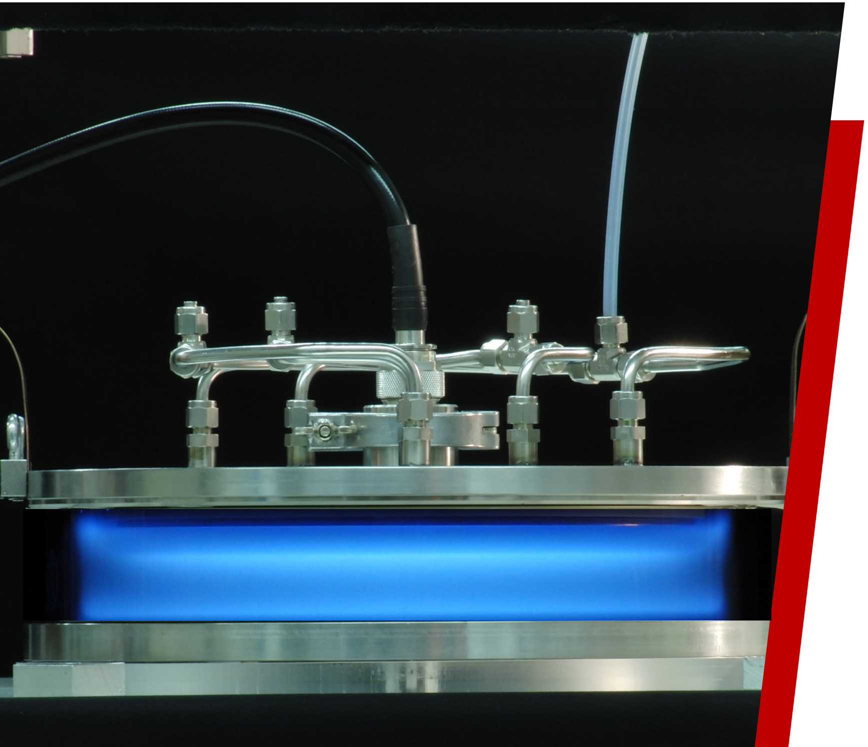
swiss physical society

SPS Annual Meeting 2024
Zurich, September 9 - 13, 2024

Empa
Materials Science and Technology



Physics and Education

A Journey into Plasma Physics

Dirk Hegemann

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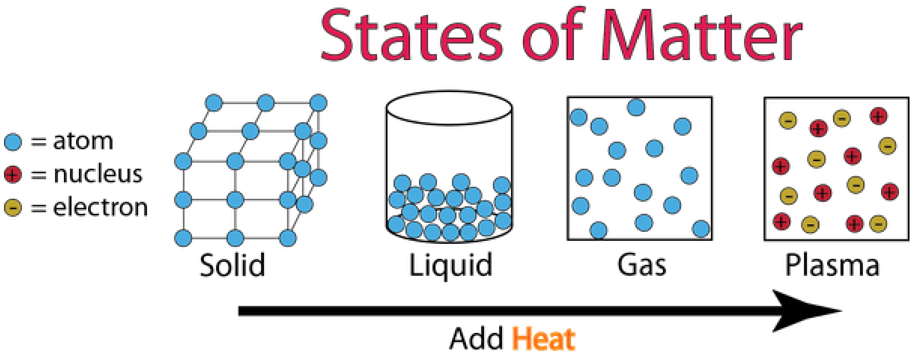
Outline

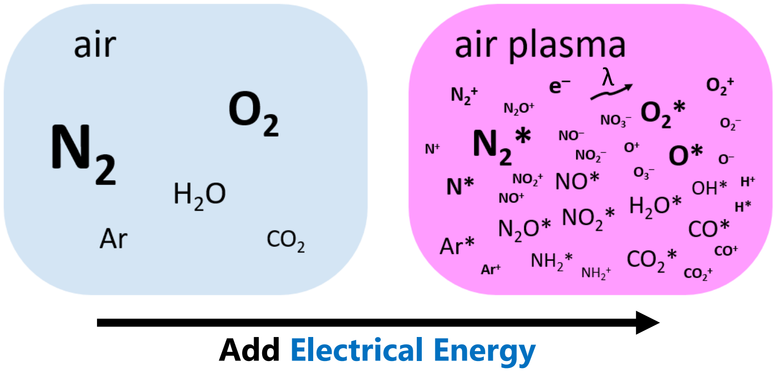
Physics and Education – A Journey into Plasma Physics

- What is a plasma?
- Plasma in nature
- Plasma in technology
- Conclusions

What is a Plasma?

A plasma is a reactive, (partly) **ionized medium** (a gas)
***showing collective behavior* that can be generated by supply of energy.**





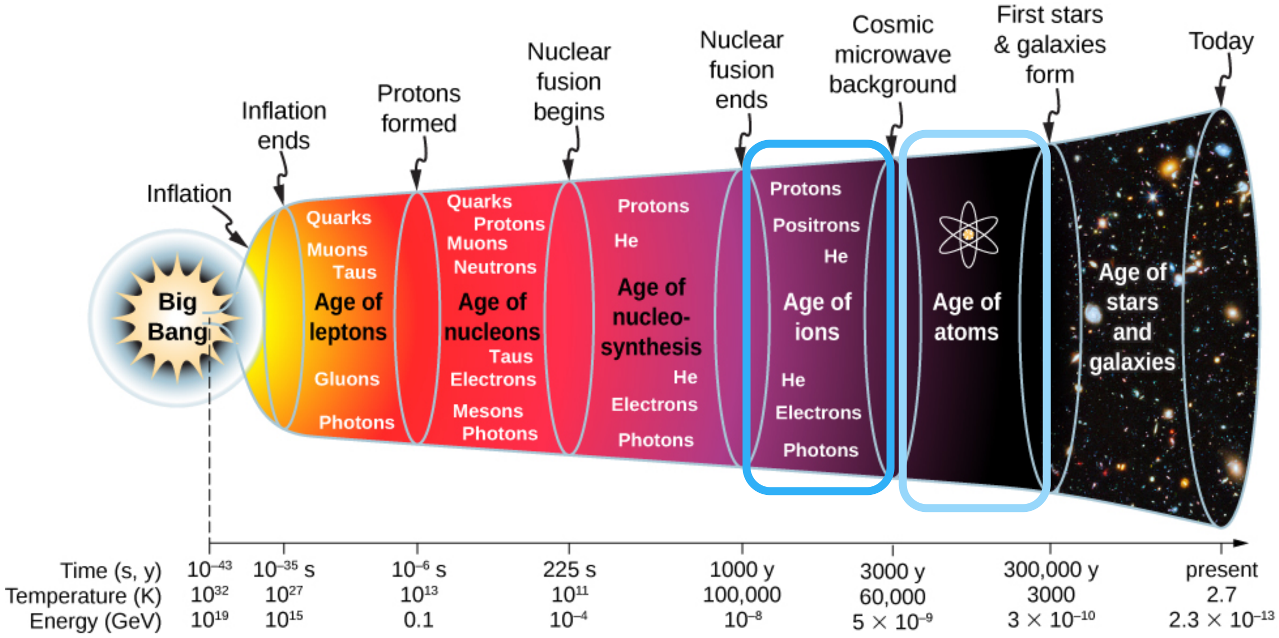
$$L_{plasma} \gg \lambda_{Debye} = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}}$$

Debye length

fully ionized plasma ⟷ **partly ionized plasma**
majority of reactive species
(since $E_{ion} > E_{exc}$)

***n_e*: electron density**; T_e: electron temperature

Plasma in the Early Universe



The universe cools below 60’000 K and atoms form. Photons do not interact strongly with neutral atoms, so they “decouple” from atoms constituting the cosmic microwave background radiation.

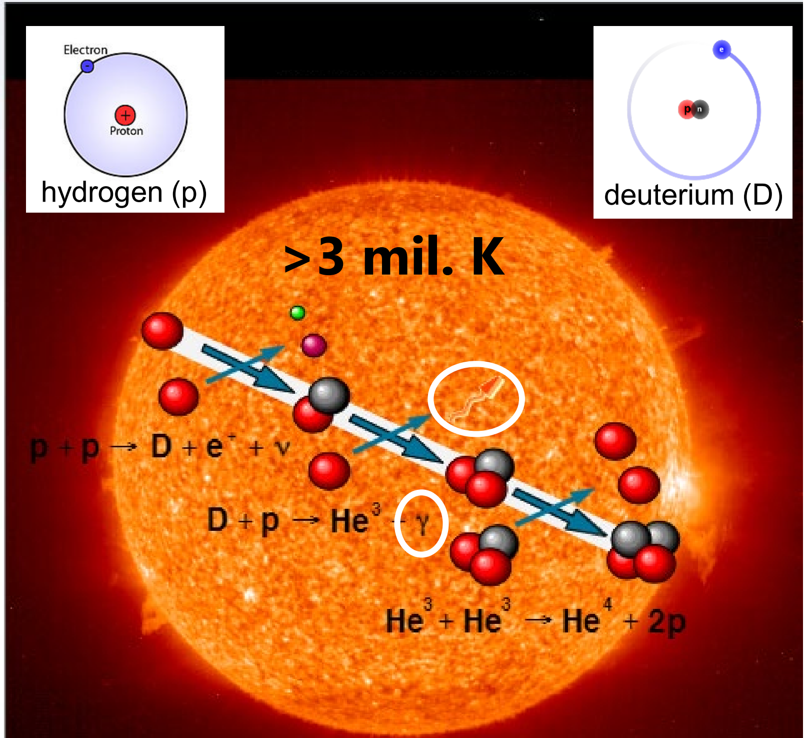
→ **no plasma**

The universe is hot enough to ionize any atoms formed yielding electrons, positrons, protons, light nuclei, and photons.

→ **thermal plasma**

https://pressbooks.online.ucf.edu/osuniversityphysics3/chapter/evolution-of-the-early-universe/

Plasma in the Universe – Star Formation



Sibylle Günter, Max-Planck-Institut für Plasmaphysik, Garching/Greifswald

→ **thermal plasma** (yielding fusion)

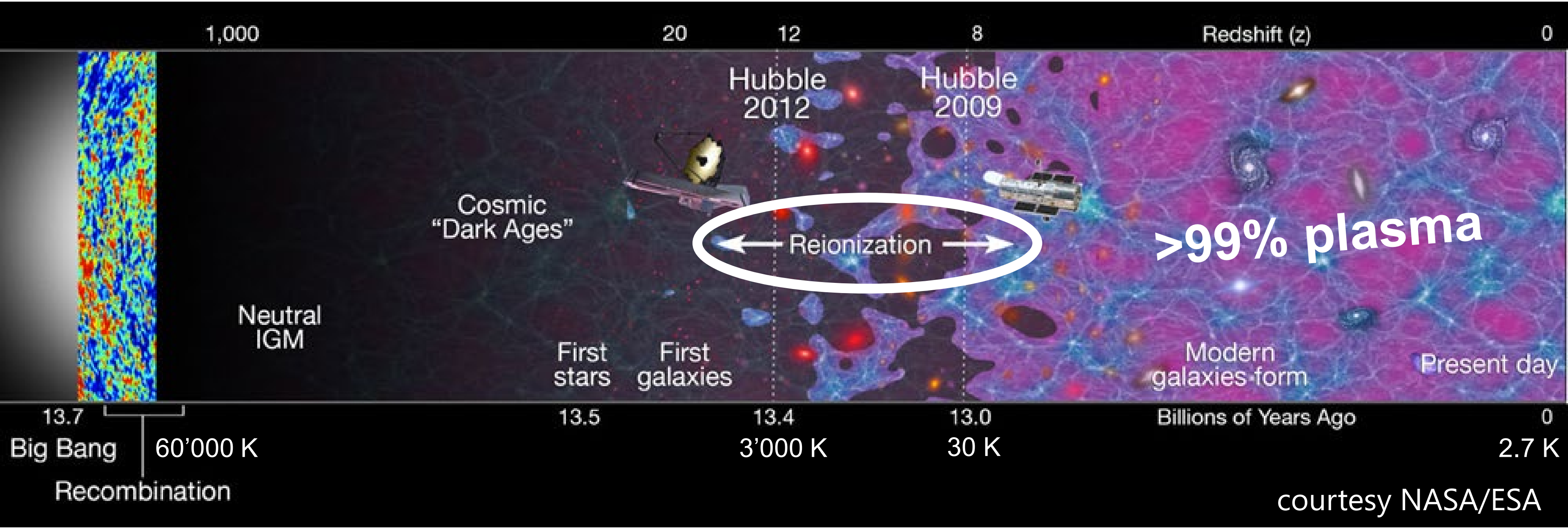
→ **occurrence of gamma radiation** (at high energy around 1 MeV)

→ **13.6 eV required to ionize hydrogen (H) in the universe**

→ **reionization**

1 eV ≡ $1.602 \cdot 10^{-19}$ J

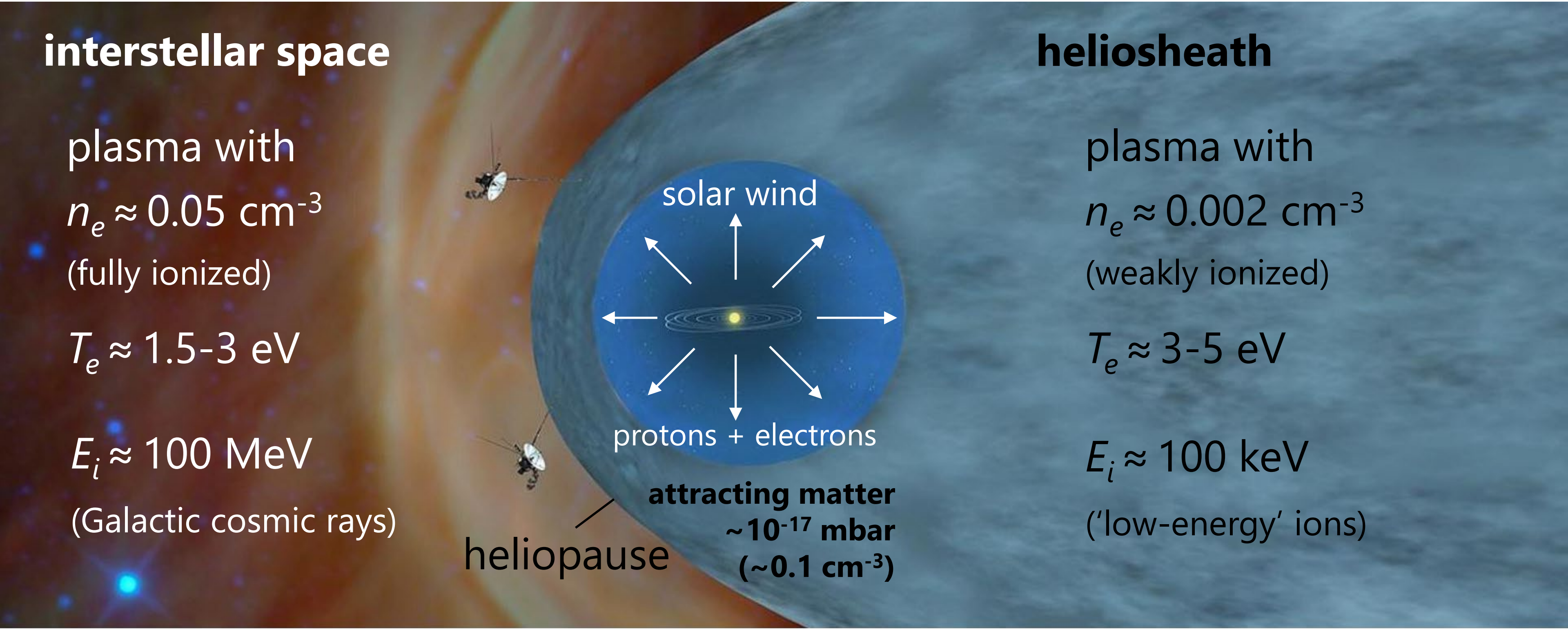
Plasma in the Later Universe (until today)



→ electromagnetic plasma activation (not a thermal plasma)

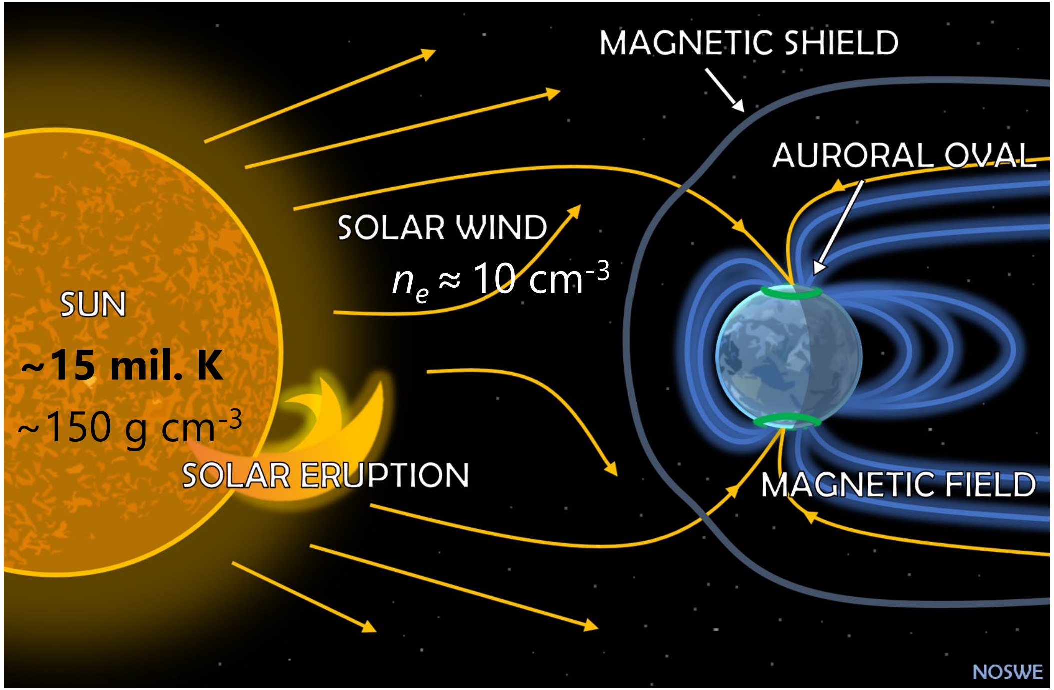
http://burro.case.edu/Academics/Astr328/Notes/SFRhist/reionization.html

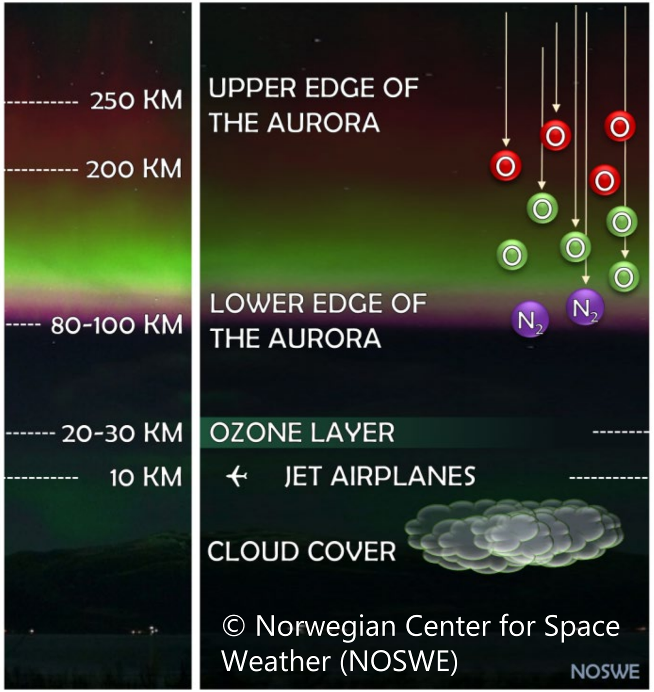
Plasma in the Universe – around Stars (our Sun)



Nature Astronomy 2019

Plasma in the Universe – around Planets (our Earth)





→ solar wind causing plasma activation of Earth's atmosphere

Plasma on Earth – Auroras (Polar Lights)

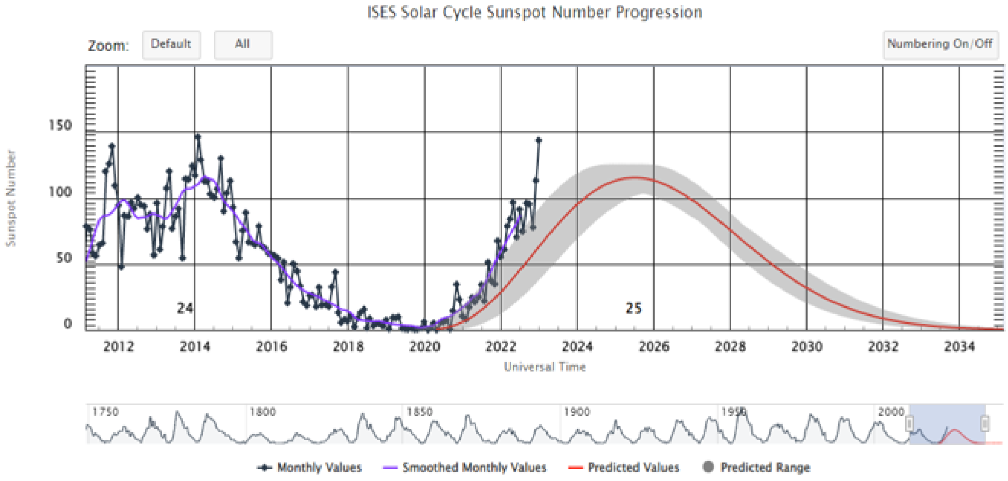
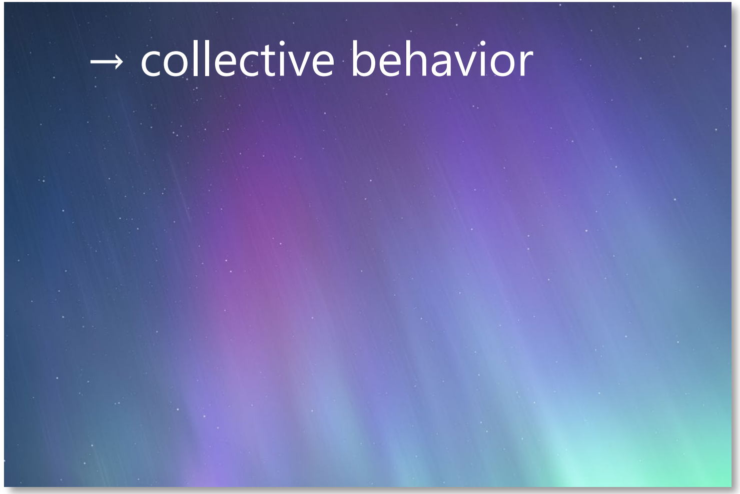


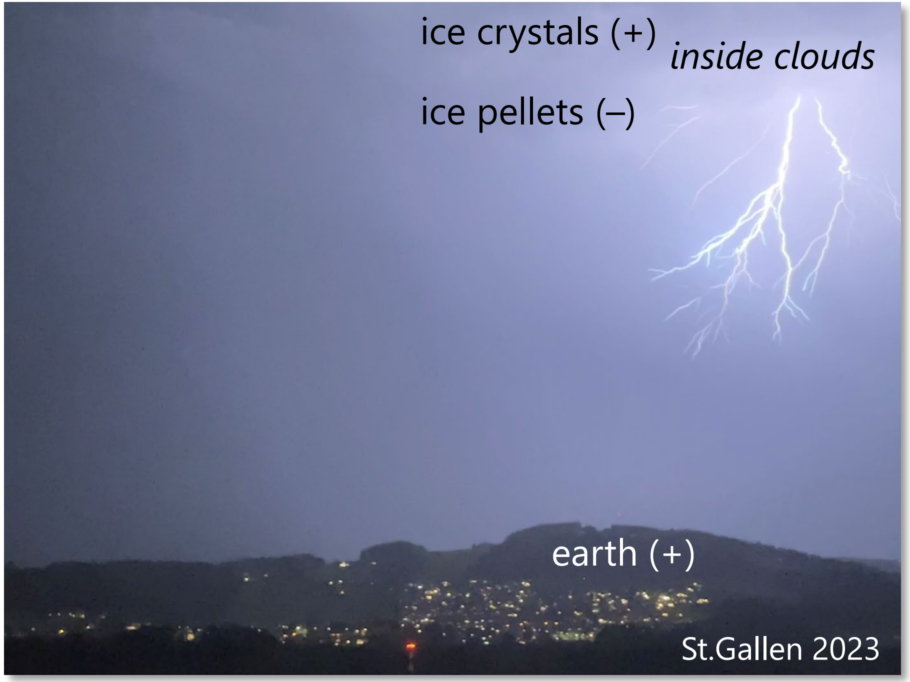
Figure 1 – Predicted Sunspot Activity



Polar light (© freepik)

→ the low pressure plasma follows Earth's magnetic field lines

Plasma on Earth – Lightning and Volcanic Eruptions



$O_2 \rightarrow O_2^*$

$O_2 + e^- \rightarrow {}^{\bullet}O_2^-$

$H_2O - e^- \rightarrow {}^{\bullet}OH \rightarrow H_2O_2$

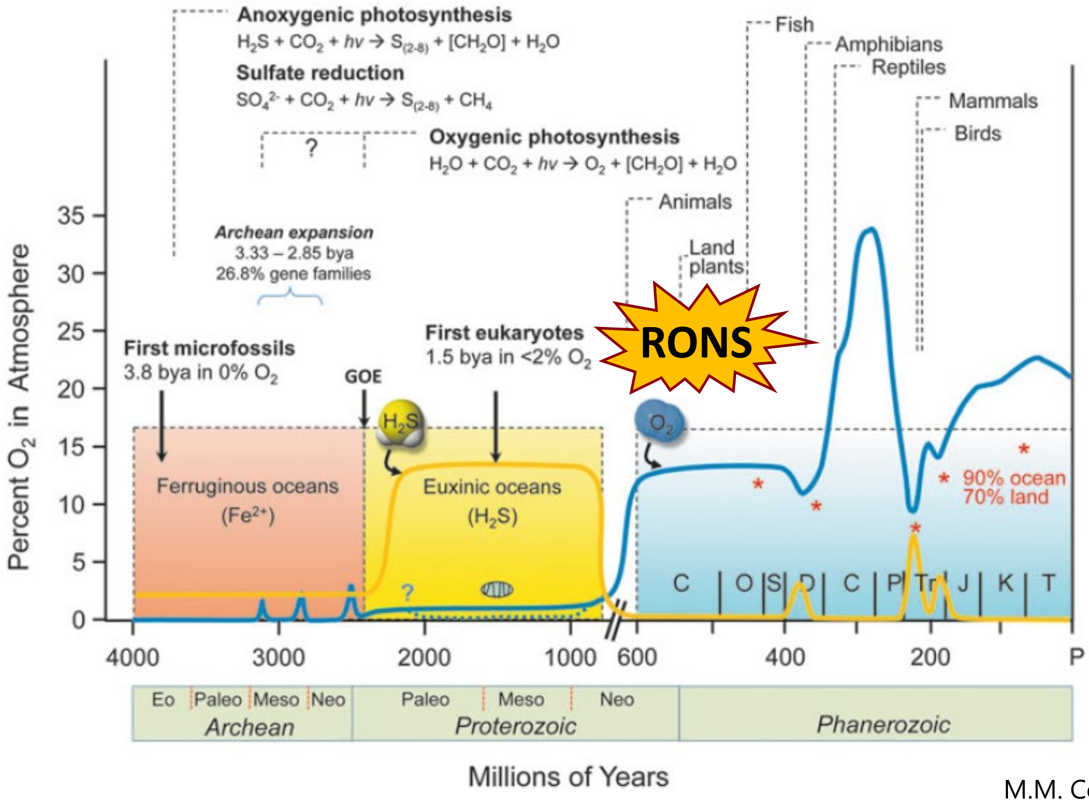
$O_2 \rightarrow 2\,{}^{\bullet}O$

$N_2 \rightarrow 2\,{}^{\bullet}N$

${}^{\bullet}O + {}^{\bullet}N \rightarrow {}^{\bullet}NO / {}^{\bullet}NO_x$

→ formation of reactive oxygen and nitrogen species (RONS)

Plasma on Earth – Fitness for Life?

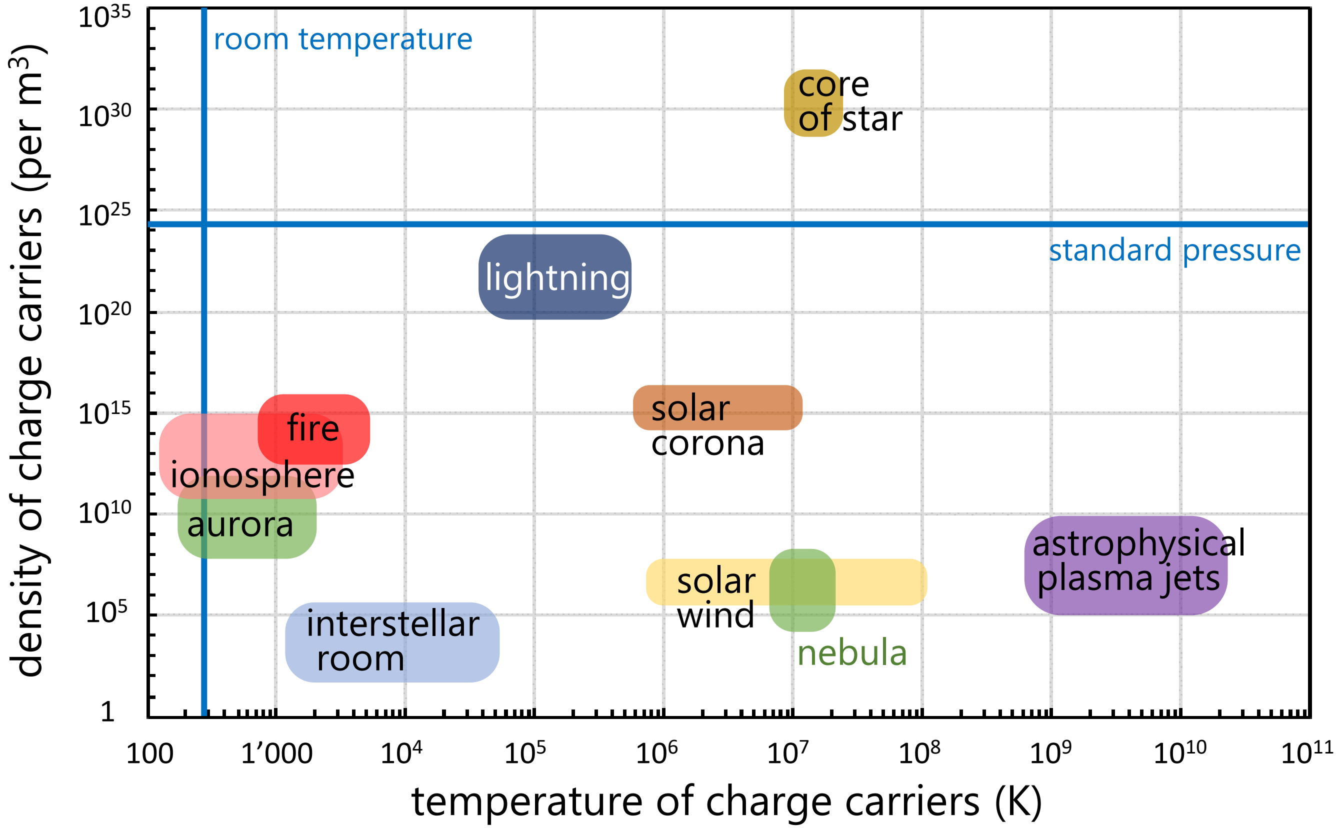


Combined oxygen production by cyanobacteria and primitive plants oxidized all the oceanic iron and sulfide, and around 600 million years ago, atmospheric O_2 began to increase to present-day levels.

Due to **RONS** by lightning and volcanic activity, organisms had to develop antioxidant strategies, increasing their **robustness** and **fitness for life**.

M.M. Cortese-Krott et al., *Antioxidants Redox Signaling* 27 (2017) 684

Natural Plasma



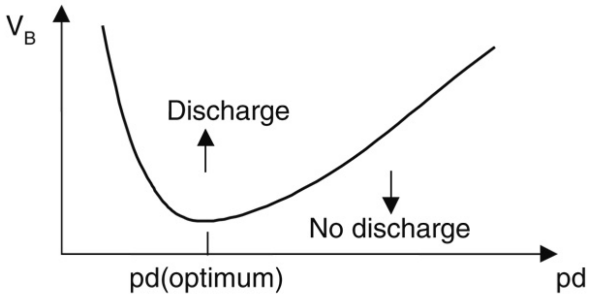
What Can We Learn from Plasmas in Nature?

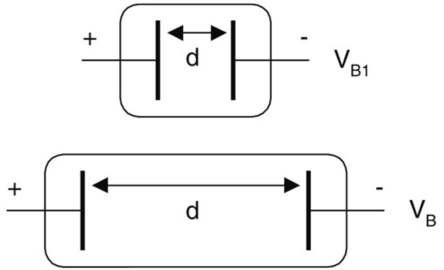
- **Thermal plasma** by heating to (extremely) high temperatures
  → plasma fusion (as in stars)

- **Non-thermal plasma** by electromagnetic activation
  → plasma at low temperatures
  → electrical breakdown
  → plasma physicochemistry

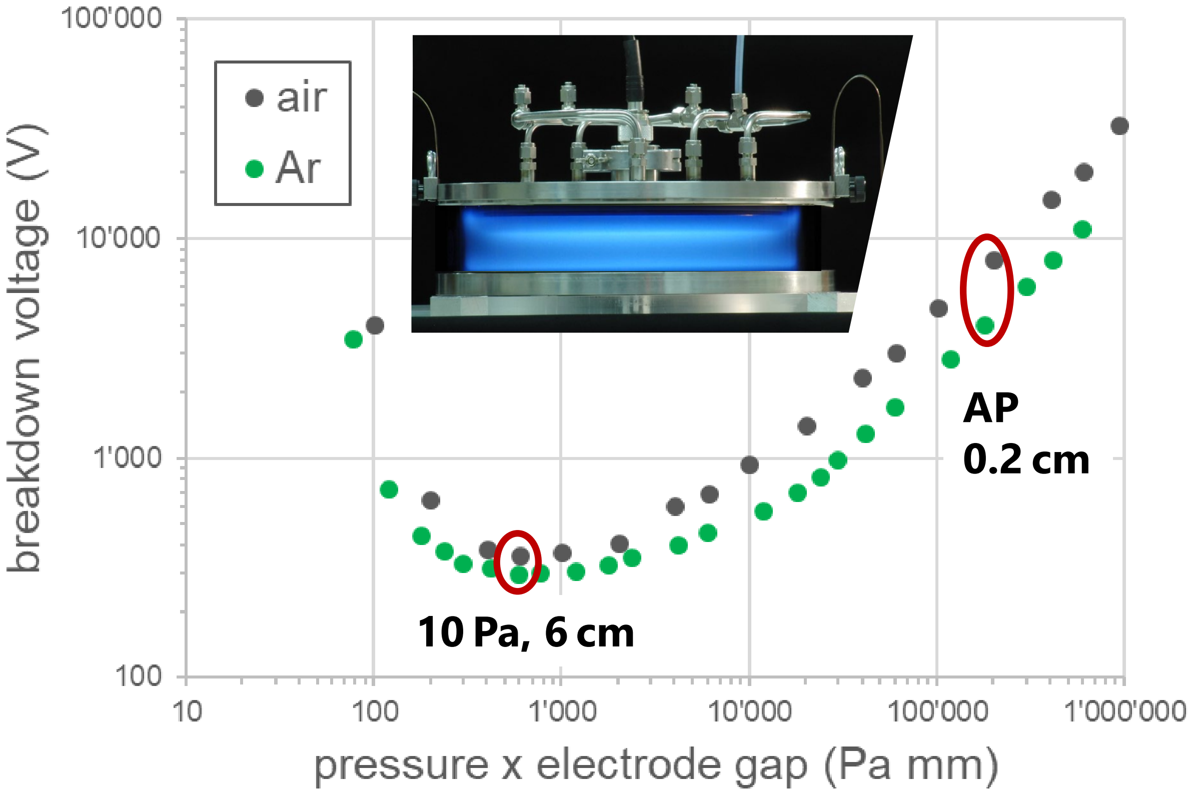
- Plasmas for technology at **low (LP) and atmospheric pressure (AP)** enabled

Electric Plasma Ignition – Paschen Curve



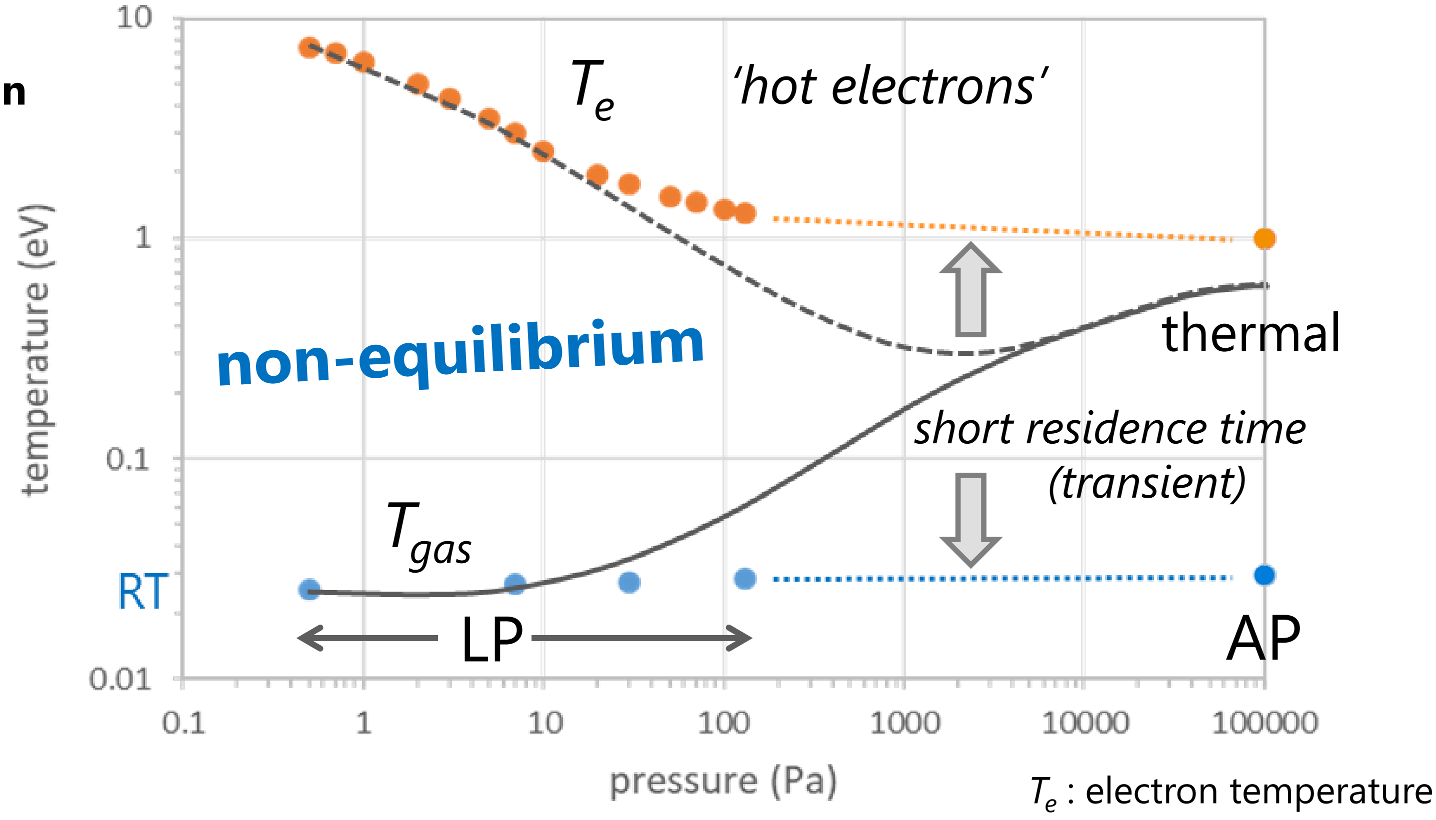


V_B: breakdown voltage
p: pressure; d: electrode gap



Plasma Processing at Non-Equilibrium Conditions

ionization degree ~10^-5

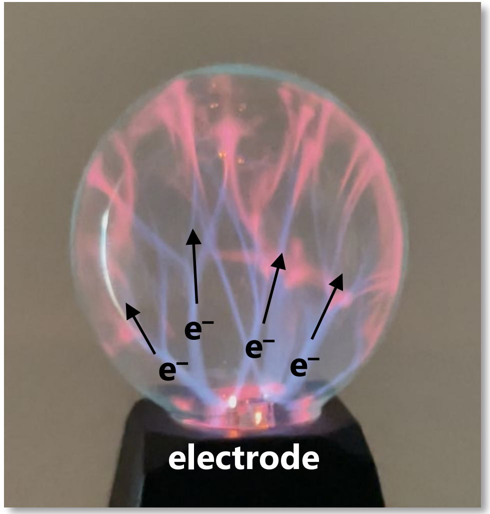


T_e : electron temperature

T_{gas} : gas temperature

Plasma Ball – Example for 'Cold' Plasma at Low Pressure

e.g. 95% neon and 5% xenon
at **~0.01 atm** (1000 Pa)



Transformation from battery voltage (5 V) to **2-5 kV** at 20-40 kHz

The oscillating voltage changes the electric field and the path of the electrons, resulting in the tentacles.

During this process, **the inert gas atoms are excited, resulting in colorful light.** The color of the light depends on the type of inert gas introduced into the ball by its excitation energies.

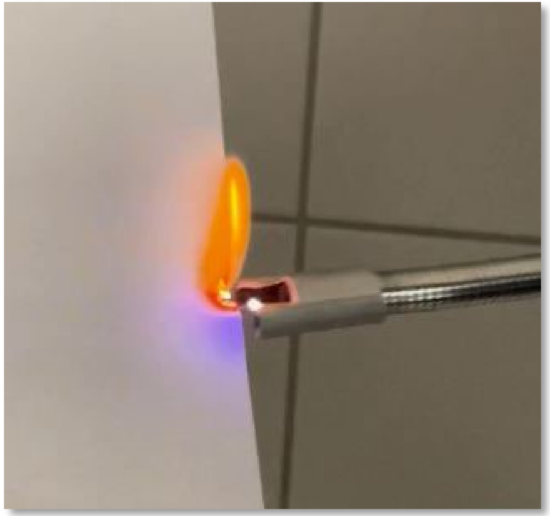
"When you touch it, the electricity is looking for a ground path. You are fairly conductive – your body is mostly water. "

Plasma Lighter – Example for ‘Hot’ Plasma at Atmosphere

air at atmospheric pressure

Transformation from battery voltage (3.7 V) to **>3 kV** at ~15 kHz

Two electrodes are charged by a potential difference of >3’000 V to meet breakdown in air.
The current flowing between the electrodes ionizes the air creating a plasma. The electrical arc thus generated can be used as a heat source **to get things on fire by heating up to about 1’000°C.**



Non-Thermal Plasma – Plasma Physicochemistry

plasma $L >> \lambda_{Debye}$

quasi-neutrality

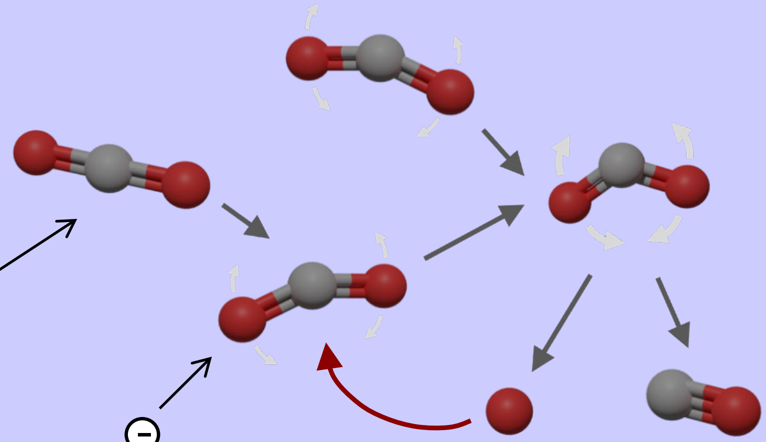
electron density n_e = ion density n_i

$\vec{E}$

electron temperature $T_e >> T_{gas}$

mass of ions $m_i >> m_e$

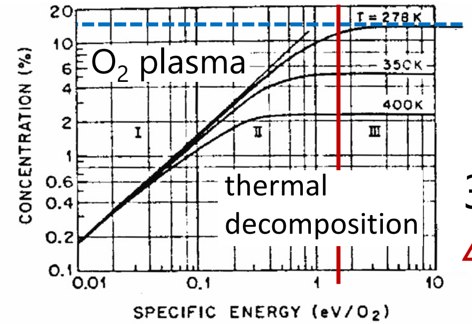
excitation + dissociation



→ **energy uptake by molecules in plasma: 10s of eV**

Non-Thermal Plasma – Plasma Chemistry

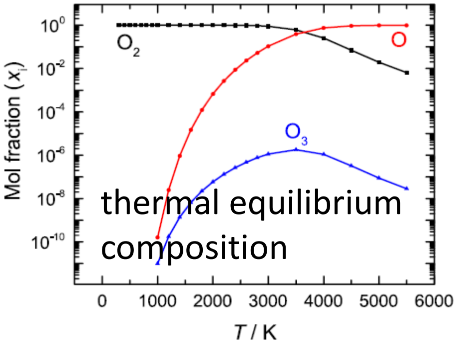
Ozone synthesis

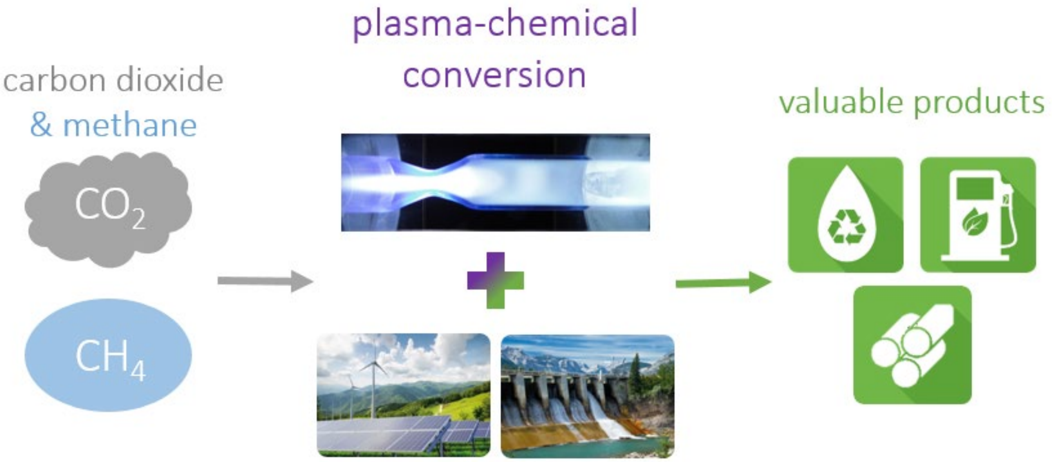


>10% O_3
(per O_2)

$3\,O_2 \rightarrow 2\,O_3$

$\Delta H \approx 1.5$ eV



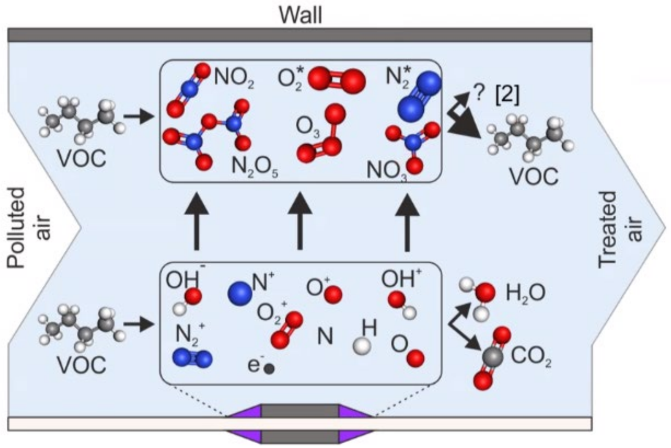


→ **electrical upcycling of climate gases into valuable products using dry chemistry at non-equilibrium conditions**

Non-Thermal Plasma – Plasma Chemistry

Exhaust gas cleaning + air pollution control

air → **AP plasma module** → activated air → exhaust gas



Plasma module

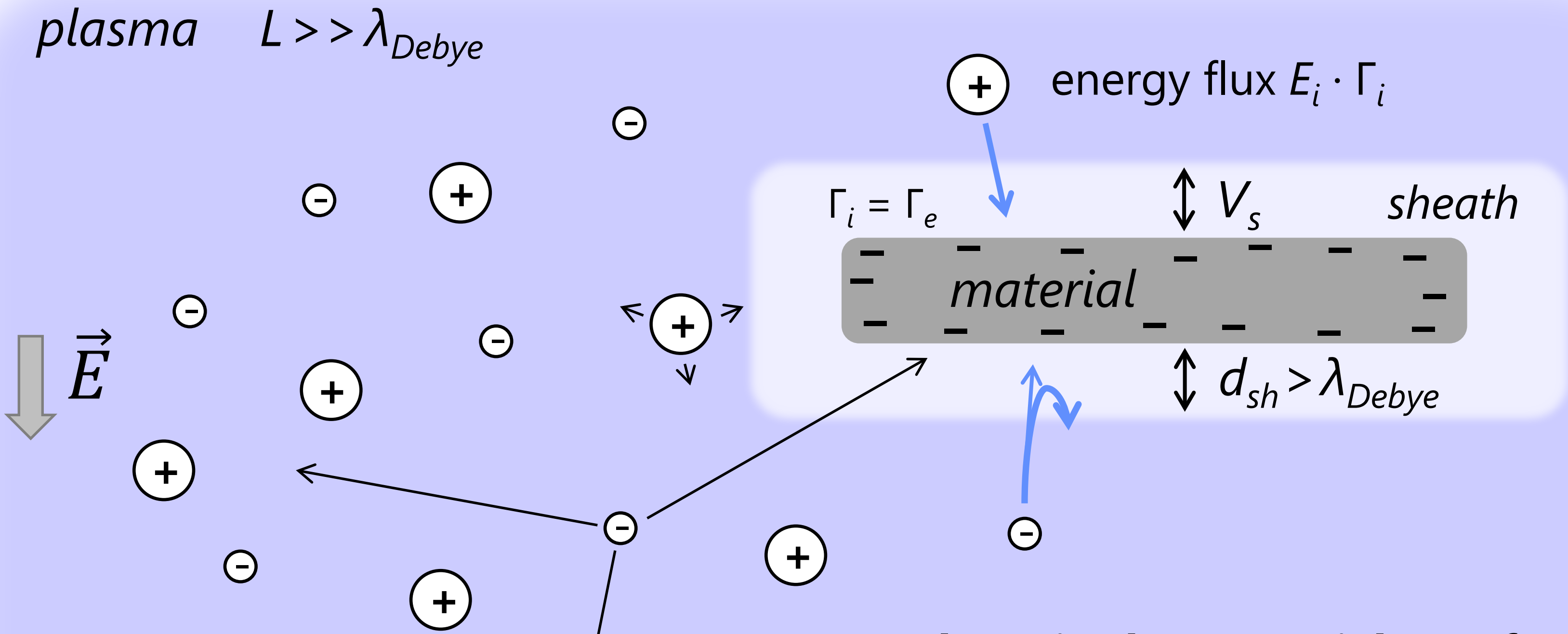
L. Schücke et al.,
J. Phys. D: Appl. Phys. 2022, 55, 21520

Plasma module operating with 15 kV voltage,
60 kV/cm field strength, ~1 kW electrical power

VOC: volatile organic compounds

Industrially:
80-90% removal of exhaust emissions

Non-Thermal Plasma – Plasma Physics



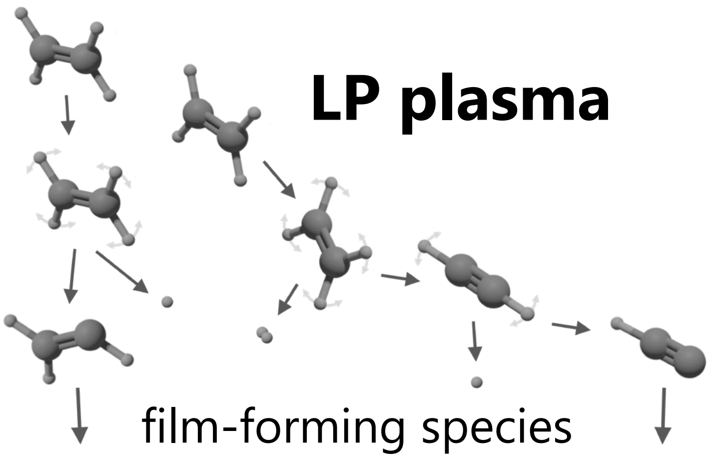
electron temperature $T_e >> T_{gas}$

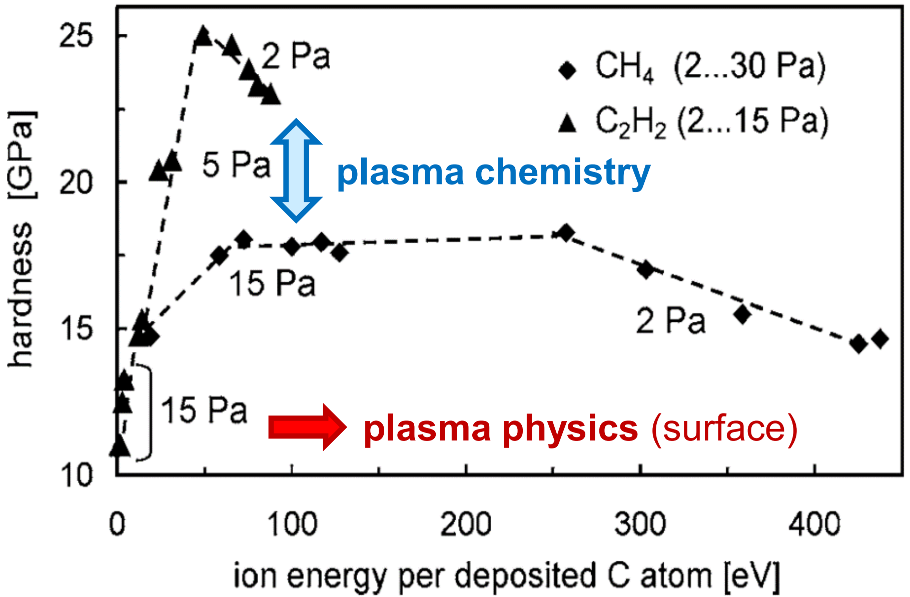
mass of ions $m_i >> m_e$

→ **energy deposited at material's surface: 10s of eV**

Non-Thermal Plasma – Plasma Deposition

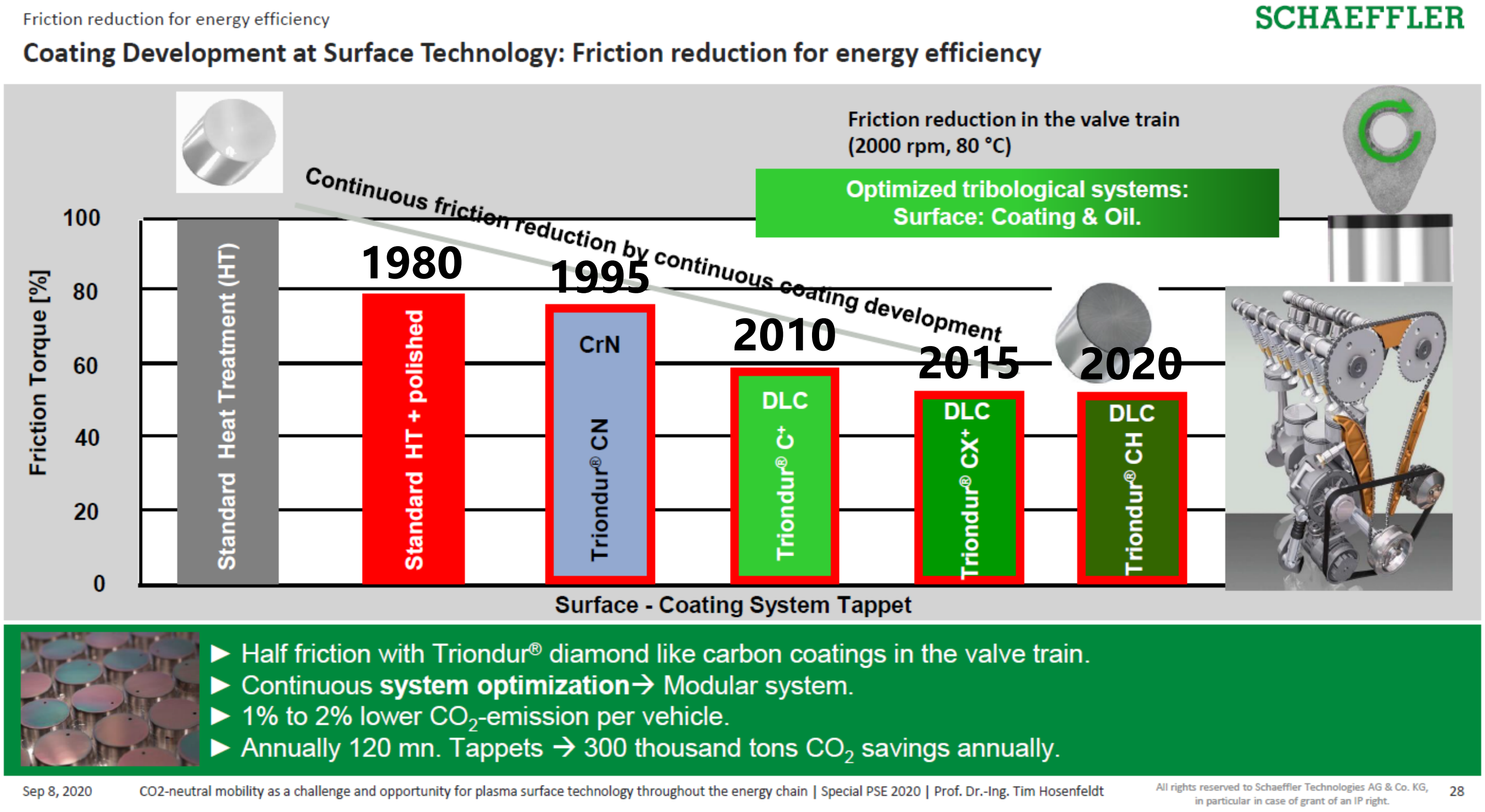
Hydrocarbons in plasma to deposit hard diamond-like coatings (DLC)



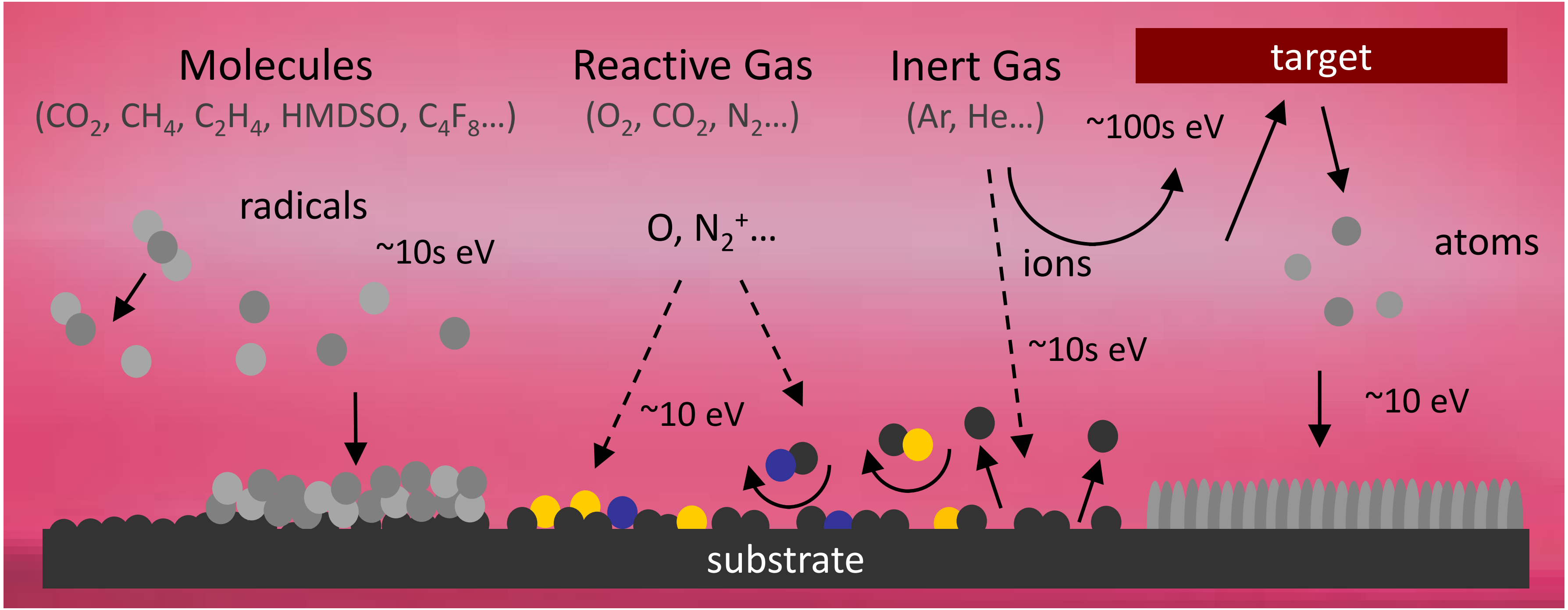


→ control of gas phase and surface processes to adjust film properties

DLC in Automotive Industry



Plasma Processing at Non-Equilibrium Conditions



plasma gas conversion

plasma polymer deposition

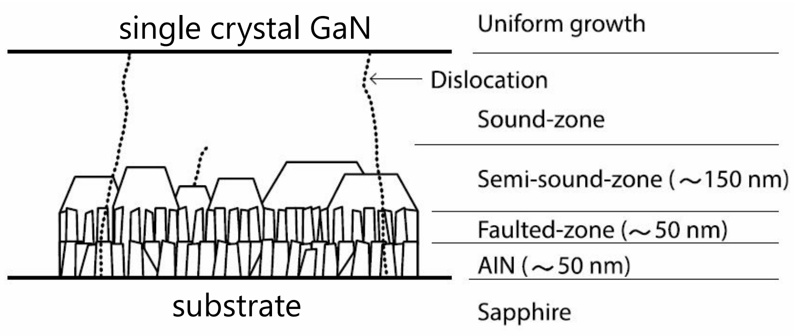
plasma activation

plasma etching

plasma sputtering

Impact of Plasma Technology – Semiconductors

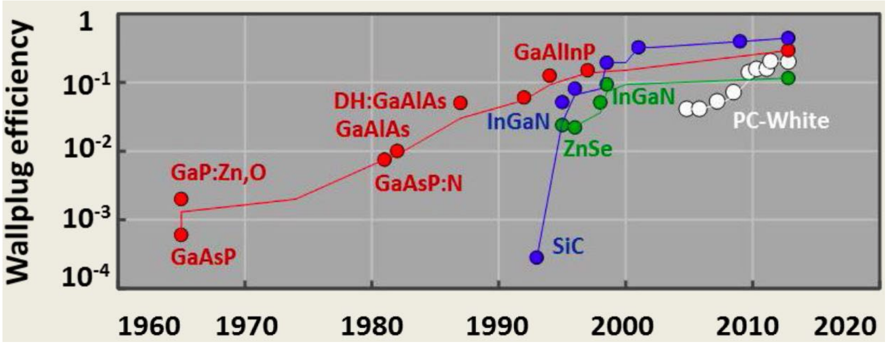
Growth of high quality GaN films (3.4 eV direct bandgap) on Al_2O_3 (sapphire) using a buffer layer made of AlN
→ base layer for **blue LEDs**



→ **growth of single crystals introducing vertical gradients** (non-equilibrium plasma)

Nobel Price in Physics 2014

Isamu Akasaki, Hiroshi Amano, Shuji Nakamura

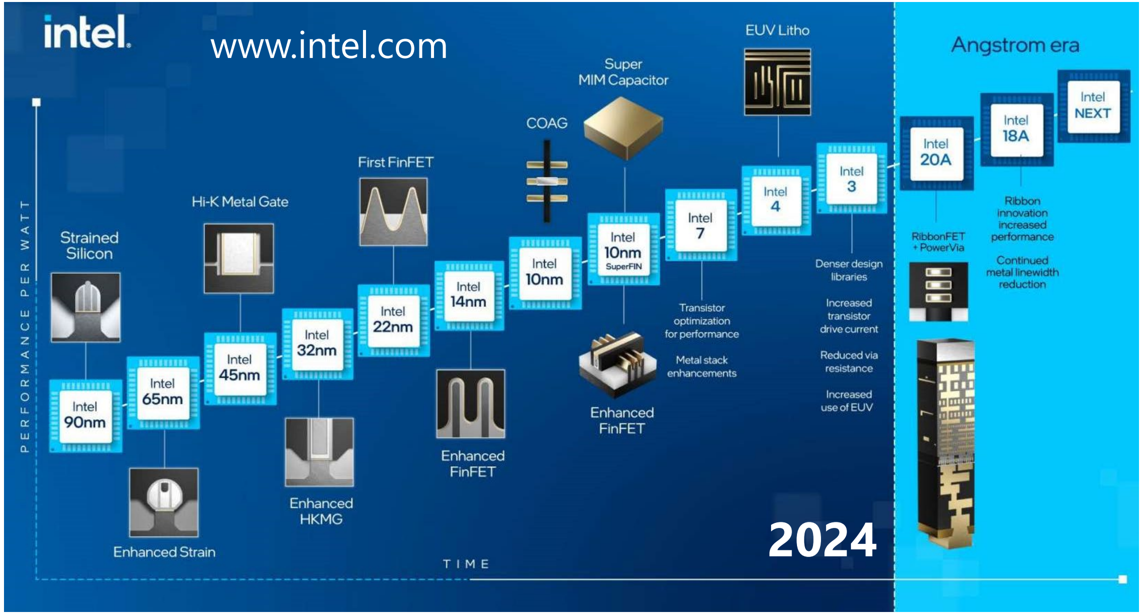


PC-White: phospor-converted white light based on efficient blue LEDs

http://www.nobelprize.org/nobel_prizes/physics/laureates/2014/advanced.html

Moore's Law – Now and in the Future

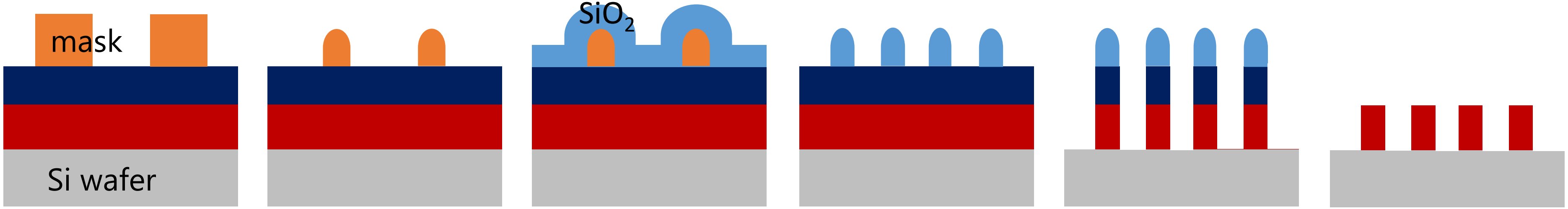
Moore's Law is the observation that the number of transistors on an integrated circuit will double every two years with minimal rise in cost. (Gordon Moore, Intel 1965)



Currently driven by AI and robotics

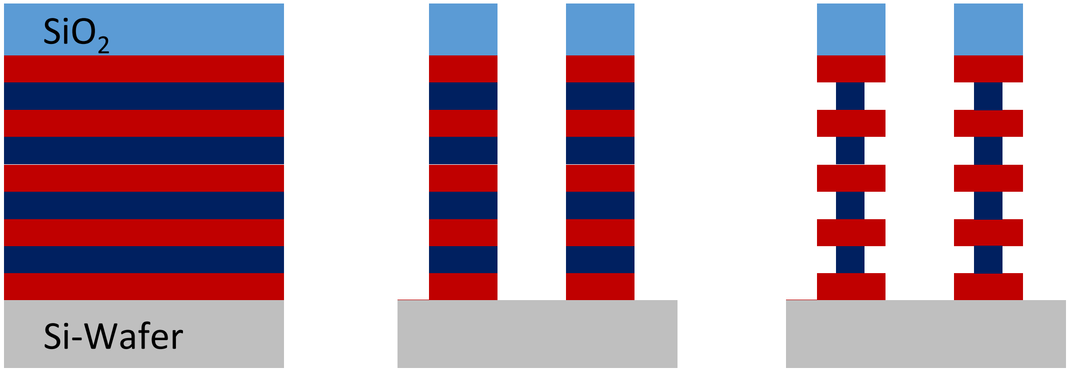
Moore’s Law – Now and in the Future

lithography | plasma etch 1 | plasma coating | plasma etch 2 | plasma etch 3 | plasma etch 4



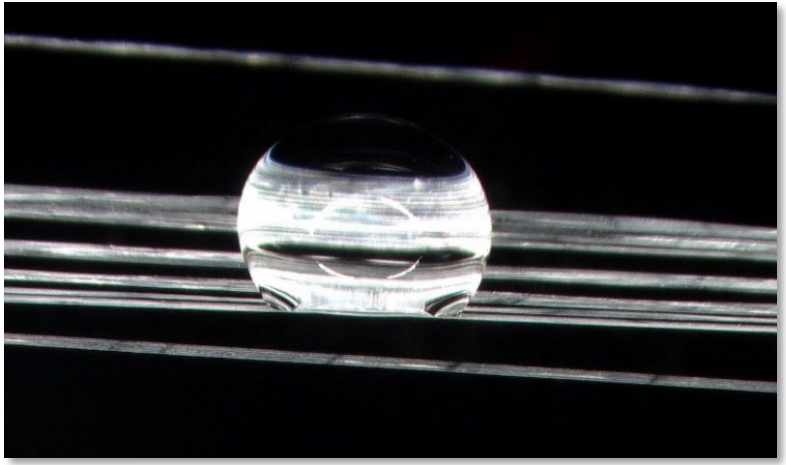
plasma coatings | plasma etching 1 | plasma etching 2

next generation

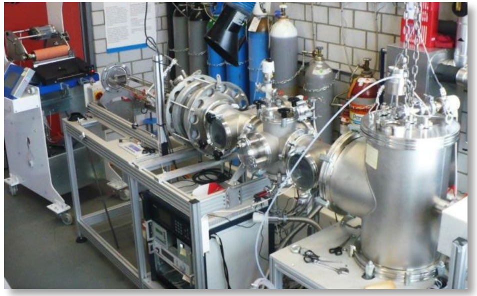


smaller structure sizes and 3D architecture

Potential of Ultrathin Siloxane Films Replacing PFAS



Water repellence on 300 % elongated elastic fiber (20x magnification)



Pilot-scale plasma reactor (winding at ambient conditions)

PFAS

Per- and polyfluoroalkyl substances have unique properties in terms of water, oil and stain repellence. Due to human health and environmental risks, however, the replacement of PFAS became a pressing social challenge.

→ Empa developed a plasma process to obtain **water repellent** and **fast drying** fibers & textiles – ultrathin glass-like hydrophobic layers cover even elastic fibres.

→ Roll-to-roll pilot-scale reactor demonstrates industrial feasibility enabling industrial transfer.

Empa Materials Science and Technology

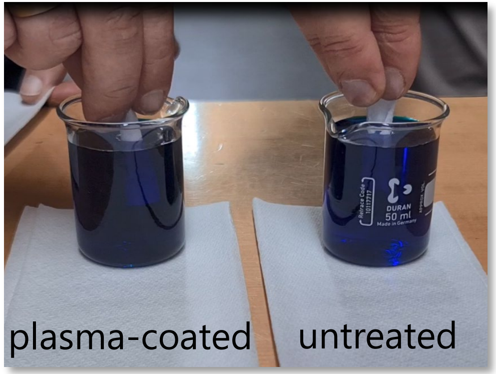
LOTHOS

beag ...more than just yarn

CILANDER SWISS | TEXTILE | 1814

Innosuisse

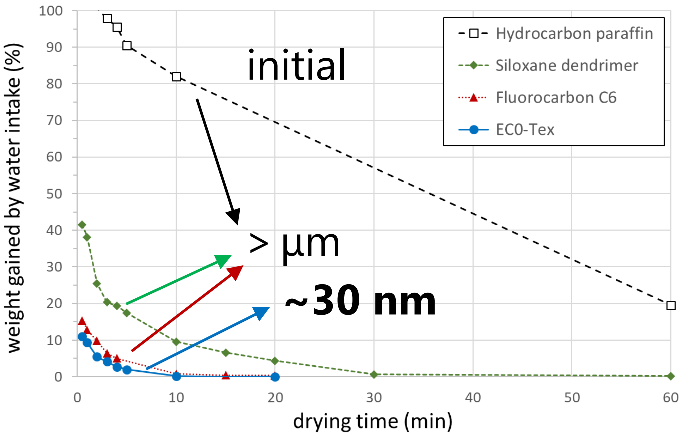
Potential of Ultrathin Siloxane Films Replacing PFAS

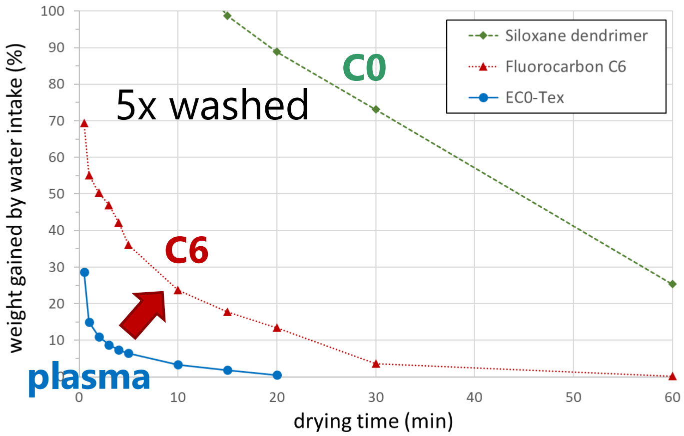


enhanced capillary depression +

rapid drying properties +

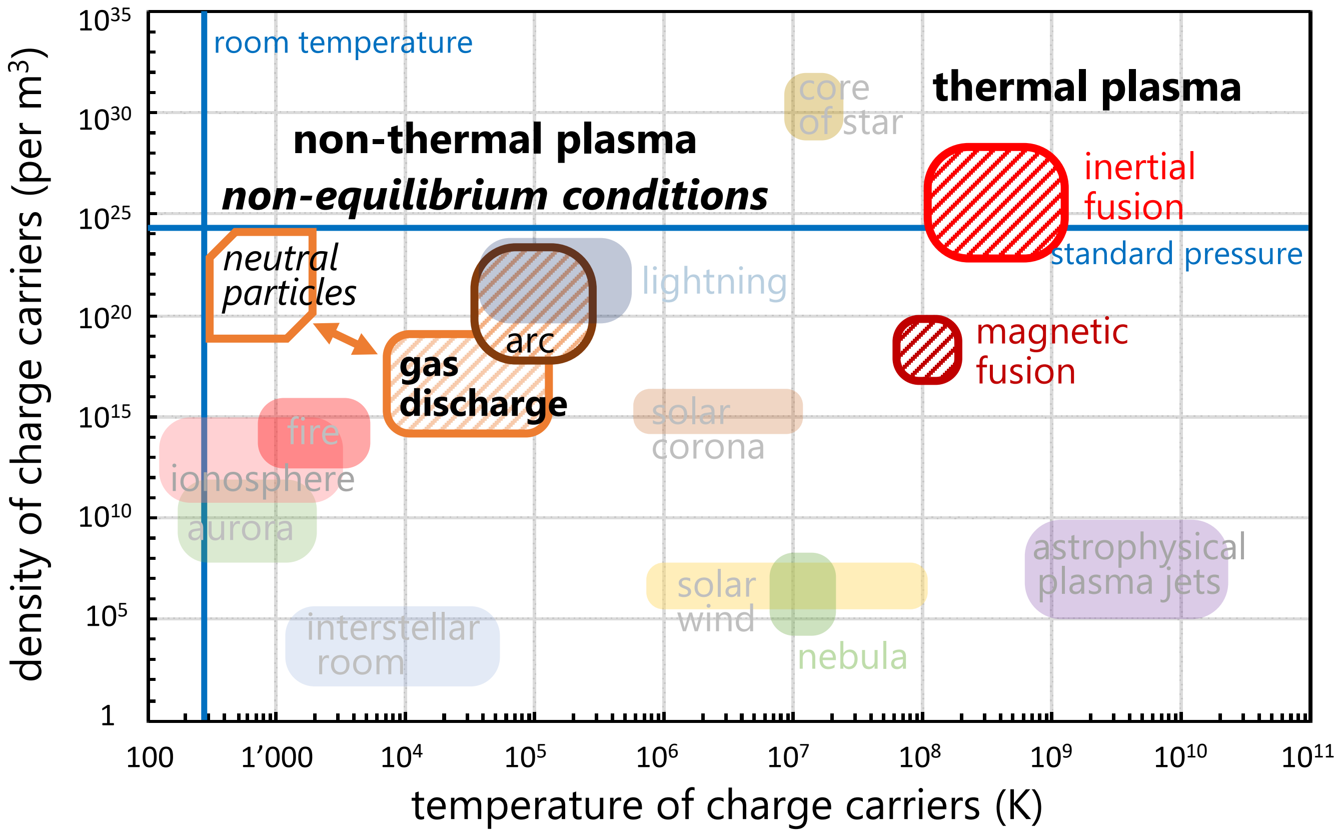
less chemicals, high durability





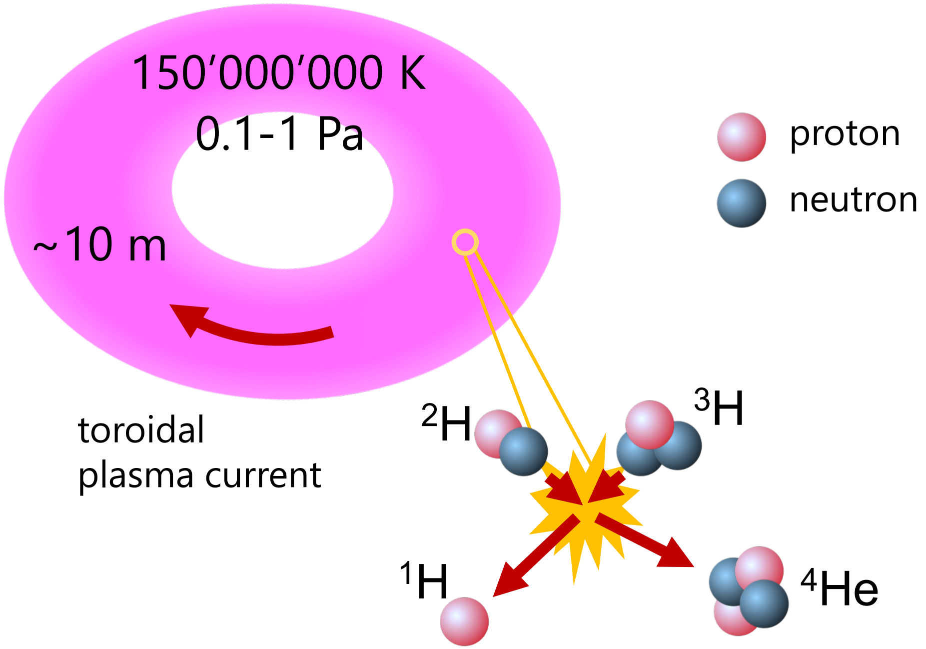
Patent application filed 09.2023

Man-Made Plasma

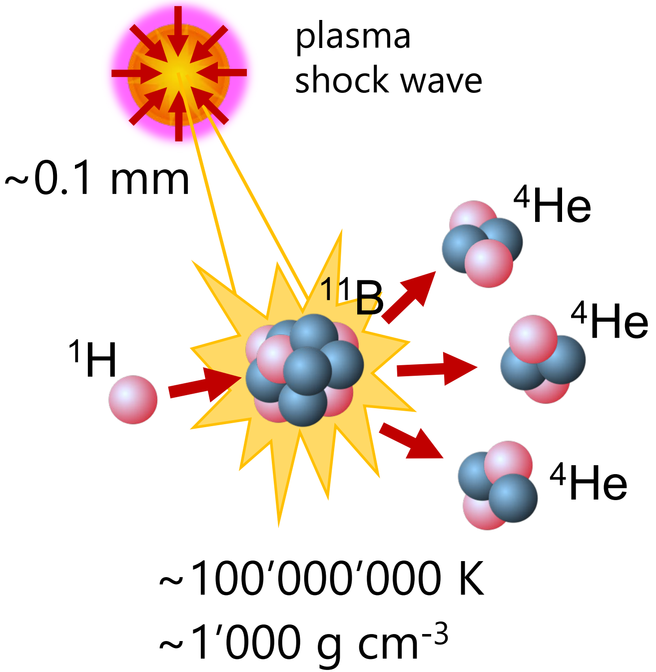


Thermal Plasma – Plasma Fusion

Magnetic Confinement Fusion

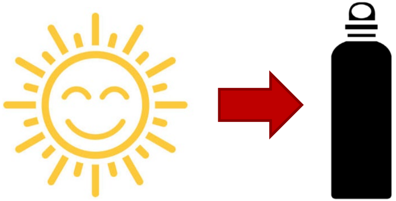


Inertial Confinement Fusion – Laser-induced densification



Thermal Plasma – Plasma Fusion: ITER

"We put a sun in a thermos bottle"
Sabine Griffith, ITER, 10.08.2024



Conclusions

Physics and Education – A Journey into Plasma Physics

- Plasma as 'beautiful' state of matter: luminous, unusual behavior
  → triggering interest of students

- Plasma state 'rules' the universe: stars, nebula, jets, interstellar space
  → thermally and electromagnetically activated plasma

- Plasma as 'hidden champion': technical use of plasma in many important fields
  → LP vs. AP (simple demo); plenty of examples for product manufacturing

- Plasma helping to solve urgent societal tasks: PFAS, air/water cleaning, energy

Empa – The Place where Innovation Starts

- Plasma & Coating Group

Dr. Dirk Hegemann
dirk.hegemann@empa.ch

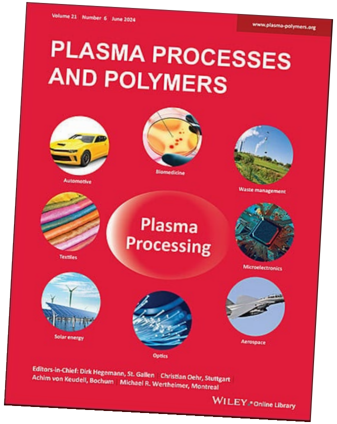
- Funding

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

Swiss National Science Foundation



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Thanks for your Attention!