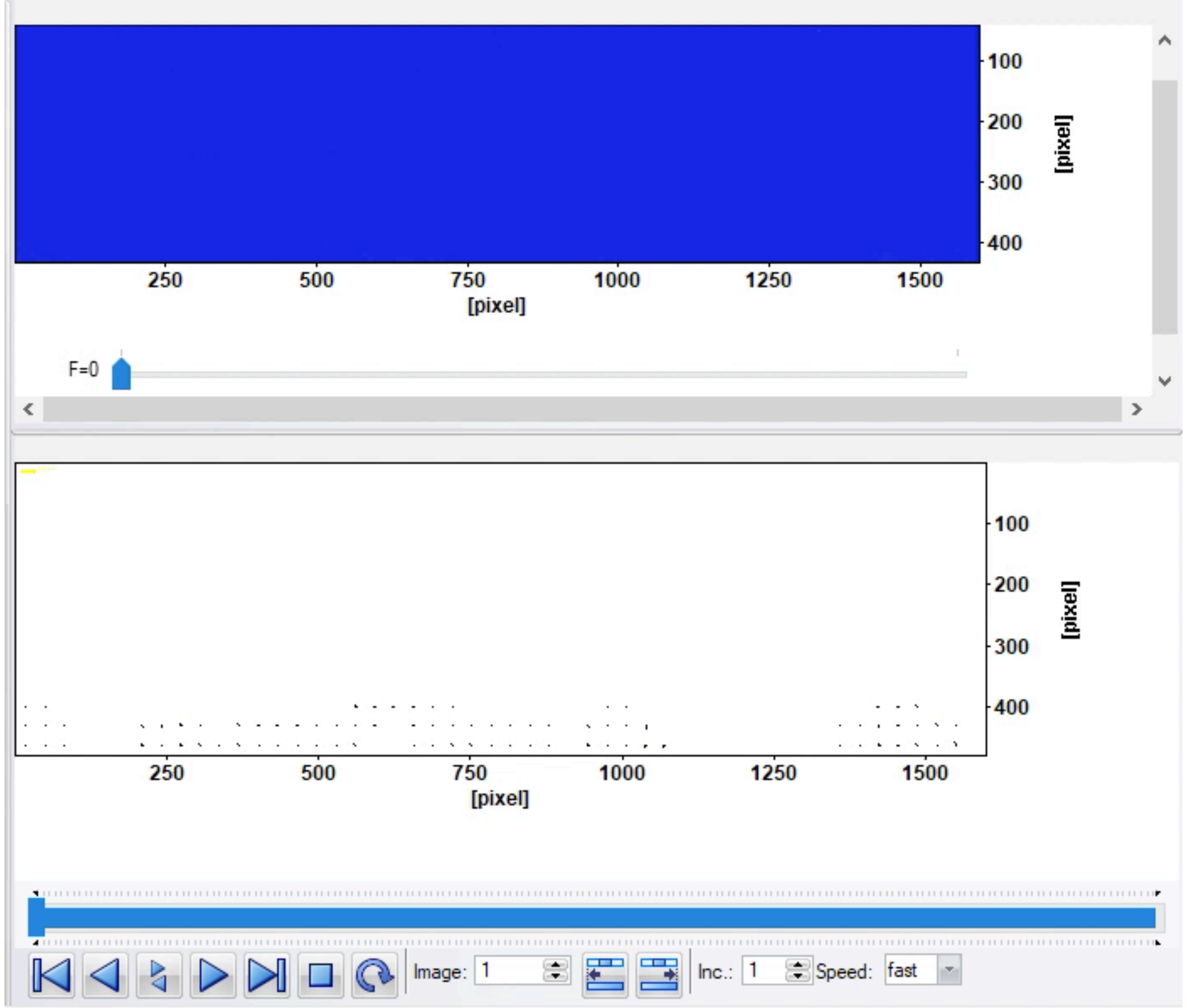



The Particle Image Velocimetry (PIV) technique is used to measure and characterize the flow of particles in the PK-4 experiment

# Auburn microgravity research on PK-4




Using PIV to reconstruct flow and thermal energy at the onset of polarity switching

- How is flow kinetic kinetic energy redistributed  in the system?

# RECENT ADVANCES IN DUSTY PLASMA RESEARCH:
## MAGNETIC FIELD EFFECTS

# What lessons can be learned from basic research on dusty plasmas?

- The laboratory and space dusty (complex) plasma communities have been active for almost three decades.
- Research on dusty plasmas have made important contributions to the understanding of:
  - Charging processes - with applications to *in-situ* probes
  - Transport of microparticles via electrostatic, ion and neutral drag forces
  - Ion dynamics near surfaces
  - Growth of particles in reactive plasmas
  - Collective modes
    - Dust-modified plasma instabilities
    - Dusty plasma instabilities


3-micron silica particles in an argon plasma (1/10th speed) [Auburn University]

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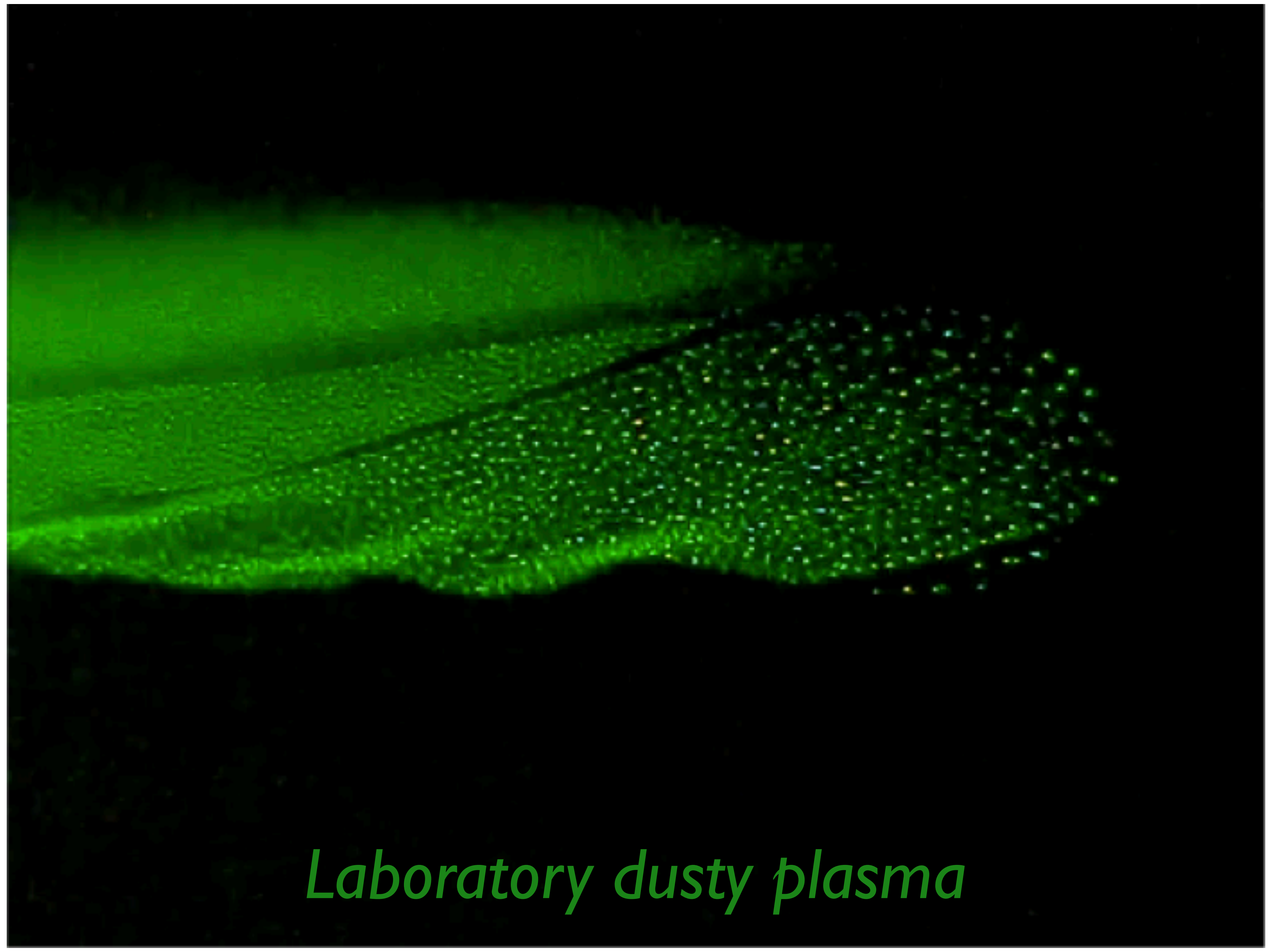
Magnetic Field Effects???




3-micron silica particles in an argon plasma (1/10th speed) [Auburn University]

# Magnetized dusty plasmas in nature

STAR FORMATION IN MAGNETIC DUST CLOUDS

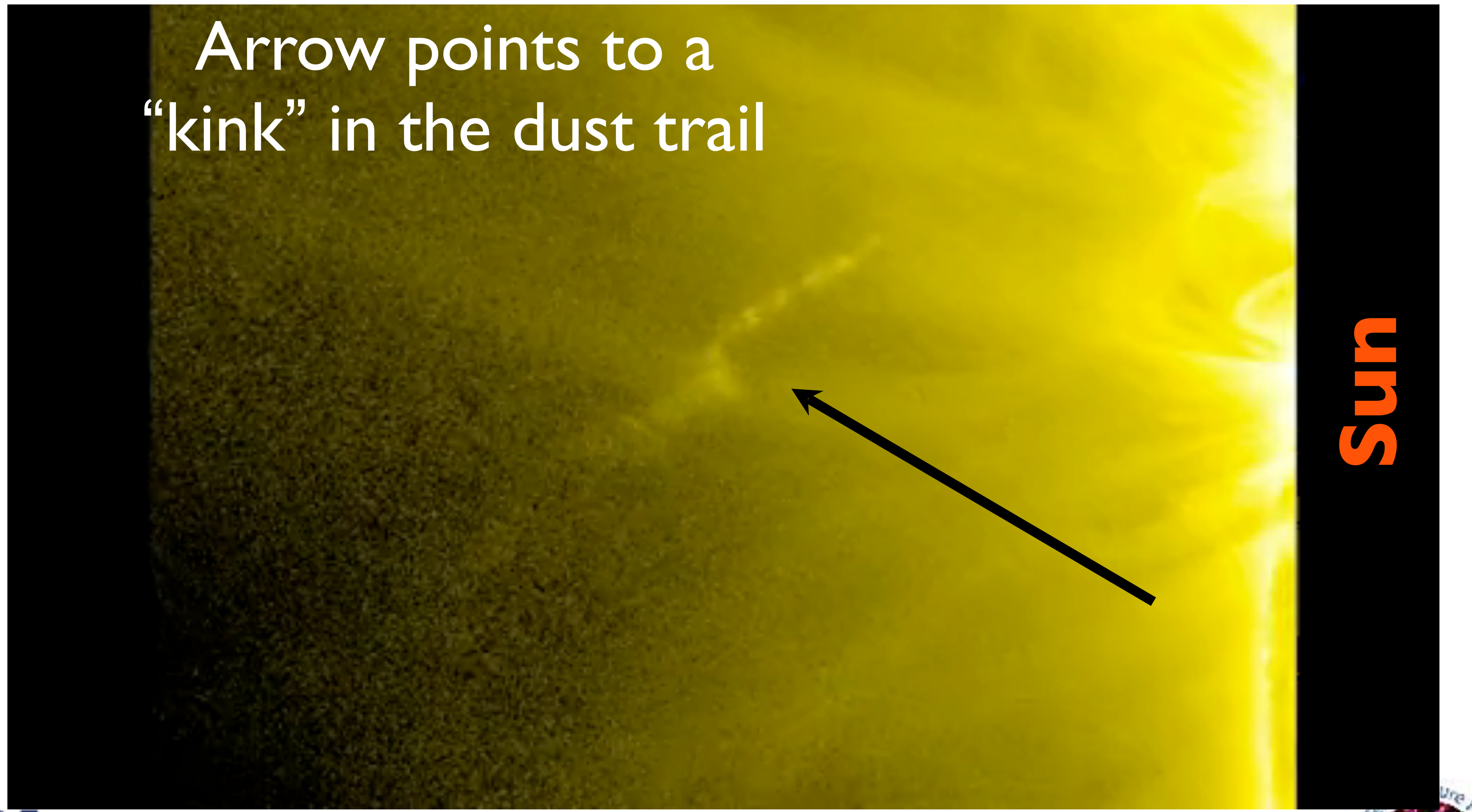
*L. Mestel and L. Spitzer, Jr*

*ApJ*, **116**, 503 (1956)

(Received 1956 July 27)*

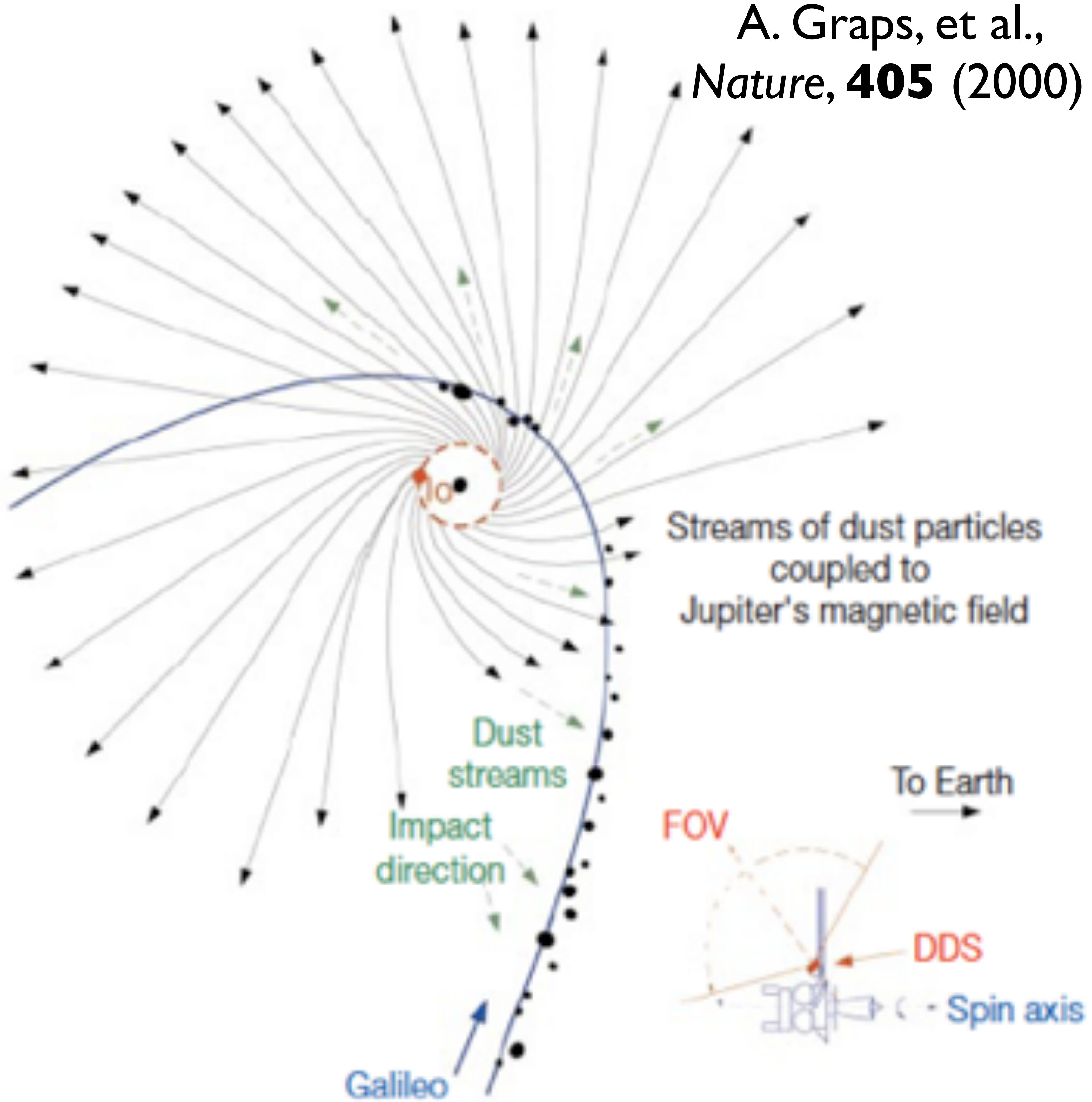
*Summary*

The paper deals with the problem of gravitational condensation in the presence of a magnetic field. It is shown that as long as the field is frozen into the contracting cloud the magnetic pressure sets a lower limit to the mass that can remain gravitationally bound: if the field is taken as $10^{-6}$ gauss in regions of density 10 H atoms/cm$^3$, this lower limit is $\simeq 5 \times 10^2 \odot$. However, if the bulk of the cloud is obscured from galactic starlight by dust grains, the plasma density within the cloud will decline rapidly, as ions and electrons attach themselves to the grains. When the plasma density is low enough the frictional coupling between plasma and neutral gas will be so small that the distorted magnetic field will be able to straighten itself, dragging the remains of the plasma with it, while the bulk of the cloud contracts across the field. With the magnetic energy so reduced to a small fraction of the gravitational energy, the cloud is able to break up into stars.




http://www.nasa.gov/multimedia/videogallery/index.html?media_id=124915541 - Comet LoveJoy (2011)

A. Graps, et al., *Nature*, **405** (2000)




$$m\frac{d\vec{v}}{dt} = q_d\left(\vec{E} + \vec{v}\times\vec{B}\right) + \vec{F}_G + \vec{F}_d + \vec{F}_r$$

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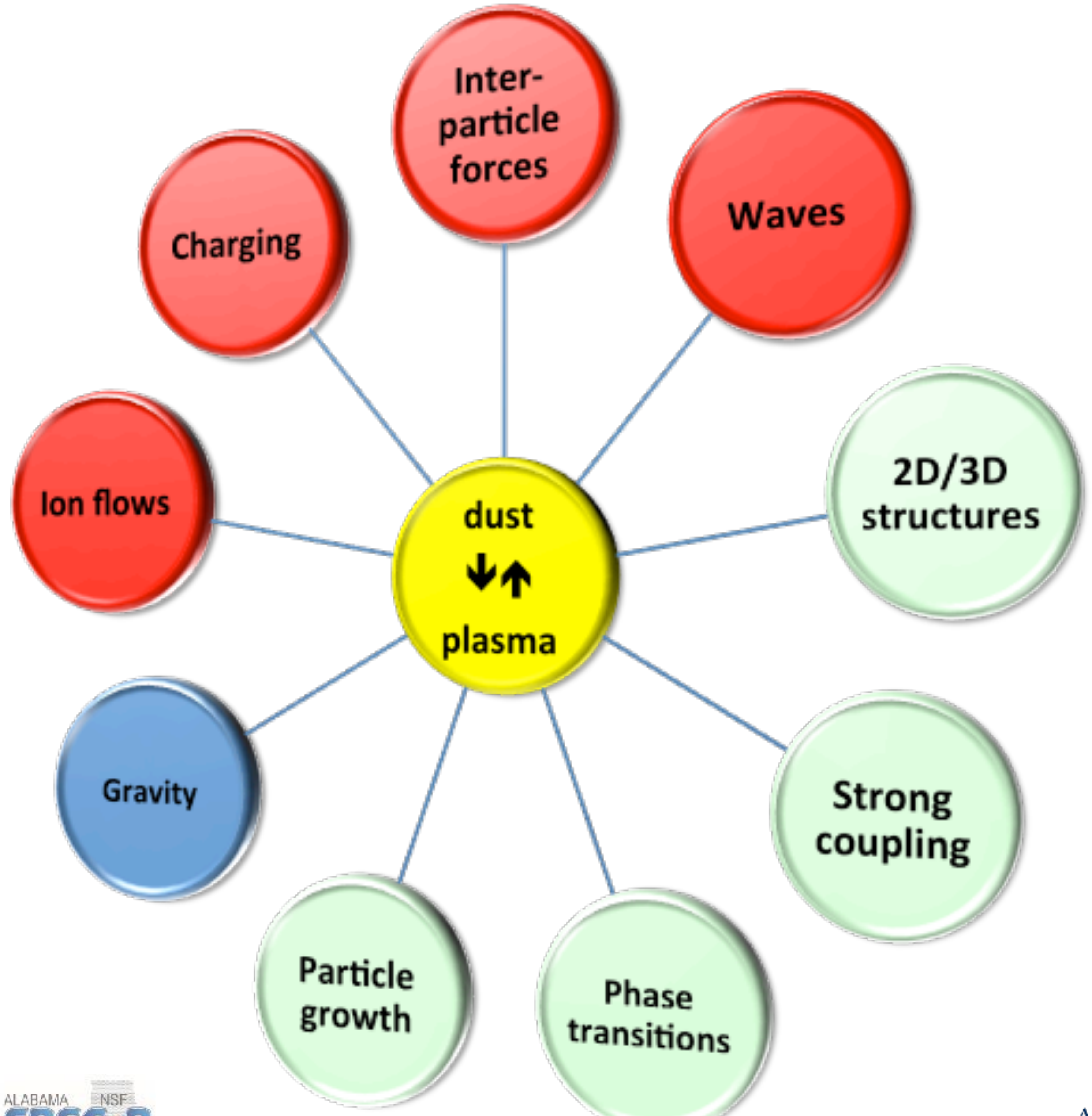
# The magnetic field alters the coupling between the dust particles and the surrounding plasma

- Direct effects:
  - modified ion and electron collection
  - changes net force on the dust grain
  - alters formation of sheaths
  - modifies waves and introduces new wave modes

- Indirect effects:
  - modifies formation of 2D and 3D structures
  - alters conditions for phase transitions
  - affects how particles may form

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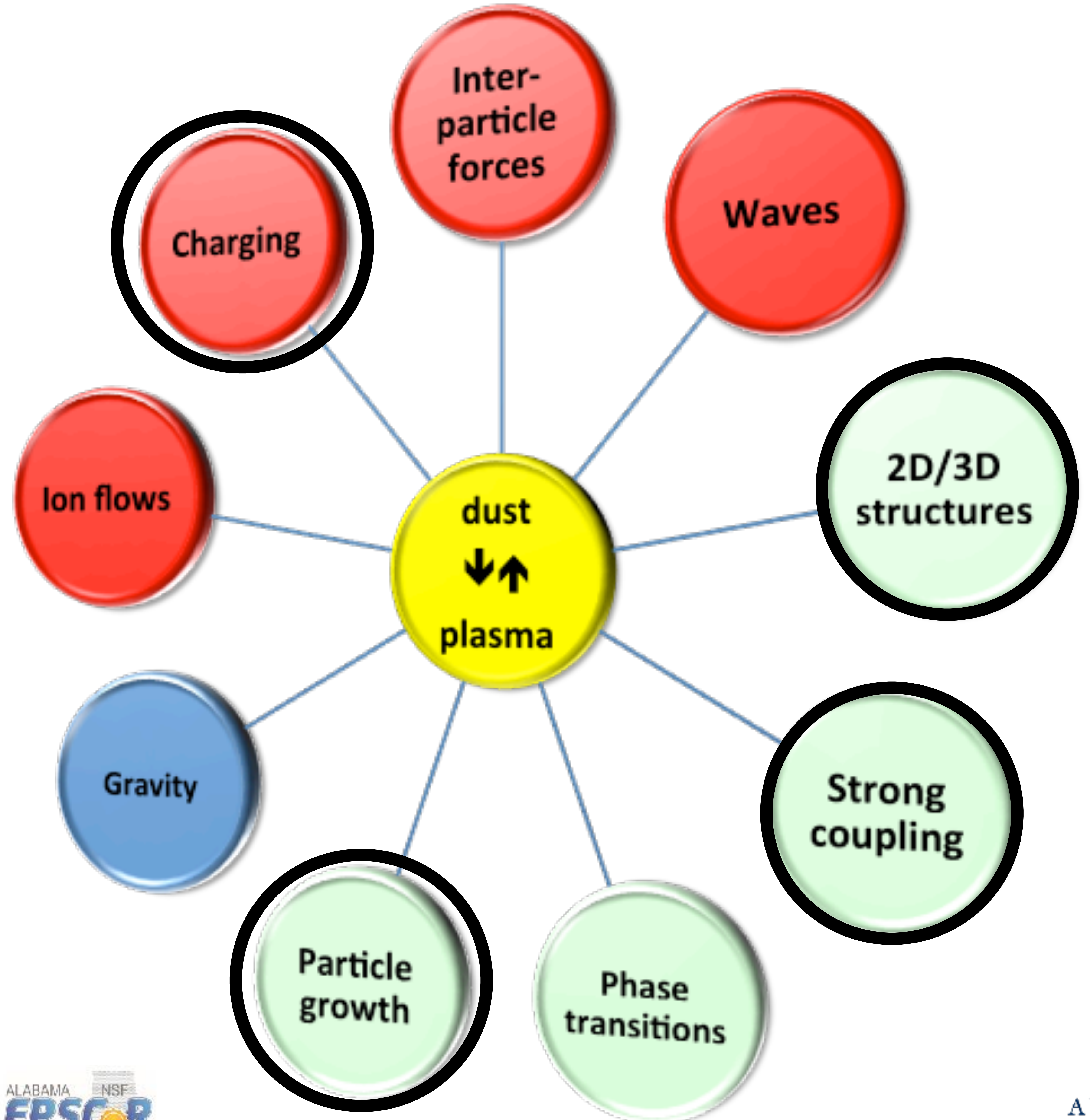

# Technical challenges in magnetizing a dusty plasma in the laboratory

- Magnetization criterion
  - Magnetic force will be comparable to the other forces acting upon the dust grain
- Challenges:
  - Dust grain charge, $Z_d \sim 1000$
  - Dust grain mass, $m_d > 10^8\ m_{ion}$
- That is: $q_d/m_d << e/m_{ion} << e/m_{elec}$

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  - gyroradius to exp. size: $\frac{\rho}{L} \sim \frac{a^2 v_d}{BL} << 1$
  - gyrofreq. to collision freq.: (Hall parameter) $\frac{\omega_c}{\nu_{dn}} \sim \frac{B}{aP} > 1$
  - magnetic to gravitational force: $\frac{F_m}{F_g} = \frac{Q_d v_d B}{m_d g} \sim \frac{v_d B}{a^2} \geq 1$

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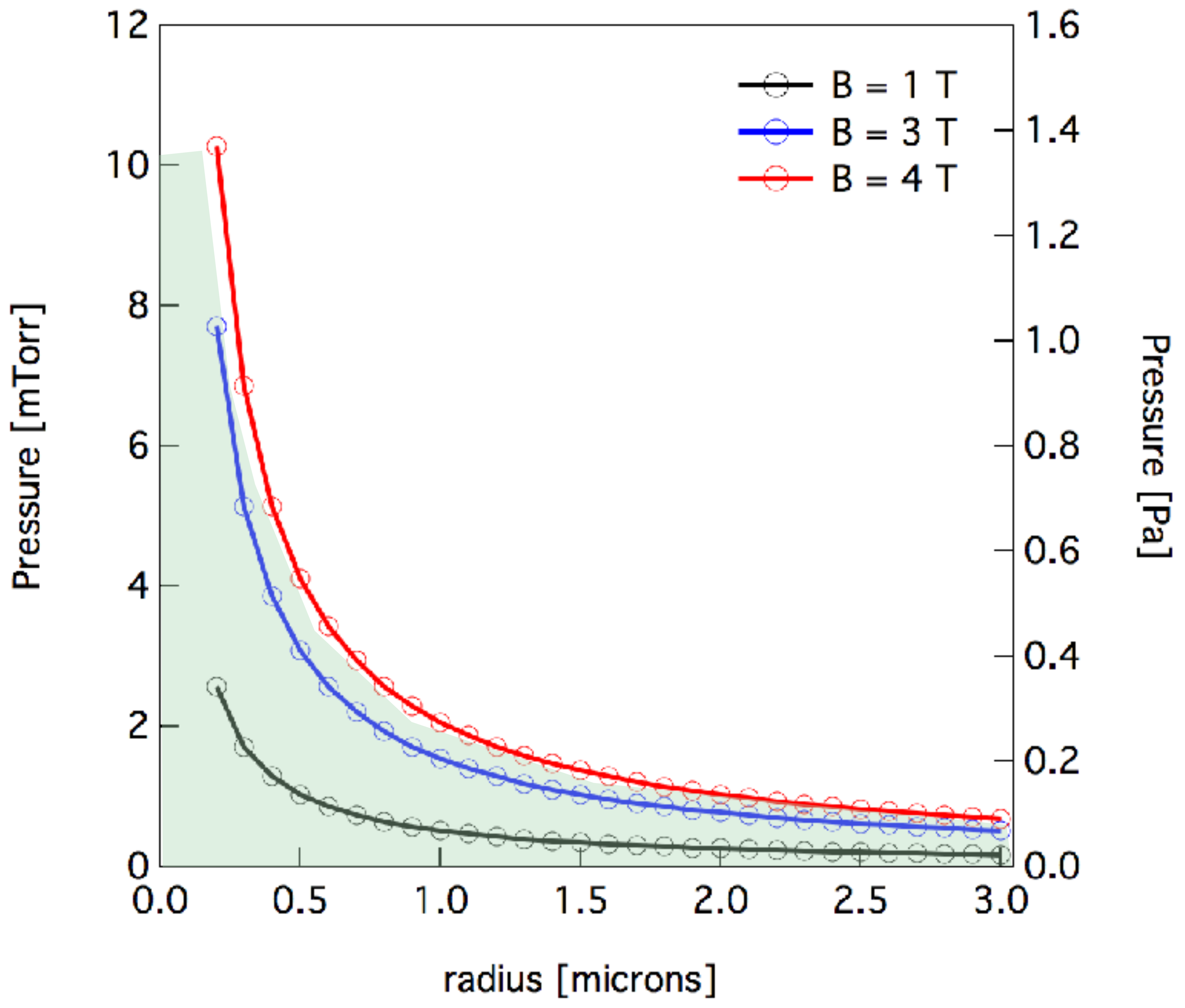
- Scaling of pressure vs. grain radius for the condition: $\tau_{collision} / \tau_{cyclotron} = 1$

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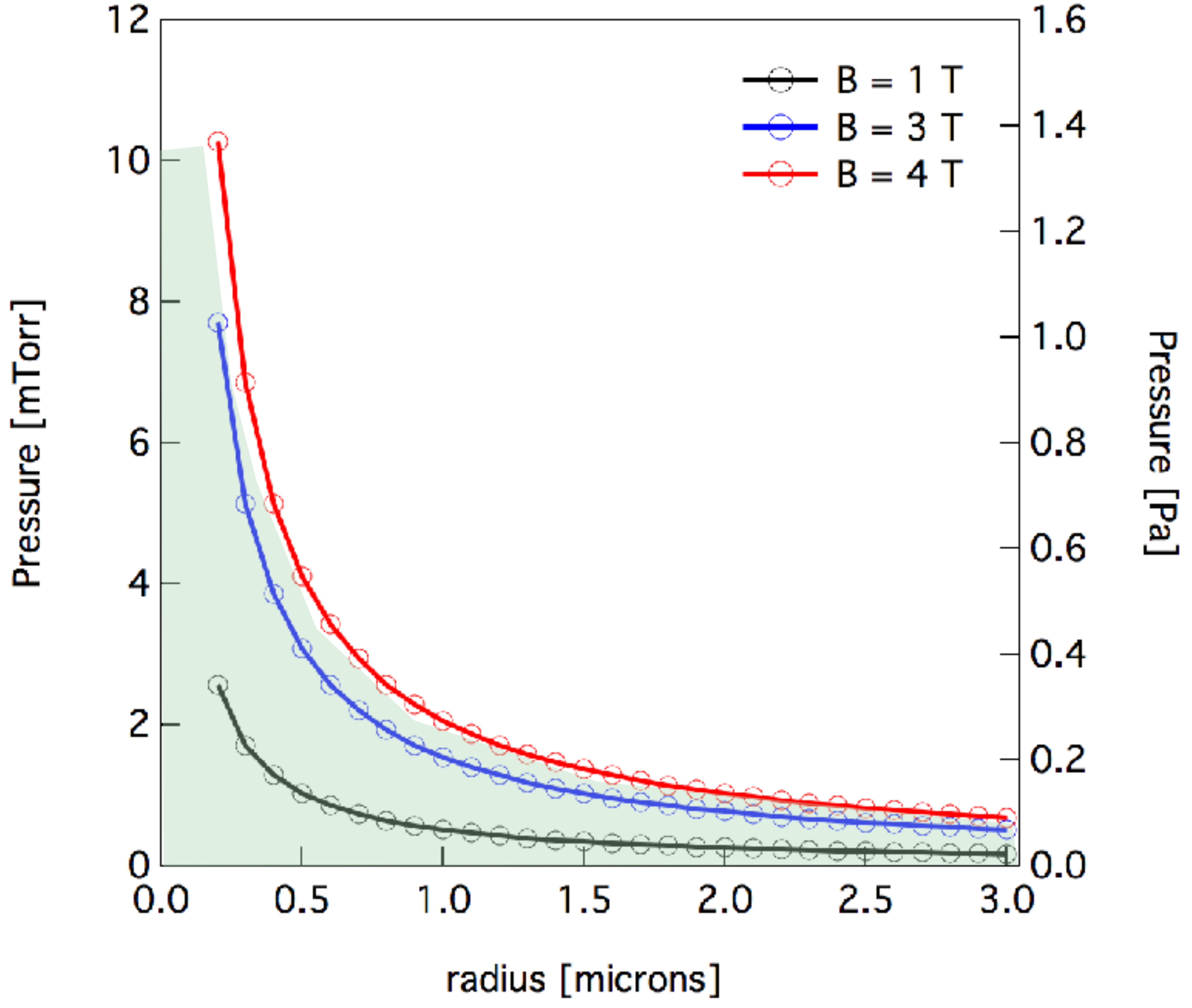
**Key result: Maximize B/a**

- Scaling of pressure vs. grain radius for the condition: $\tau_{collision} / \tau_{cyclotron} = 1$

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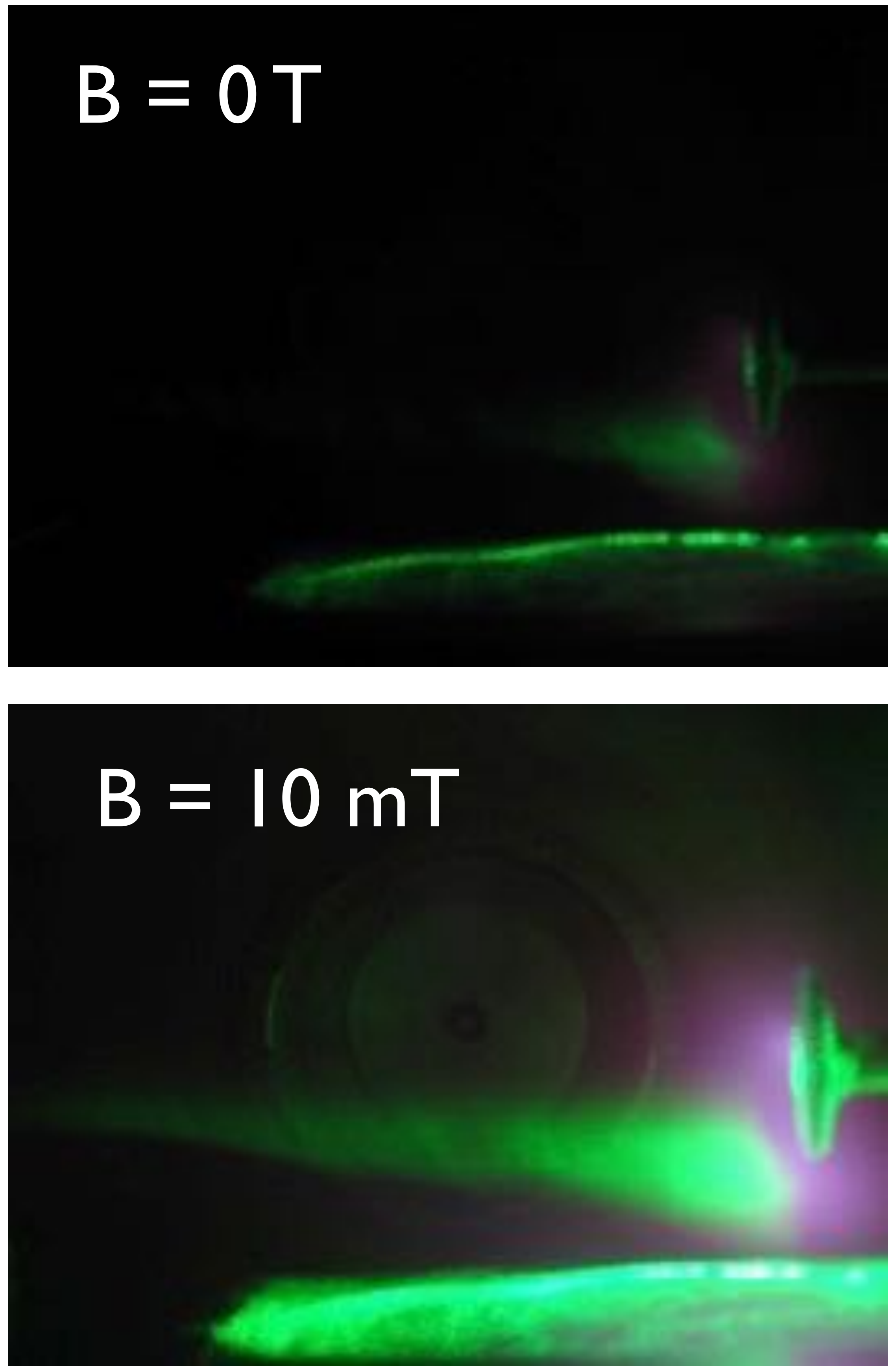
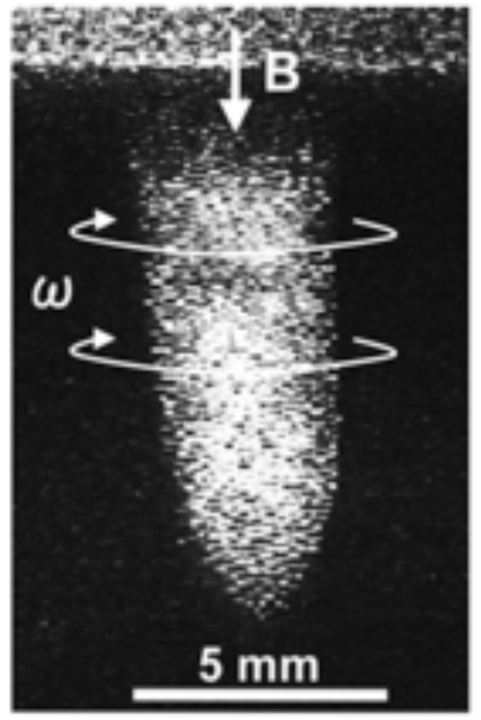
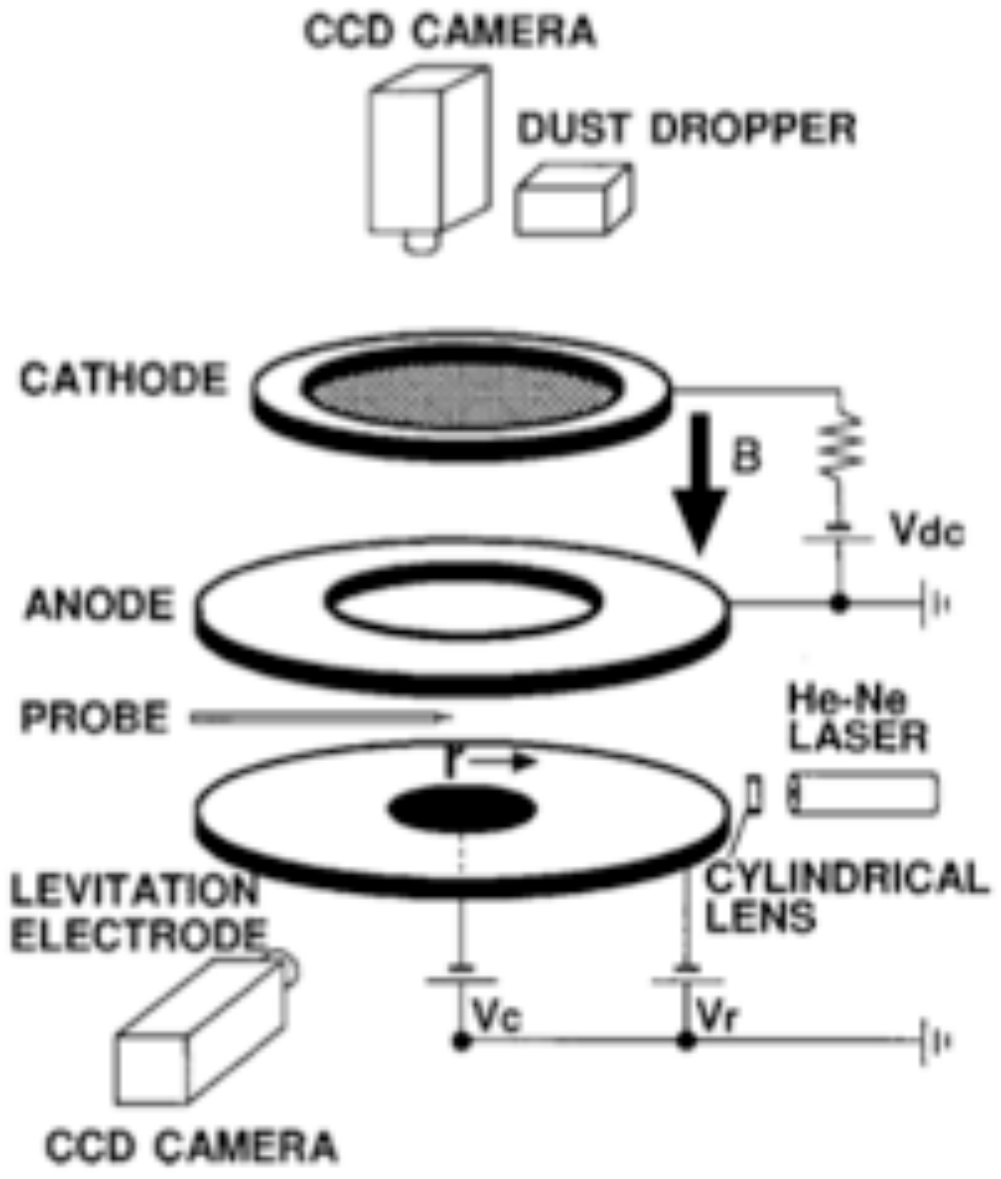
# Past and current studies of complex plasmas in magnetic fields: an incomplete list

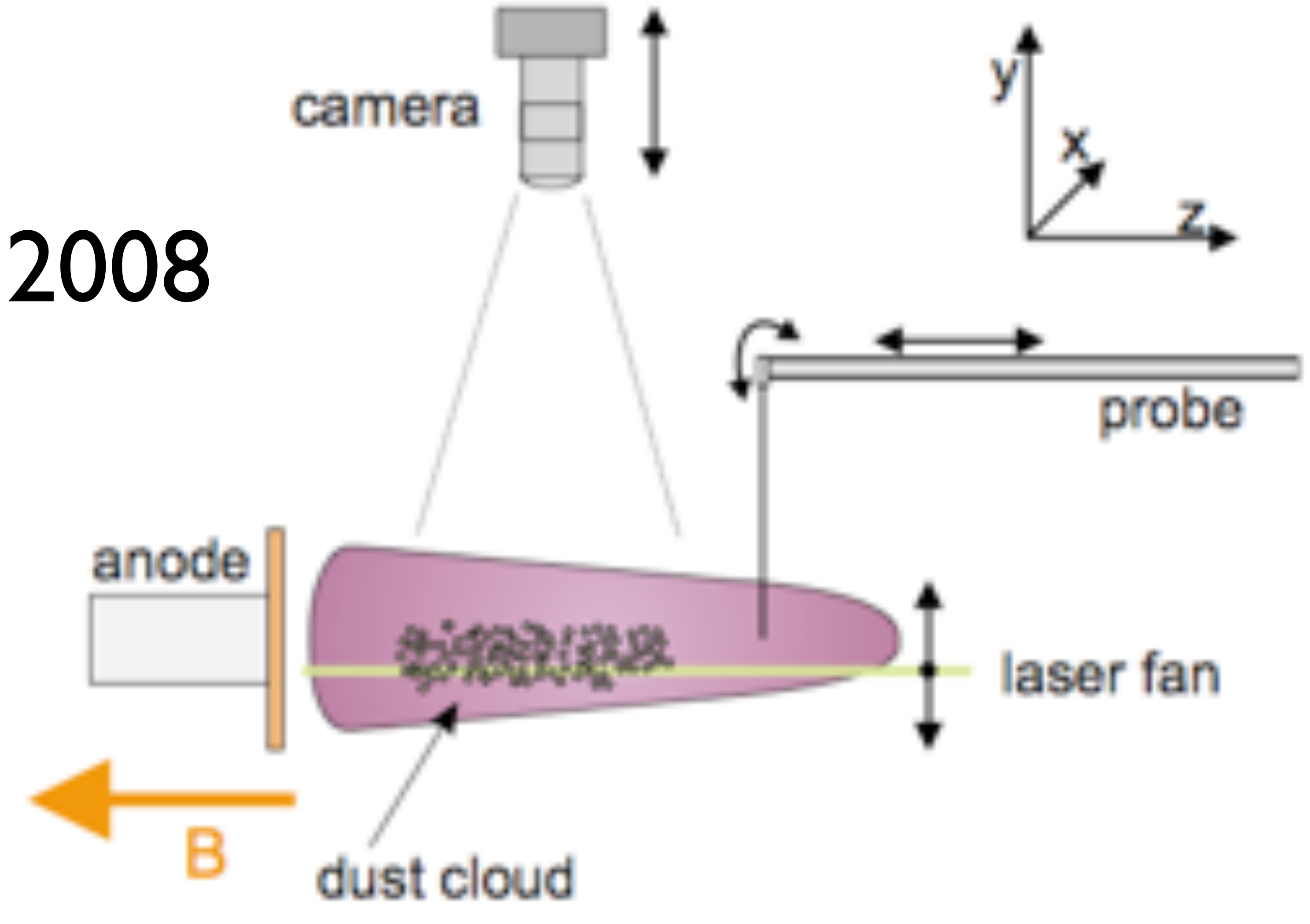



Merlino, 1997

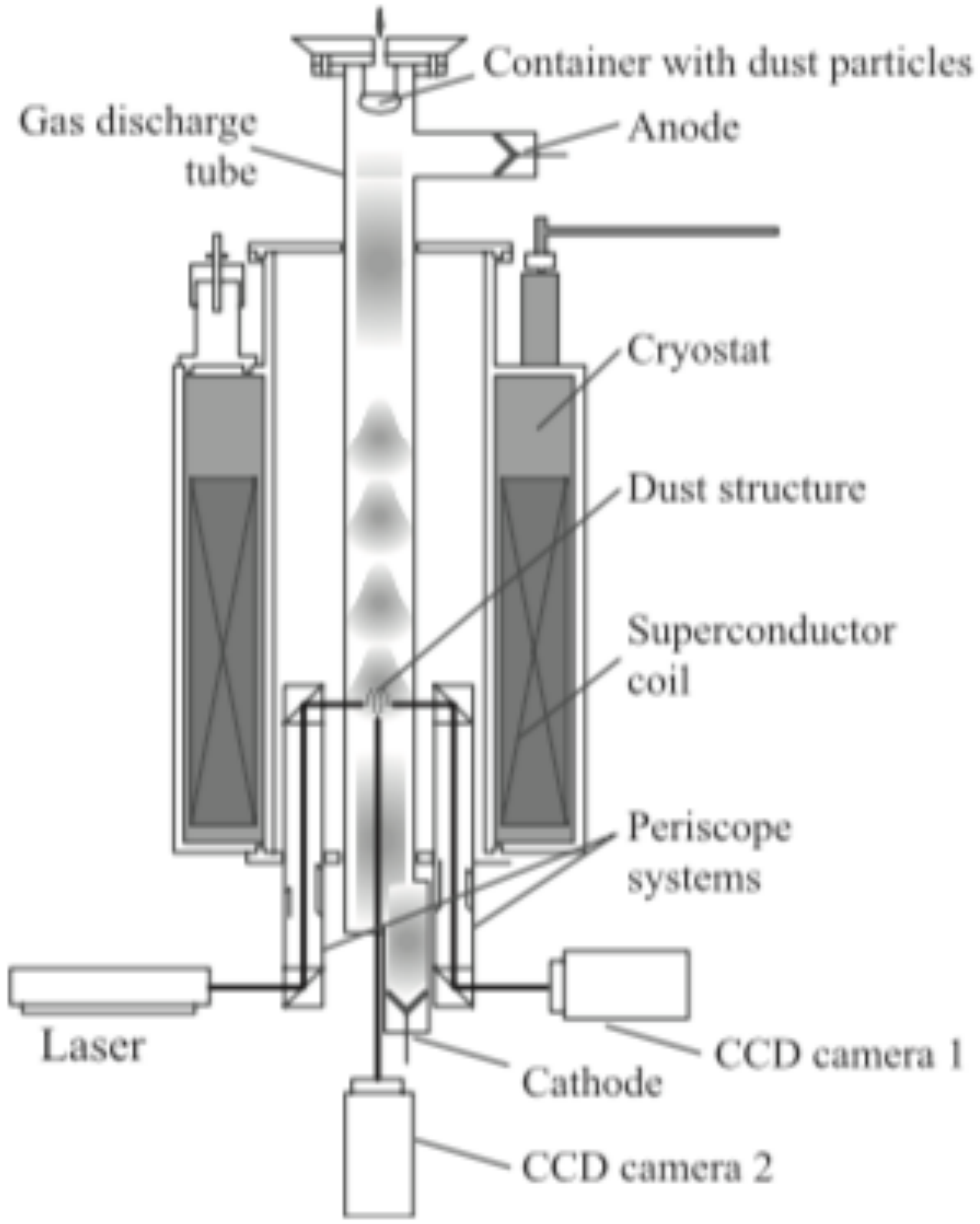



N., Sato 2001



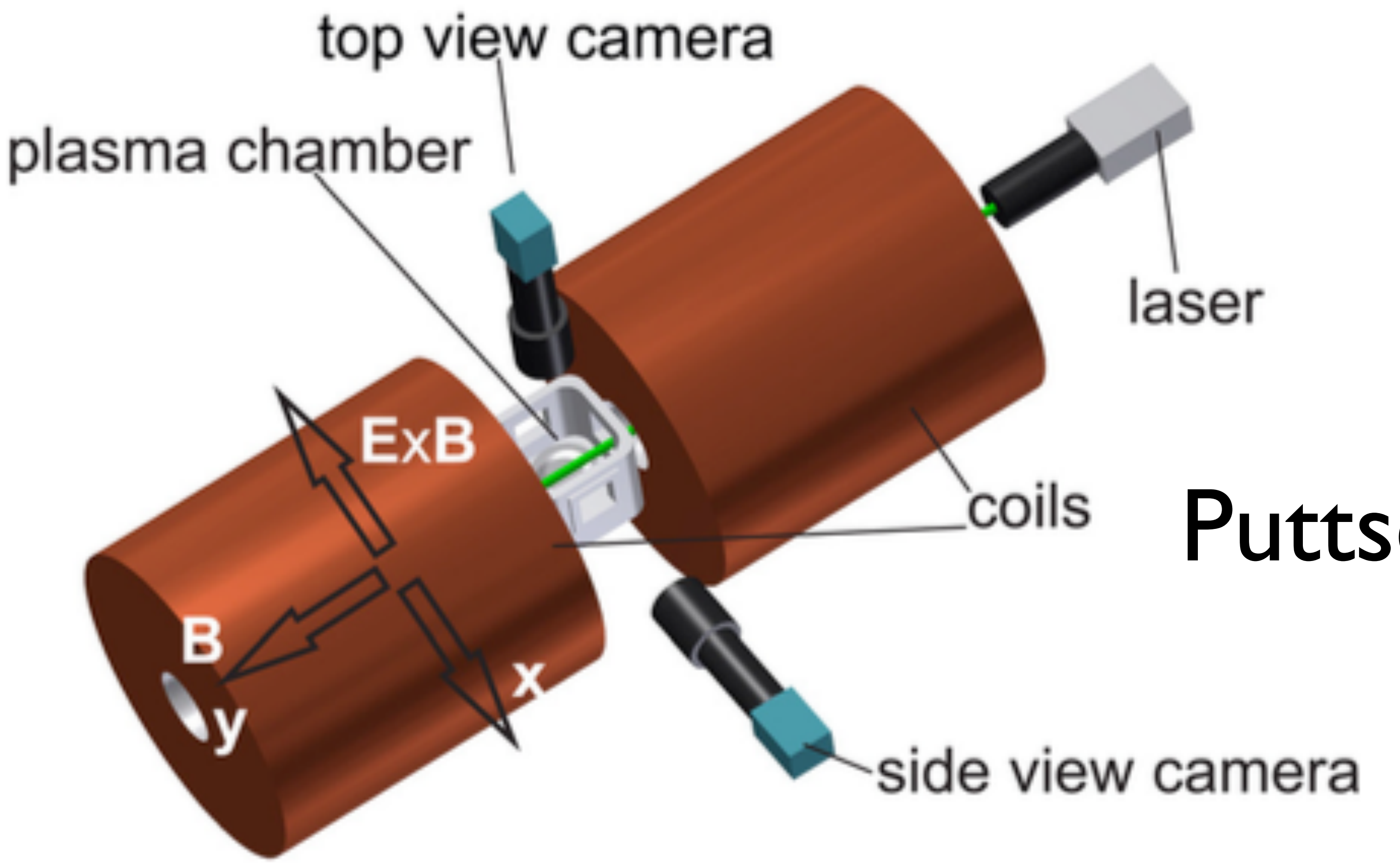




I. Pilch, 2008

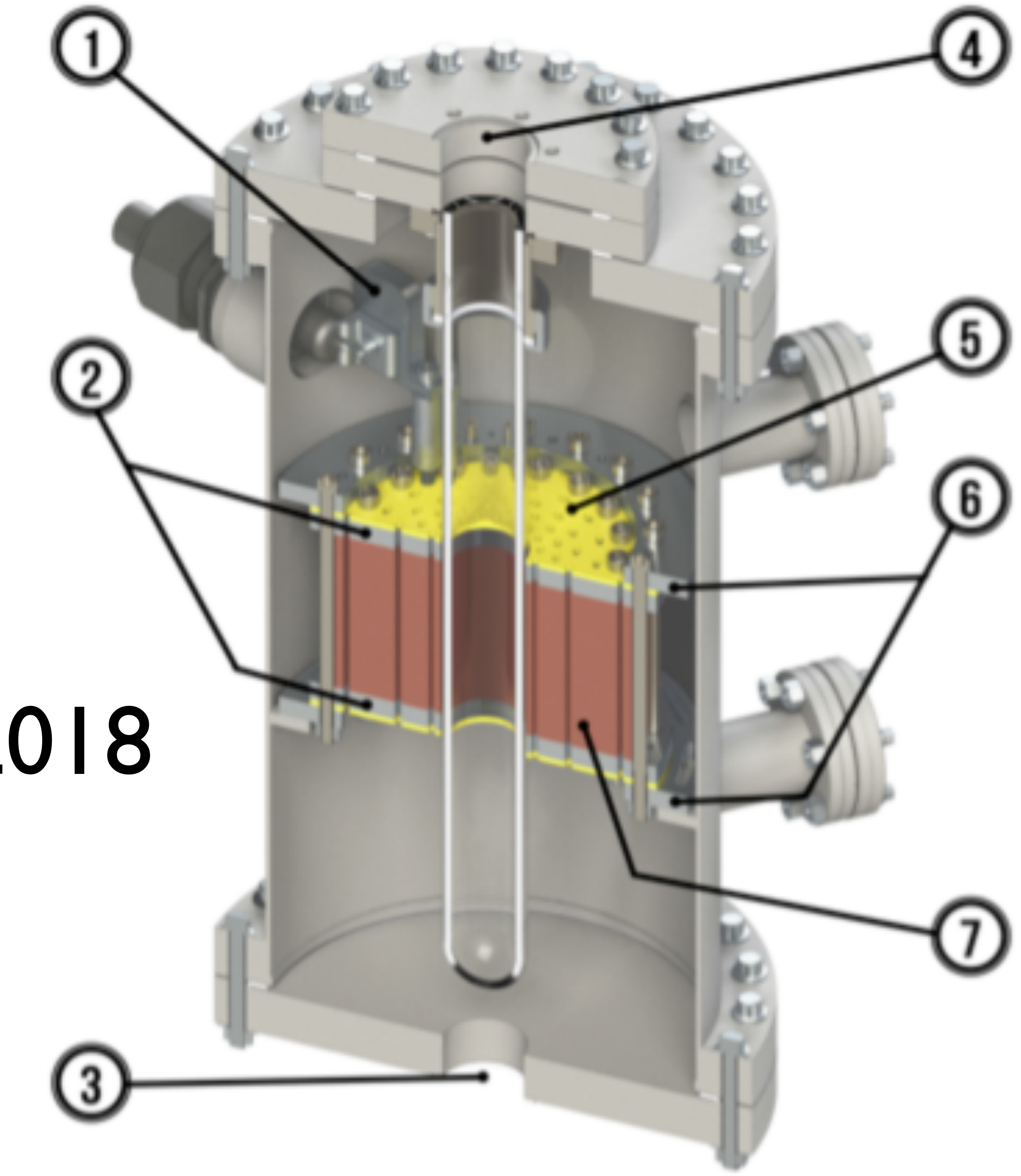



Vasiliev, 2011

# Past and current studies of complex plasmas in magnetic fields: an incomplete list

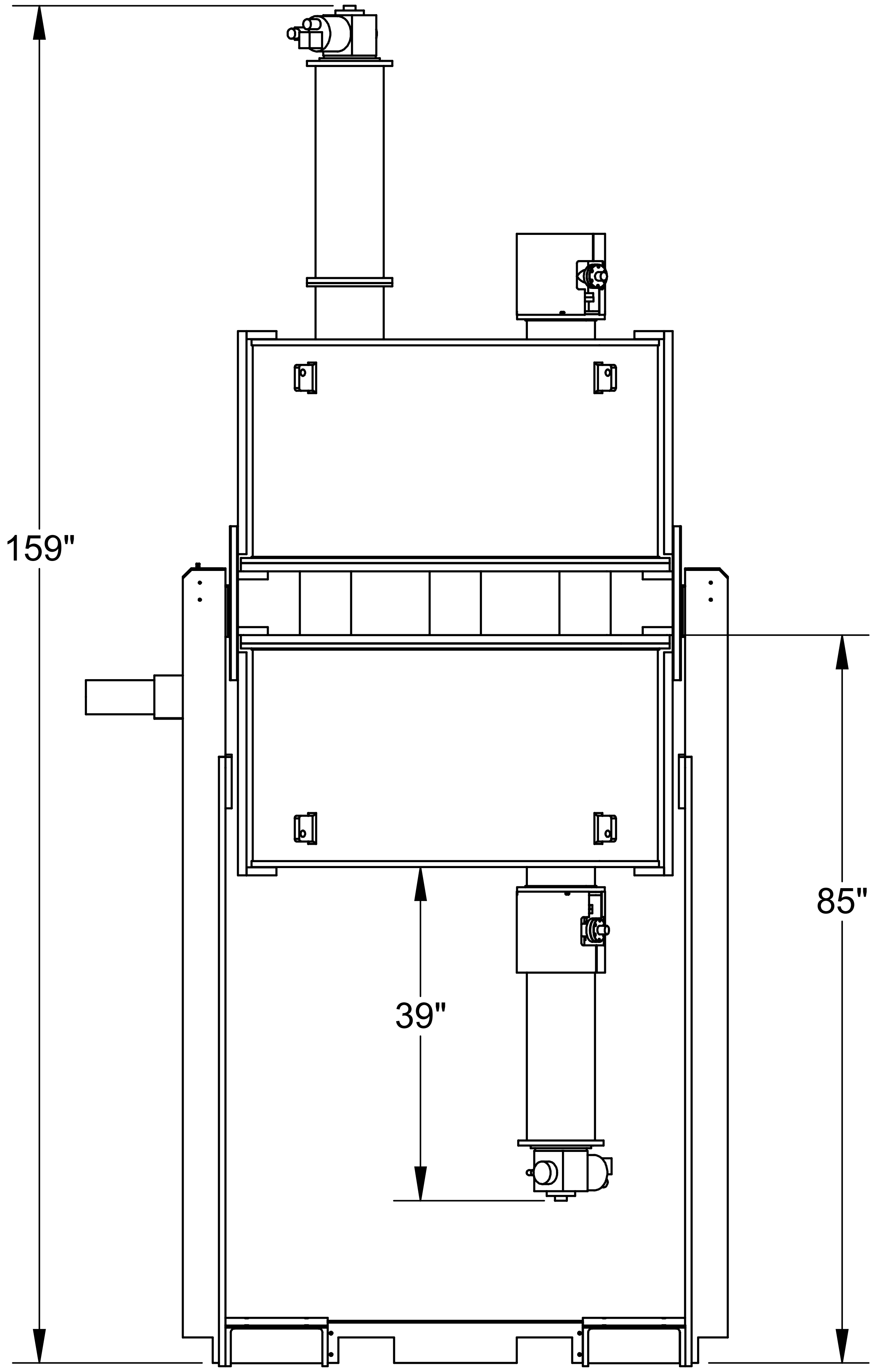


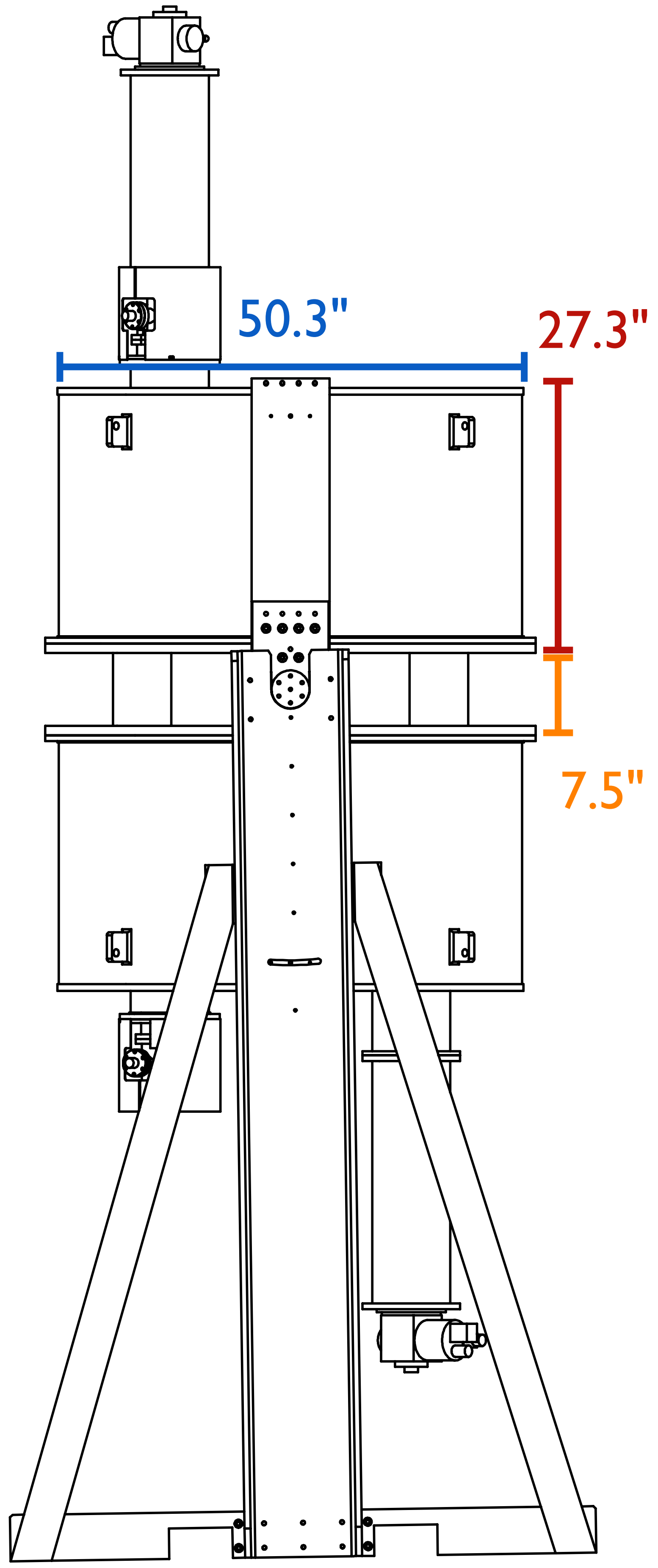

Puttscher, 2018




Bates, 2018


# MDPX: A cryogen-free, superconducting, multi-configuration magnetic field system featuring a large split-bore design to maximize diagnostic access

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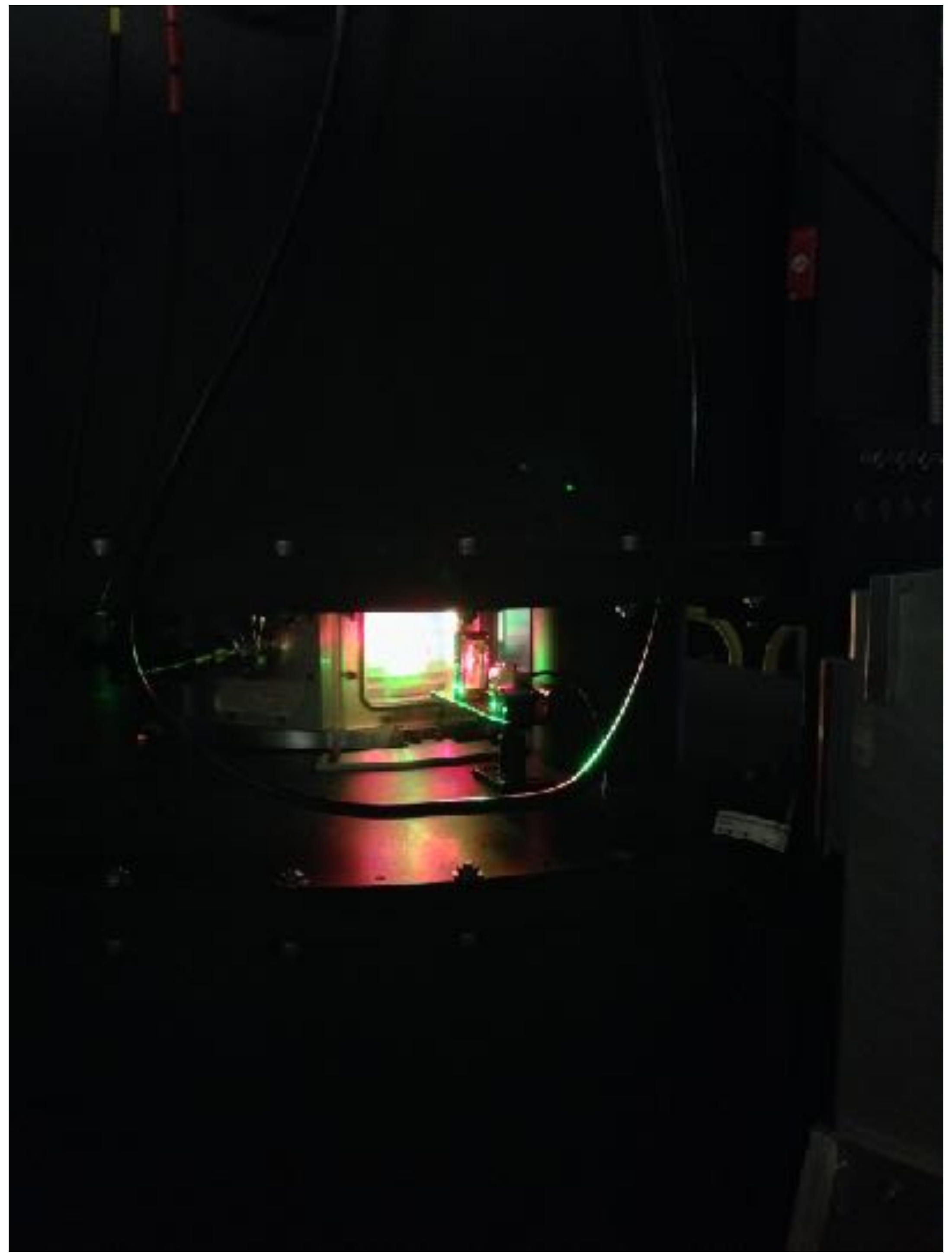
# MDPX: A cryogen-free, superconducting, multi-configuration magnetic field system featuring a large split-bore design to maximize diagnostic access

- 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> = 0.5 μm, 2 μm, 8 μm
- Diagnostics:
  Langmuir probes
  Triple probe ($n_e$, $T_e$, $V_p$)
  DPSS lasers
  High-speed video cameras
  (100-1000 fps)
- Plasma parameters (@ B = 0 T):
  $T_e$ = 1- 5 eV, $T_i$ = 1/40 eV
  $n_e \sim n_i \sim 2$ to $8 \times 10^{15}$ m$^{-3}$



| | |
|---|---|
| Magnetic field: | 3.3 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)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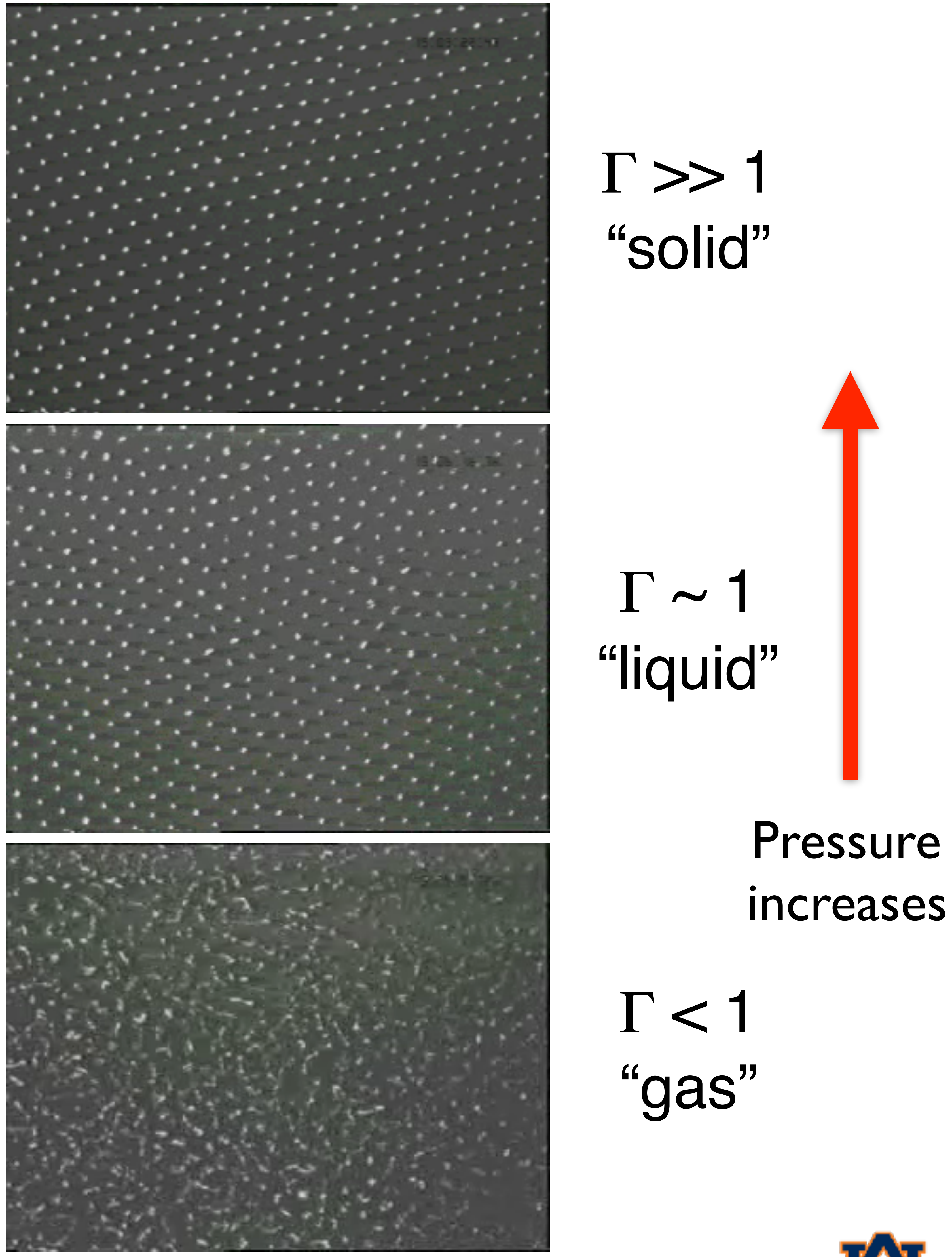
# Fundamental Parameters (4): Coupling parameter is a measure of self-organization

- $\Gamma$ (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

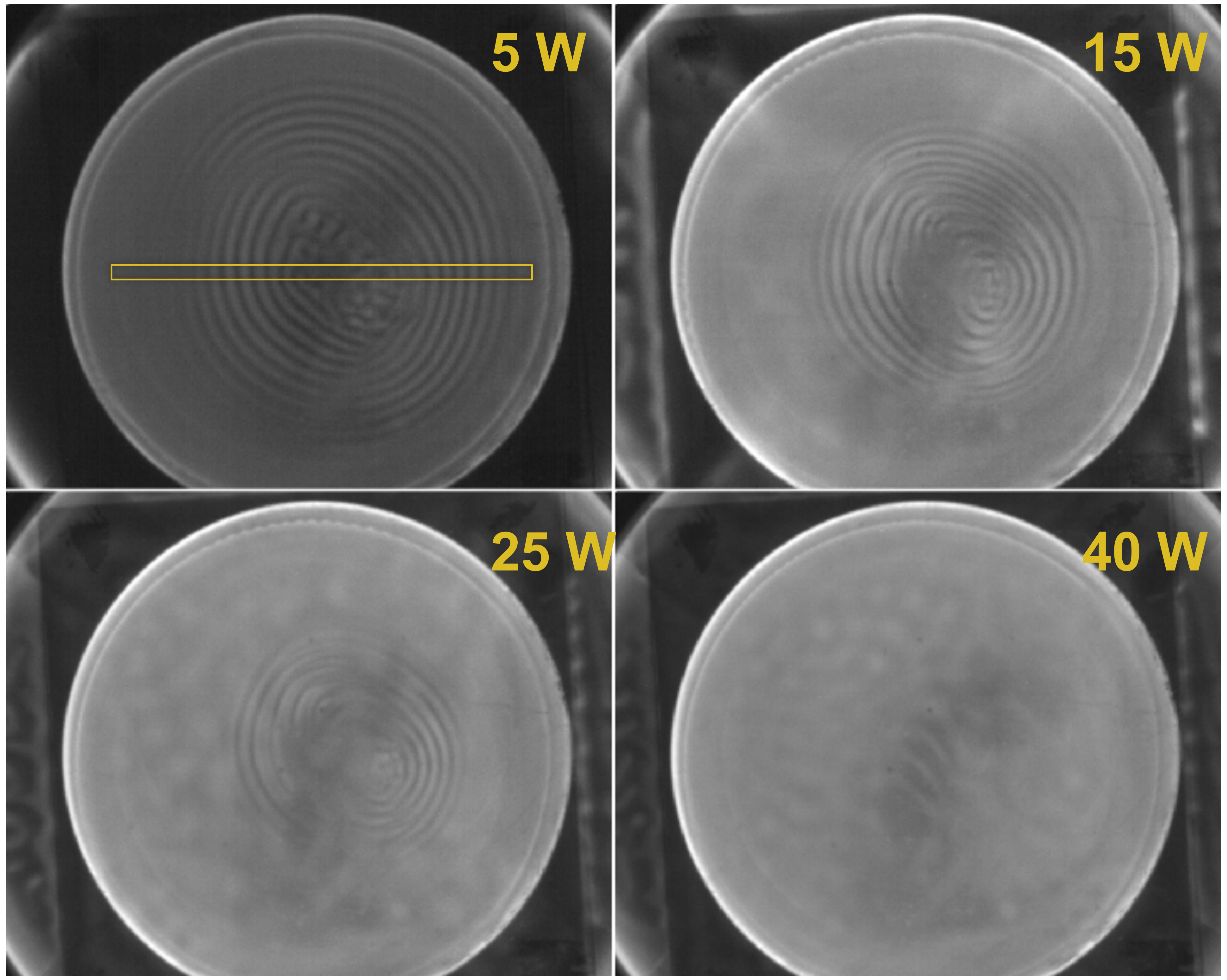
Yukawa, Debye-Hückel: $\varphi \sim \dfrac{\exp\left(-r/\lambda_D\right)}{r}$

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

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



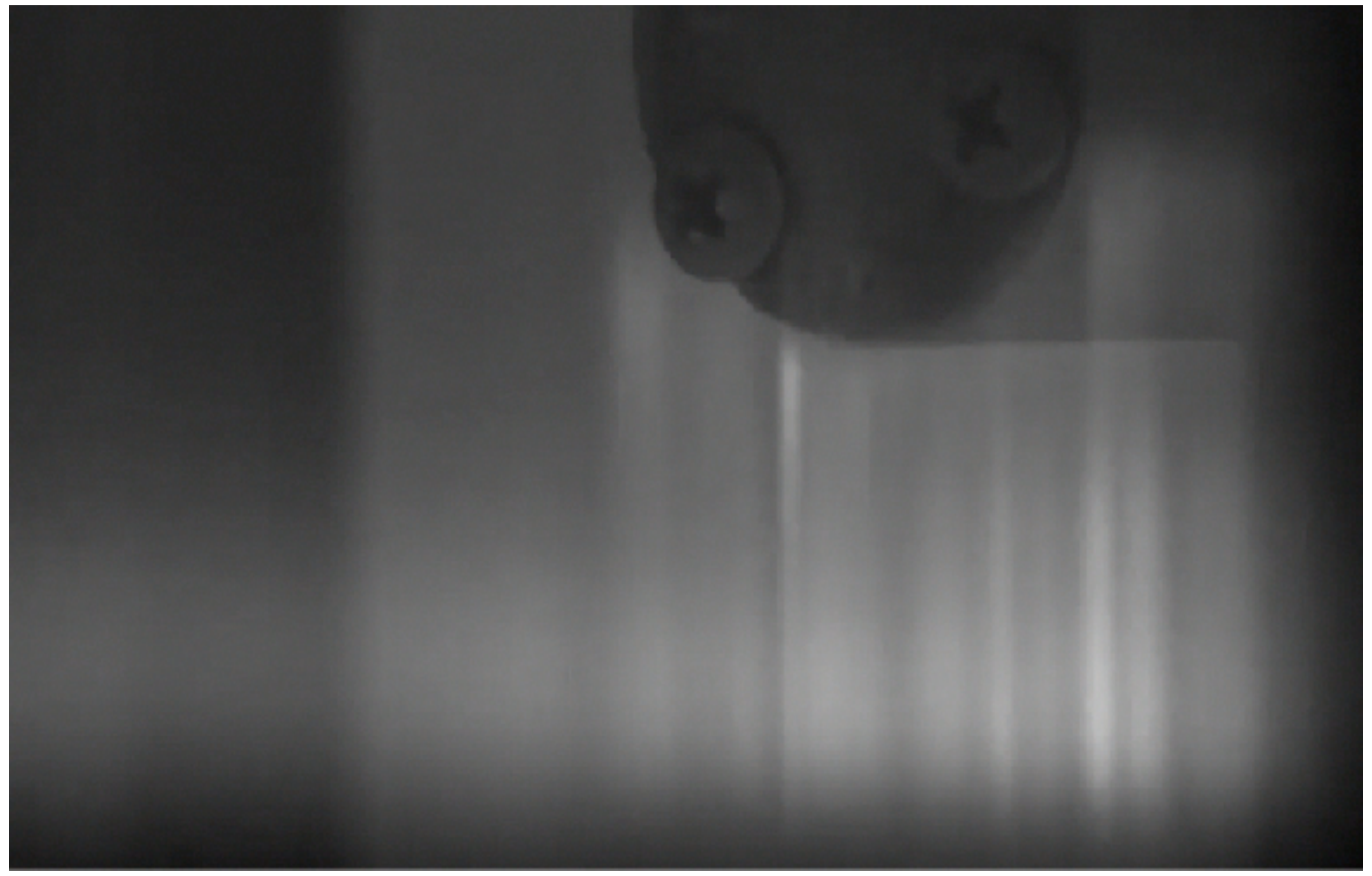
# FILAMENTATION: ORDERED, PLASMA STRUCTURES

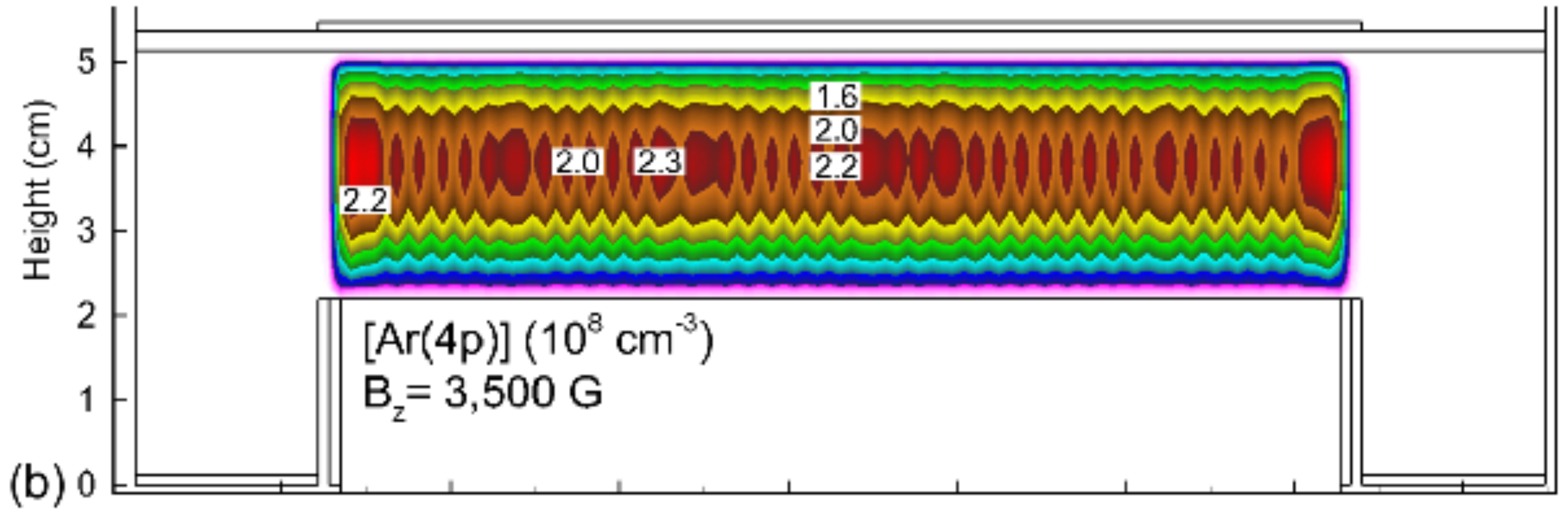



**Scaling of filaments with RF power in MDPX**

- **The presence of filaments (plasma structures aligned parallel to the magnetic field) has been reported in earlier works [e.g., Schwabe, et al., PRL, 2011].**
- **Filaments generally appear at low pressure, at low rf power, and at higher magnetic fields**
- **Few extensive, systematic studies have been performed, nor is there a comprehensive model to describe them.**

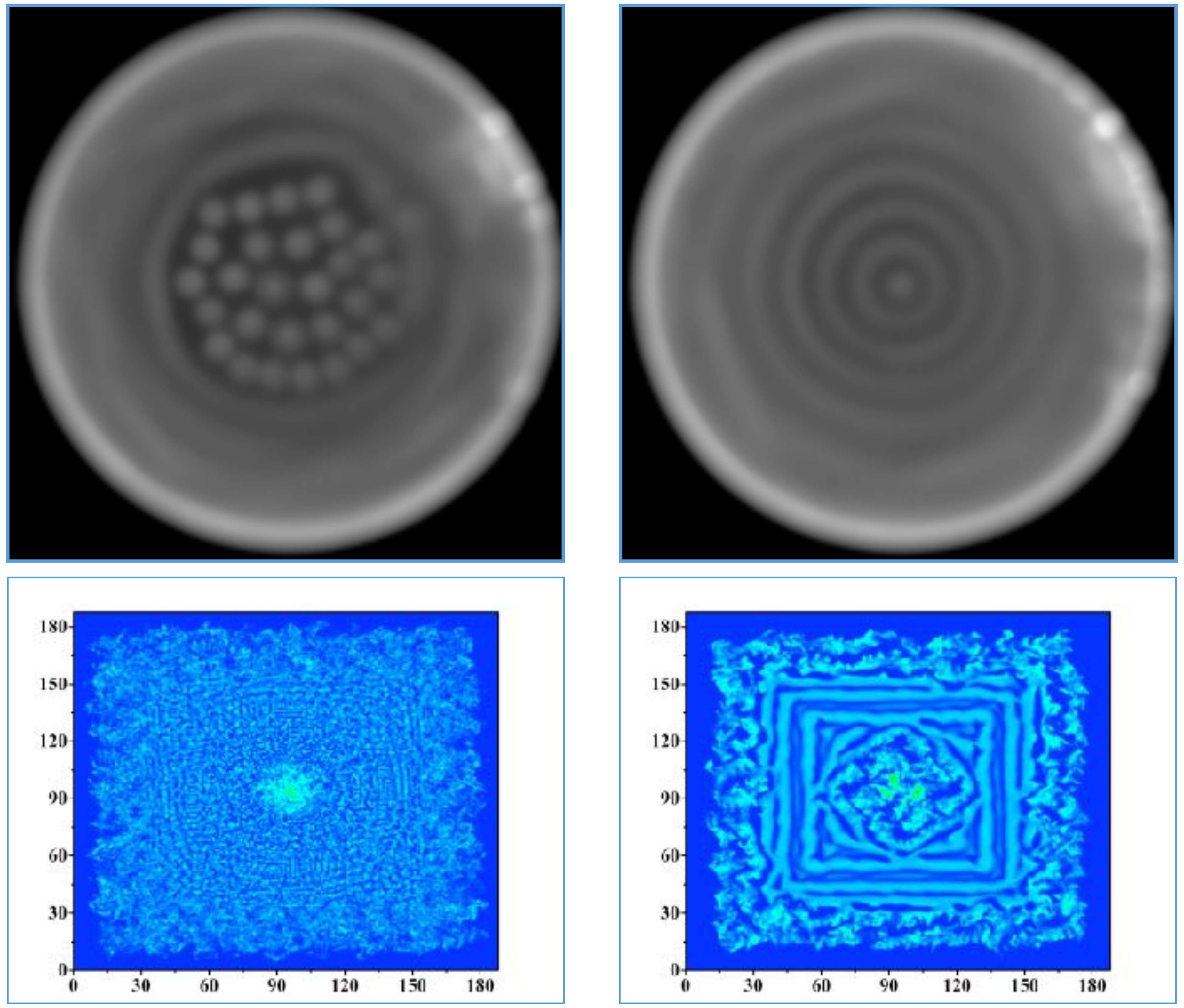
# FILAMENTATION: ORDERED, PLASMA STRUCTURES






2-D modeling of filaments
Using M. Kushner
Hybrid Plasma Equipment Model (HPEM)

Menati, Thomas, Kushner,
submitted to PoP, 2019



3-D modeling of filaments
Using Menati fluid code

Menati, Konopka, Thomas (in prep)

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# Gridding: Imposed, Ordered dust Structures

- At magnetic fields, B ≥ 1 T, dust particles are observed for form a new type of ordered structure
- This structure had the same spatial ordering as mesh electrodes at the plasma boundary (Δz ~ 60 mm)

**Image spatial resolution**

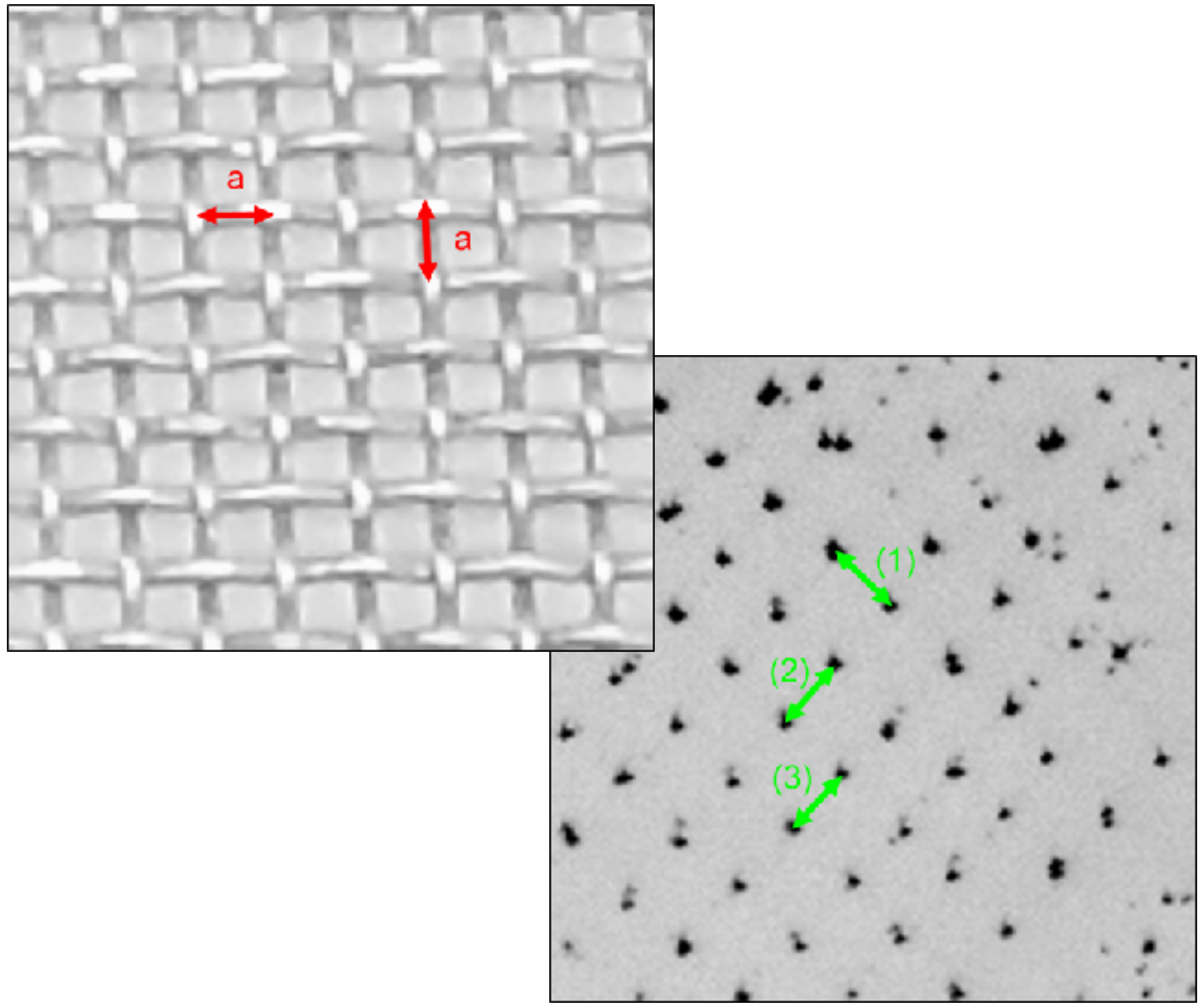
**45.5 μm/pix**

**Wire center-to-center spacing**

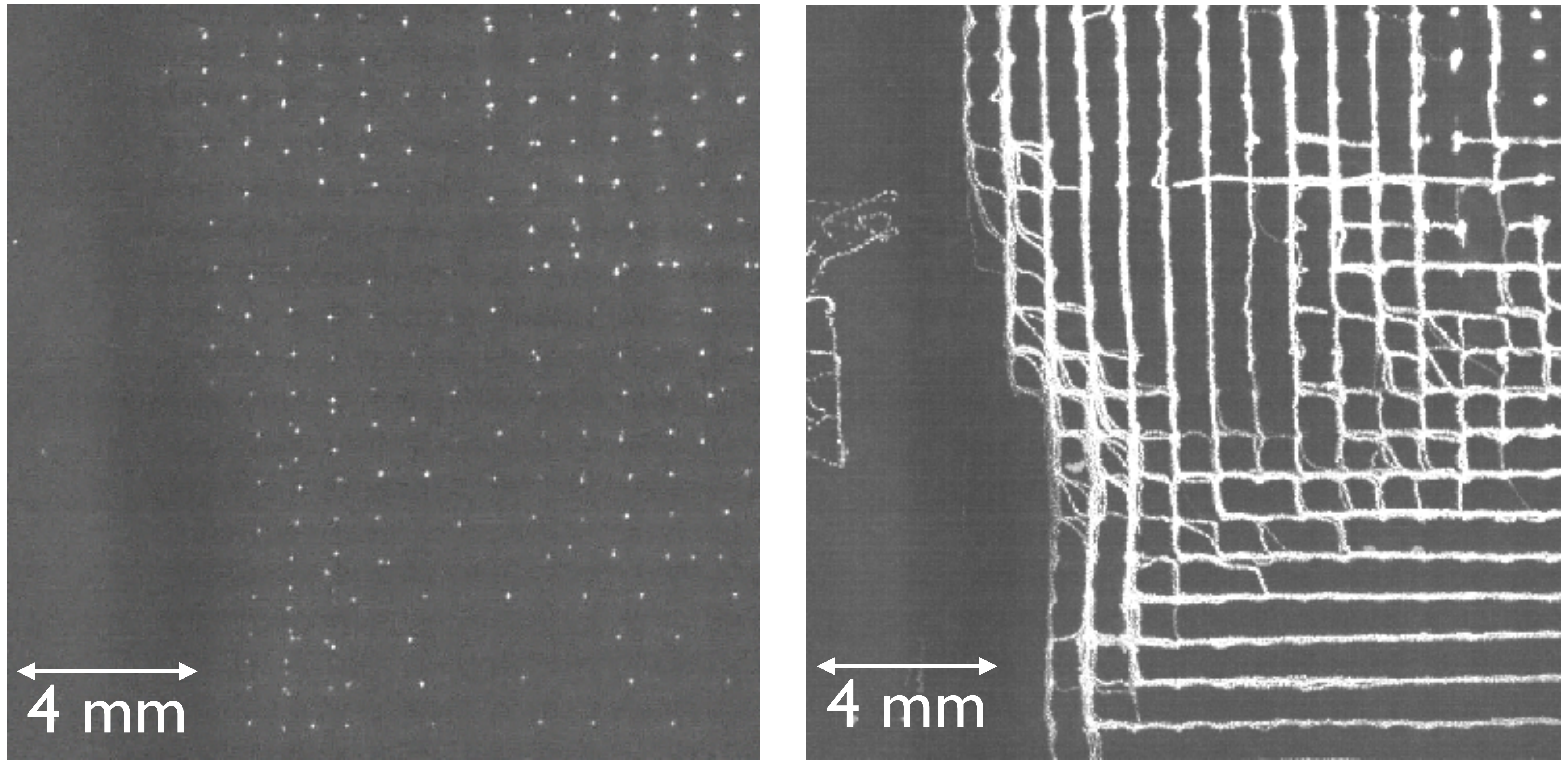
**a = 838.2 ± 139.7 μm**

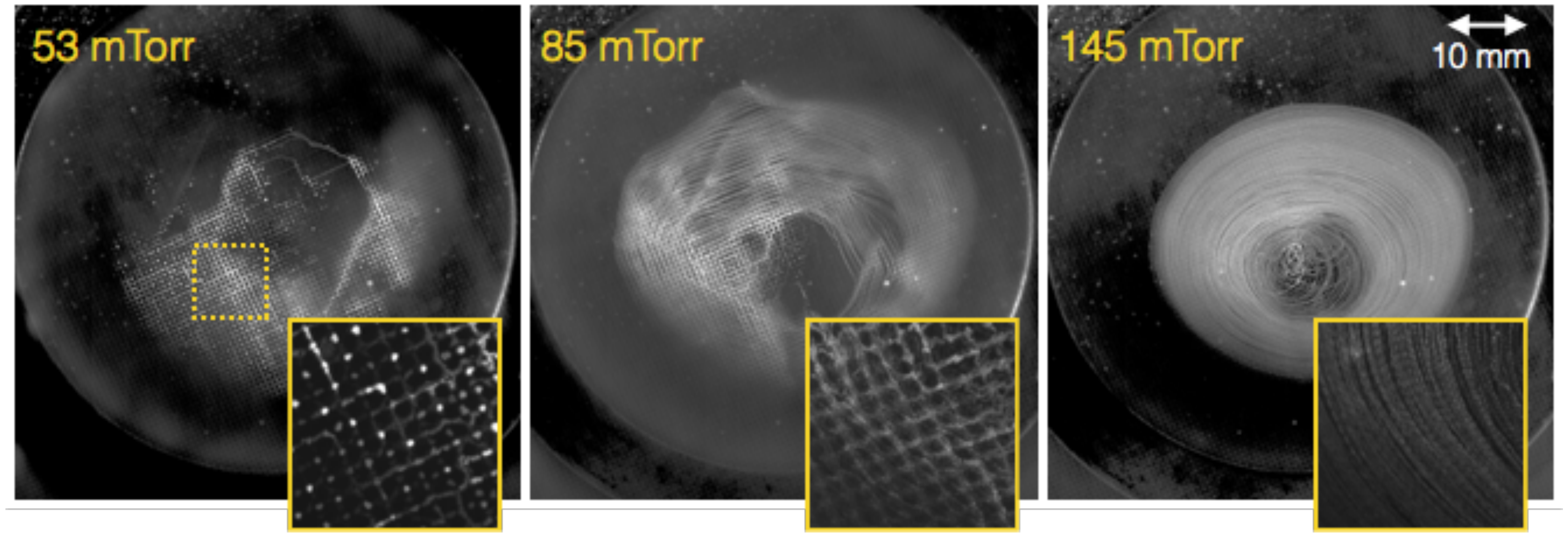
**Sample measurements**

**(1) 19.80 pix ~ 900.9 μm**
**(2) 19.91 pix ~ 908.6 μm**
**(3) 18.77 pix ~ 854.0 μm**



# Gridding: Imposed, Ordered dust Structures

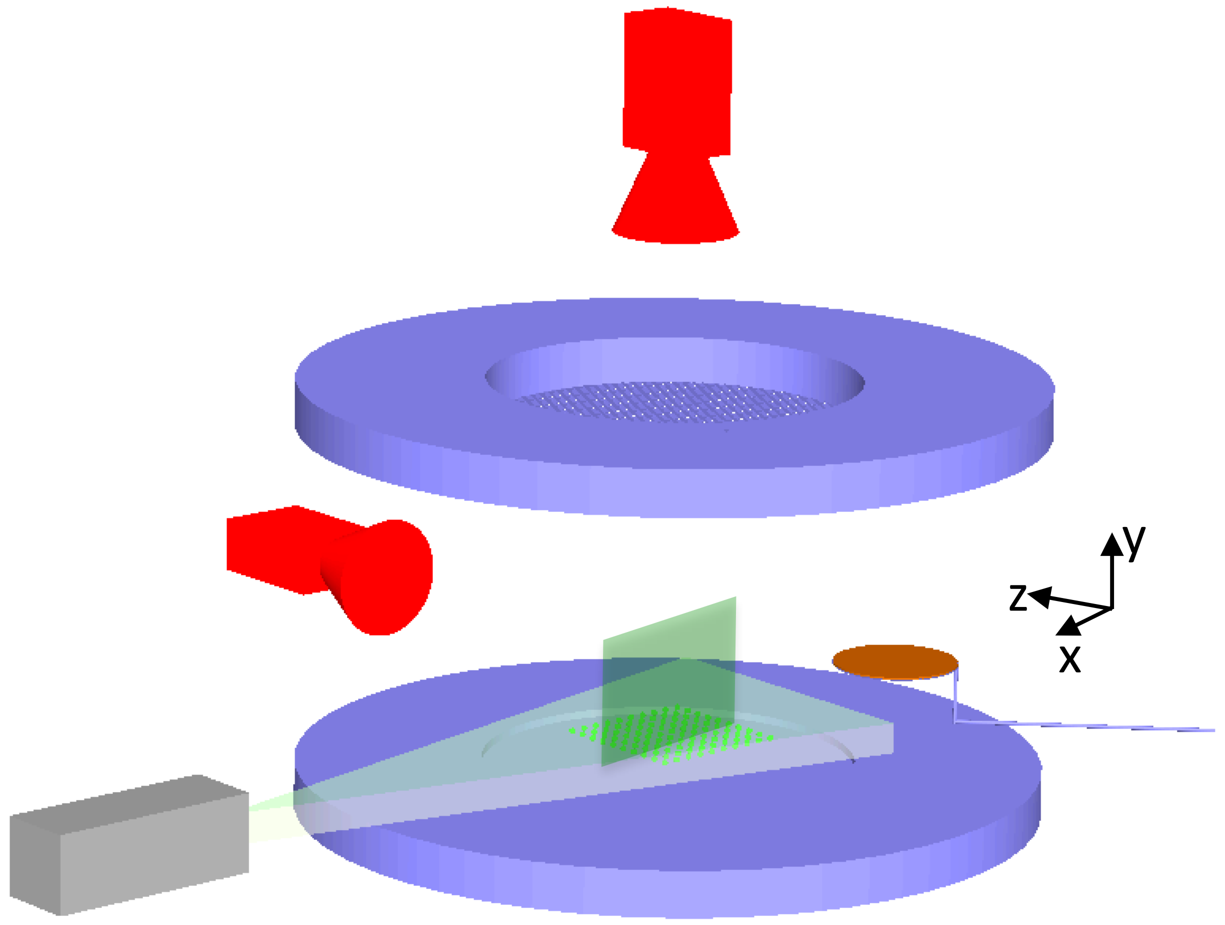



**pressure increasing** →

Measurement conditions:

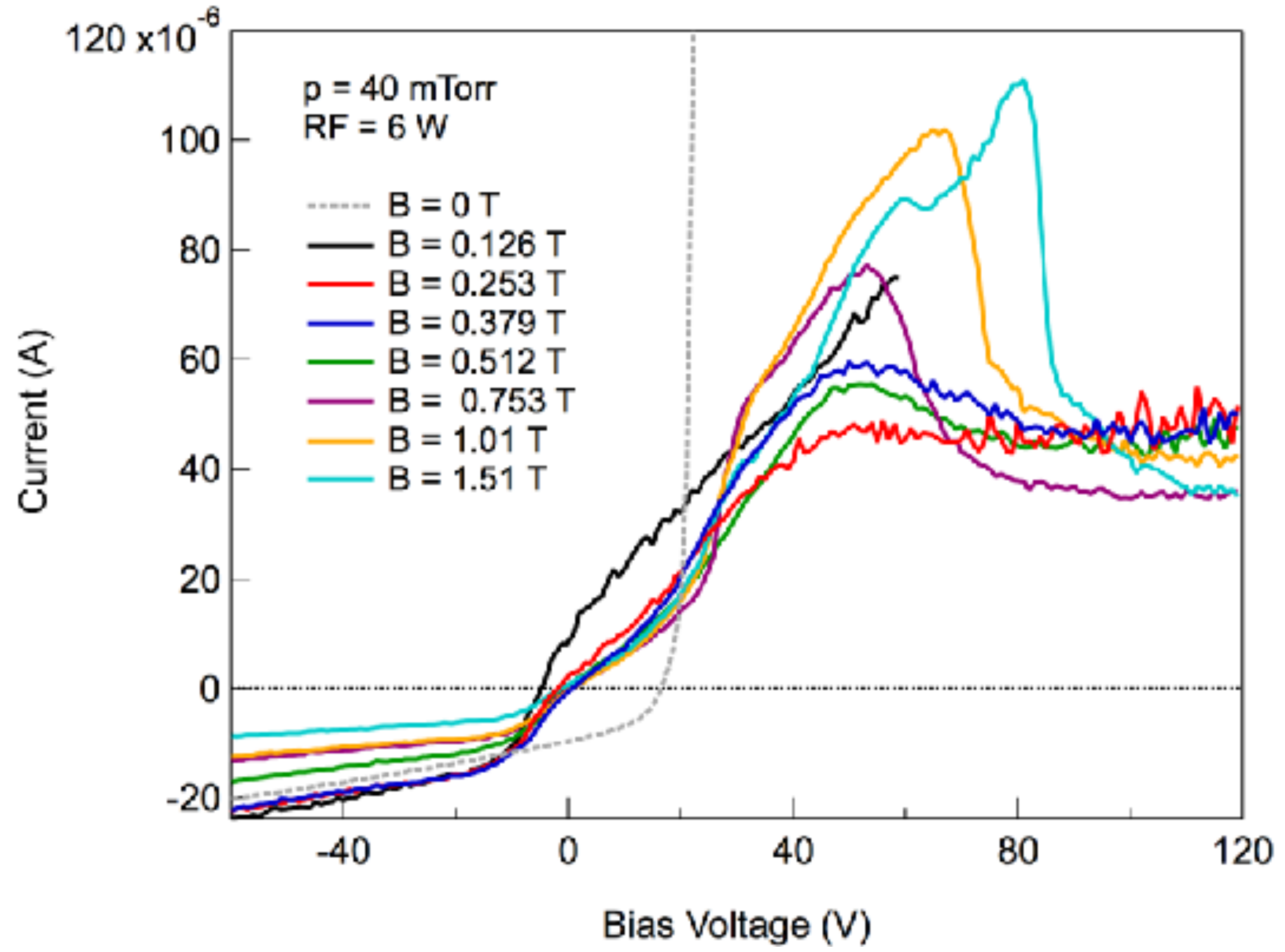
B = 2.02 T
P = 137 mTorr / 19.5 Pa
RF power = 1.6 W



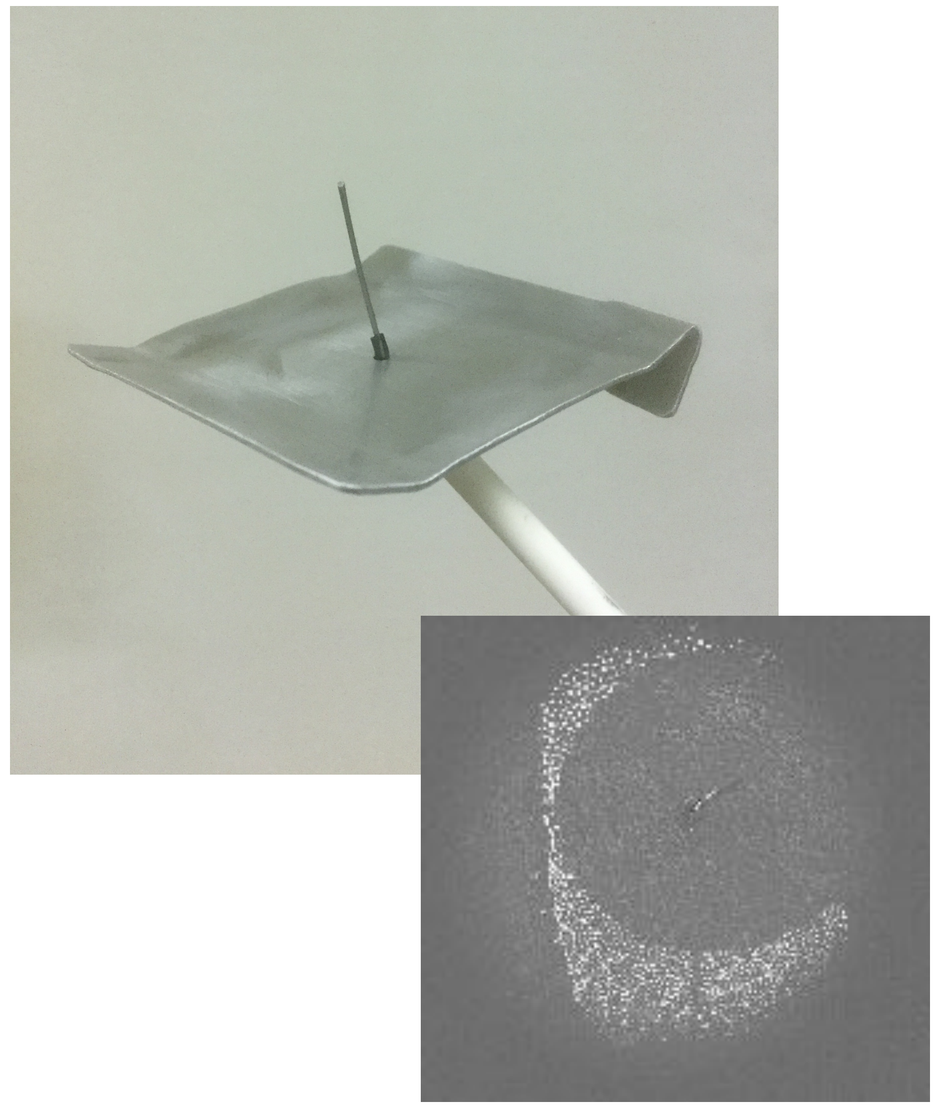

- At lower pressures (p < 140 mTorr / 20 Pa), the dust particles can form an ordered pattern.
- With increasing pressure the particles can become unlocked from the grid.
- With increasing magnetic field, particles become strongly confined to the pattern established by the mesh.

*E. Thomas, et al., Phys. Plasmas, 22, 113708 (2015)*

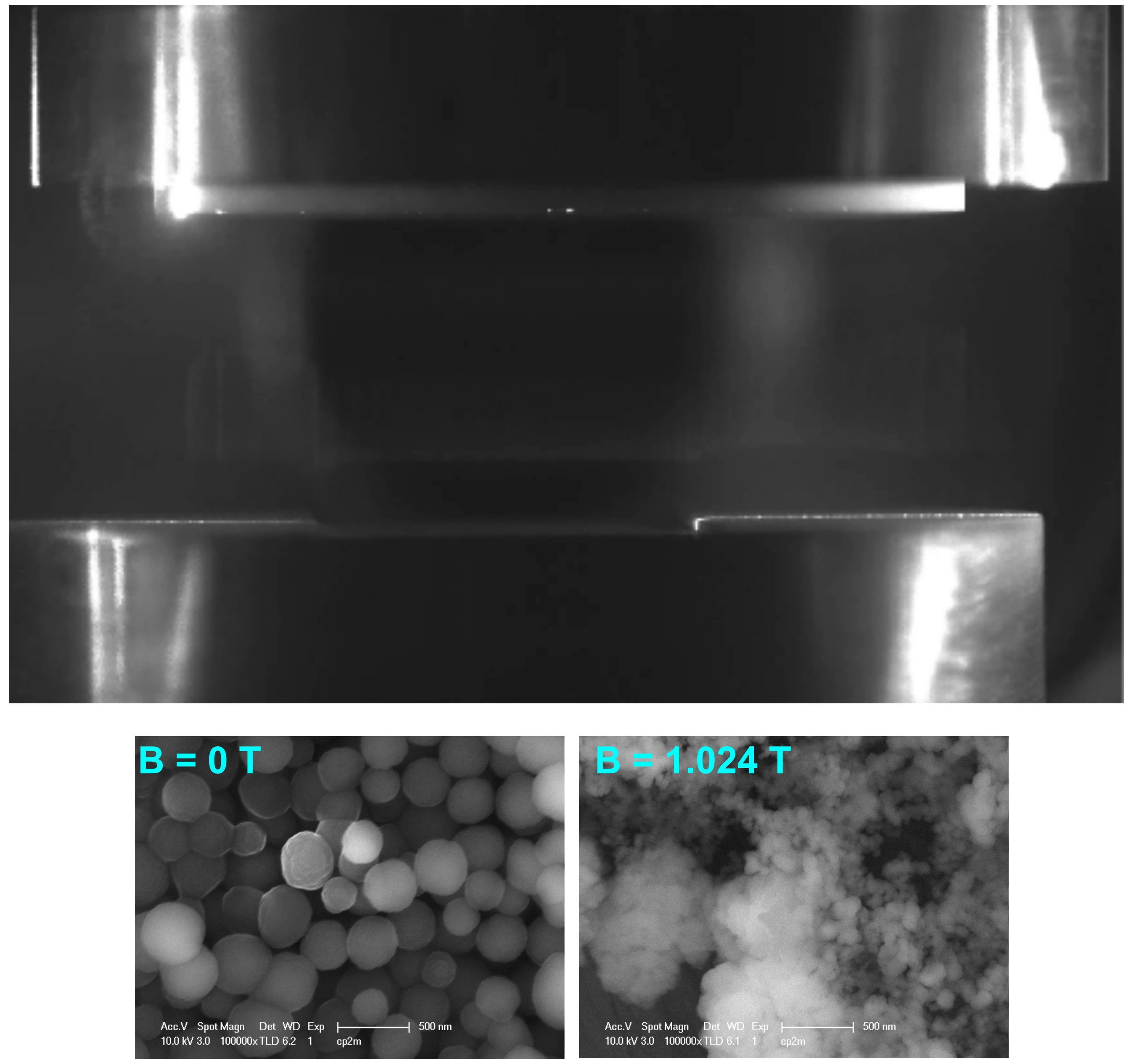
# Auburn studies of magnetized dusty plasmas



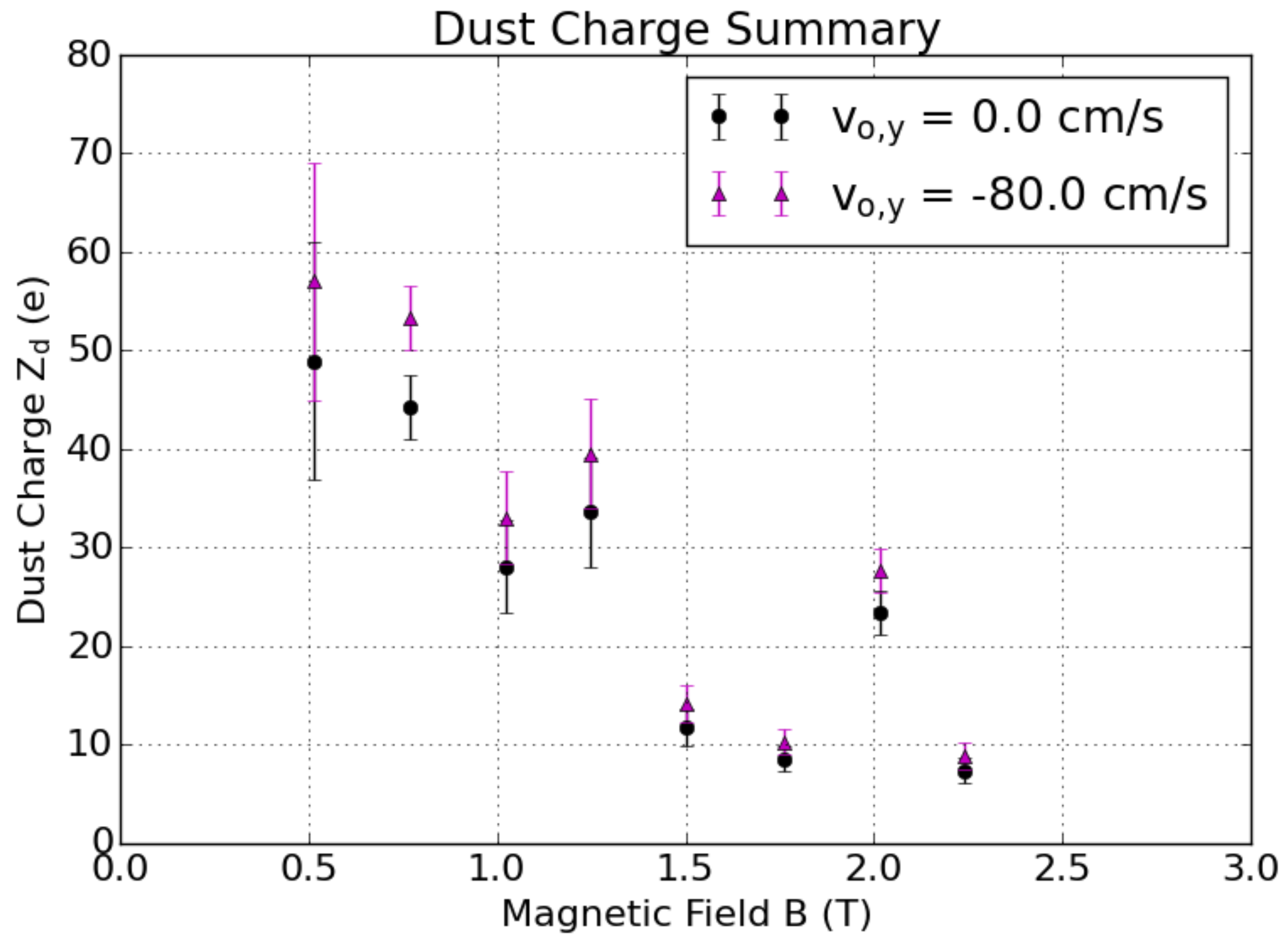

Non-ideal probe measurements



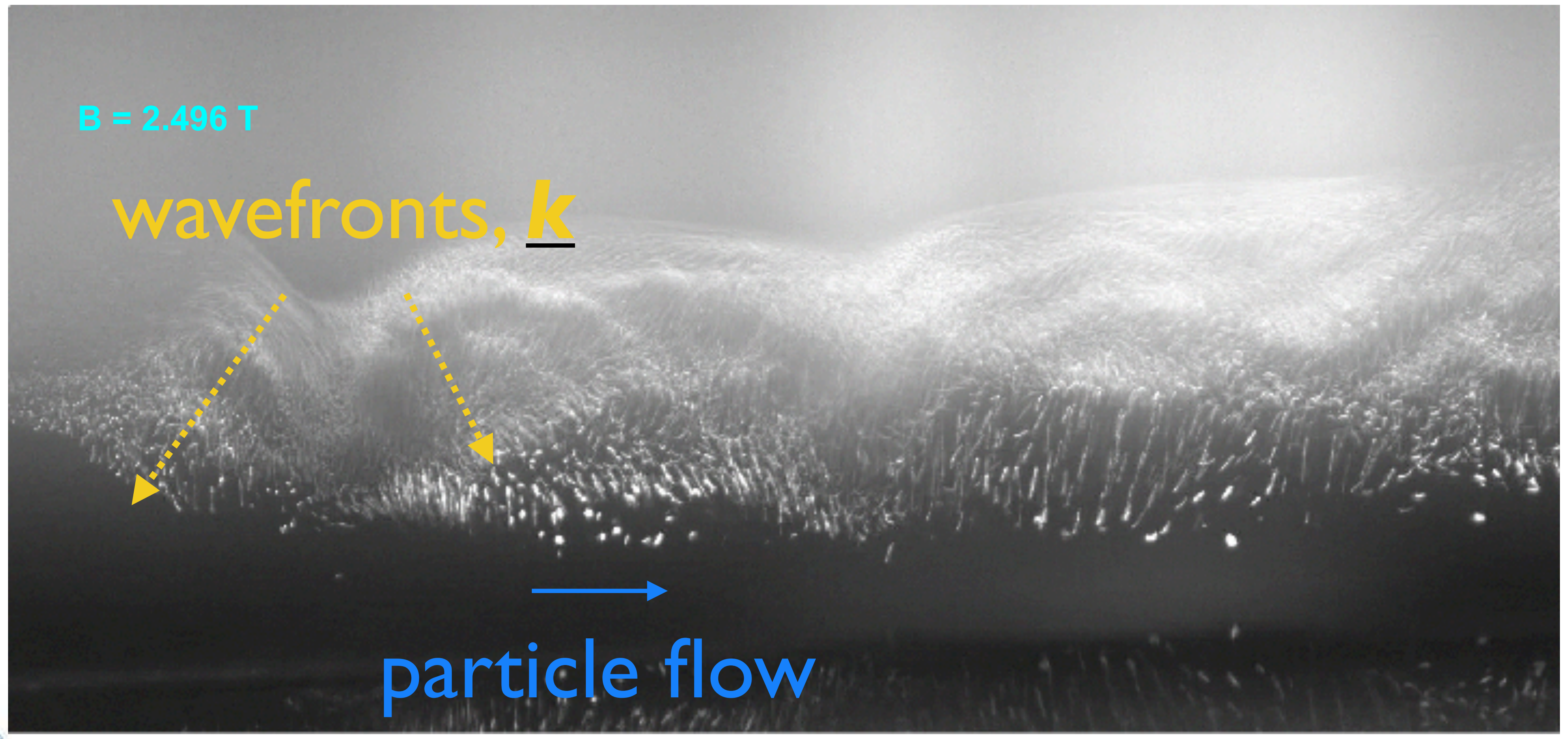
Probe-induced voids in magnetized plasmas




Modified particle growth




Charge from g x B deflection




Dust waves in magnetized plasmas

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# OUTLOOK FOR
# DUSTY PLASMA RESEACH

# 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.

# References

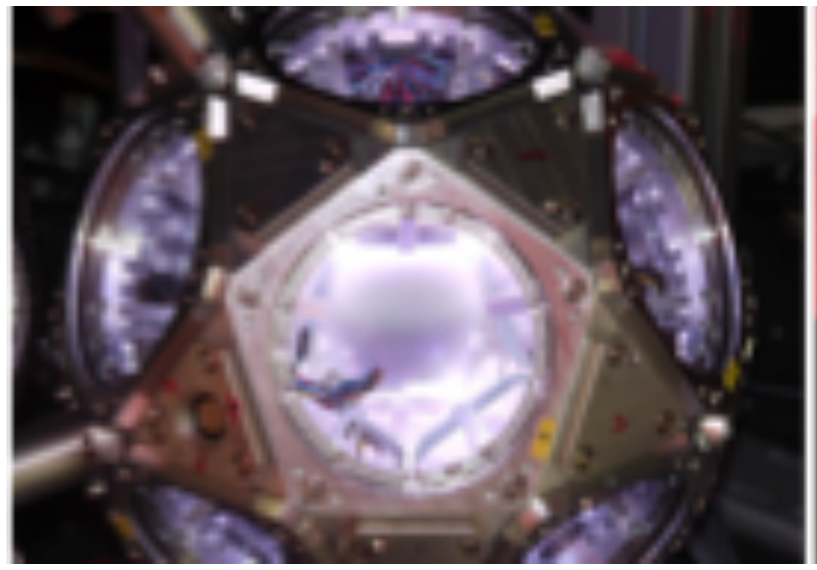
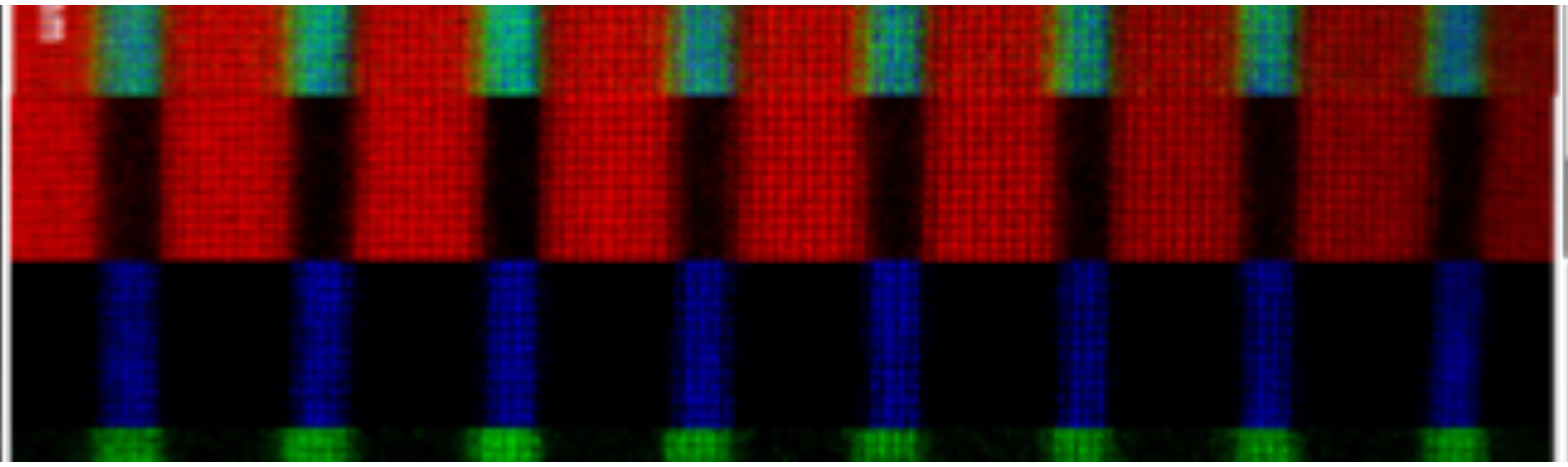
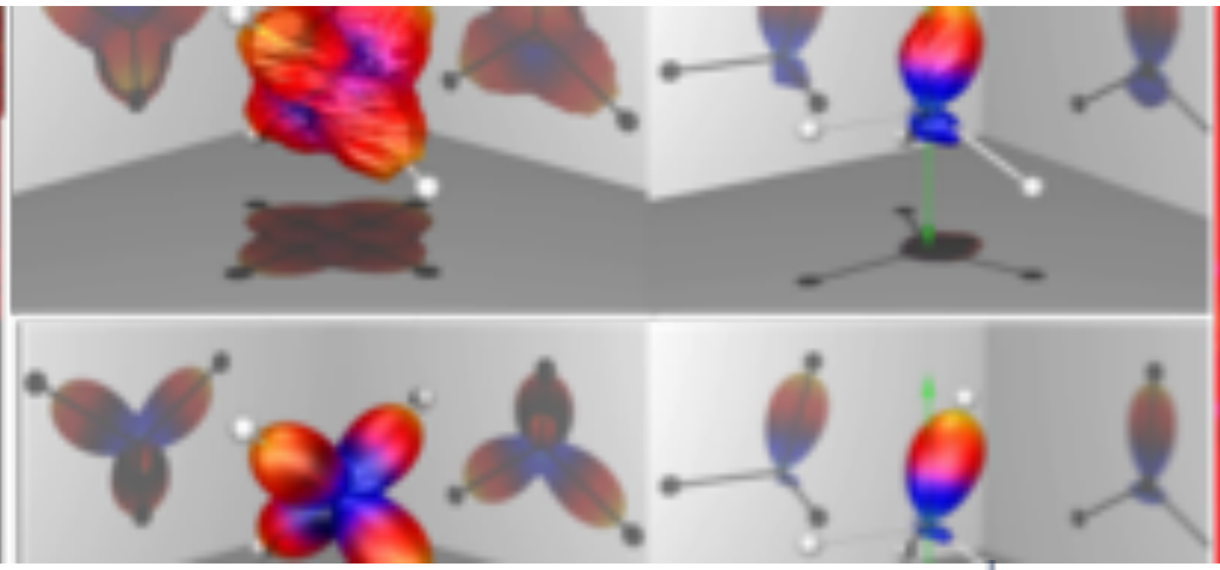
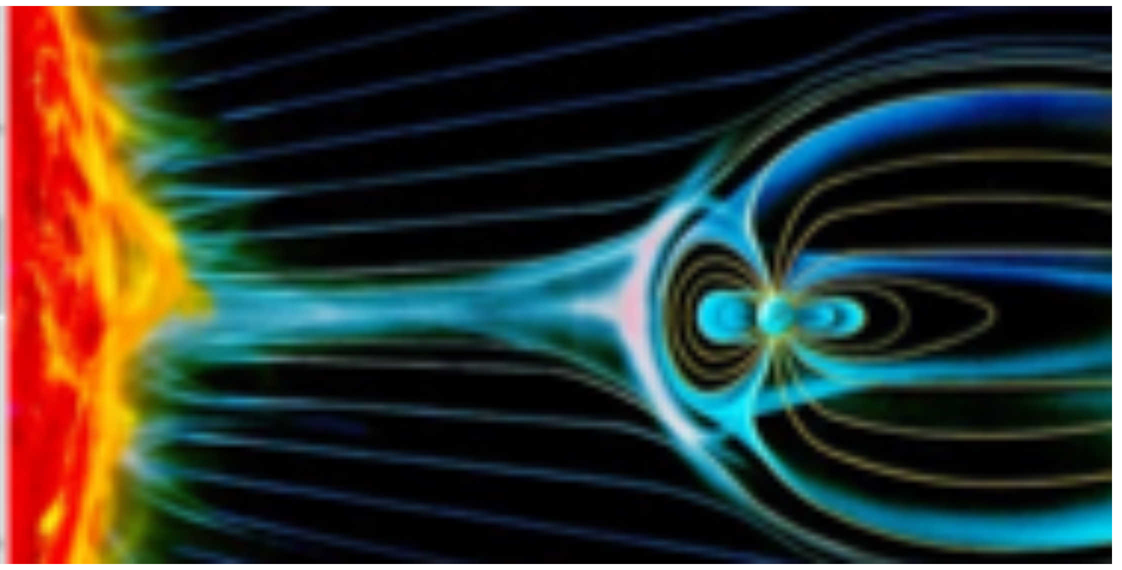
- Journals
  - TPS – IEEE Transactions on Plasma Science
  - PoP – Physics of Plasmas
  - PRL – Physical Review Letters
  - PRE – Physical Review E
  - PPCF – Plasma Physics and Controlled Fusion
  - PSS – Planetary and Space Science

- Textbooks
  - *Introduction to Dusty Plasma Physics* – P. Shukla and A. Mamun
  - *Physics and Applications of Complex Plasmas* – S. Vladimirov, K. Ostrikov, and A. Samarian
  - *Plasma Physics* – A. Piel

# 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*

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