COMPLEX PLASMAS

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Cassini-Huygens
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"Scientists tend to resist interdisciplinary inquires into their own territory"

HANNES ALFVÉN

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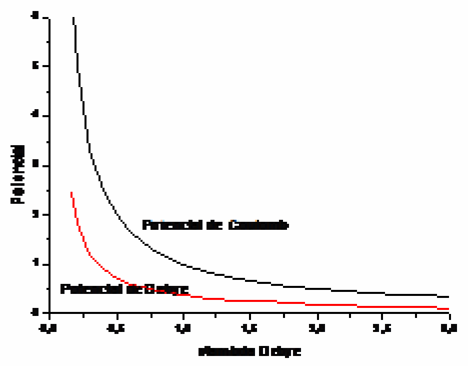
Plasmas: Basic Parameters

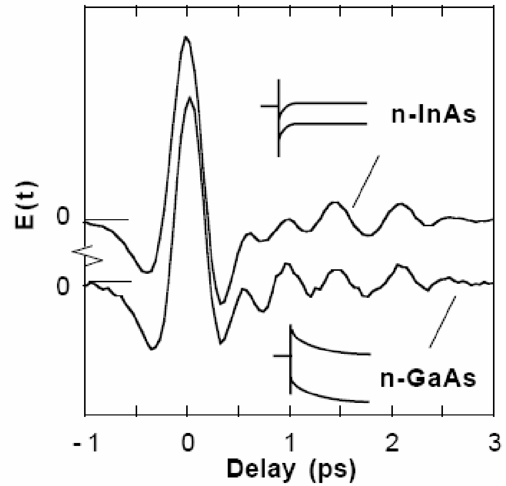


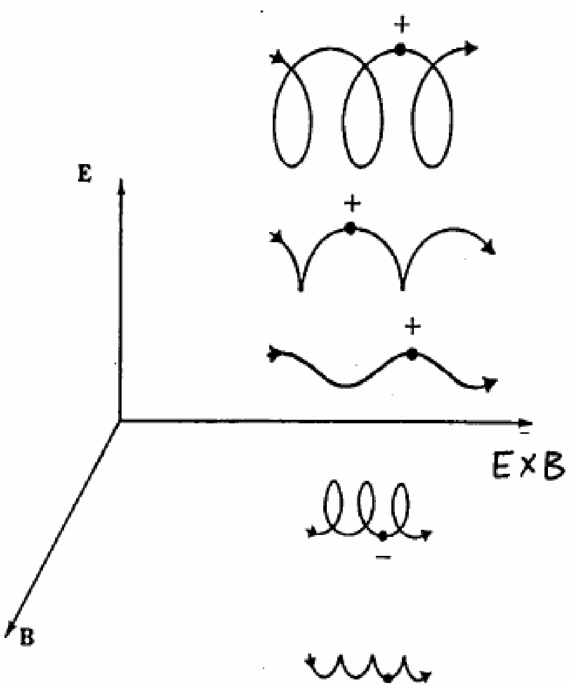
$$\phi(r) = \frac{q_t}{4\pi\varepsilon_0 r} e^{-\sqrt{2}\frac{r}{\lambda_D}}$$

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{ne^2}}$$

$$\omega_p = \sqrt{\frac{ne^2}{m_e \varepsilon_0}}$$

$$f_p(MHz) = 9 \times \sqrt{n(m^{-3})}$$





$$\vec{v}_D = \frac{\vec{F} \times \vec{B}}{qB^2}$$

Classical and Strong Coupled Plasmas

Plasma parameter

$$g \equiv \frac{1}{n\lambda_D^3} << 1$$

Measure of the relevance of collective effects

Coupling parameter

$$\Gamma \equiv \frac{q^2}{4\pi\varepsilon_0 d(k_B T)}$$

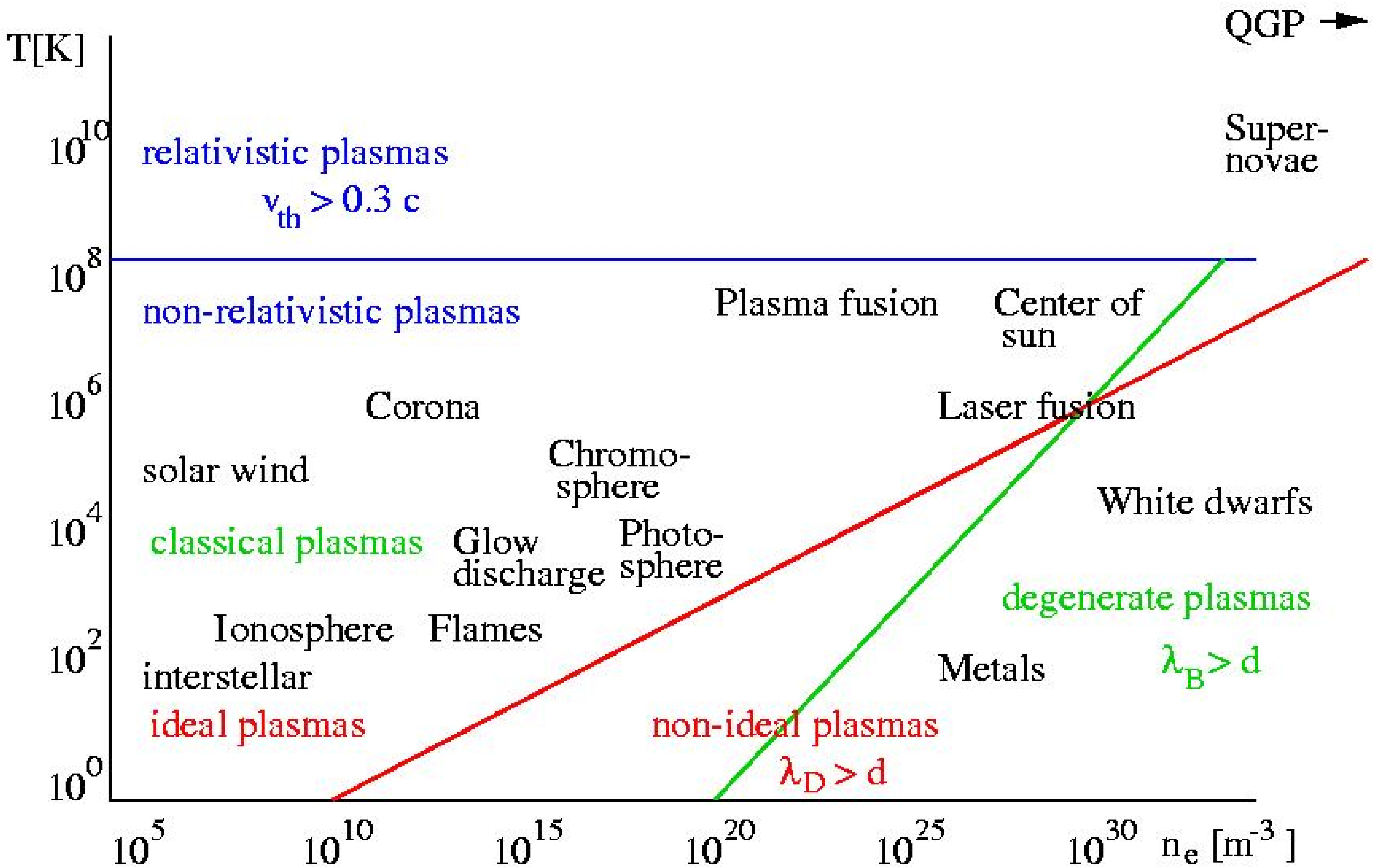
Measure of the "strenght" of closed particle interactions

Ideal plasmas: g << 1, Γ << 1 (most plasmas: Γ < 10^{-3}; pure electron - ion)

Strongly coupled plasmas: Γ > *O* (1)

Γ > 172 Coulomb crystal

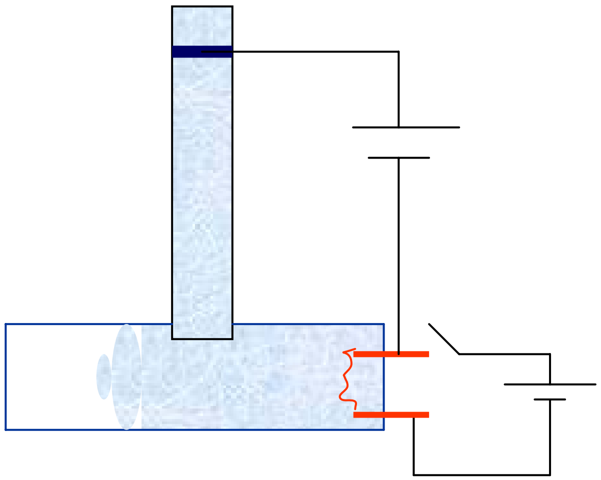
Plasma Characteristics Dependent Mainly on Density and Temperature



Complex (Dusty) Plasmas

Irving Langmuir (1924)
[I. Langmuir, C.G. Found, A.F. Detmer; Science 60, 392 (1924)]

Investigation of Argon discharge in pirex tube (p = 2 – 4 Torr)



Cathode heating circuit interrupted by 0.5s

↓

Decreased electron emission from cathode

↓

Voltage across the arc increased

↓

Sputtered Tungsten "globules" from cathode entered the plasma

"phenomena of remarkable beauty which may prove of theoretical interest"

"The globules must get negatively charged, dressed by a cloud of positive charges"

What is a dusty plasma?

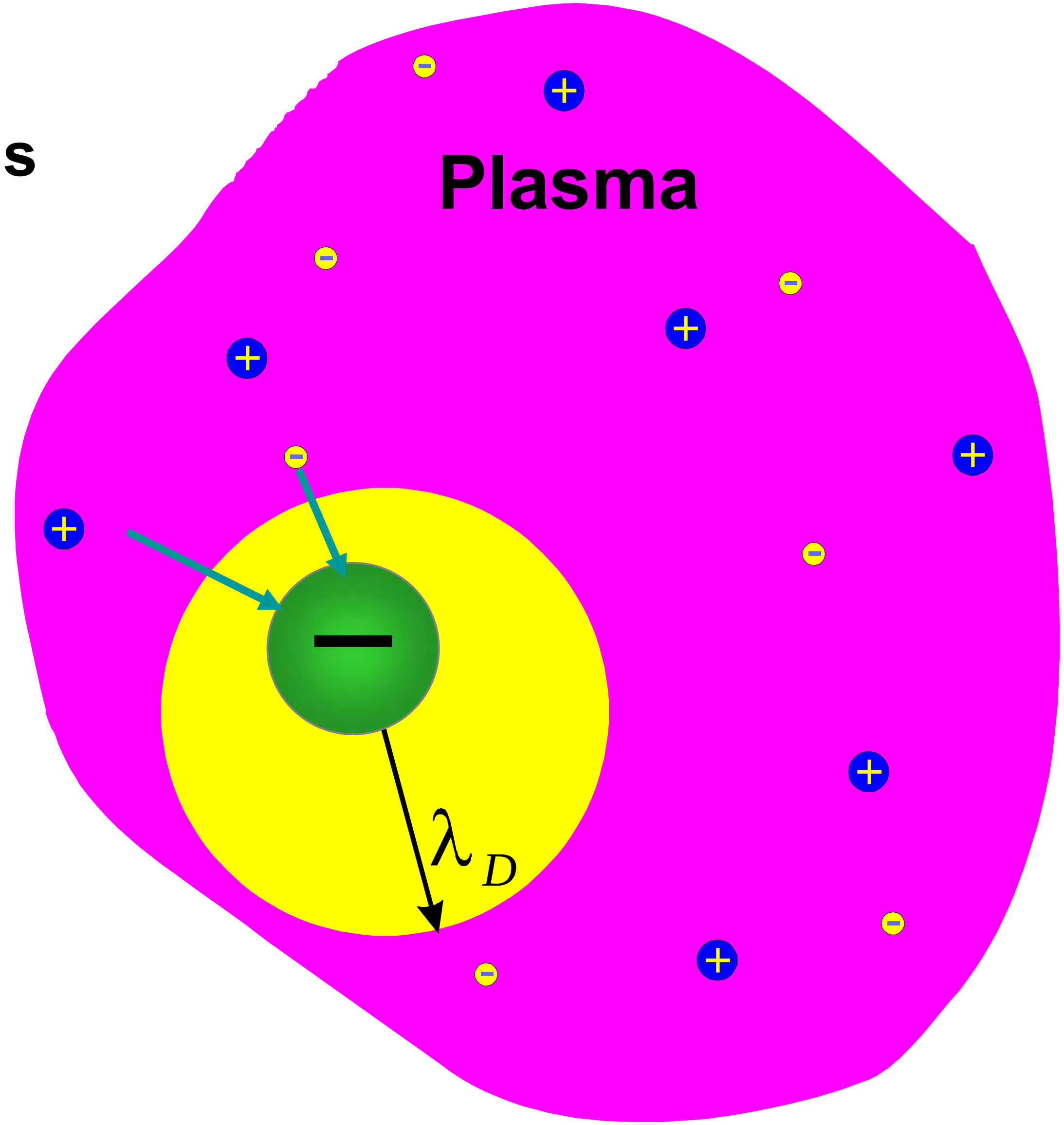
plasma = electrons + ions

small particle
of solid matter

- absorbs electrons and ions

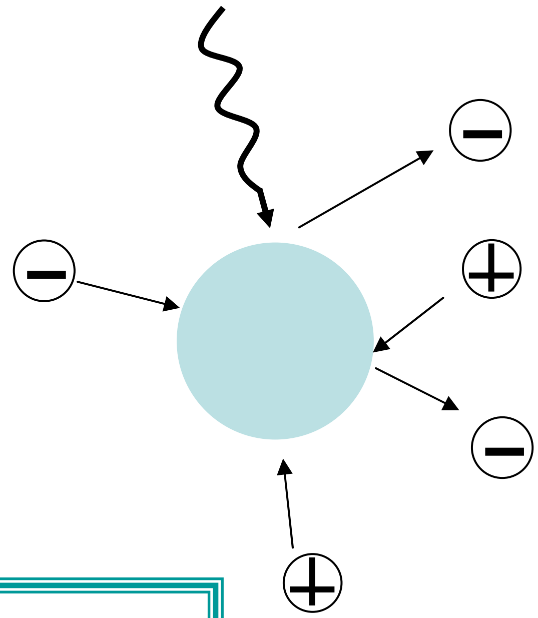
- becomes negatively charged

- Debye shielding



Dust Charging Processes

- electron and ion collection
- secondary emission
- UV induced photoelectron emission



Total current to a grain = 0

$$\Sigma I = I_e + I_i + I_{sec} + I_{pe} = 0$$

The Charge on a Dust Grain

In typical lab plasmas $I_{sec} = I_{pe} = 0$

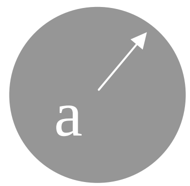
Electron thermal speed >> ion thermal speed so the grains charge to a negative potential V_S relative to the plasma, until the condition $I_e = I_i$ is achieved.

$$I_e = en_e\sqrt{\frac{kT_e}{m_e}}\ \exp\left(\frac{eV_S}{kT_e}\right)\ \pi a^2$$

electron repulsion

$$I_i = en_i\sqrt{\frac{kT_i}{m_i}}\left(1-\frac{eV_S}{kT_i}\right)\ \pi a^2$$

ion enhancement



$Q = (4\pi\varepsilon_o a)\ V_S$

Typical Laboratory Plasma

For $T_e = T_i = T$ in a hydrogen plasma

$V_S = -2.5\,(k_B T/e)$

If $T \approx 1$ eV and $a = 1\ \mu$m,

$Q \approx -2000\ e$
Mass $m \approx 5 \times 10^{12}\ m_p$

Affect coupling parameter,

$\Gamma \sim Q^2$

but not much plasma parameter of background

System still exibts collective behavior of classical plasmas, such as instabilities, but may become "strongly coupled"

Who cares about dusty plasmas?

Solar system

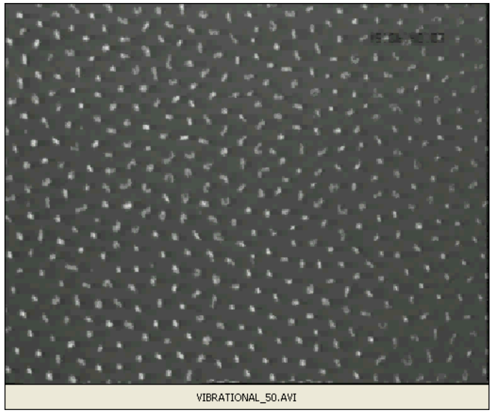
- Rings of Saturn
- Comet tails
- Planetary formation

Manufacturing

- Particle contamination
  (Si wafer processing)
- Nanomaterial synthesis

Basic physics

- Coulomb crystals
- Waves
- Much more ...



Growth of the Area

<u>Astrophysics</u>: observation of spokes in Saturn's B Ring

[B.A. Smith et al.; Science <u>215</u>, 504 (1982)]

<u>Microelectronic Industry</u>: realization that contamination of semiconductor materials in plasma processing tools due to particles grown in the plasma.

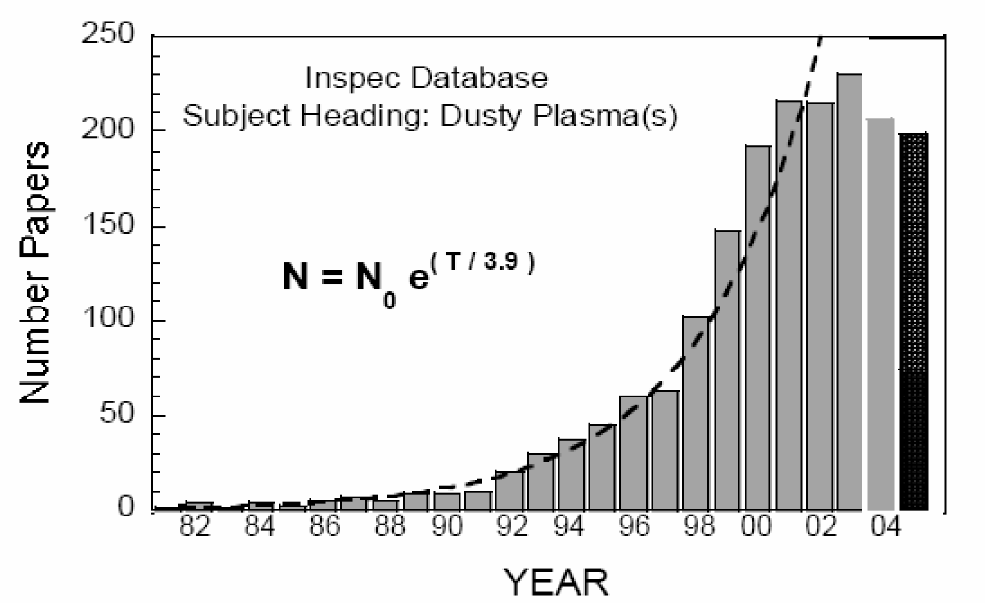
[G.S, Selwyn, J.E. Heidenreich, K.L. Haller; Appl. Phys. Lett. <u>57</u>, 1878 (1990)]

<u>New Physics</u>: dust-acoustic waves, plasma crystals, and non-gaussian statistics (More is Different !)

[N.N. Rao, P.K. Shukla, M.Y. YU; Planet. Sci. <u>30</u>, 543 (1990)]

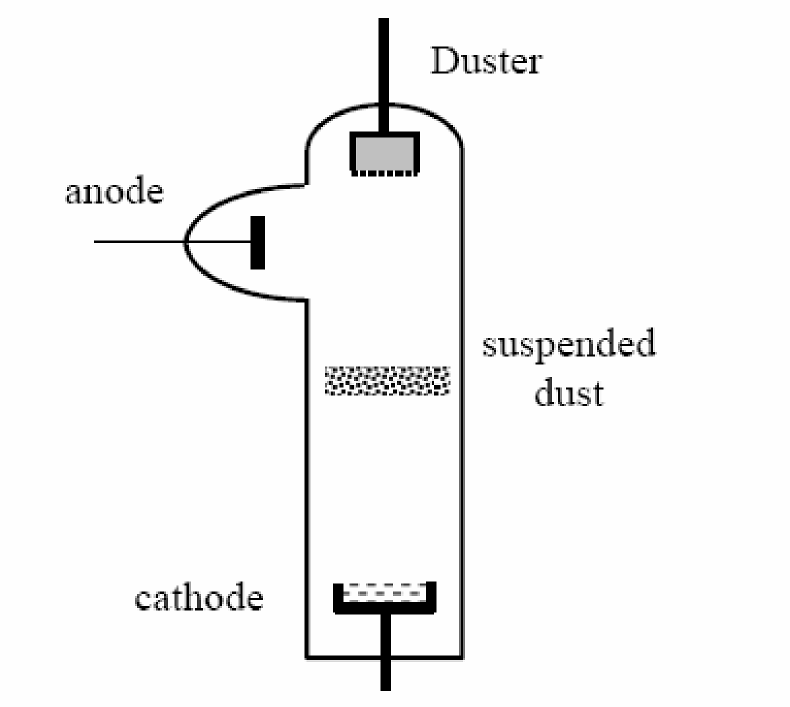
[J.H. Chu, Ji-Bin Du, I. Lin; J. Phys. D: Applied Phys. <u>27</u>, 296 (1994)]

[B. Liu, J. Goree; Phys. Re. Lett. <u>100</u>, 055003 (2008)]



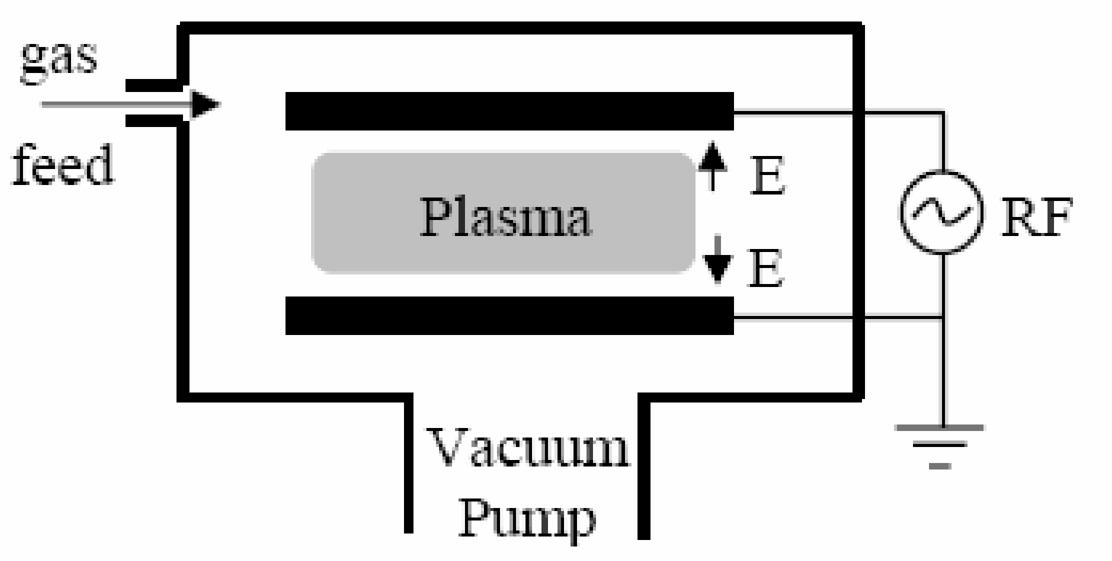
Dusty Plasma Production

Glow Discharge



RF Produced Plasma

(GEC Reference Cell)



[V.E. Fortov et al;

Phys. Lett. A 229, 317 (1999)]

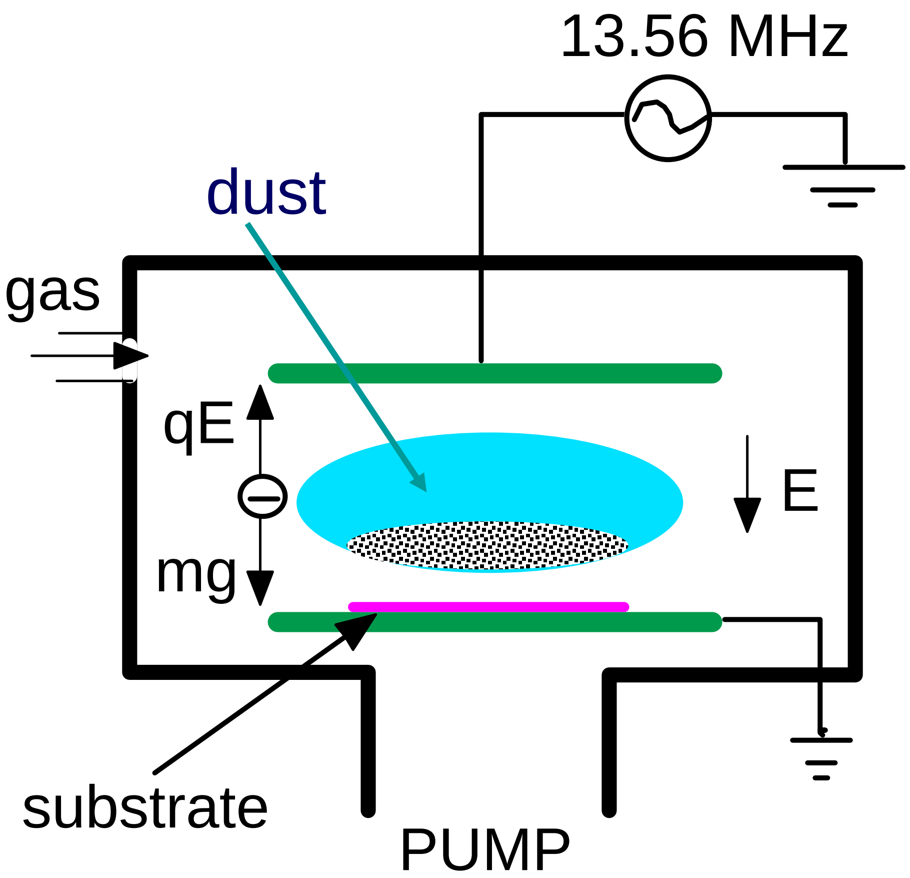
Dust: kaolin (1 – 15 μm)

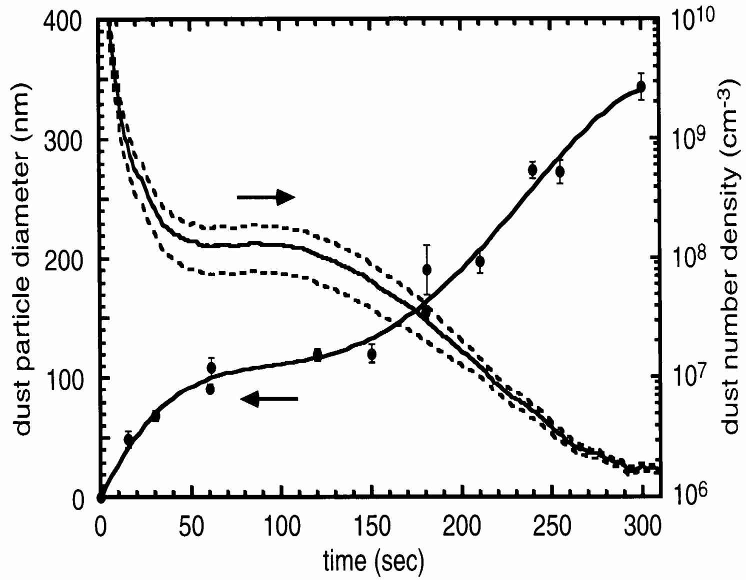
Device where formation of plasma crystals first observed ($SiH_4/O_2/Ar$ or graphite elect.)

[J.H. Chu et al; Phys. Rev. Lett. 72, 4009 (1994)]

[H. Thomas et al; Phys. Rev. Lett. 72, 652 (1994)]

Semiconductor Processing System





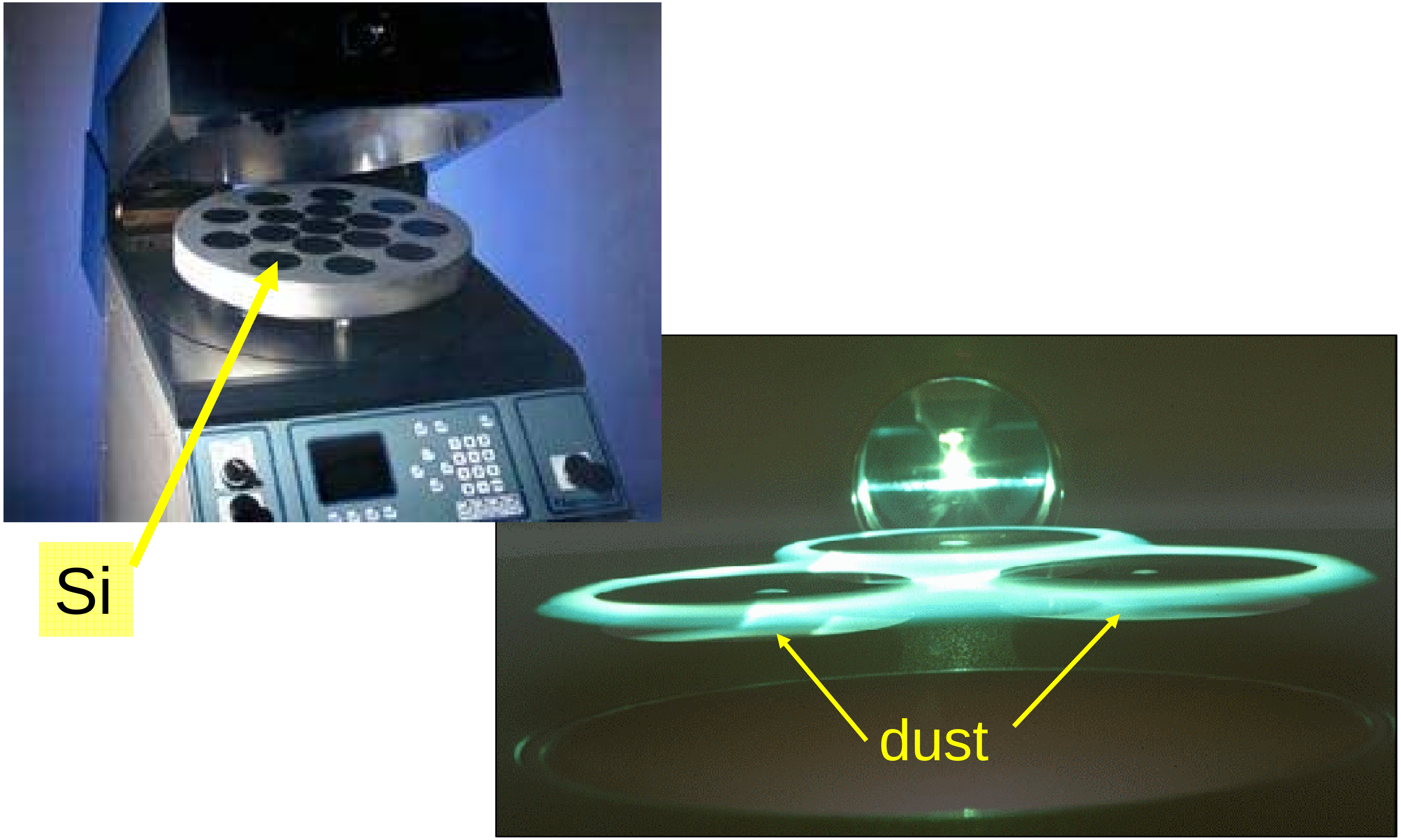
silane (SiH_4) + Ar + $O_2 \rightarrow$ SiO_2 particles

Dusty Plasma Production

Auburn Dusty Plasma Experiment

3 micron particles
illuminated by a He-Ne laser

Semiconductor Manufacturing



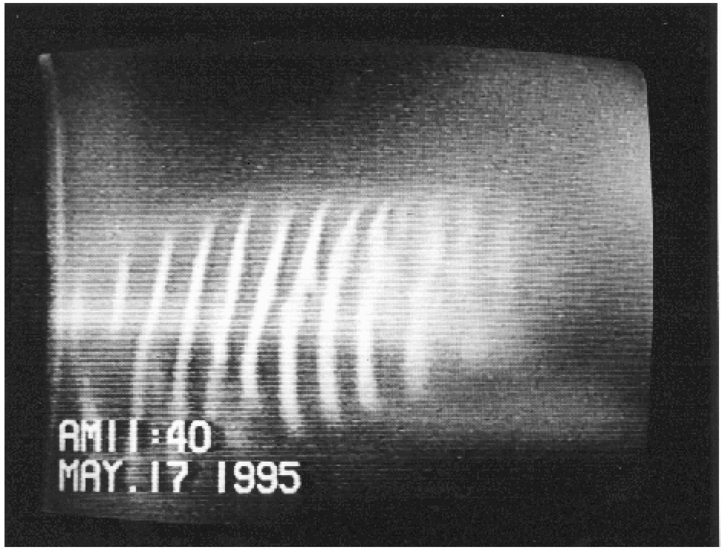
Dust – Acoustic Wave

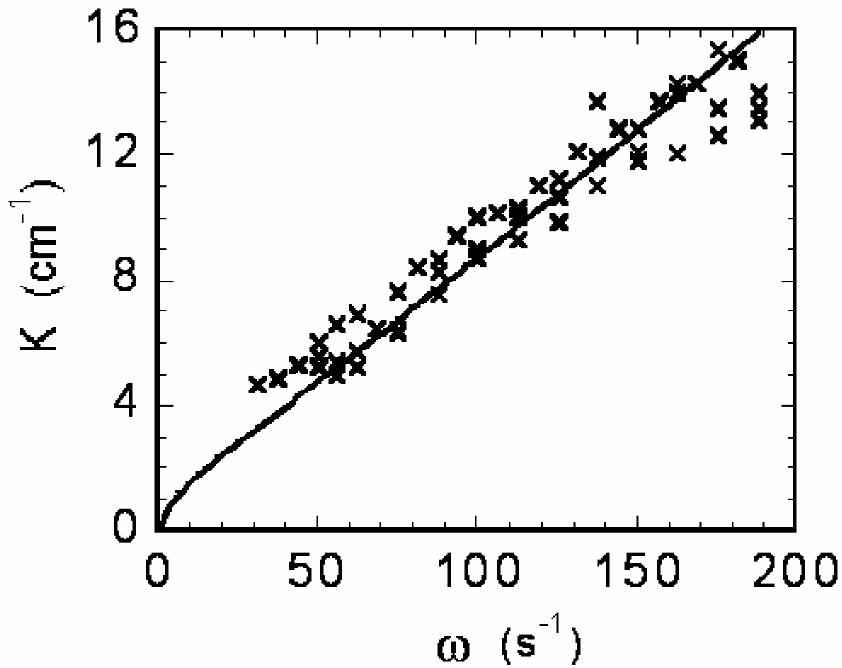
Monochromatic plane wave solutions for $T_e = T_i = T$

$$f\lambda = C_{DA} = \sqrt{\frac{kT}{m_d} Z_d \frac{1-\delta}{1+\delta}}$$

dust mass

where $d = n_{do}/n_{+o}$





Dust – Acoustic Wave

Plasma crystal “melting”
by dust-acoustic wave shock
and recrystalization

Important Recent Results

Dust particles drive a new type of Magnetorotational Instability, relevant for the accretion disk of protostars
[A. B Mikhailovskii et al; Phys. Plasmas 15, 014504 (2008)]

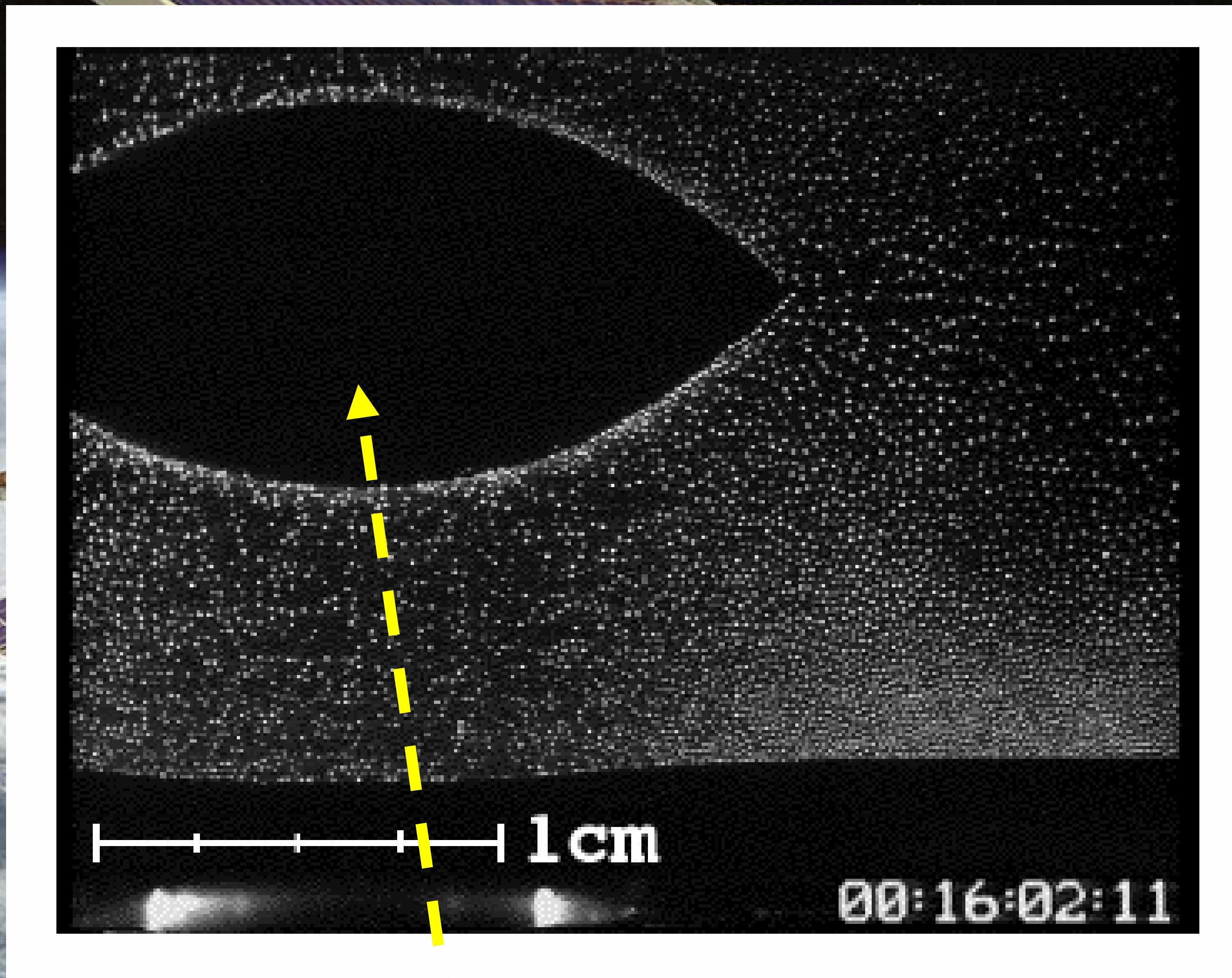
Dusty plasmas will play a fundamental role at the plasma – wall interface of fusion reactors
[A.Y. Pigarov et al; Phys.Plasmas 12, 122508 (2005)]

Three dimensional dusty plasmas formed in the absence of gravity show "ion – drag" voids
[A.P. Nefedov et al; New Journal of Phys. 5, 33.1 (2003)]

Super diffusion and non – Gaussian statistics observed in a 2-D dusty plasma
[B. Liu and J. Goree; Phys. Rev. Lett. 100, 055003 (2008)]

Dusty plasma experiments carried out in micro-gravity in the International Space Station

[A.P. Nefedov et al; New Journal of Phys. 5, 33.1 (2003)]



Region with plasma but no dust particles

Super diffusion and non – Gaussian statistics in 2-D dusty plasma

[B. Liu and J. Goree; Phys. Rev. Lett. 100, 055003 (2008)]

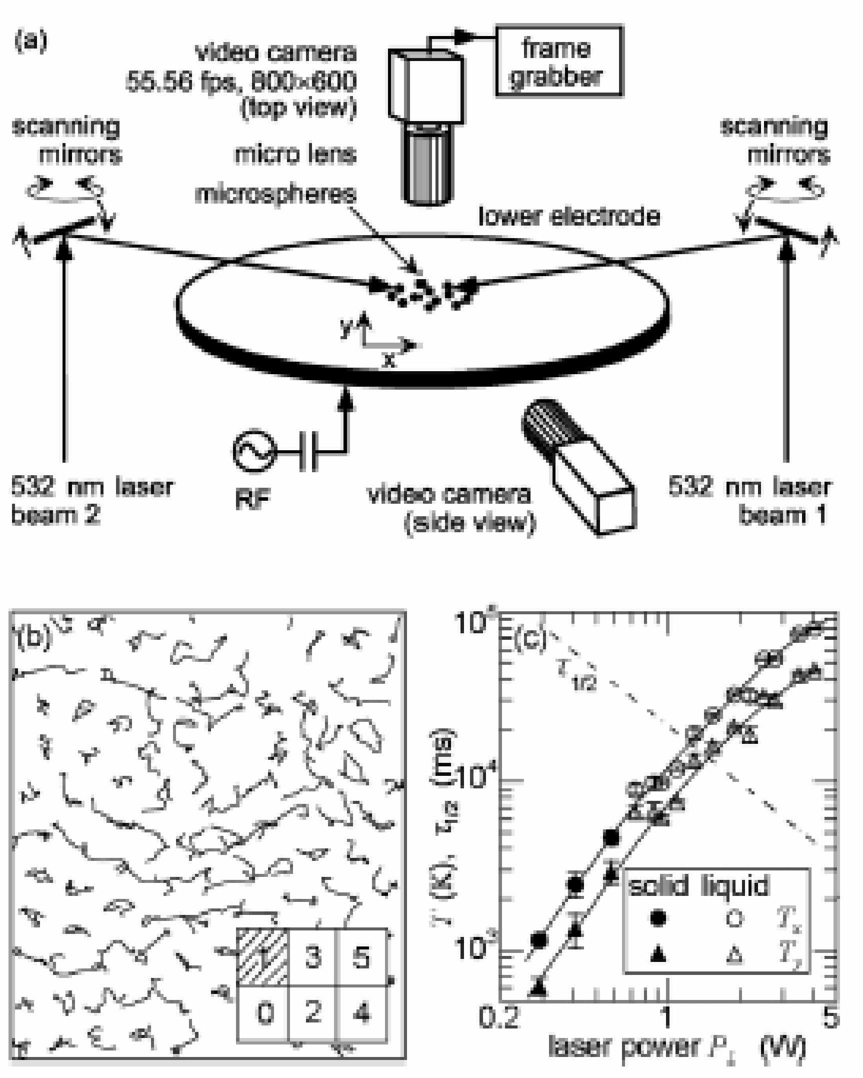
- Single-layer dusty plasma
- Yukawa interaction
- Fricitonal dissipation
- Laser radiation pressure heating

Mean-square displacement - MSD

$$\left\langle \left[x(\Delta t) - x(0)\right]^2 \right\rangle$$

Probability Distribution Function – PDF: histogram of

$$\left| x(\tau) - x(0) \right|$$

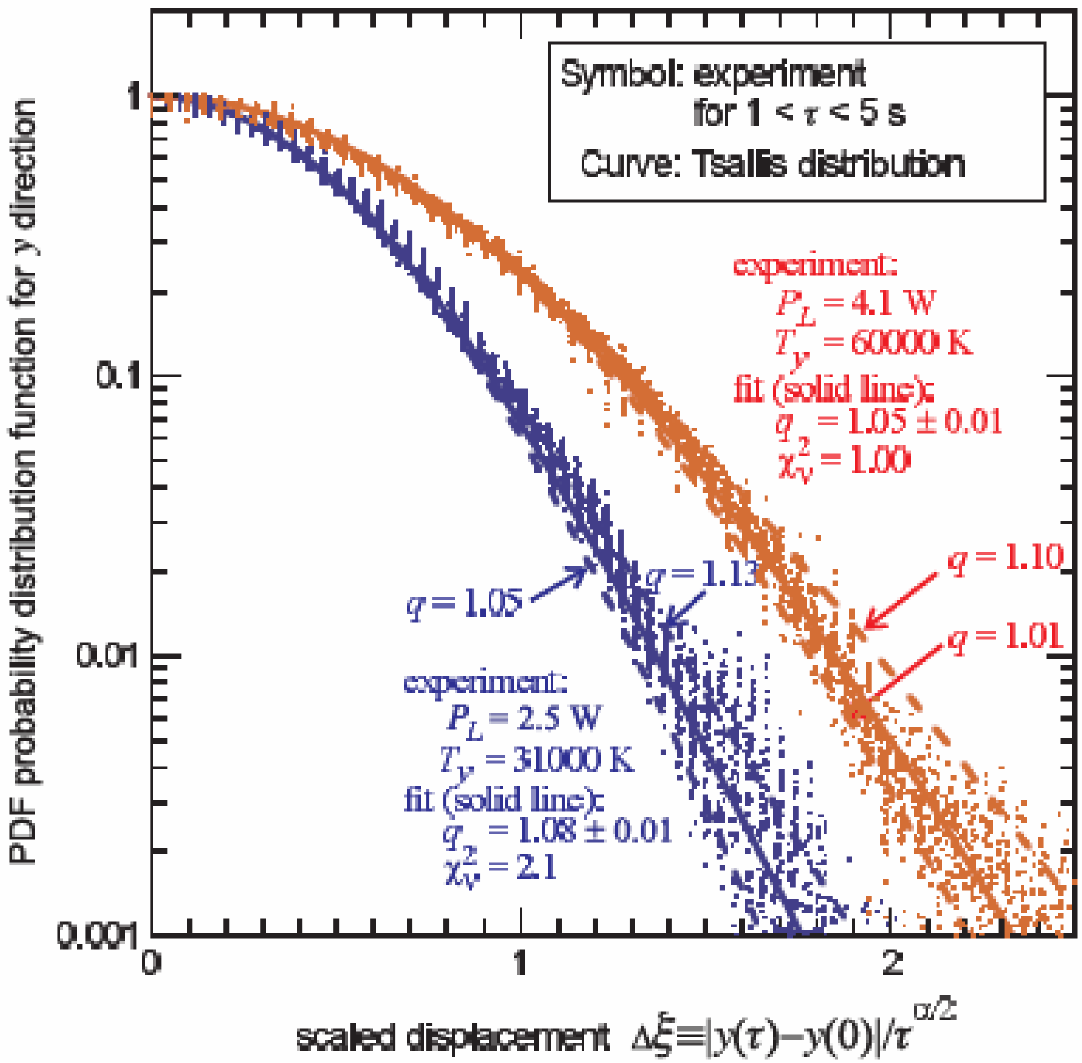


Super diffusion and non – Gaussian statistics in 2-D dusty plasma

[B. Liu and J. Goree; Phys. Rev. Lett. 100, 055003 (2008)]

Tsallis distribution for a random variable

$$\left[1-\beta(1-\boldsymbol{q})\boldsymbol{z}^{2}\right]^{1/(1-\boldsymbol{q})}$$



Research Program

- Investigate effect of magnetic field in dusty plasmas (rotational instability)
- Investigate models based upon non – extensive statistical mechanics to describe relevant processes in complex plasmas
- Start an experimental program to investigate complex plasmas, both from the perspective of basic physics as for nano fabrication

"We have to learn again that science without contact with experiments is an enterprise which is likely to go completely astray into imaginary conjecture"

HANNES ALFVÉN

Research Program

RF Plasma Device – Laboratory of Plasma Applications