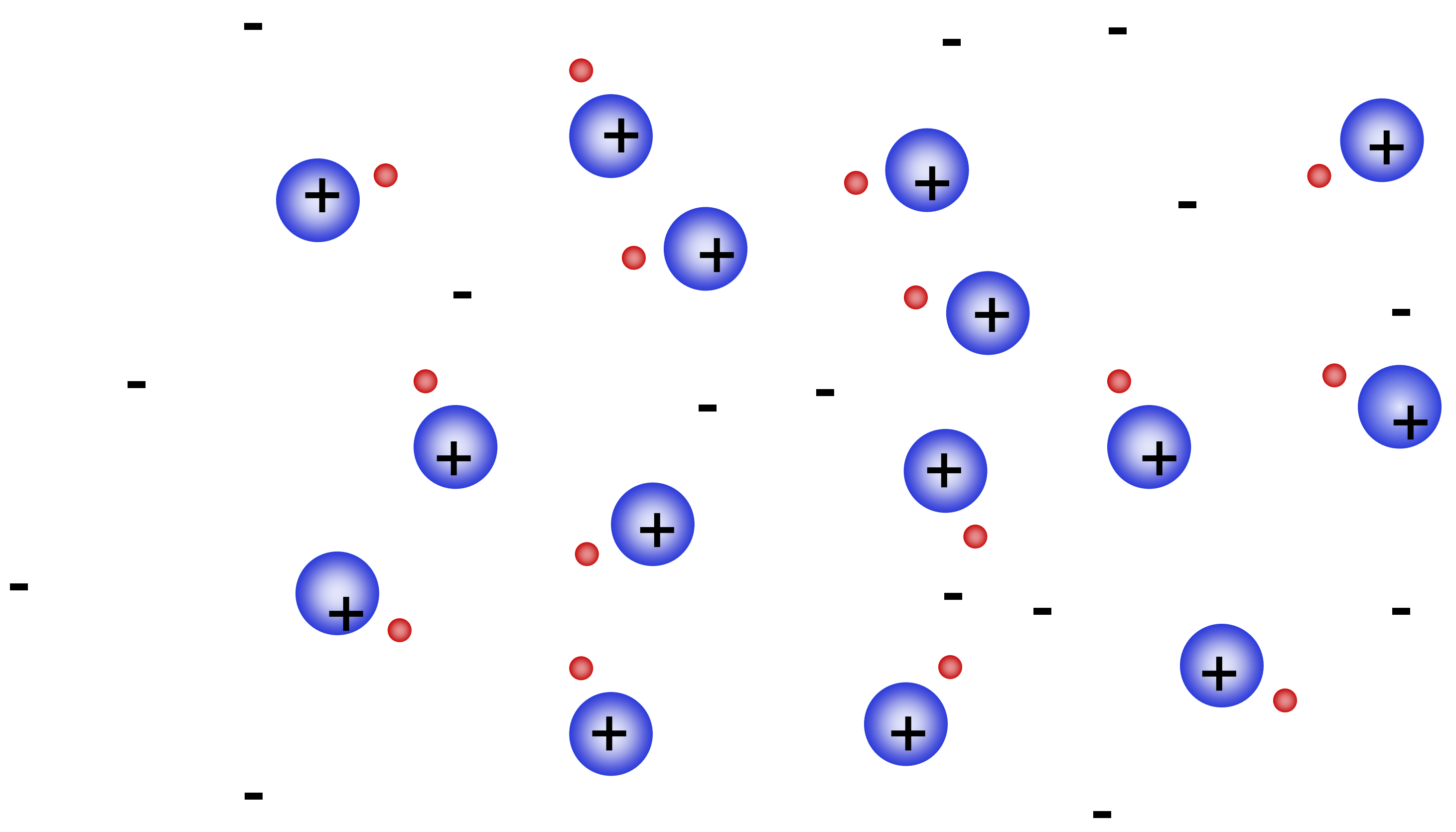
Cosmic Dust Bunnies and Laboratory Dust Crystals

Building Planets, Breaking Symmetry

Lorin Swint Matthews
Professor and Chair, Department of Physics
Associate Director, Center for Astrophysics, Space Physics, and Engineering Research
Lorin_Matthews@baylor.edu

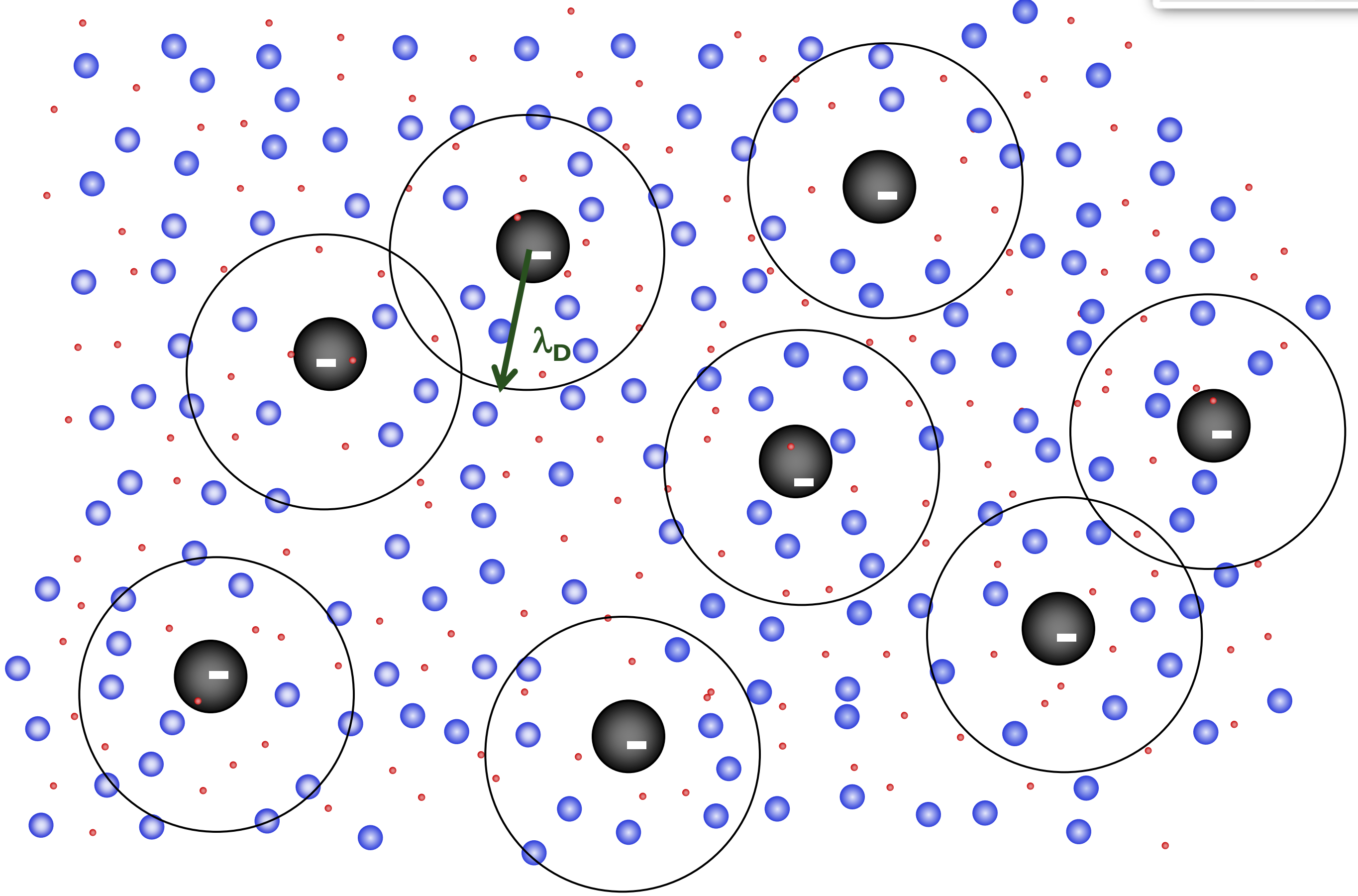
Baylor University

What is a dusty plasma?

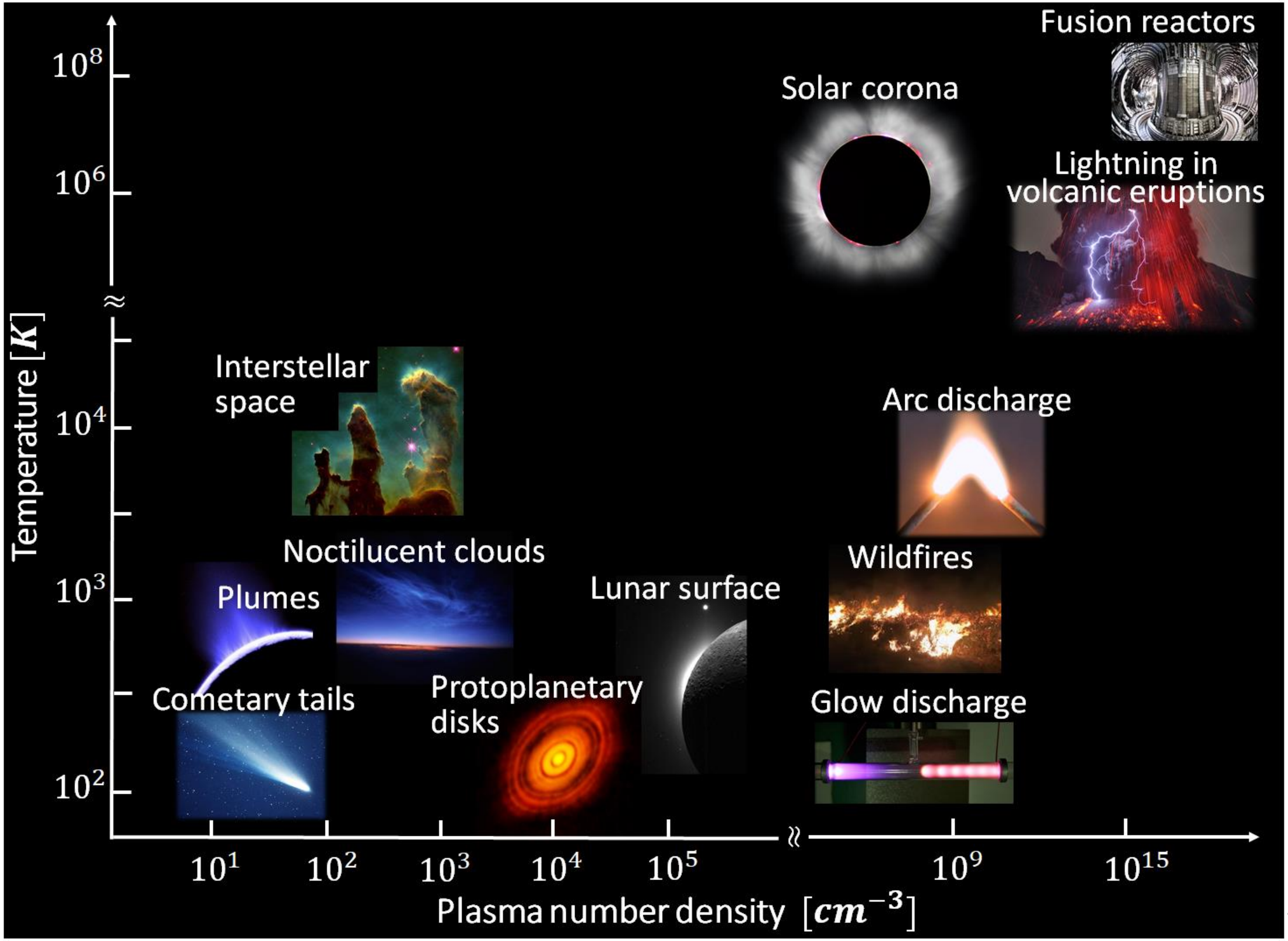


What is a dusty plasma?

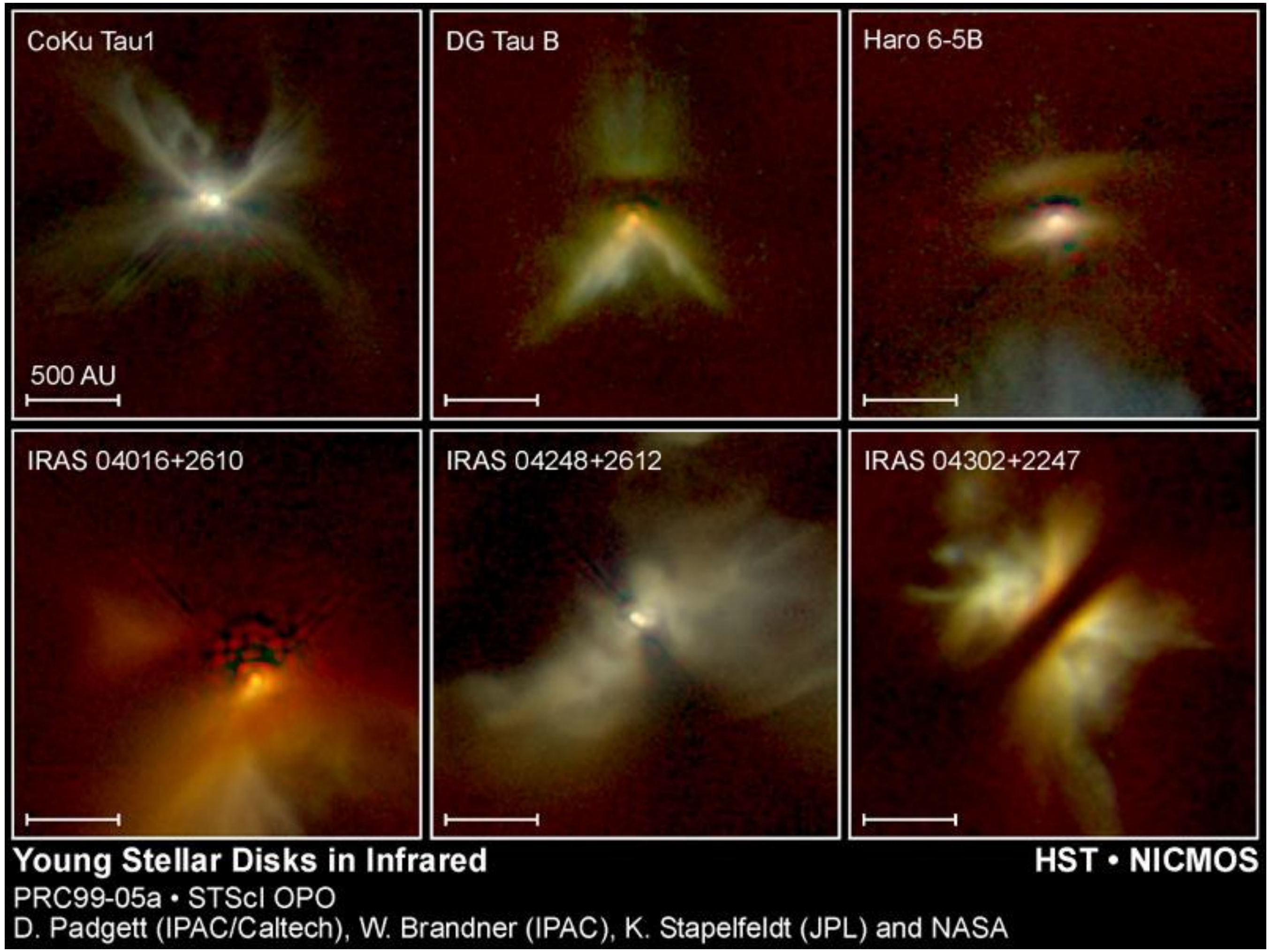
$$\Phi = \frac{1}{4\pi\epsilon_0}\frac{q}{r}e^{-r/\lambda_D}$$



Dusty Plasma Parameter Space



Why study dusty plasmas?



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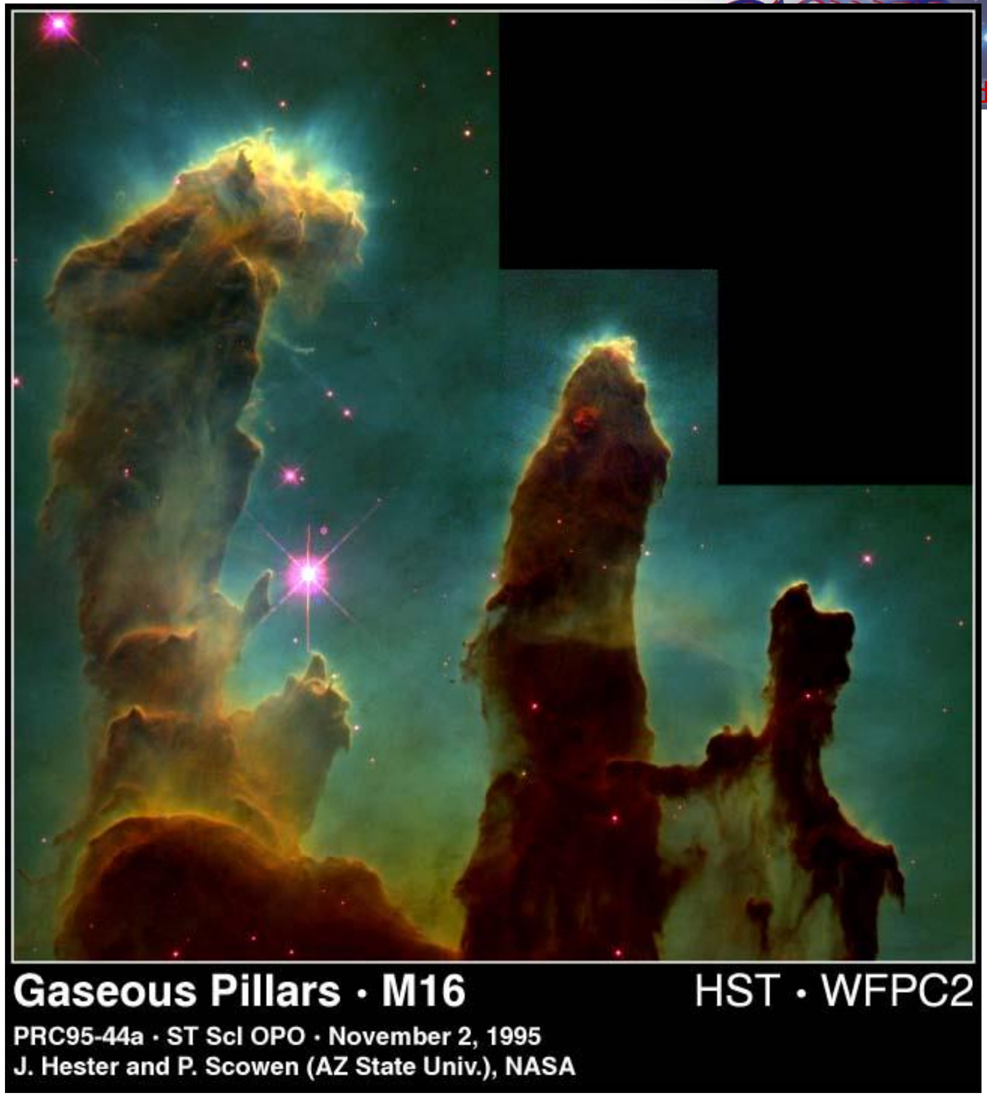

Why study dusty plasmas?

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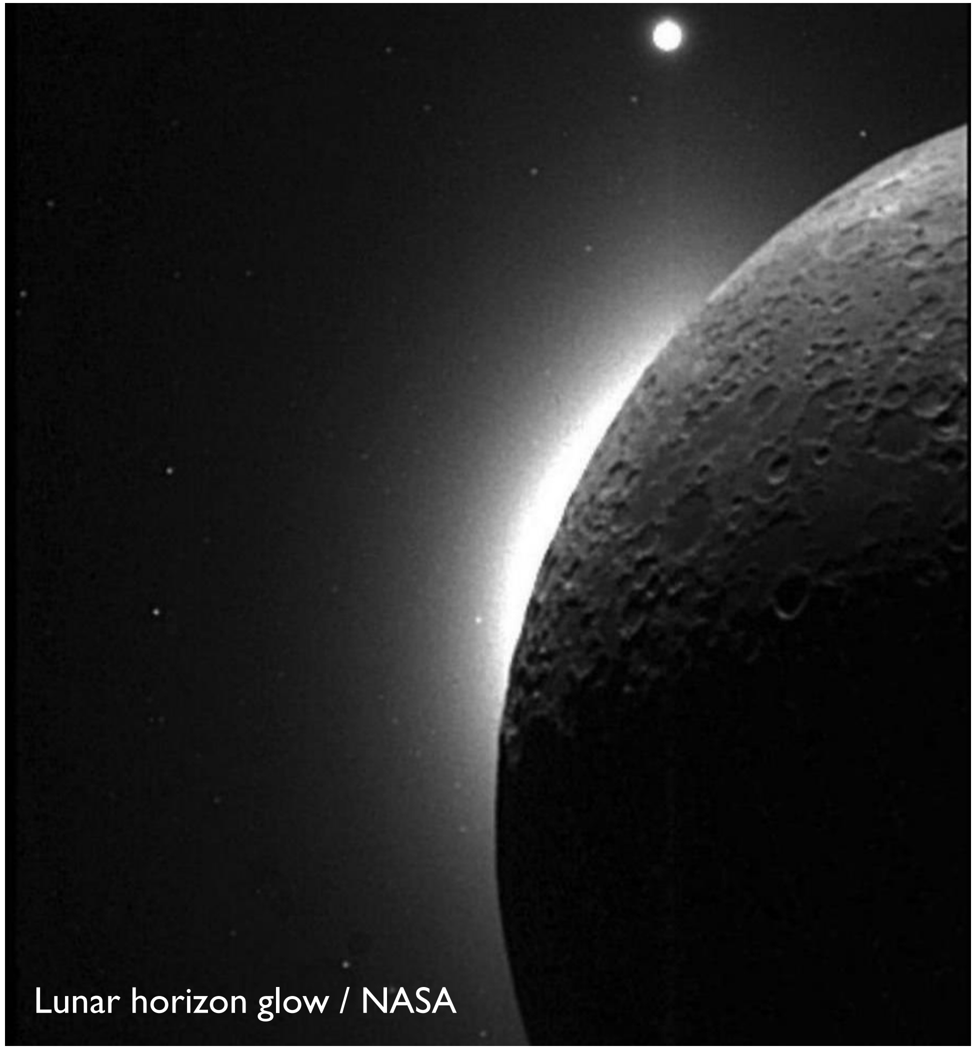
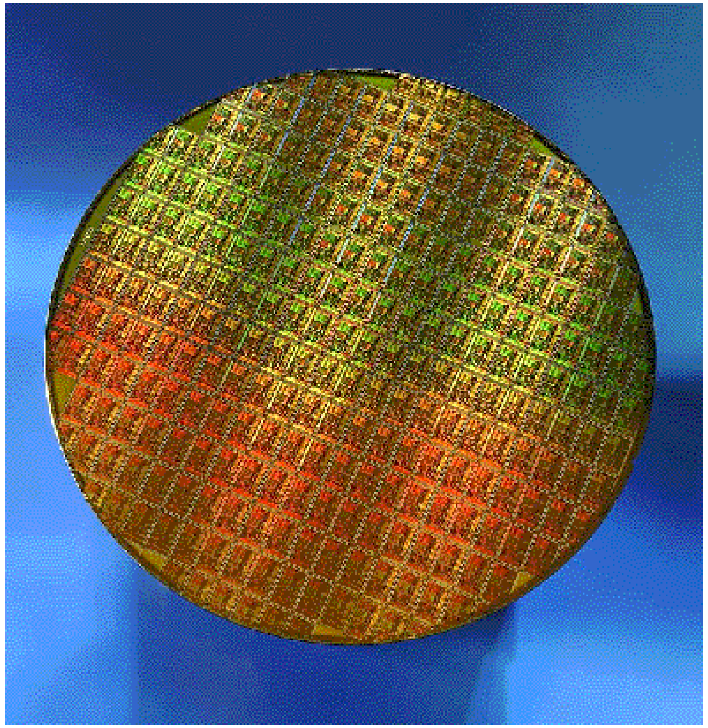
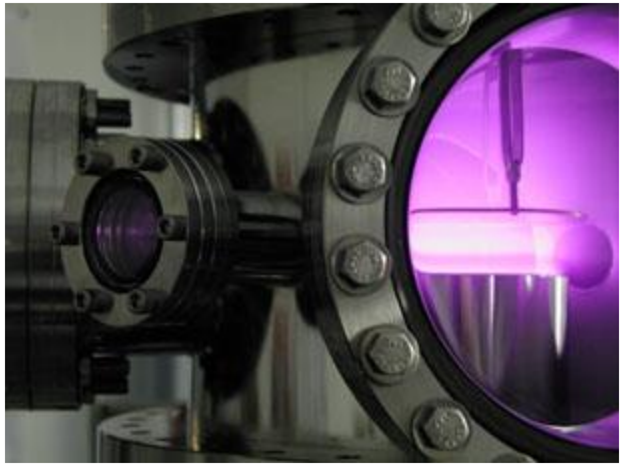


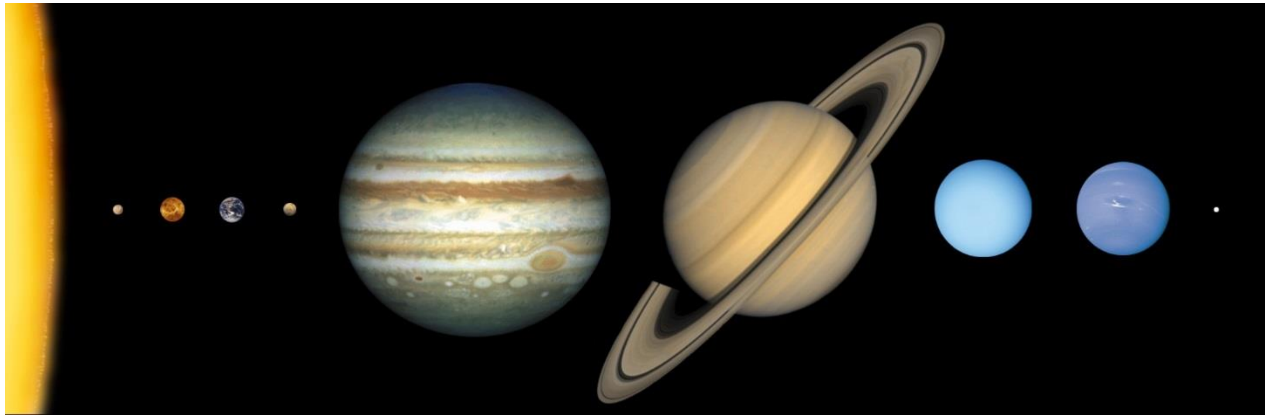
Why study dusty plasmas?





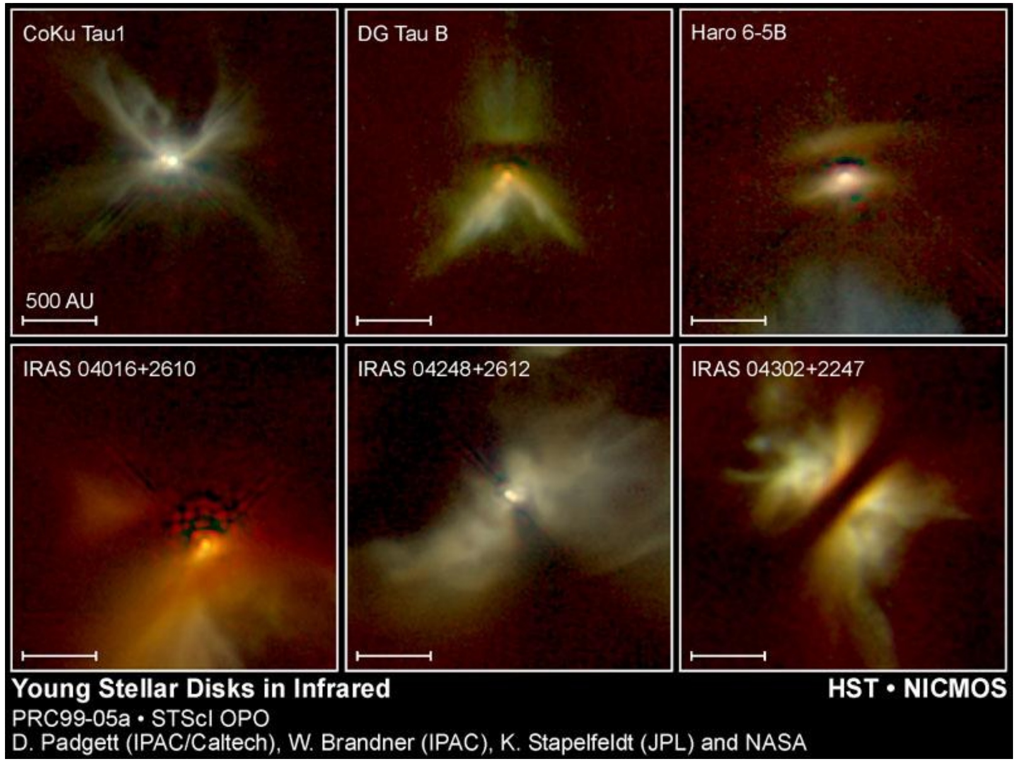
Are other solar systems like ours?

- Rocky planets close to star
- Gas giants far away from star
- Liquid water on planet in the Habitable Zone



Credit: Lunar and Planetary Institute

Circumstellar Disks



HL Tau

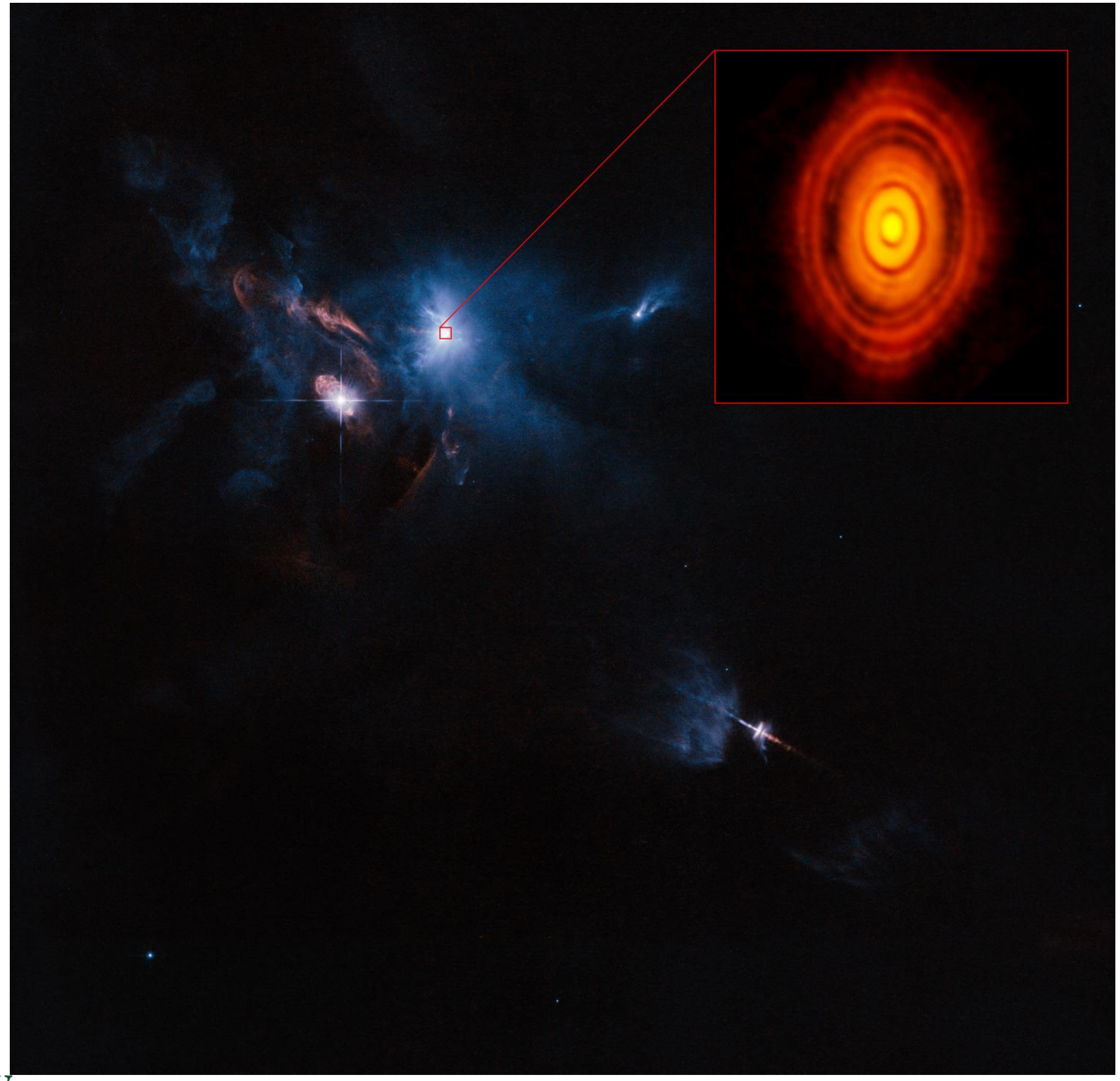
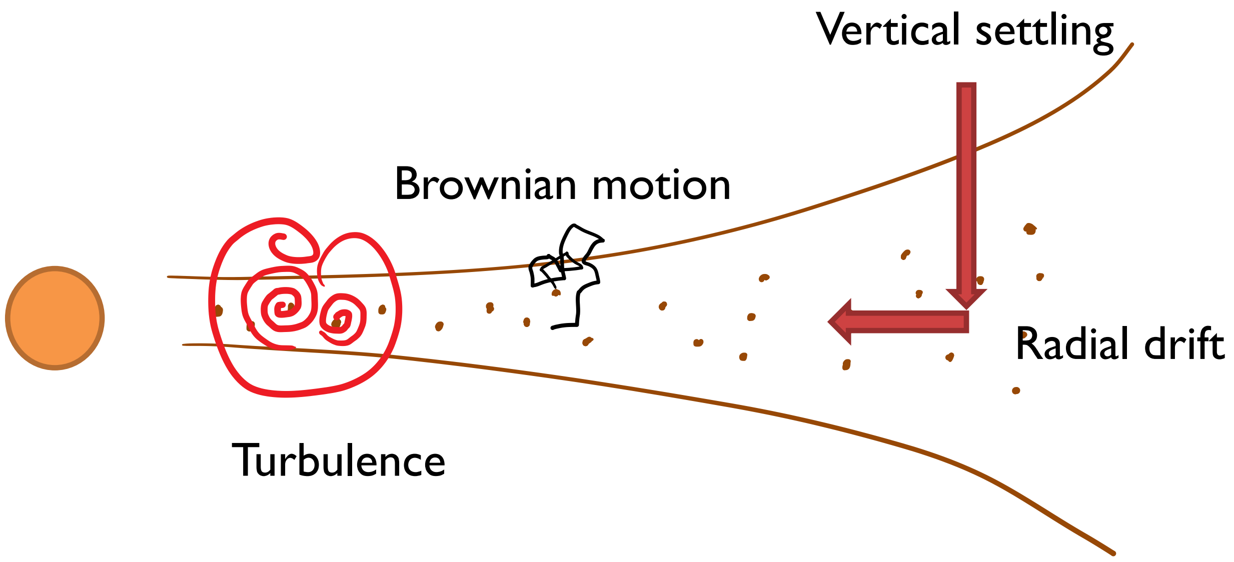


Image: Atacama Large Millimeter Array

Dust in its natural habitat: Building Dust Bunnies

- Calculating charge on dust
- Modeling collisional growth of charged dust

Relative motion of dust

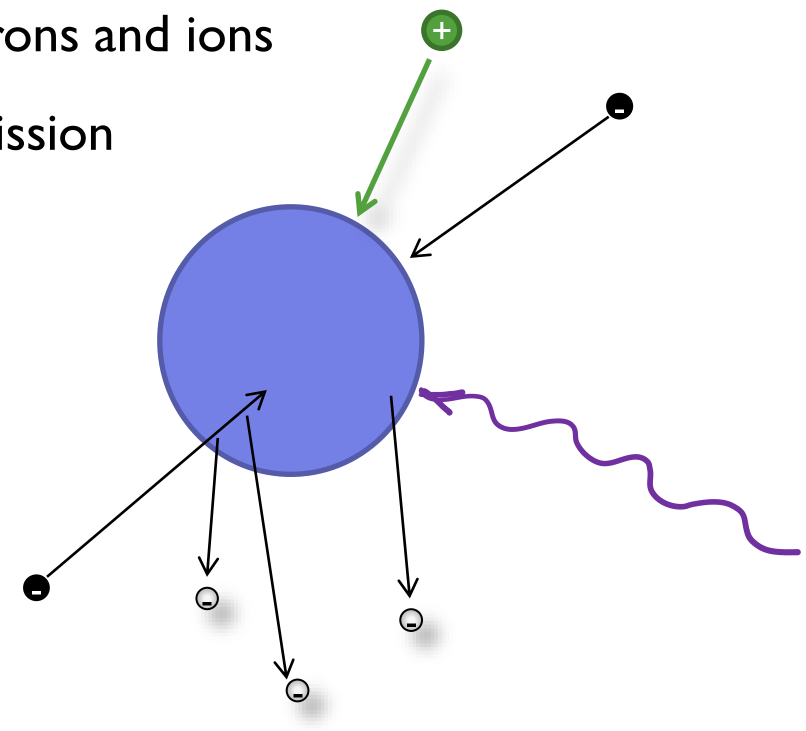


Grain Charging

Primary currents: electrons and ions

Secondary electron emission

Photoemission



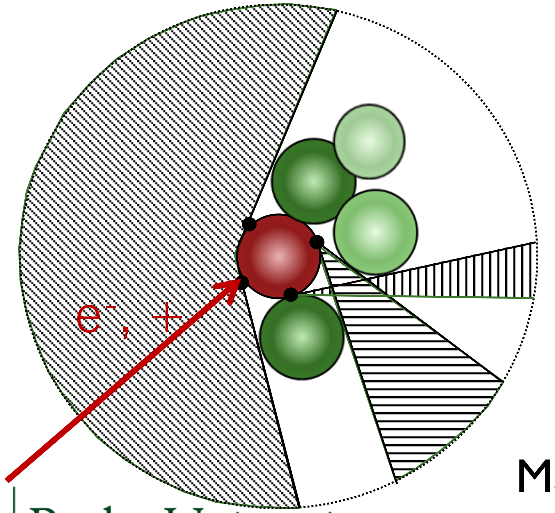
Simulating dust charging

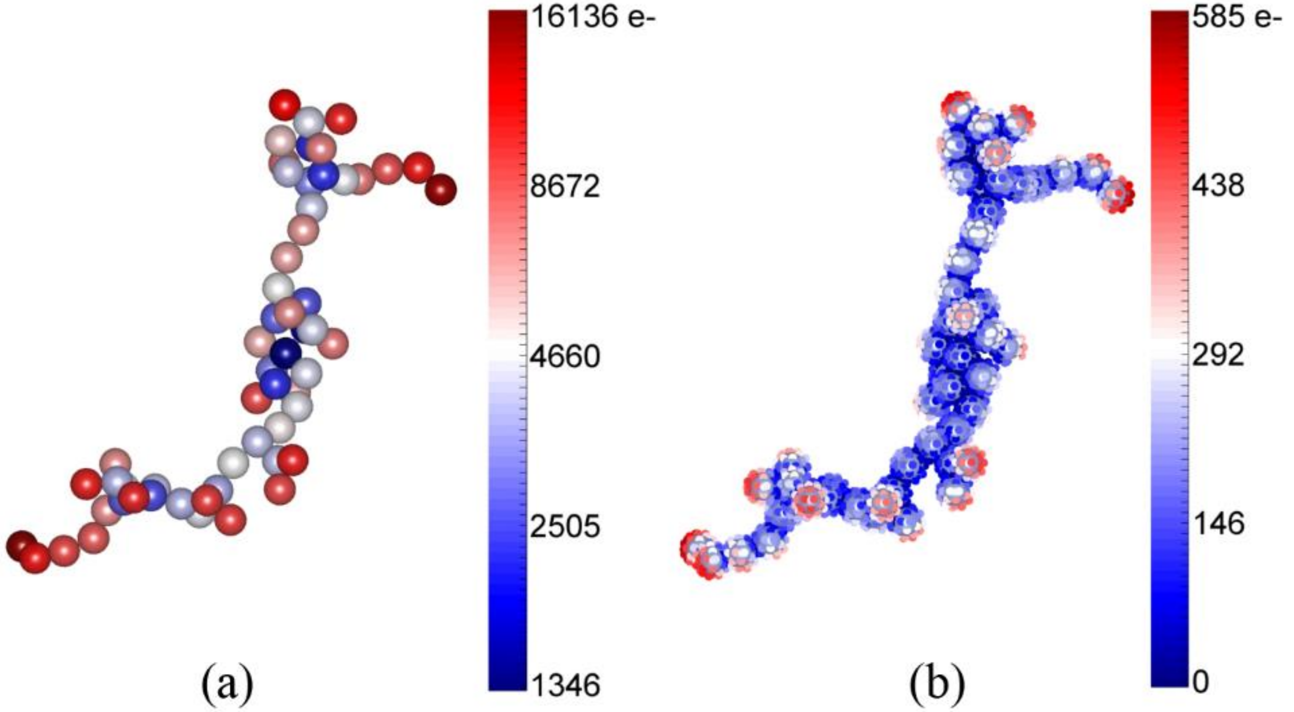
$$J_j = n_j e_j \int_{v_{min,j}}^{\infty} \pi\left(1 - \frac{2e_j\phi_s}{m_j v^2}\right) f(v) v^3 dv \int \cos(\theta)\, d\Omega$$

$$\frac{dQ}{dt} = \sum_j J_j(\phi_s)$$

$$Q = C\phi_s$$

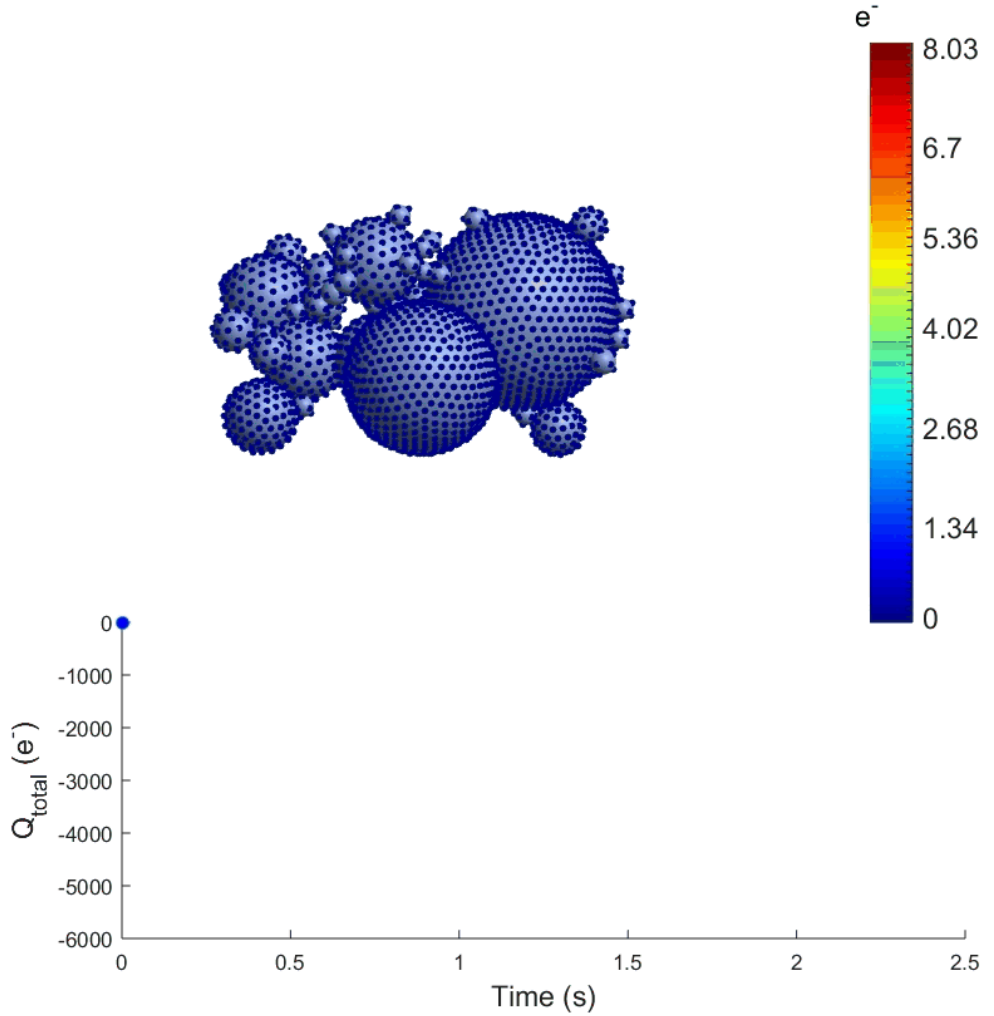
Line of sight approximation
OML LOS





Matthews & Hyde, *NJP*, **11**, 063030, 2009
Matthews, Coleman, Hyde, *IEEE Trans. on Plasma Sci.*, 2016

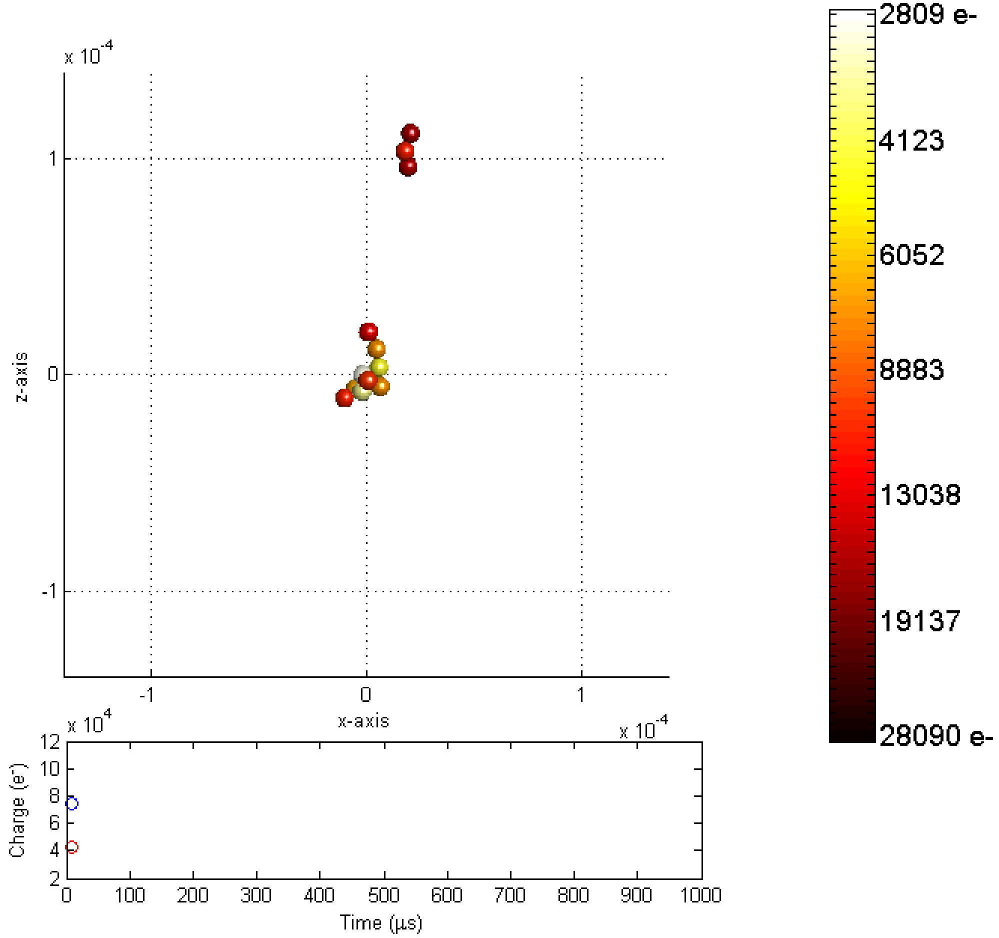
Aggregate Charge



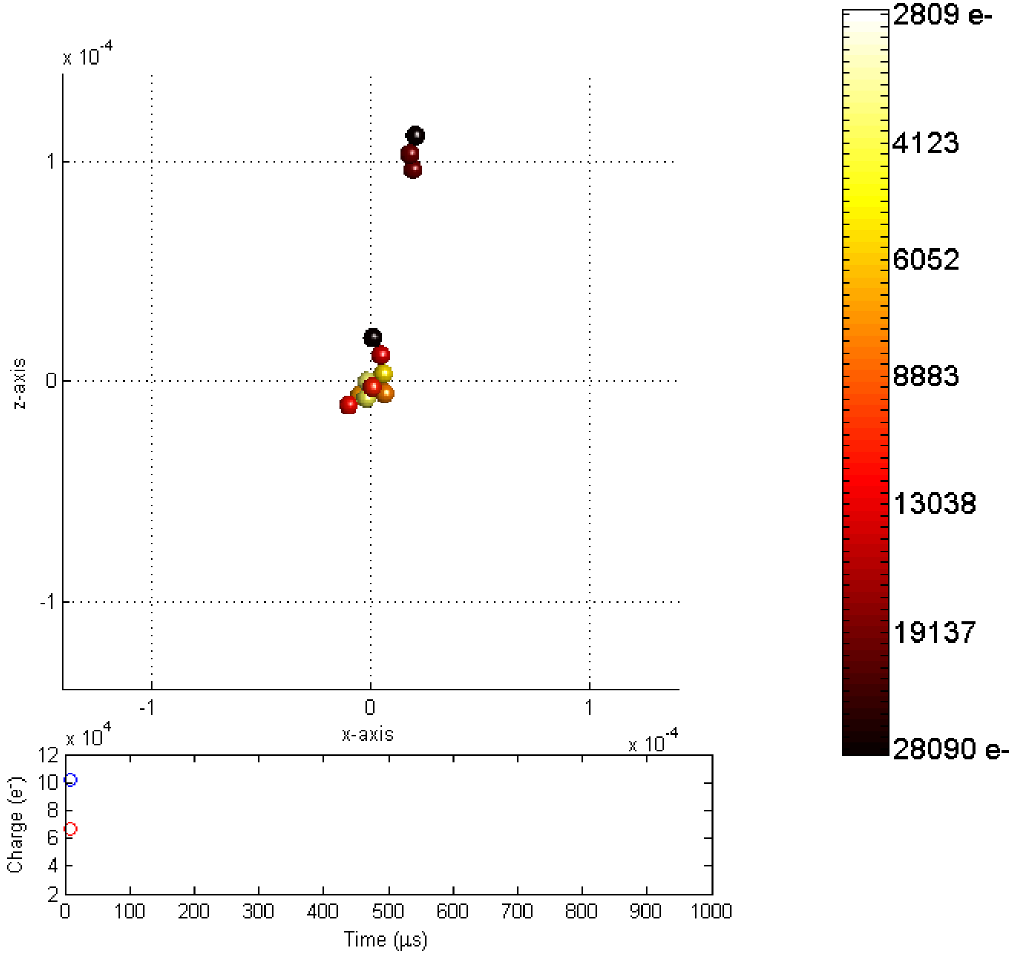
More charge on patches on the extremities of the aggregate surface

Charging time is fast compared to dust dynamics

Incoming aggregate contributes to blocked lines of sight

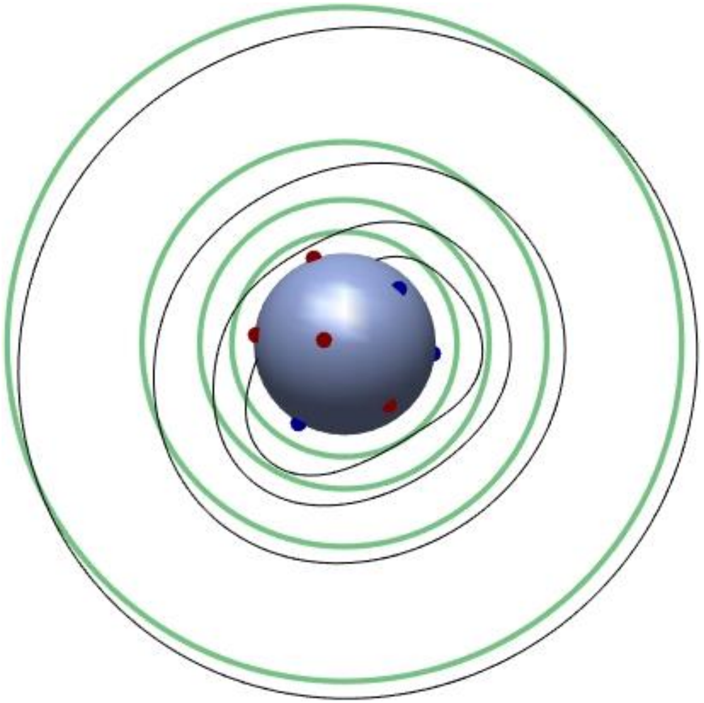


Charging time is slow compared to dust dynamics

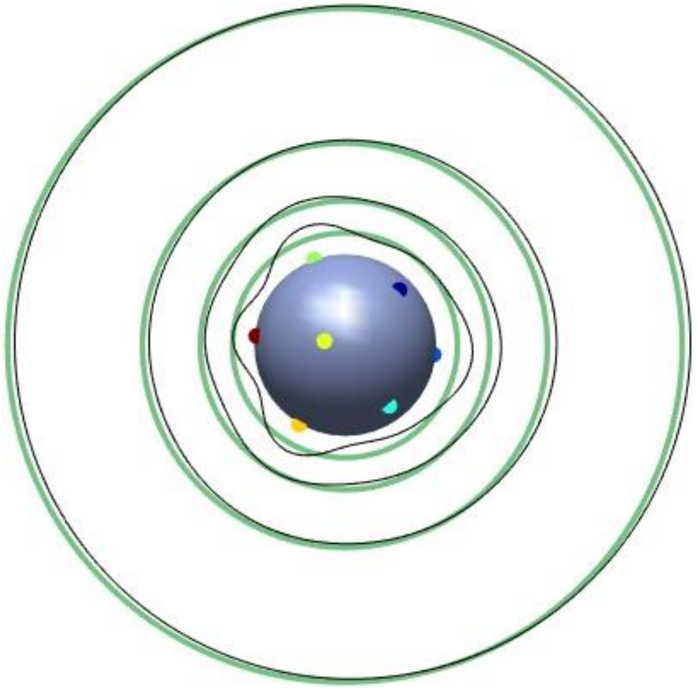


Asymmetric Potentials

Protoplanetary Disk Plasma
a = 100 nm
$\langle Q \rangle = 4.7\ e^-$



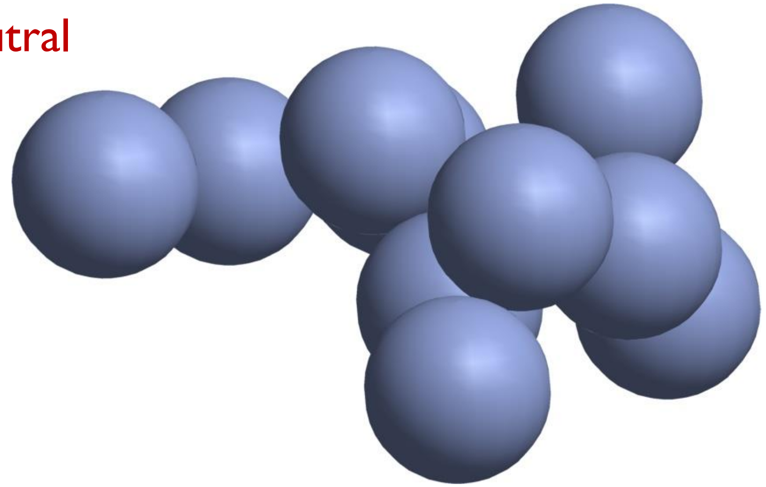
Laboratory Plasma
a = 100 nm
$\langle Q \rangle = 214\ e^-$



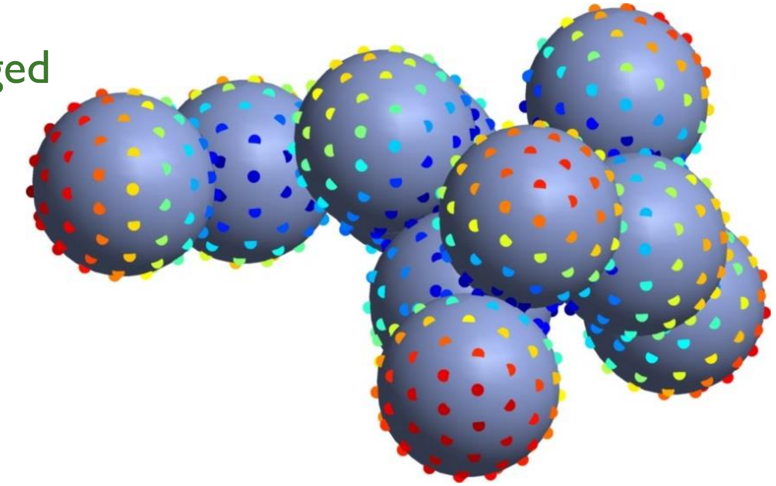
Matthews, Shotorban, and Hyde, *Astrophysical Journal,* 776, 2013
Matthews, Shotorban, and Hyde, PRE, 97, 2018

Timescale of Charging vs Aggregate Dynamics

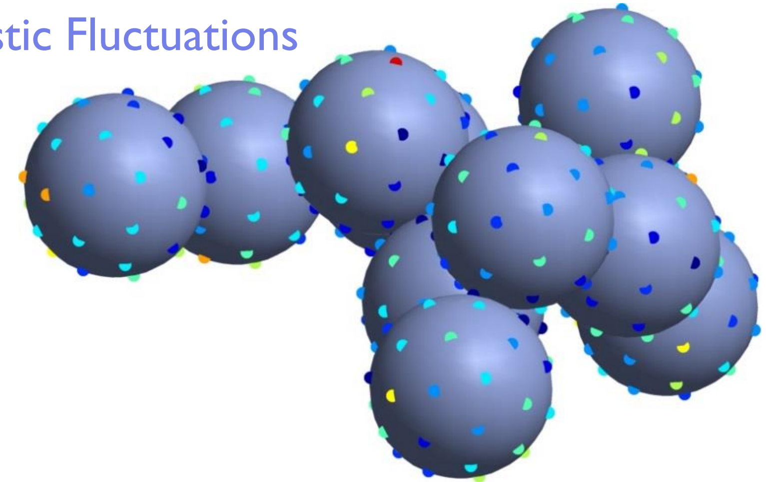
Neutral



Time-averaged

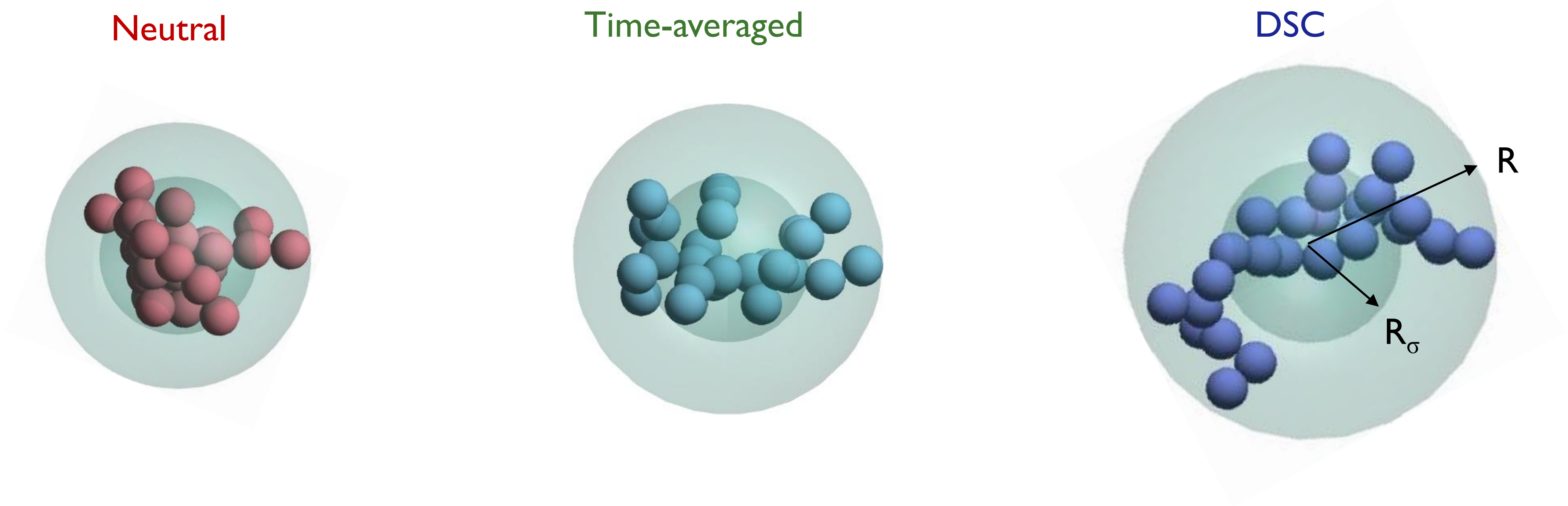


Discrete Stochastic Fluctuations



Differences in Aggregates

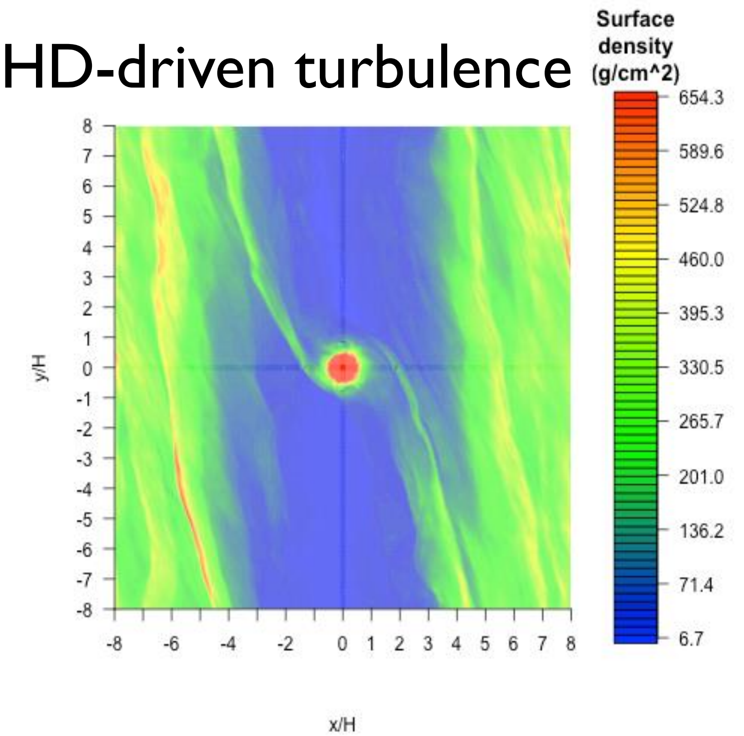
Stochastic charge fluctuations cause formation of elongated aggregates



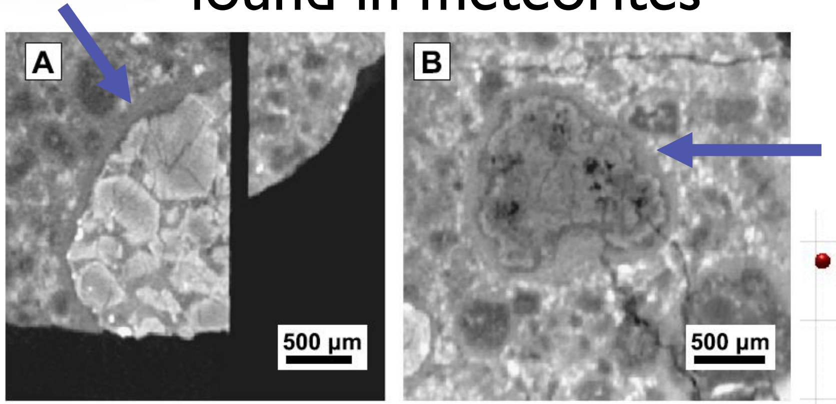
Matthews, Shotorban, and Hyde, PRE, 97, 2018

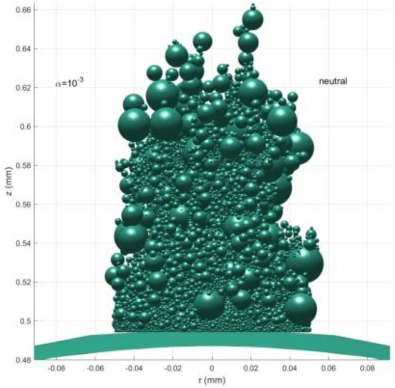
Dust/plasma interactions
Processes in protoplanetary disks

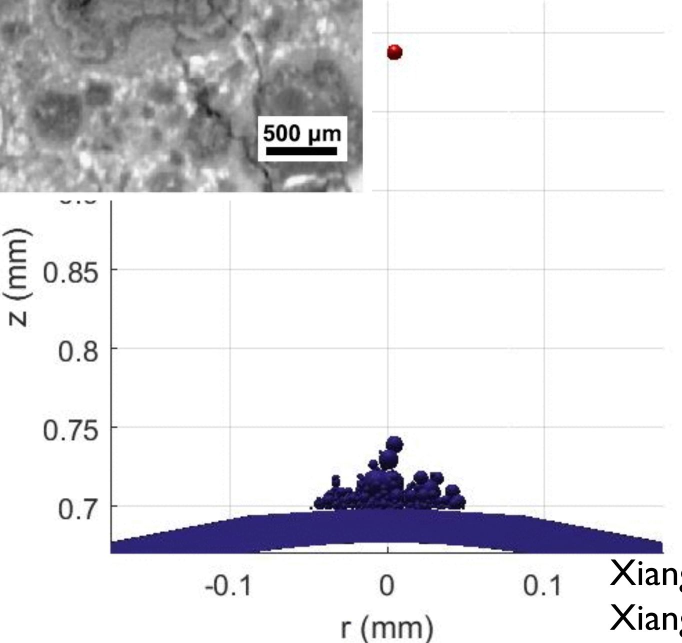
MHD-driven turbulence



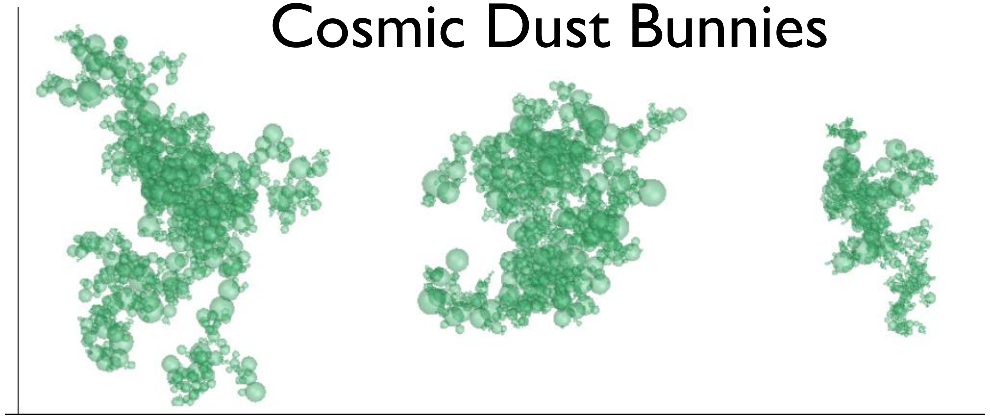
Growth of chondrule rims found in meteorites





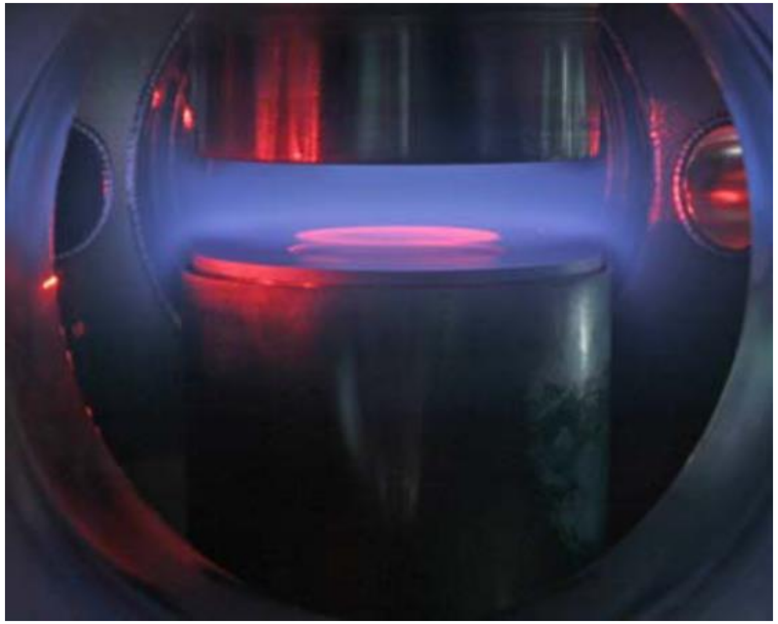


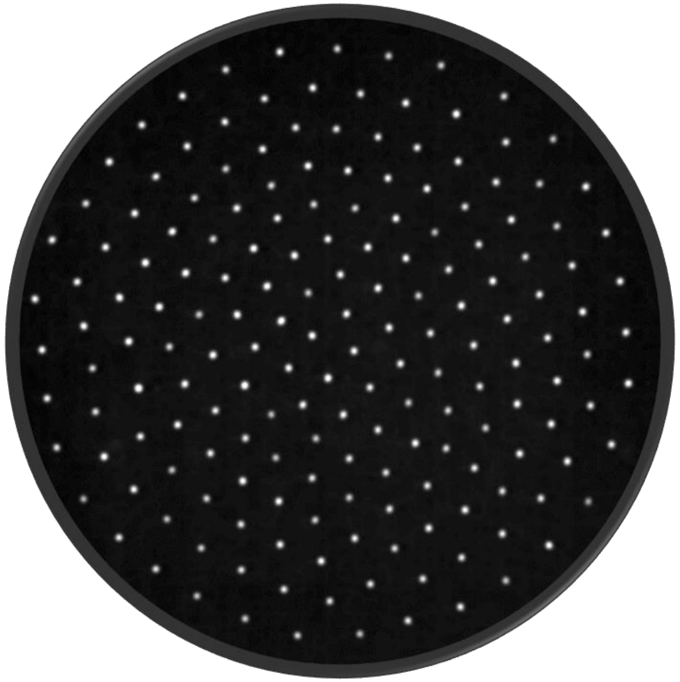
Cosmic Dust Bunnies



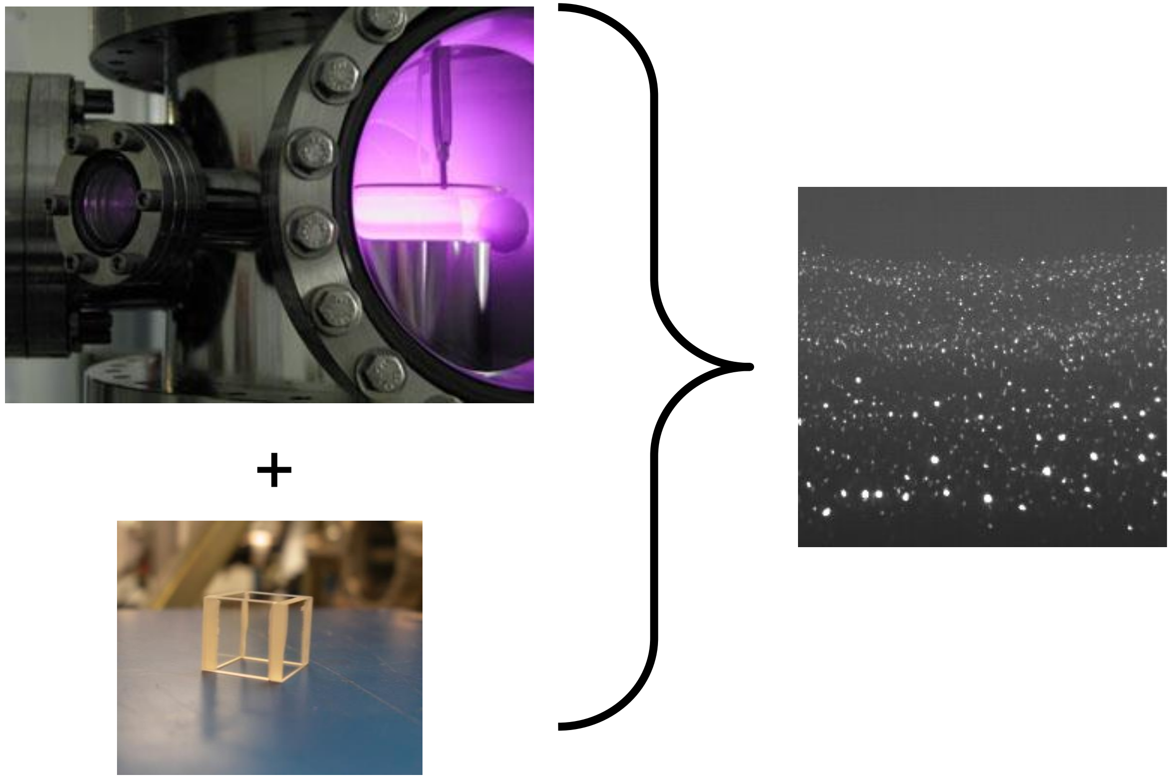
Xiang *et al.*, *Icarus*, 354, 114053, 2021
Xiang *et al.*, *Astrophysical Journal*, 897(2), 182, 2020

Dust in the Lab:
Aggregates, dust crystals and self-ordering structures



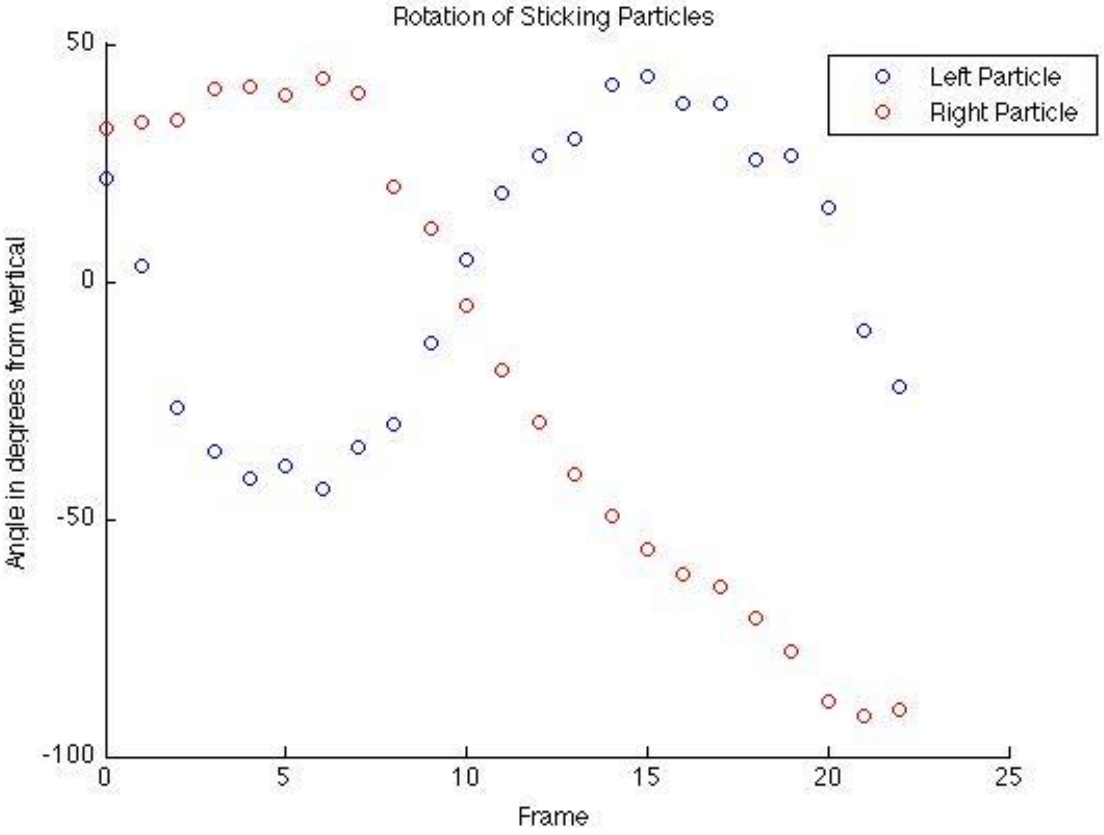


Growing Aggregates in the Lab

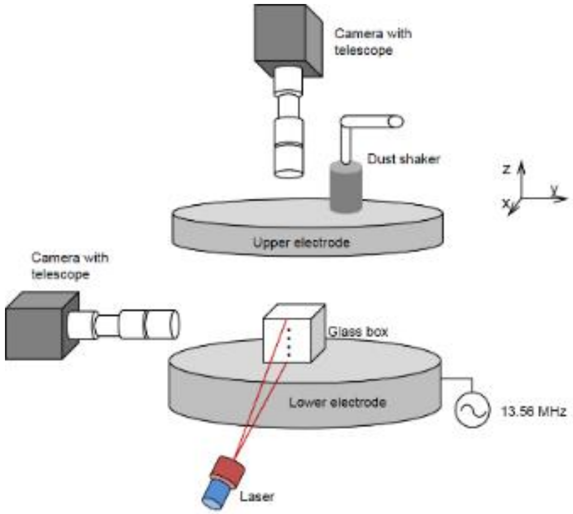


Du, Thomas, Ivlev, Konopka, and Morfill, PoP **17** 113710 (2010)
Matthews, Carmona-Reyes, Land, and Hyde, *AIP Conf. Proc.* 1397, 397 (2011)

Dipole Interactions

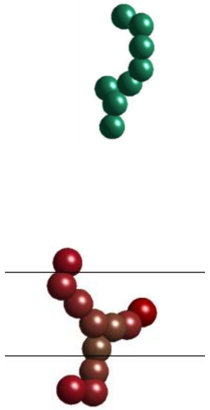


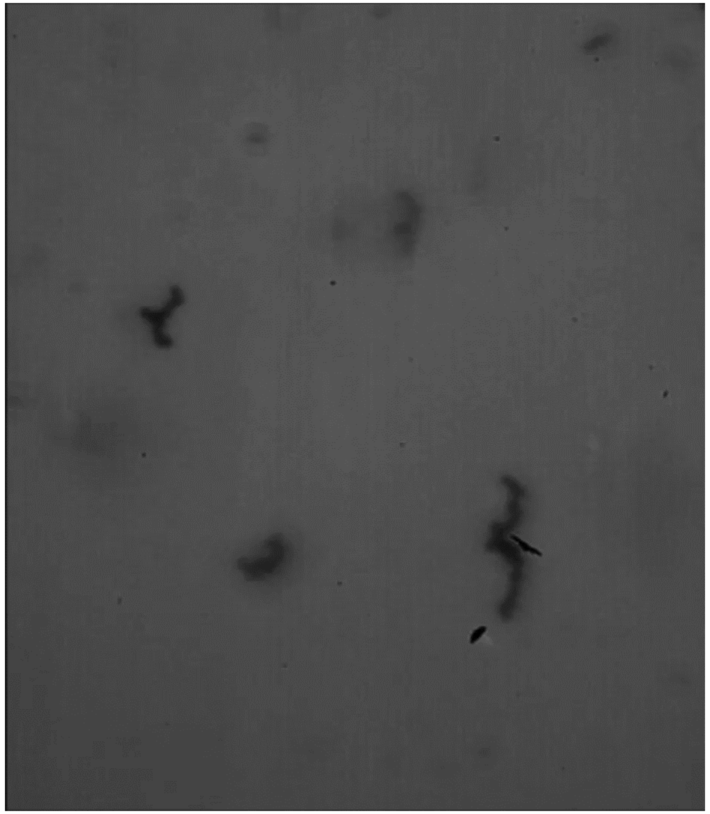
Rotation/Helical Motion



Gold-coated mf particles
d = 8.94 μm

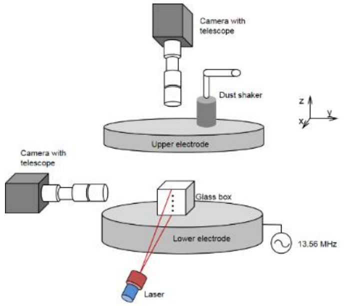
3000 fps
Rotational period ~ 15 ms

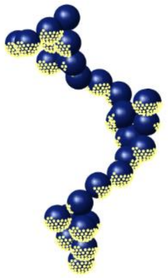


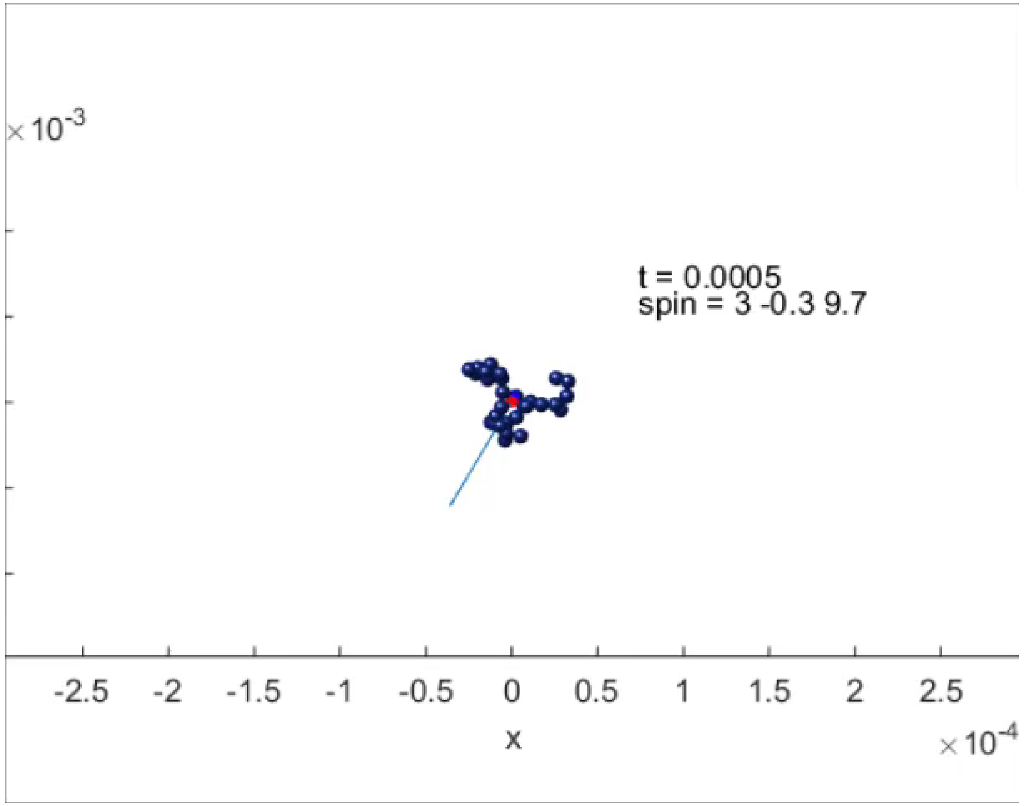


Yousefi, et al., "Measurement of net electric charge and dipole moment of dust aggregates in a complex plasma," *Phys. Rev. E*, 90(3), 033101, 2014.

Rotation/Helical Motion: Numerical Model

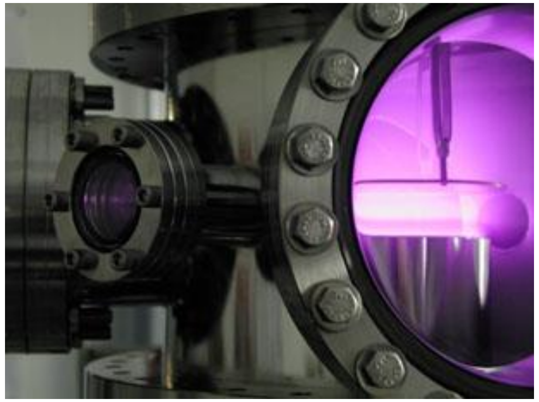






Thermophoretic Force due to temperature gradient

Dust Structure Formation in Experiments



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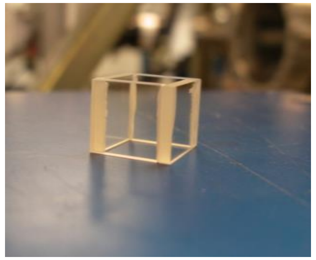

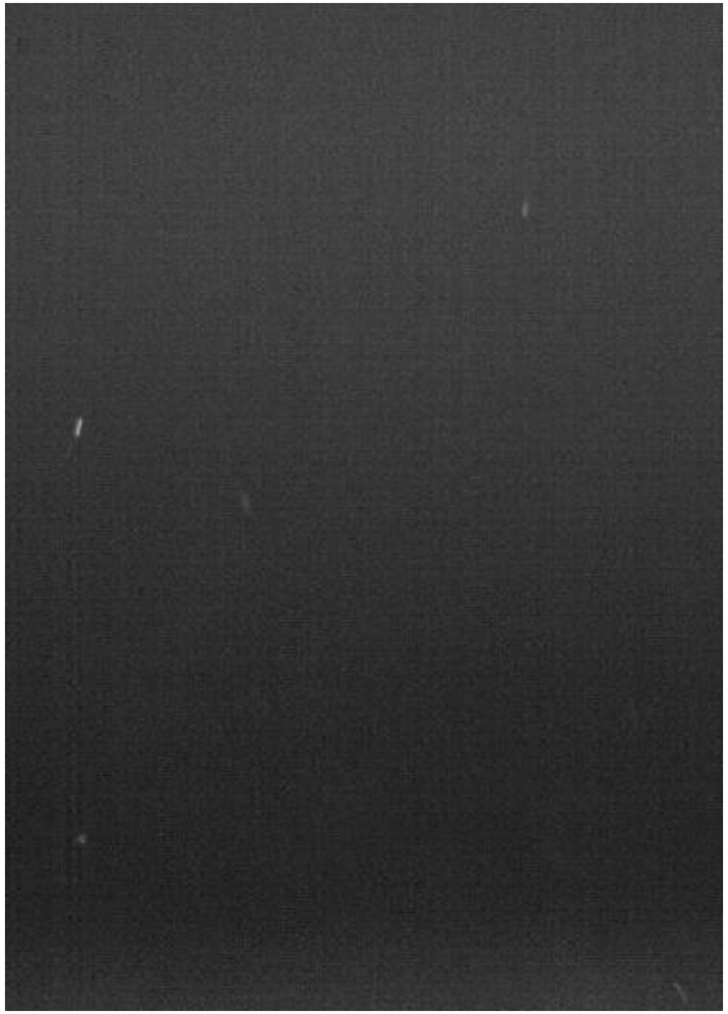

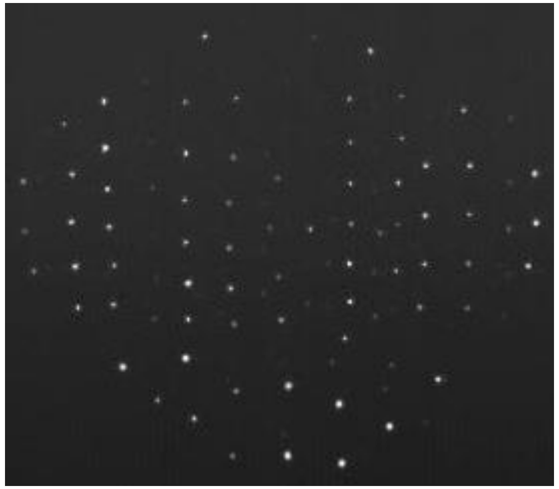

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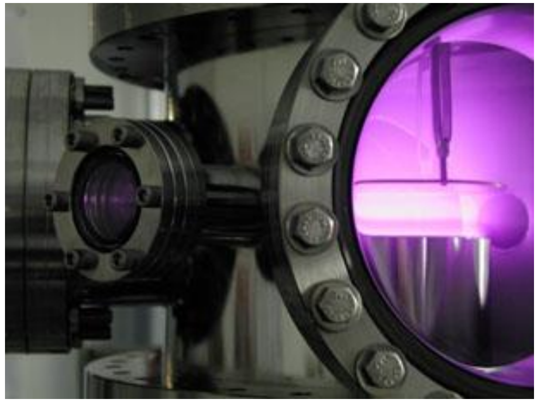

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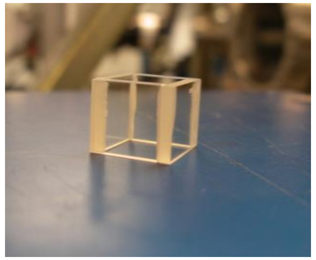
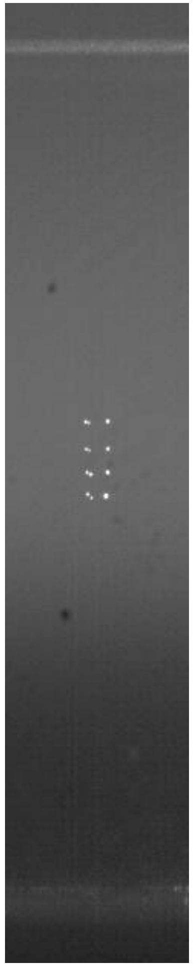
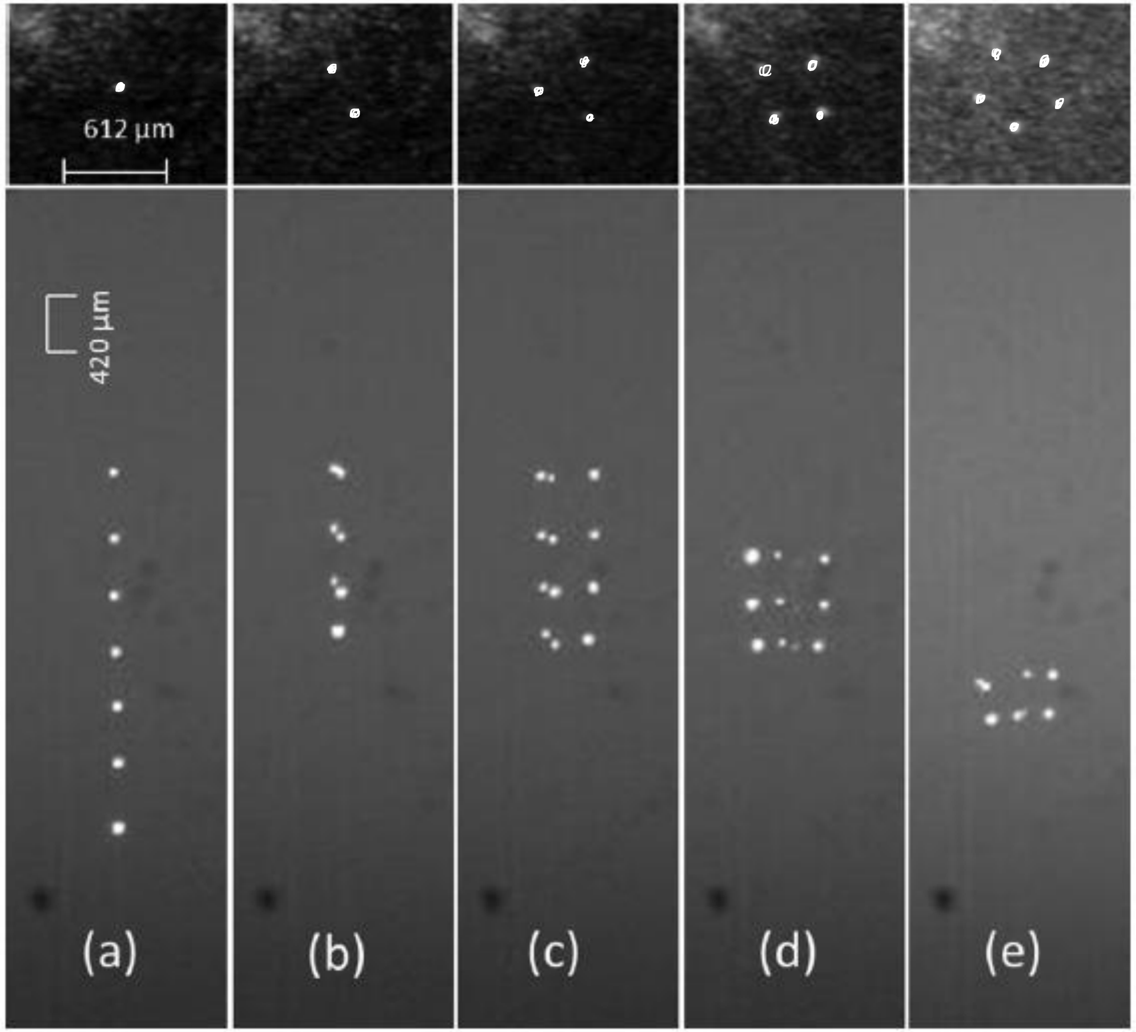


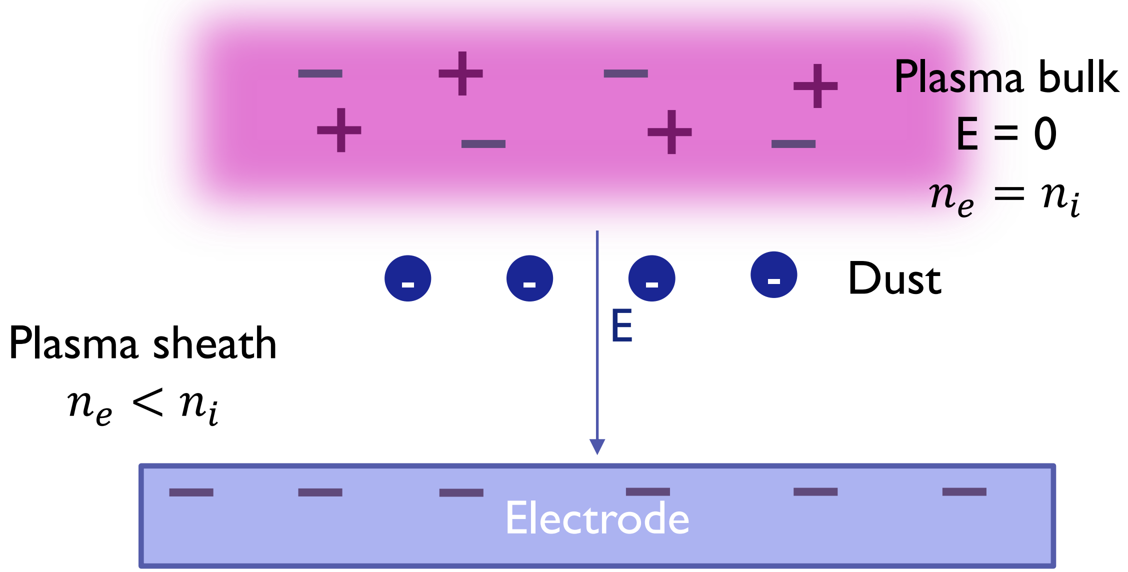




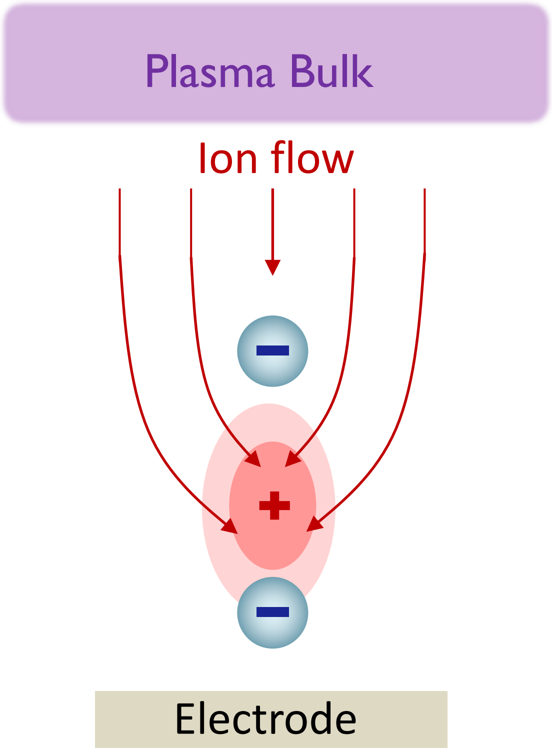
Kong et al., Phys Rev E, 90, 013107, 2014

Plasma Sheath

- All surfaces in a plasma are charged (negatively)
- Electrons repelled – density given by Boltzmann distribution
- Ions accelerated from the bulk – density determined by continuity of flow
- Difference in density allows electric field to exist

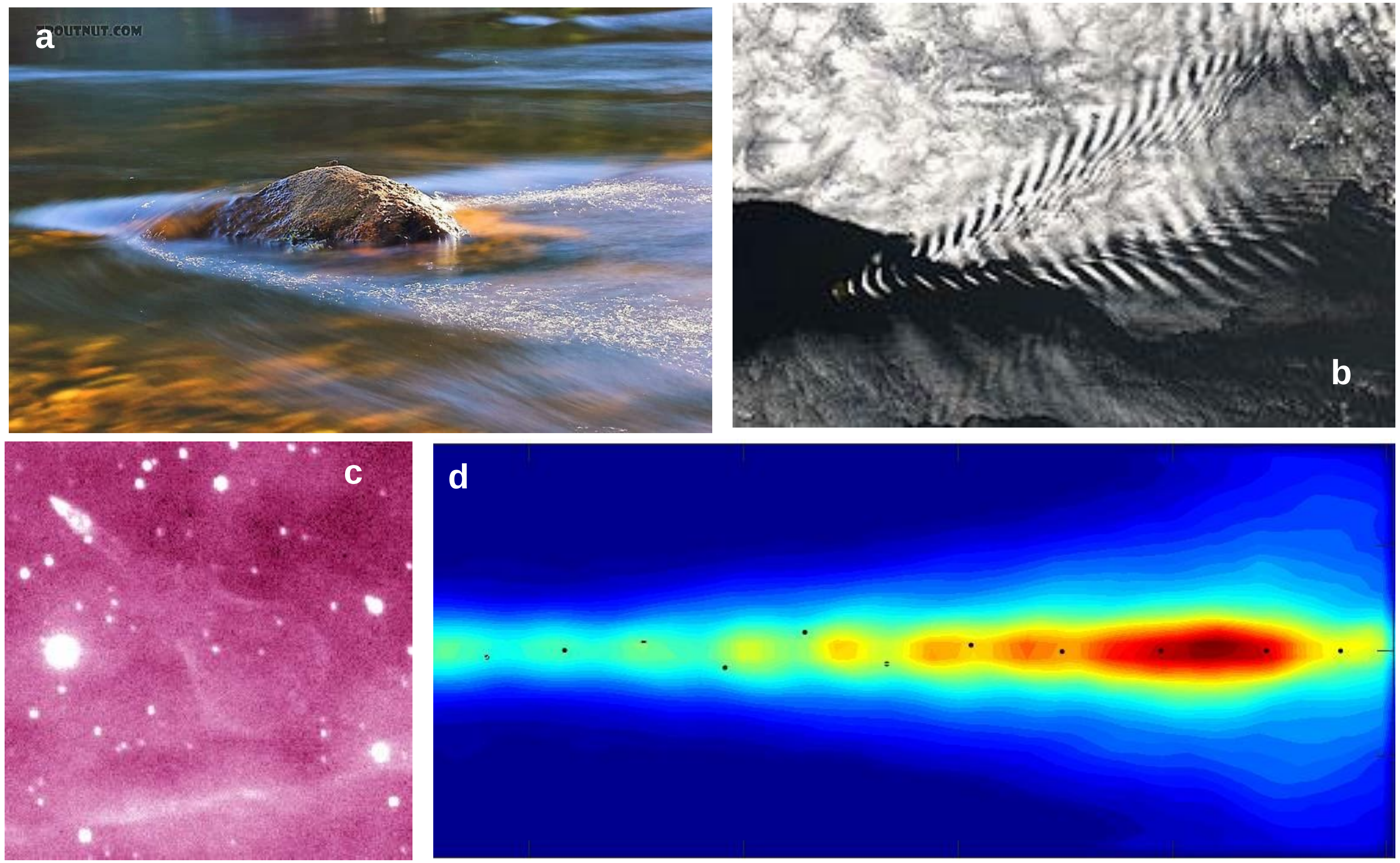


Ion Wake Field – Broken Symmetry



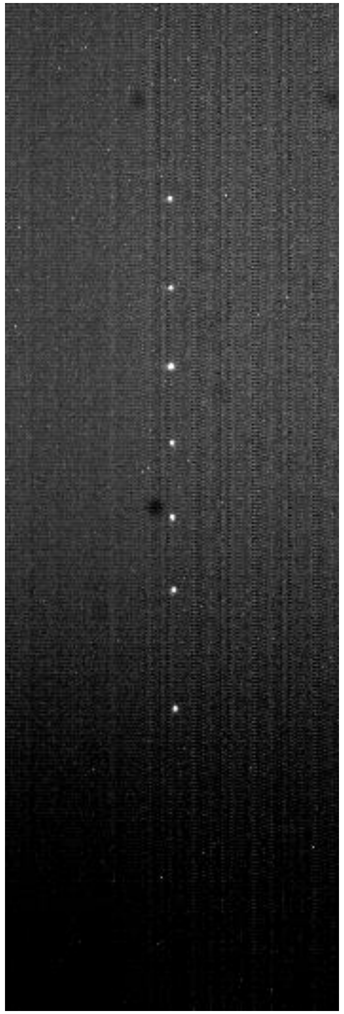
$$M = \sqrt{\frac{kT_e}{m_i}}$$

Wakefields



a) Water wake (troutnut.com) b) Wave cloud pattern in the wake of the Île Amsterdam (NASA) c) Guitar Nebula wake behind a neutron star (Palomar Observatory) d) Ion density distribution in the wake of dust grains in a plasma with ion flow.

1. Probing the Ion Wake: In gravity

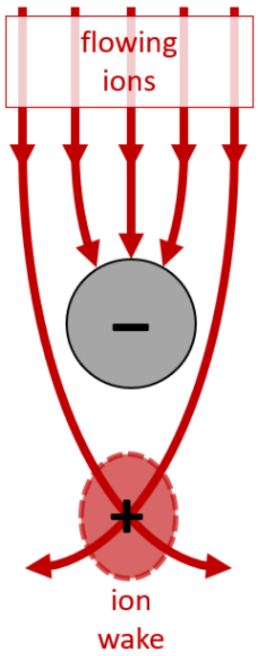


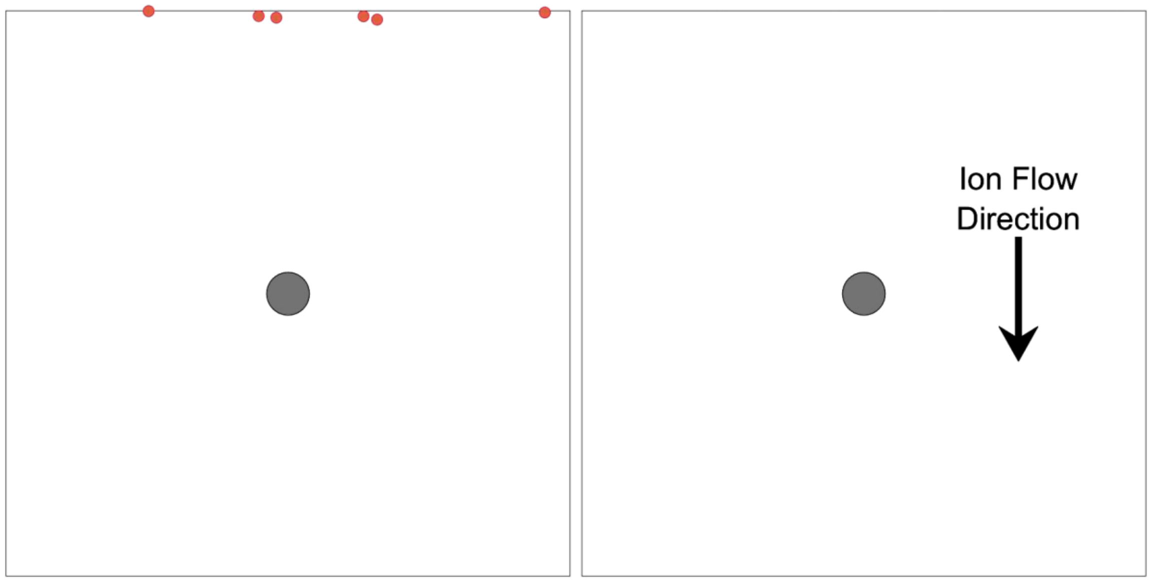
DRIAD: Dynamic Response of Ions and Dust

Matthews et al., *Physics of Plasmas*, 2020.

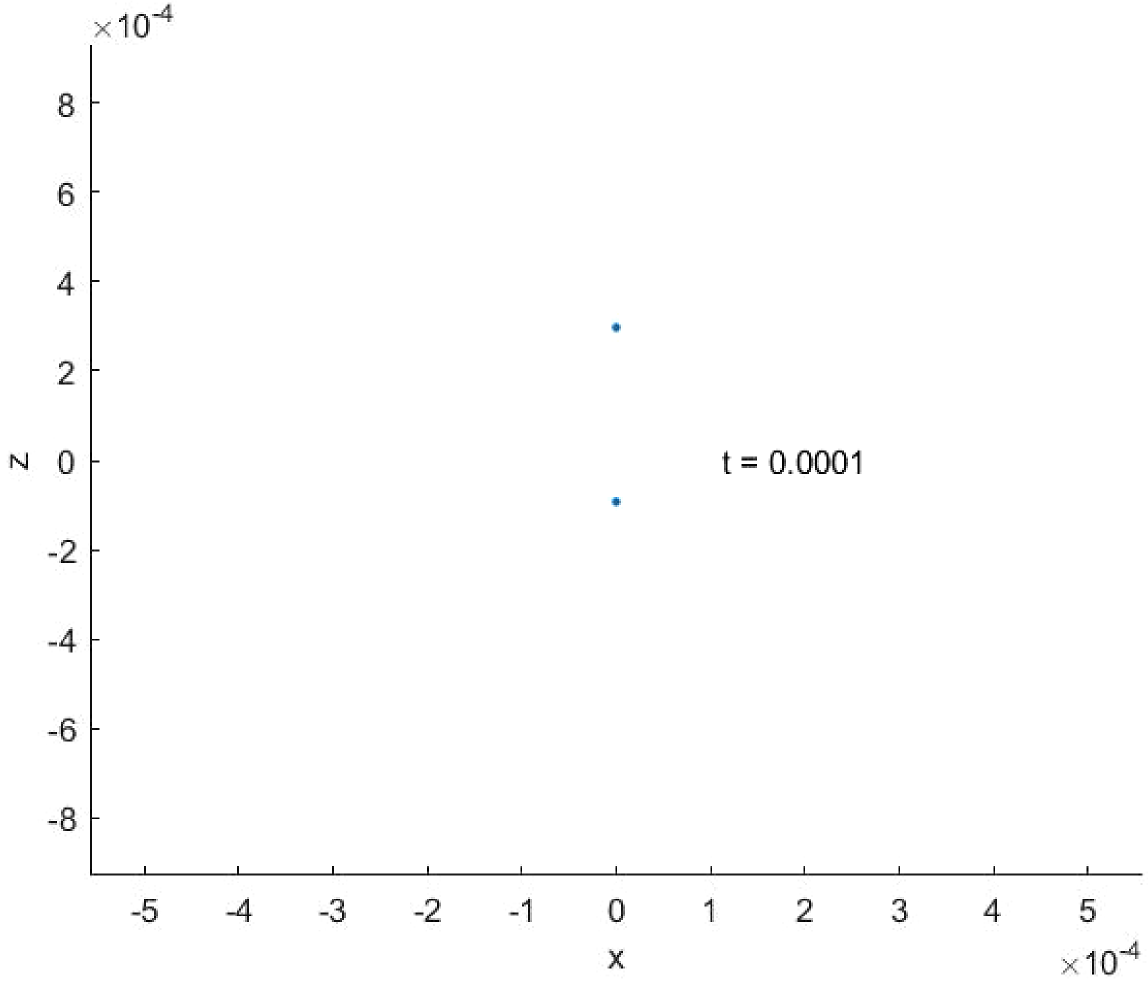
Modeling Ion Wake

- Accumulation of positive charge density
  - depends on:
    - dust grain charge
    - ion flow speed
    - presence of additional dust grains



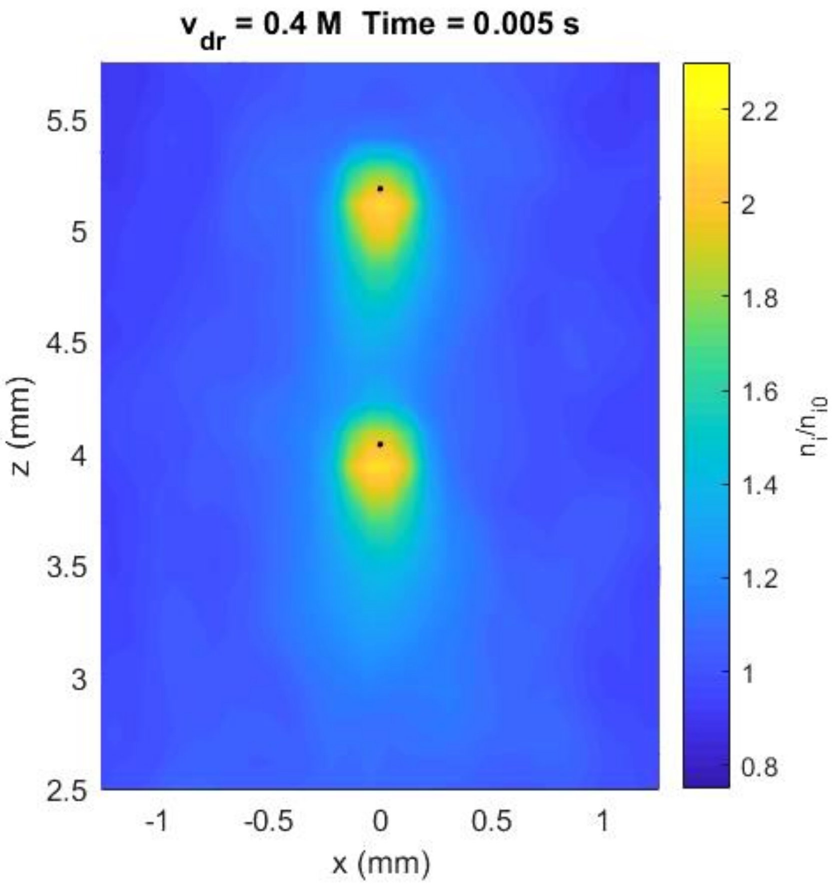


What we see in the lab: the dust

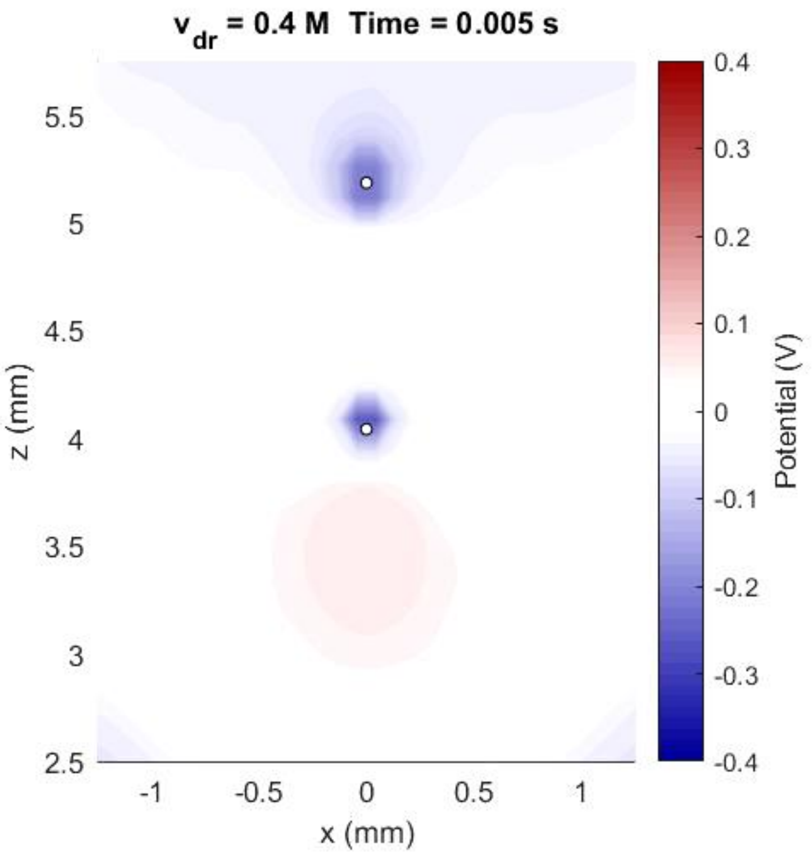


What we see in the simulation: Ions and Dust

Ion Density

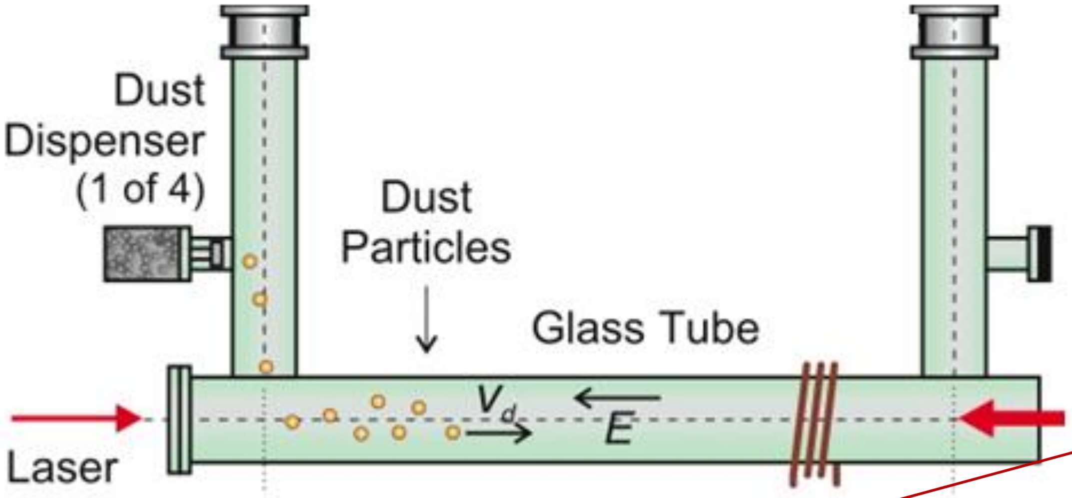


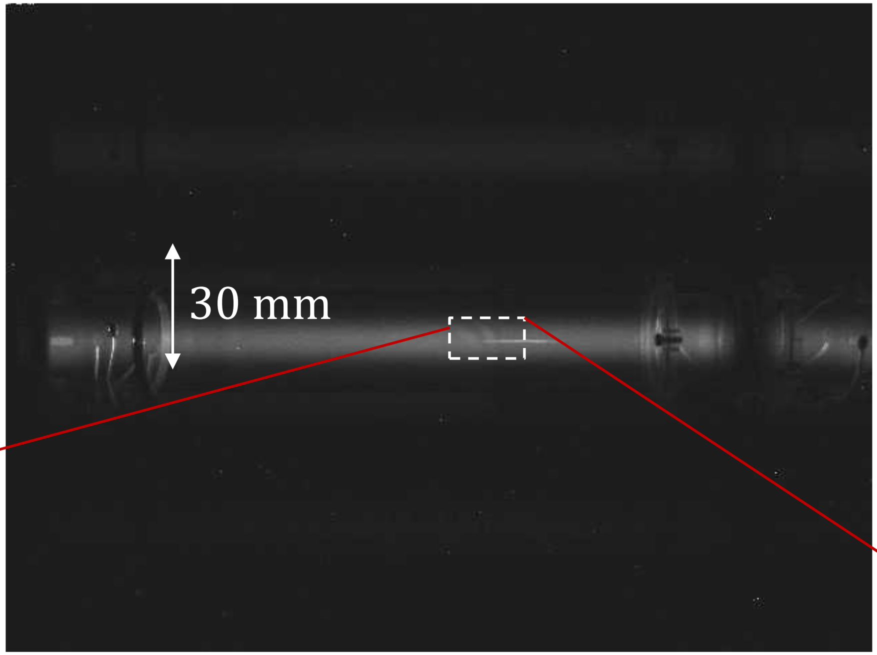
Electric Potential

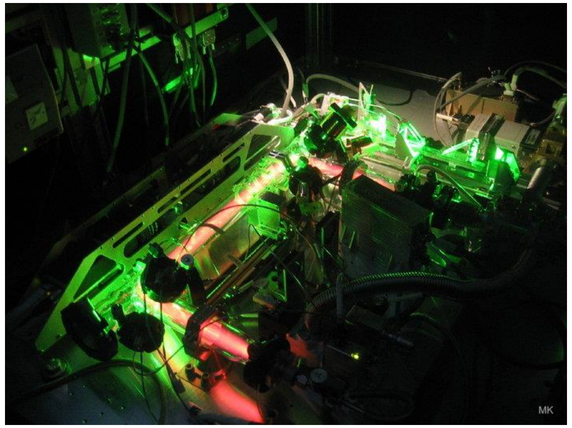


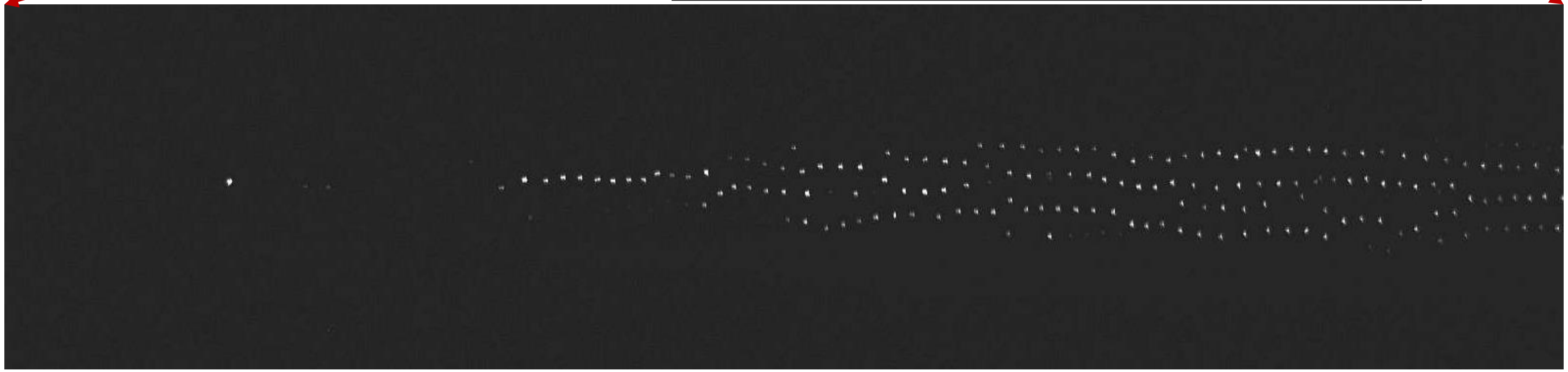
Matthews et al., *Physics of Plasmas*, 2020.

Plasma Kristal-4 Experiment on the ISS







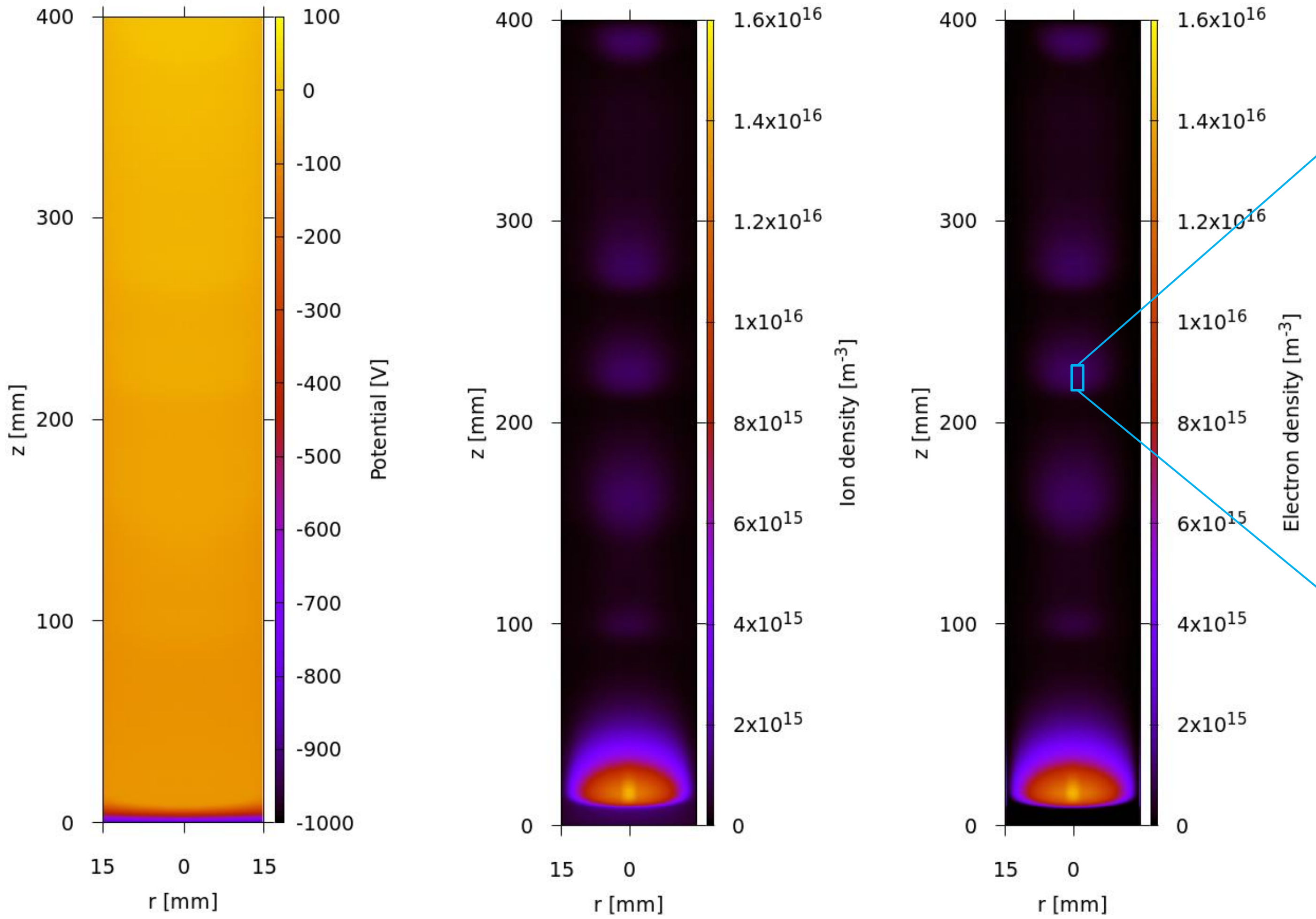


Fink, Thoma, and Morfill, Microgravity Science and Technology 23.2 (2011)

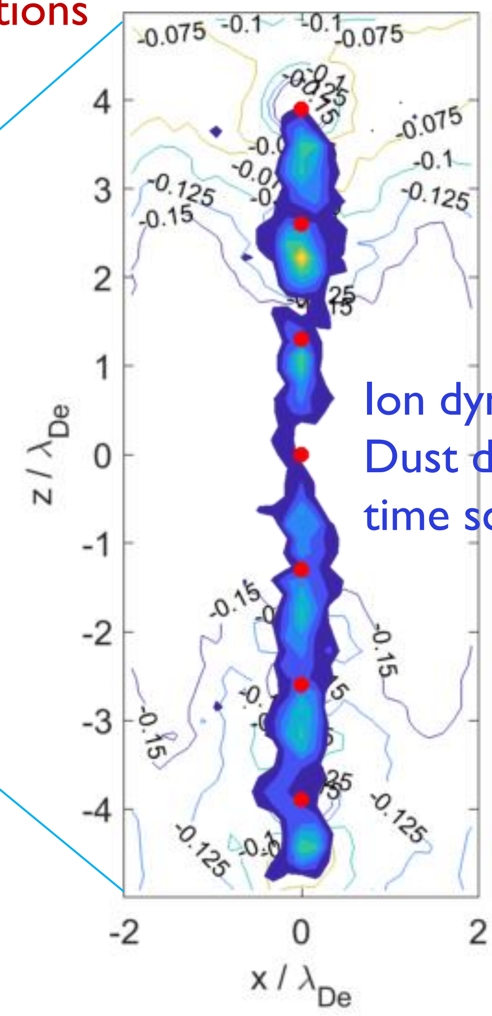
Modeling Ion Flow in PK-4

www.baylor.edu/CASPER

PIC/MCC code provides plasma densities and potential for experimental conditions



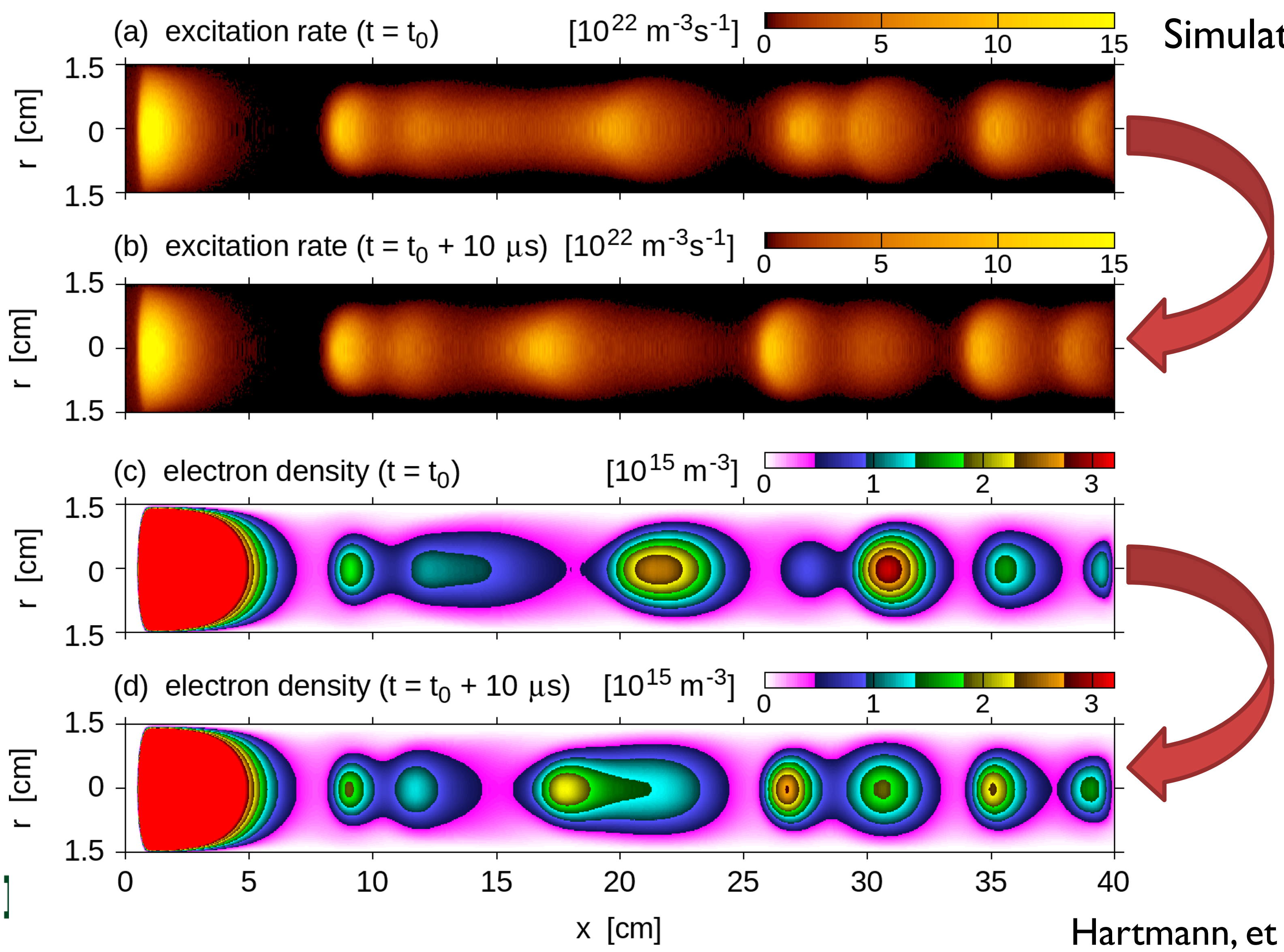
MD code models local dust / ion dynamics



Ion dynamics on ns time scale
Dust dynamics on sub-ms time scale

Hartmann et al, *PSST,* 2020.

Short time scales

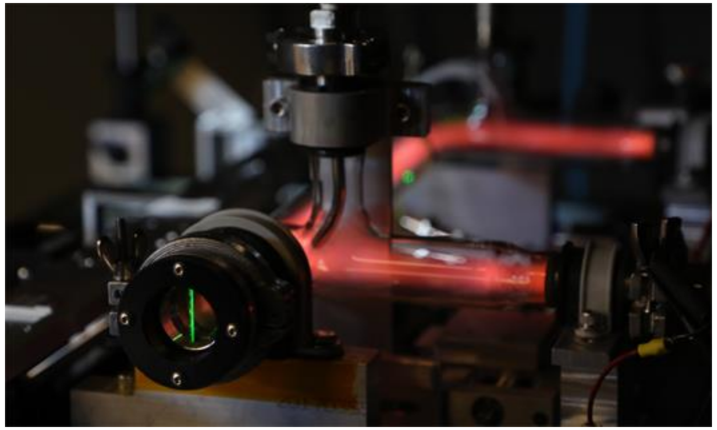


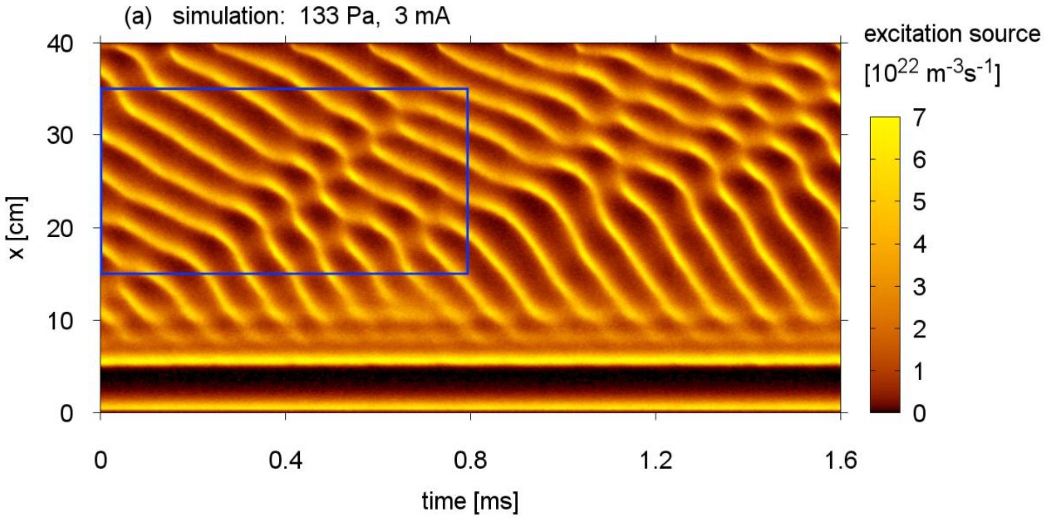
Simulation acquisition time 1 μs

10 μs time difference

Hartmann, et al., *PSST*, 2020

Comparison between PIC and PK-4

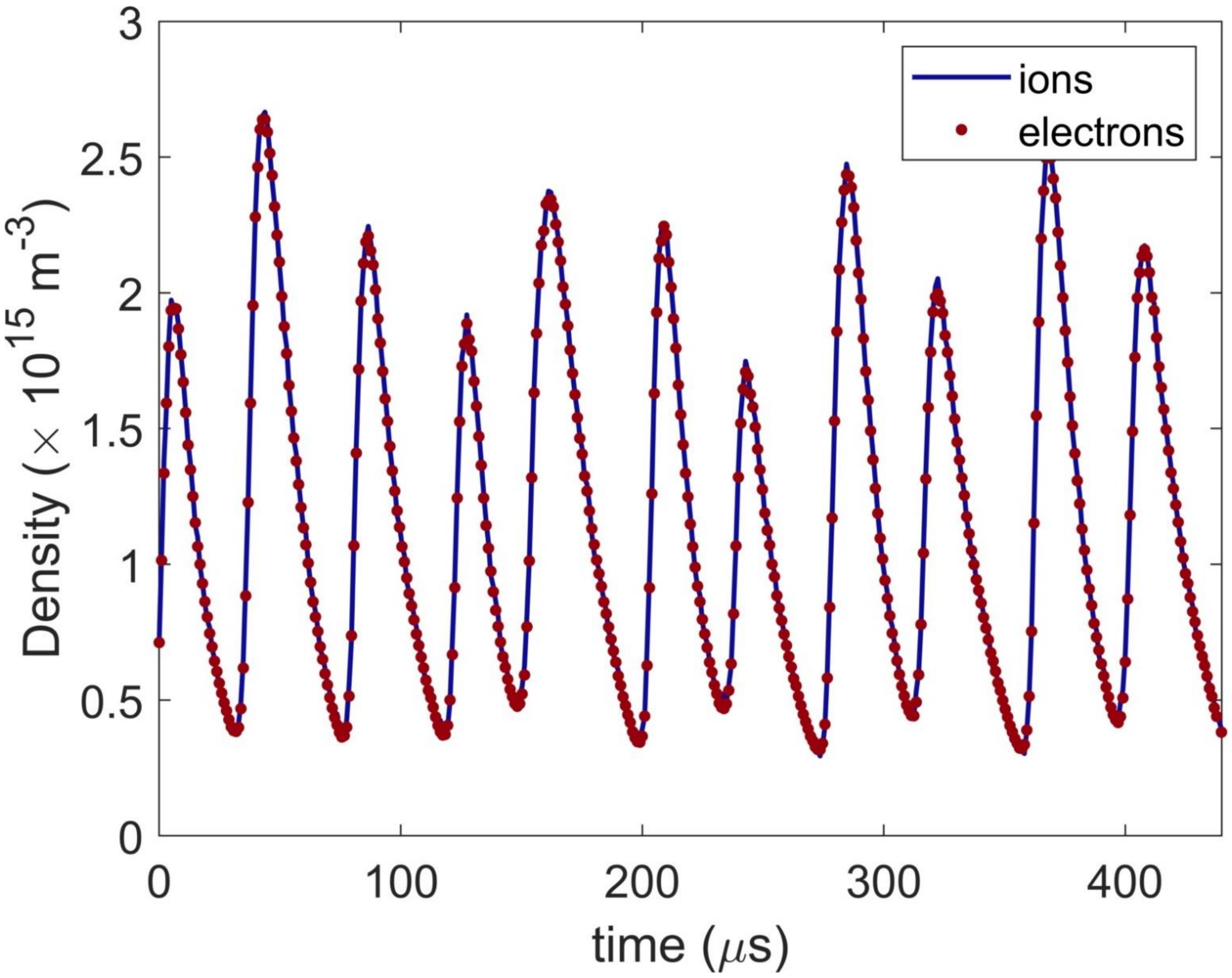




BU-PK4 experiment is a mockup of the actual PK4 onboard the ISS

Hartmann, et al., *PSST*, 2020

Time-varying data from PIC model of PK-4

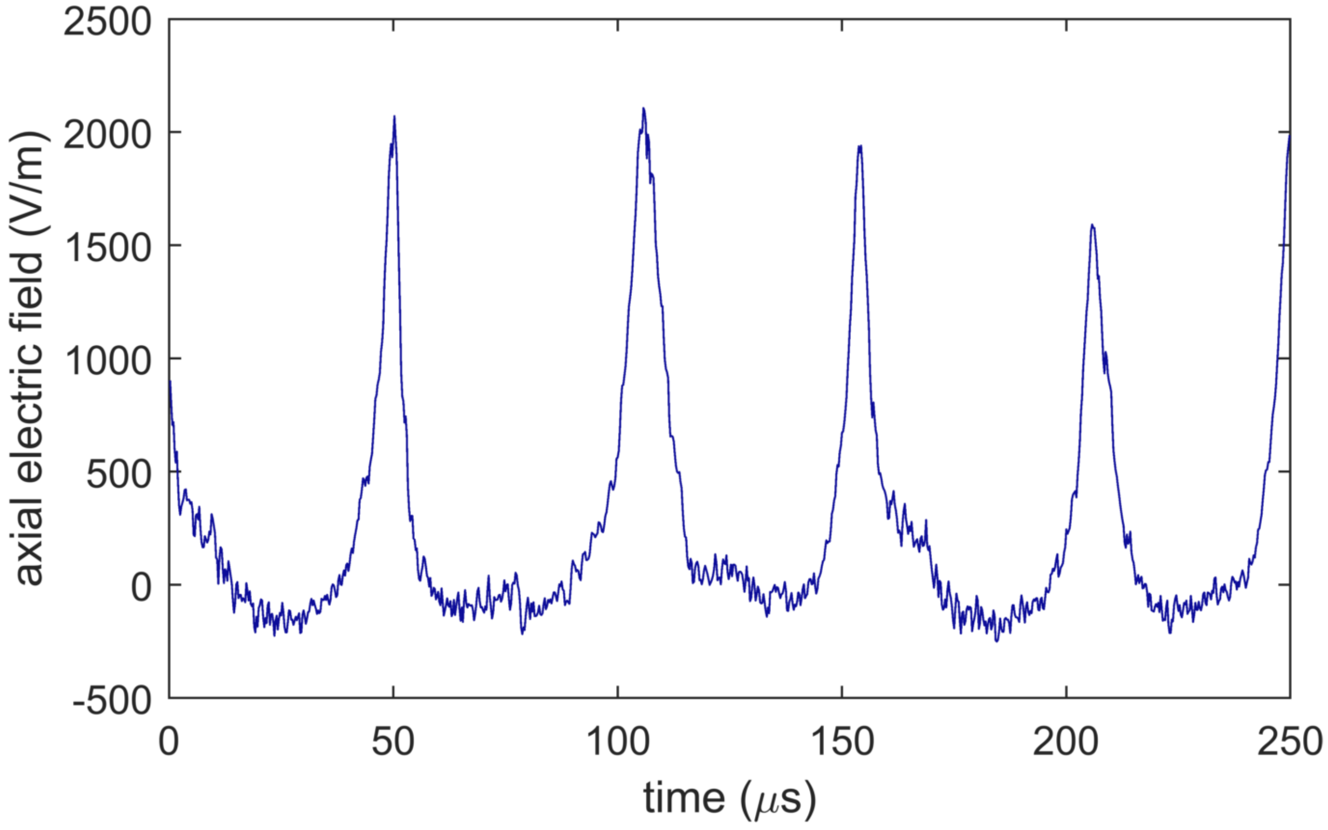


Density variations

Alexandria Mendoza

Matthews et al., *JPP*, 87(6), 2021
Vermillion et al., *PoP*, 29, 2022

Time-varying data from PIC model of PK-4



Electric Field variations


Alexandria Mendoza

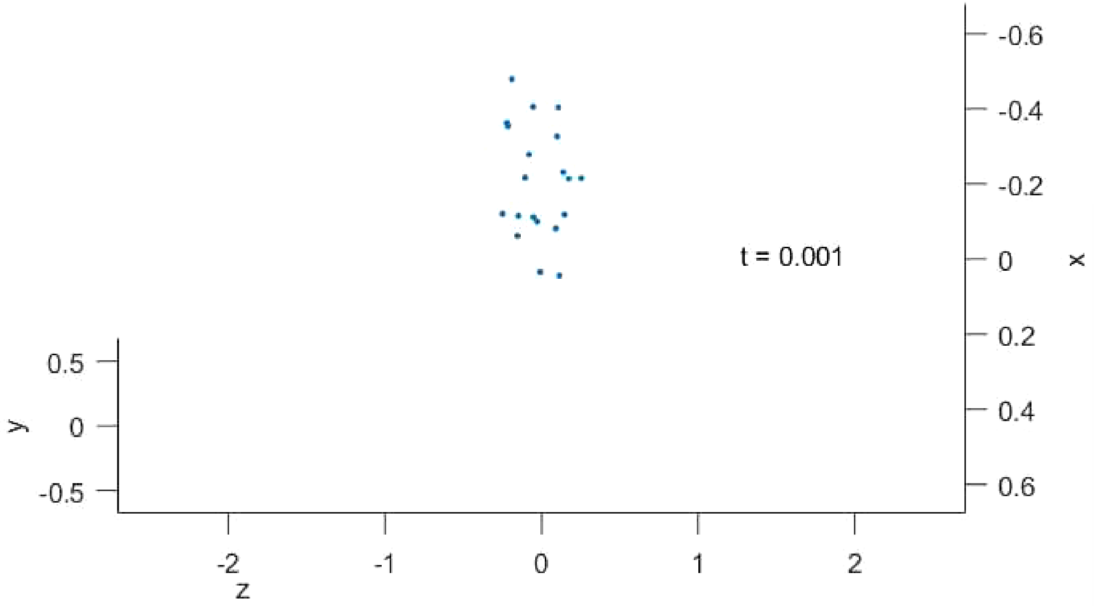

Katrina Vermillion

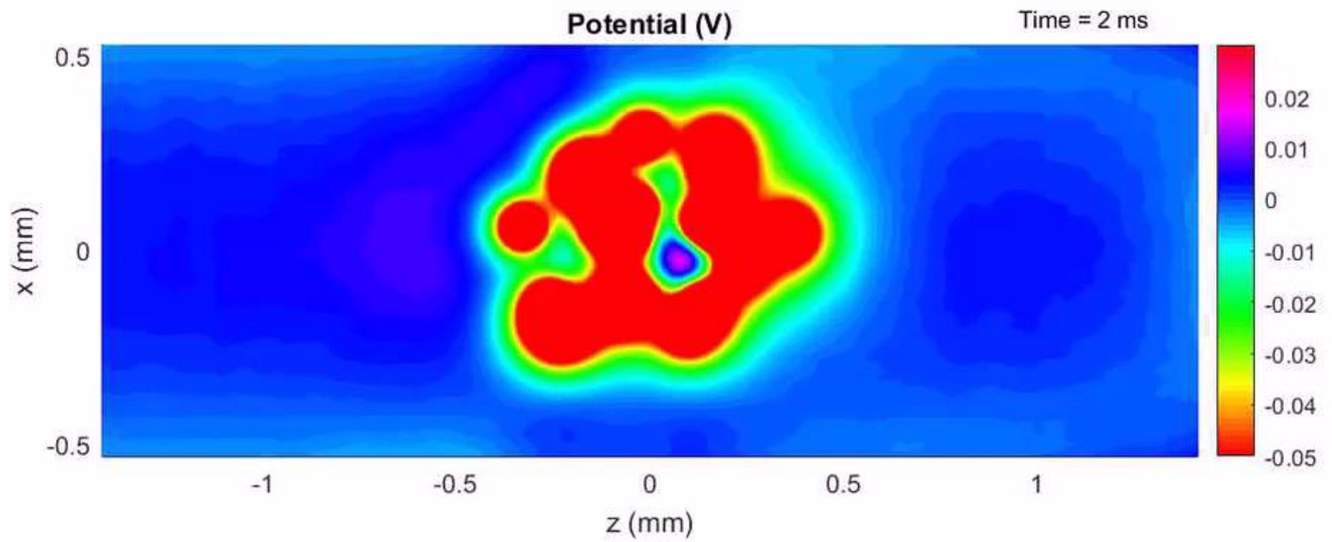

Eva Kostadinova

Matthews et al., *JPP*, 87(6), 2021
Vermillion et al., *PoP*, 29, 2022

CASPER www.baylor.edu/CASPER

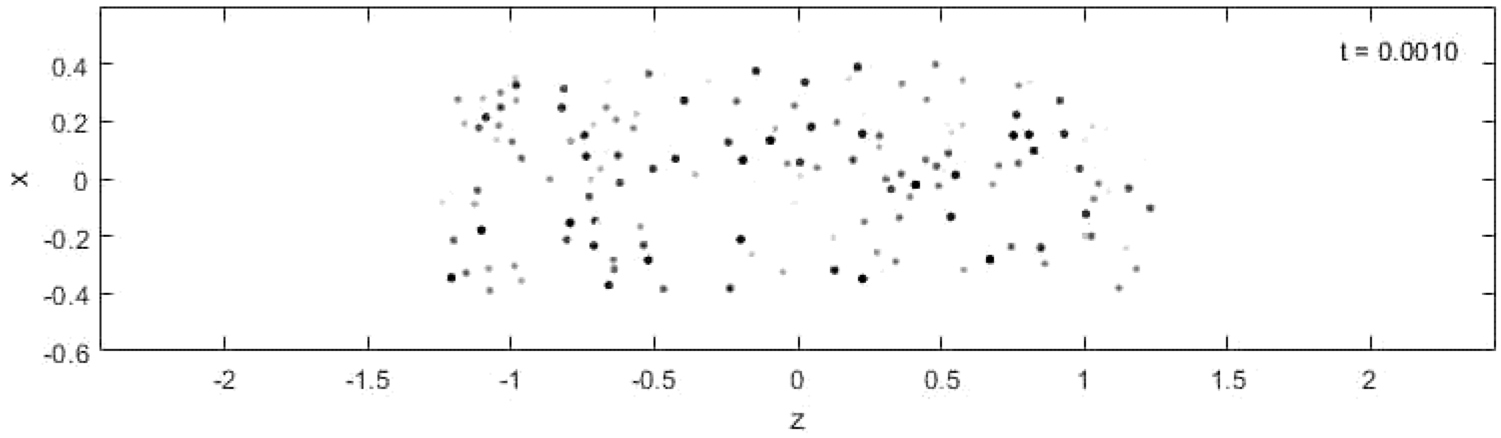
Dust dynamics



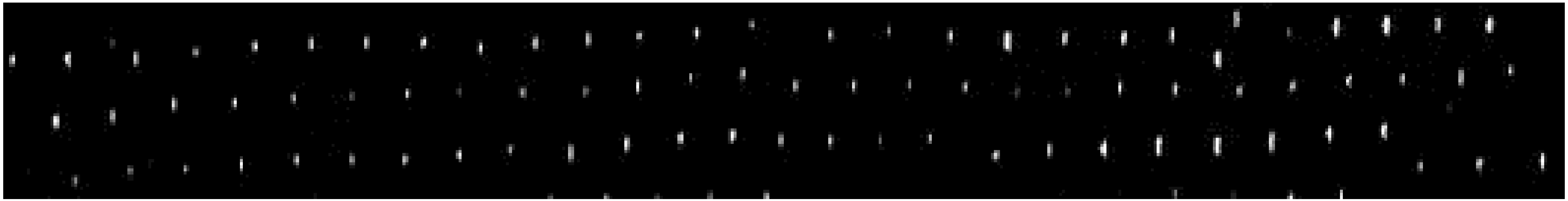


Dust motion in a central slice

Simulation data



Experimental data



ESA / Roscosmos Experiment Plasmakristall-4

Emerson Gehr

Abigail Terrell

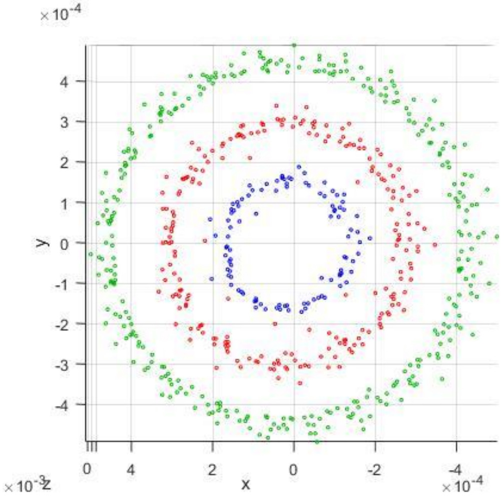
Equilibrium dust structure

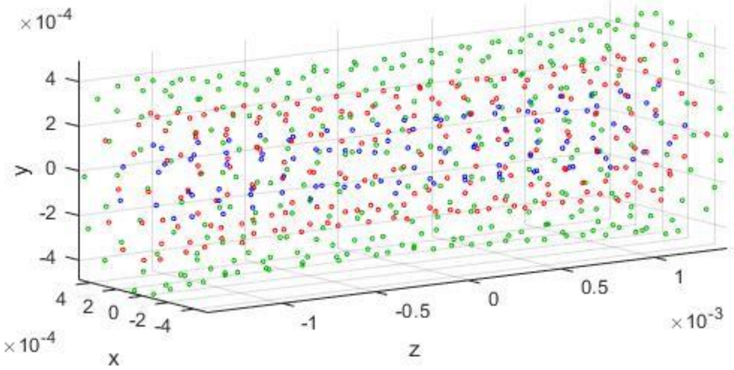
N = 1000 dust particles
a = 1.69 μm

Three nested cylinders

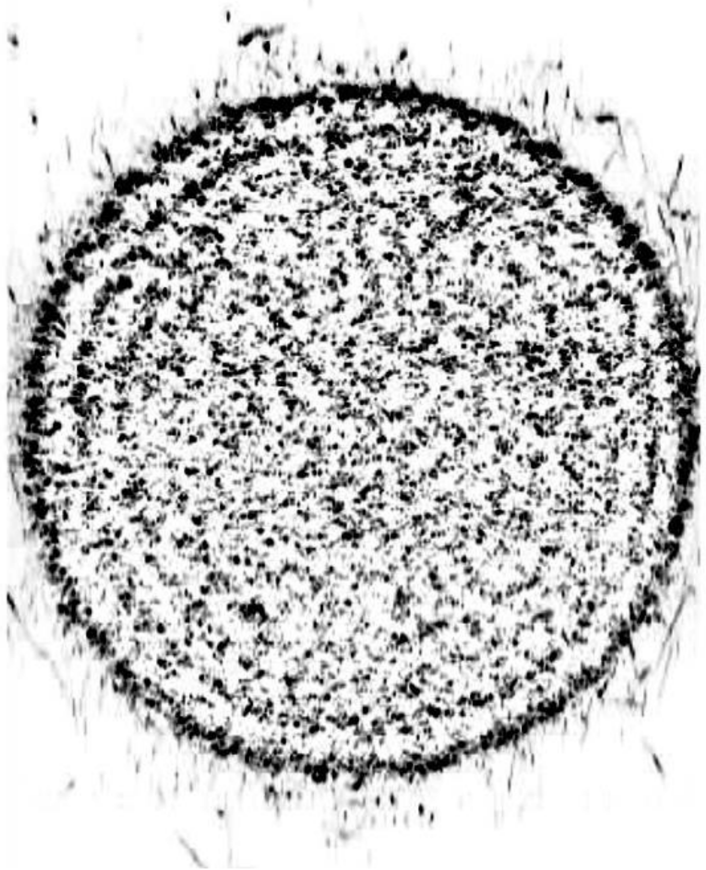
Particles on the ends of cylinder not shown

Simulation data





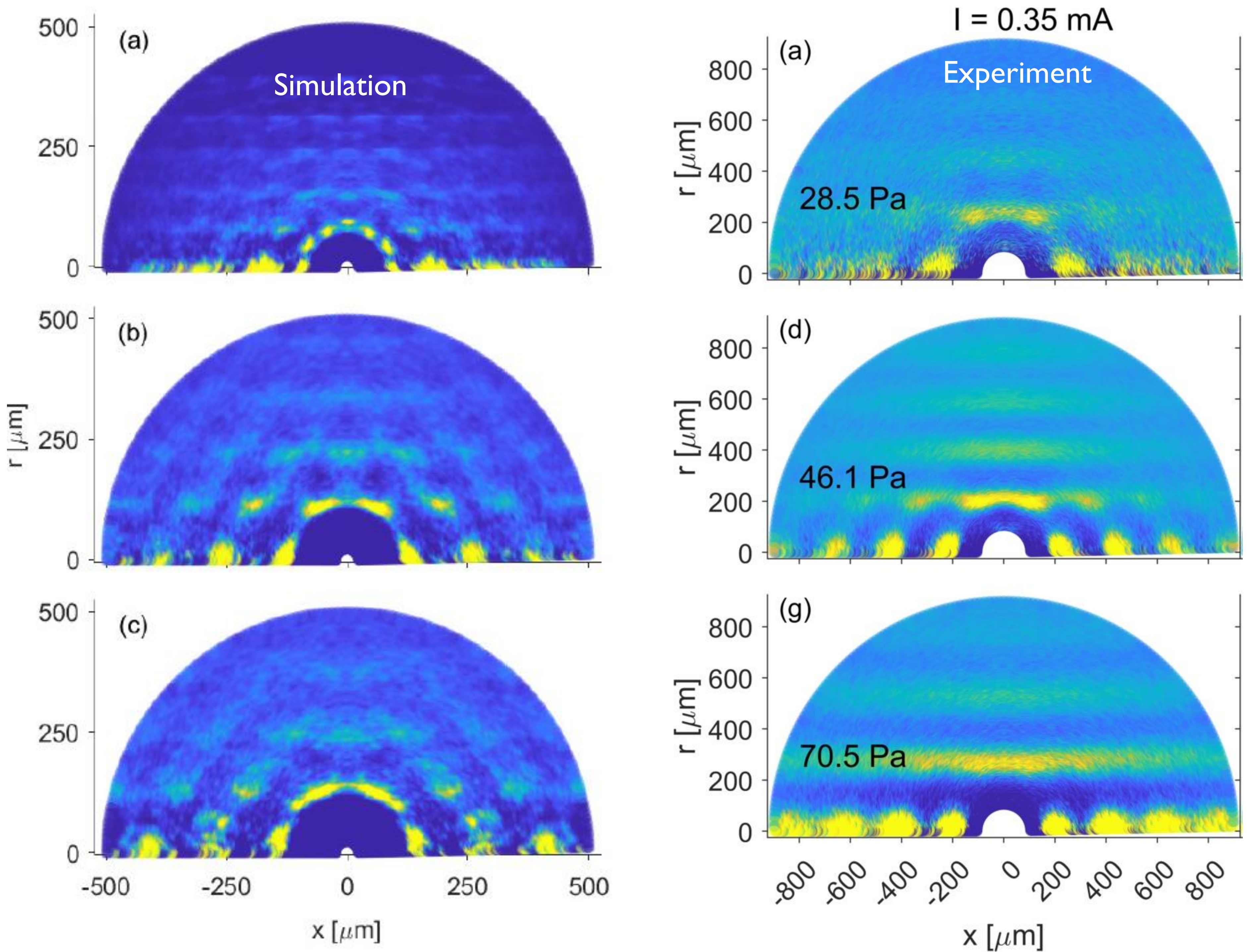
Experimental data



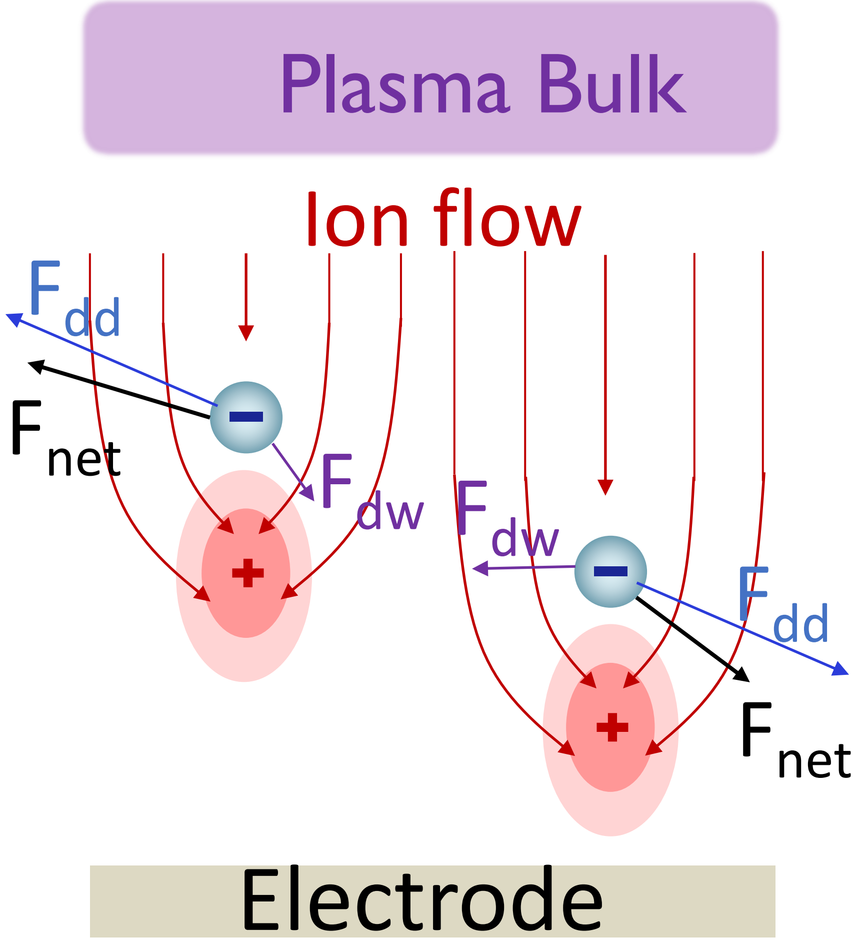
Compare Crystal Order

$G_\phi(r,\theta)$

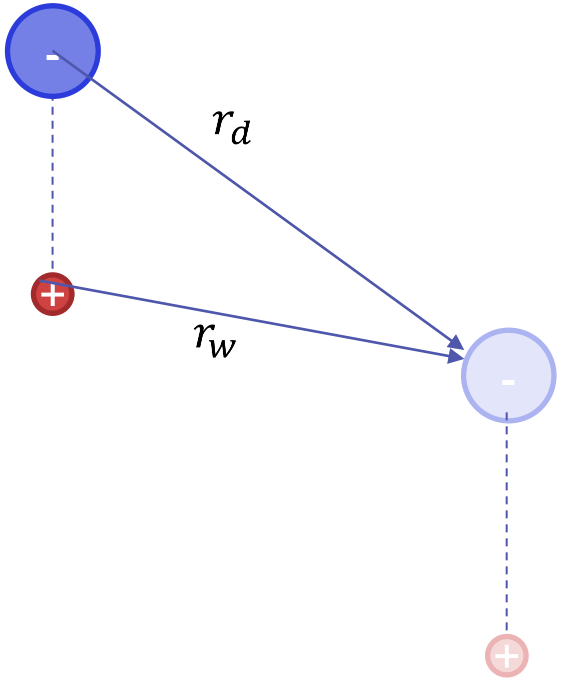
Probability of finding a particle at a given location



Dust-dust interaction: broken symmetry



Point Wake Model

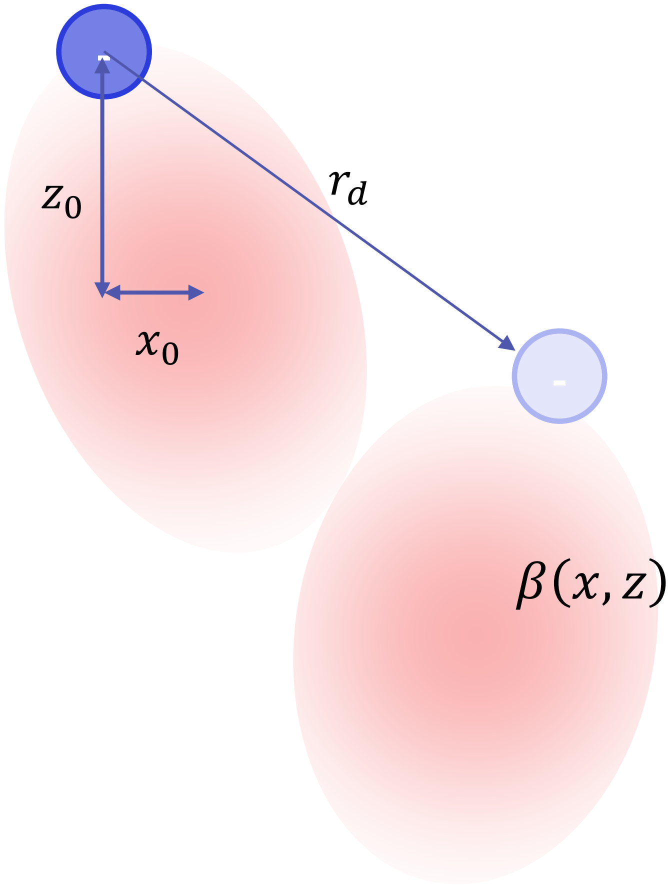


$$\phi = \phi_{dust} + \phi_{wake}$$

$$\phi_{dust} = \frac{Q_d}{4\pi\epsilon_0 r_d} \exp\left(\frac{r_d}{\lambda_D}\right)$$

$$\phi_{wake} = \frac{\alpha Q_d}{4\pi\epsilon_0 r_w} \exp\left(\frac{r_w}{\lambda_D}\right)$$

Gaussian Cloud Wake Model

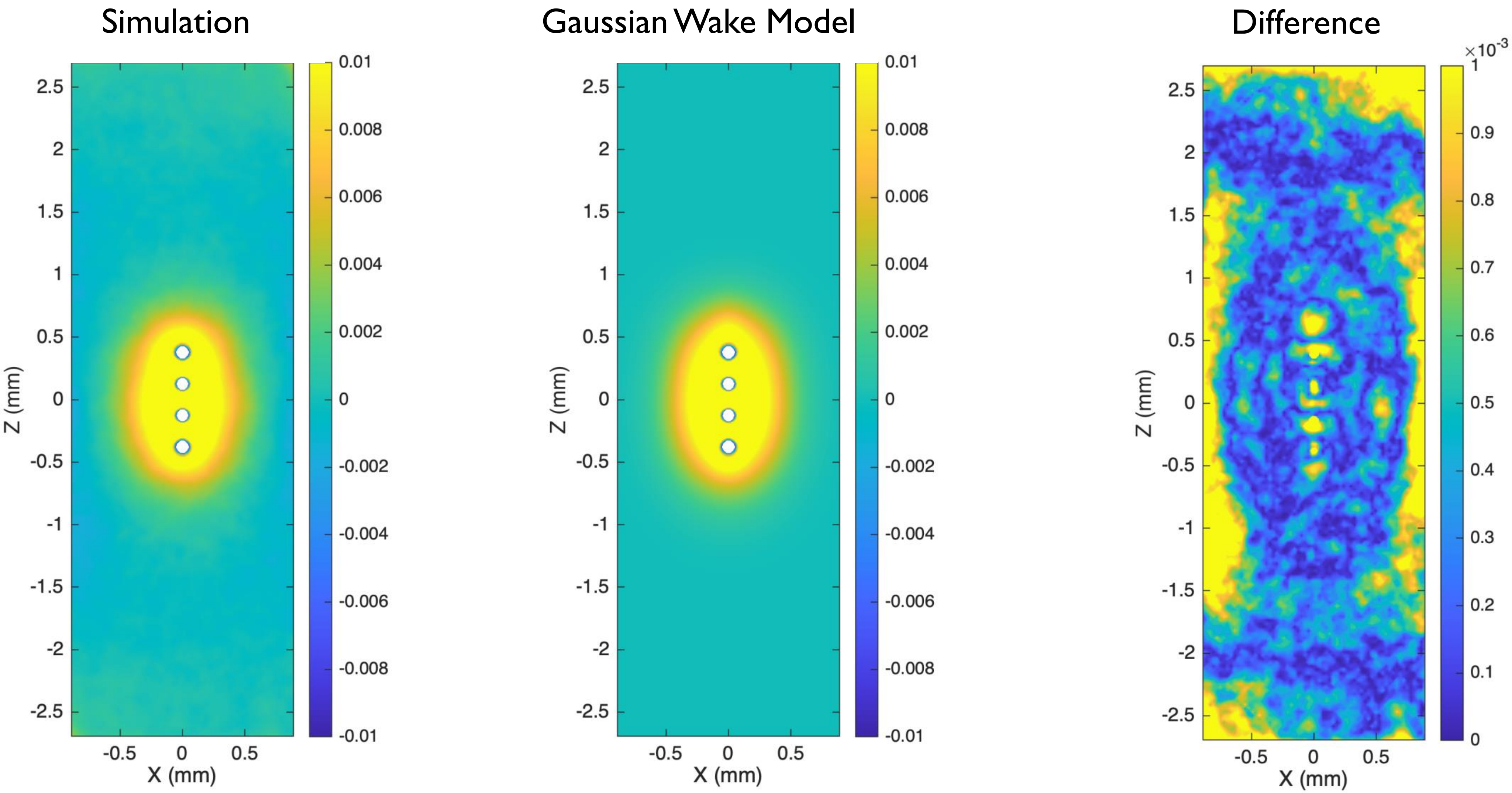


$$\phi = \phi_{dust} + \phi_{wake}$$

$$\phi_{dust} = \frac{Q_d}{4\pi\epsilon_0 r_d}\exp\left(\frac{r}{\lambda_D}\right)$$

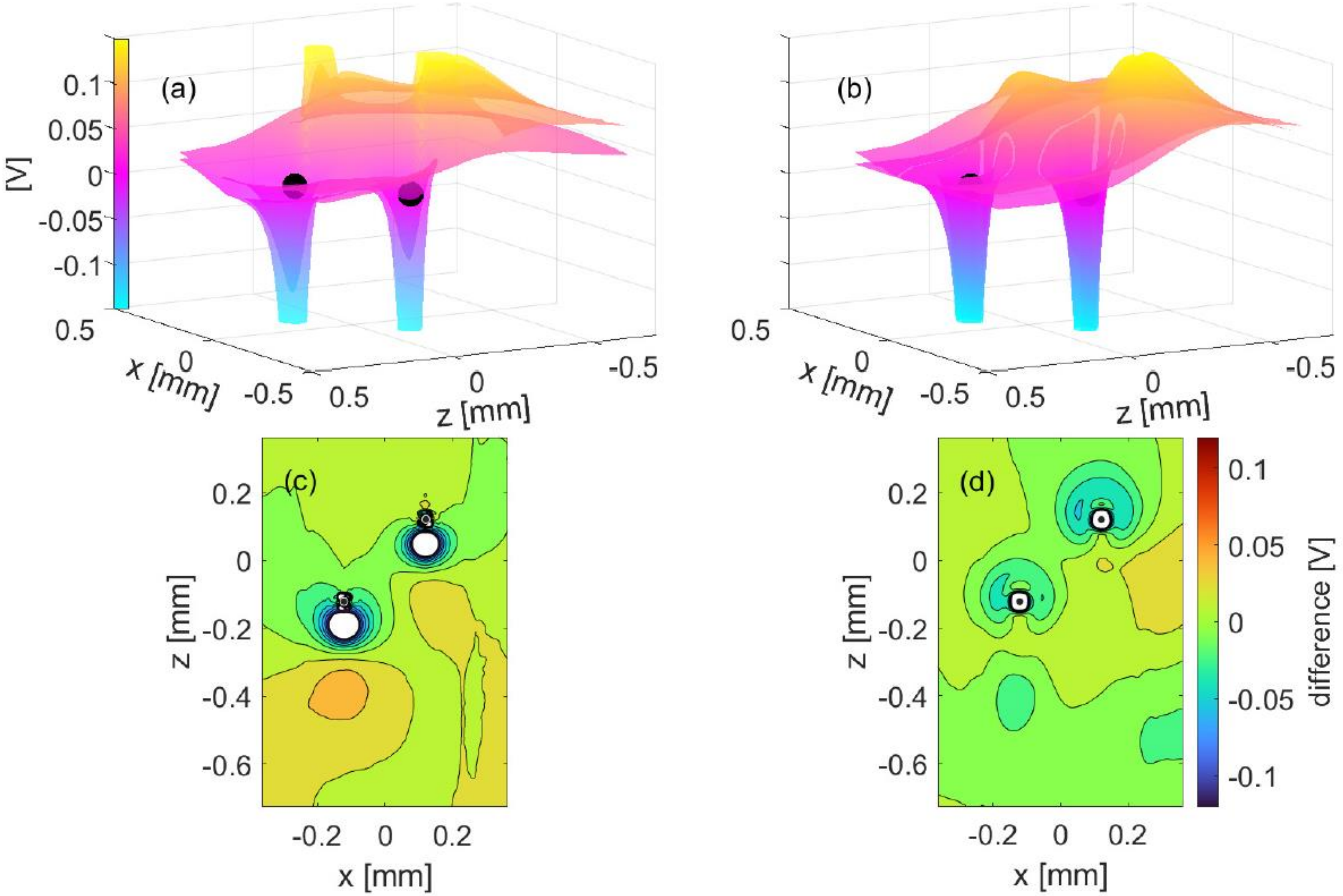
$$\phi_{wake} = \frac{\alpha Q_d}{4\pi\epsilon_0\lambda_{De}M^2}\exp[\beta(x,z)]$$

$$\beta(x,z) = -a(x-x_0)^2 - 2b(x-x_0)(z-z_0) - c(z-z_0)^2$$


Simulation
Gaussian Wake Model
Difference
Z (mm)
X (mm)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0.01
0.008
0.006
0.004
0.002
-0.002
-0.004
-0.006
-0.008
-0.01
×10-3
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

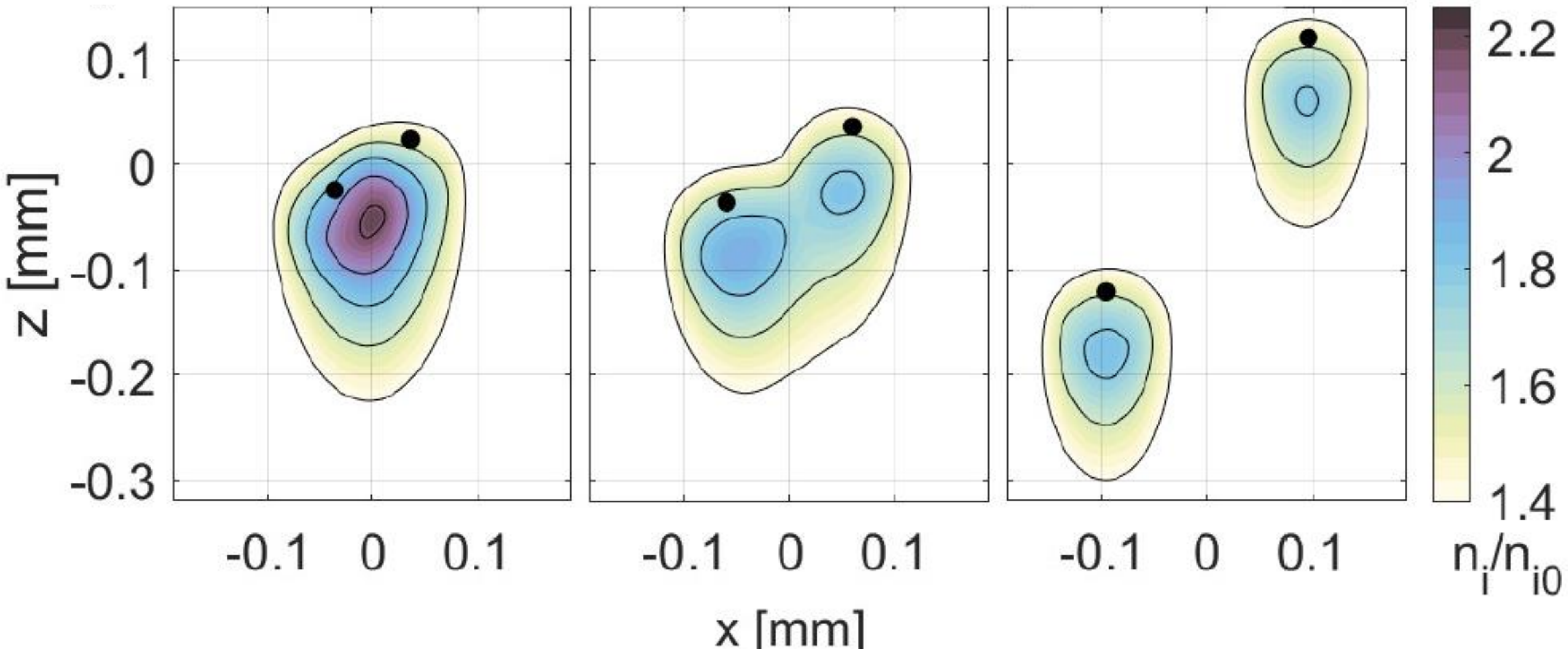
Point Wake Model

Gaussian Cloud Wake Model



Vermillion et al., submitted to PoP, 2024

Ion Wakefield changes based on dust separation



The structure of the universe is wrapped up in the structure of tiny dust particles.

Thank you for your attention!

Time for questions….

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF NASA NVIDIA

This work is supported by NASA grant #1571701, NSF grants PHY-1704023, 1707215, 2308743, DOE grants DE-SC0021334, DE-SC0024681 and NVIDIA Applied Research Accelerator Program.