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Effects of electron-ion collisions on stopping powers in warm dense matter

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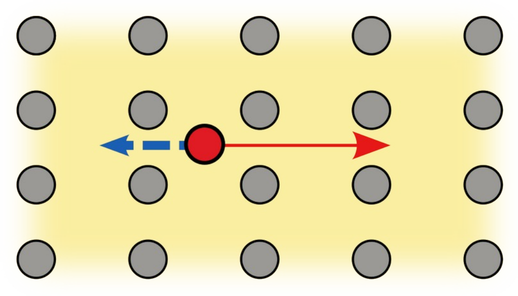
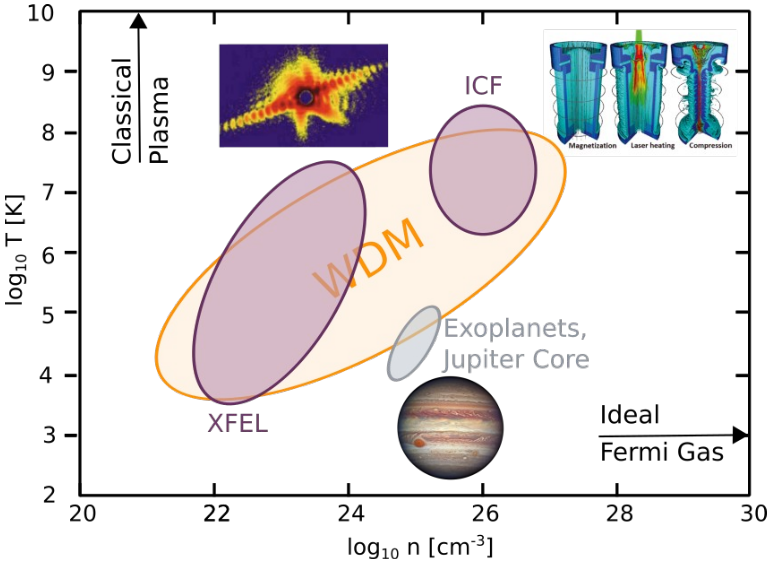
Stopping powers are important in fusion experiments



- The stopping power is the energy lost as a charged particle moves through a plasma

- Stopping powers describe α-particle self-heating in inertial confinement fusion (ICF) experiments, which go through the warm, dense matter regime

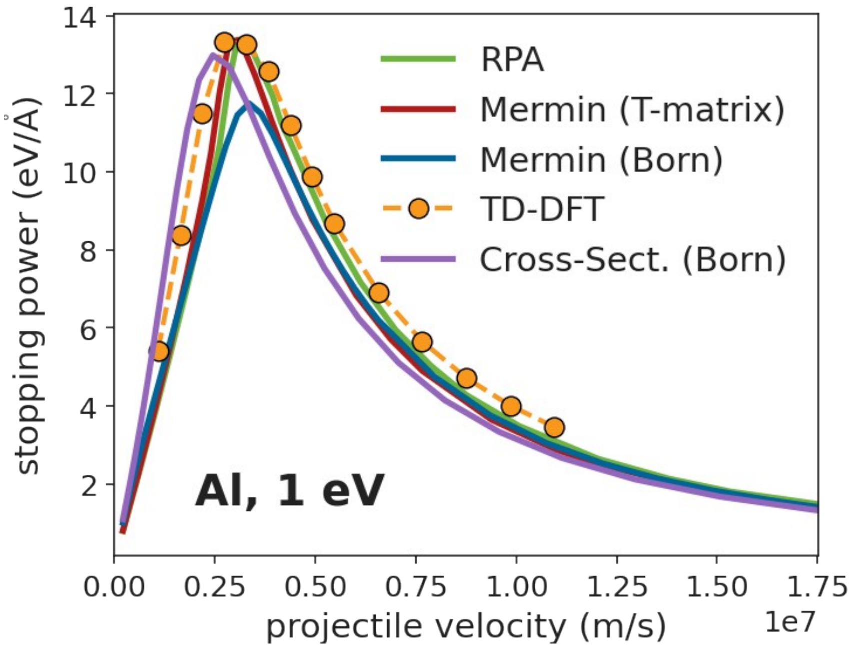


T. Dornheim, S. Groth, M. Bonitz *Phys. Reports* **744** (2018)

P. F. Knapp *et al.* *Physics of Plasmas* **22** (2015)

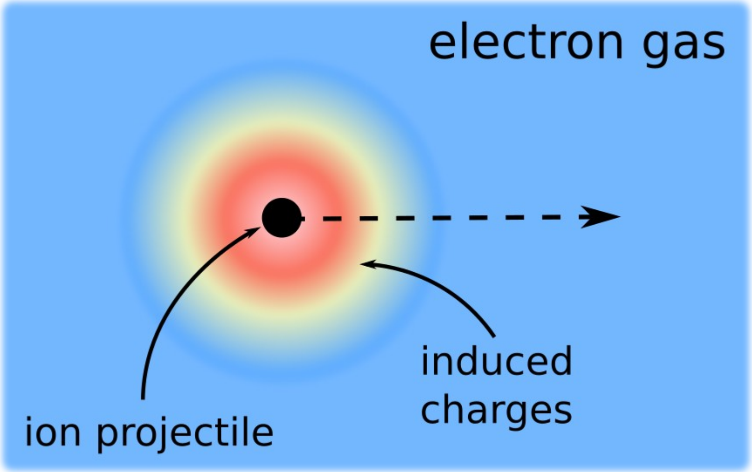
Various microscopic models for stopping exist

1. Expensive **first-principles** methods
   - real-time time-dependent density functional theory (TD-DFT)
2. Inexpensive *reduced-physics* methods
   i. Dielectric formalism
   ii. Scattering theory [1,2]



[1] C. F. Clauser, N. R. Arista, *Phys. Rev. E* **97** (2018)
[2] N. R. Arista, P. Sigmund, *Phys. Rev. A* **76** (2007)

The dielectric function describes the dynamic electron screening



$$\phi^{\text{tot}}(\mathbf{q},\omega) = \phi^{\text{ind}}(\mathbf{q},\omega) + \phi^{\text{ext}}(\mathbf{q},\omega)$$

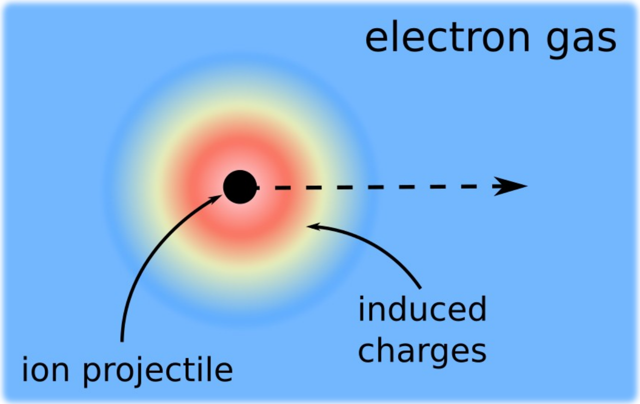
- The dielectric function generalizes the dielectric constant for dynamic/non-uniform fields

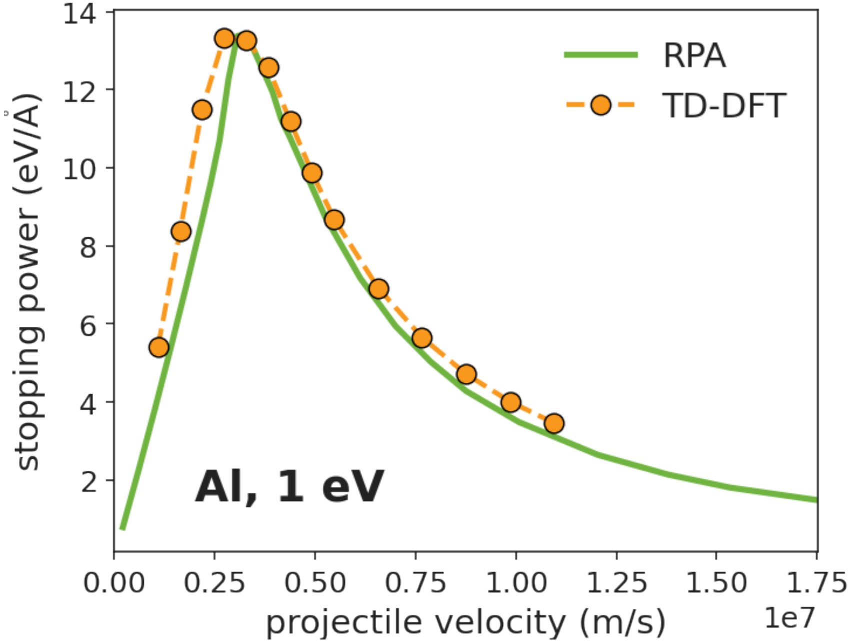
$$\phi^{\text{tot}}(\mathbf{q},\omega) = \frac{1}{\epsilon(\mathbf{q},\omega)}\phi^{\text{ext}}(\mathbf{q},\omega)$$

- The induced charge density will create an **electric field** that acts against the ion projectile
- This induced field depends on $\epsilon(\mathbf{q},\omega)$ and the external charge

We rely on approximations to calculate the dielectric function

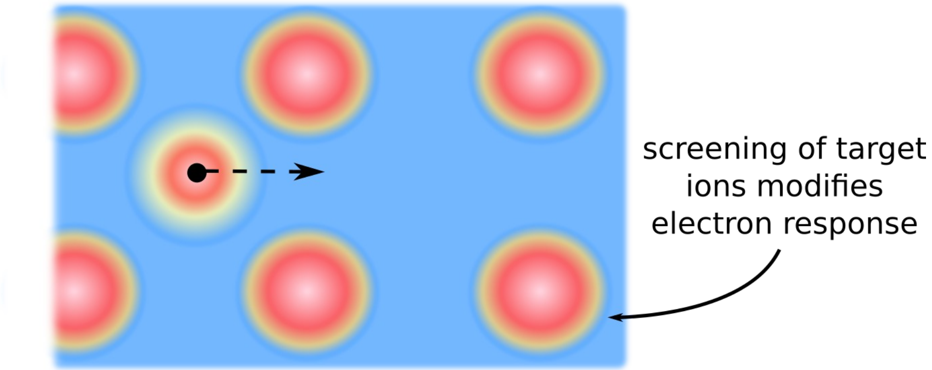
- Our dielectric model is based on a uniform electron gas (UEG) description of the free electrons – random phase approximation (RPA)

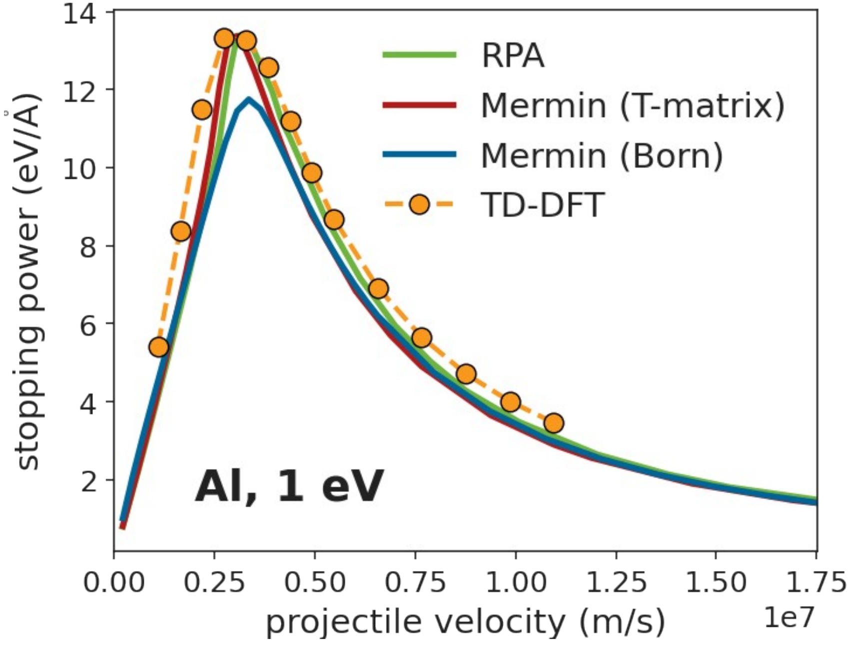




Going beyond the RPA picture with collisions frequencies

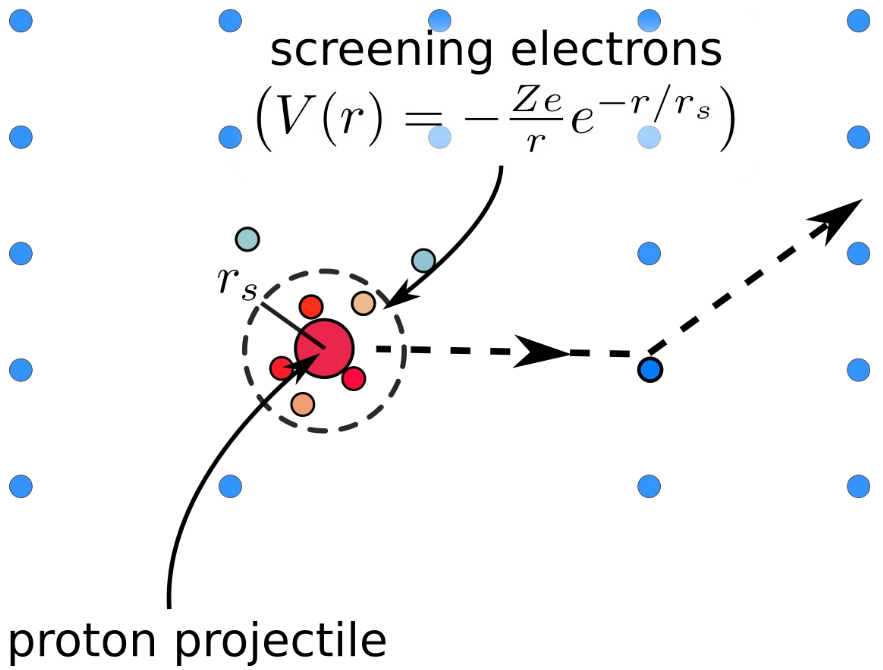
- We modify the RPA by including dynamic **electron-ion collision frequencies** – Mermin dielectric
- These are calculated with **Born** or **transition-matrix** cross-sections using an **average-atom** model – depend on the target material





We can also compute stopping powers directly from scattering cross-sections [1,2]

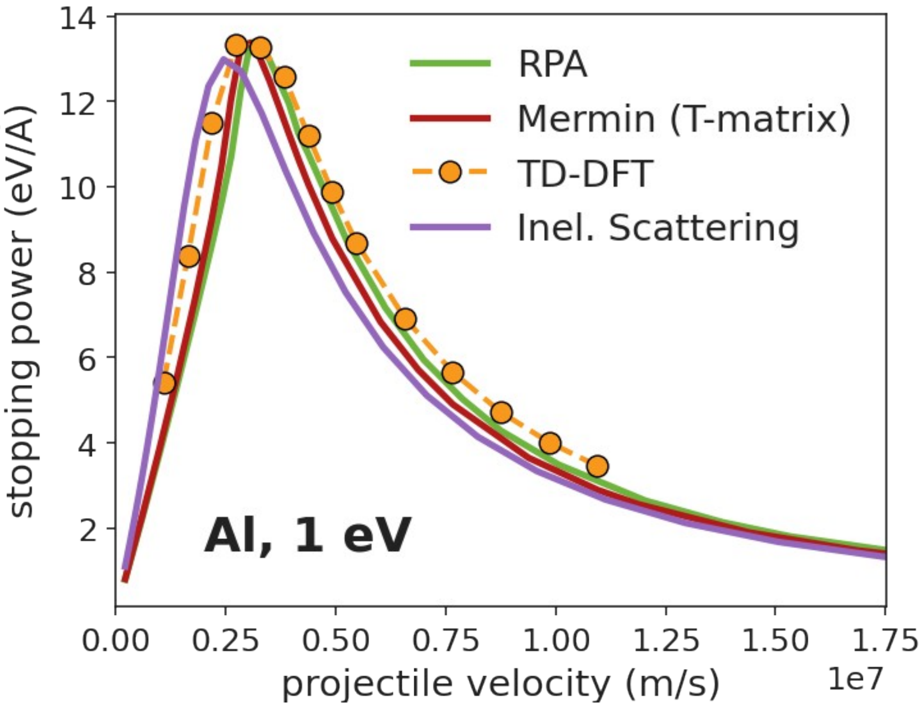
- Projectile traveling through a UEG
- Energy loss as a series of inelastic scattering events between projectile and electrons
- Yukawa potential for screening



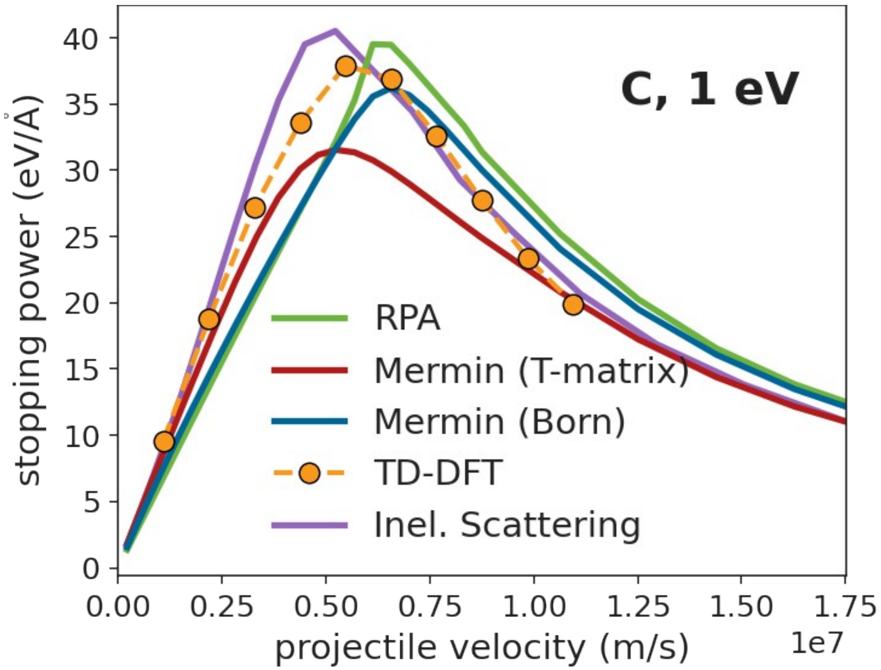
[1] C. F. Clauser, N. R. Arista, *Phys. Rev. E* **97** (2018)
[2] N. R. Arista, P. Sigmund, *Phys. Rev. A* **76** (2007)

Comparing reduced-physics models to TD-DFT for aluminum

- Proton projectile with a warm, dense aluminum target ($k_B T$ = 1 eV, 2.7 g/cm³)
- Free-electron stopping (ignoring bound electron contribution)
- Low-velocity shift in the inelastic scattering Bragg peak



Stopping results in warm, dense carbon

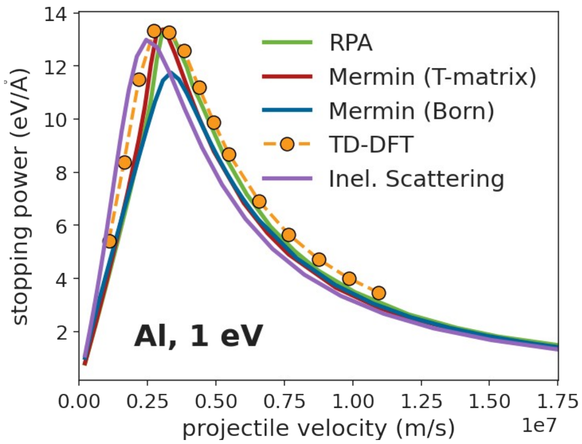


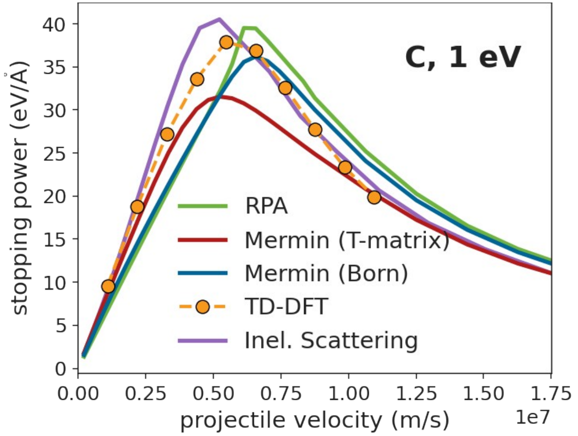
- Proton projectile with a carbon target ($k_B T$ = 1 eV, 10 g/cm^3)
- (Free-electron stopping)
- Mermin dielectric with T-matrix collisions and inelastic scattering theory stopping models agree best with TD-DFT's low velocity behavior

Reduced-physics models are computationally inexpensive

- Overall, good agreement with our TD-DFT data for aluminum at 1 eV; for carbon, fair agreement with Mermin (T-matrix) and scattering theory model

- **Dielectric formalism**: Born failed to describe collisions between free-electrons and (average-) atoms in our target





Future Work:

- Consider non-ideal density of states calculated from AA in scattering theory stopping calculations

- Within the dielectric formalism, can we approximate non-ideal stopping with a modified e-i collisions?