

Evdokiya (Eva)
Kostadinova

Assistant Professor
Physics Department
Leach Science Center, Office: 3125
Auburn University, AL 36849
Office phone: (334) 844-4298

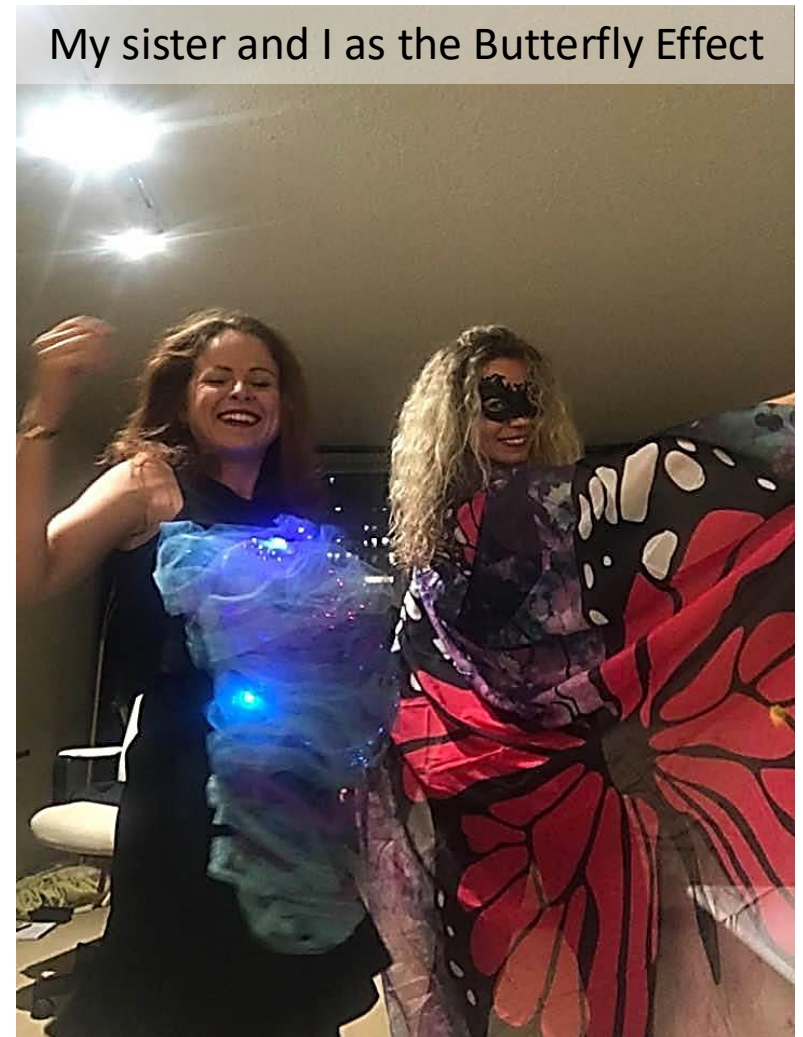
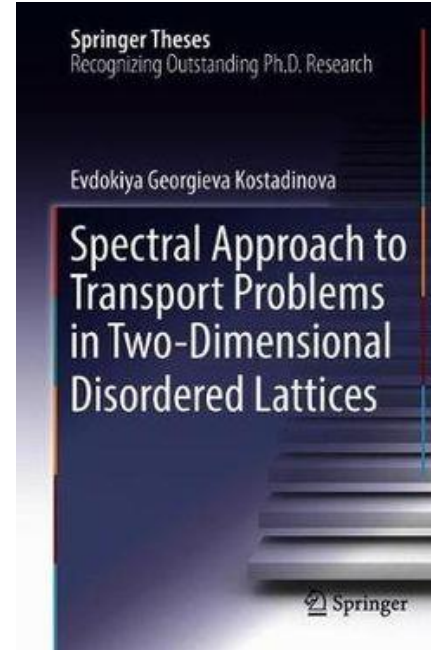
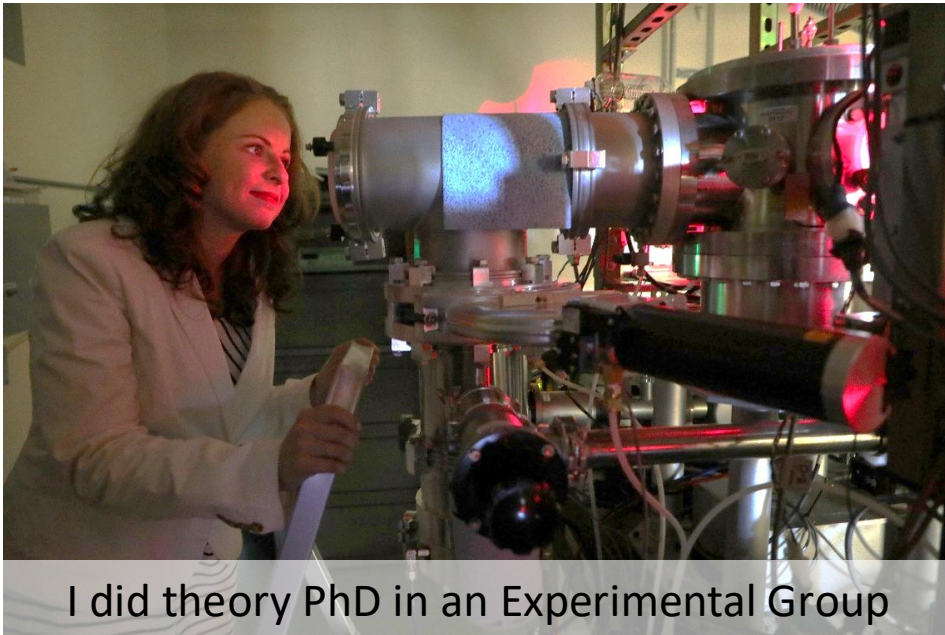


AUBURN

UNIVERSITY

Brief Bio

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



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

Scientific research work

- Reduced-gravity physics
- Fusion Energy
- Space Weather
- Heat shields for spacecrafts
- Astro-plasma-chemistry

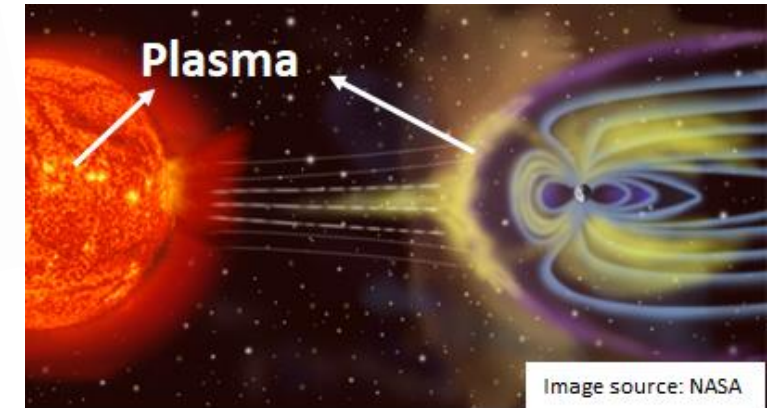
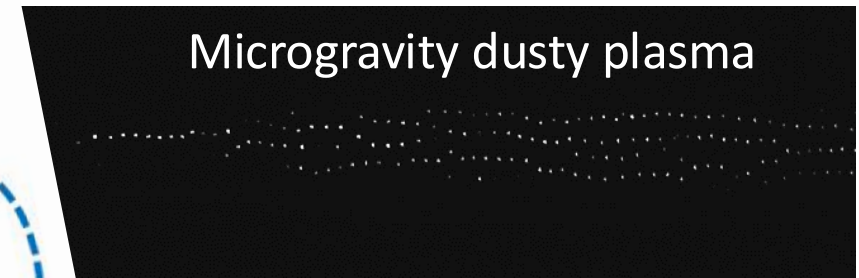
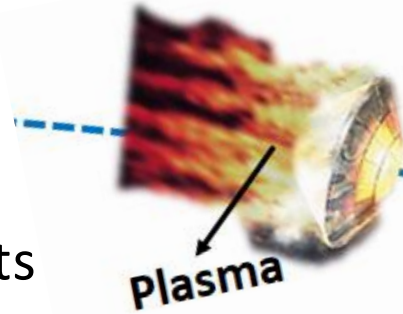
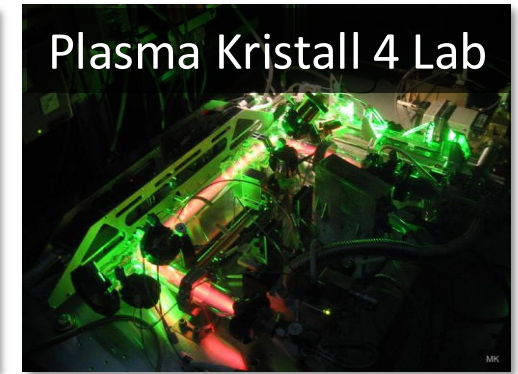
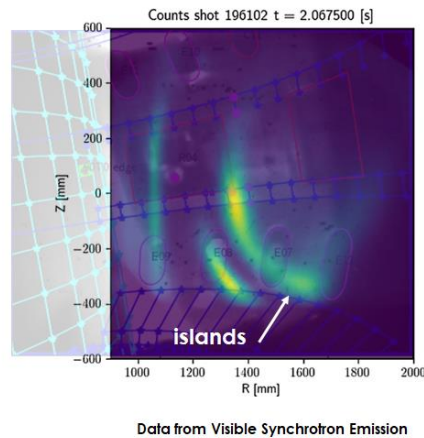
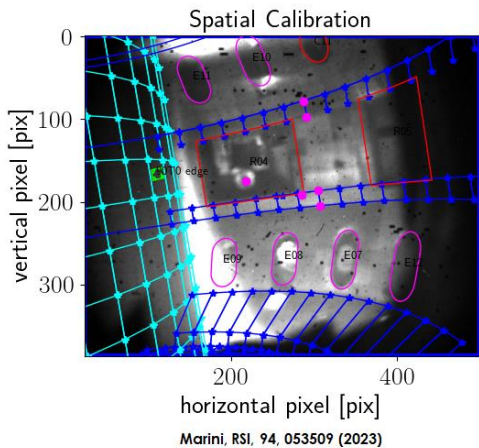


Image source: NASA



All these projects are at the intersection of plasma and another field: applied math, chemistry, biology, fusion energy, aerospace engineering



IPL

INTERDISCIPLINARY PLASMA LAB

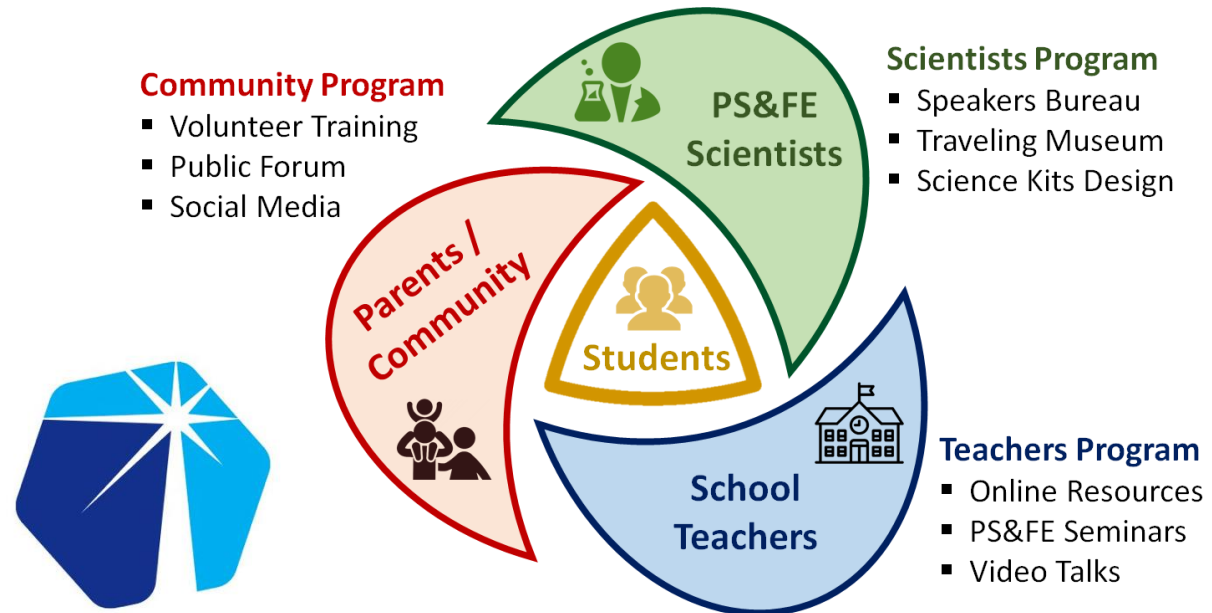
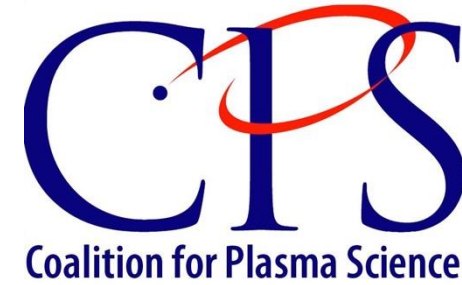
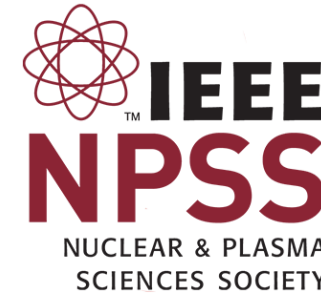
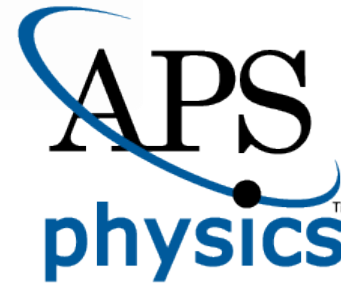


ipl.auburn.edu

Interdisciplinary Plasma Lab (IPL)

Public Engagement Work

- **Plasma NET** (Network for Engagement & Training), co-founder with Shannon Greco (PPPL); plasmanow.org
- **CPS** (Coalition for Plasma Science), Chair; plasmacoalition.org
- **FPS** (Fusion Power Associates), Vice-Chair for Plasma; fusionpower.org
- **MagNETUS**, Onboarding, ExCom Liaison; magnetus.net
- **LaserNET**, Scientific Advisory Board; lasernetus.org
- **APS DPP** – co-Chair of [Education & Outreach](#) with Arturo Dominguz (PPPL), ExCom Member-at-Large
- **IEEE NPSS PSAC** ([Plasma Science & Applications](#)) - ExCom Member-at-Large



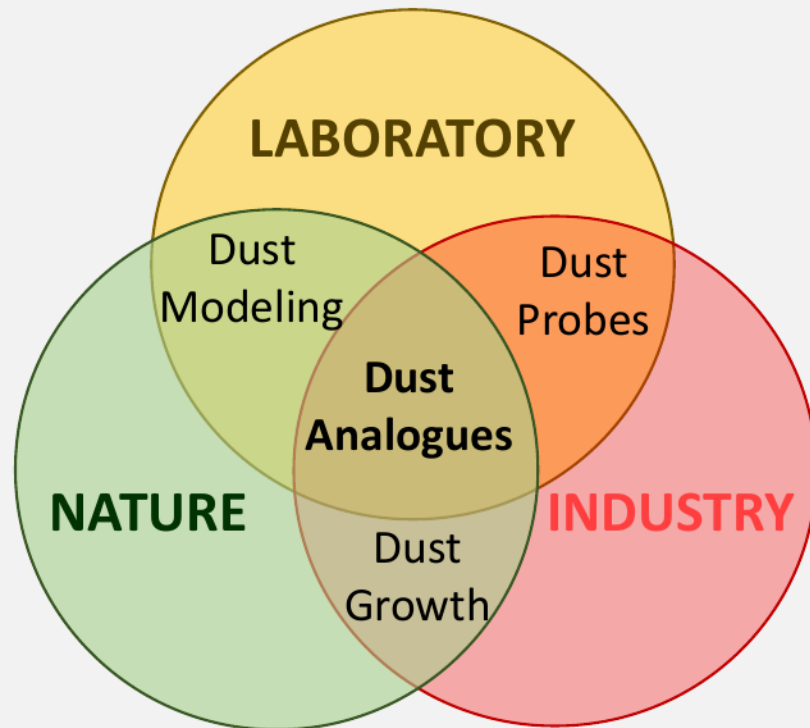
Dusty Plasmas

Outline

- Dusty Plasmas in the Universe**
- Dusty Plasmas in the Lab
- Modeling Dusty Plasmas
- Concluding Remarks

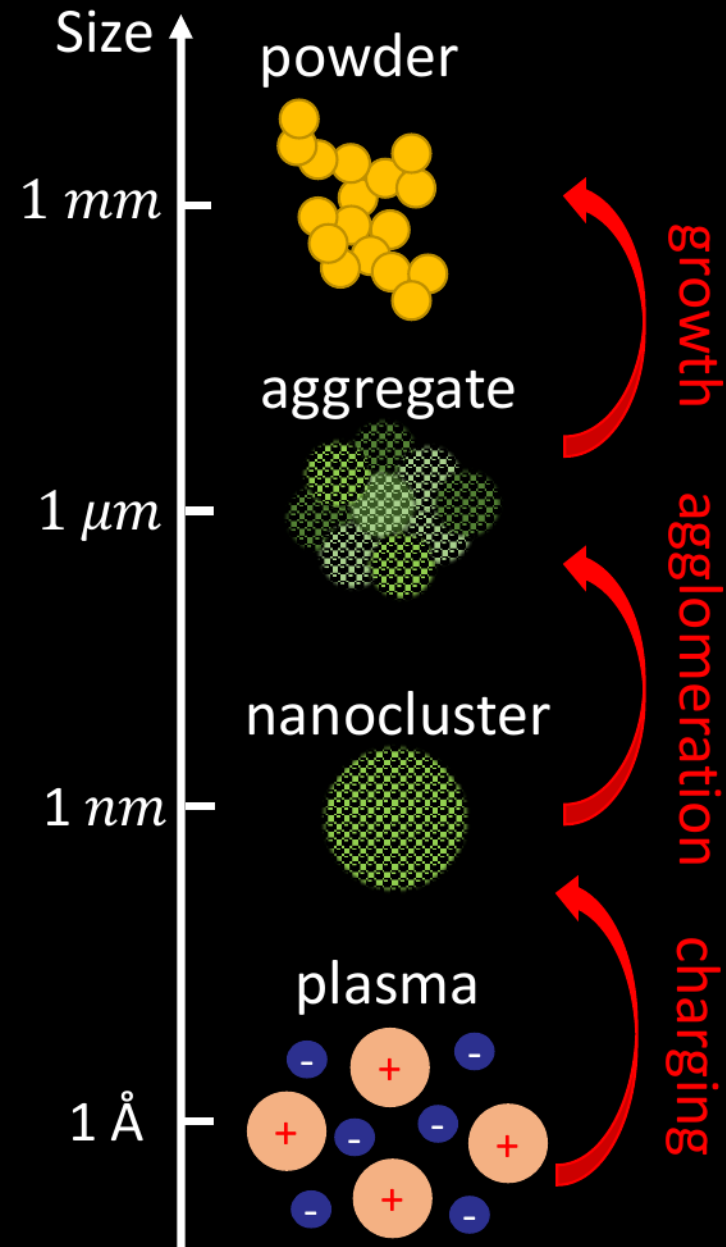
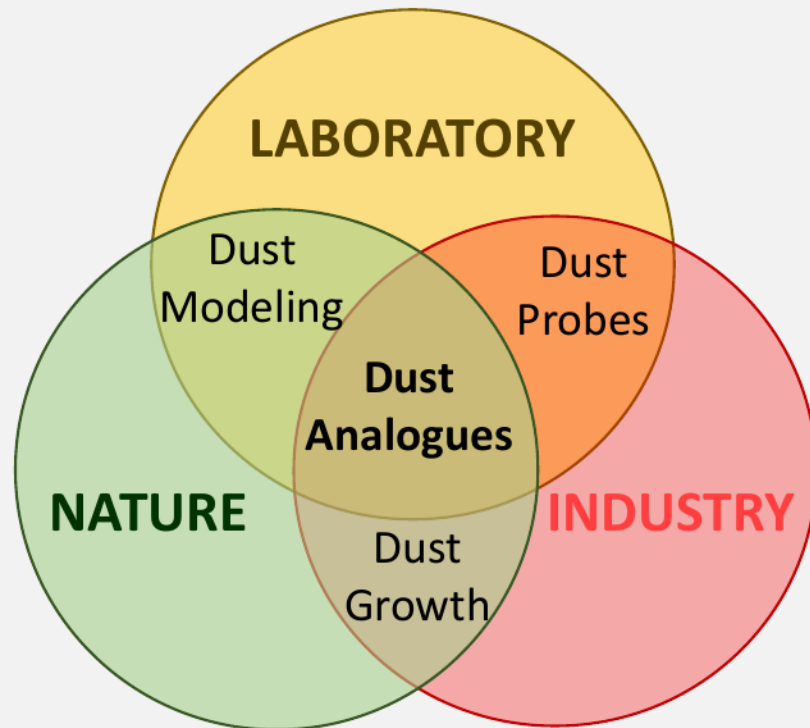
Scope of Dusty Plasma Research

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



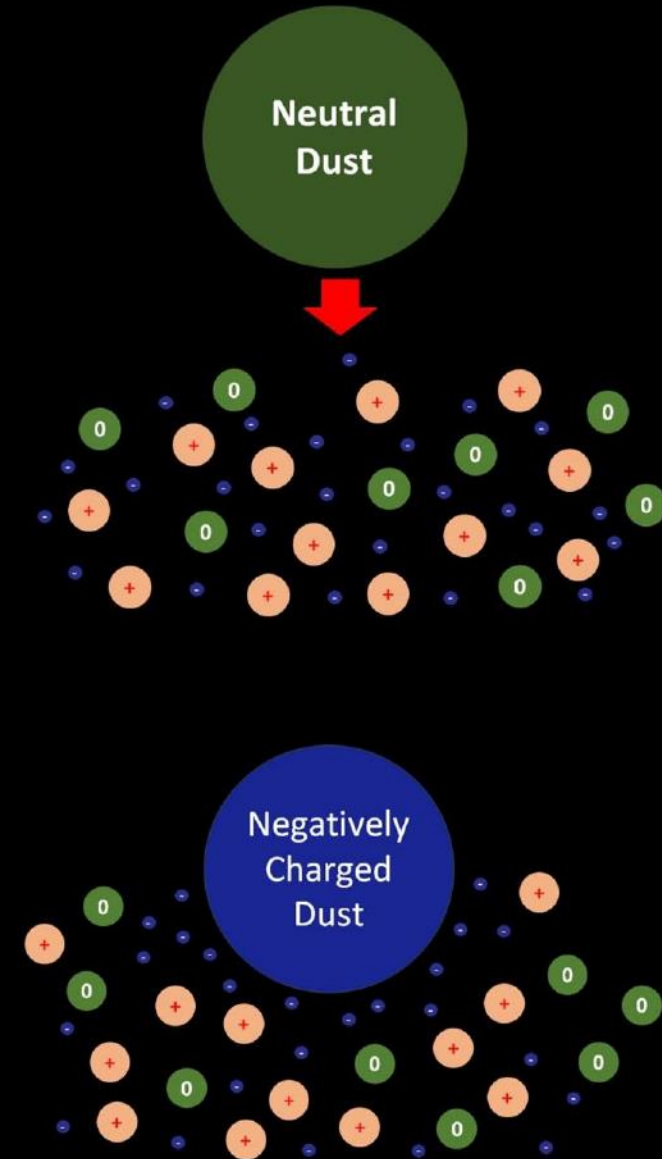
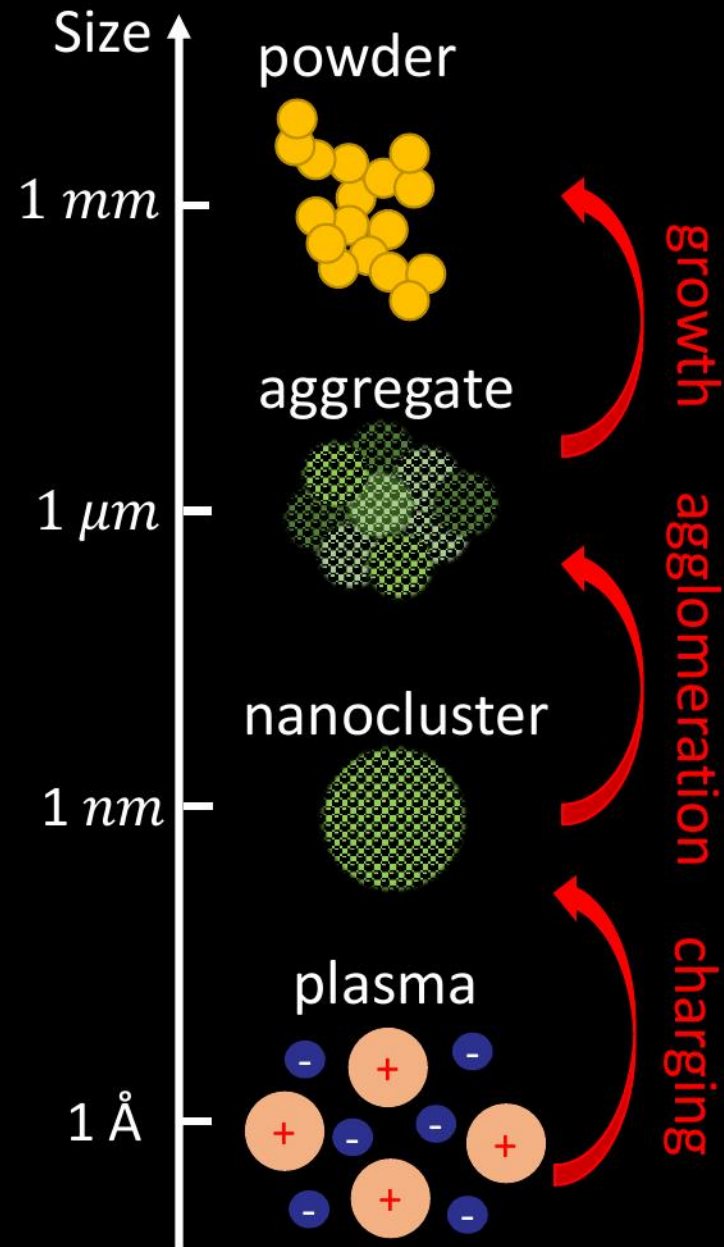
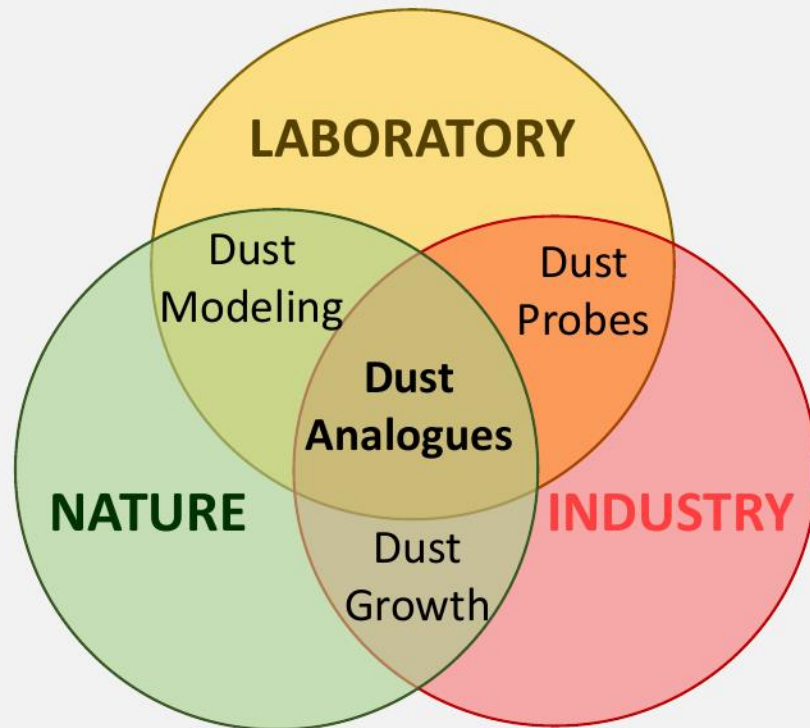
Scope of Dusty Plasma Research

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

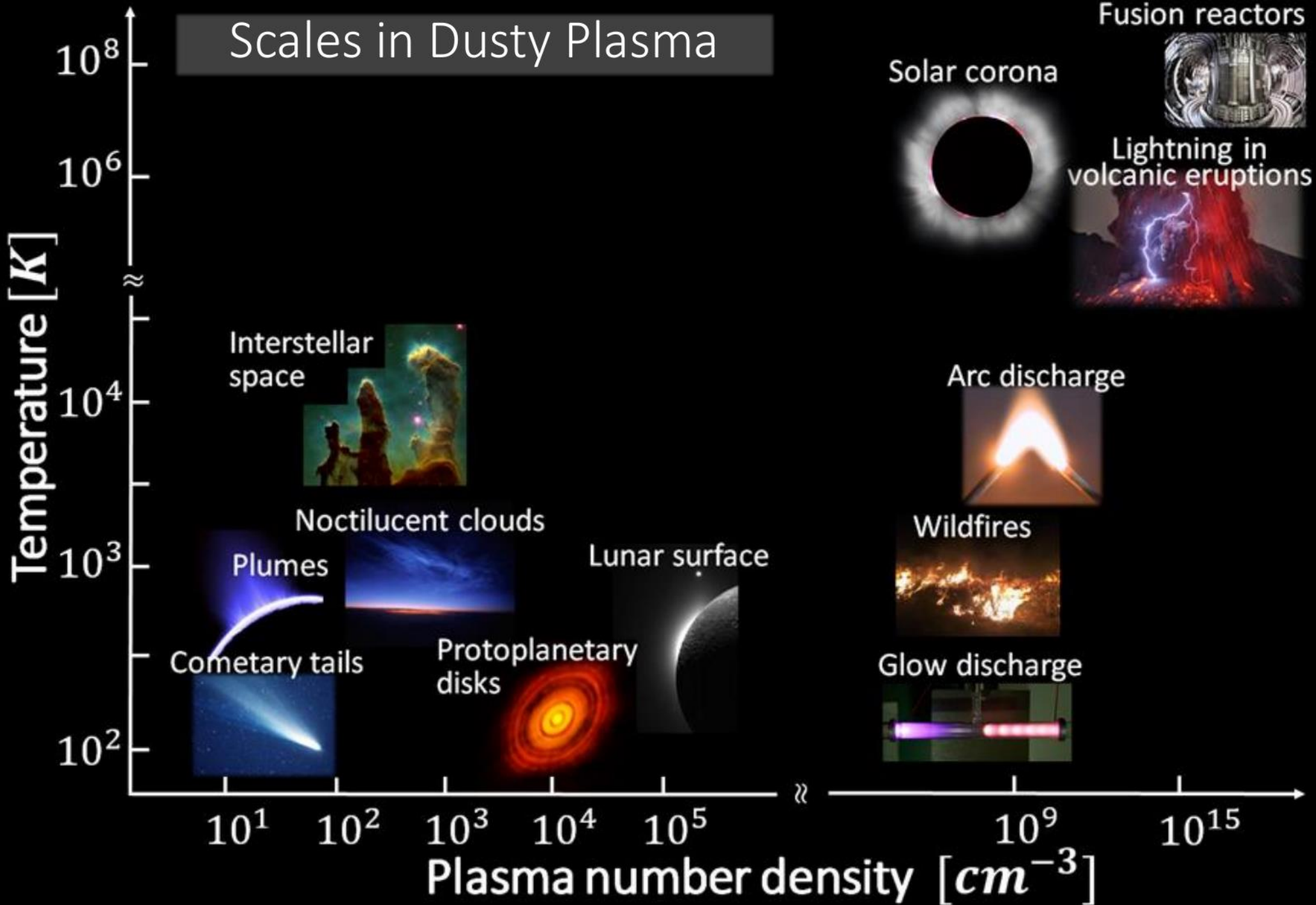


Scope of Dusty Plasma Research

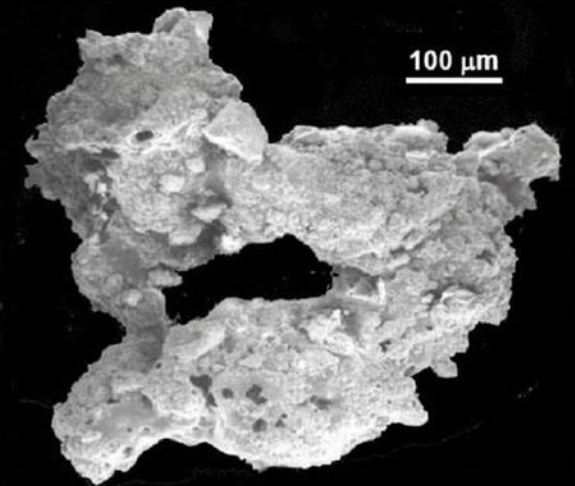
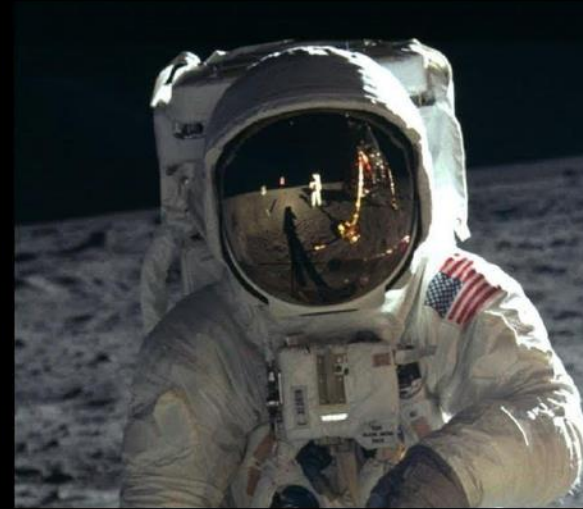
- Dusty plasmas are four-component plasmas consisting of electrons, ions, neutrals and charged, solid or liquid particulates (“dust”).
- Dust particles can appear in plasmas over vast scales – from laboratory to astrophysical systems.



Scales in Dusty Plasma



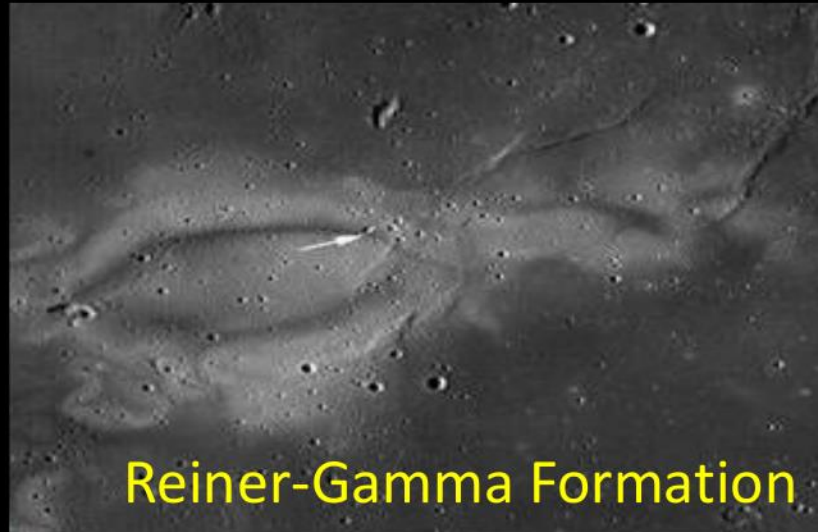
Dusty Plasmas on the surface of the Moon



“...lunar dust, itself the Number 1 environmental problem on the Moon.”

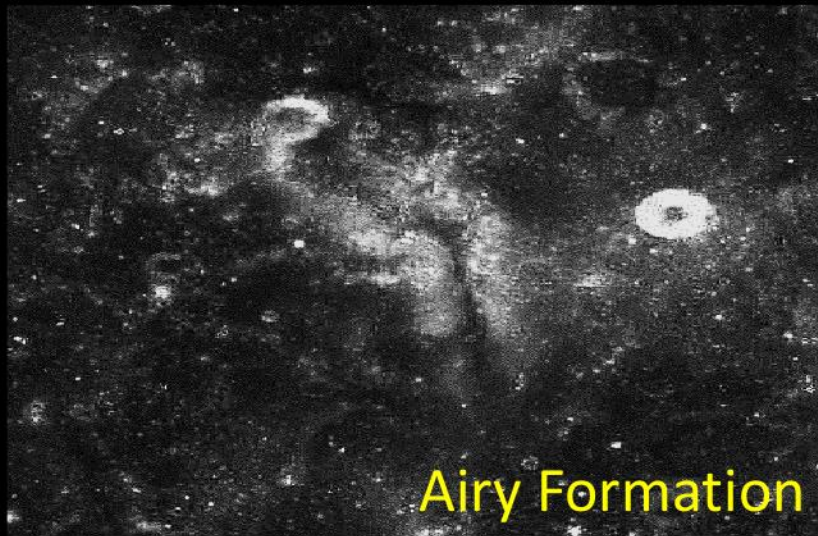
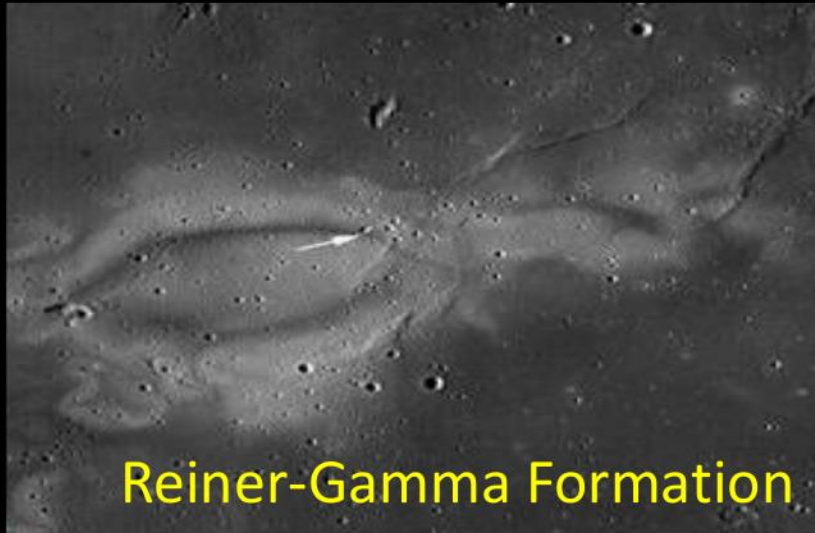
O'Brien, B. J., & Gaier, J. R. (2009, November). Indicative Basic Issues About Lunar Dust in the Lunar Environment. In *Annual Meeting of the Lunar Exploration Analysis Group* (Vol. 1515, p. 52).

Lunar tattoos (swirls)

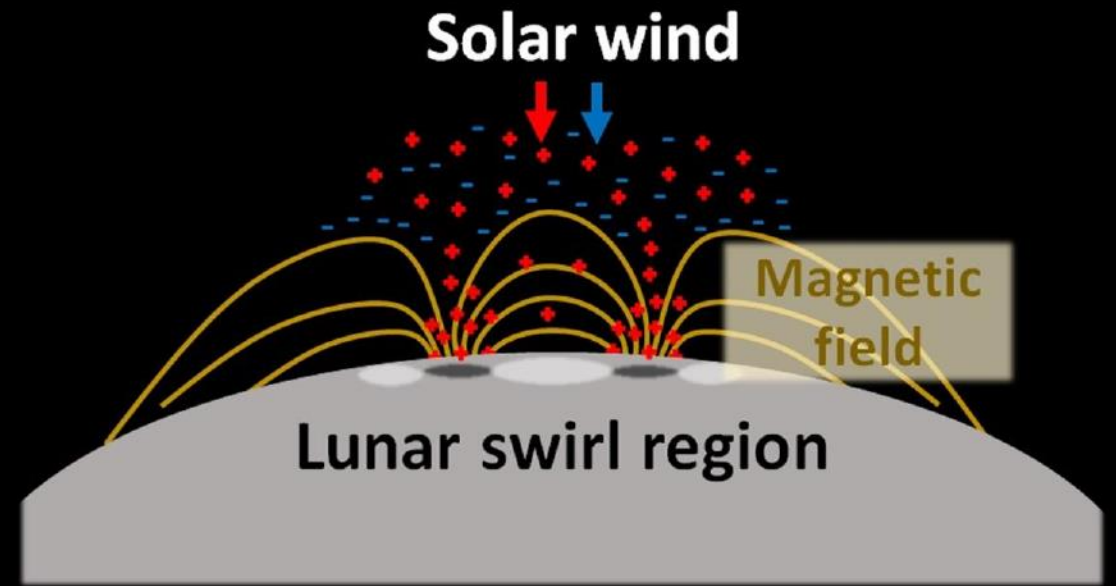


Credit: NASA, JPL, USGS

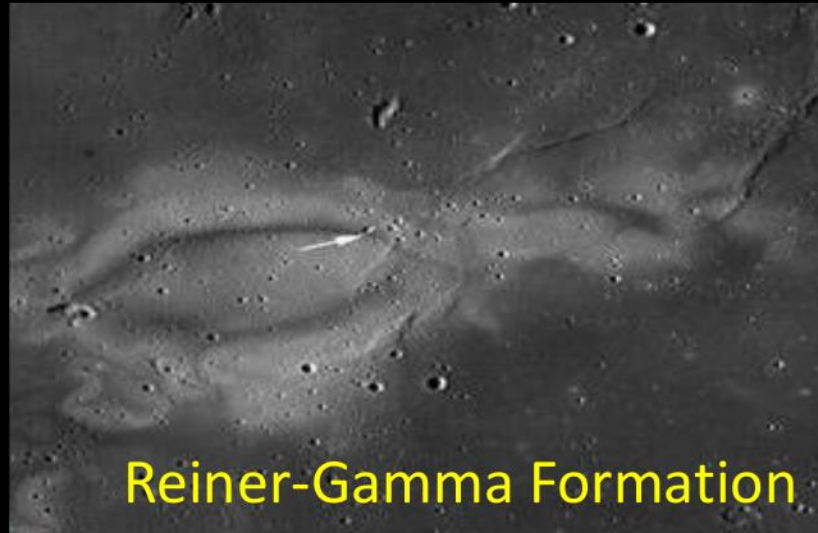
Lunar tattoos (swirls)



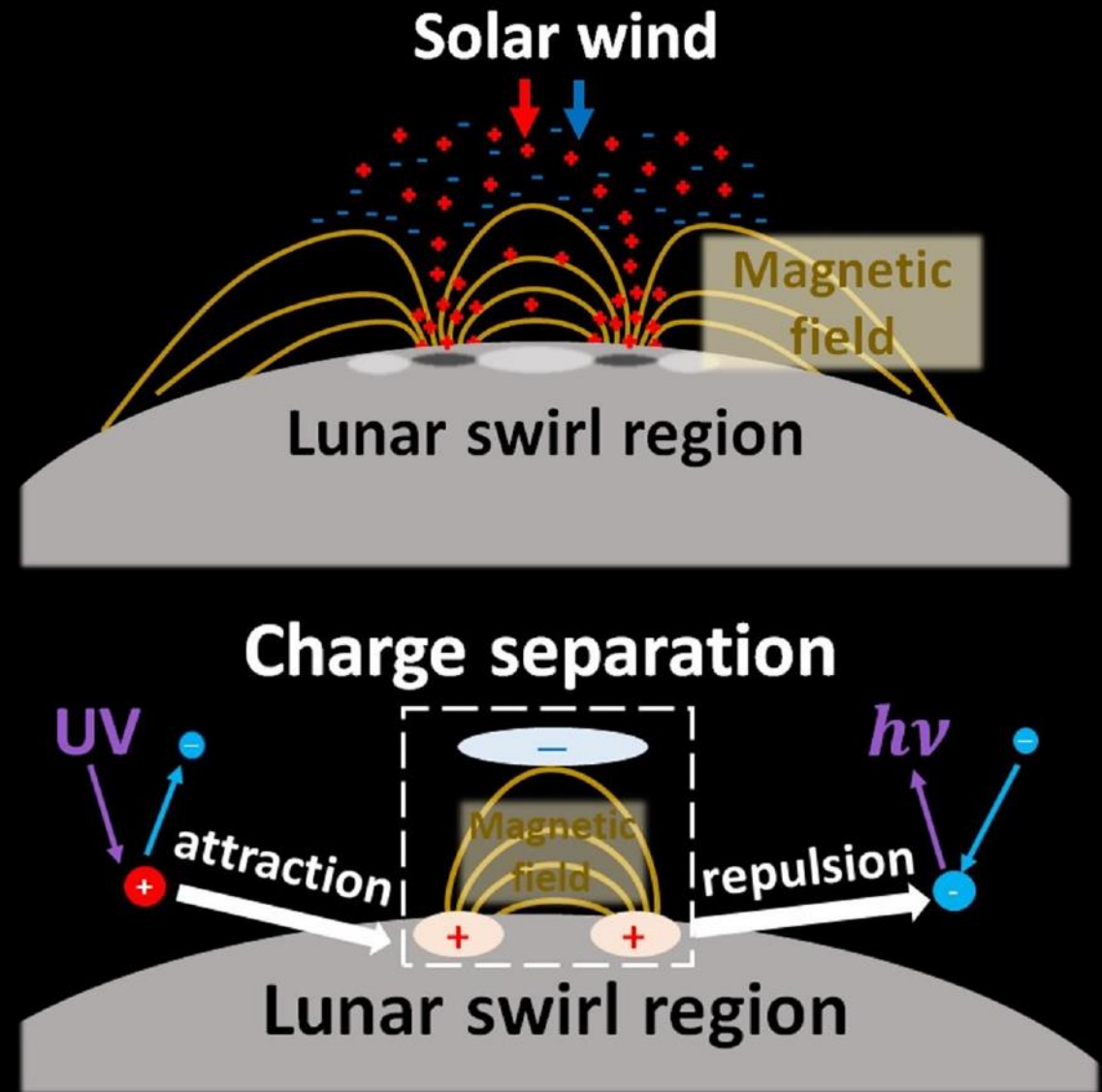
Credit: NASA, JPL, USGS



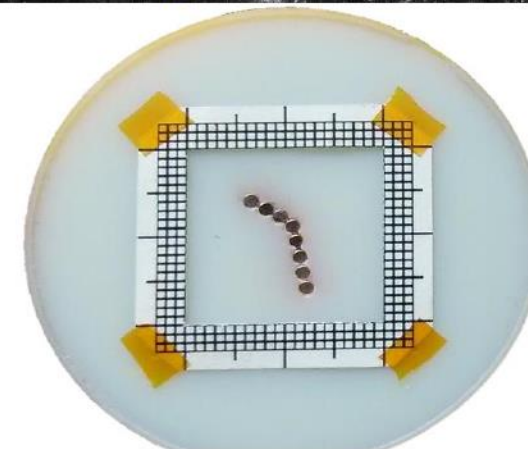
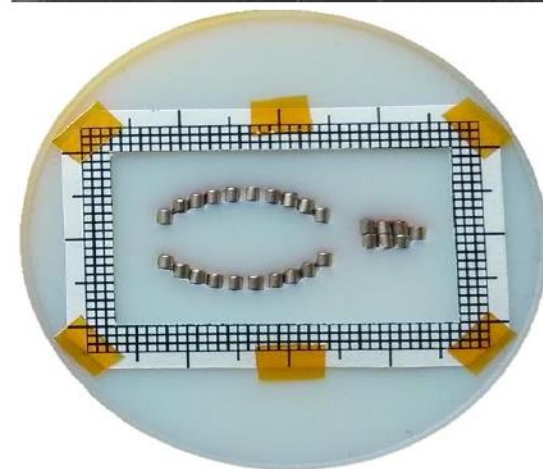
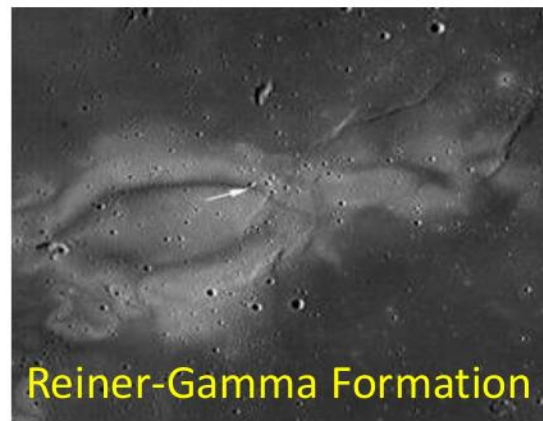
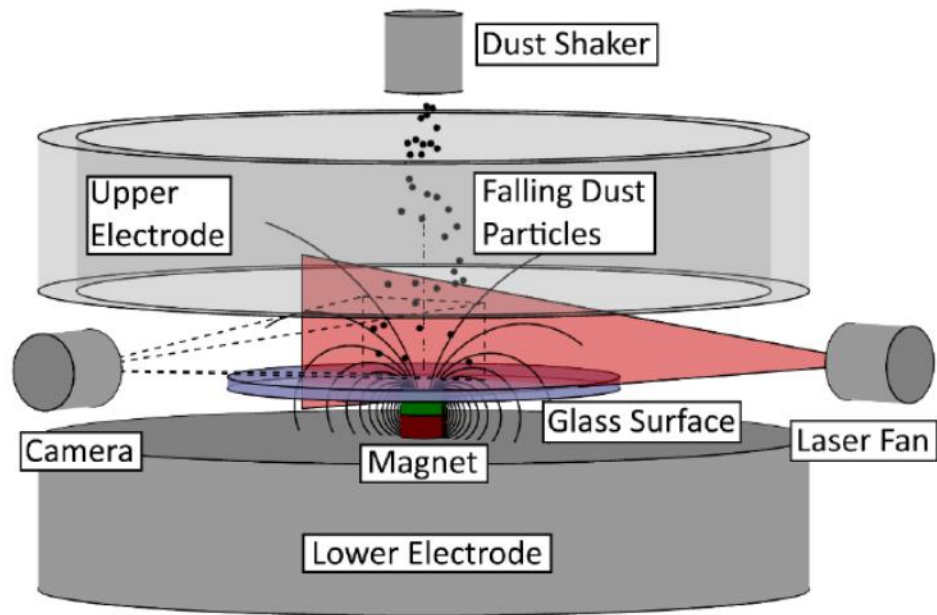
Lunar tattoos (swirls)



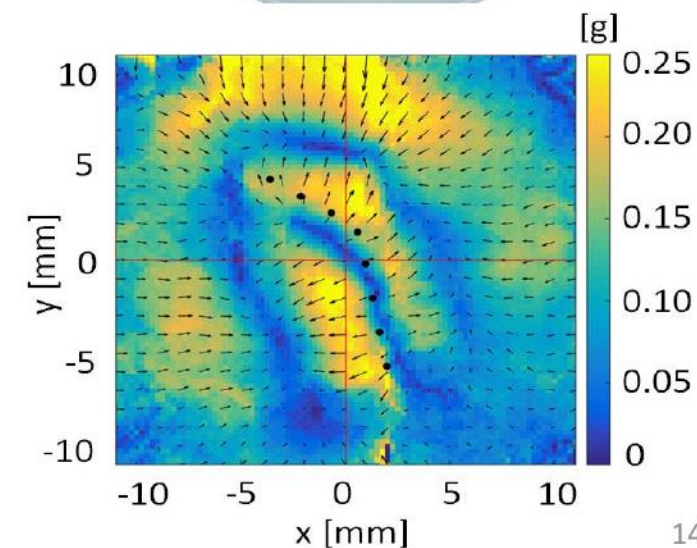
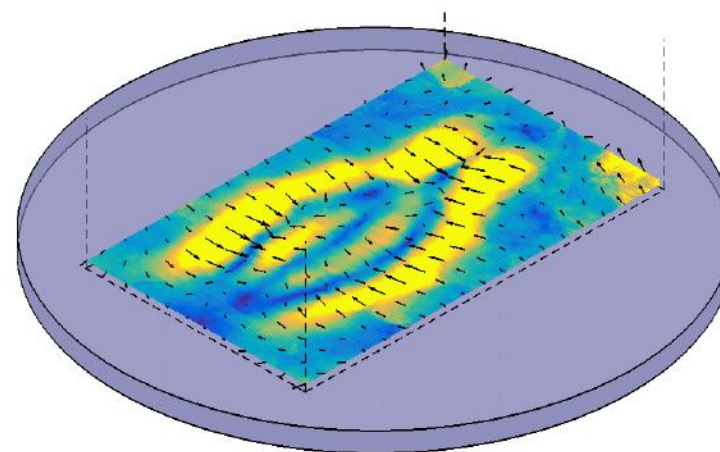
Credit: NASA, JPL, USGS



Scaling of Lunar Swirls



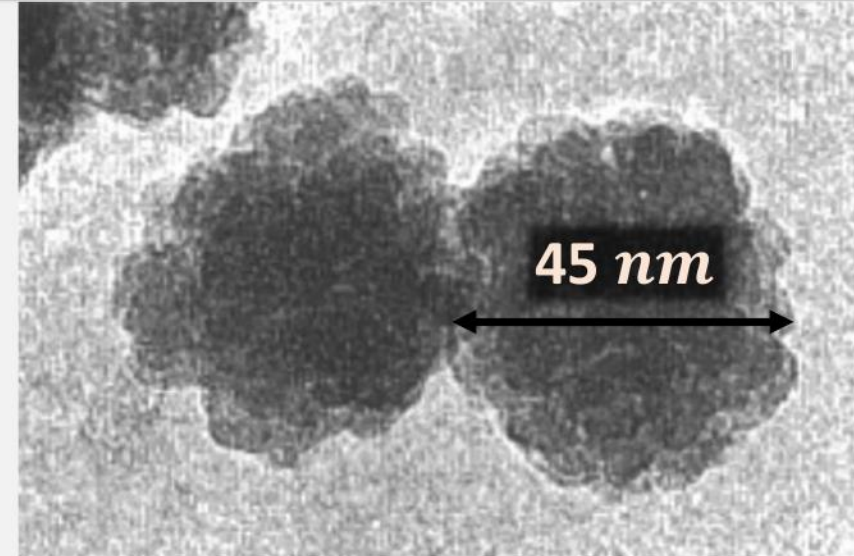
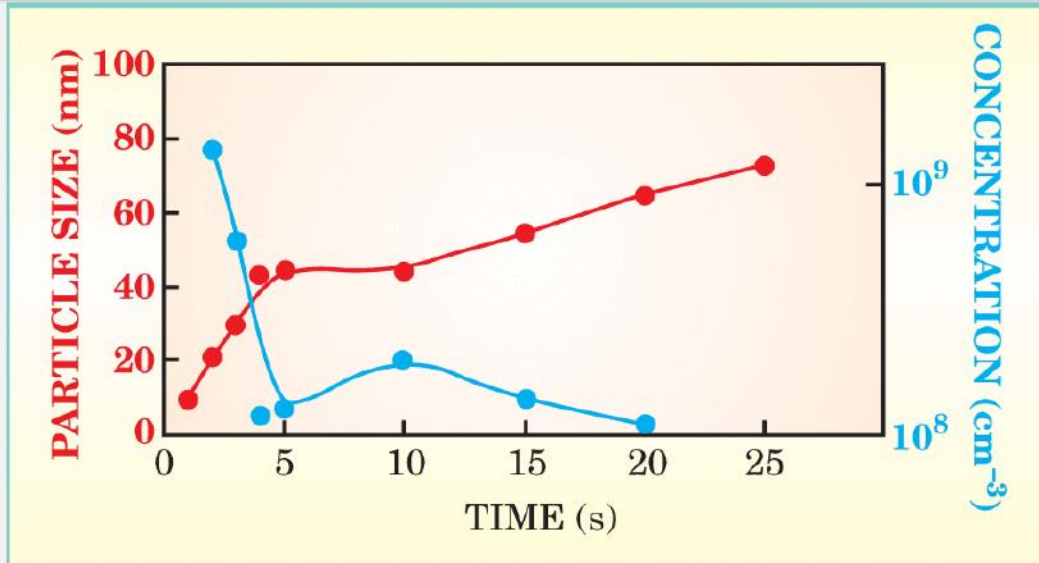
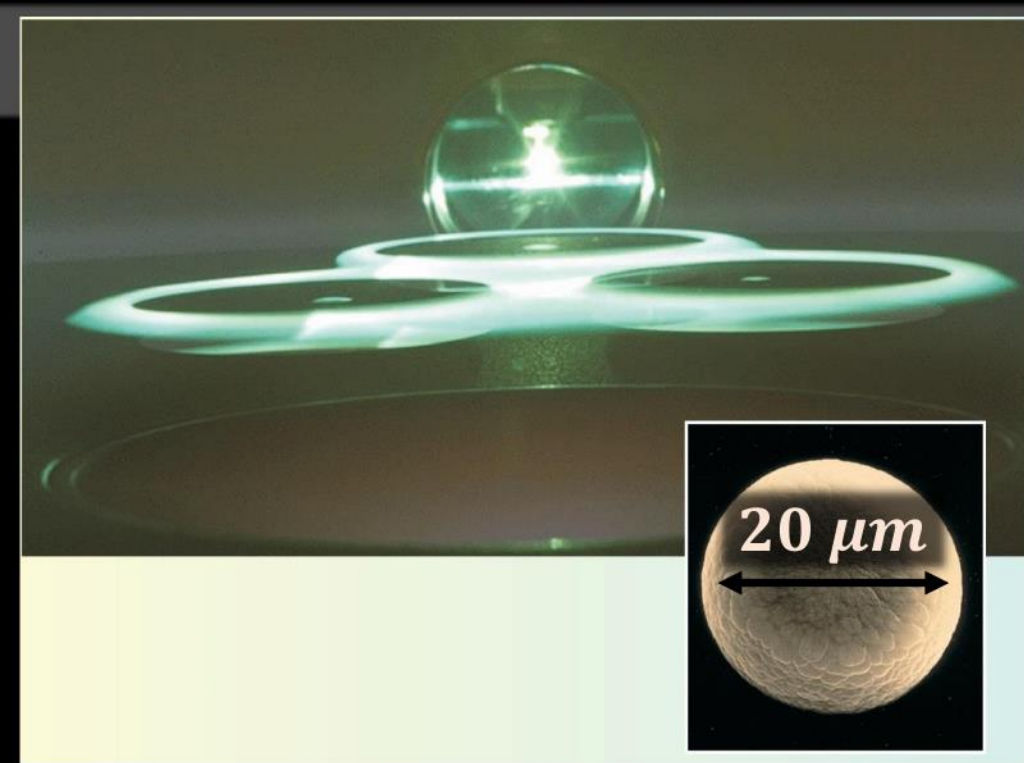
- ❑ Interaction b/w the solar wind and weak B-field in the lunar crust yields lunar dust transport and formation of **lunar swirls ~100 km in size.**
- ❑ Similar processes seem to guide dust transport in laboratory plasmas and the formation of **dusty plasma swirls ~20 mm in size.**



Credit: CASPER lab, Baylor

Dusty plasmas in industry

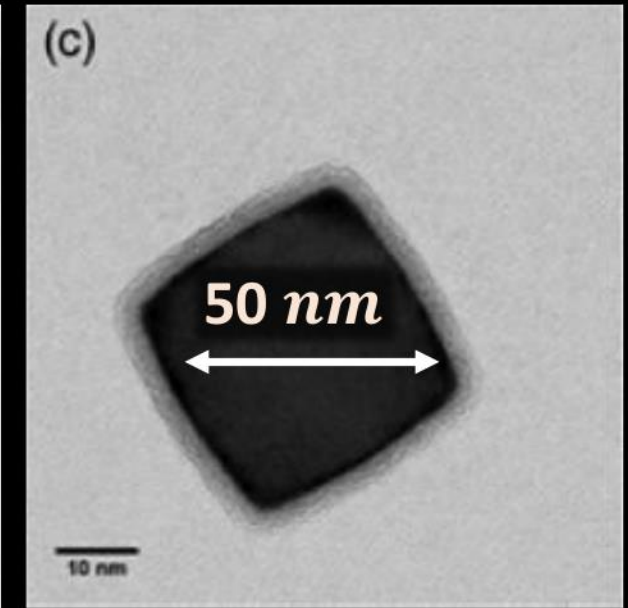
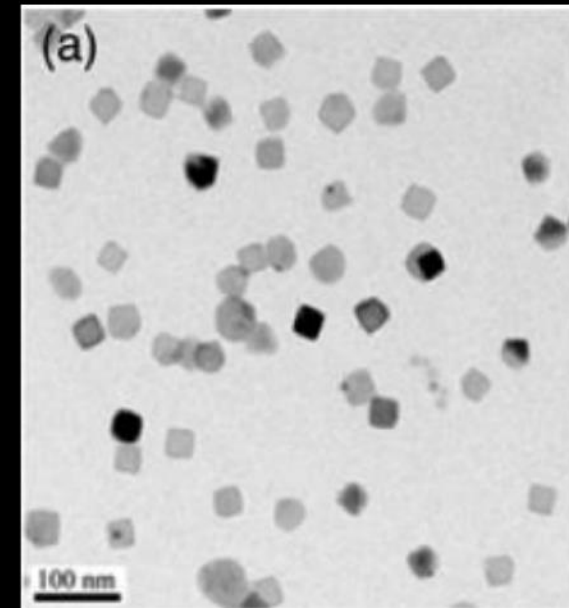
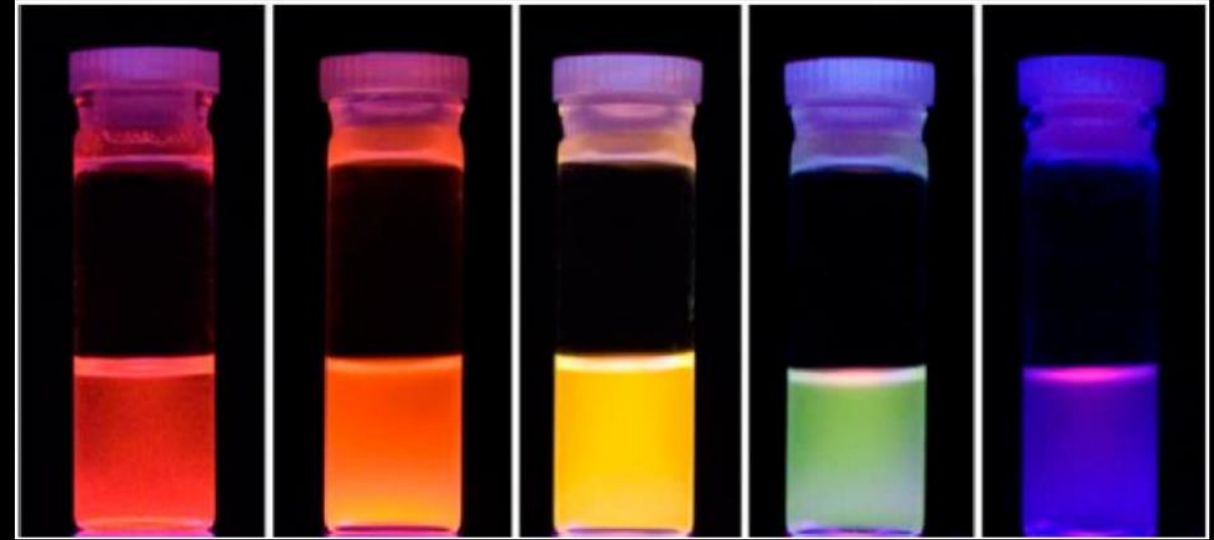
- ❑ Up to **50%** of all semiconductor chips are contaminated during processing due to dust formation.
- ❑ **“Killer Defects”** are caused by dust larger than half the width of an etched feature on the wafer
- ❑ The U.S. semiconductor industry generated global sales of **\$166 billion** out of a \$335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



Dusty plasmas in industry

Nonthermal plasma synthesis of nanocrystals

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



Particulates in Edge Plasma → Interfacial Plasma Physics

“Dust” Particulates

wall material

Natural

pellets / powders

Introduced

Topics in interfacial plasmas

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

Plasma Parameters

$$n = 10^{17} - 10^{20} m^{-3}$$

$$T_e = 1 - 100 eV$$

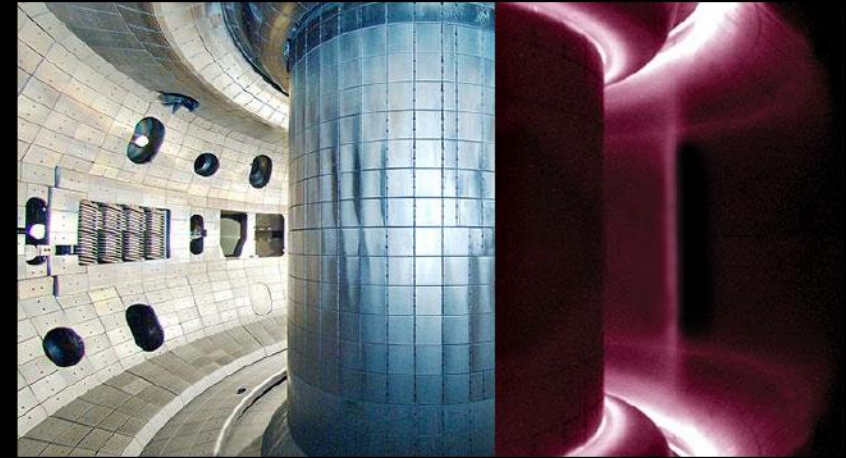
$$B = 1 - 10 T$$

Grain Parameters

$$r_d = nm - cm$$

Material: Be, C, W

$$v_d = 10 - 60 m/s$$



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

“Dust” Particulates

wall material

Natural

pellets / powders

Introduced

Frontier Science in Tokamaks

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

Plasma Parameters

$$n = 10^{17} - 10^{20} m^{-3}$$

$$T_e = 1 - 100 eV$$

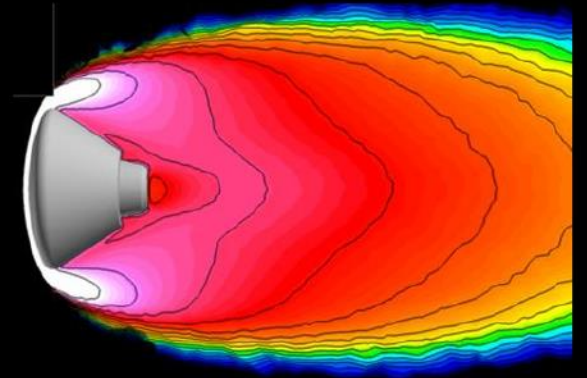
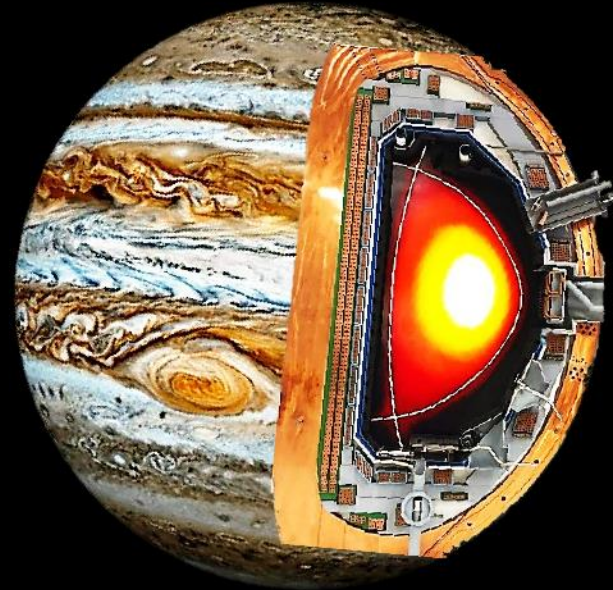
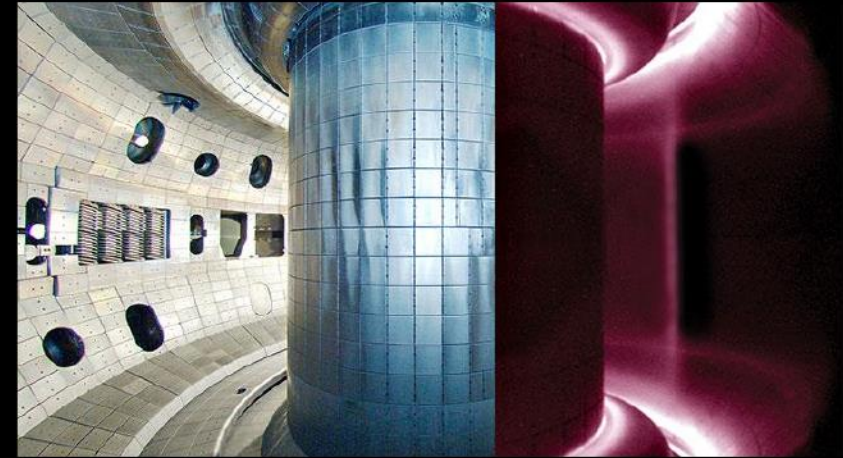
$$B = 1 - 10 T$$

Grain Parameters

$$r_d = nm - cm$$

Material: Be, C, W

$$v_d = 10 - 60 m/s$$



Why **Dusty Plasma Physics** is a separate field?

Why **Dusty Plasma Physics** is a separate field?

Has been around longer than you think



Early temperature
measurement in a dusty plasma

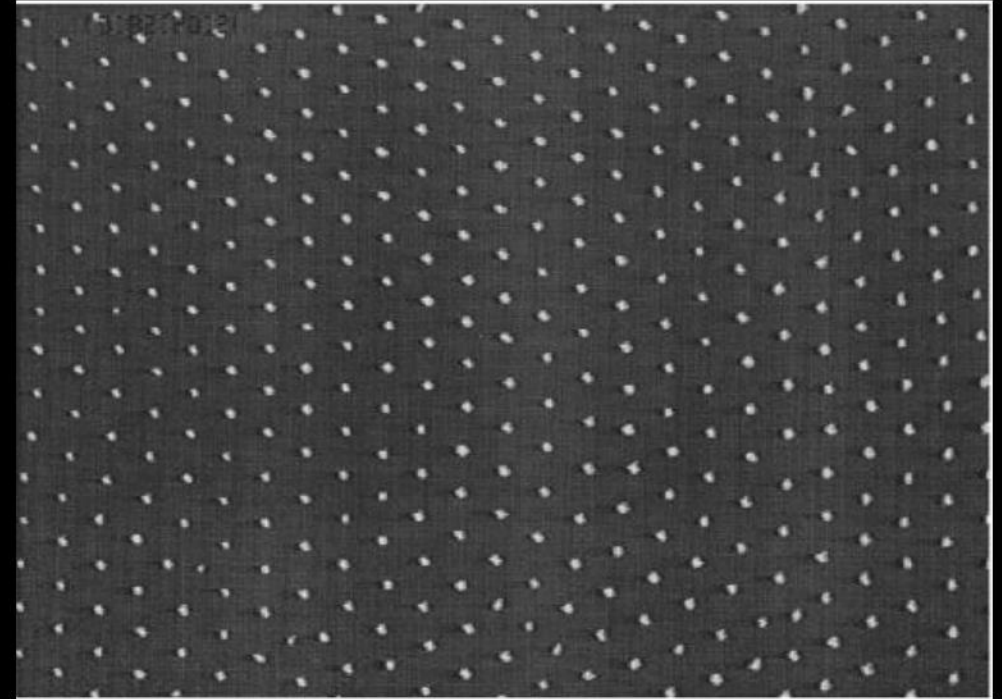
Why **Dusty Plasma Physics** is a separate field?

Has been around longer than you think

More fundamental than you think



Early temperature
measurement in a dusty plasma



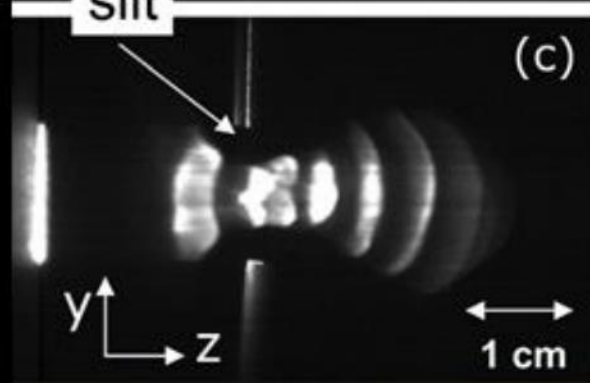
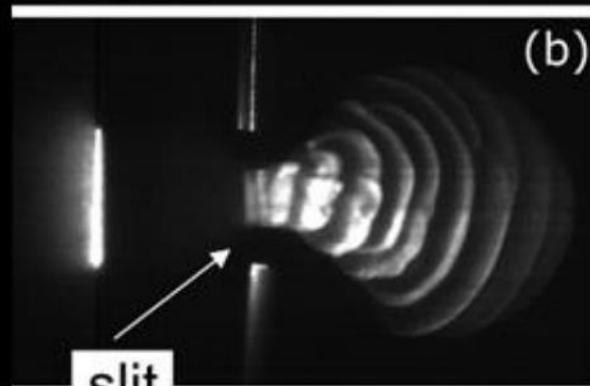
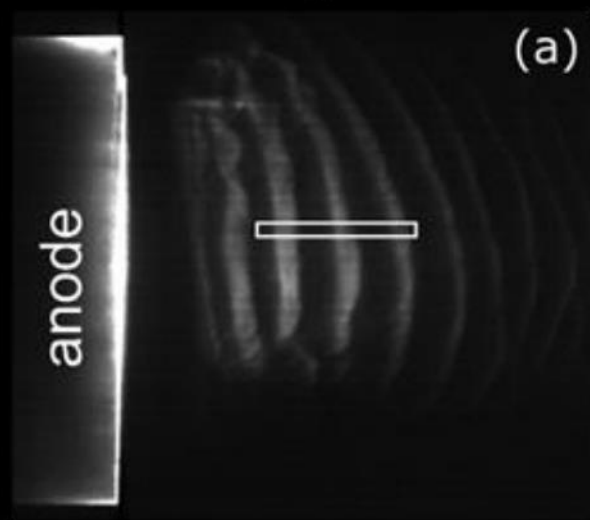
The discovery of the world's
first 2D dusty plasma crystal

Dusty Plasmas

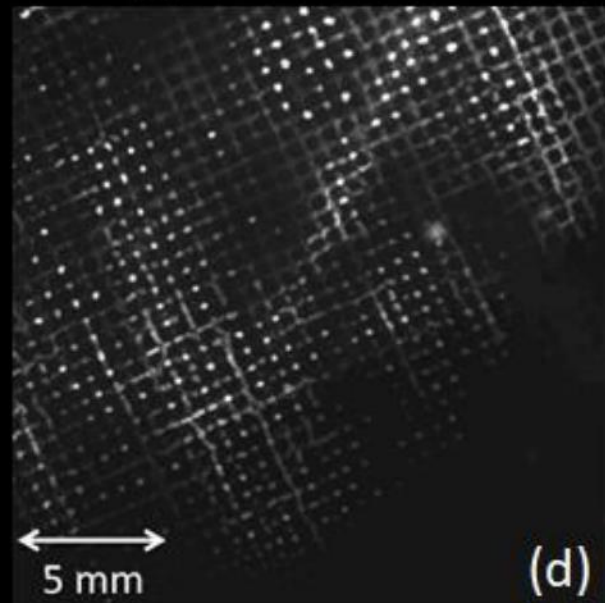
Outline

- ❑ Dusty Plasmas in the Universe
- ❑ **Dusty Plasmas in the Lab**
- ❑ Modeling Dusty Plasmas
- ❑ Concluding Remarks

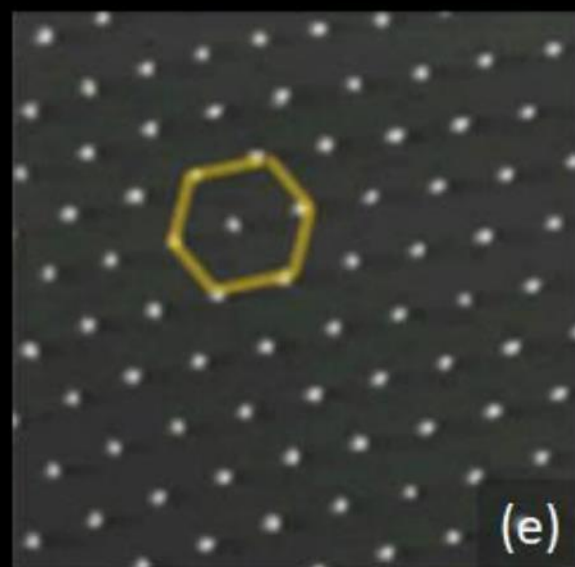
Wave dynamics



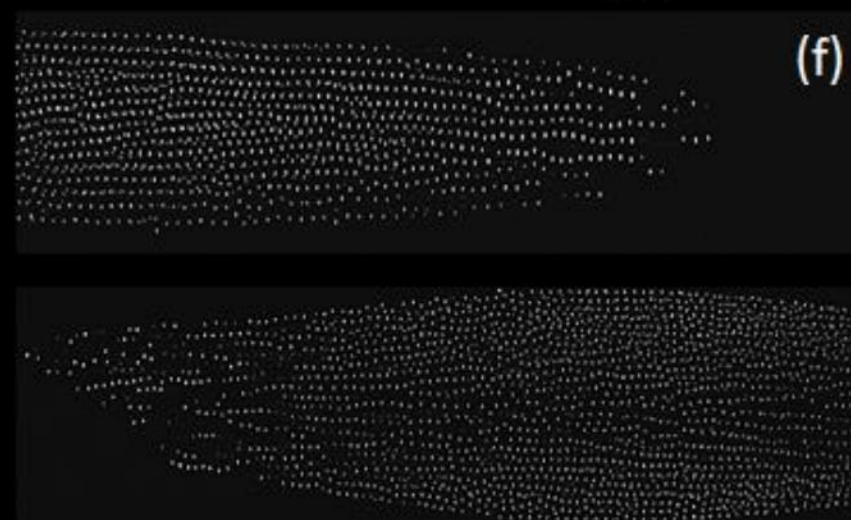
Magnetized fluids



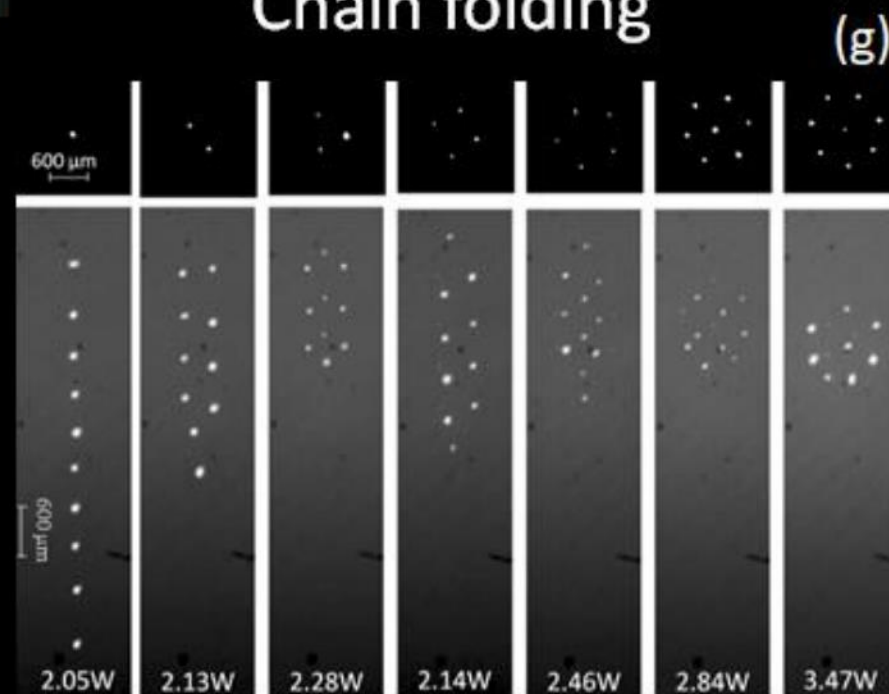
2D crystals



Electrorheology



Chain folding

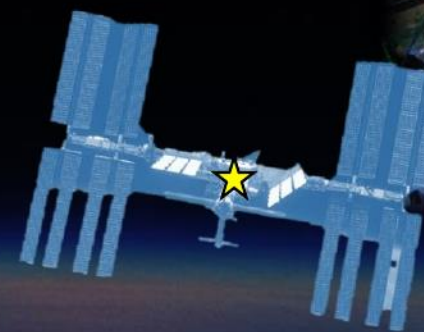


International Collaborations in Dusty Plasmas

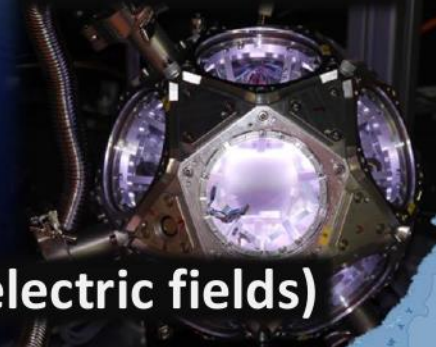
PK-4 (DC, microgravity)

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

Reactive Plasma



Dodecahedron



(tailored electric fields)

Zy-flex

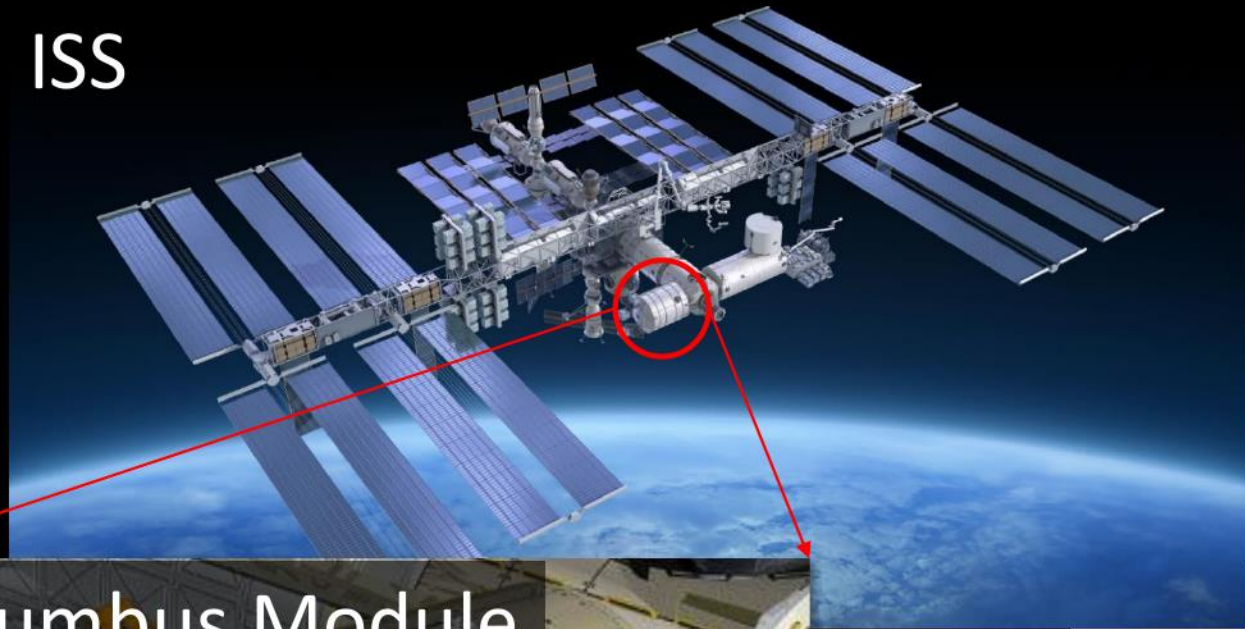


RF (electrostatic)

MDPX (magnetized)

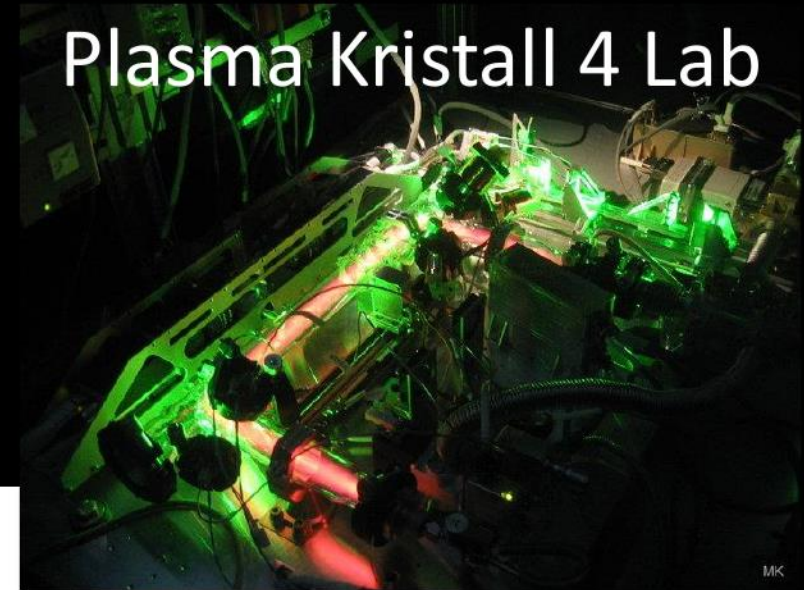
Dusty plasma experiments on the ISS

ISS

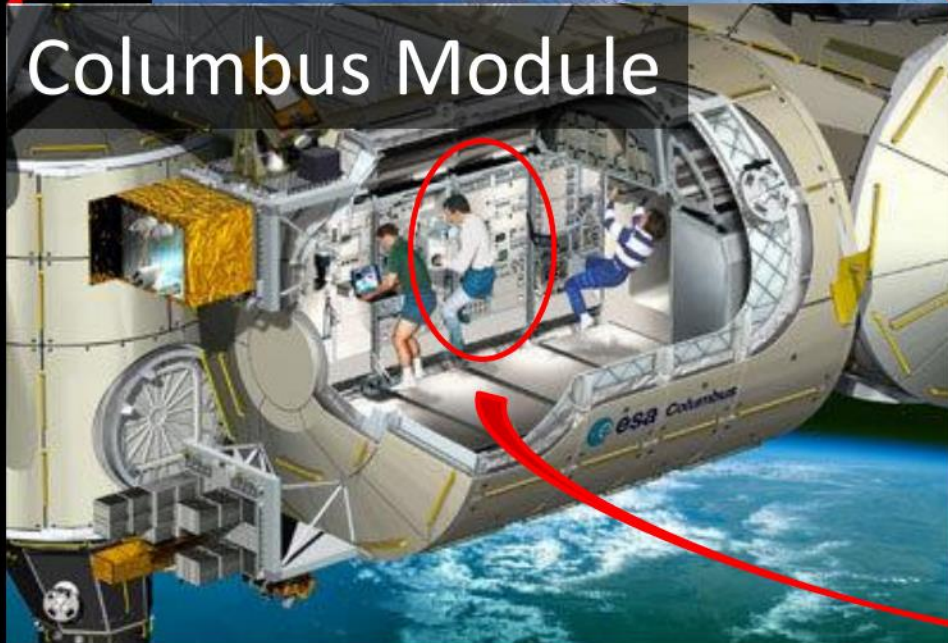


Images credit: German Aerospace Center (DLR)

Plasma Kristall 4 Lab

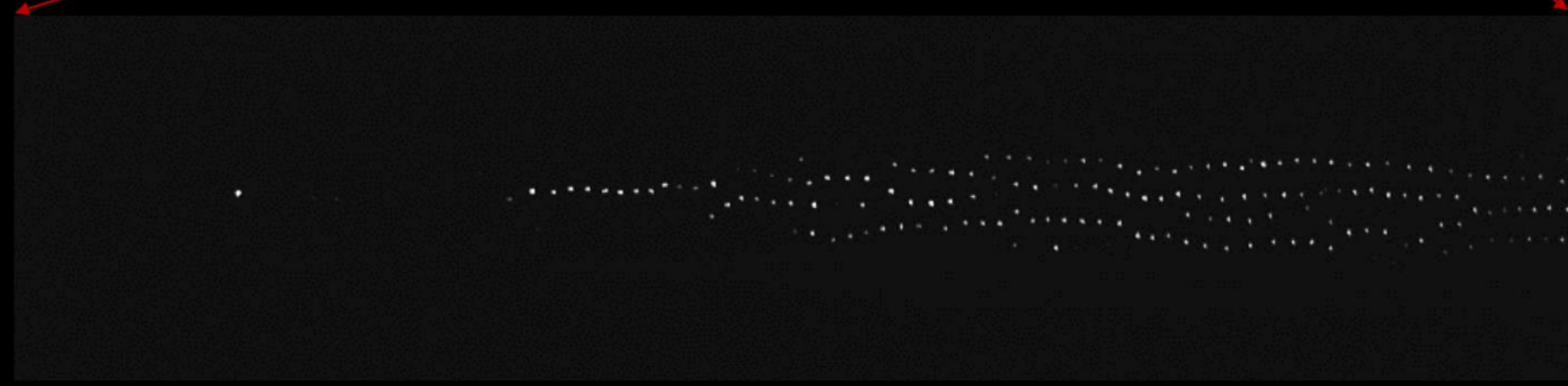
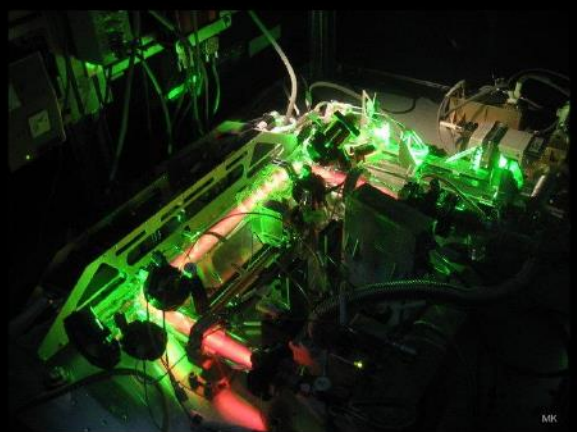
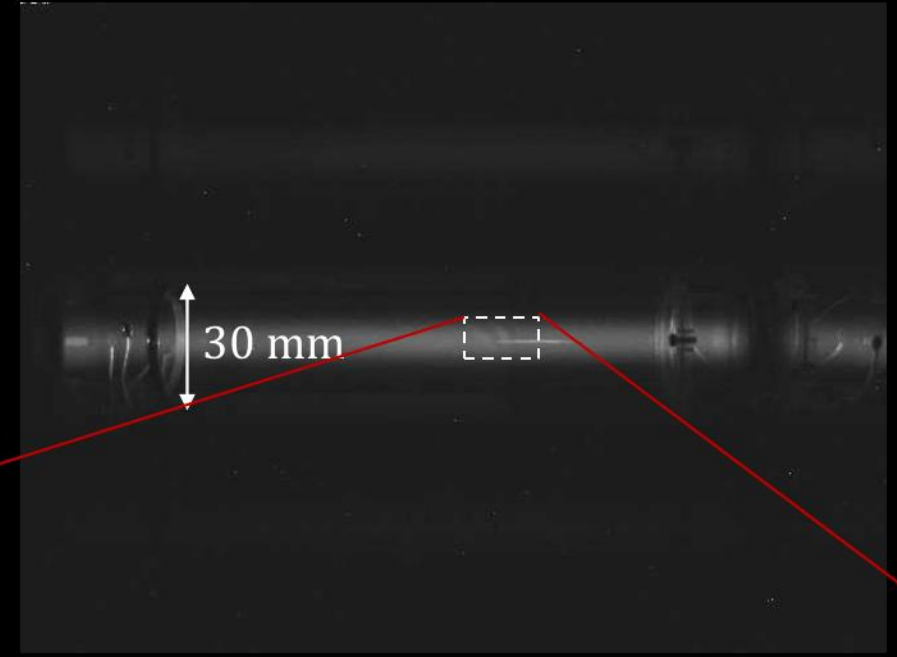
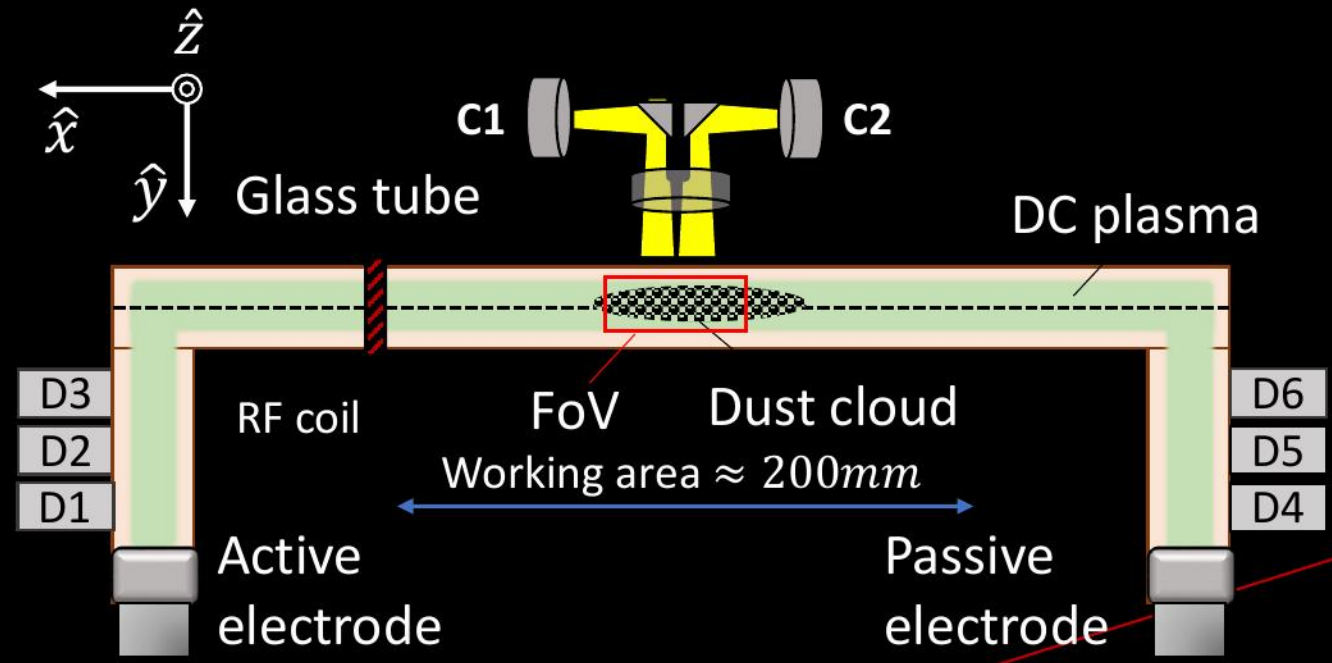


Columbus Module



Laboratory cabinet with drawers for the instruments of the experiment

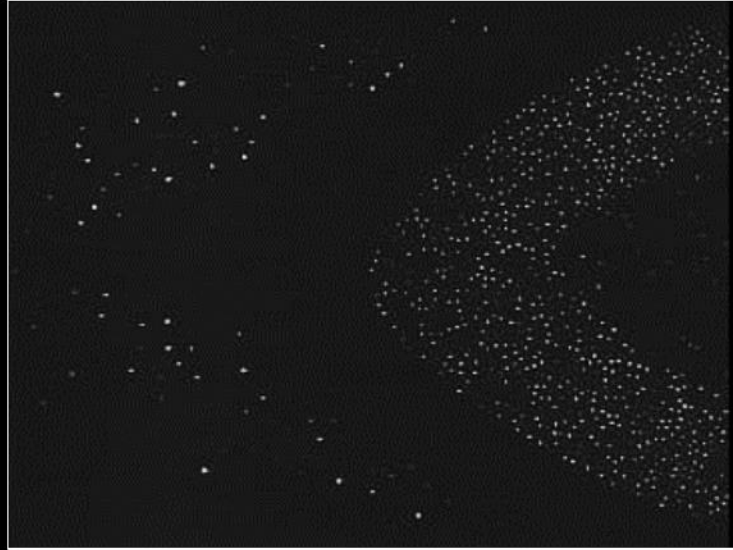
Plasma Kristall – 4 (PK-4) Experiment on the ISS



PK-4 ISS Observed Phenomena

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

Dust ordering around RF glow



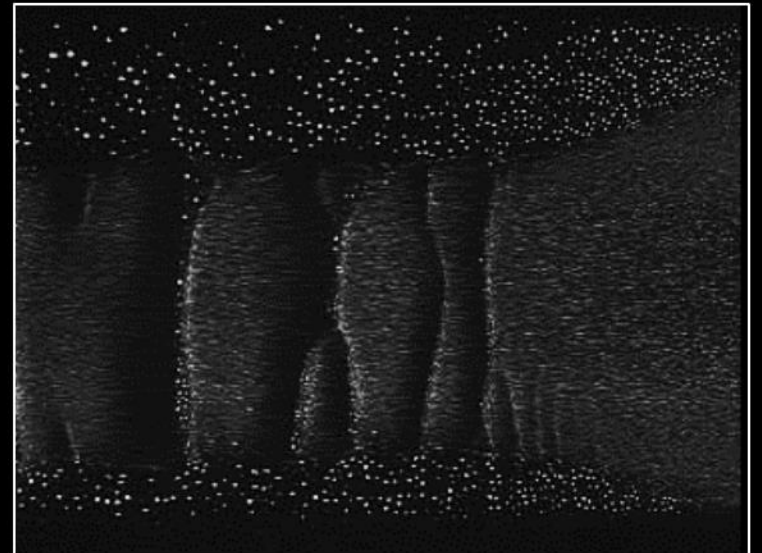
Dust jets



Dust ordering by size

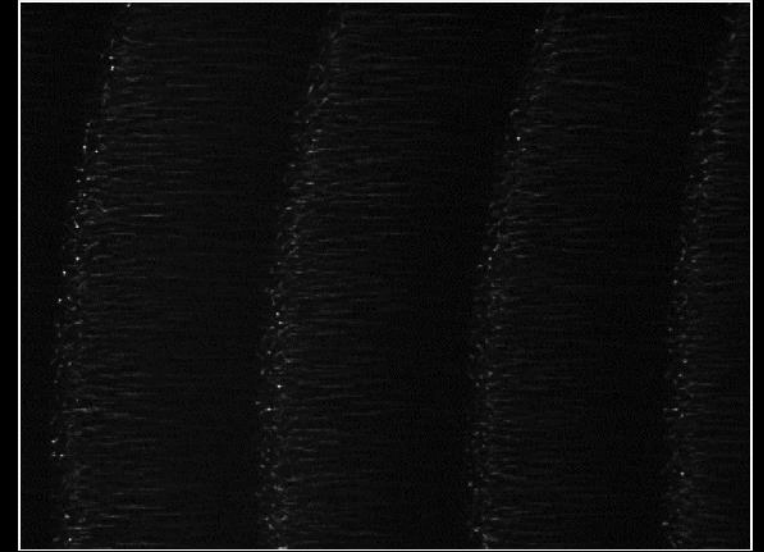
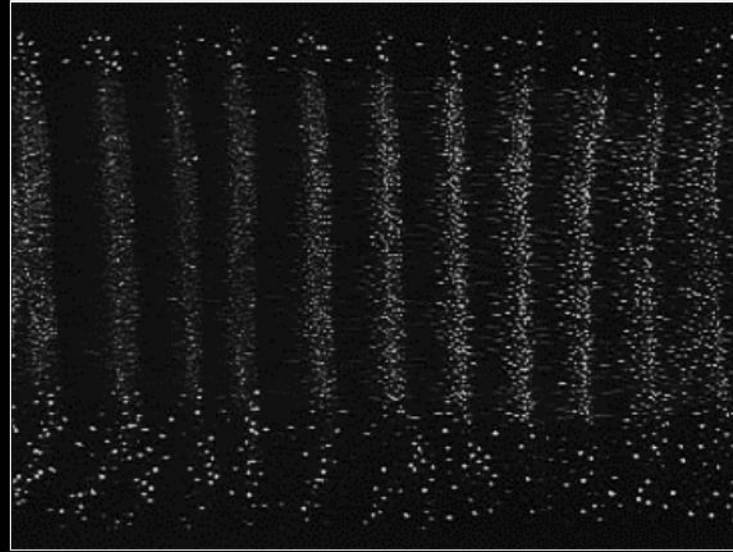


Solitons

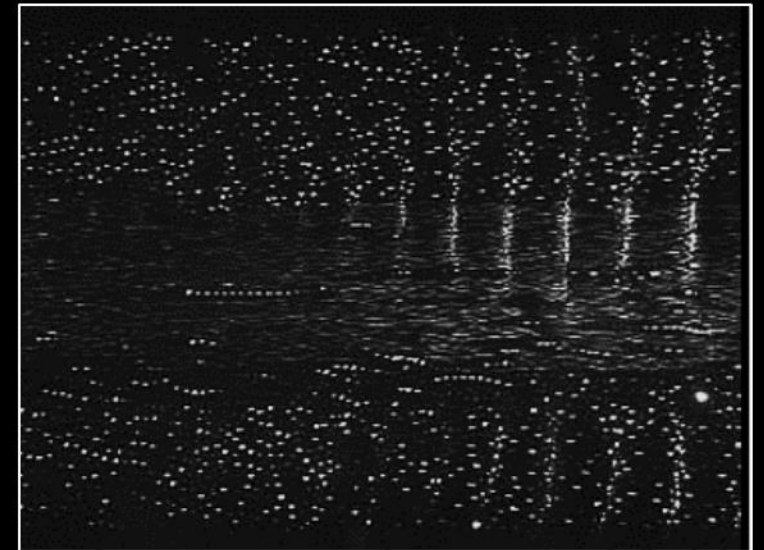
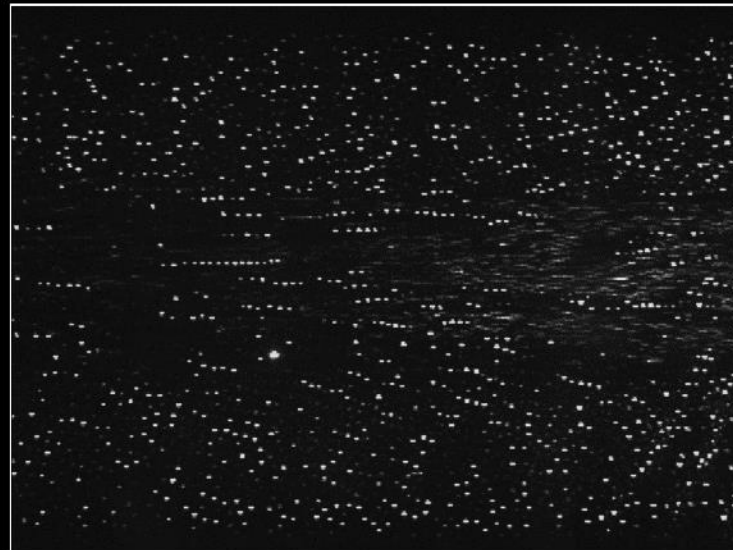


Microgravity dusty plasmas are ideal for studying fundamental processes in fluid dynamics at the individual particle level.

Dust acoustic waves



Dust lane formation



Dusty Plasmas

Outline

- Dusty Plasmas in the Universe
- Dusty Plasmas in the Lab
- Modeling Dusty Plasmas**
- Concluding Remarks

Fundamental parameters

α = electrons (e), ions (i), dust (d), neutrals (n)

n_α – Plasma density of species α

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

$v_{th,\alpha}$ – Thermal velocity

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

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

η_{ij} - Collision frequency b/w species

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

Fundamental parameters

α = electrons (e), ions (i), dust (d), neutrals (n) can measure

n_α – Plasma density of species α
 T_α – Temperature (*often assumed room temp. for neutrals/ions/dust*)

$v_{th,\alpha}$ – Thermal velocity

$\lambda_{D,\alpha}$ – Debye length

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

η_{ij} – Collision frequency b/w species

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

Expressions

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

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

Can't measure dust charge directly

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

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

Number density

$$n_{\alpha} = \int_{-\infty}^{\infty} f_{\alpha}(\vec{v}) d^3 \vec{v}$$
$$d^3 \vec{v} = v^2 \sin \theta dv d\theta d\phi$$

Number density

$$n_{\alpha} = \int_{-\infty}^{\infty} f_{\alpha}(\vec{v}) d^3 \vec{v}$$
$$d^3 \vec{v} = v^2 \sin \theta dv d\theta d\phi$$

Thermalized plasma \rightarrow

Maxwellian velocity distributions

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

Number density

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

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

Temperature

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

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

Thermalized plasma \rightarrow

Maxwellian velocity distributions

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

$\alpha = \text{electron or ion}$

Number density

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

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

Temperature

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

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

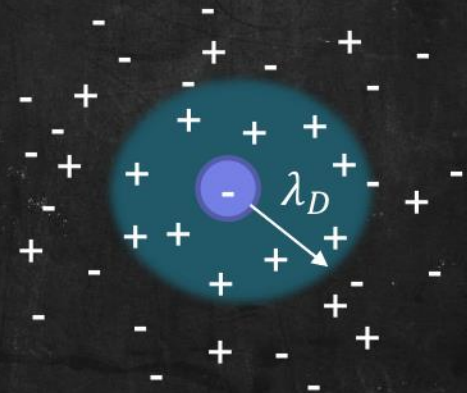
Thermalized plasma \rightarrow
Maxwellian velocity distributions

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

Yukawa Shielding potential

Can't measure dust
 charge directly

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



Finding dust charge: Equilibrium condition

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

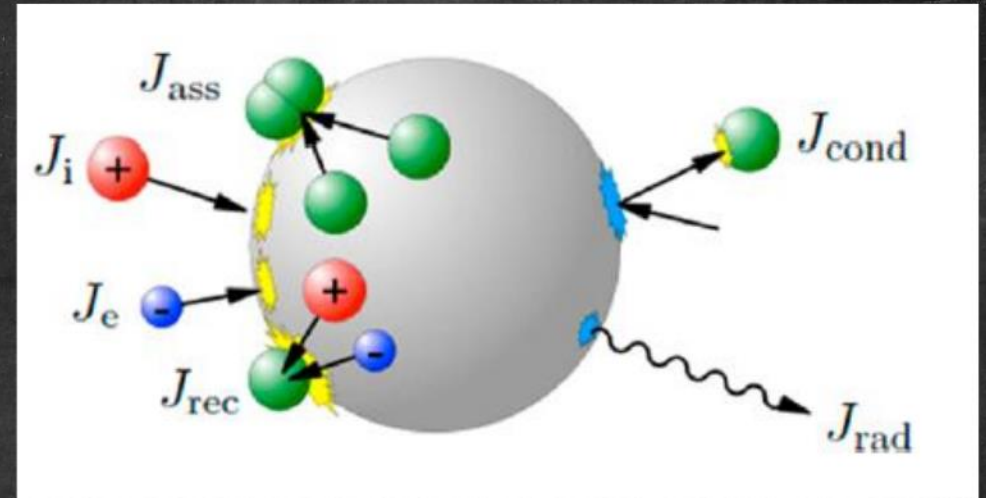
$$\frac{dQ}{dt} = \sum_i J_i(\phi_s) = 0$$

- Charge related to **surface potential**

$$Q = C\phi_s$$

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

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



Finding dust charge: Equilibrium condition

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

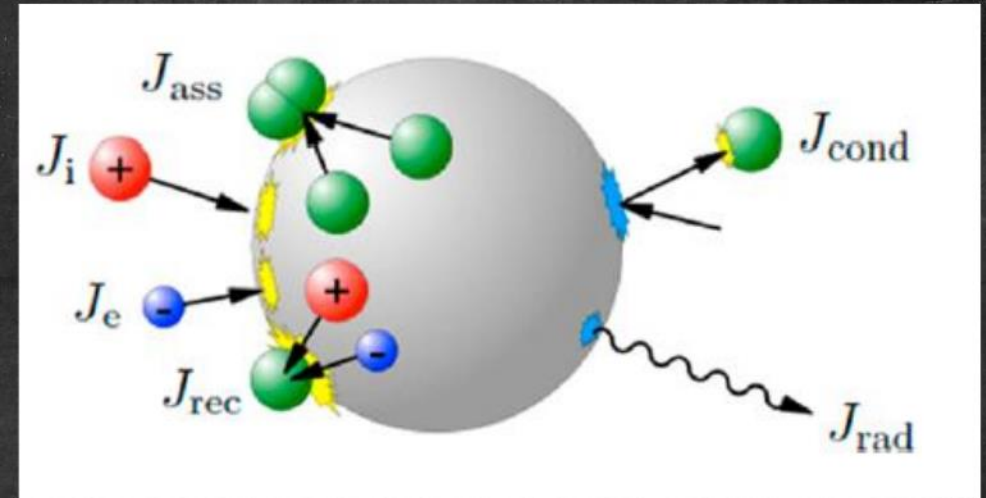
$$\frac{dQ}{dt} = \sum_i J_i(\phi_s) = 0$$

- Charge related to **surface potential**

$$Q = C\phi_s$$

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

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



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

Finding dust charge: OML theory of charging

- For lab studies, **ions and electrons are the dominant** charging mechanisms.
- Estimate the flux to the grain surface using **orbit motion limited (OML) theory**.

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

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

- Steady state: $I_e + I_i = 0$

Finding dust charge: OML theory of charging

- ❑ For lab studies, **ions and electrons are the dominant** charging mechanisms.
- ❑ Estimate the flux to the grain surface using **orbit motion limited (OML) theory**.

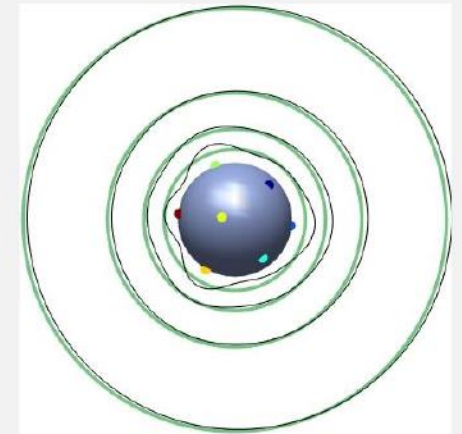
$$I_e = -4\pi r_d^2 e n_e \left(\frac{8kT_e}{\pi m_e} \right)^{\frac{1}{2}} \exp\left(\frac{e\phi_s}{kT_e} \right)$$

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

- ❑ Steady state: $I_e + I_i = 0$

OML Theory assumes

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



Finding dust charge: OML theory of charging

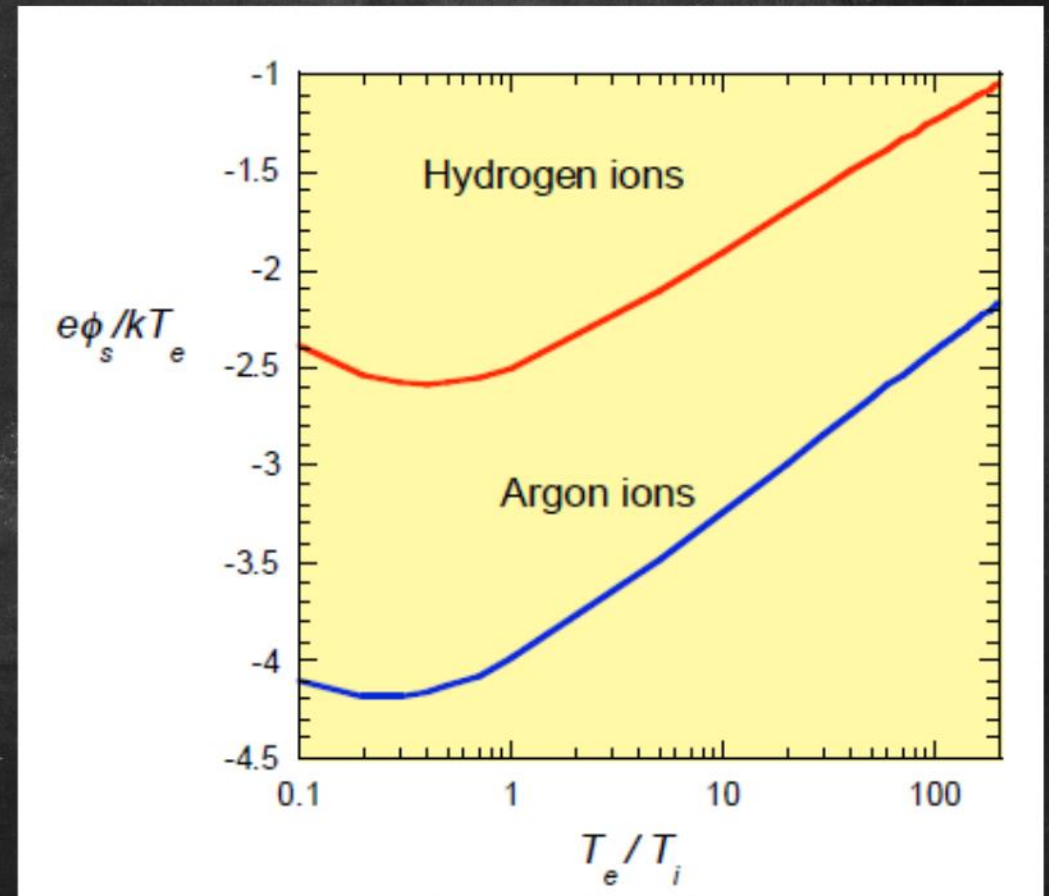
- For lab studies, **ions and electrons are the dominant** charging mechanisms.
- Estimate the flux to the grain surface using **orbit motion limited (OML) theory**.

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

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

□ Steady state: $I_e + I_i = 0$

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



Finding dust charge: Numerical solution

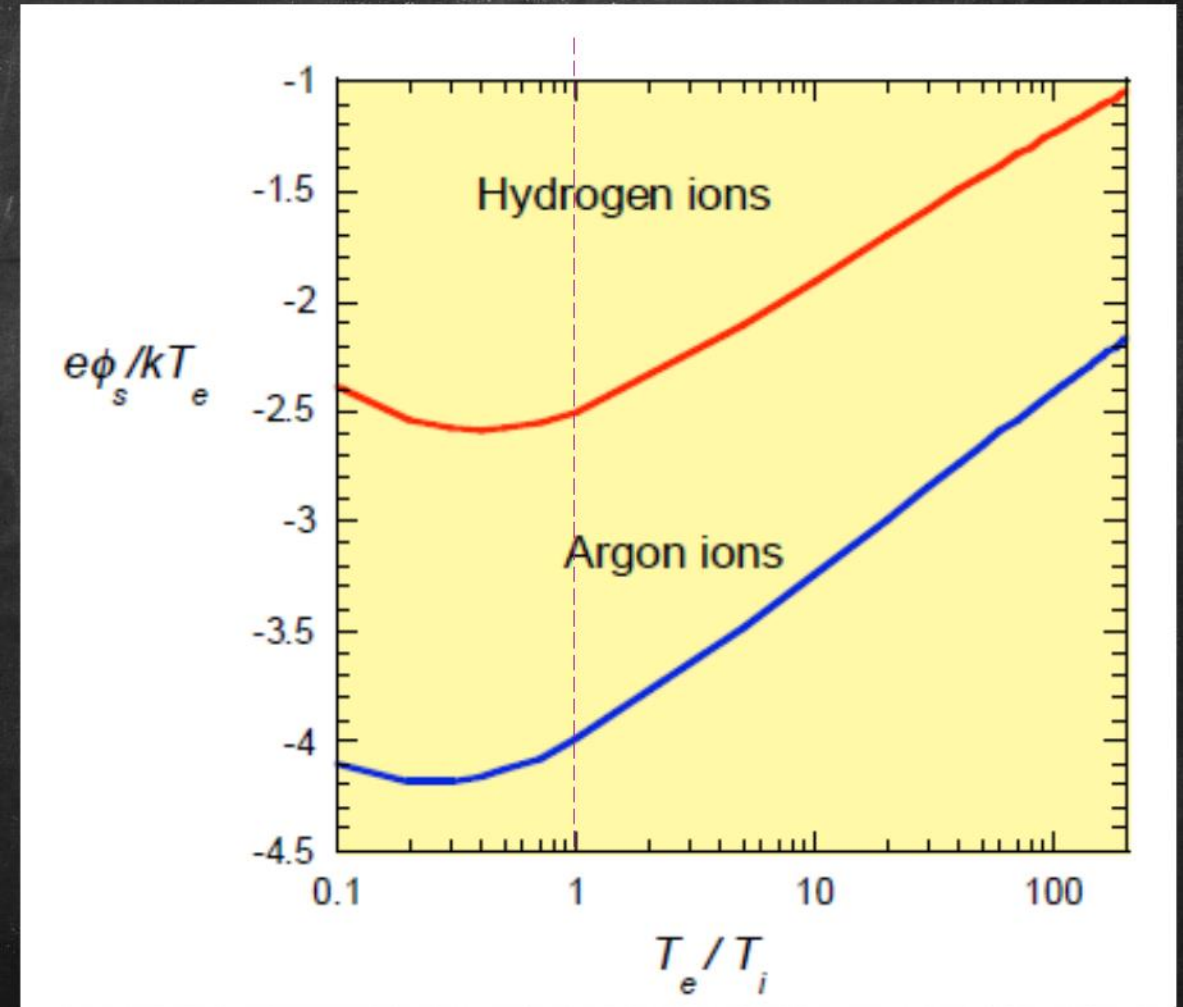
Example conditions:

- Spherical grains $1\mu\text{m}$ radius
- Hydrogen plasma

$$T_e = T_i \approx 1\text{eV}$$

$$\phi_s = -2.5 kT/e$$

$$Q_d = C\phi_s = -2000e$$



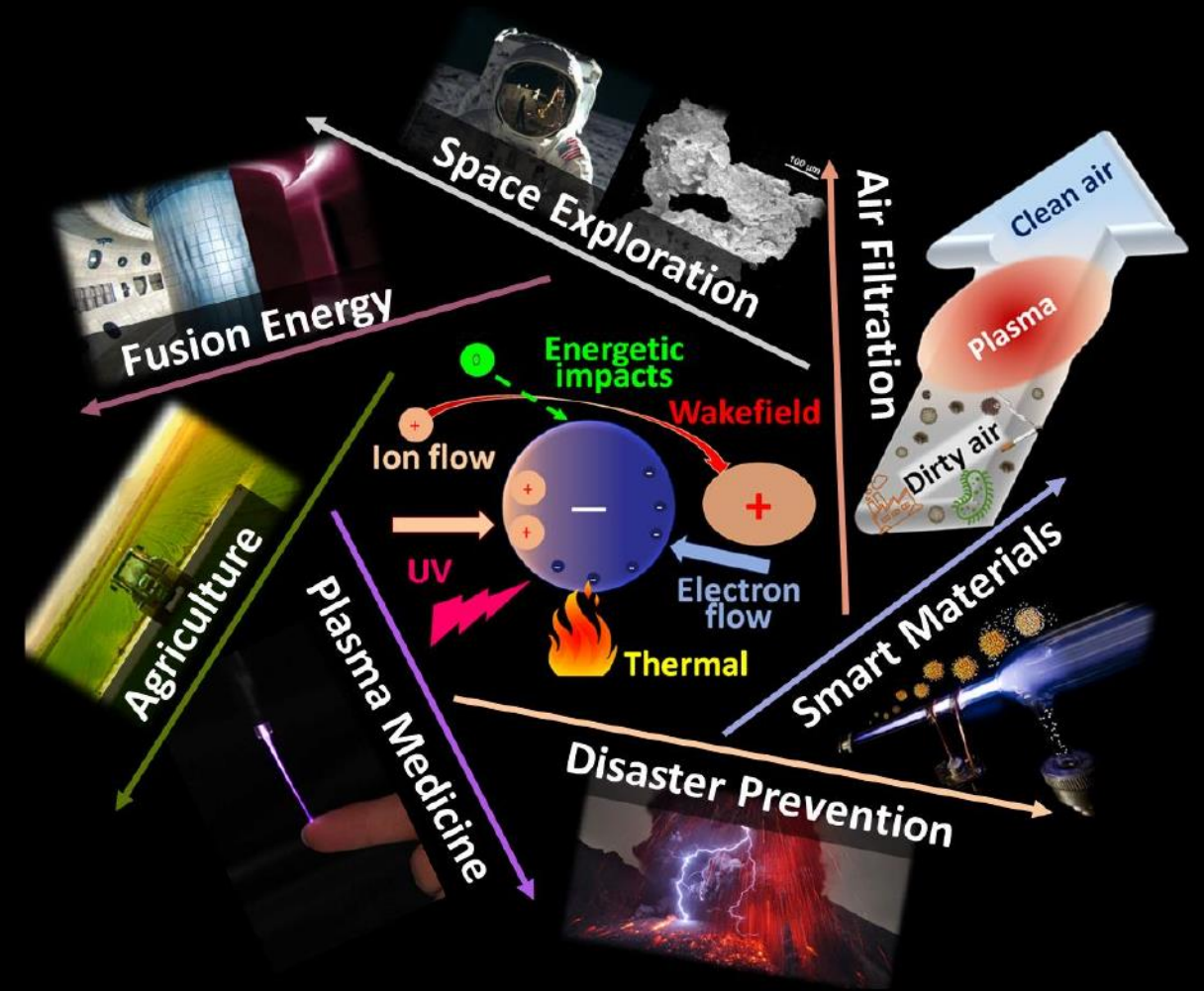
Dusty Plasmas

Outline

- ❑ Dusty Plasmas in the Universe
- ❑ Dusty Plasmas in the Lab
- ❑ Modeling Dusty Plasmas
- ❑ **Concluding Remarks**

Summary

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



Plasma Physics at Auburn University



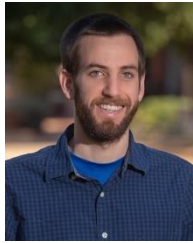
Plasma Physics Research at Auburn University

Fusion Experiments

Maurer

Ennis

Kriete



Lab & Dusty Plasma Experiments

Konopka

Chakraborty
Thakur

Thomas



Theory

Low Temp

Kostadinova

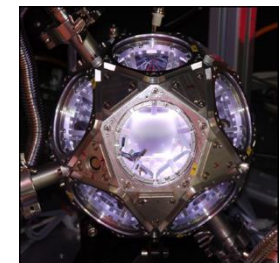
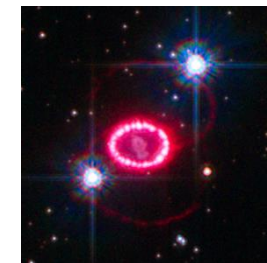
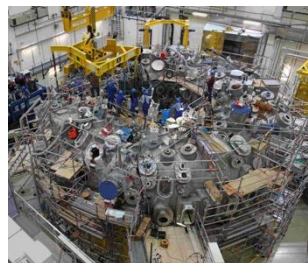
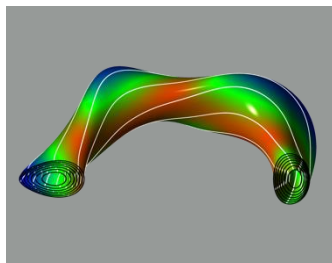
Fusion

Guazzotto



Fusion experiment
Fusion theory
Atomic processes in plasmas
Dusty plasmas
Basic plasma science

8 Faculty (plus space plasma & AMO)
5 Postdocs
2 Technicians
~20 Graduate students



Plasma Physics Research at Auburn University

Fusion Experiments

Maurer Ennis Kriete



Lab & Dusty Plasma Experiments

Konopka Chakraborty Thomas
Thakur



Theory

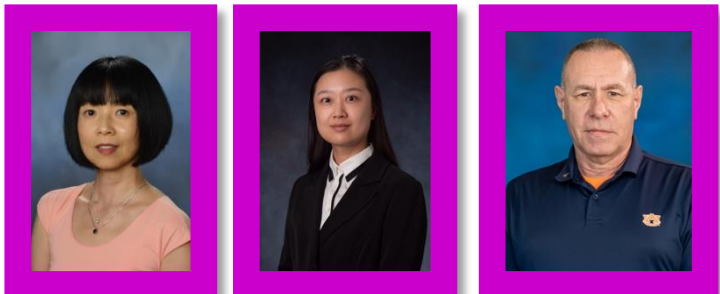
Low Temp Fusion
Kostadinova Guazzotto



\$25 million NSF grant across 9 universities and 1 industry in AL

Space Physics

Lin Zhao Adrian

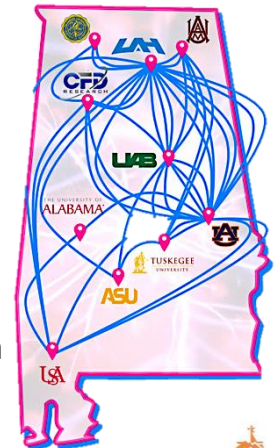


Atomic Physics

Loch



- UAH, (lead)
- Tuskegee University
- UAB
- Auburn University
- Alabama A&M University
- Oakwood University
- CFDRC
- University of South Alabama
- Alabama State University
- University of Alabama

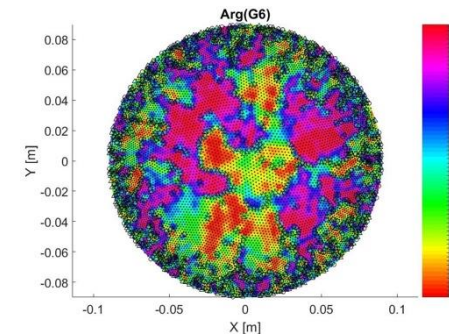


Magnetized Plasma & Dusty Plasma Research

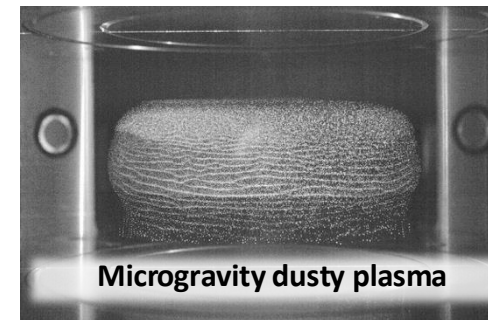
[Magnetized Plasma Research Lab \(MPRL\)](#) –
multi-user, collaborative research facility
mprl.auburn.edu

[Strategic Plasma Innovation Network \(SPI-NET\)](#) -
a consortium of institutions that engage in
fundamental plasma science with a focus on
self-organization and pattern formation in
plasmas and plasma science workforce.

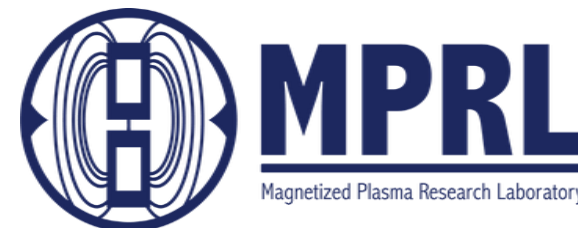
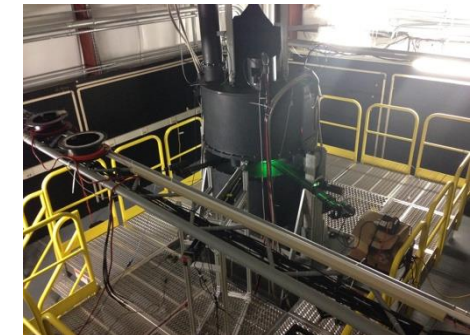
- ❑ Edward Thomas, Jr. (etjr@auburn.edu)
- ❑ Uwe Konopka (uzk0003@auburn.edu)
- ❑ Saikat Chakraborty Thakur (szc0199@auburn.edu)
- ❑ Evdokiya (Eva) Kostadinova (egk0033@auburn.edu)



Cell orientation in a
dusty plasma crystal



Microgravity dusty plasma



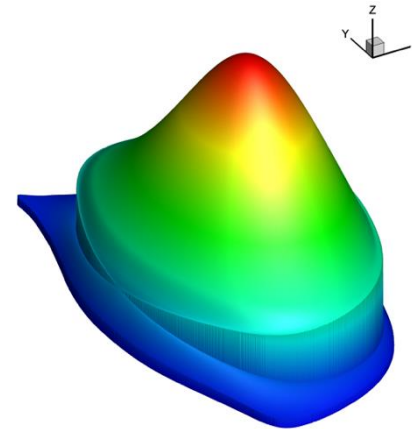
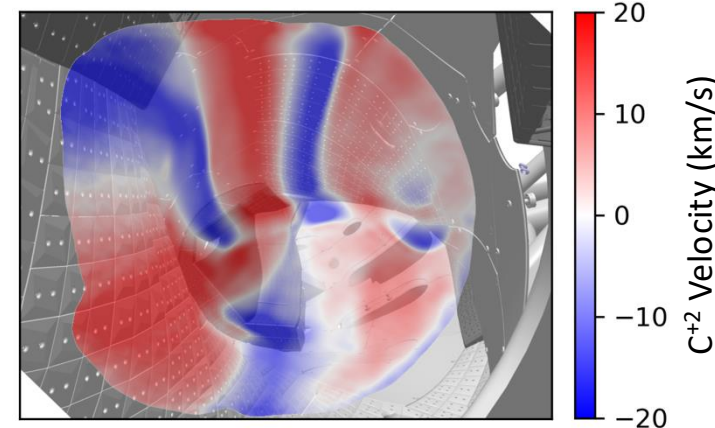
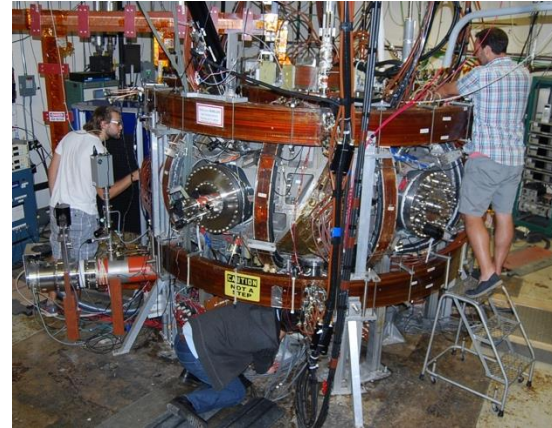
Magnetically Confined Plasma Research

[Compact Toroidal Hybrid \(CTH\)](#) – magnetically confined fusion device that can operate as a tokamak or as a stellarator

Grad students receive *hands on experience with a stellarator* and collaborate nationally at DIII-D and internationally at W7-X

Computational work takes advantage of Auburn University's own *High Performance and Parallel Computing Center*

- ❑ Dave Maurer (dam0014@auburn.edu)
- ❑ David Ennis (dae0005@auburn.edu)
- ❑ Luca Guazzotto (luca.guazzotto@auburn.edu)
- ❑ Evdokiya (Eva) Kostadinova (egk0033@auburn.edu)



Plasma density for a transonic tokamak equilibrium

