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Characterization of laser-produced strongly coupled plasma with density and temperature relevant to solar photosphere

Gunsu S. Yun[1,2]

[1]Department of Physics, Pohang University of Science and Technology (POSTECH), Pohang, Korea

[2]Division of Advanced Nuclear Engineering, POSTECH, Pohang, Korea

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POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

gunsu@postech.ac.kr

- “Classical” weakly coupled plasma
- High-density strongly coupled plasma (SCP)
- Generation of SCP state in supercritical fluids

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* In collaboration with prof. Hee-yong SUK at GIST and prof. Min-sup HUR at UNIST.

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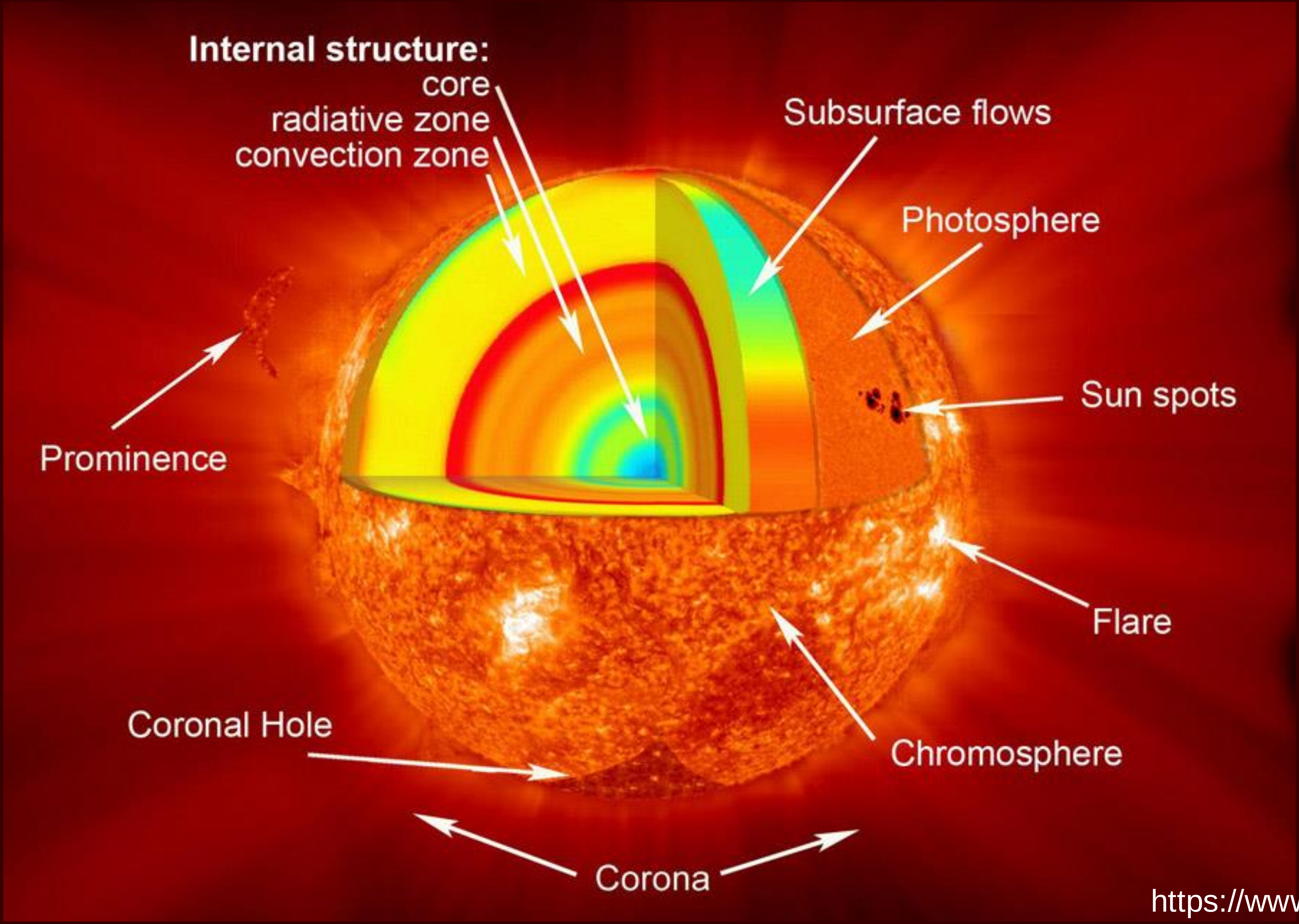
POSTECH POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY
GIST
UNIST ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY 2007
NRF National Research Foundation of Korea



https://www.ucar.edu/

I. CLASSICAL WEAKLY-COUPLED PLASMA

Plasma Taxonomy*

Fundamental plasma parameters

Debye length, number:

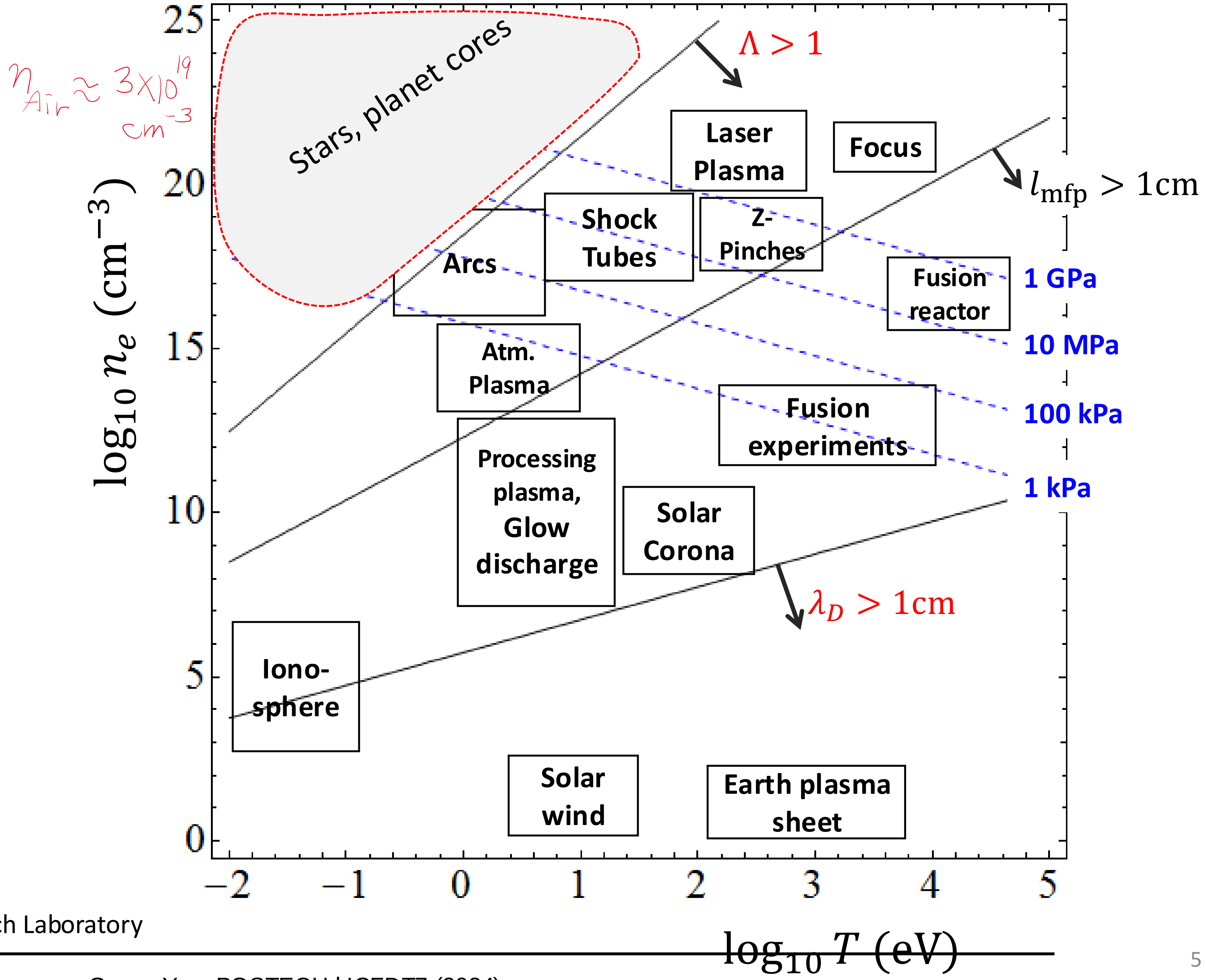
$$\lambda_{De} \quad \propto \quad \sqrt{T_e/n_e}$$
$$\Lambda \equiv n_e\lambda_{De}^3 \quad \propto \quad \sqrt{T_e^3/n_e}$$

Mean free paths:

$$l_{\text{mfp},ee}, l_{\text{mfp},ei} \quad \sim \quad T_e^2/n_e$$
$$l_{\text{mfp},en} \quad \sim \quad l/n_n$$

Equation of state:

$$p \stackrel{?}{=} nT$$



*adapted from "Plasma Formulary", Naval Research Laboratory

Debye number

$$\bar{\varphi}_t(r) = \frac{q_t}{4\pi\epsilon_0 r}\exp(-r/\lambda_D)$$

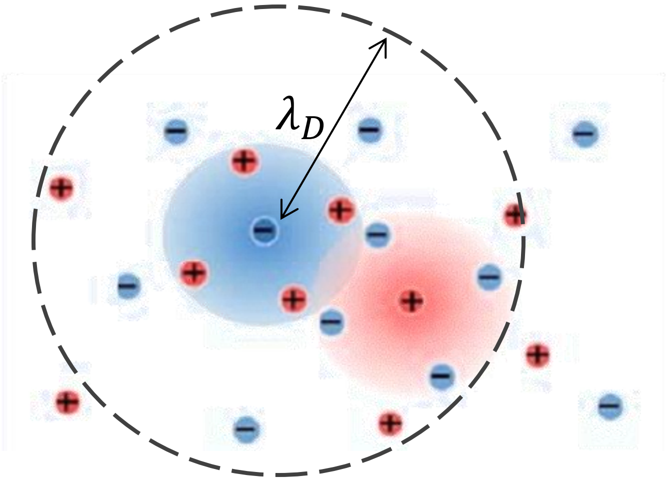
Debye number = Number of particles in the Debye "cube"
(~inverse of Coulomb "coupling" parameter)

$$\lambda_{Ds} = \left(\frac{\epsilon_0 T_s}{q_s^2 n_s}\right)^{1/2}$$

$$N_{D,s} \equiv n_s \lambda_{Ds}^3 \frac{4\pi}{3}$$

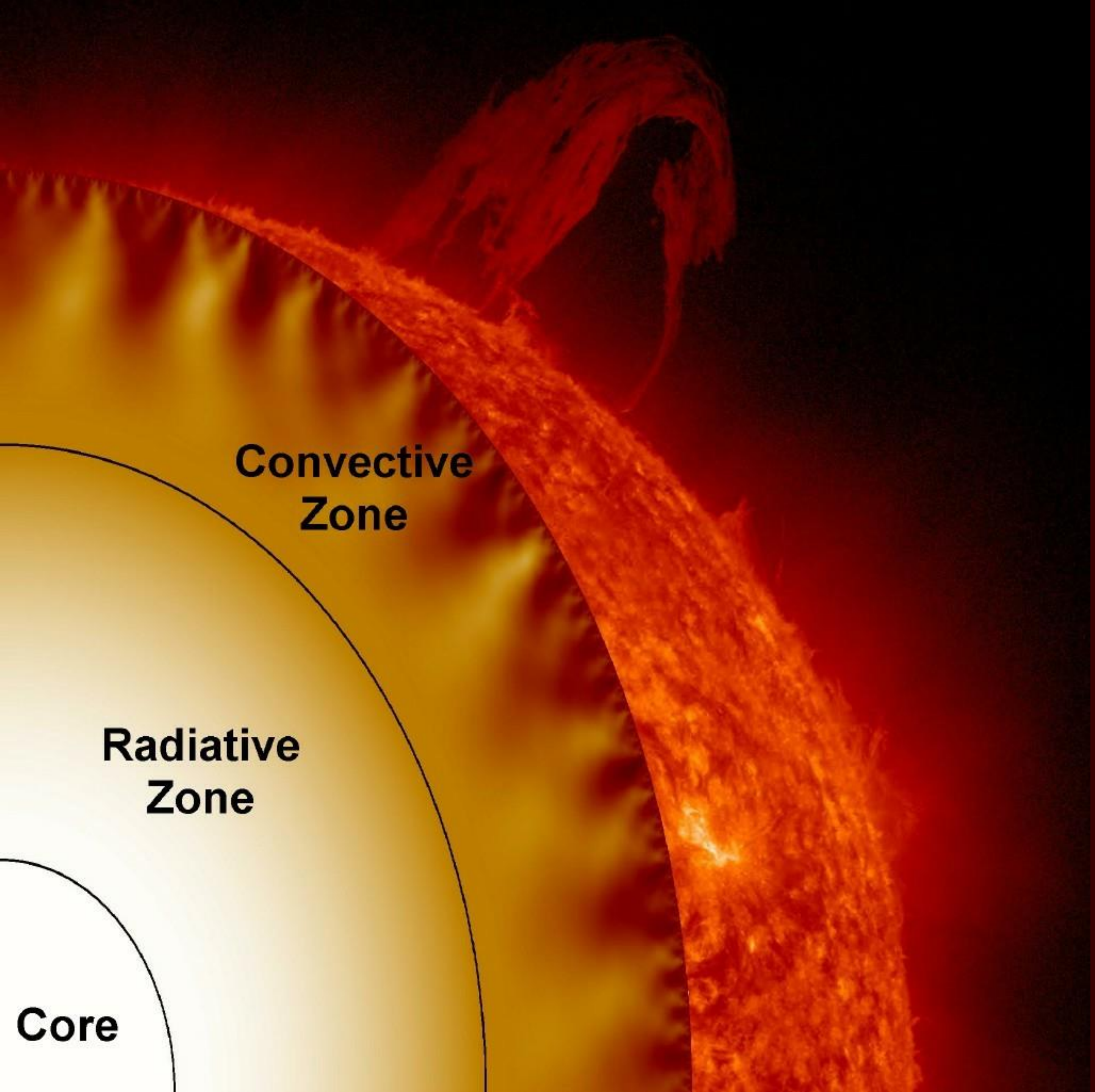
By the assumption of weak interaction,

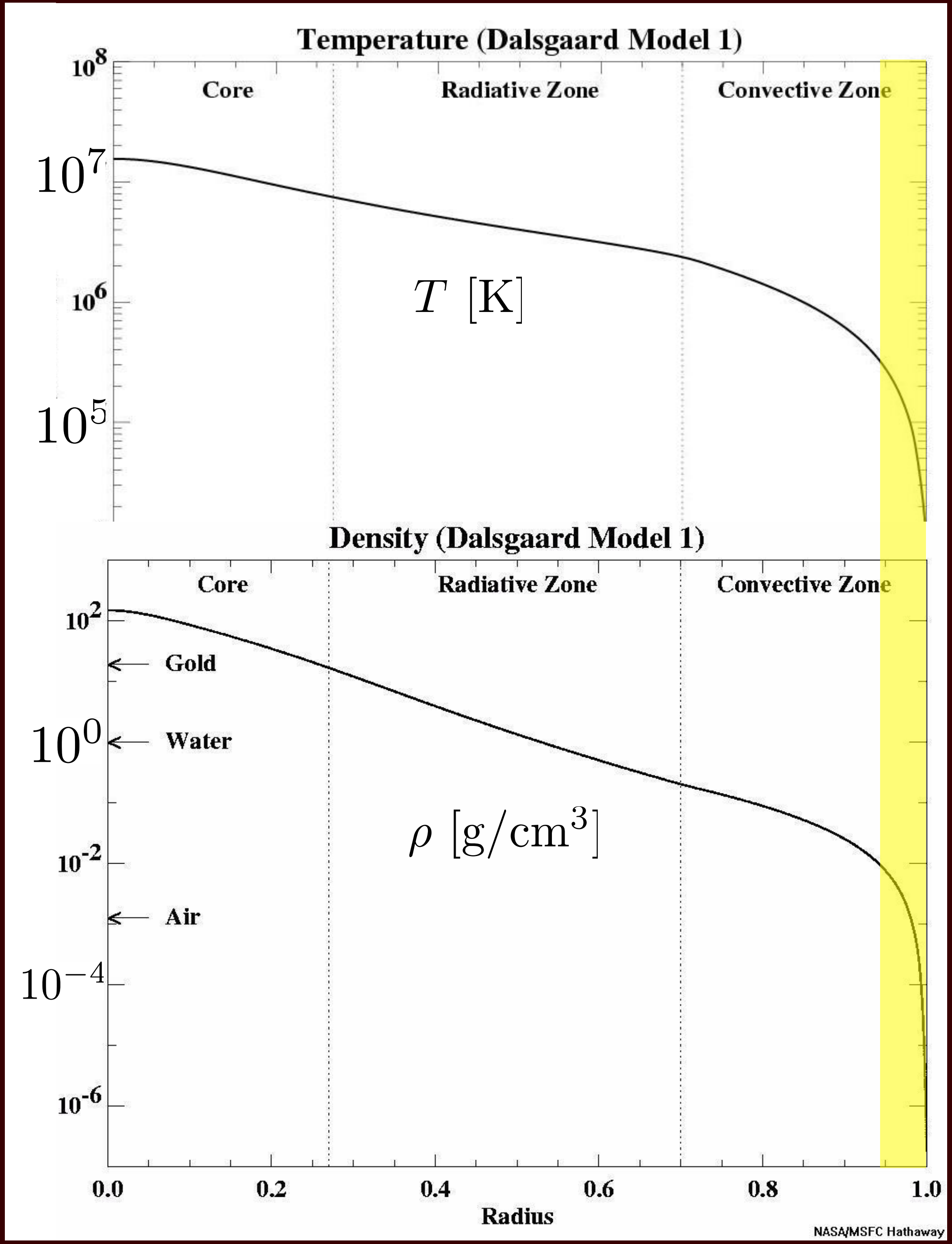
$$N_D \sim \left(\frac{\epsilon_0 T}{e^2 n^{1/3}}\right)^{3/2} \gg 1$$

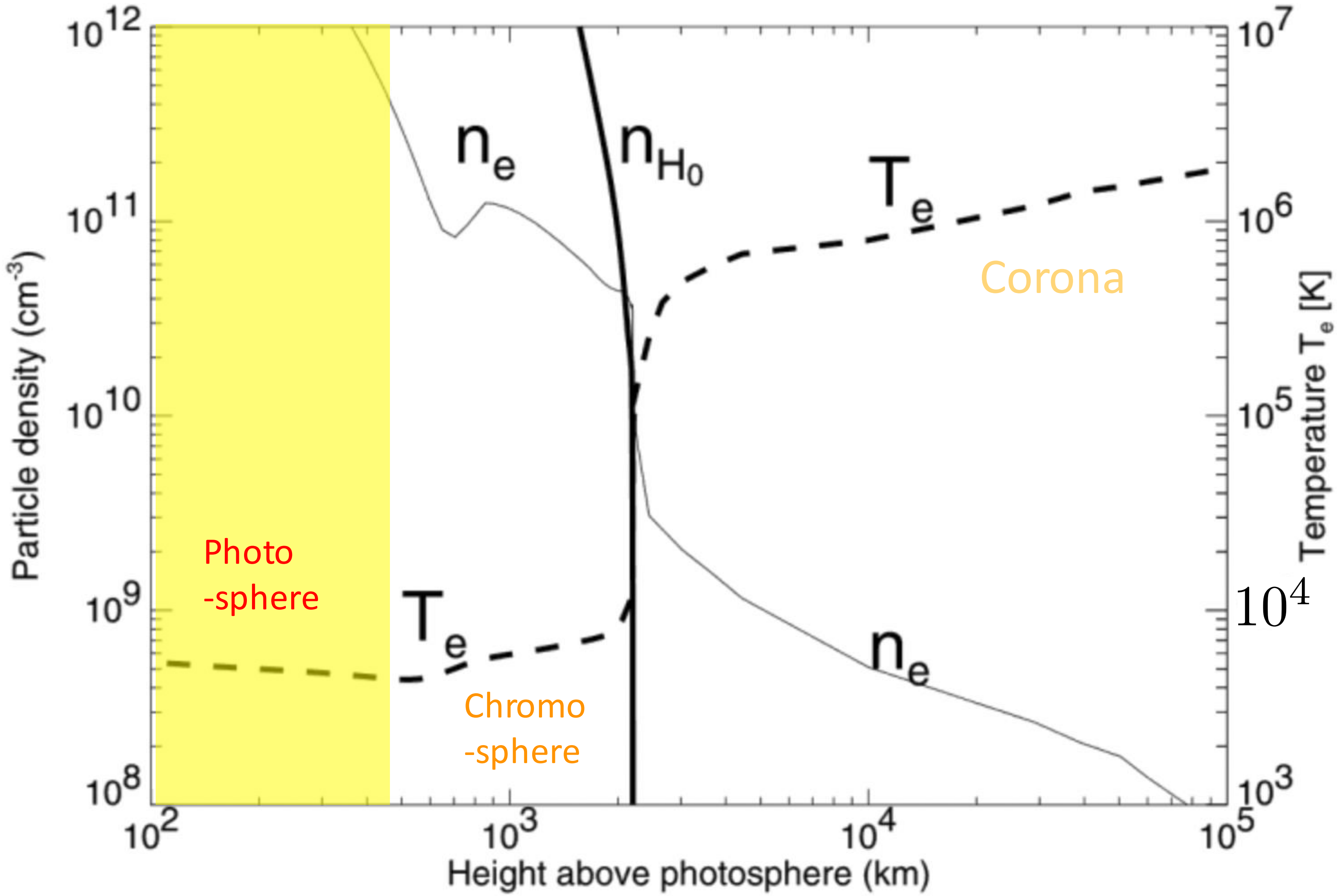


There are statistically "many" particles within the Debye sphere (cube)

II. HIGH-DENSITY STRONGLY COUPLED PLASMA (SCP)


Convective Zone
Radiative Zone
Core


Temperature (Dalsgaard Model 1)
Core
Radiative Zone
Convective Zone
10^8
10^7
10^6
10^5
T [K]
Density (Dalsgaard Model 1)
Core
Radiative Zone
Convective Zone
10^2
Gold
10^0
Water
10^{-2}
Air
10^{-4}
10^{-6}
ρ [g/cm^3]
0.0
0.2
0.4
0.6
0.8
1.0
Radius
NASA/MSFC Hathaway



Aschwanden, *Physics of Solar Corona: An Introduction*, (2004)

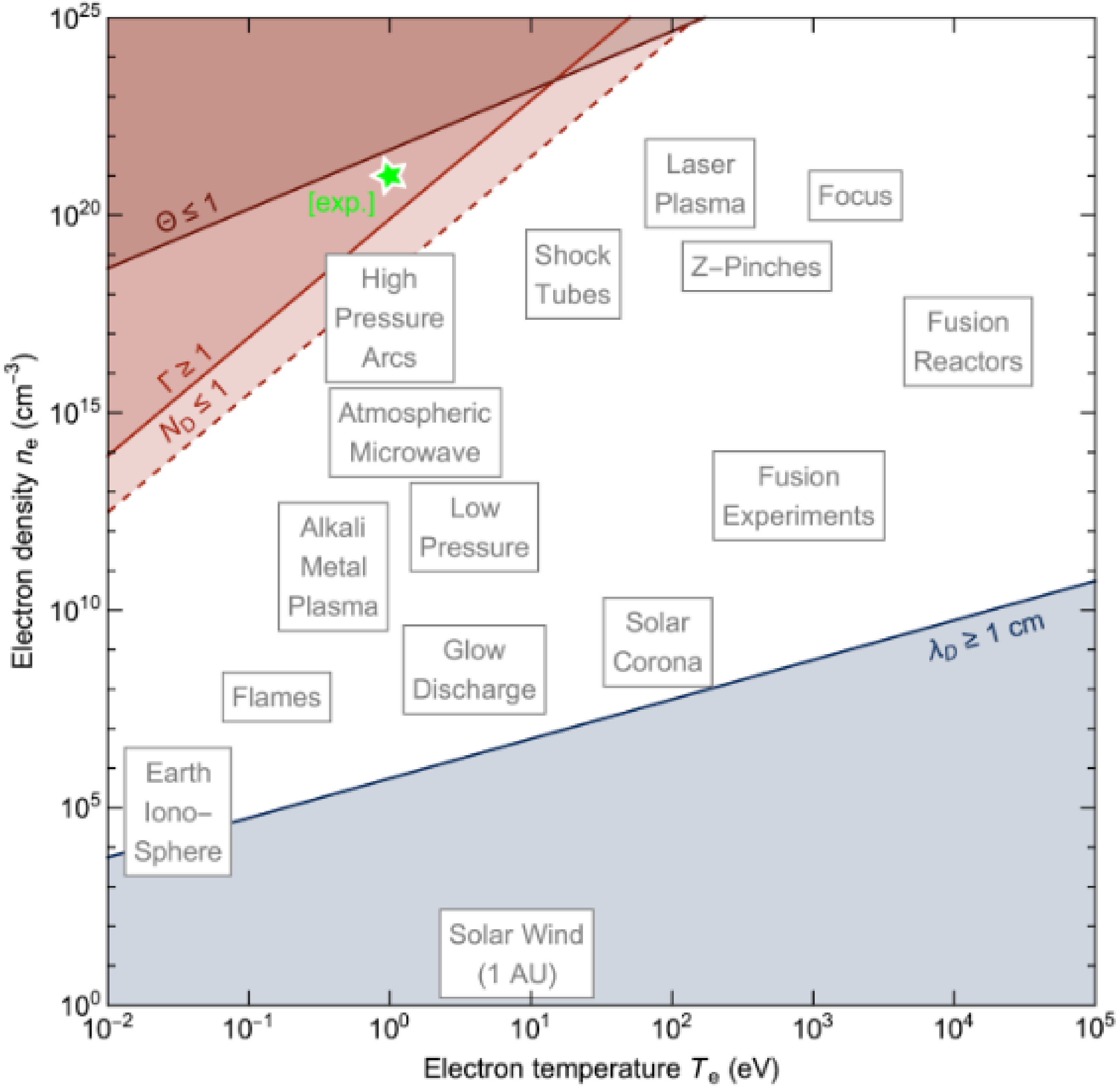
High density plasmas

The weak coupling assumption for Debye shielding is ***invalid***.

The conventional kinetic theory cannot be used for there are ***statically few particles in the Debye cube.***

$$\Gamma = \frac{U}{k_B T}$$

$$\Theta = \frac{k_B T_e}{E_F}$$



Dimensionless parameters in SCP

Fermi energy	$E_F = \frac{\hbar^2}{2m_e}(3\pi^2 n)^{2/3} \propto n^{2/3}$
Coulomb potential energy	$U = \frac{e^2}{4\pi\epsilon_0 a} \propto n^{1/3}$
Kinetic (thermal) energy	$k_B T$

$$\Theta = \frac{k_B T_e}{E_F}$$

$$\Gamma = \frac{U}{k_B T_e}$$

$$r_s = \frac{a}{a_0} \sim \frac{U}{E_F}$$

$$\frac{U}{E_F} = 2\left(\frac{4}{9\pi}\right)^{2/3} \frac{a}{a_0} \approx 0.543\, r_s$$

To describe

fully or partially **degenerate** (QM rather than classical)

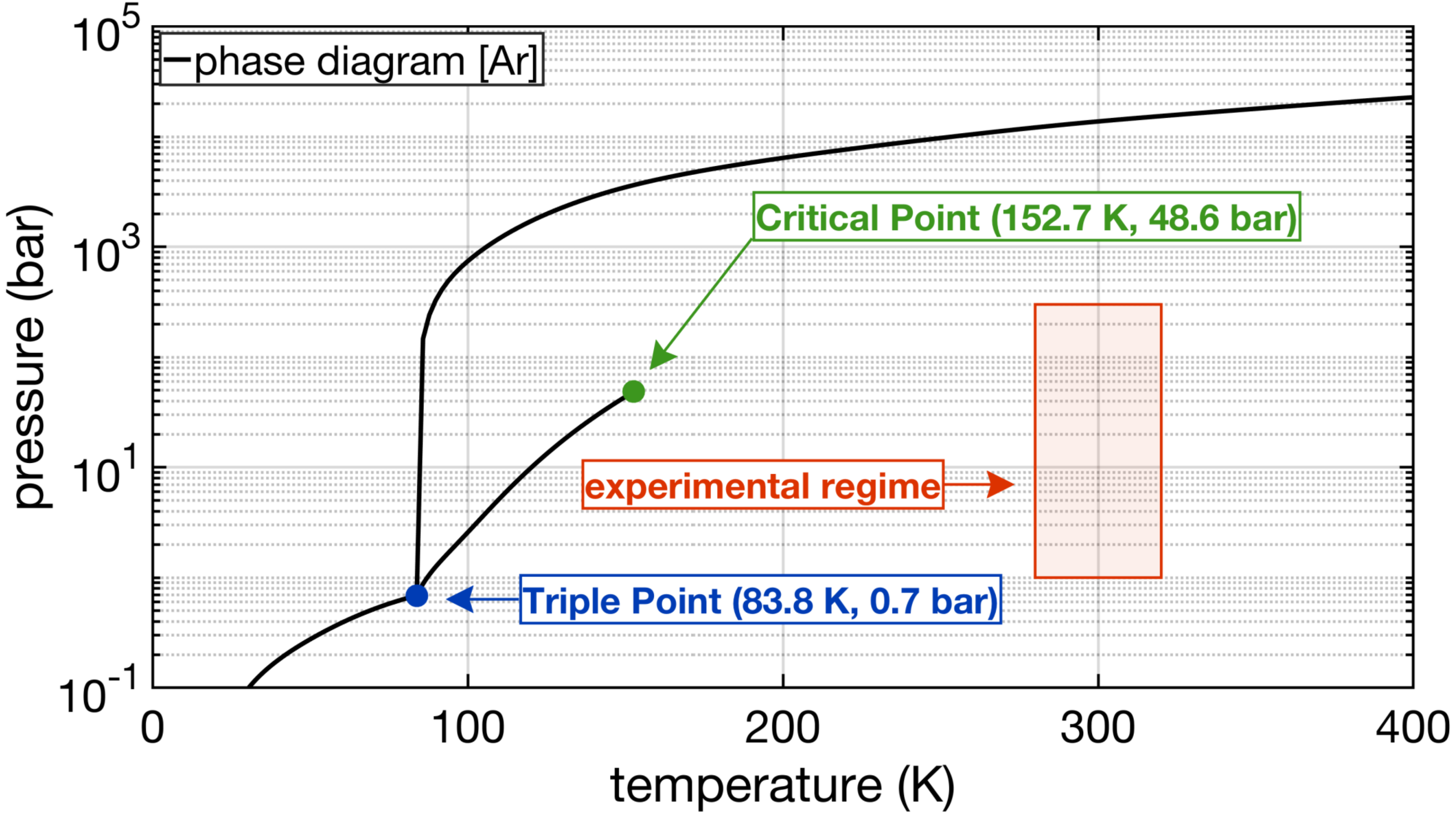
dense plasma systems

We need a priori **Equation of State** (EoS; thermodynamic) and **Opacity** (photon transport) for **“closure”**

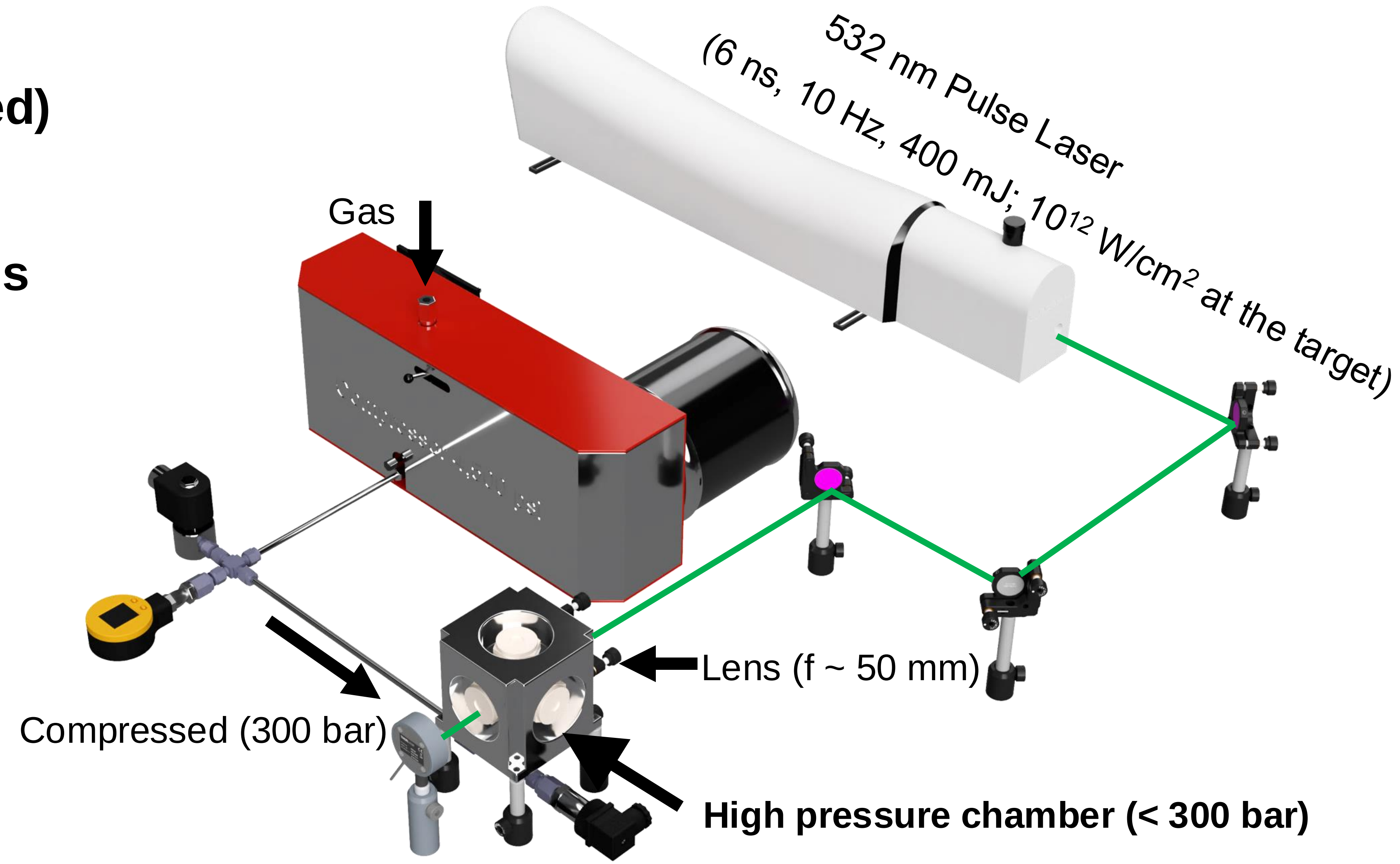
SCP EXPERIMENTS IN SUPERCRITICAL FLUID (SCF)

Supercritical Fluid (SCF) Argon

D. Bolmatov et. al., Sci. Rep. **5**, 15850 (2015)

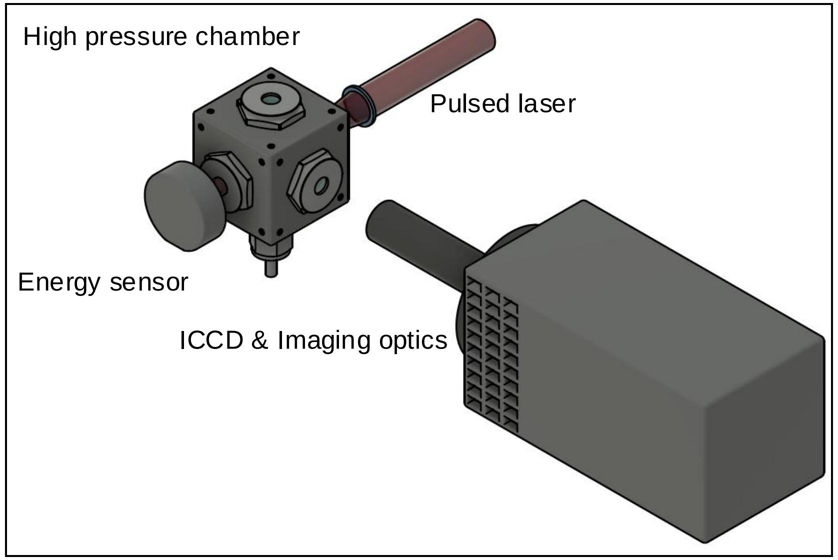


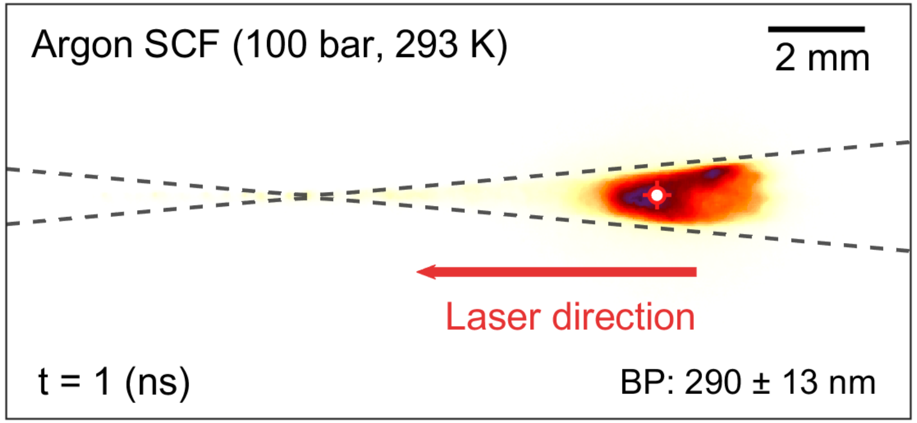
Experimental scheme (simplified) for discharge in supercritical fluids

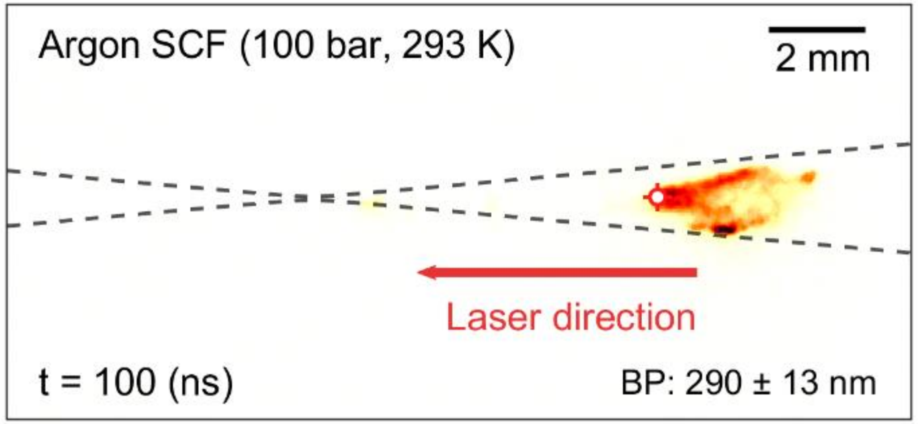


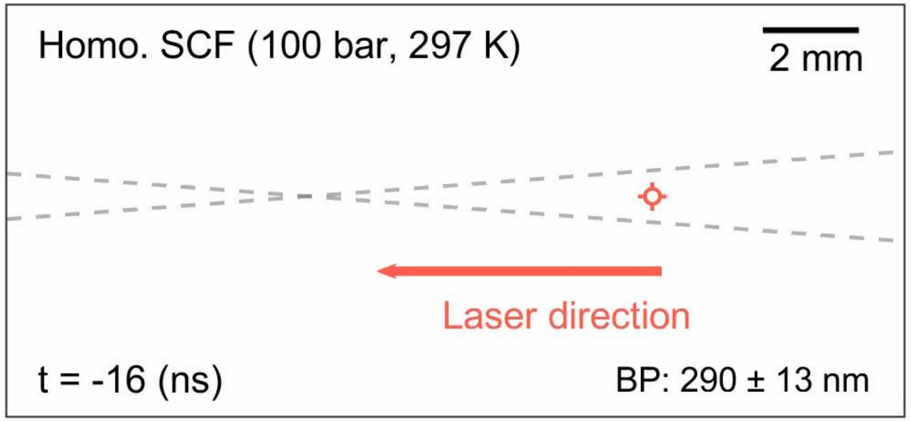
S. Lee et al., *Nature Comm.* **12**, 4630 (2021)

Plasma produced in the Ar supercritical fluid





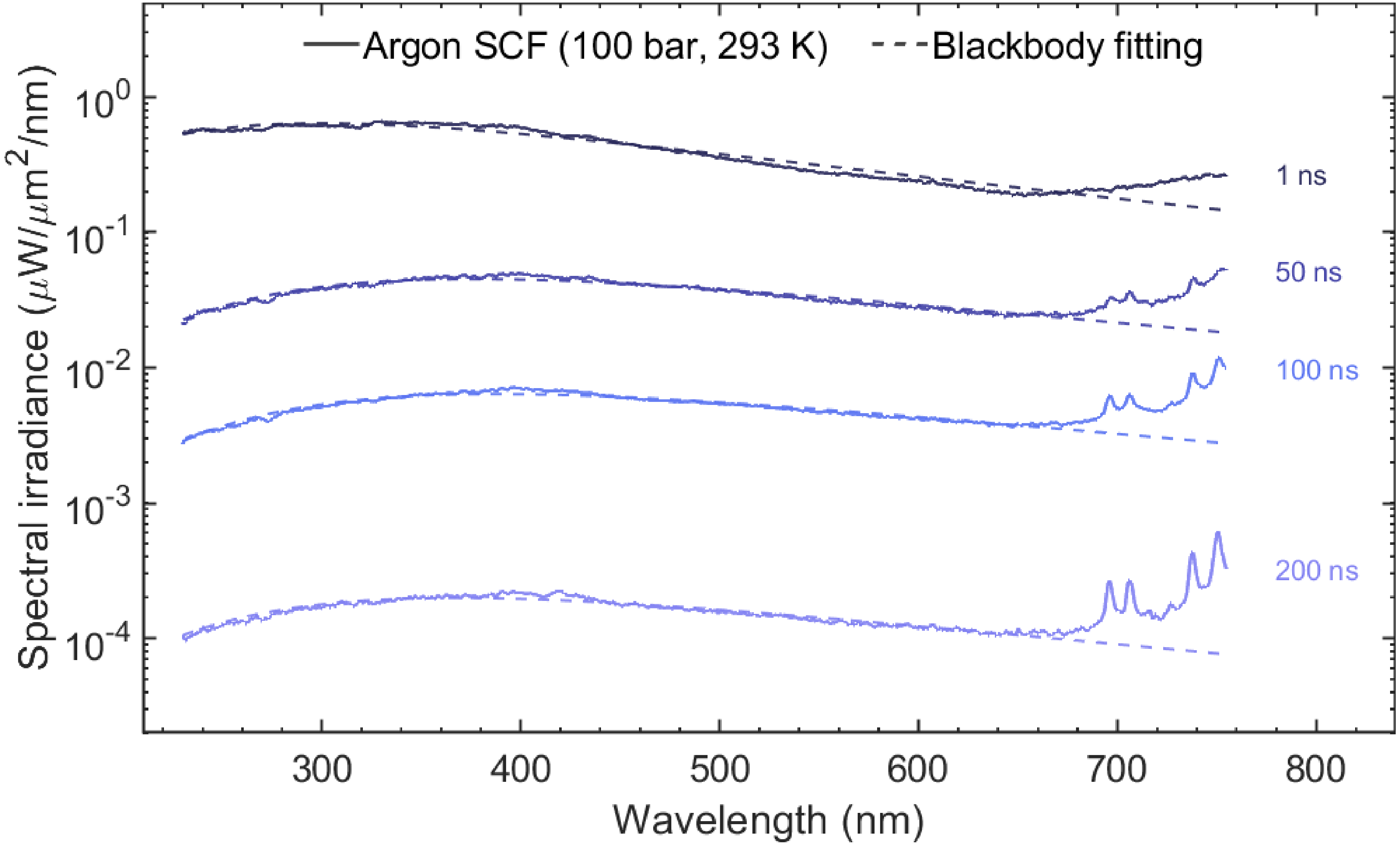




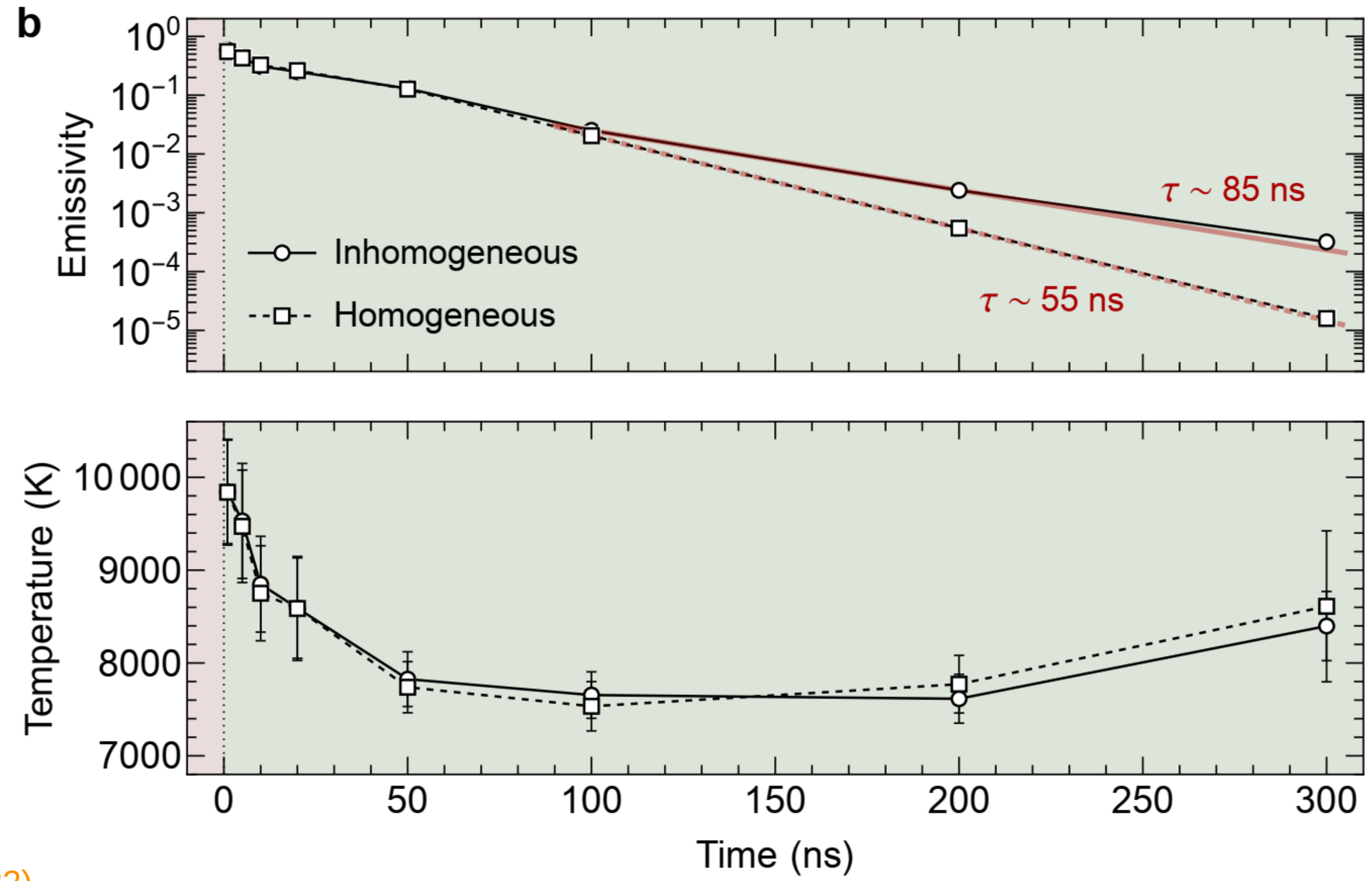
Blackbody fitting of the emission spectra

$$I_{\exp}(\lambda;T) = \varepsilon \frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda k_B T}\right) - 1\right]}$$

S. Lee et al., *Plasma Phys. Control. Fusion* **64**, 095010 (2022)



Temperature $T \sim 1\ \mathrm{eV}$

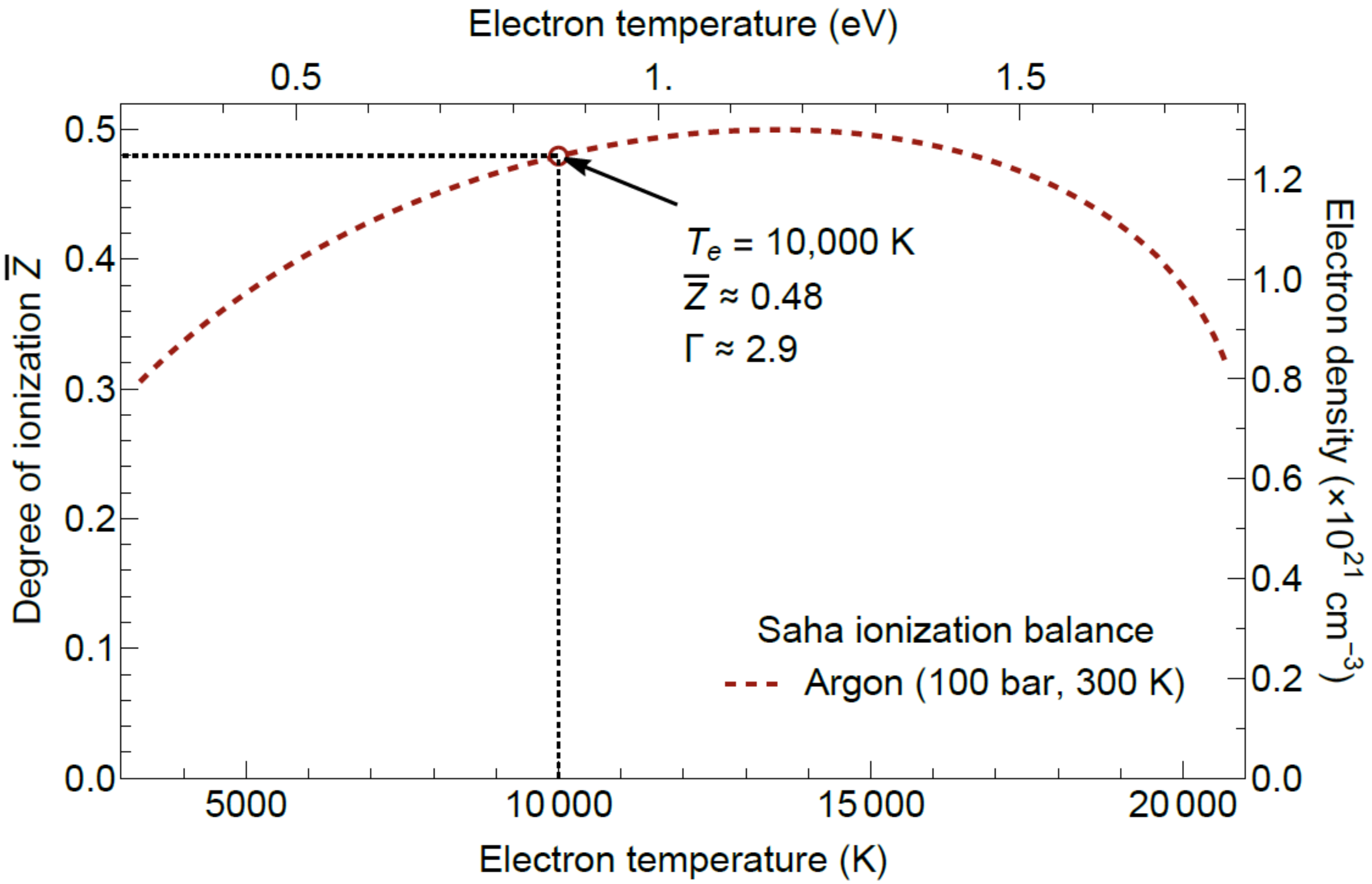


S. Lee *et al* *PPCF* (2022)

Density $n_e \sim 10^{21}\ \mathrm{cm}^{-3}$

Estimated from the measured T_e and the Saha relation with the **ionization potential depression (IPD)**

(cf. Bataller et al., PRL 2014)



$$\Delta\chi = \bar{Z}^{\frac{1}{2}}(\bar{Z}+1)^{\frac{3}{2}}\frac{e^2}{\lambda_{D,e}}$$

$$\frac{n_{i+1}n_e}{n_i} = \frac{2}{\lambda_{\mathrm{th}}^3}\frac{g_{i+1}}{g_i}\exp\left[-\frac{\chi_i - \Delta\chi(n_e,T)}{k_B T}\right]$$

$$\frac{n_1 n_e}{n_0} \approx \frac{n_e^2}{n-n_e} = \frac{2}{\lambda_{\mathrm{th}}^3}\frac{g_1}{g_0}\exp\left[-\frac{\chi_0 - \Delta\chi(n_e,T)}{k_B T}\right]$$

$$\Longrightarrow n_e = n_e(T)$$

S. Lee *et al* *PPCF* (2022)

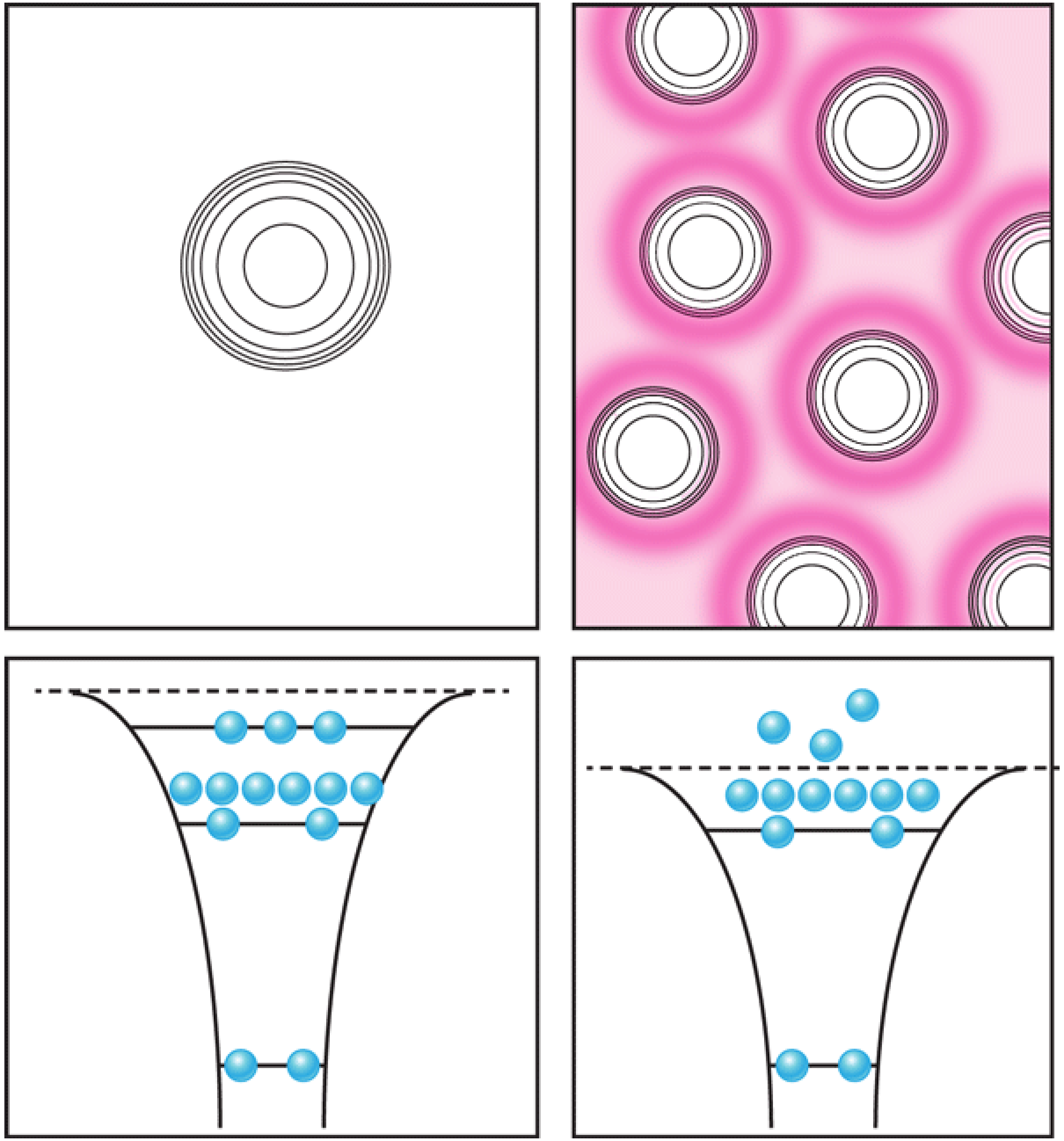
continuum lowering

+ pressure ionization

→ **ionization potential depression (IPD)***

In dense plasma, the energy level of the continuum is *lowered* and the ionization potential is reduced. It becomes easy to produce SCP!

*Bataller et al., PRL (2014)
Ciricosta et al., PRL (2012)

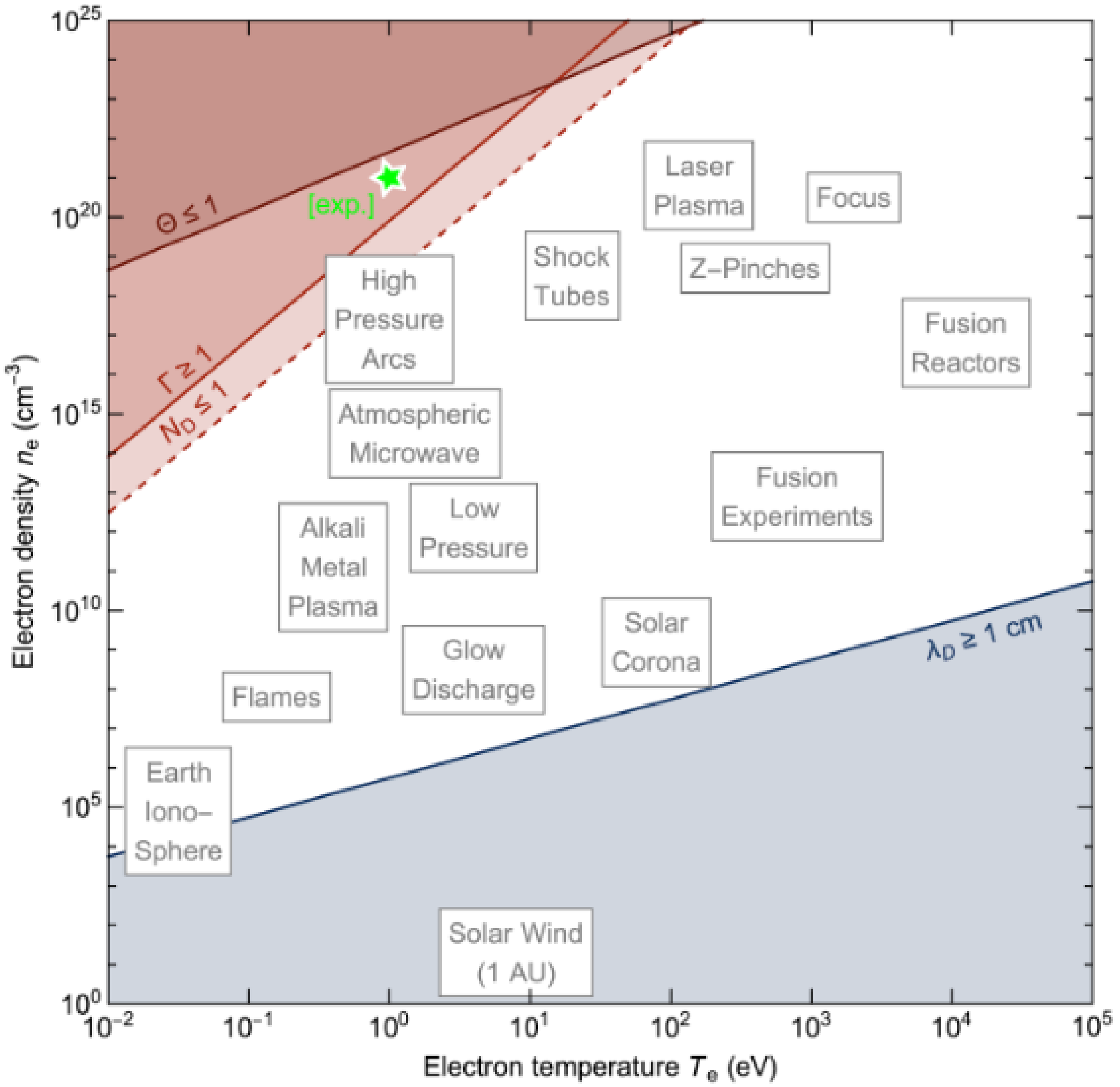


Summary

Moderately-coupled and weakly-degenerate plasmas are generated in SCF medium (~100 bar), relevant to the plasma states in the Solar photosphere, where the ionization potential reduction (IPD) is the dominant ionization mechanism.

$$T_e \sim 1 \text{ eV}$$
$$n_e \sim 10^{21} \text{ cm}^{-3}$$

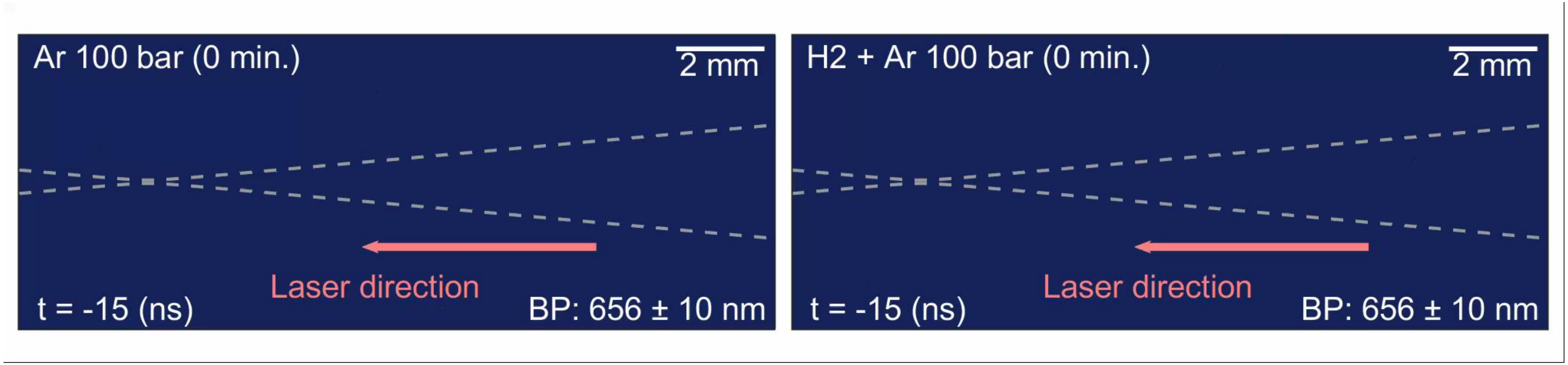
$$\Gamma \sim 1 - 10$$
$$\Theta \sim 1 - 10$$



On-going research

- Quasi-steady SCP state (lifetime > 1 ms)

to identify the transport mechanisms of energy and particles;
to determine the equation of states



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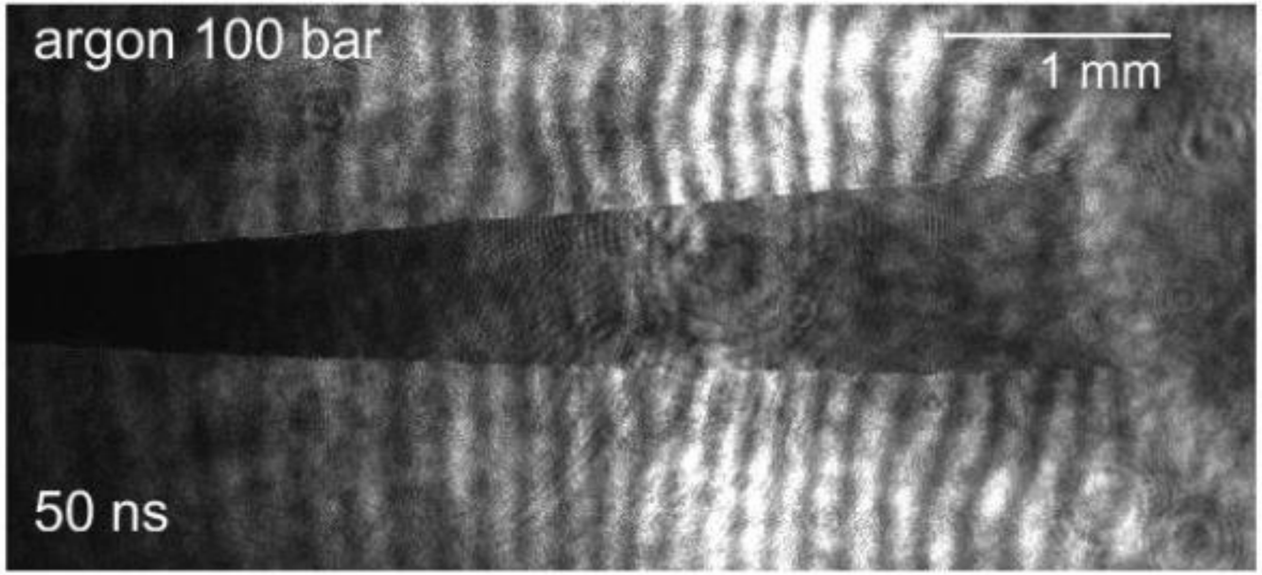
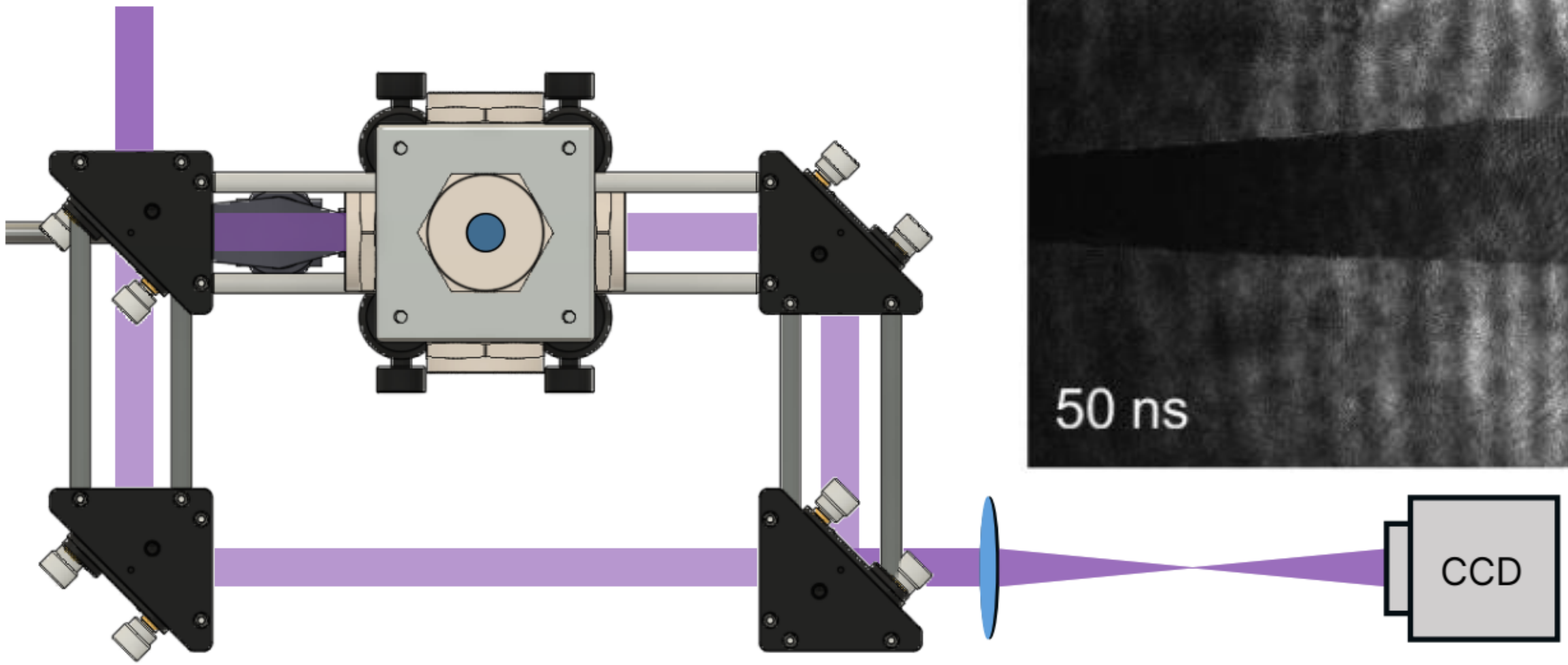
On-going research

- Direct determination of electron density

Plasma is too dense even for 266 nm !





$$\lambda = 266 \text{ nm}$$
$$n_c = 1.57 \times 10^{22}\,\text{cm}^{-3}$$

J. Lee *et al* *in preparation*