Charging of nanograins in cold dusty plasmas: from noctulescent clouds to Enceladus plume and cometary environments

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Nano grains

- What are they?
- Where are they found?
- What makes them different?
- How are they charged in cold plasmas?
- … and in dusty plasmas

What are they?

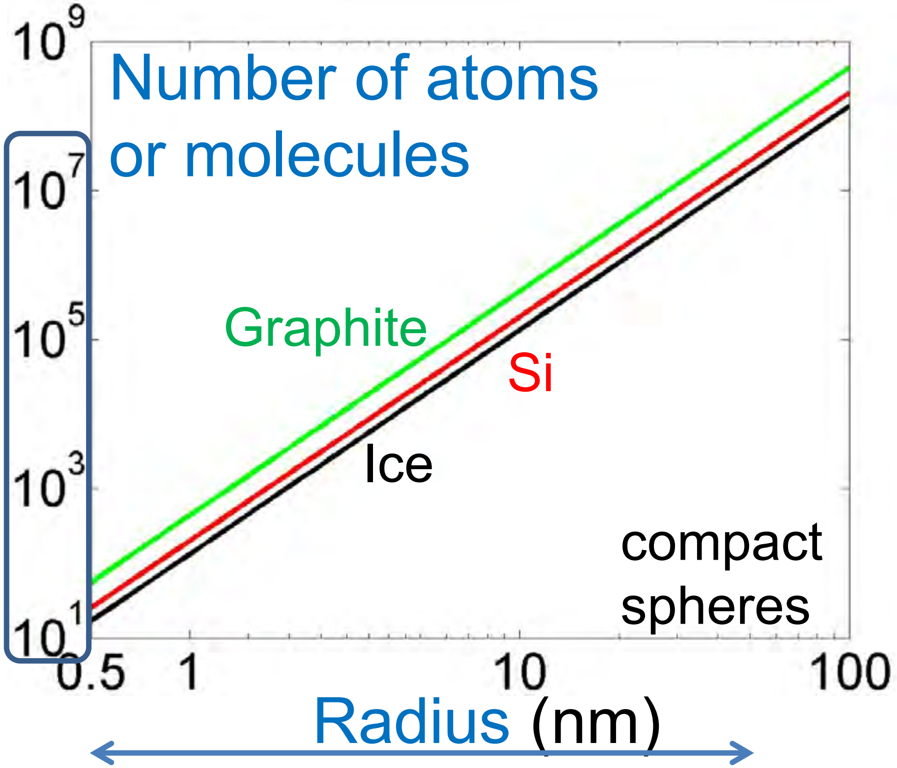
- **Original definition of a nanoparticle:** a particle that consists of a countable number of atoms

What are they?

- Size

International Council of Chemical Associations

ISO TS 27687 **Nano-object**: has at least one external dimension between 1 and 100 nm

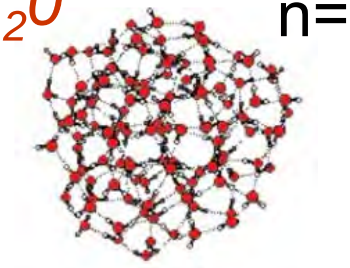


What are they?

- *The size may determine the structure*

Cluster of H_20 molecules

disordered structure



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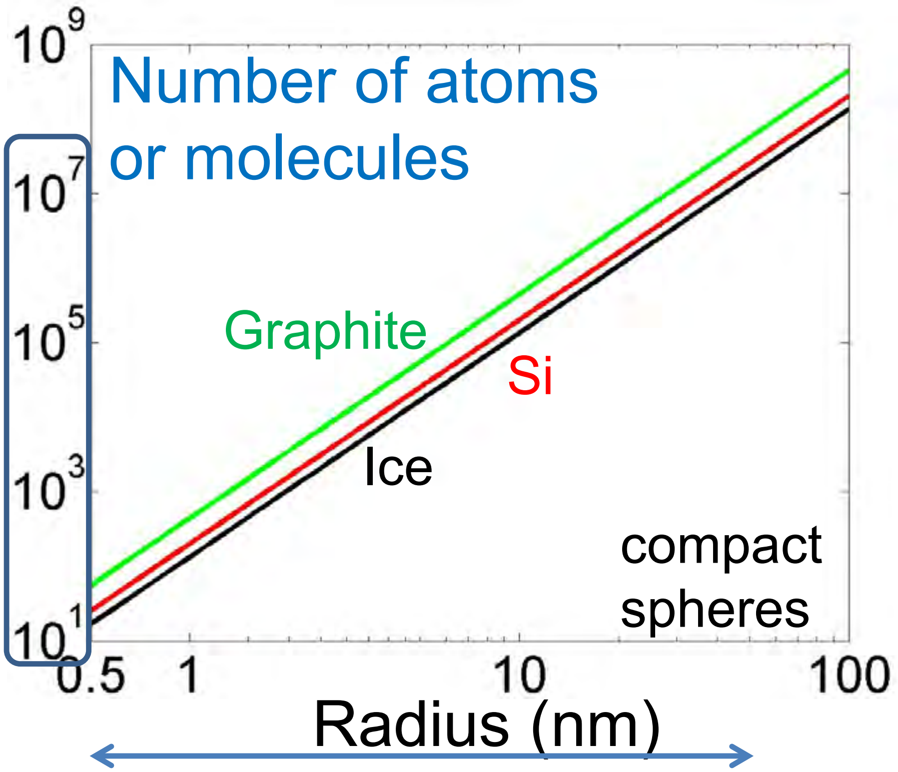

What are they?

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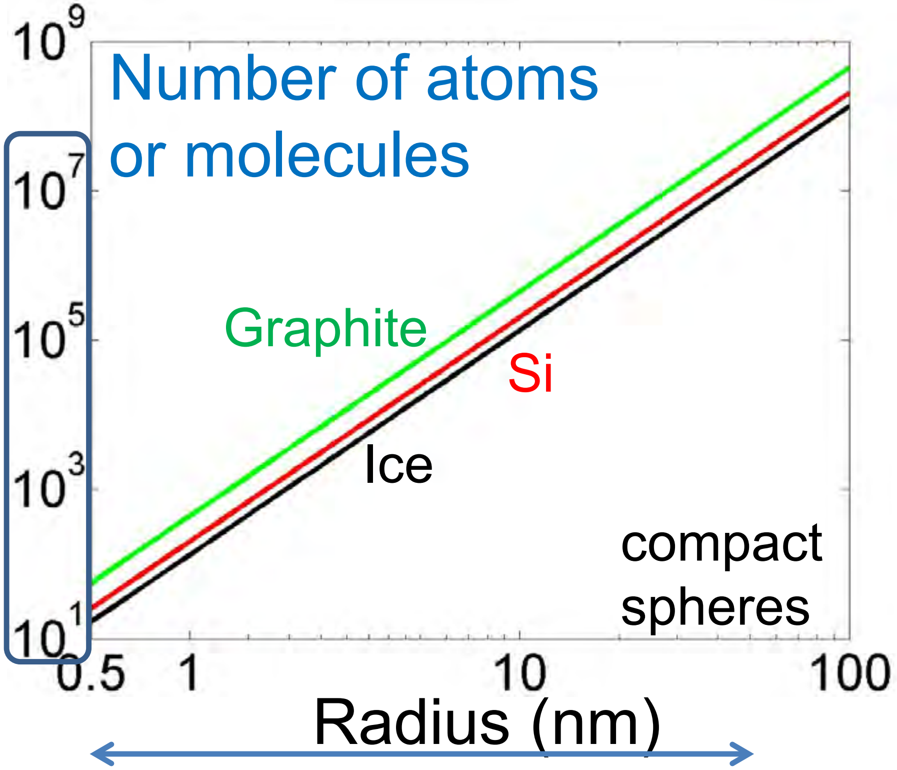

Cluster of H_20 molecules

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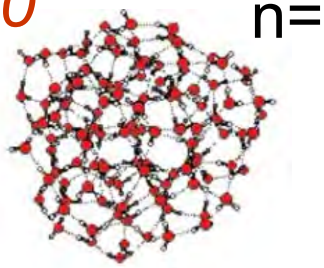
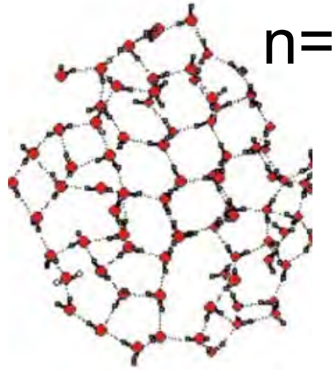




Smallest ice crystal

90 – 115 K

[Pradzynski 2012]

What are they?

100 nm

10 nm

1 nm

Bulk matter

Nano particles

Molecules

0.1 µm

10 Å

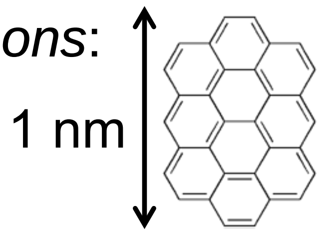
1 Å

Bohr radius

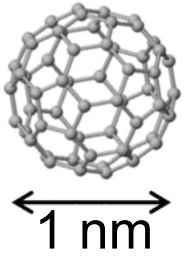
Macromolecule or nano grain?

A various fauna ..

Polycyclic Aromatic Hydrocarbons: ≥ $C_{32}H_{14}$



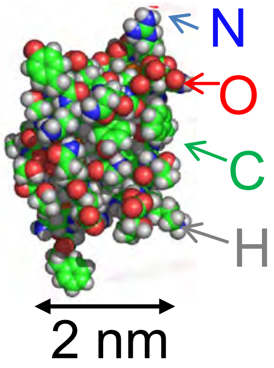
Fullerenes: C_{60} ⟶ C_{400}



2-D

Biology

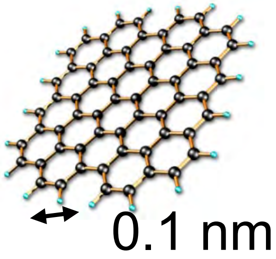
Insulin



3-D

Nanotechnology

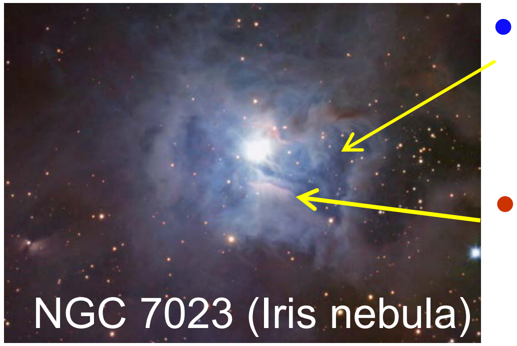
Graphene



Where are they found?

T. Ungerer

- **Interstellar space** *Inferred from:*

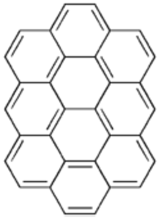


- far UV extinction

  $a < \lambda/2\pi \approx 10$ nm [Weingartner & Draine 2001]

- IR emission [Sellgren 1984; Draine & Li 2001]

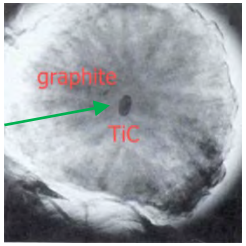
  due to stochastic heating (PAH's)

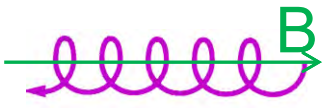


- *Interstellar nanograins cannot enter the heliosphere*

  except embedded in larger grains

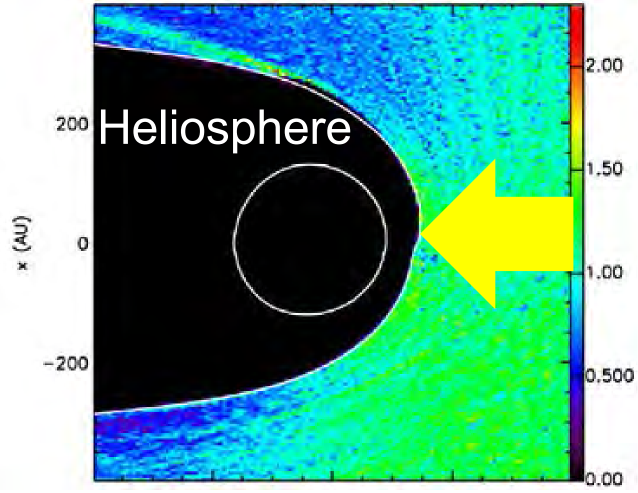
Presolar TiC nanocrystal





↕r_{gyr} $\ll L_B$

dust density (10 nm) relative to value in ISM [Slavin et al. 2010]



Where are they found?

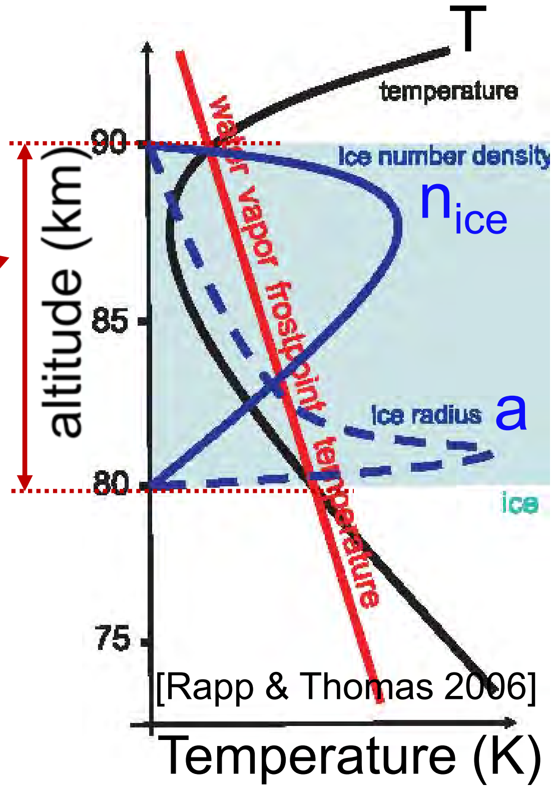
- **Planetary environments**
  - Polar mesosphere in summer: coldest place on Earth

- **“Smoke particles”**: a few 0.1 nm to a few nm (from condensation of meteoritic matter)
- **Charged aerosols**: a few nm to 100 nm

[e.g. Friedrich & Rapp 2009]

T < water vapor frost point:

- Large quantities of charged nanodust (ice): up to a few $10^3/cm^3$

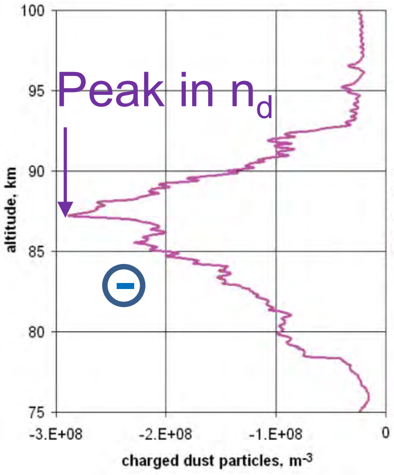


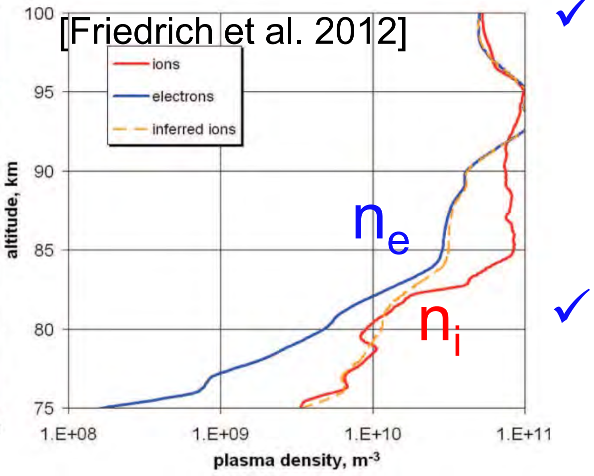
[Rapp & Thomas 2006]

Where are they found?

- **Planetary environments**

P. Dalin-IRF (Kiruna) - Mann et al. 2013





[Friedrich et al. 2012]

- Polar mesosphere in summer: coldest place on Earth
  - **Nanodust produces:**

✓ NoctuLescent Clouds (ground obs.)/ Polar Mesospheric Clouds (SC obs.): ice grains a > 20 nm scatter light

✓ Decreases in electron density n_e associated to increases in (negatively charged) dust density n_d

✓ Polar Mesosphere Summer Echoes: strong backscatter of radio waves (50 - 10^3MHZ) [e.g; Rapp & Lübken 2004]

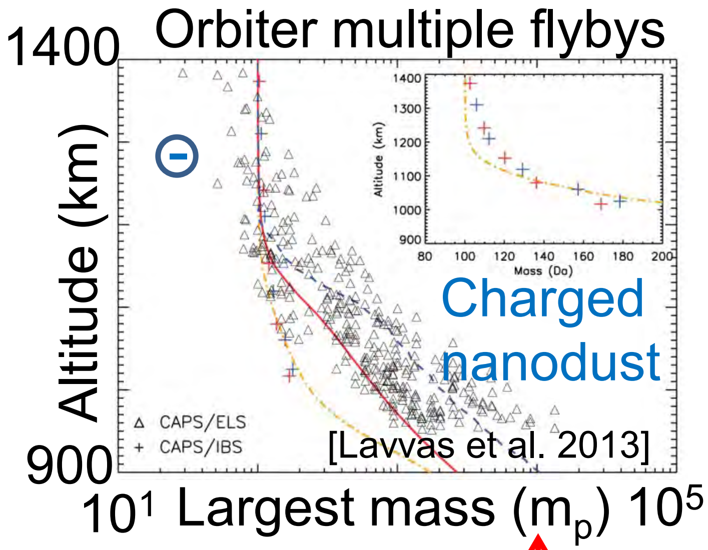
Where are they found?

- **Planetary environments**

  Farther out ..

  - Titan atmosphere

    [Coates et al. 2007, 2009]



Radius $a \sim 1.6$ nm if $\rho \sim 10^3$ kg/m^3

$a \sim 16$ nm if $\rho \sim 1$ kg/m^3

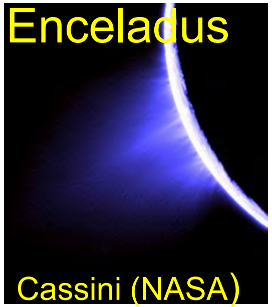
Cassini/CAPS (Plasma Spectrometer)

serendipitous detection (charged nanodust of energy/charge in the range of the instrument)

Where are they found?

- **Planetary environments**

  - o Enceladus plume

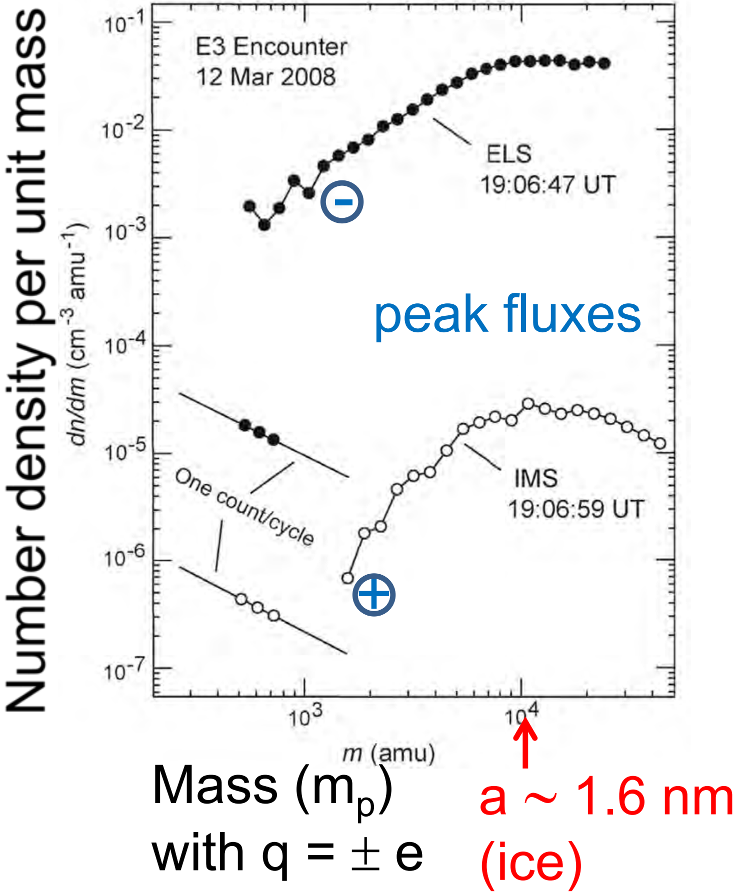


[Jones et al. 2009]

Cassini/CAPS (Plasma Spectrometer)

serendipitous detection (charged nanodust of energy/charge in the range of the instrument)

[Hill et al. 2012]



Where are they found?

- **Planetary environments** (and farther out)
  - o Fast (~300 km/s) nanodust streams
    - …accelerated by corotation electric field of Jupiter
    - … and Saturn [Kempf et al. 2005]

Dust detectors on Ulysses/Galileo/Cassini: **serendipitous** detection outside calibration range

Original results from calibration
V ~ 20-56 km/s
m ~ 10^{-19} - 10^{-16} kg [Grün et al. 1992]

From dynamics
V > 200 km/s
m ~ 10^{-21} kg [Zook et al. 1996]

[Krüger 2003; Hsu et al. 2012]

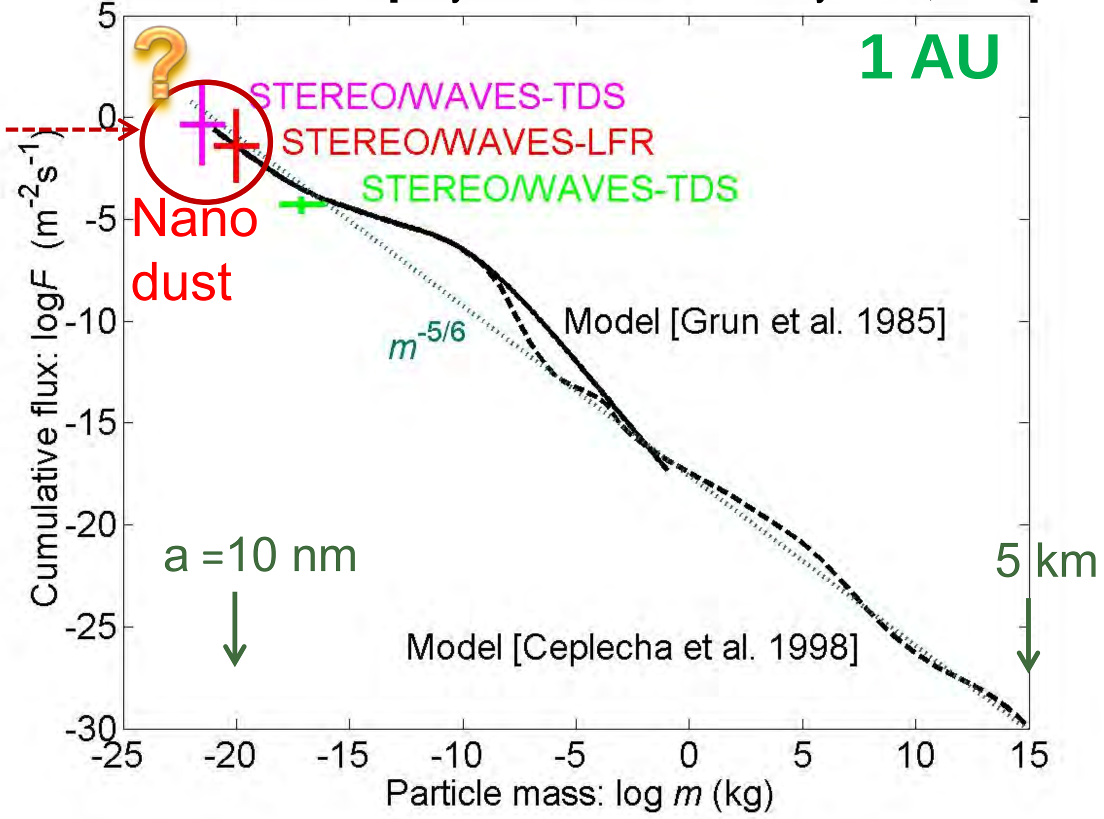
- **Comets** Ion mass spectrometers on Giotto & Vega-1: **serendipitous** detection: m ~ 0.5 10^{-21} kg at 10^6 km from nucleus of Halley [Utterback & Kissel 1990 Sagdeev 1985, 1989]

Where are they found?

- **Interplanetary medium**

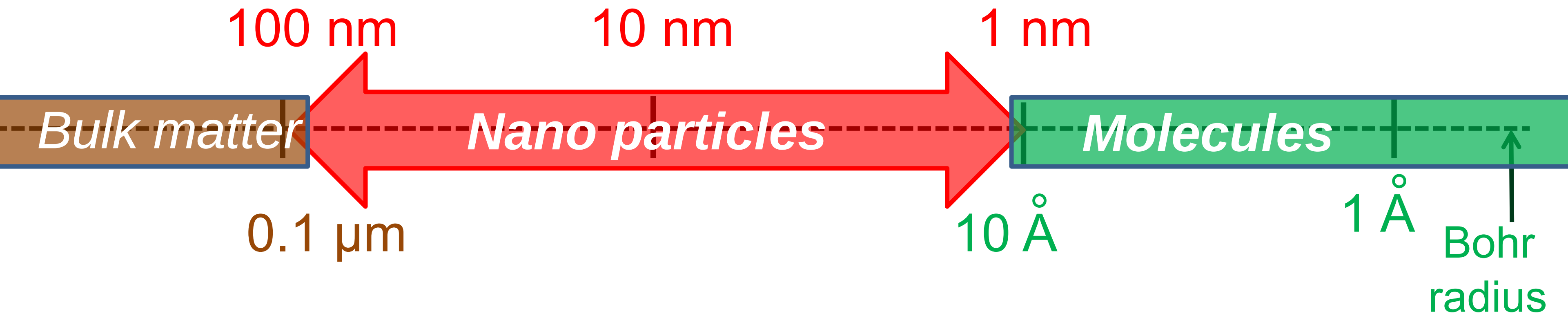
Nano grains accelerated by the magnetized solar wind

STEREO/WAVES: **serendipitous** detection (voltage pulses from **high-speed** (~300 km/s) dust impacts on SC)



[Meyer-Vernet & Zaslavsky 2009, 2012]

What makes them different?



100 nm

10 nm

1 nm

Bulk matter

Nano particles

Molecules

0.1 µm

10 Å

1 Å

Bohr
radius

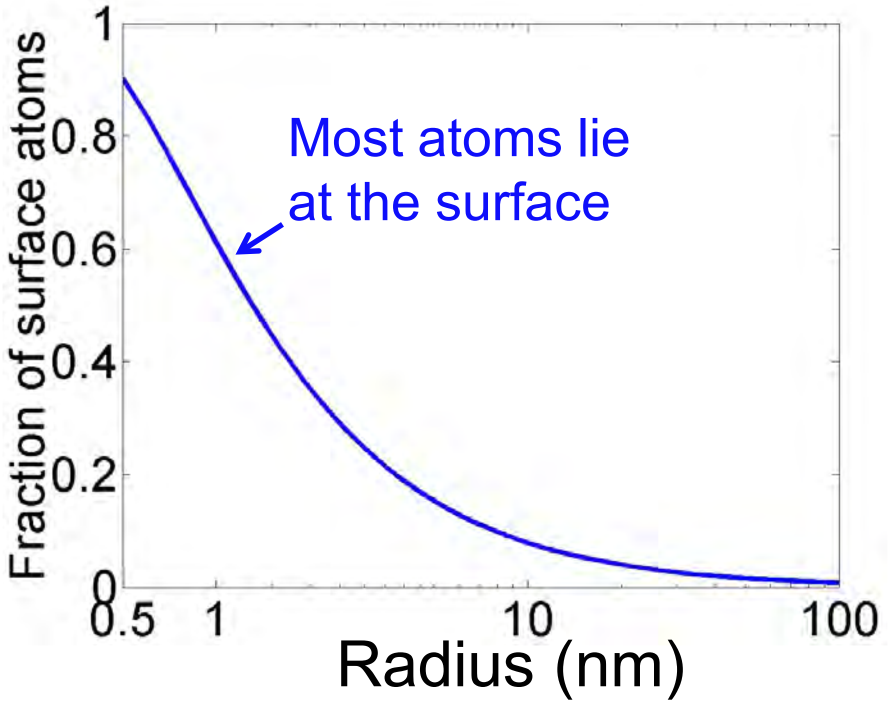
Transition between molecular and bulk properties

- ***Consensus on nanoparticles:*** **their properties are different from those of bulk material**

What makes them different?

- *Large proportion of surface atoms*

Surface atoms have too few bonding partners
→ free radicals = surface “dangling bonds”
→ mean-square displacements of surface atoms are relatively large

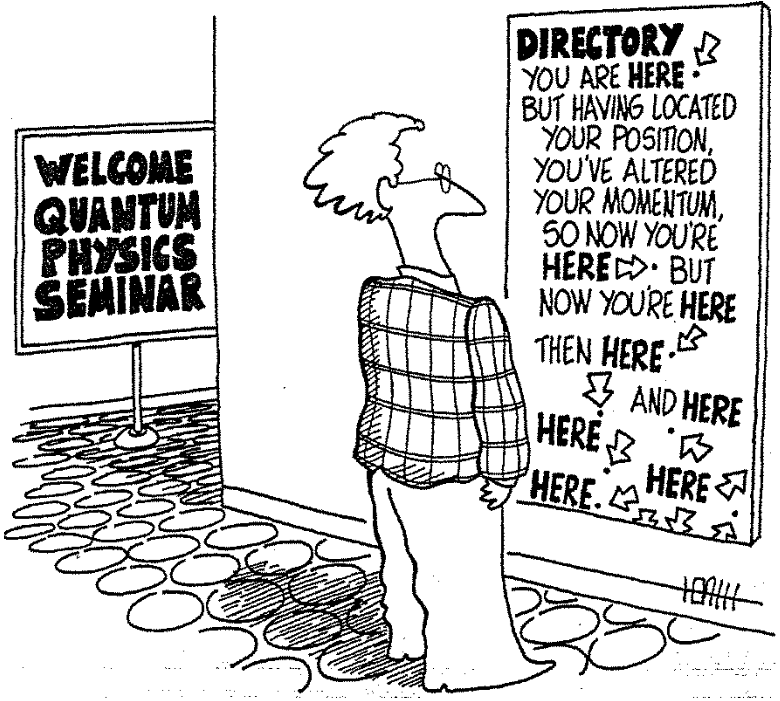


- ✓ Melting point & latent heat decrease
- ✓ Diffusion coefficient increases
- ✓ Optical properties change
- ✓ Much chemical activity at surface
- ✓ Surface reconstruction
- ✓ Coagulation

decrease in surface energy

What makes them different?

- *Quantum confinement*



Heisenberg: $\Delta x \, \Delta p = h/2\pi$

electron confined in nanograin of radius a:

$\Delta x \sim a \rightarrow$ momentum: $\Delta p = h/(2\pi\Delta x)$

$\rightarrow$ confinement energy: $E_0 \sim \Delta p^2/2m_e$

► Quantized energy levels $E_n = n^2h^2/[8m_e(\Delta x)^2]$

Affects optical & electrical properties [e.g. Li 2004]

What makes them different?

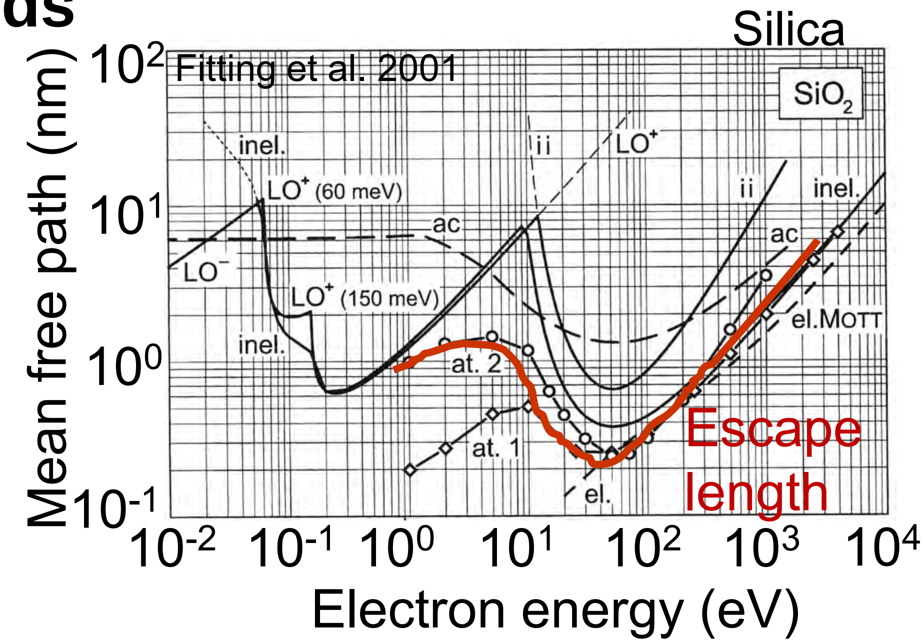
- *Size compared to basic scales*

✓ **Electron free path in solids**

~ 1 nm

for E < 100 eV

atomic scale: 2 r_B ⟶



→ **electron secondary emission increases**
[Draine & Salpeter 1979; Chow et al. 1993]

→ **electron sticking coefficient decreases** if $a \lesssim l_e$

What makes them different?

- *Size compared to basic scales*

✓ **Photon scales**

- Photon attenuation length ~ 10 – 100 nm

  $\gg$

- Photoelectron escape length l_e ~ 0.5 – 5 nm

► **Photoelectron yield increases** if $a \lesssim l_e$

photoelectrons have a better chance to escape [Watson 1972; Draine 1978]

► **can be counterbalanced by:**

- Increase of electron removal energy:

~ work function + $\boxed{(3/8)\,(e^2/4\pi\varepsilon_0 a)}$

[Wong et al. 2003]

Image charge contribution

Note: for $a > l_e$ *: yield* ↘ *when* a ↘ [de Heer 1993; Abbas et al. 2007]

- Photon wave length (UV) $\lambda > a$

→ photon absorption cross-section/$(\pi a^2) \propto a$ (Rayleigh)

What makes them different?

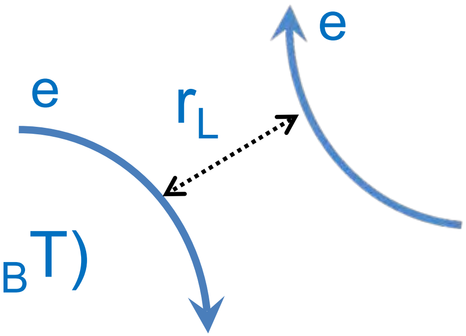
- *Size compared to basic scales*

✓ **Plasma Landau radius**

$e^2/(4\pi\varepsilon_0 a r_L) = mv^2/2$ ⇒ $r_L = e^2/(4\pi\varepsilon_0 k_B T)$

Coulomb energy

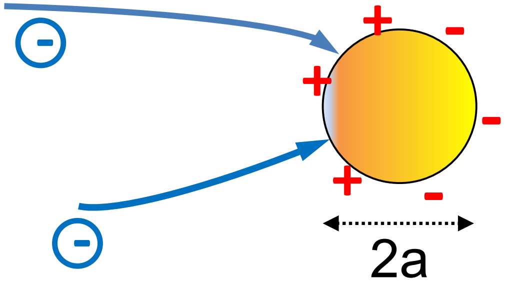
kinetic energy



→ If $\mathbf{a} \lesssim \mathbf{r_L}$, dipole induced by an approaching charge strongly curves its trajectory

→ increases currents

$r_{L\,nm} = 1.4 / T_{eV}$



⇒ Concerns nanograins if T < 2 eV

Note:
other plasma scales

- $a \ll L_D \Rightarrow$ grain's capacitance $C \approx 4\pi\varepsilon_0 a$
- $a \ll$ free path $\approx [n_e\, r_L^2 \ln(1/\Gamma)]^{-1}$

In general

Plasma coupling parameter

What makes them different?

- *High charge-to-mass ratio*
  - Dynamics and pick-up in magnetized plasmas
  - Dusty plasma effects
- *Further charge effects of relative importance ↗ as a ↘*
  - Nucleation: charged grain attracts molecular dipoles → decreases free energy

$$G_0 = \boxed{4\pi a^2\sigma} - \boxed{N k_B T \ln(S)}$$ - Coulomb term

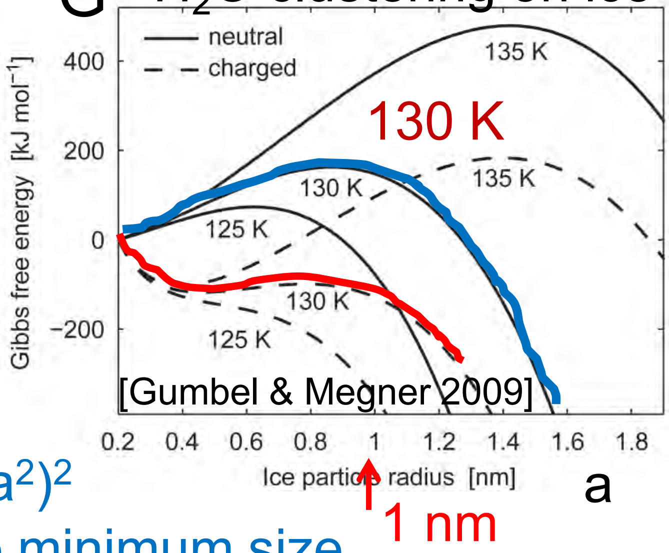
↑ *energy to form surface*

$\propto a^3$

↖ *Energetic preference for condensation*

Can suppress barrier of potential

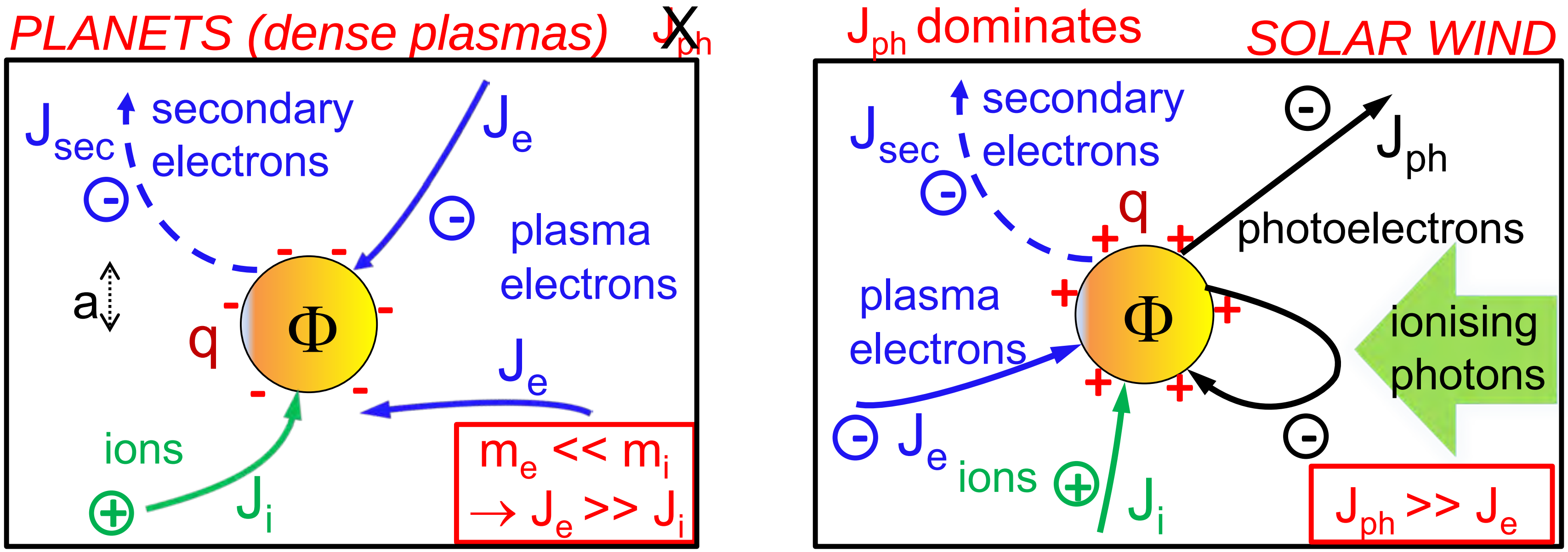
G H$_2$O clustering on ice



[Gumbel & Megner 2009]

  - Electrostatic disruption: stress $\propto (q/a^2)^2$ → makes grain explode → may determine minimum size

Electric charging: basics



Q: grain's charge; Φ: grain's potential relative to ambient plasma

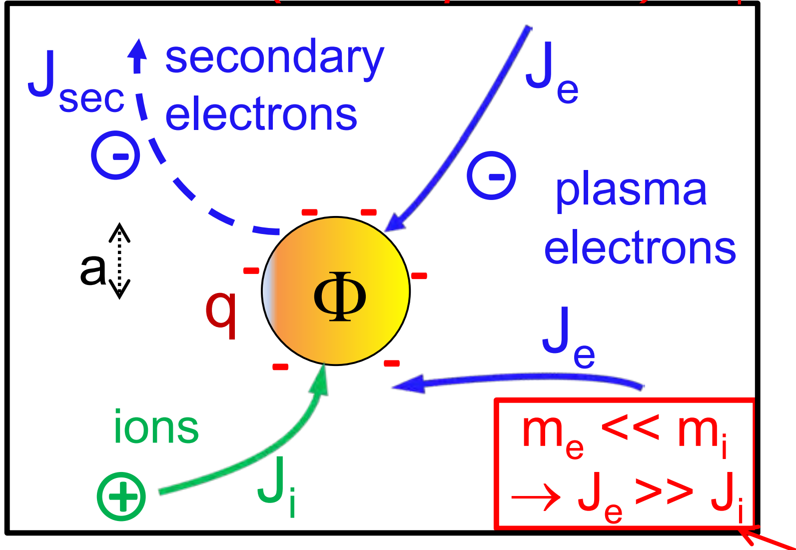
- Charging governed by incoming plasma electrons until grain **negative** charge repels them sufficiently to balance other currents

[e.g. Whipple 1981]

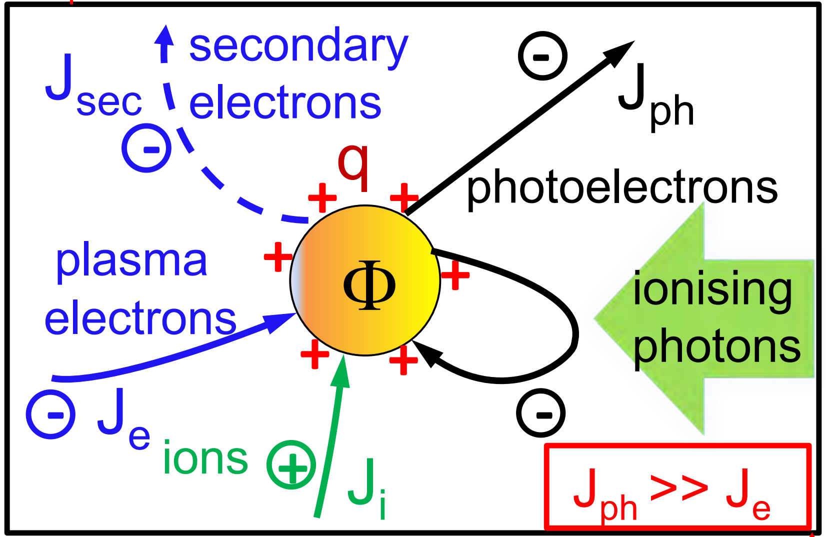
- Charging governed by escaping photoelectrons until grain **positive** charge binds them sufficiently for escaping photoelectrons to balance other currents

Electric charging: basics

PLANETS (dense plasmas) ~~J_{ph}~~



J_{ph} dominates *SOLAR WIND*



- At equilibrium: potential energy = a few times kinetic energy of dominant charging particles ⇨ $|e\Phi| \approx \eta\, k_B \boxed{T}$
- Charge: $q \approx \boxed{4\pi\varepsilon_0 a}\Phi$ ⇨ $|Z|=|q/e| \approx \eta\, a/r_L$

capacitance of a sphere

T_e or T_{ph}

a few eV

$r_L = e^2/(4\pi\varepsilon_0 k_B T)$

$\eta \sim 1$ (order of mag.) determined by details of charging processes

if $|Z| >> 1$, i.e. $a > r_L$

Electric charging

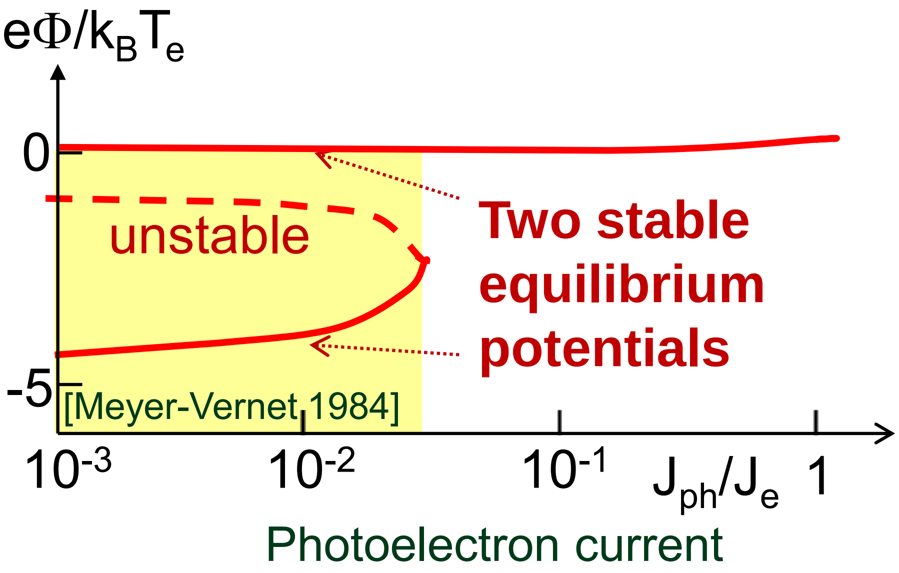
Beware: tricky cases

- *Secondary emission not negligible*

Sensitivity to parameters near T at which $J_{sec} \sim J_e$ [Laframboise et al. 1982]

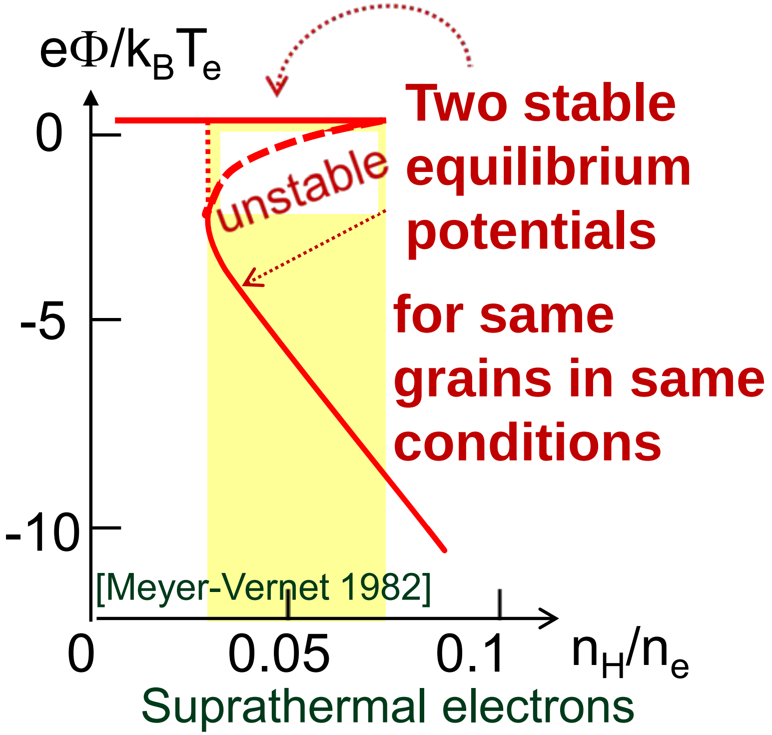
- *Non-maxwellian plasma*

→ Unstable solutions



Two stable equilibrium potentials

[Meyer-Vernet 1984]



Two stable equilibrium potentials

for same grains in same conditions

[Meyer-Vernet 1982]

Secondary emission: $\delta = 3$

$E_M = 400$ eV; T= 25 eV $T_H/T_e = 100$

Electric charging

Beware: tricky cases

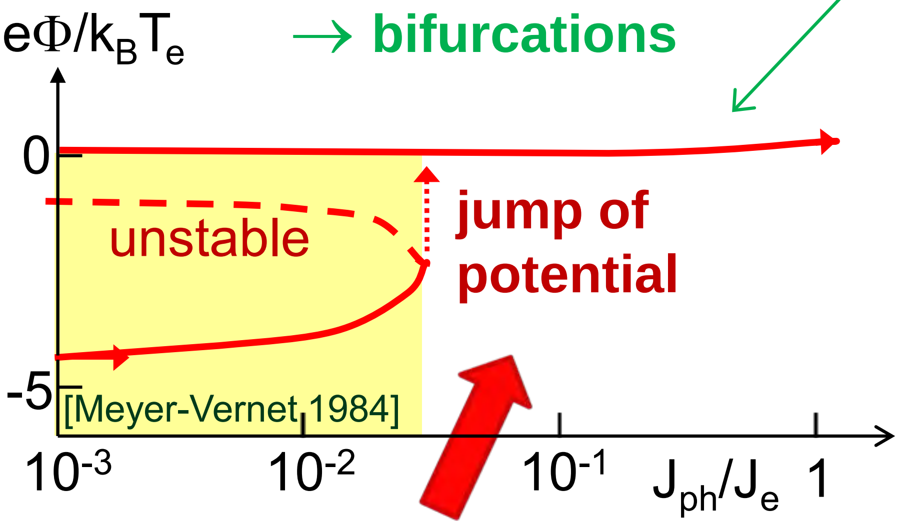
- *Secondary emission not negligible*

Sensitivity to parameters near T at which $J_{sec} \sim J_e$ [Laframboise et al. 1982]

- *Non-maxwellian plasma*

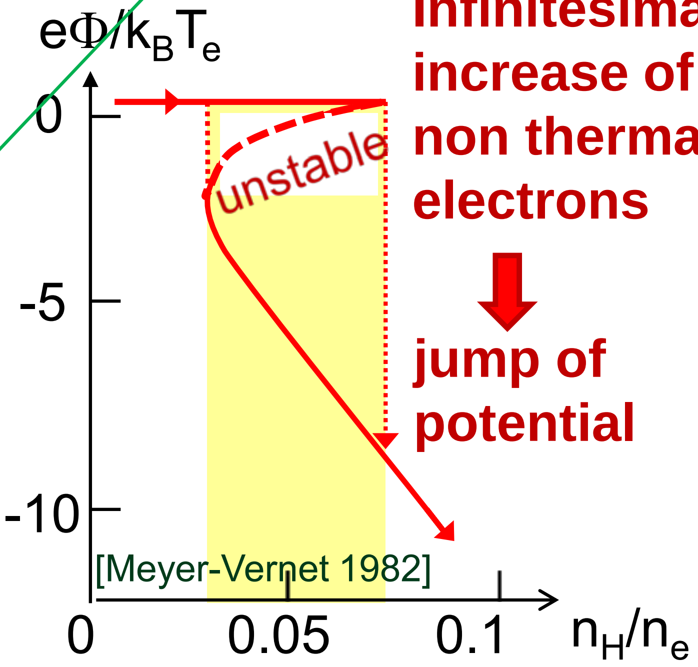
→ **Unstable solutions**

→ **bifurcations**



Infinitesimal increase of photoemission

2-D cuts in multi-dimensional space of parameters

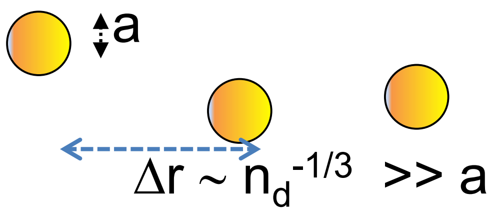


Infinitesimal increase of non thermal electrons

jump of potential

Electric charging in **dusty** plasmas

n_d grains/m^3 ; n_e (n_i) electrons (ions)/m^3



$L_D = [4\pi\, r_L(n_e+n_i)]^{-1/2}$ $(T_e \sim T_i)$

Fraction of charges carried by grains = $Z\, n_d/(n_e+n_i) = \eta P$

$P = 4\pi\, n_d\, a L_D^2$

- If P > 1, Debye sheaths overlap

→ electrons depleted

→ reduces grain's charge

[Havnes et al. 1984, Whipple et al. 1985]

- If P >> 1: $Z \sim -a/(P\, r_L) \ll 1$

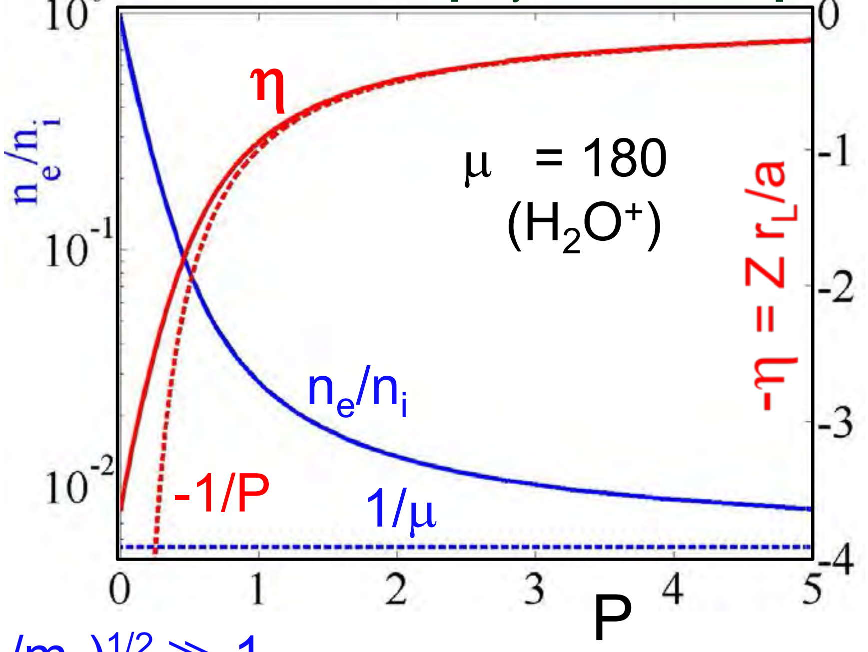
limit to el. depletion: $n_e/n_i \sim 1/\mu$

[Mendis & Rosenberg, 1994; Mendis 2002

$\uparrow$

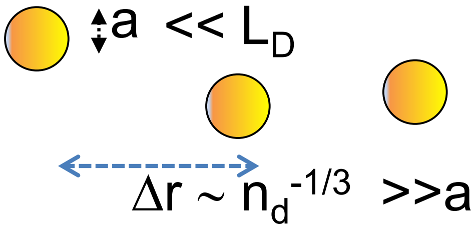
$\mu = (s_e/s_i)(v_{the}/v_{thi}) \sim (m_i/m_e)^{1/2} \gg 1$

[Meyer-Vernet 2013]



Electric charging in **dusty** plasmas

n_d grains/m^3 ; n_e (n_i) electrons (ions)/m^3



$a << L_D$

$\Delta r \sim n_d^{-1/3} >> a$

$L_D = [4\pi\, r_L(n_e+n_i)]^{-1/2}$

Beware!

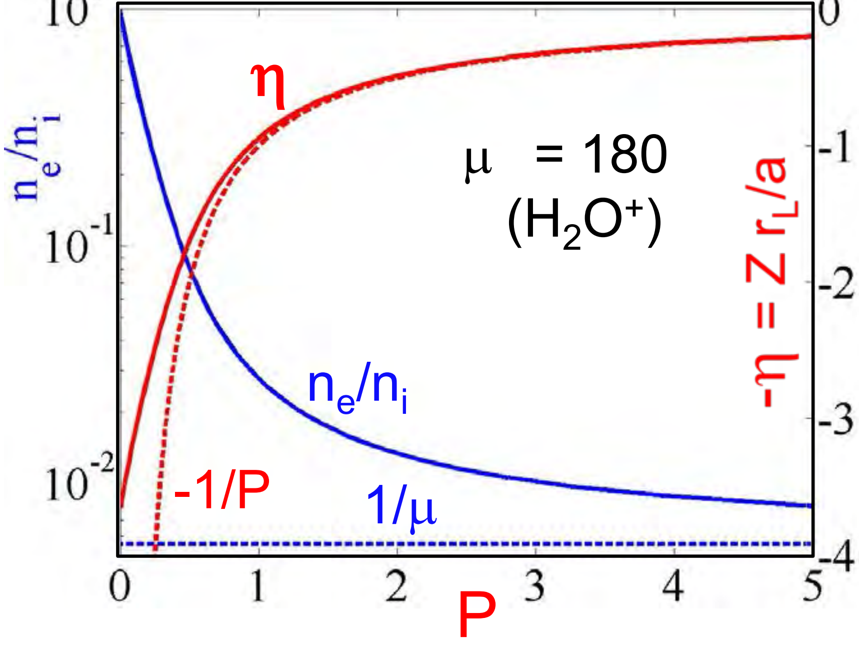
Densities **inside** dusty plasma

Fraction of charges carried by grains = $Z\, n_d/(n_e+n_i) = \eta P$

$\boxed{P = 4\pi\, n_d\, a L_D^2}$

➡ $P \neq$ "Alfvén parameter" which refers to n_e **outside** a "dust cloud" [Havnes1987, 1989; Goertz 1989]

[Meyer-Vernet 2013]



Electric charging

➢ Important limitations for nanodust

- **Long charging time scales**:

  $\tau \sim RC \sim (dI/d\Phi)^{-1}C \sim [4\pi a r_L J/e]^{-1}$ if $a > r_L$

  $\tau \sim [(2\pi a)^{3/2} r_L^{\,1/2} J_e]^{-1}$ if $a < r_L$

- **Field emission limits negative charge**:

  Limiting electric field for (electron) field emission: $\Phi/a \sim 10^9$ V/m

➡ Maximum number of electrons on a nanograin:

$|Z_{MAX}| \sim 1 + 0.7\, a^2_{(nm)}$

Electric charging in **cold** dusty plasmas

- Nanodust: $a \lesssim r_L \approx 1.4/T_{(eV)}$ nm

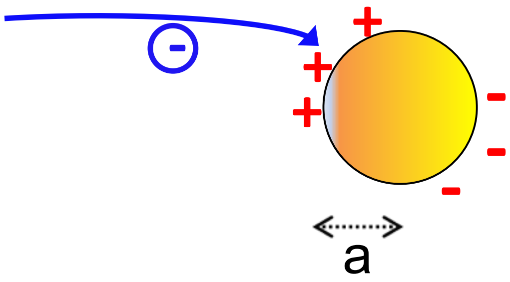
Examples:

- Earth's ionosphere: $r_L \approx 5 – 100$ nm
- Jupiter/IO torus: $r_L \sim 0.1 - 1.5$ nm (Te from [Bagenal 1994]; [Moncuquet et al. 1995])
- Saturn (3-10 R_S): $r_L \sim 0.3 - 3$ nm (Te from [Sittler et al. 2006; Schippers et al. 2013]
- Comet plasma tail: $r_L \sim 1$ nm (Te from [Meyer-Vernet et al. 1986] measure *in situ* of Giacobini-Zinner plasma tail by ICE/radio instrument: $n_e \approx 10^3$, $T_e \approx$ 1 eV)

Electric charging in **cold** dusty plasmas

- Nanodust: $a \lesssim r_L \approx 1.4/T_{(eV)}$ nm

Two major consequences:



1. Approaching charge is strongly attracted by induced dipole

Potential energy $e^2/(4\pi\varepsilon_0 a) \gtrsim k_B T$

→ increases currents

→ decreases charging time scales

[Natanson 1960; e.g. Draine & Sutin 1987; Rapp & Lübken 2001]

- 2. Grain's number of charges $|Z| \approx \gamma a/r_L \gg 1$

→ statistical treatment: $f(Z)\, J_i(Z) = f(Z+1)\, J_e(Z+1)$

probability for charge state Z

[Draine & Sutin 1987] deduce moments, as:

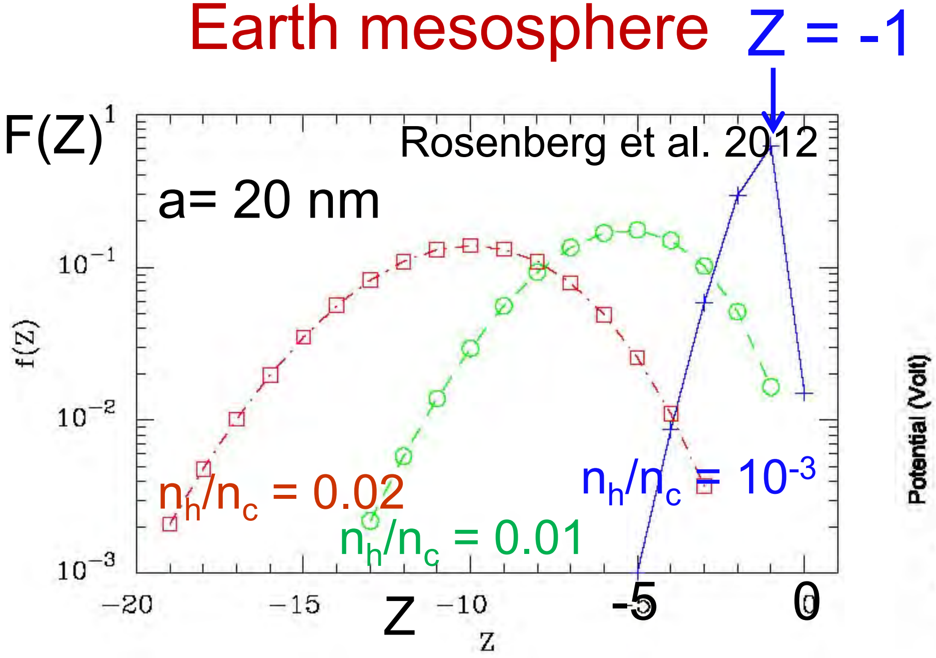
average charge state: $< Z > = \sum Z \; f(Z)$

Electric charging in **cold** dusty plasmas

Examples:

Probability distribution of
Z = q/e at equilibrium

Earth mesosphere

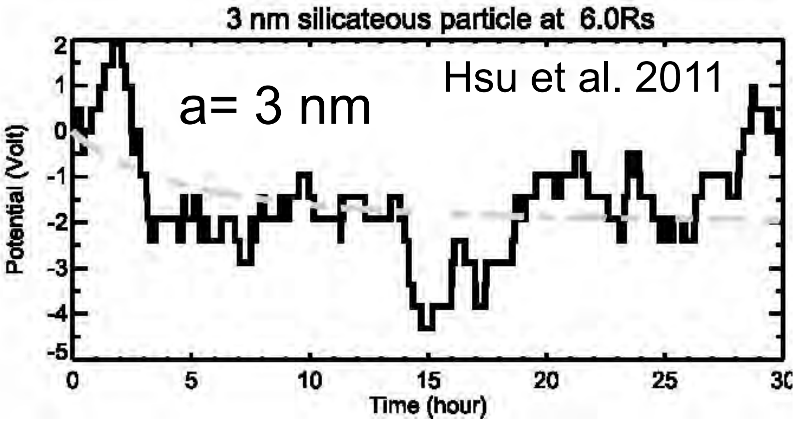


T_c = 0.015 eV+ hyperthermal electrons at 3.5 eV

Variation of grain's
potential with time

Inhomogeneous Poisson process approach

Saturn's magnetosphere



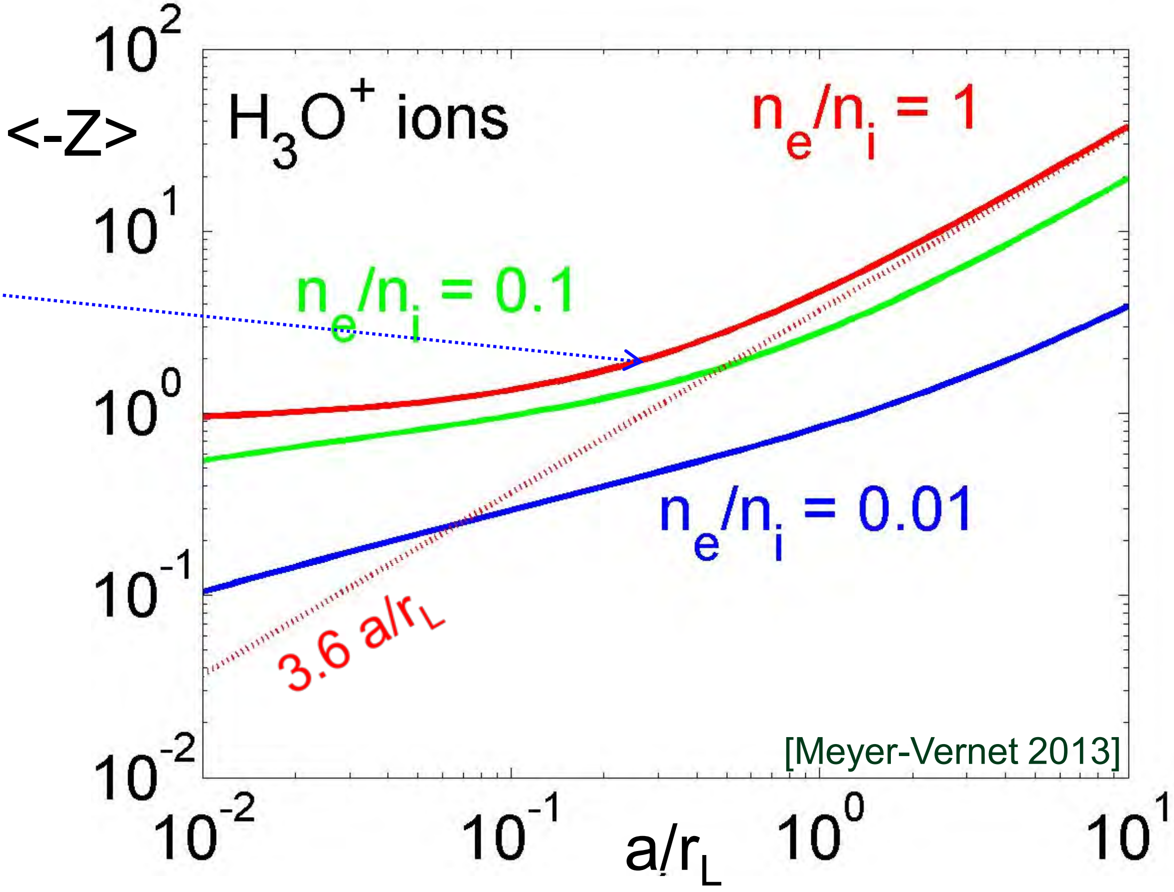
Electric charging in **cold** dusty plasmas

Average number of charges on a grain

without field emission

no longer proportional to grain size

$< Z > \not\propto a$



(if J_{ph} negligible)

Electric charging in **cold** dusty plasmas

Average number of charges on a grain

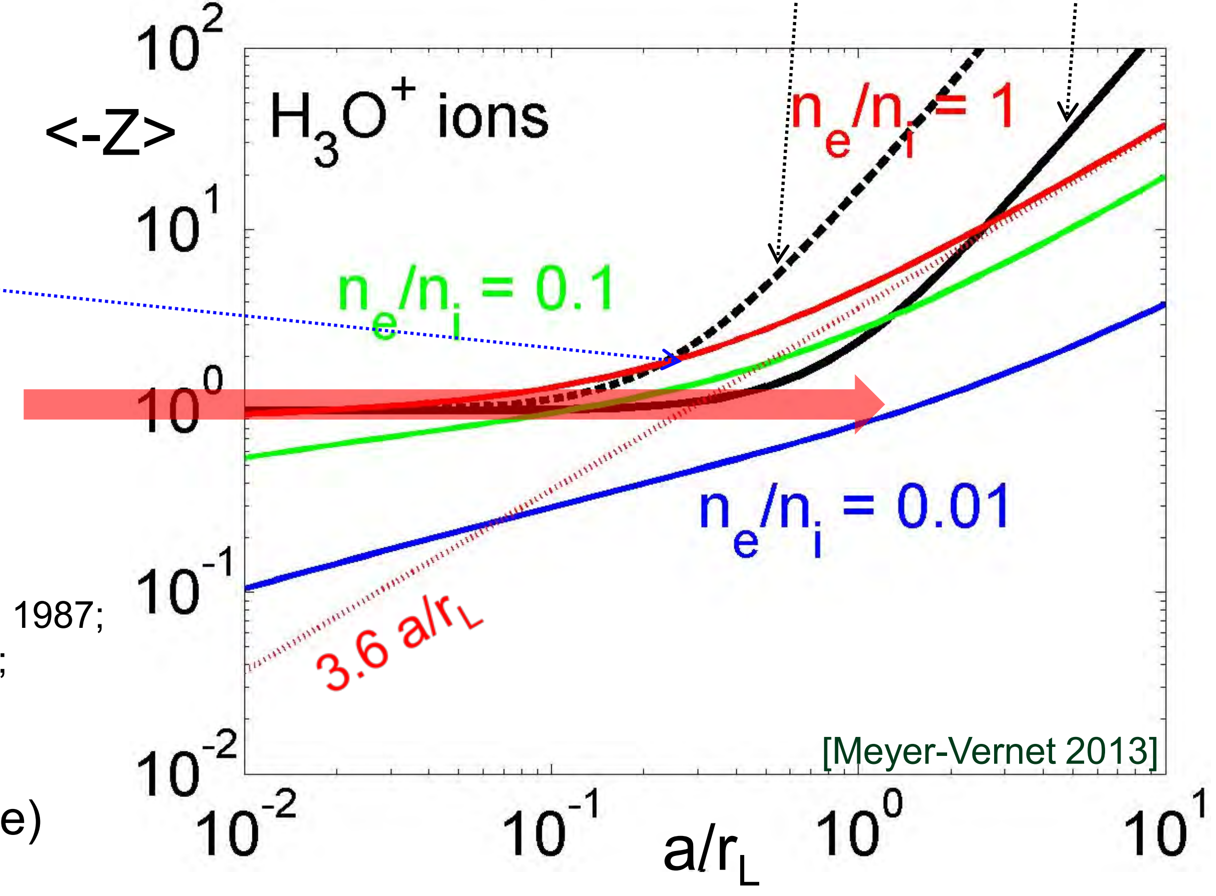
no longer proportional to grain size

Z_{MAX} due to field emission limit

T = 0.3 eV T = 1 eV

$< Z > \not\propto a$

$< Z > \approx 1$

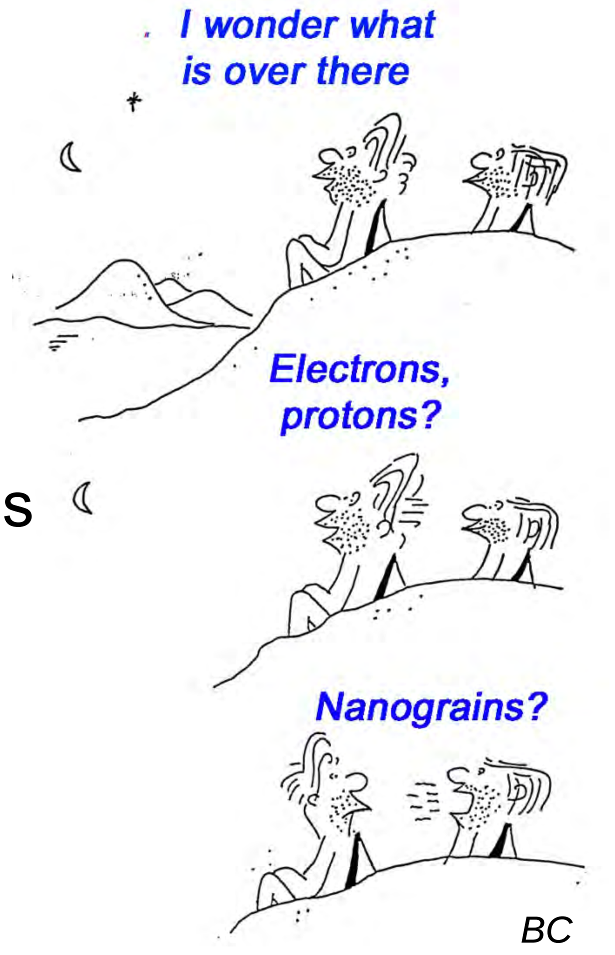


[Meyer-Vernet 2013]

[e.g. Draine & Sutin, 1987;
Rapp & Lübke 2001;
Hill et al. 2012]

(if J_{ph} negligible)

Conclusions



BC

Beware of nanograins:

- Ubiquitous
- Physical properties different
- Secondary emission → multiple states
  → nasty for numerical simulations
- In cold ($a \lesssim r_L$) dense plasmas,
  nanograin carries $|\langle Z \rangle| \sim 1$ electron
  → $q/m \propto a^{-3}$ (instead of a^{-2})
- Were detected **serendipitously** in most environments …

Will crop up when you don’t expect them