Physics of low-temperature plasmas

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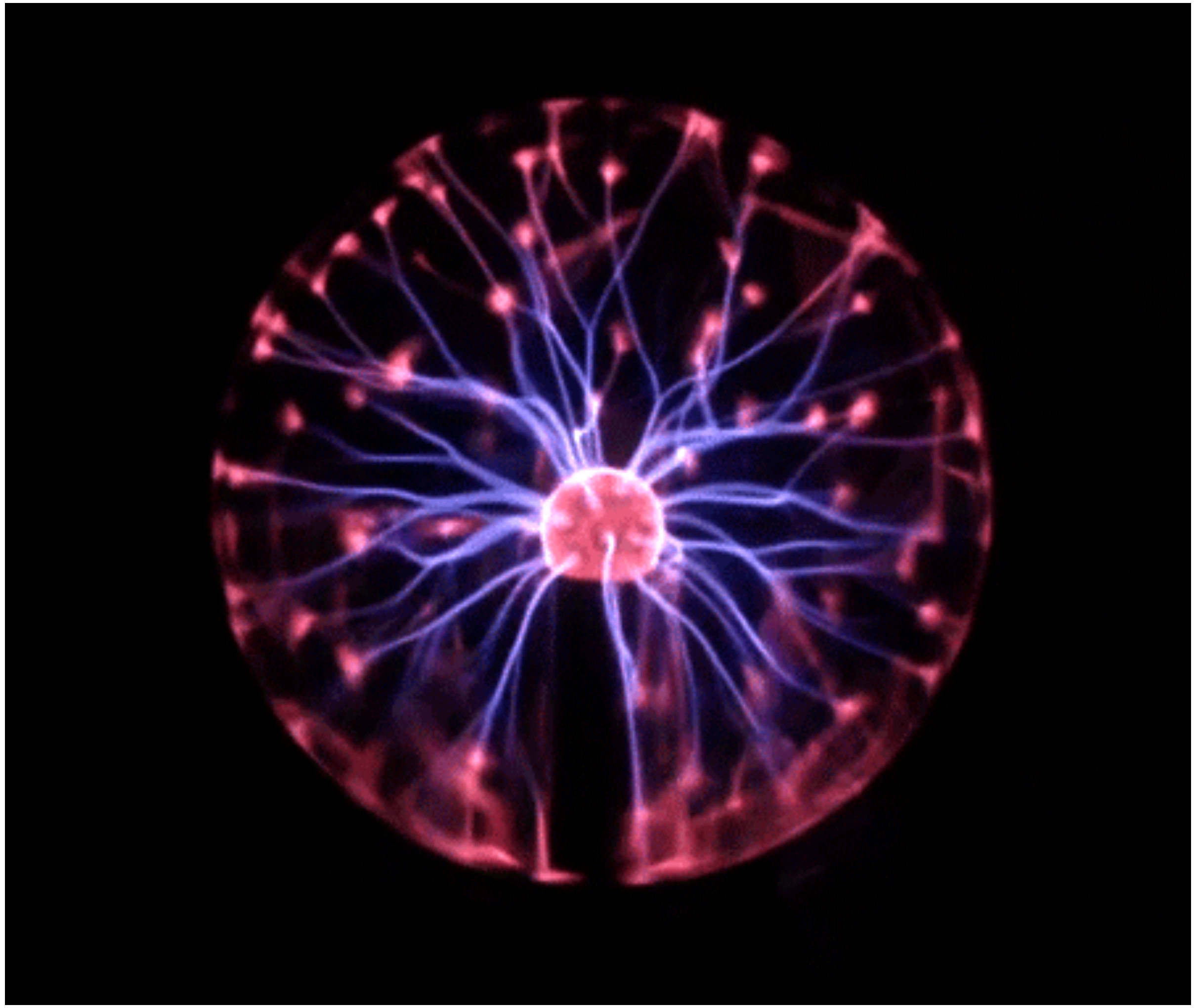
Introduction: setting the stage

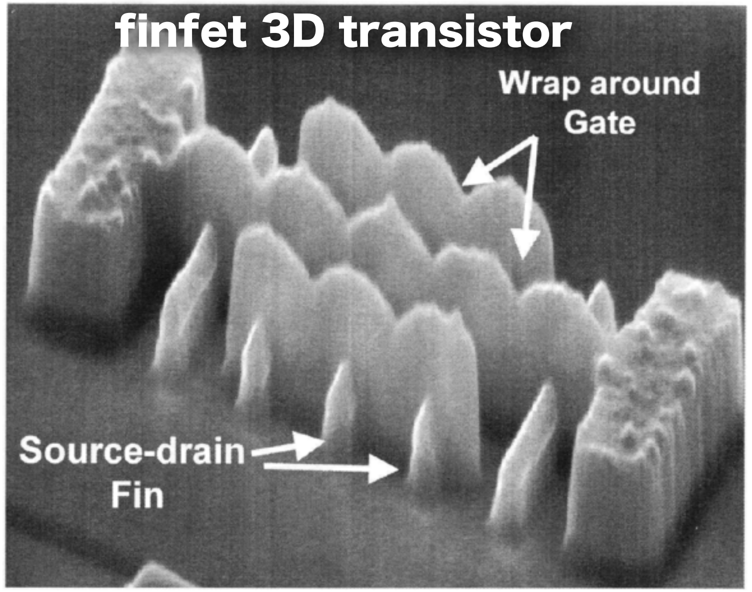
PHYSICS of low temperature plasmas

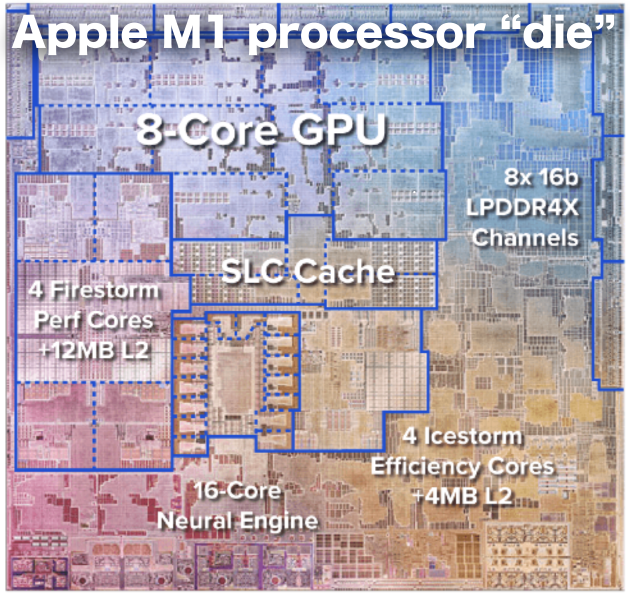
- thermodynamics
- statistical mechanics
- fluid dynamics
- classical mechanics
- waves
- electricity and magnetism
- atomic physics
- quantum
- chemistry



https://gfycat.com/gifs/search/plasma+globe

Low temperature plasmas at work





< 9 mm

16 B transistors

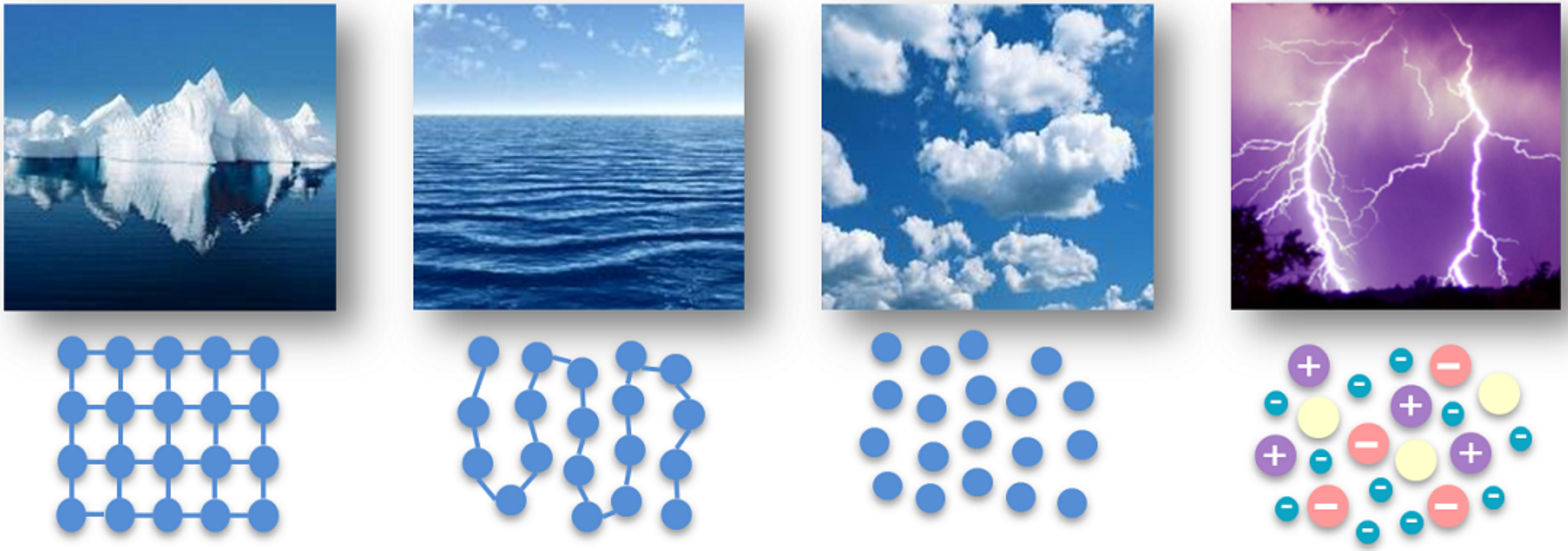
https://www.flickr.com/photos/dlr_de/41361769882/in/album-72157693770479701/

What is a low temperature plasma?

- What is a plasma?
- What is temperature?
- In what sense is the temperature *low*?

Plasma as the 4th state of matter

Solid | Liquid | Gas | **Plasma**



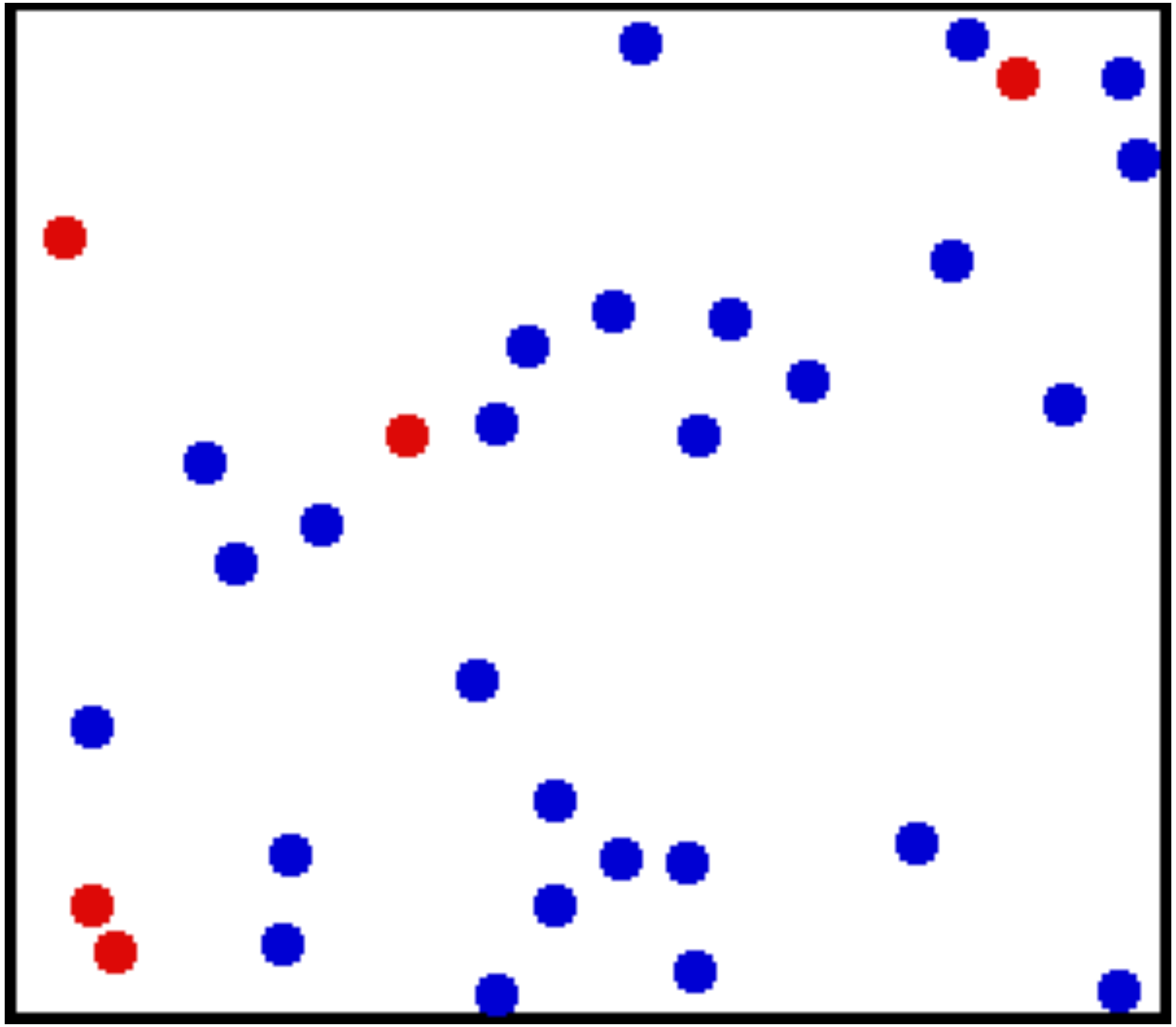
Deformable | Compressible | Conductive

http://www.grinp.com/plasma/physics.html

What is a low temperature plasma?

Temperature: elastic collisions *thermalize* populations

- ***elastic* collisions** - particles "bounce" off one another; kinetic energy is conserved
- energy becomes randomly distributed among the particles over time - this is *thermal equilibrium*



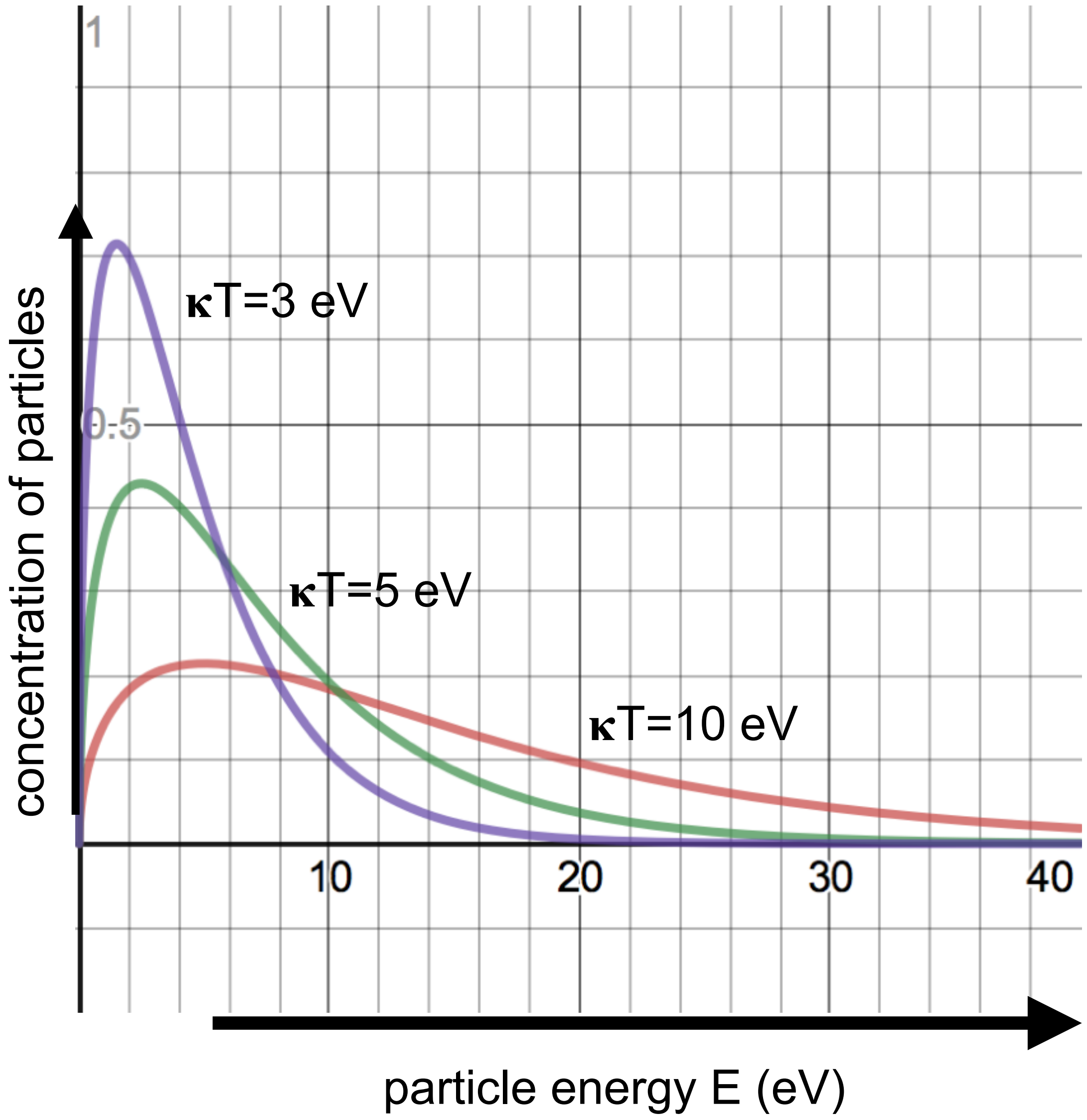
A. Greg (Greg L at English Wikipedia) / Public domain

Thermal Equilibrium

- System energy is randomly distributed among particles through collisions
- Pairs of particles exchange energy in collisions, but for the system as a whole, the relative numbers of particles for each energy does not change.
- The shape of the distribution can be represented by a single parameter - temperature T
- Called “Maxwell-Boltzmann” or “Maxwellian” distribution

$$g(E) = 4\pi n(2\pi\kappa T)^{-3/2}\sqrt{2E}\exp\left(-\frac{E}{\kappa T}\right)$$

- $\kappa = 8.6 \times 10^{-5}\,\mathrm{eV/K}$ is the Boltzmann constant
- electron volts (eV) are units of energy
- $1\,\mathrm{eV} \simeq 1.6 \times 10^{-19}\,\mathrm{J}$
- $\kappa T = 1\,\mathrm{eV}$ corresponds to $T \sim 11{,}600\,\mathrm{K}$

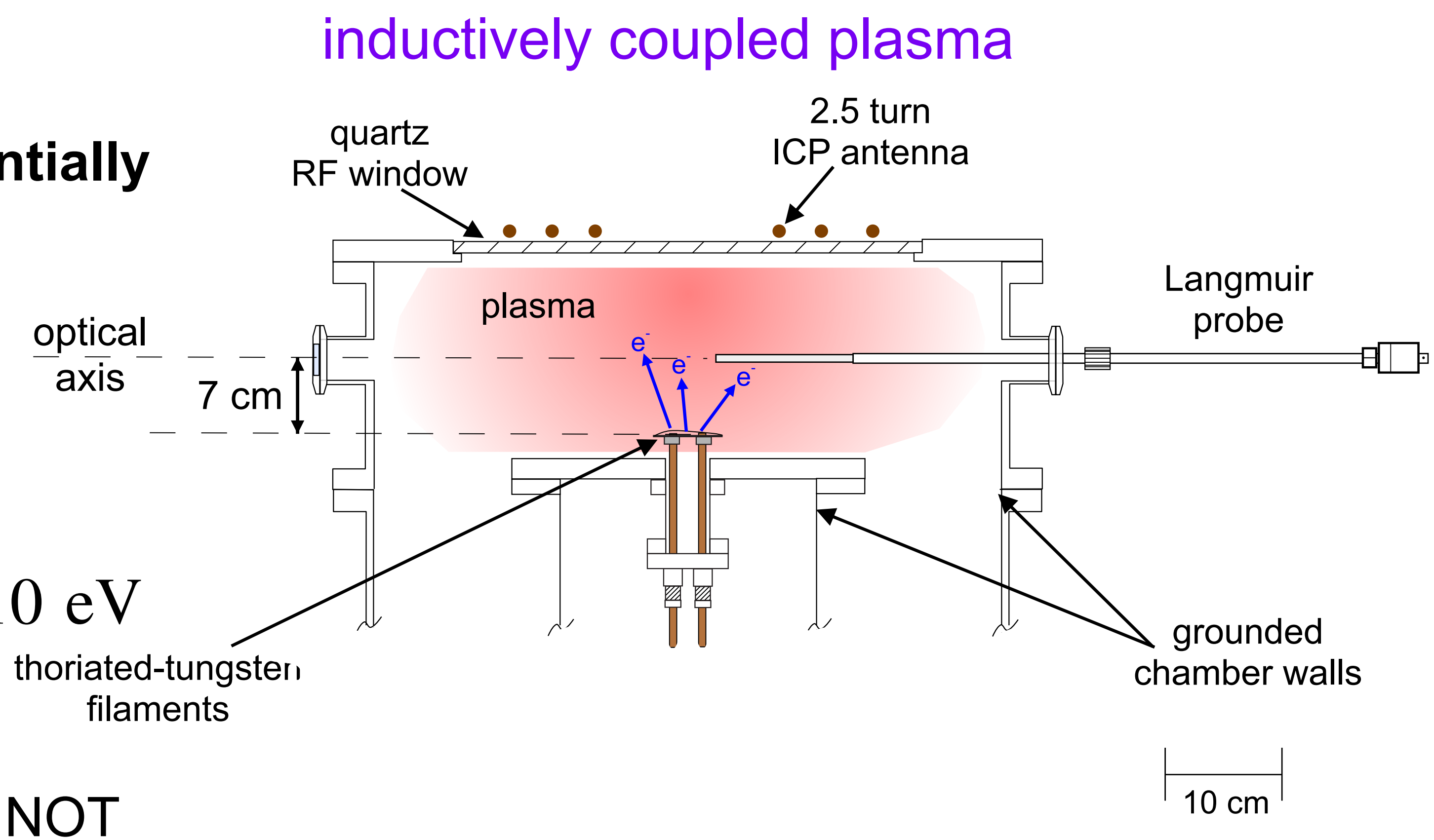


Temperature case study: inductively coupled plasma

- AC currents in spiral antenna produce high frequency electric fields inside plasma volume
- **electrons (low mass!) are preferentially accelerated by electric fields**:
  - Lorentz Force

$$\vec{a} = \frac{\vec{F}}{m} = \frac{q}{m}\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

  - and heated
- electrons thermalize to $\kappa T_e \sim 1 - 10 \text{ eV}$
- atoms and ions remain near room temperature
- Many low temperature plasmas are NOT in thermal equilibrium: $T_e > T_{\text{ion}} \simeq T_{\text{gas}}$



Elastic collisions: low-temp plasmas are often *not* in thermal equilibrium

electron

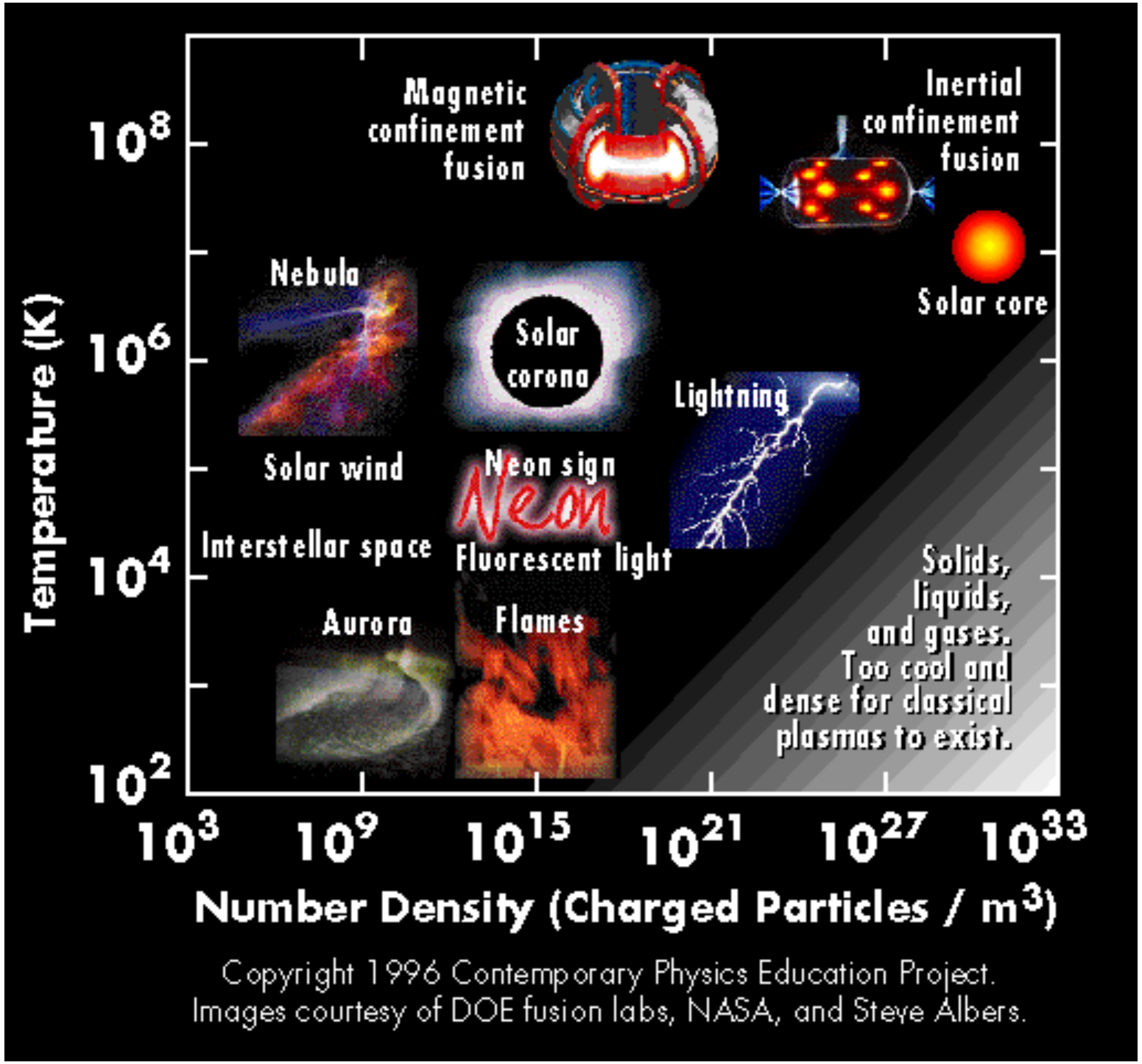
*Unequal masses: kinetic energy transfer is **weak***

electron

electron

Equal masses: kinetic energy transfer is very efficient

High and low temperature (*it's all relative!*) plasmas



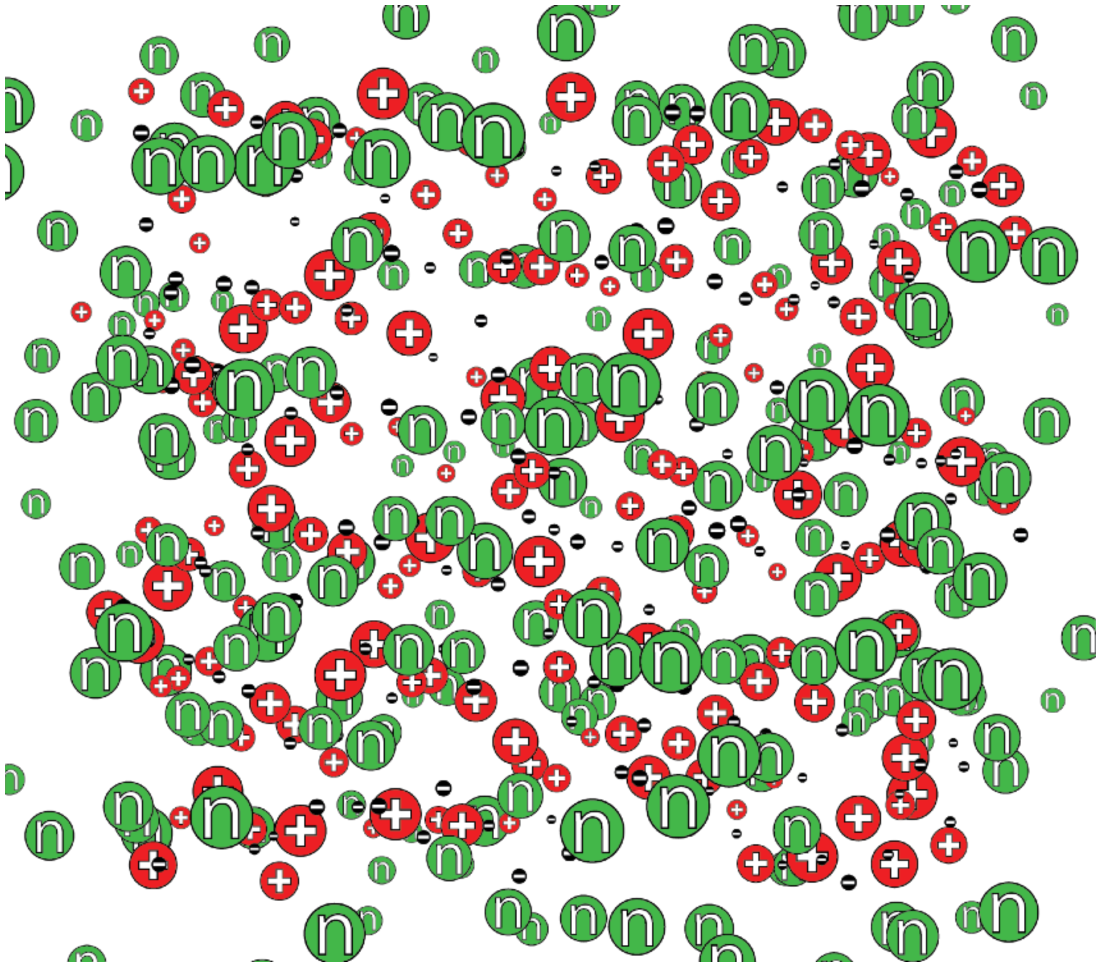
High temperature vs. low temperature plasmas

	High T	Low T
usually fully ionized?	yes	no
collisions with neutrals?	rare	frequent
plasma waves	likely	damped by collisions
surface boundaries?	rare	common
fusion reactions	maybe	no

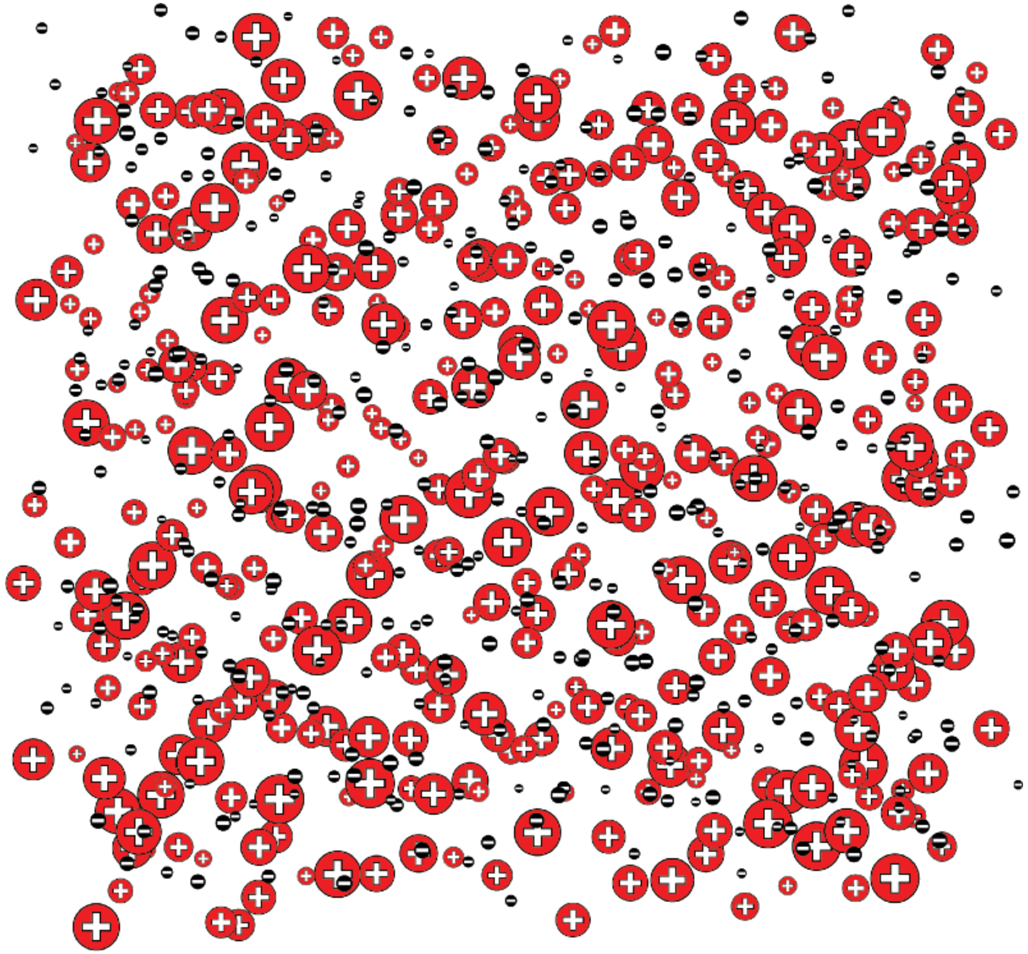
Low temperature plasma superpowers: #1 Electron-neutral collisions

Low-temperature plasmas are often *partially* ionized

Partially ionized plasma

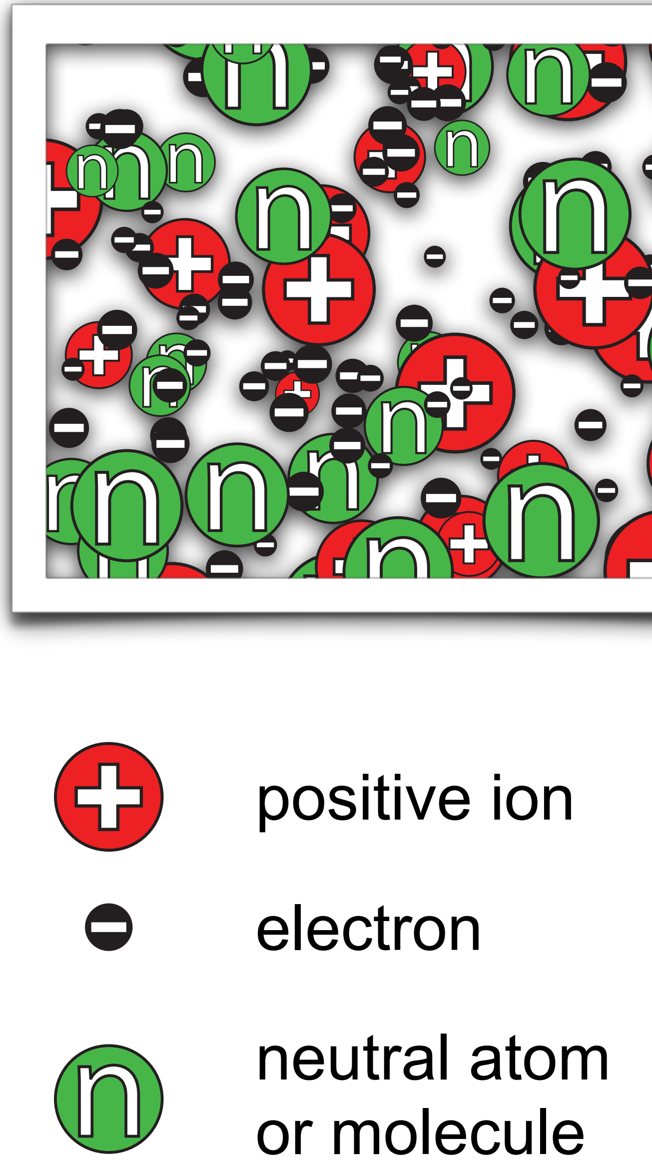


Fully ionized plasma



Partially ionized plasmas

- Collisions between electrons and neutral particles play *really, really* important roles
- Electron-neutral inelastic collisions:
  - ionization - sustains plasma
  - excitation - results in photon emission
  - dissociation - exotic chemistries



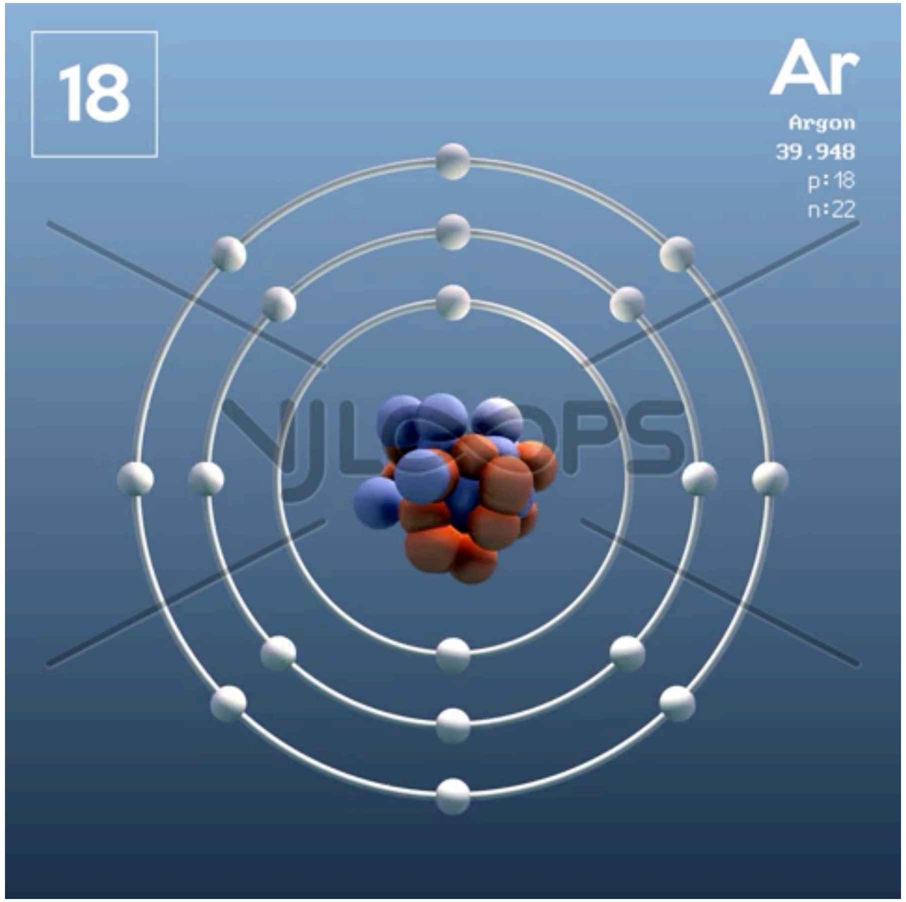
Where does the energy go in partially ionized plasmas??

- kinetic energy $= \frac{1}{2} m v^2$

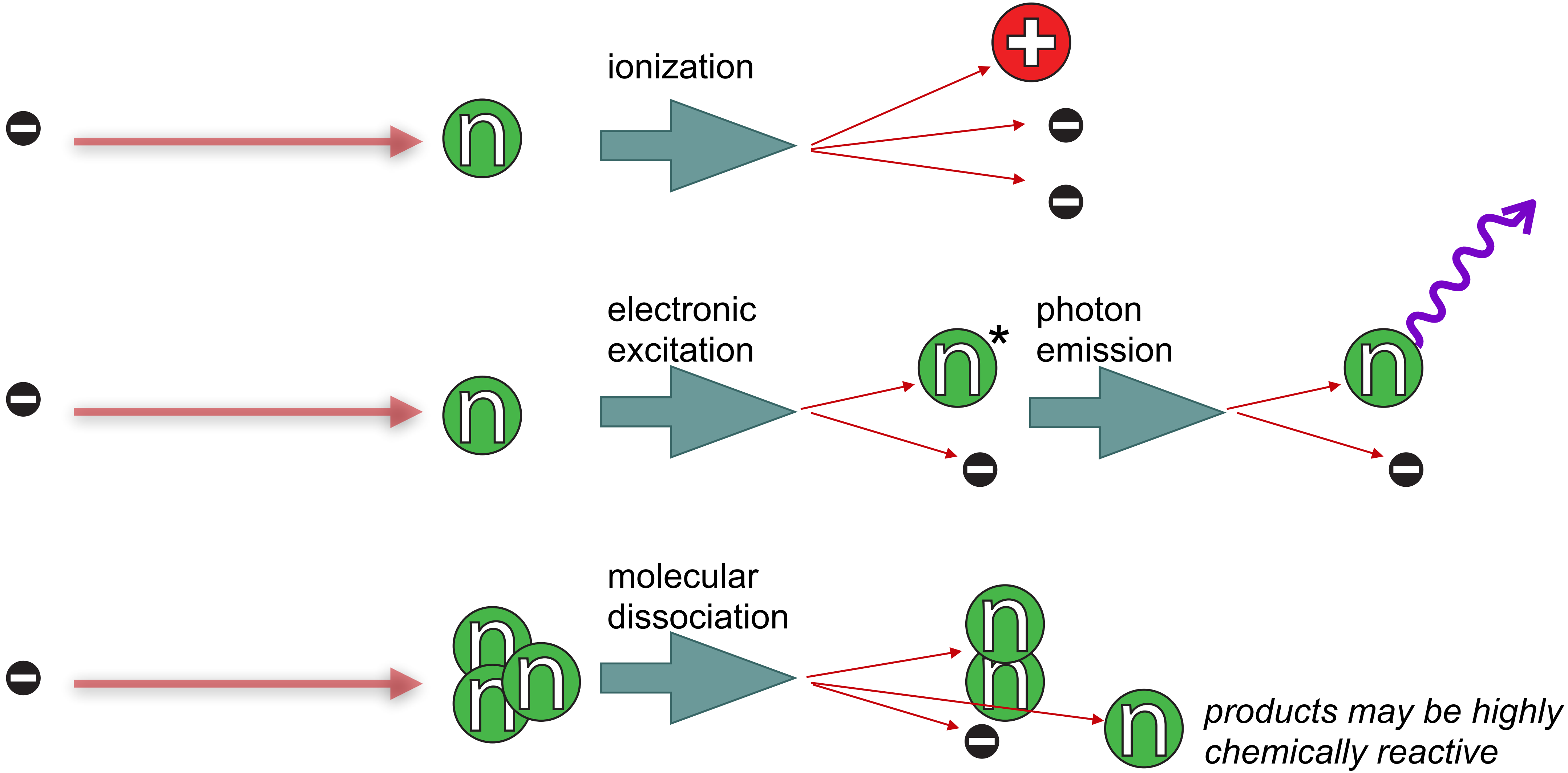
- acceleration in EM fields:
$$\vec{F} = m\vec{a} = m\frac{\mathrm{d}v}{\mathrm{d}t} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$
- electrons gain energy more readily from electric fields
- electron mass is smaller, but velocity is bigger
- electrons have high kinetic energy
- elastic collisions thermalize electron population
- *inelastic* electron-neutral collisions consume electron kinetic energy with important outcomes

Inelastic electron-neutral collisions

- If free electron kinetic energy is sufficiently high, it may be utilized in several ways upon collision



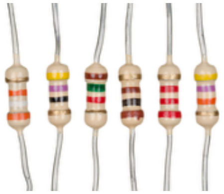
Electron-neutral inelastic collisions:
what happens to electron kinetic energy?

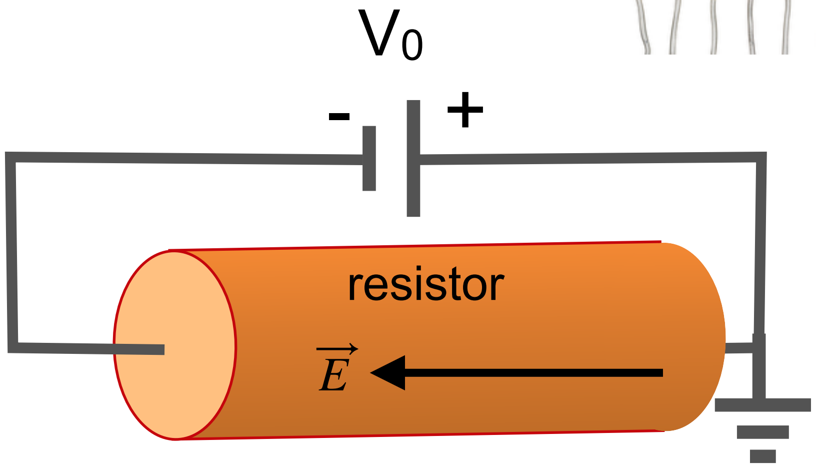


Low temperature plasma superpowers:
#2 Surfaces and plasma sheaths

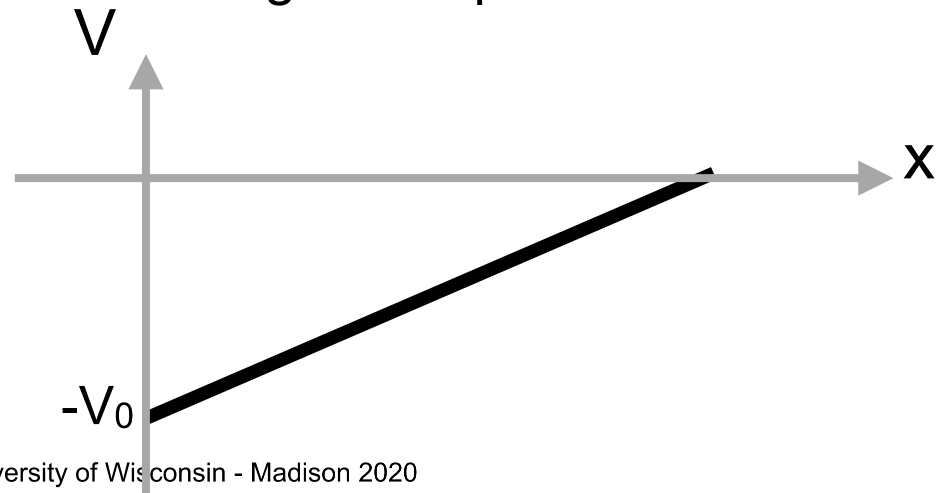
Potential (voltage) profile across plasma - **sheaths** form next to surfaces

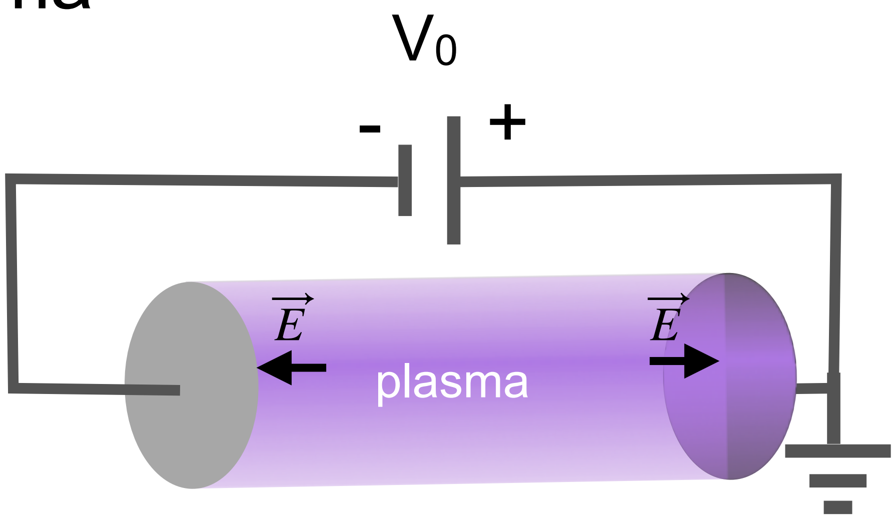
- Contrast plasma to resistor

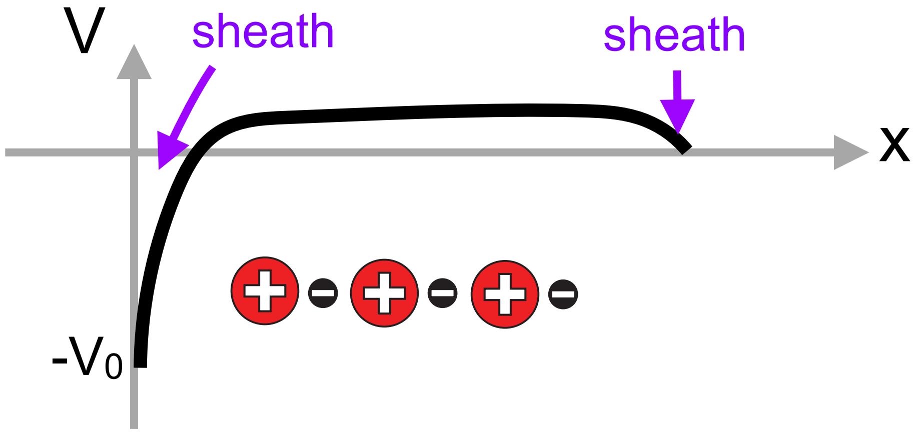




- Resister voltage axial profile is *linear.*



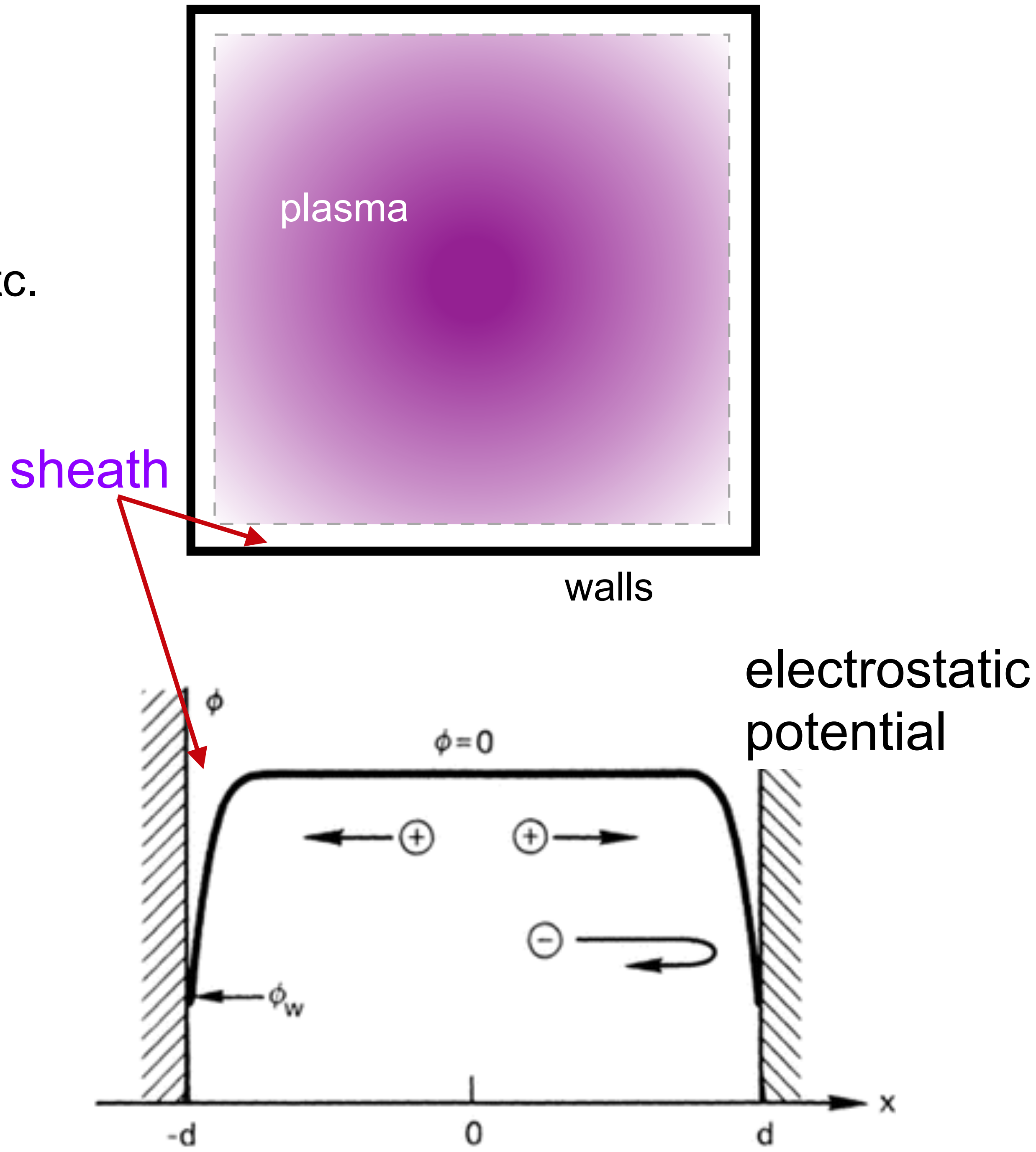




Positive and negative charges respond to electric field, forming sheaths at electrodes. Ions accelerate into negative electrode

What is a plasma sheath?

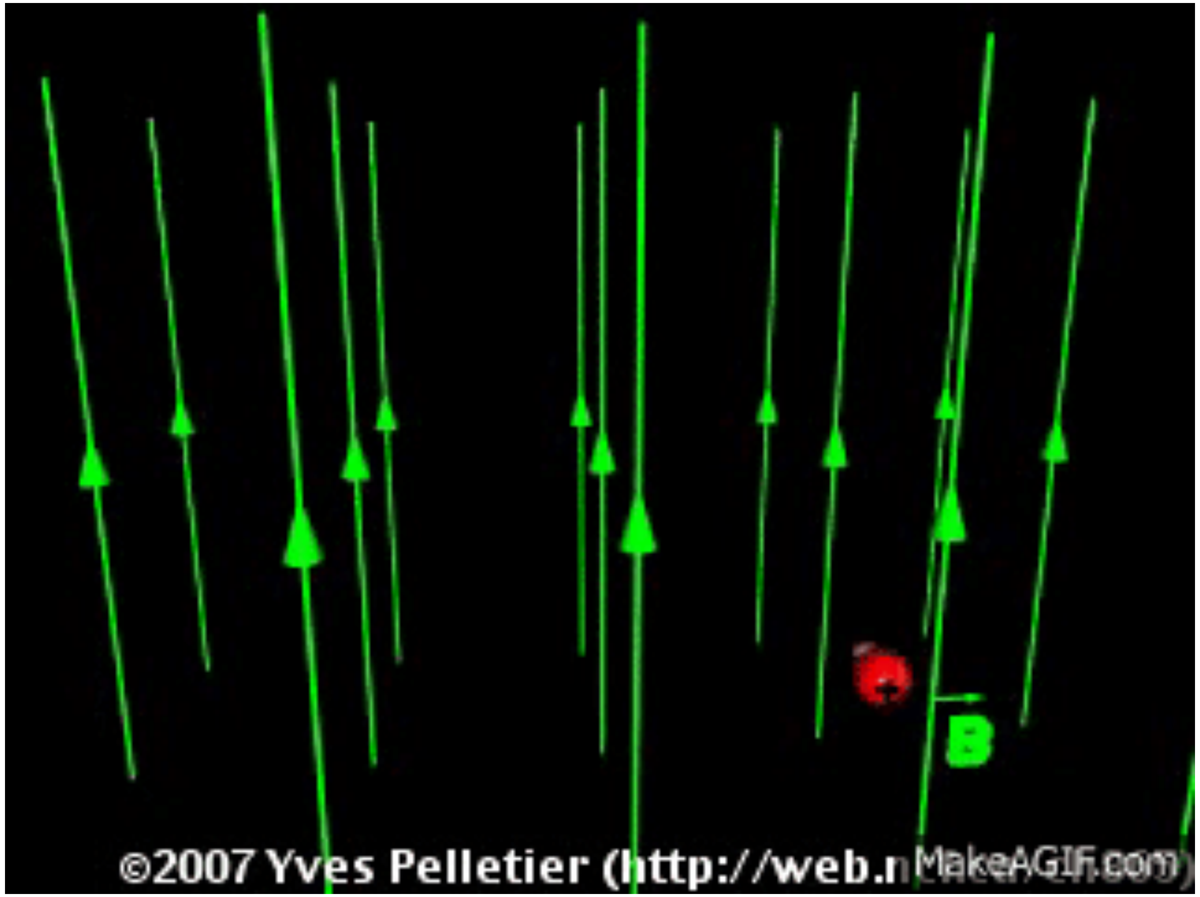
- Plasma sheath is a boundary layer between plasma and solid surface:
  - container wall,electrodes, substrate, etc.
- *Interior* of plasma volume:
  - Charges shift position to maintain charge balance
  - electric field weak due to shielding by plasma
- **Sheath region**
  - Strong electric field
  - plasma density low
  - unequal positive and negative charge densities
  - **ions *accelerated* into surfaces**
    - **removal of surface material**
    - **ion implantation**



Low temperature plasma superpowers: #3 Magnetic fields and low-T plasmas

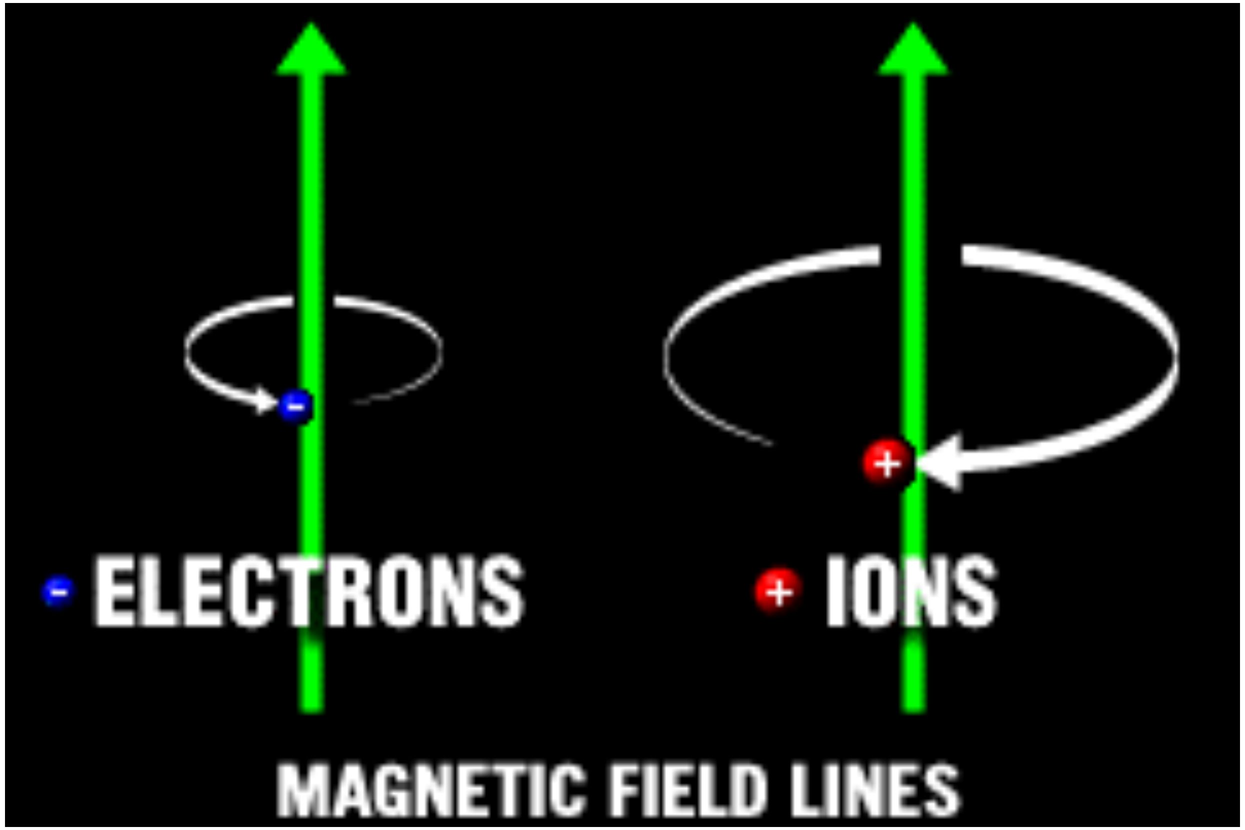
Partially ionized plasmas: charged particles in magnetic field

- In the absence of collisions
  - charges in magnetic field undergo helical orbits
  - “guiding centers” follow magnetic field lines - **magnetic confinement**



Charged particles in magnetic fields

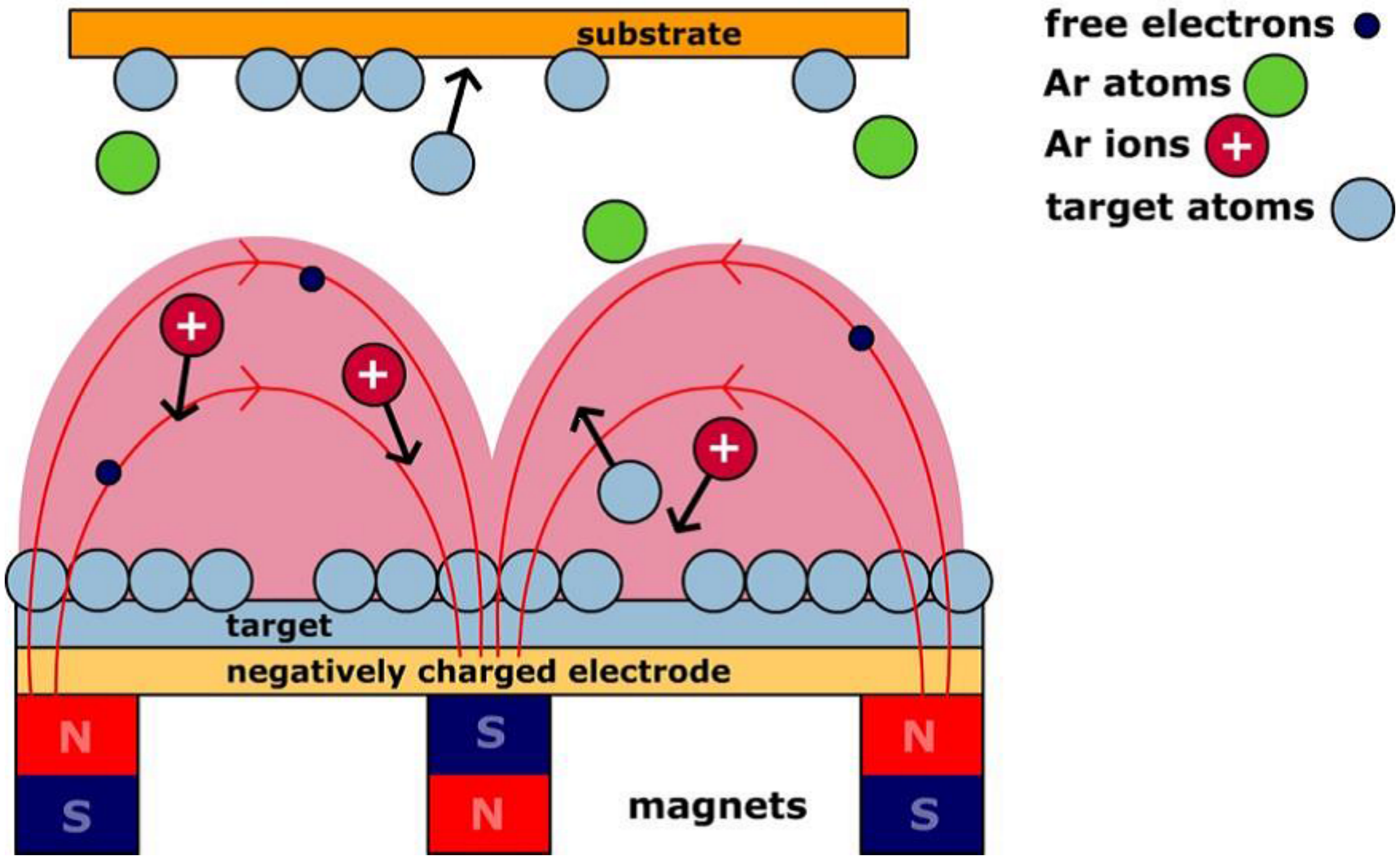
- Lorentz Force equation
- smaller mass, smaller orbit radius
- higher kinetic energy, higher orbit radius
- **collisions with neutrals disrupt orbital motion - interfere with magnetic confinement**
- **plasmas at low gas pressures are better confined by magnetic field due to reduced collision frequency**



Case study: planar magnetron sputter deposition

Case study: planar magnetron thin film deposition

- Magnetic field
  - electrons confined
  - ion orbit too big
- Electric field
  - negative voltage applied to electrode
  - sheath forms above “target”
    - strong electric field
    - ions accelerated into surface
      - target atoms sputtered
      - electrons released - “secondary emission”
    - secondary electrons enter plasma with high energy due to acceleration in sheath
- Diffusion
  - uncharged target atoms traverse the plasma
  - some reach substrate and stick to form thin film



http://nabis.fisi.polimi.it/equipments/aja-atc-orion-8-sputtering-system/

Parting comments

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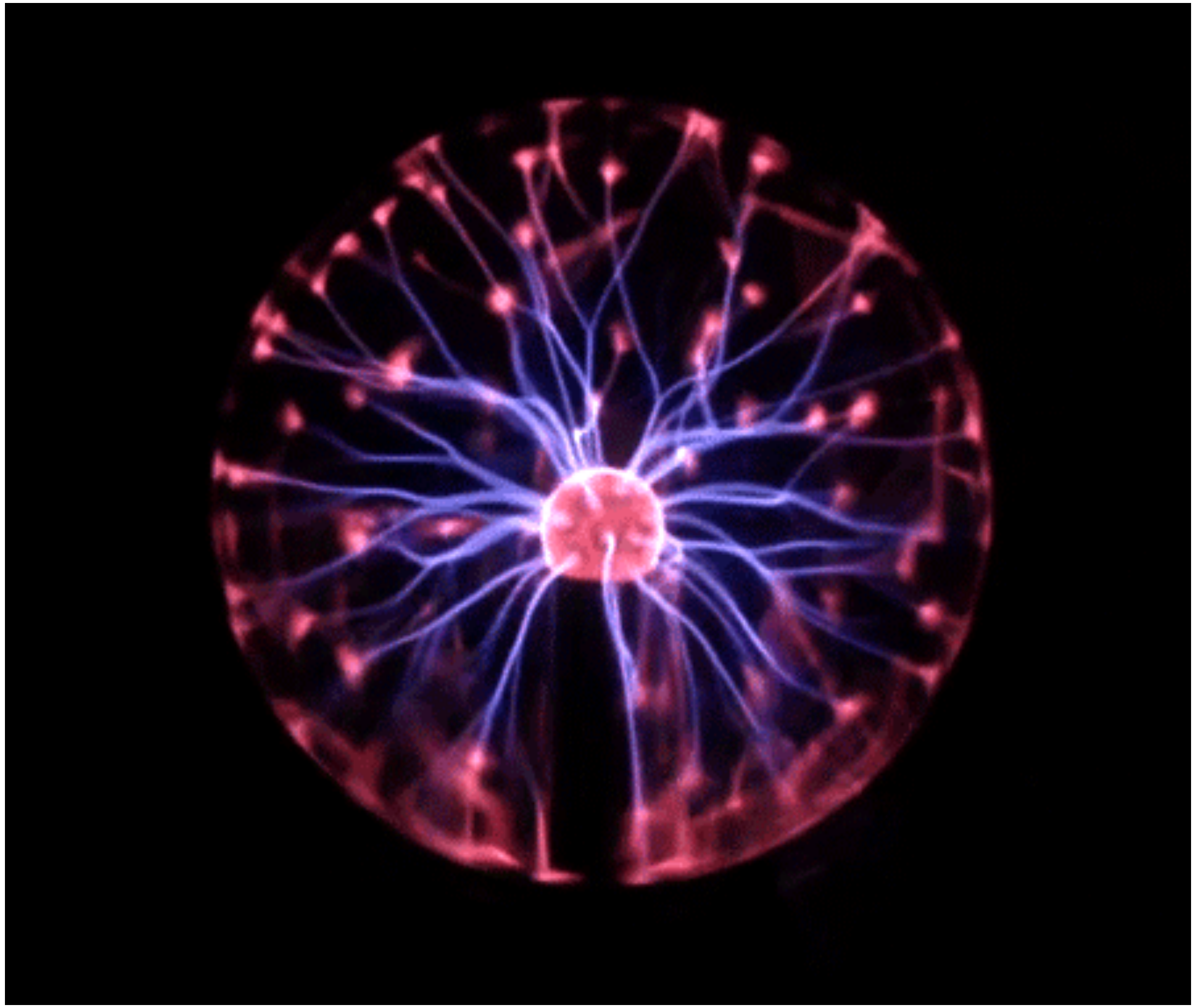

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Final thoughts

- Stop and smell the roses - savor the richness of plasma physics; no need to rush.
- Delve into the various physics sub-disciplines relevant for plasmas - a great foundation for understanding plasmas.
- Plasma physicists use an odd collection of units - get to know them and relevant conversion factors. Seek out shortcuts in plasma formulary and/or textbook appendices.
- Embrace opportunities - the skills you acquire will benefit you in ways you cannot imagine now.
- UW-Madison is home to world-renowned experts in a breadth of plasma research areas - it is a great place for graduate degrees in plasmas!