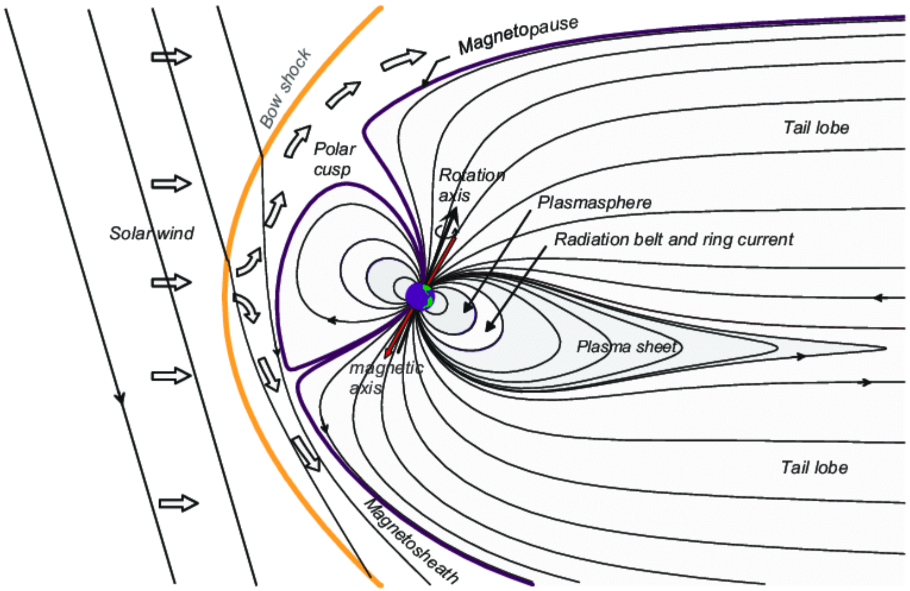
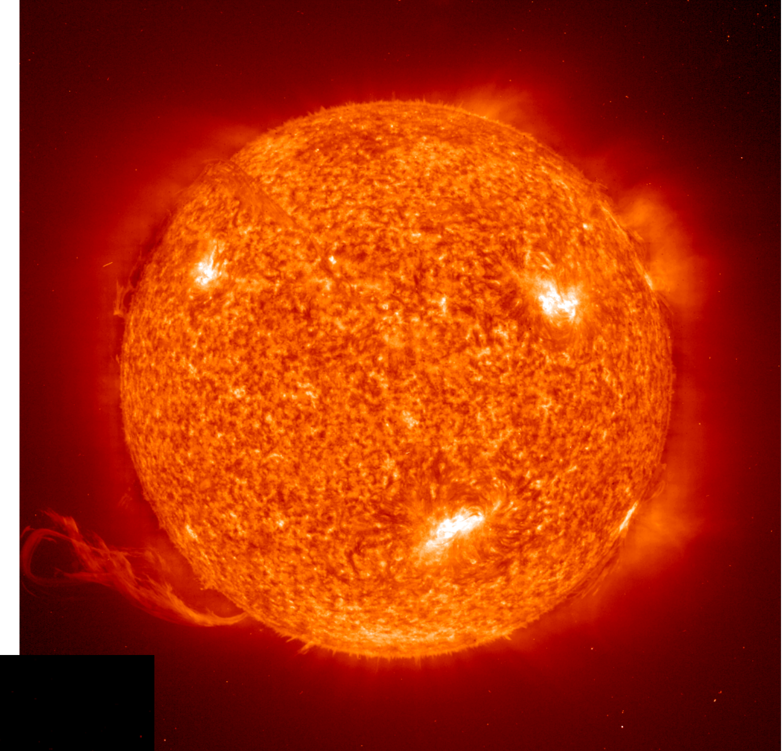
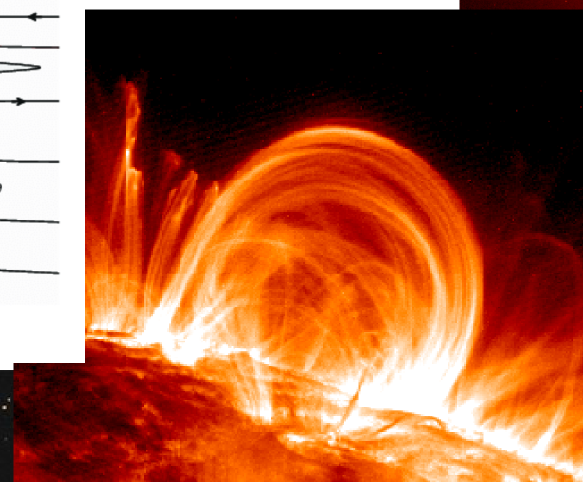
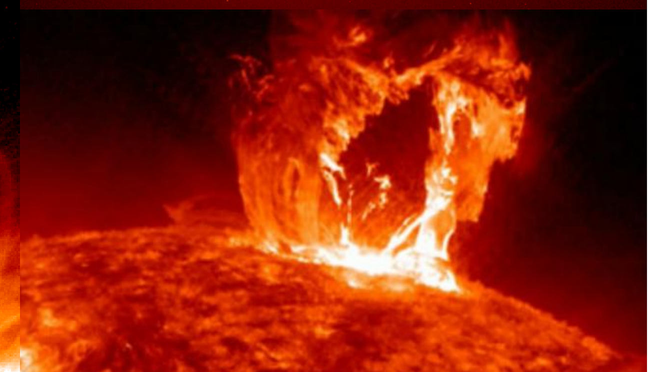
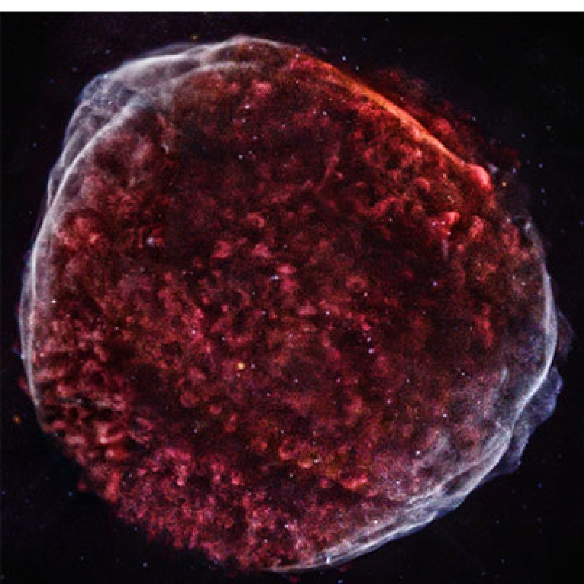
Dynamics of cosmic plasma

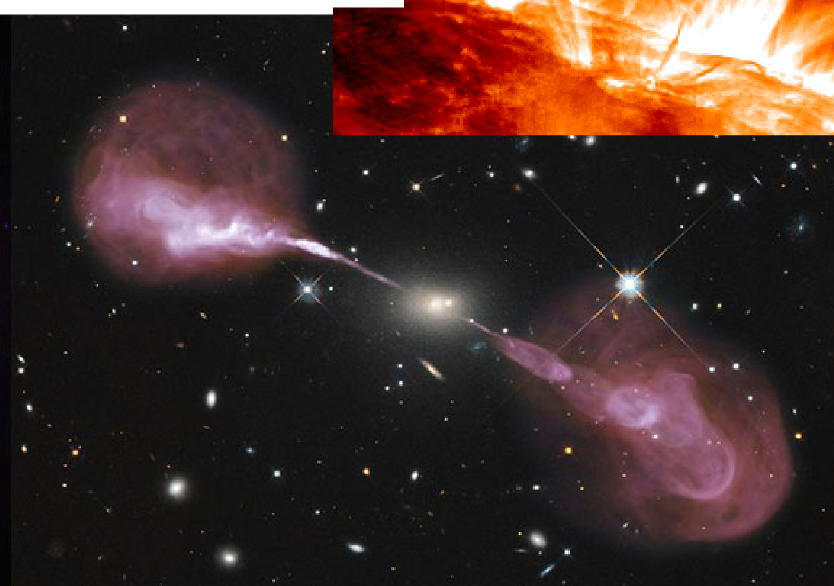












Matter in the known universe is often classified in terms of four states: solid, liquid, gaseous, and plasma

Ignoring the more speculative nature of dark matter, matter in the universe consists for more than 90% of plasma

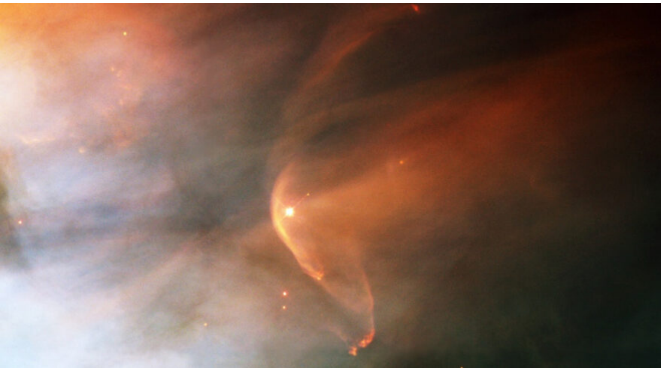
Whether a given substance is found in one of these states depends on the random kinetic energy (thermal energy) of its particles, i.e., on its temperature

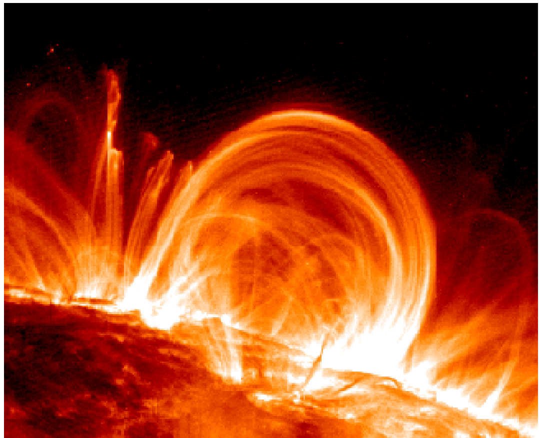
Kinetic energy per particle is for solid state ~**0.01 eV**, liquid ~**0.1 eV**, gas ~**1 eV**

~ order of magnitude

$$1 \text{ eV} \approx 1.602 \times 10^{-19} \text{ J}$$

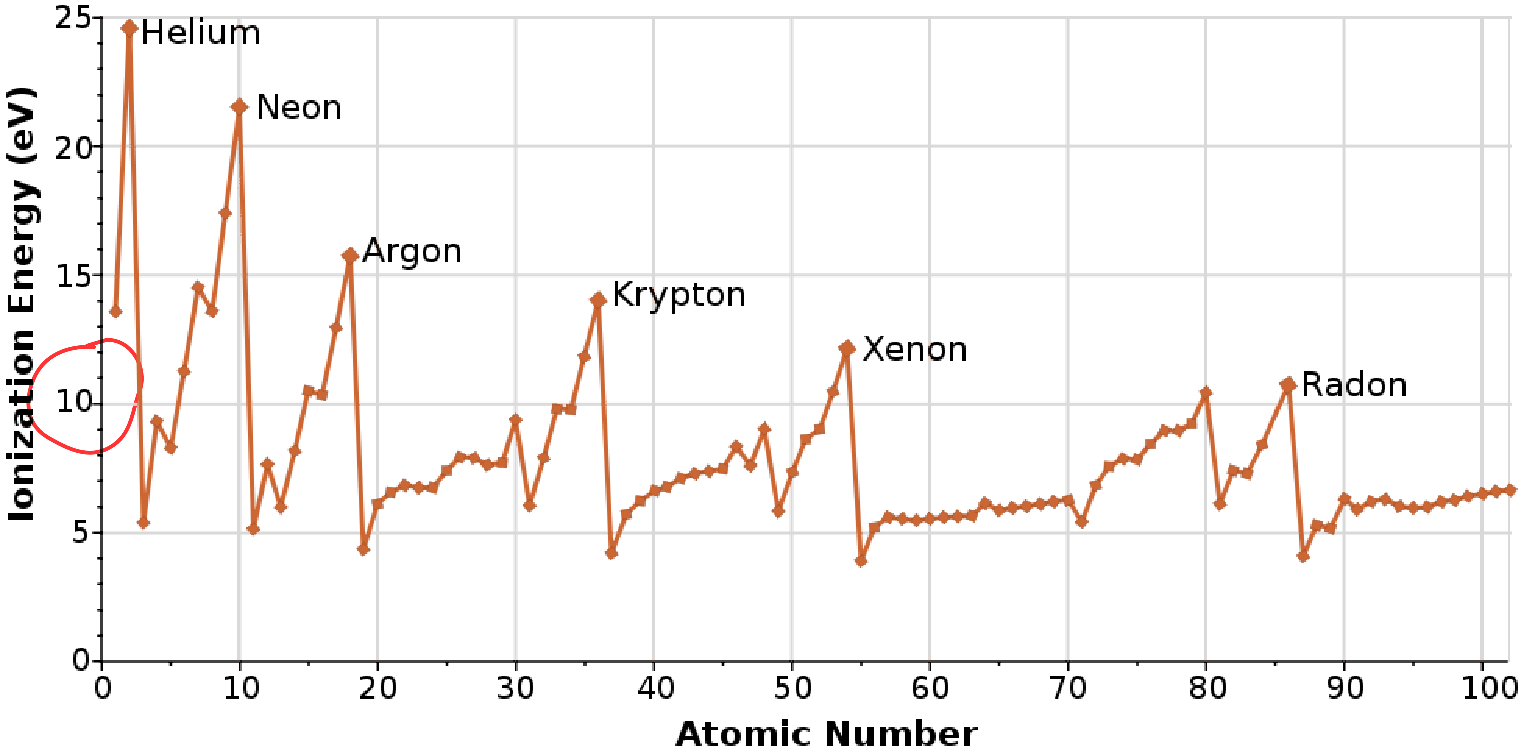
$$1 \text{ J} = 10^{7} \text{ erg}$$





What about ~10 eV?

Heat up a neutral gas → thermal ionization



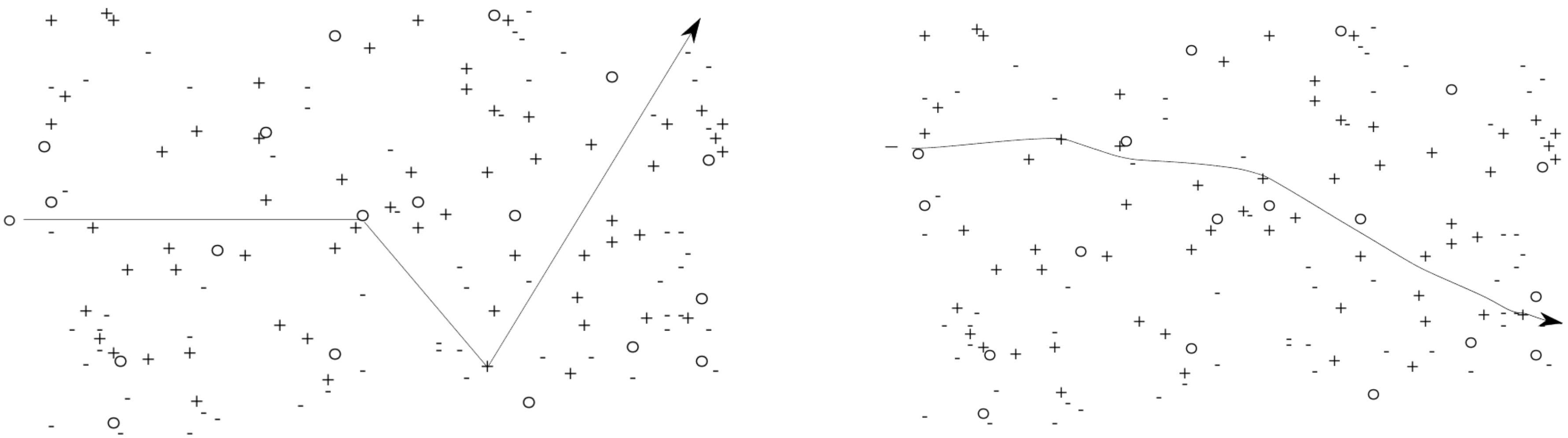
neutral → ionized

A plasma is an ionized gas

In an ordinary gas, neutral particles move about freely until a collision occurs – **short range, binary** event in which two particles hit each other

In a plasma, the charged particles are subject to **long range, collective,** Coulomb interactions with many distant encounters

Collective behavior – even at low ionization level



A plasma is a system of charged and neutral particles which exhibits collective behavior

One can generalize this statement to every system which exhibits collective behavior – not just gaseous plasmas (quark-gluon plasma,…)

Weakly, partially, fully ionized plasmas

Intermezzo

How do we get an ionized gas in the Universe?

How do we get an ionized gas in the Universe?

$$\mathrm{A} + \mathrm{A} \rightarrow \mathrm{A}^{+} + \mathrm{e}^{-} + \mathrm{A}$$

thermal collisional ionization (rise a temperature (mean kinetic energy) of TE system – more collisions)

stellar interiors

$$\mathrm{A} + \mathrm{e}^{-} \rightarrow \mathrm{A}^{+} + 2\mathrm{e}^{-}$$

collisional ionization by free electrons – electron impact ionization

Solar corona, hot ionized ISM

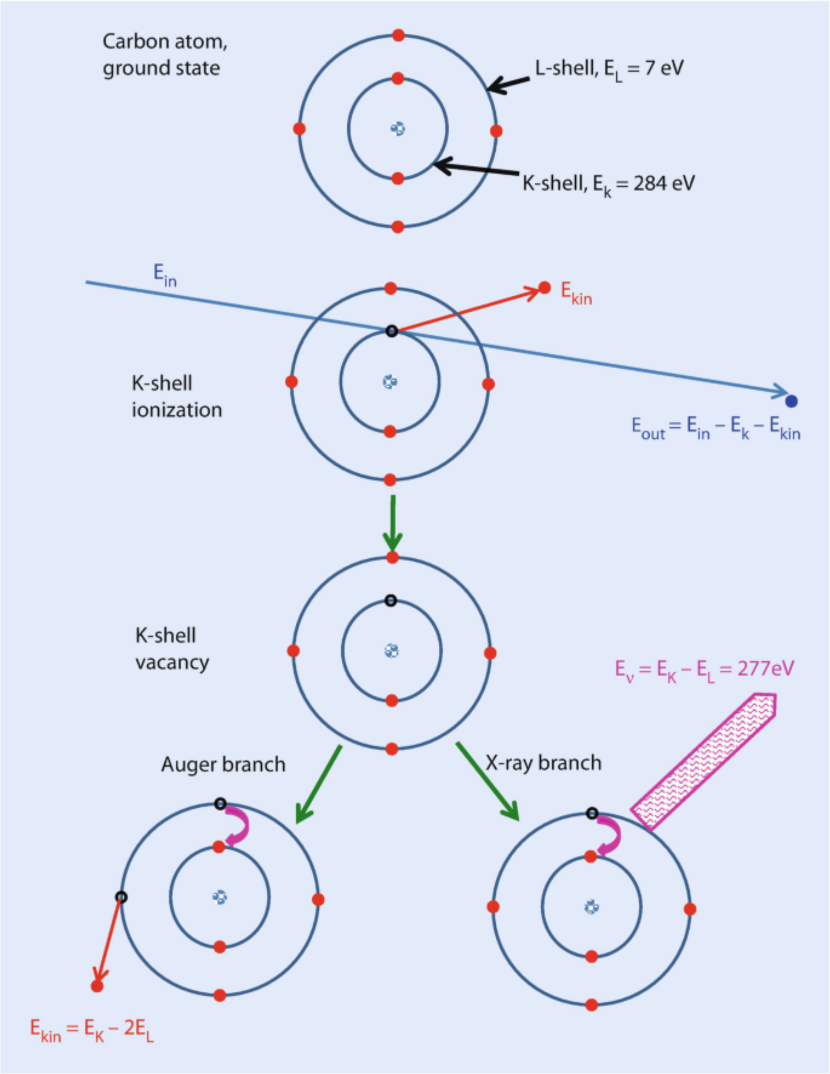
photo-ionization

$$\mathrm{A} + h\nu \rightarrow \mathrm{A}^{+} + \mathrm{e}^{-}$$

Earths ionosphere (Solar UV radiation), ISM around hot O/B stars (HII regions), planetary nebulae

inner shell ionization

auto-ionization



How do we get an ionised gas in the Universe?

$$H_2 + CR \rightarrow H_2^+ + e^-,$$

inelastic collisions with high energy particles (cosmic rays)

cores of molecular clouds

$$H_2^+ + H_2 \rightarrow H_3^+ + H,$$

The H_3^+ ion is believed to play an important role in astrochemistry, by initiating the chains of reactions that lead to the production of many of the complex molecular species observed in the ISM

ionization by (collisionless) shock waves

Supernova remnants, bow shocks, majority of shocks all over the Universe

electron capture ionization or electron attachment

$$H + e^- \rightleftarrows H^- + h\nu$$

an important source of continuum opacity in the case of the Sun

Usually F, G and K stars – a lot of free electrons in the atmosphere due to the ionization of metals with low ionization potential (Na, Mg, Al, Si, Ca, Fe,...)

How do we get an ionised gas in the Universe?

Charge-exchange or charge-transfer processes

Young supernova remnants: shock wave through the partially ionized medium

Neutral H atoms that pass though the shock front can be:

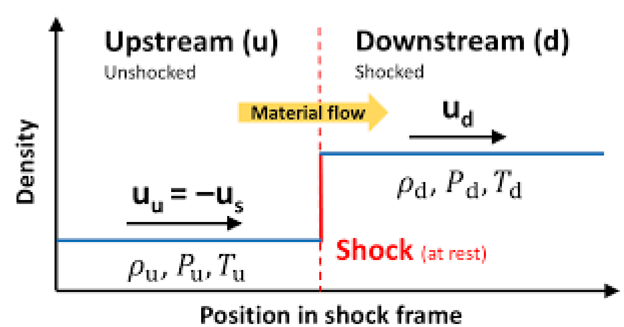
ionized,

just found in an excited state and then emit narrow Balmer lines (physics of the upstream medium),

or **charge-transfer with energetic ions** can happen

$$\underset{\text{Slow}}{H} + \overset{\text{Fast}}{H^+} \to \overset{\text{Slow}}{H^+} + \underset{\text{Fast}}{H}$$

if found in excited state after the charge-transfer process – broad Balmer lines (physics of the downstream medium)



Every elementary ionization process has its own inverse elementary recombination (e.g., photo-ionization – radiative recombination,...)

Ionization-recombination equilibrium (the rate of ionization equals the rate of recombination)

Recombination of one type vs. ionization of another type, e.g., stellar coronas or hot ISM: electron impact ionization vs. radiative recombination (collisional ionization equlibrium, CIE)

photo-ionization equilibrium (photo-ionization nebulae)

Non-equilibrium ionization (NEI) is also expected, e.g., in most SNRs

Shocks create an ionizing (under-ionized) plasma that slowly reaches CIE

There are some SNRs that have their plasmas in a recombination-dominant state (over-ionized plasma) – Such plasmas have a higher ionization degree than that expected in CIE, therefore they were dubbed over-ionized, recombining plasmas

...back to the main physical parameters that define particular plasma state…

Macroscopic quasi-neutrality

Example:

Number density of particular hydrogen (p + e) TE (thermodynamic equilibrium) plasma (equal for protons and electrons) is 10^{14} m^{-3}

Imagine a sphere of R=1m inside that TE plasma

If electron leakage, due to the thermal, chaotic, motion is 1%,

find the electrostatic potential on the sphere

electrostatic potential Φ, and electron charge q_e

$$\Phi = \frac{1}{4\pi\varepsilon_0}\frac{Q}{R} \qquad Q = \rho^{\mathrm{el}} \cdot V = |q_{\mathrm{e}}|(n_{\mathrm{p}} - n_{\mathrm{e}}) \cdot \frac{4}{3}\pi R^3$$

Result: 6 kV

Macroscopic quasi-neutrality

For example: electron temperature ~10^6 K → kT = 86 eV

Remeber: 1 eV → 11600 K

Electrons do not have enough thermal energy to leak through the spherical boundary: $kT < |q_e|\Phi$

In fact, electrons from the tail of Maxwell distribution can leak first → if electron leakage is ~0.015% electrostatic potential is ~90 V → for R=1m sphere we can not have the difference between proton and electron number densities of order 1% → system is electrically neutral if we are interested in the processes at spatial scales of around 1m and more

If we let R=10 cm, for 1% leakage: Φ ~ 600 V > kT

So, if we are interested in more and more larger spatial scales we get fully electrically neutral system

Macroscopic quasi-neutrality

Order of magnitude for R of the sphere that encompasses volume from which all the electrons can leak – electron Debye radius:

$$r_{\mathrm{De}} = \sqrt{\frac{\varepsilon_0 k T_{\mathrm{e}}}{n_{\mathrm{e}} q_{\mathrm{e}}^2}}$$

Below Debye radius we do not have electroneutrality

For Solar corona (10^{14} m^{-3}, $T_e = 10^6$ K), it is of 6.9 mm (but SC is not in TE)

An ionized gas, in general, is not a plasma, but plasma is an ionized gas

Screening of the Coulomb potential

Due to the well-known property of the Coulomb force, that particles of the opposite sign are attracted to each other, and those of the same sign are repelled, around each specific charged particle in a given gas plasma, **an uneven charge distribution is formed** in which particles of the opposite sign dominate – **a cloud of charges** is formed

The creation of such a charge distribution around each charged particle in the plasma is an important manifestation of the collective interaction

Screening of the Coulomb potential

All charged particles from the cloud itself move at their thermal speeds, and clouds structure and shape constantly change over time – the potential of the electrostatic field in the vicinity of an arbitrary charged particle in the plasma is not given by the standard Coulomb expression (in a vacuum) but has a significantly different dependence on distance

The electrostatic potential around each charged particle in the plasma will tend to zero faster than the classical Coulomb potential at distances greater than the Debye characteristic length

Screening of the Coulomb potential

Screening or shielding of the electrostatic field of charged particles in the plasma leads to the macroscopic (quasi) electroneutrality already on the spatial scales of the order of **ten Debye radii**

Strictly speaking, electrostatic field shielding is a manifestation of a collective process involving both electrons and ions

The characteristic Debye length of a gas plasma is often defined as follows:

$$r_{\mathrm{D}} = \left(\sum_{\alpha} \frac{1}{r_{\mathrm{D}\alpha}^2} \right)^{-1/2} , \quad r_{\mathrm{D}\alpha} = \sqrt{\frac{\varepsilon_0 k T_\alpha}{n_\alpha q_\alpha^2}}$$

For the case of classical, non-relativistic gas plasmas in TE, the Debye-Hückel potential was derived:

$$\Phi^{\mathrm{DH}}(r) = \frac{1}{4\pi\varepsilon_0} \frac{q}{r} e^{-r/r_{\mathrm{D}}}$$

Screening of the Coulomb potential

At distances of the order of several Debye radii, the electrostatic field of the particle is almost completely shielded (screened)

Each charged particle interacts only with those charged particles located in a sphere of radius of the order of Debye characteristic length around it

The effects of collective interaction (due to the considered shielding process) come to the fore only at the spatial scales larger than a few Debye radii

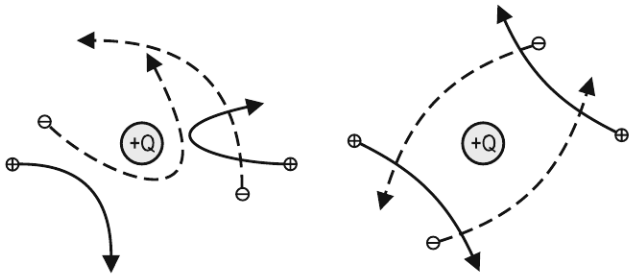
On spatial scales significantly larger than the Debye radius, the set of charged particles will be electroneutral, so that one of the criteria for establishing the plasma state can now be defined

$$L \gg r_{\mathrm{D}} \qquad\qquad \sum_{\alpha} q_{\alpha} n_{\alpha} \approx 0$$

Screening of the Coulomb potential

The Debye characteristic length increases with increasing temperature (thermal movement of charged particles is more intense), and decreases with increasing number density of charged particles (then the intensity of electromagnetic interaction increases)

With the increase of kT, the trajectory of the charged particle (in the electrostatic field of the second charge) will be more stretched – therefore, the shielding process will be less efficient, that is, the Debye radius will be larger



What is the average number of particles participating in the shielding process?

How many charged particles, in average, are in the Debye sphere?

Let's estimate the number of (free) electrons N_{De} in the Debye sphere of radius r_{De}

$$N_{\mathrm{De}} = \frac{4}{3}\pi r_{\mathrm{De}}^3 \cdot n_{\mathrm{e}} \propto \frac{T_{\mathrm{e}}^{3/2}}{n_{\mathrm{e}}^{1/2}}$$

The Coulomb coupling parameter Γ is defined as the ratio of the mean electrostatic potential energy per particle to the mean thermal energy per particle – this parameter describes the extent to which the energy of the electrostatic interaction affects the dynamics of individual particles in the system – if we only observe electrons then we can write

$$\Gamma_{\mathrm{e}} = \frac{q_{\mathrm{e}}^2}{4\pi\varepsilon_0 r_{\mathrm{WS_e}} k T_{\mathrm{e}}}, \quad r_{\mathrm{WS_e}} = \left(\frac{3}{4\pi n_{\mathrm{e}}}\right)^{1/3} \approx n_{\mathrm{e}}^{-1/3}$$

If the unit of volume contains *n* particles of some kind, then one particle on the average has n^{-1} space at disposal

If that volume is cube → mean particle distance is $n^{-1/3}$

If that volume is ball → mean particle distance is

$$r_{\mathrm{WS_e}} = \left(\frac{3}{4\pi n_{\mathrm{e}}}\right)^{1/3} \approx n_{\mathrm{e}}^{-1/3}$$

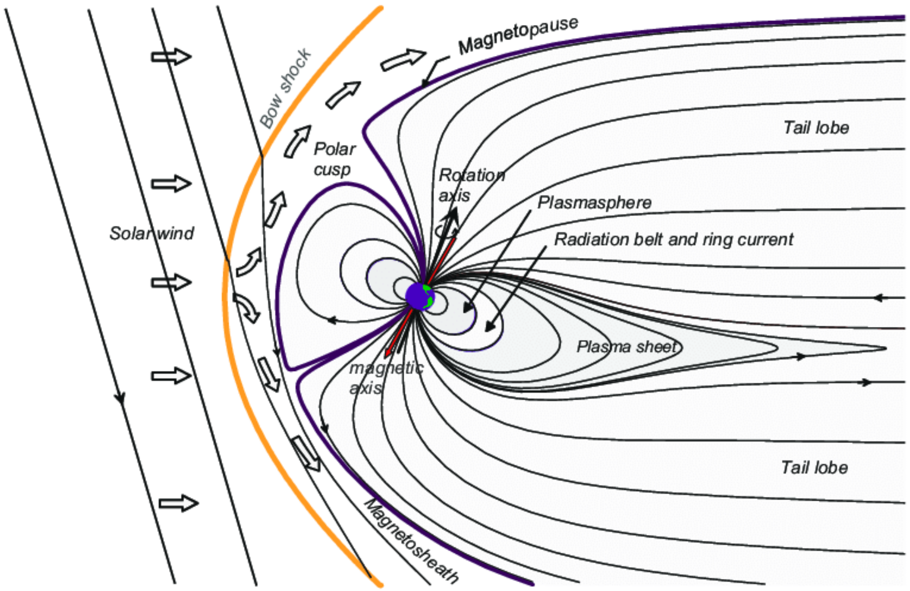
We are only interested in **weakly coupled plasmas**

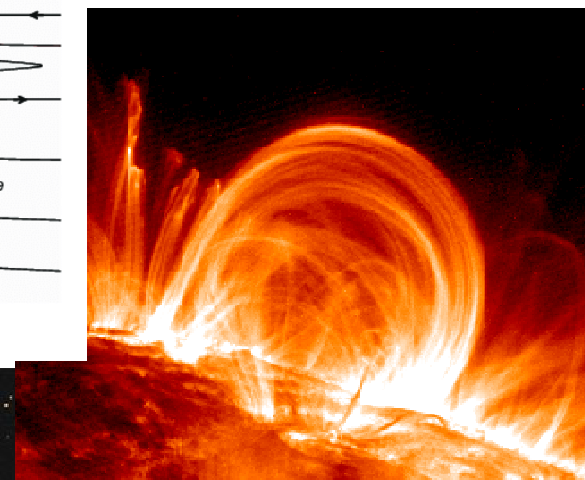
$$\Gamma \ll 1$$

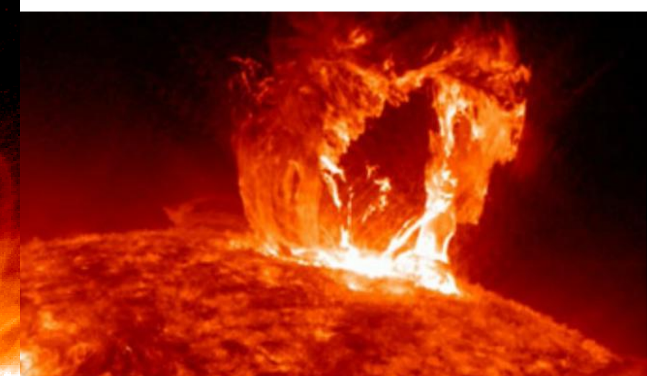
$$\Gamma_{\mathrm{e}} = \frac{1}{3} N_{\mathrm{De}}^{-2/3} \propto \frac{n_{\mathrm{e}}^{1/3}}{T_{\mathrm{e}}}$$

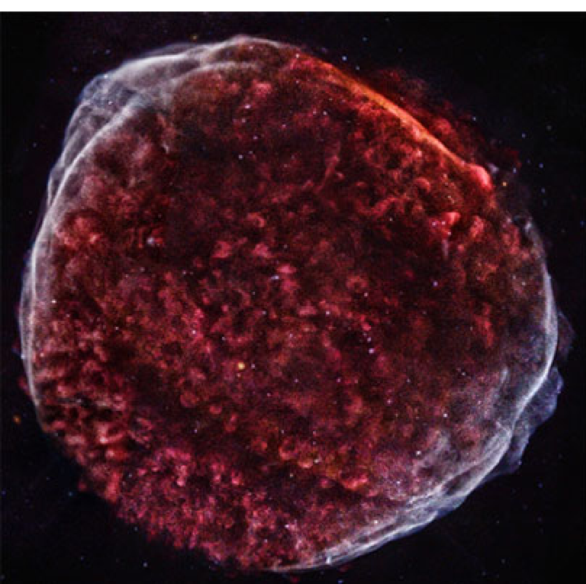
$$N_{\mathrm{D}} \gg 1$$

$$\Lambda = 3N_{\mathrm{D}}/4\pi$$







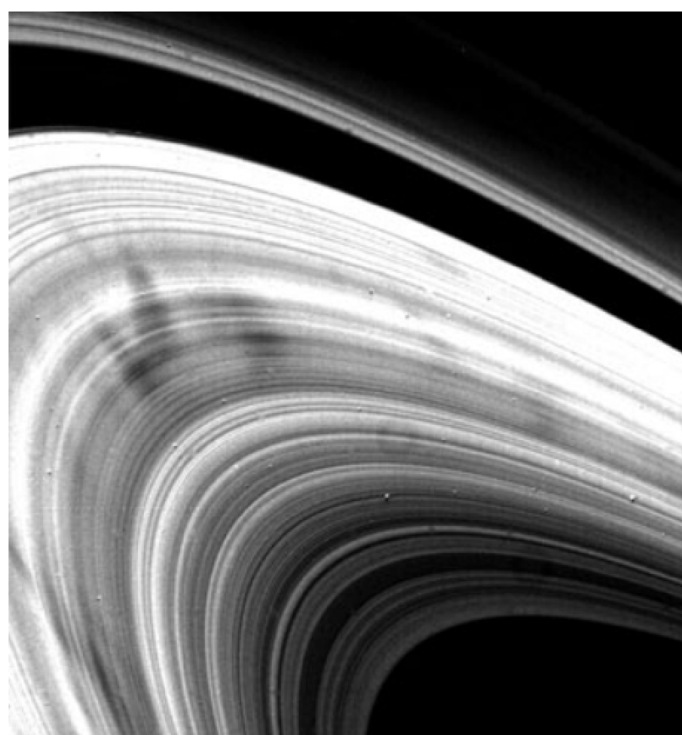


The presence of multiply charged particles of interstellar dust ($q > 100|q_e|$) can significantly change the characteristics of the plasma in which they are located – in this case, the value of Γ (which depends on the charge) can be additionally increased

Dust in plasma vs. dusty plasma

Dusty plasmas will not be discussed further, but it should be noted that they are also present in the universe (planetary rings, comets, the Zodiac cloud, interstellar matter, protostellar nebulae,...)

Fig. 1.13 Dark radial "spokes" were observed in Saturn's B-ring during the fly-by of the Voyager 2 spacecraft [30]. These structures are attributed to a collective motion of electrically-charged fine dust particles. (Courtesy NASA/JPL-Caltech)



Quantum effects begin to emerge when the mean inter-particle distance is of the order of the thermal de Broglie wavelength

$$T \lesssim \frac{h^2}{km} n^{2/3}$$

When the uncertainty in the position of plasma particles becomes comparable to their mean, mutual distance

The de Broglie wavelength for electrons is higher than for ions – quantum effects will, for this reason, be observed first in electrons

Degeneracy parameter for non-relativistic electrons

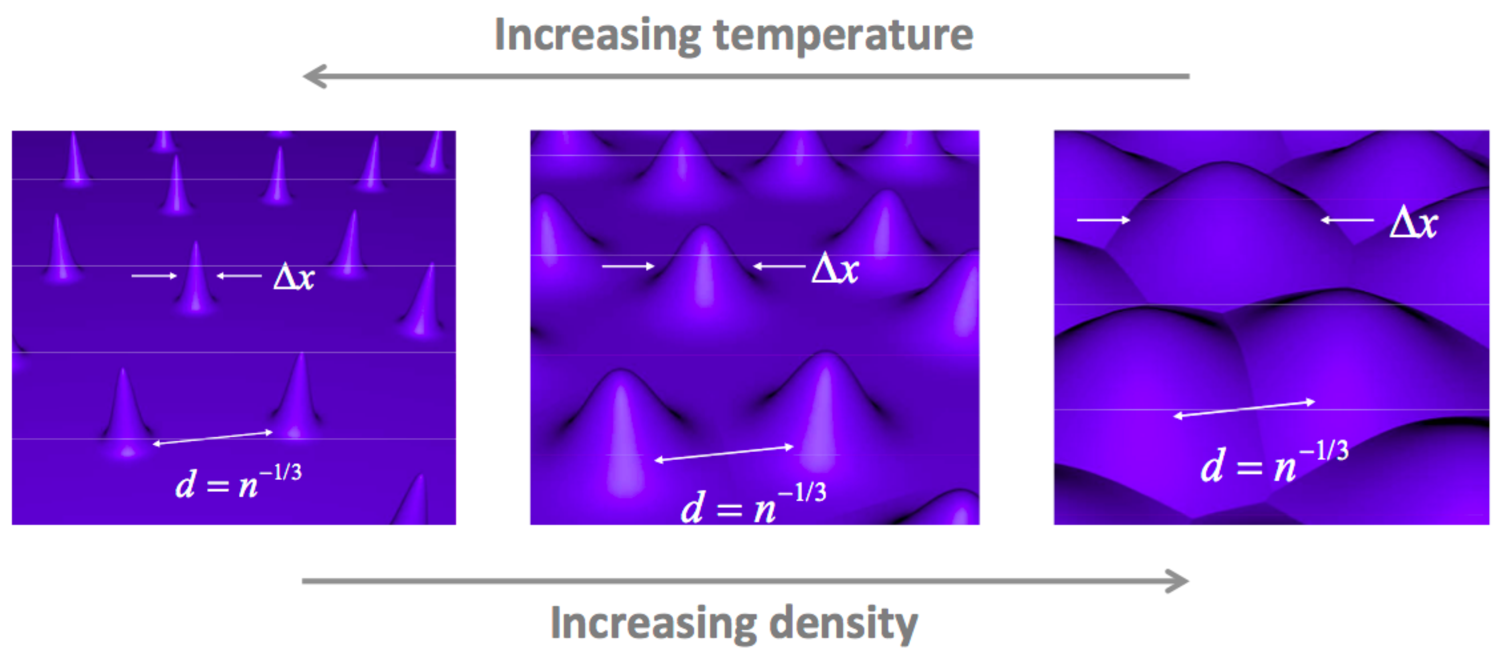
$$\theta_{\mathrm{de}} = \frac{kT_{\mathrm{e}}}{\epsilon_{\mathrm{F}}}, \quad \epsilon_{\mathrm{F}} = \frac{h^2}{8m_{\mathrm{e}}} \left(\frac{3n_{\mathrm{e}}}{\pi} \right)^{2/3}$$

$T_{\mathrm{e}} \gg T_{\mathrm{d}}$

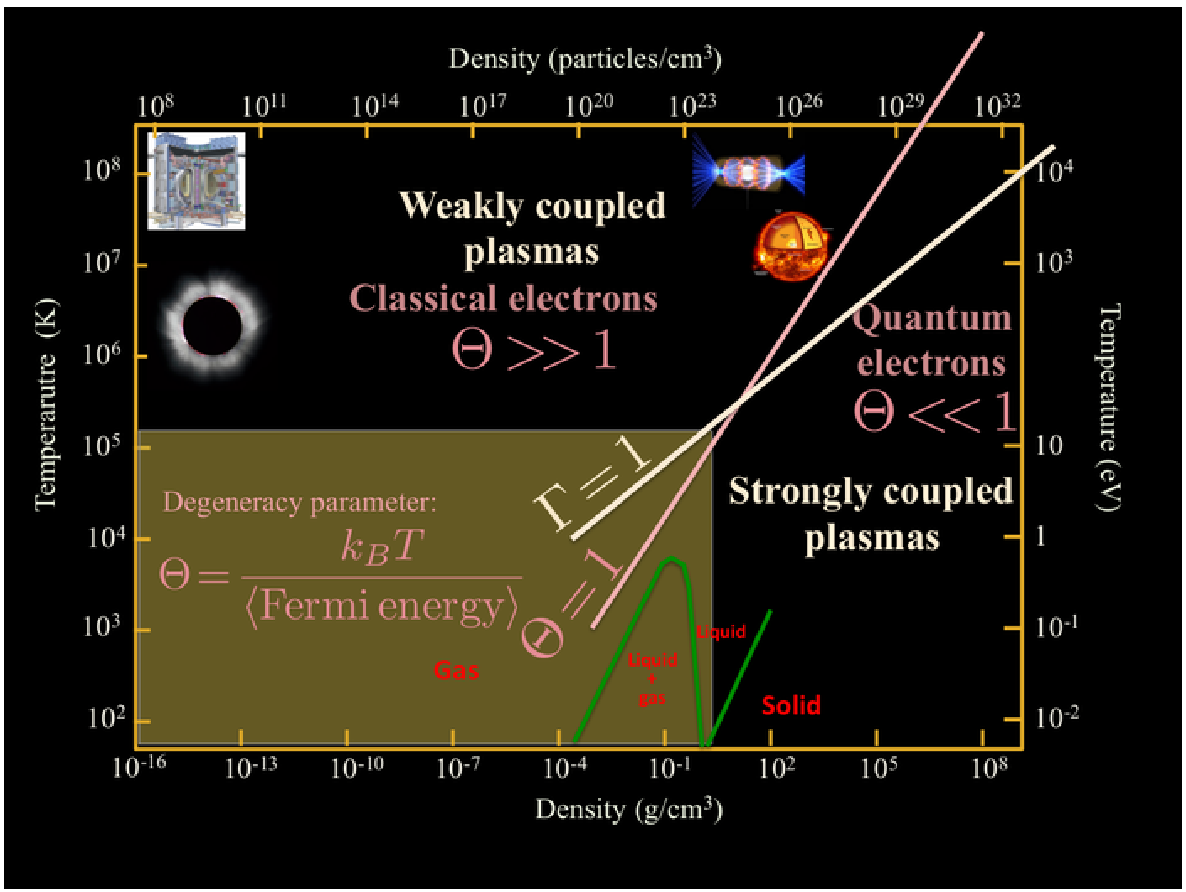
$\theta_{\mathrm{de}} \gg 1$

classical plasmas

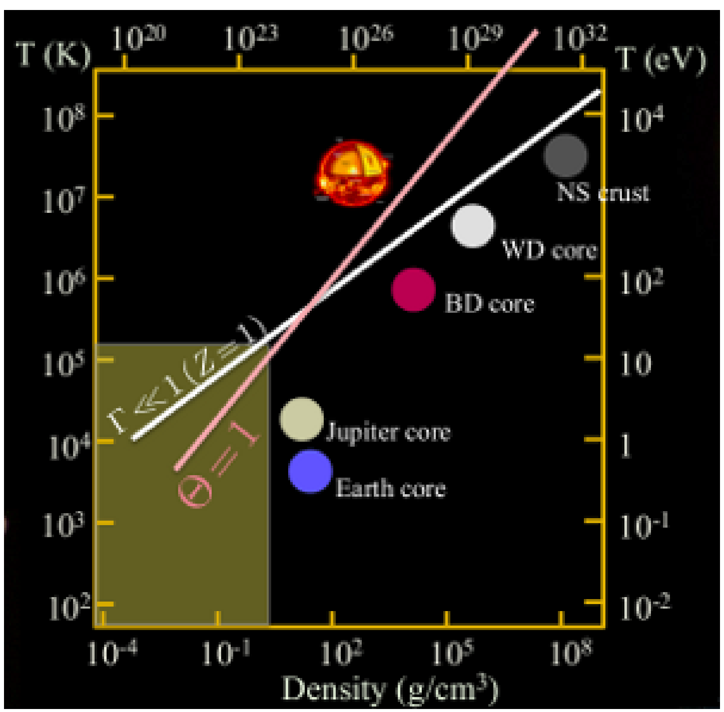
quantum plasmas (white and brown dwarfs, neutron stars)



Increasing temperature
Δx
Δx
Δx
d = n^{−1/3}
d = n^{−1/3}
d = n^{−1/3}
Increasing density



Density (particles/cm³)
10⁸ 10¹¹ 10¹⁴ 10¹⁷ 10²⁰ 10²³ 10²⁶ 10²⁹ 10³²
Weakly coupled plasmas
Classical electrons
Θ >> 1
Quantum electrons
Θ << 1
Strongly coupled plasmas
Γ = 1
Θ = 1
Degeneracy parameter:
Θ = k_B T / ⟨Fermi energy⟩
Gas
Liquid + gas
Liquid
Solid
Temperarutre (K)
10⁸ 10⁷ 10⁶ 10⁵ 10⁴ 10³ 10²
Temperature (eV)
10⁴ 10³ 10 1 10⁻¹ 10⁻²
10⁻¹⁶ 10⁻¹³ 10⁻¹⁰ 10⁻⁷ 10⁻⁴ 10⁻¹ 10² 10⁵ 10⁸
Density (g/cm³)



T (K)
T (eV)
10²⁰ 10²³ 10²⁶ 10²⁹ 10³²
10⁸ 10⁷ 10⁶ 10⁵ 10⁴ 10³ 10²
10⁴ 10² 10 1 10⁻¹ 10⁻²
NS crust
WD core
BD core
Jupiter core
Earth core
Γ ≪ 1 (Z = 1)
Θ = 1
10⁻⁴ 10⁻¹ 10² 10⁵ 10⁸
Density (g/cm³)

Pulsar magnetospheres, PWNs, AGNs, relativistic beams,… → relativistic plasmas

If we have TE system at $T>5.9\times10^9$ K ($kT_e > m_e c^2$) → relativistic

Pair creation and pair annihilation even at 10^8 K

$$\Gamma \ll 1$$

We are now only interested in **classical non-relativistic weakly coupled plasmas**

$$\Gamma_e = \frac{1}{3} N_{De}^{-2/3} \propto \frac{n_e^{1/3}}{T_e}$$

$$N_D \gg 1$$

$$\Lambda = 3N_D/4\pi$$

Electron plasma oscillations

A large number of different types of oscillations and waves (collective movements of particles) can be realized in the cosmic plasma

The study of such a coherent movement of plasma components is of great importance

The reference time period, i.e. the characteristic time scale in plasma dynamics is determined by the period of electronic plasma oscillations

We are talking about electrostatic oscillations that arise as a characteristic response of the plasma to a local violation of the macroscopic electroneutrality

The frequency of these oscillations is given by:

$$\omega_{\mathrm{pe}} = \sqrt{\frac{n_{\mathrm{e}} q_{\mathrm{e}}^2}{\varepsilon_0 m_{\mathrm{e}}}}, \quad \omega_{\mathrm{pe}} = 2\pi \nu_{\mathrm{pe}}$$

Electron plasma oscillations

Disturbance of the volume charge density in the plasma is accompanied by the establishment of a very strong electric field that provides the corresponding restitution force

Such a collective, oscillatory movement (consecutive transformations of electrostatic potential energy into kinetic energy of particles and vice versa) is led by electrons, due to a much smaller mass, i.e. greater mobility compared to other types of charged particles in the plasma

Although the mentioned, short-period separation of positive and negative charges is established (rapid oscillations of the volume charge density), if sufficiently slow processes in the plasma are considered, the system, in the average, can be considered quasi-neutral

We are interested in slow enough processes at time scales much larger than the period of electronic plasma oscillations

$$\tau \gg \tau_{\mathrm{pe}}$$

Collisions and plasma oscillations

Collisions between particles dampen any ordered motion, including oscillatory/wave motion

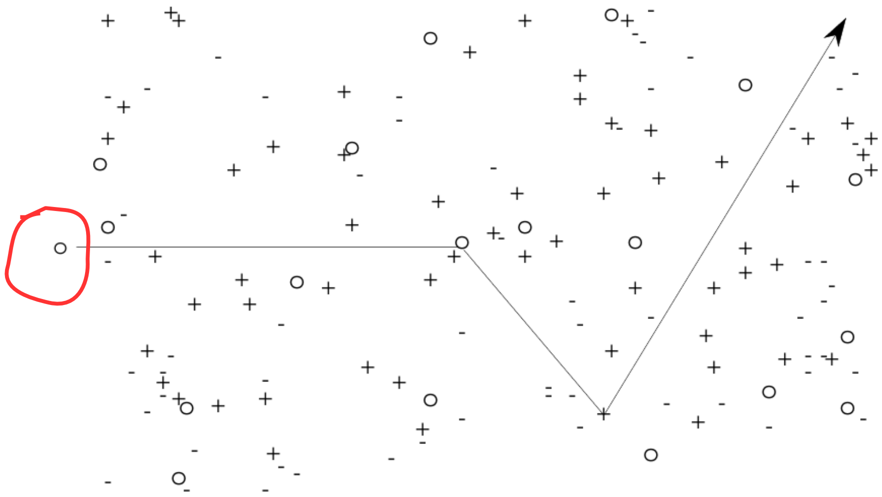
What will be the impact of the collision on the collective, plasma oscillations?

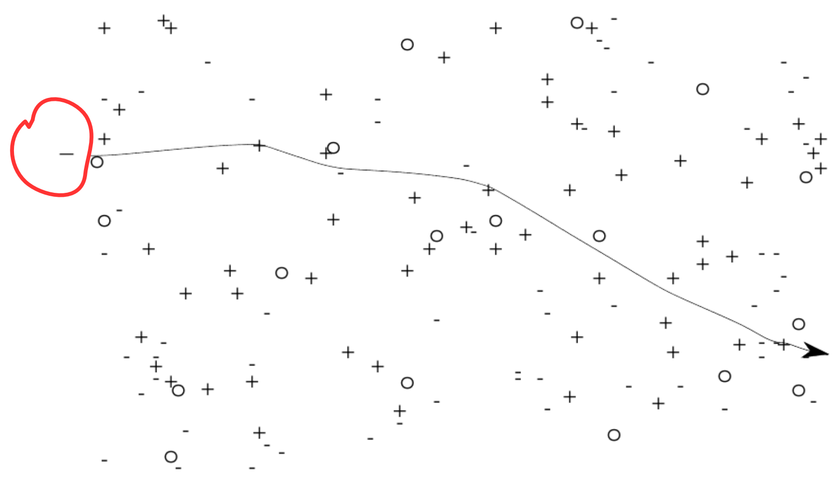
The movement of charged particles in a fully ionized plasma is significantly different in character from the thermal movement of atoms and molecules in a neutral gas

Particle trajectories in neutral gas are broken lines consisting of straight segments with sharp breaks (dominated by binary collisions in the case of short-range forces)

Trajectories of charged particles in the plasma are, due to the property of the Coulomb interaction, smooth, continuous curved lines

Collisions and plasma oscillations





Collisions and plasma oscillations

Due to the long-range nature of the Coulomb force, each charged particle in the plasma actually simultaneously interacts with all other charged particles within its local Debye sphere

However, such an interaction, due to the fact that the average electrostatic potential energy per particle is many times smaller than the average thermal energy per particle, rarely leads to a sudden change in the particle's motion

We can often treat this complex interaction in the approximation of a large number of independent binary Coulomb interactions

Collisions and plasma oscillations

An important property of the interaction of two charged particles in a plasma (Coulomb, binary elastic collisions) is that the most probable (most frequent) collisions are those that result in small scattering angles

In other words, collisions with a very small momentum transfer dominate – the so-called weak collisions

The scattering angle for this case is less than 90deg

On the contrary, strong collisions correspond to large scattering angles

Thus, the Coulomb interaction is highly anisotropic

Collisions and plasma oscillations

Unlike neutral gases, in the case of fully ionized plasmas, the momentum transfer collision frequency is defined as a measure of the frequency with which the trajectory of an charged particle of a certain type, due to Coulomb interaction with other particles of an arbitrary type, changes significantly, i.e. deviates by 90°

The mean free path of a charged particle in the plasma will be the length that particle needs to travel, colliding with other charges, so that its trajectory does change by 90°

Collisions and plasma oscillations

Collisional and collisionless plasmas $r_{\mathrm{mfp}} \ll L$

$$v_{\mathrm{th},\alpha} = \sqrt{\frac{kT_\alpha}{m_\alpha}}.$$

$$r_{\mathrm{mfp}} = v_{\mathrm{th}} \cdot \tau_{\mathrm{coll}}$$

$$v_{\mathrm{th,e}} = r_{\mathrm{De}} \cdot \omega_{\mathrm{pe}}$$

$$N_{\mathrm{De}} = \frac{4}{3}\pi r_{\mathrm{De}}^3 \cdot n_{\mathrm{e}} \propto \frac{T_{\mathrm{e}}^{3/2}}{n_{\mathrm{e}}^{1/2}} \qquad N_{\mathrm{D}} \gg 1$$

$$\Gamma_{\mathrm{e}} = \frac{1}{3} N_{\mathrm{De}}^{-2/3} \propto \frac{n_{\mathrm{e}}^{1/3}}{T_{\mathrm{e}}} \qquad \Gamma \ll 1$$

$$\Lambda = 3N_{\mathrm{D}}/4\pi \qquad \Lambda \gg 1$$

$$\omega_{\mathrm{coll}} \sim \frac{\ln\Lambda}{\Lambda} \cdot \omega_{\mathrm{p}}, \quad \Lambda \propto \frac{(kT)^{3/2}}{n^{1/2}} \qquad \omega_{\mathrm{p}\alpha} \gg \omega_{\mathrm{coll},\alpha}$$

$$\omega_{\mathrm{coll,en}} \propto n_{\mathrm{n}}\sqrt{T_{\mathrm{e}}} \qquad \tau_{\mathrm{pe}} \ll \tau_{\mathrm{coll,en}}$$ if there are neutrals

$$r_{\mathrm{mfp}} = v_{\mathrm{th}} \cdot \tau_{\mathrm{coll}}$$

$$v_{\mathrm{th},\alpha} = \sqrt{\frac{kT_\alpha}{m_\alpha}}.$$

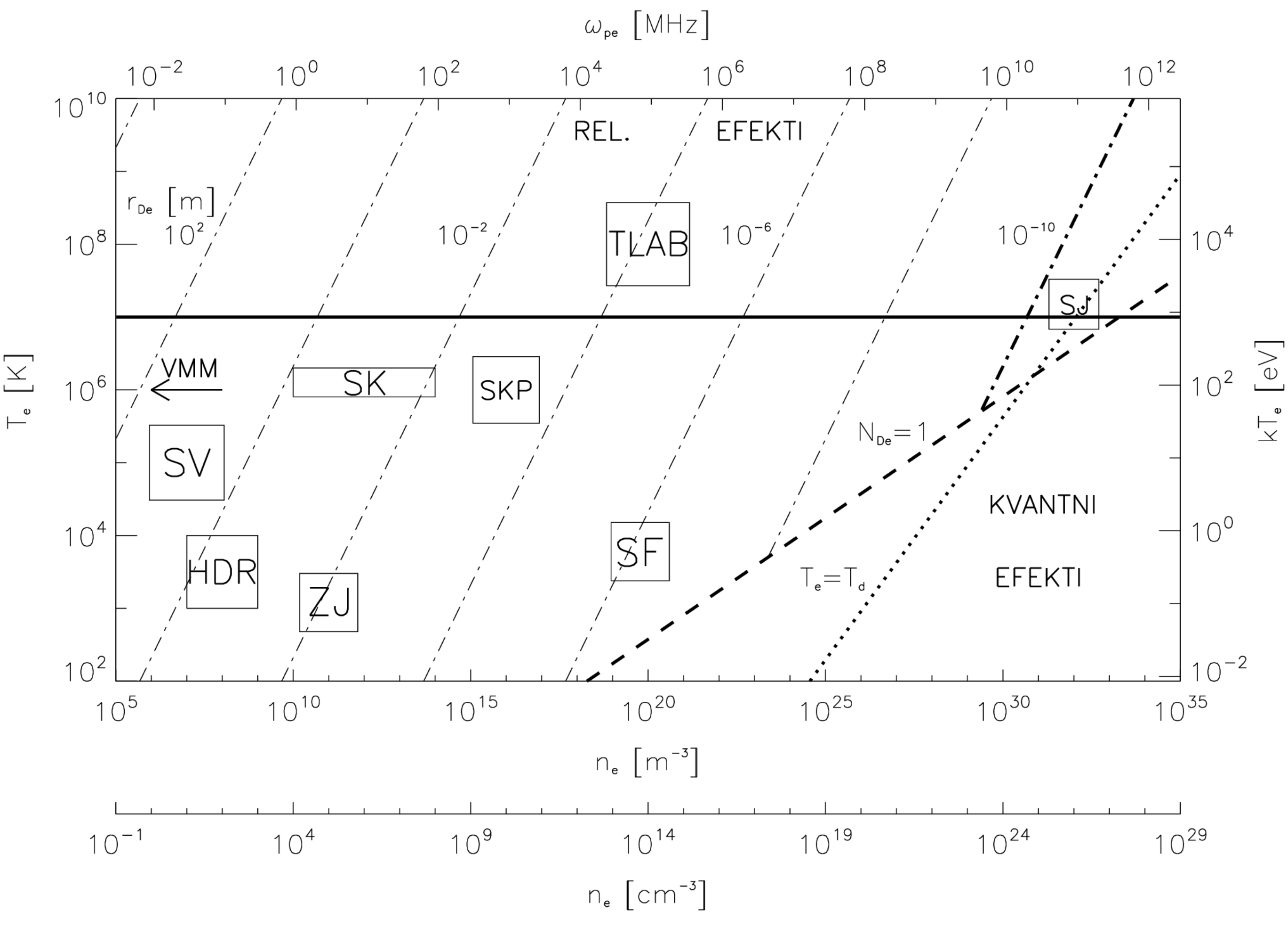
$$\omega_{\mathrm{coll}} \sim \frac{\ln \Lambda}{\Lambda} \cdot \omega_{\mathrm{p}}, \quad \Lambda \propto \frac{(kT)^{3/2}}{n^{1/2}}$$

$$v_{\mathrm{th,e}} = r_{\mathrm{De}} \cdot \omega_{\mathrm{pe}}$$

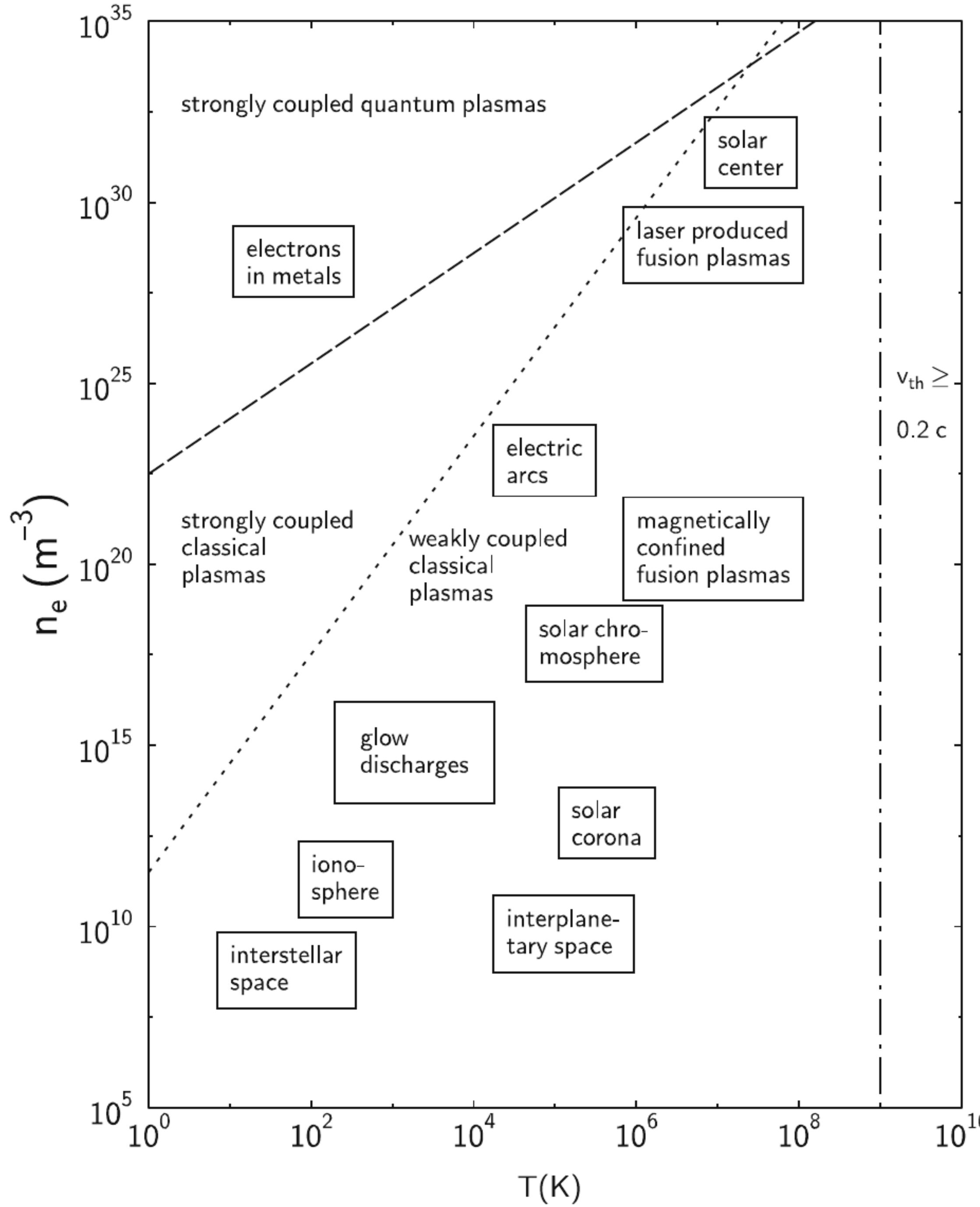
$$\Lambda \gg 1$$

$$r_{\mathrm{mfp}}/r_{\mathrm{D}} \gg 1$$

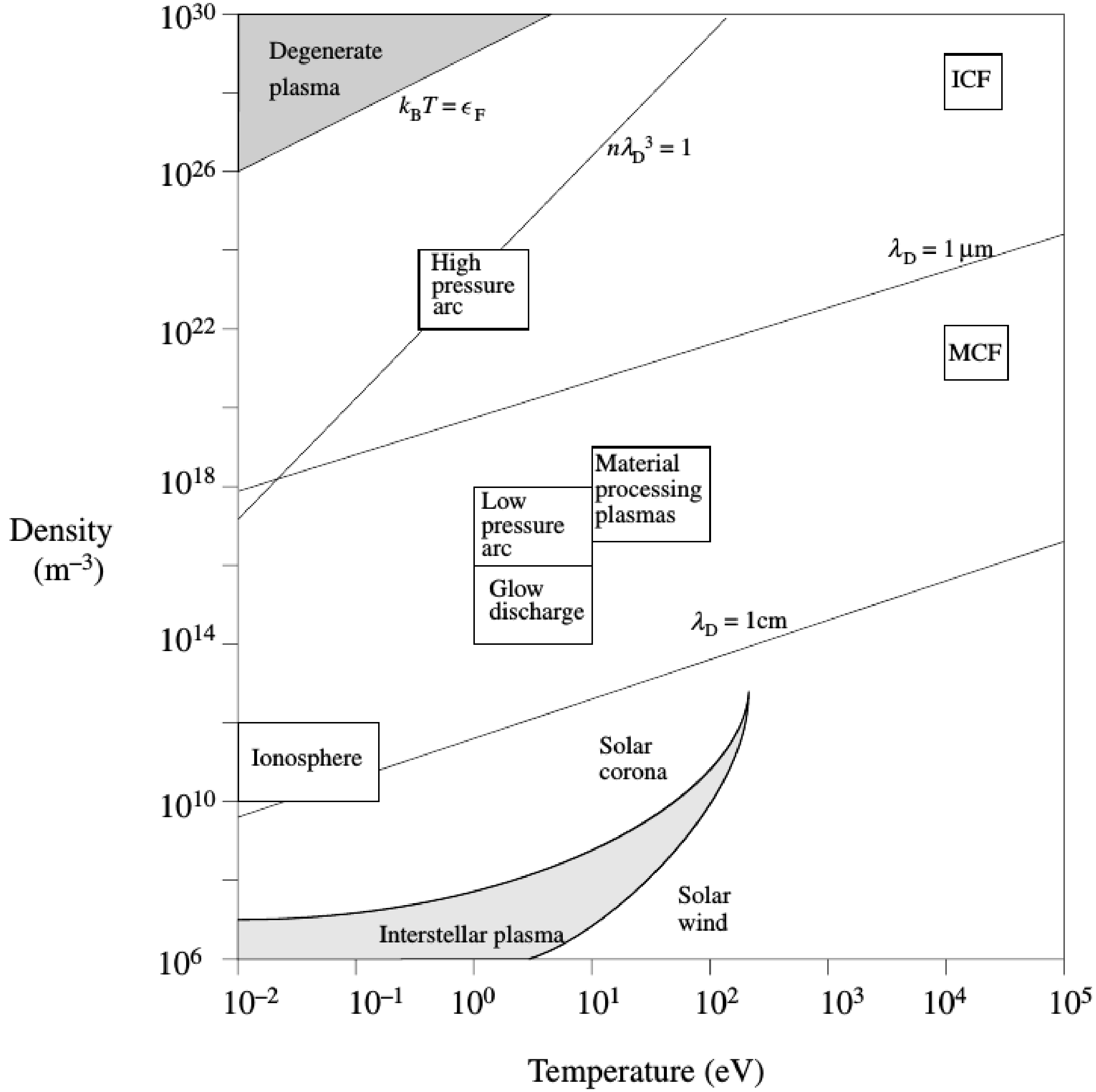
n-*T* diagram



ωpe [MHz]
10−2
10^0
10^2
10^4
10^6
10^8
10^10
10^12
REL.
EFEKTI
rDe [m]
10^2
10−2
10−6
10−10
TLAB
SJ
VMM
SK
SKP
SV
NDe=1
KVANTNI
EFEKTI
HDR
ZJ
SF
Te=Td
Te [K]
kTe [eV]
ne [m−3]
ne [cm−3]



strongly coupled quantum plasmas
solar center
laser produced fusion plasmas
electrons in metals
$v_{th} \geq$ 0.2 c
electric arcs
strongly coupled classical plasmas
weakly coupled classical plasmas
magnetically confined fusion plasmas
solar chro-mosphere
glow discharges
solar corona
iono-sphere
interplane-tary space
interstellar space
n_e (m^{-3})
T(K)
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}



Degenerate plasma
$k_B T = \epsilon_F$
$n\lambda_D^3 = 1$
ICF
High pressure arc
$\lambda_D = 1\,\mu m$
MCF
Material processing plasmas
Low pressure arc
Glow discharge
$\lambda_D = 1cm$
Ionosphere
Solar corona
Solar wind
Interstellar plasma
Density (m^{-3})
10^{30}
10^{26}
10^{22}
10^{18}
10^{14}
10^{10}
10^{6}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Temperature (eV)