The electron screening effect with a magnetic field on the massive stars

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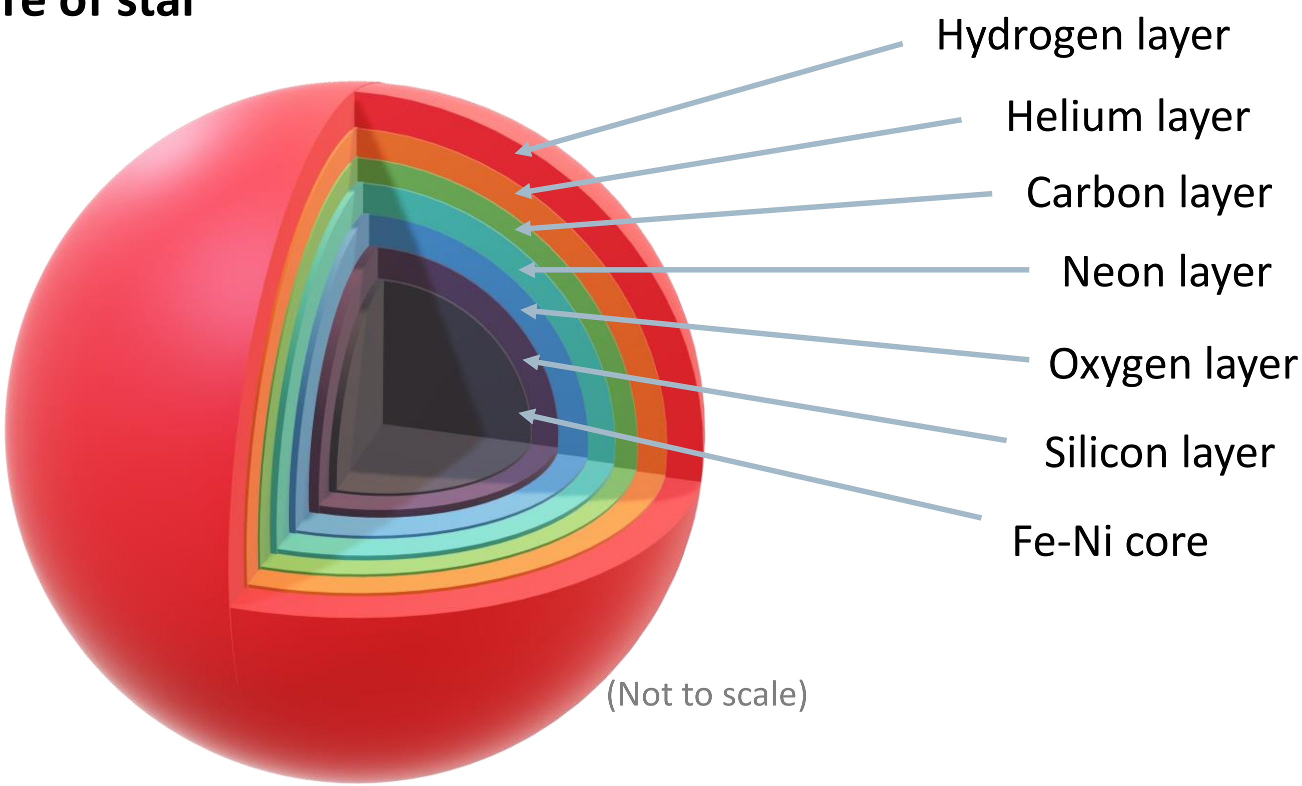
Introduction

- **Structure of star**

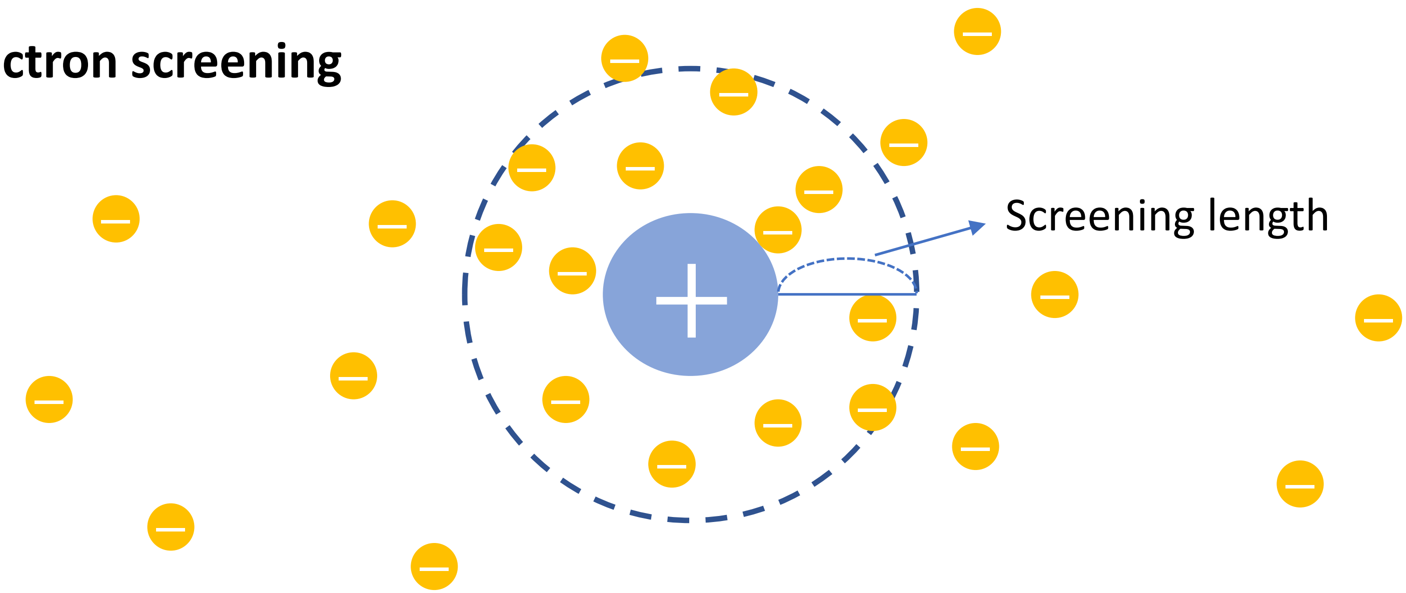


➢ Stars generate the energy through the thermonuclear reactions

➢ Stellar evolution occurs through various burning stage depending on their total mass.

Introduction

- **Electron screening**



➢ In the environment of ionized stellar plasma, nuclei are surrounded by electron cloud.

➢ The Coulomb barrier of screened nuclei is decreased.

➢ The electron screening effect gives a correction to the network calculation.

Formalism : Classical screening

- **Thermonuclear reaction rate**

$S(E)$: The astrophysical S-factor
Z_t: atomic number of target nucleus
Z_p: atomic number of projectile nucleus

$$\langle \sigma v \rangle \propto \int_0^{\infty} S(E) P(E) e^{-E/T} dE$$

$$P(E) = \exp\left(-\frac{2}{\hbar}\sqrt{2m} \int_{R_0}^{R_c} \sqrt{\frac{Z_t z_p e^2}{r} - E dr} \right) \equiv e^{-2\pi\eta}$$

- **Classical screening**

Z_i: atomic number of projectile i nucleus
n_{z_i}: number density of z_i nuclear

$$\nabla^2 \phi = -4\pi Z_t e^2 \delta(\vec{r}^3) - 4\pi \sum_{z_i \geq -1} z_i e n_{z_i} \exp\left[\frac{z_i e \phi}{T}\right]$$

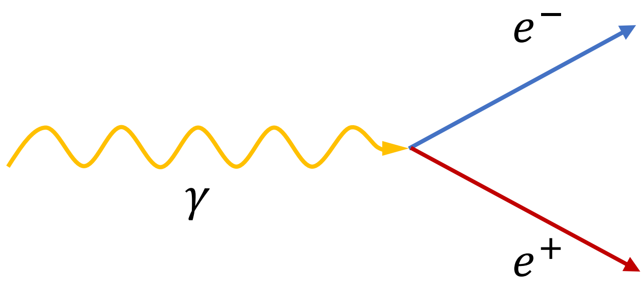
$$\phi_{screen}(r) = \frac{Z_t e}{r} \exp(-\frac{r}{\lambda_D}) \qquad \lambda_D = \sqrt{\frac{T}{4\pi e^2 \rho N_A \zeta^2}}$$

$\zeta \equiv \left(\sum_i \frac{(Z_i^2 + Z_i) X_i}{A_i}\right)^{1/2}$ N_A: Avogadro number X_i: mass fraction of nucleus i

Formalism : Relativistic screening

- **Electron-positron plasma**

$$T \gtrsim m_e \approx 0.5 \text{ MeV}$$



- **Net electron number density**

$$n_e \equiv n_{e^-} - n_{e^+} = 2\int \frac{d^3p}{(2\pi)^3}\left[\frac{1}{\exp\left[\frac{\sqrt{p^2+m_e^2}-\mu}{T}\right]+1} - \frac{1}{\exp\left[\frac{\sqrt{p^2+m_e^2}+\mu}{T}\right]+1}\right]$$

n_e: electron mass

μ: chemical potential

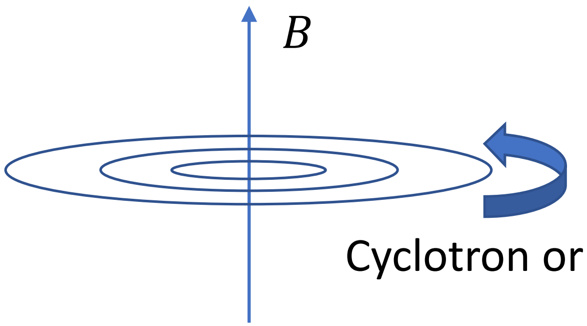
- **Screening length**

$$\frac{1}{\lambda_{TF}^2} = 4\pi e^2 \frac{\partial \mathrm{n_e}}{\partial \mu} \text{[1]} \longrightarrow \lambda_{TF} = \left[\frac{e^2}{\pi^2}\frac{\partial}{\partial\mu}\int_0^\infty dp p^2 f_{FD}(p,\mu,T)\right]^{-1/2}$$

[1] M.A. Famiano et al., Phys. Rev. C 93, 045804(2006)

Formalism : Magnetic field effect

- **Landau quantization**



$$\sqrt{eB_c} \gtrsim m_e \longrightarrow B_c \approx 4.4 \times 10^{13}\ \mathrm{G}$$ [1,2]

$$E^2 = \vec{p}^2 + m_e^2 \longrightarrow E^2 = p_\parallel^2 + eB(2n + s + 1) + m_e^2$$

n : Landau level
s =±1 (the electron spin is along or opposed to the B-field respectively)

- **Electron number density**

$$n_e = \frac{1}{\pi^2}\int_0^\infty dp p^2 f_{FD}(p,\mu,T) \longrightarrow n_e = \sum_{n=0}^{\infty}(2-\delta_{n0})\int_{-\infty}^{\infty}\frac{dp_\parallel}{2\pi}\frac{eB}{2\pi}f_{FD}(E_B,\mu,T)$$ [2]

[1] Masahiro Kawasaki and Motohiko Kusakabe. Phys. Rev. D, 86(6):063003, Sep 2012.
[2] D. Grasso and H. R. Rubinstein. Phys. Rep., 348(3):163–266, Jul 2001.

Formalism : Enhancement factor

- **Screening enhancement factor**

$$\phi_{screen}(r) = \frac{Z_t e}{r}\exp(-\frac{r}{\lambda_{TF}}) \qquad \frac{1}{\lambda_{TF}^2} = 4\pi e^2 \frac{\partial \mathrm{n_e}}{\partial \mu}$$

$$P_{screen} = \exp\left(-2\sqrt{2m}\int_{R_0}^{R_c}\sqrt{\frac{Z_t Z_p e^2}{r}e^{-r/\lambda_{TF}} - E dr}\right) = e^{x\pi\eta - 2\pi\eta}$$

$$e^{x\pi\eta} \approx e^{(x\pi\eta)_{E_0}} = e^{\frac{Z_t Z_p e^2}{\lambda_{TF} T}} \equiv f_s$$

E_0: Gamow energy

- **Thermonuclear reaction rate with screening effect**

$$\langle\sigma v\rangle_{screen} = \left(\frac{8}{\pi\mu_{pt}}\right)^{1/2}\frac{N_A}{T^{3/2}}\int_0^\infty S(E) f_s \underline{e^{-2\pi\eta}} e^{-E/T} dE$$

$$= f_s \langle\sigma v\rangle_{unscreen}$$

($e^{-2\pi\eta}$ → $e^{x\pi\eta - 2\pi\eta}$)

μ_{pt}: reduced mass

Result

- **Baryon number density**

$$n_b = \rho N_A \sum Y_i$$

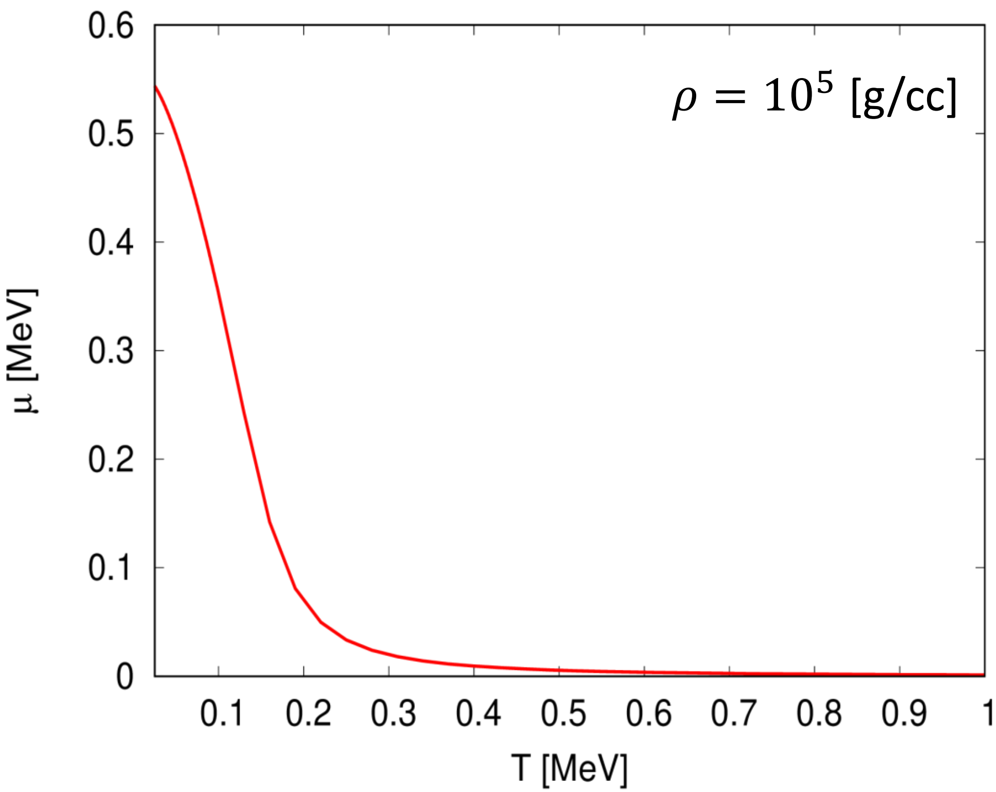
- **Net electron number density**

$$n_e = \sum_{n=0}^{\infty} (2 - \delta_{n0}) \int_{-\infty}^{\infty} \frac{dp_{\parallel}}{2\pi} \frac{eB}{2\pi} f_{FD}(E_B, \mu, T)$$

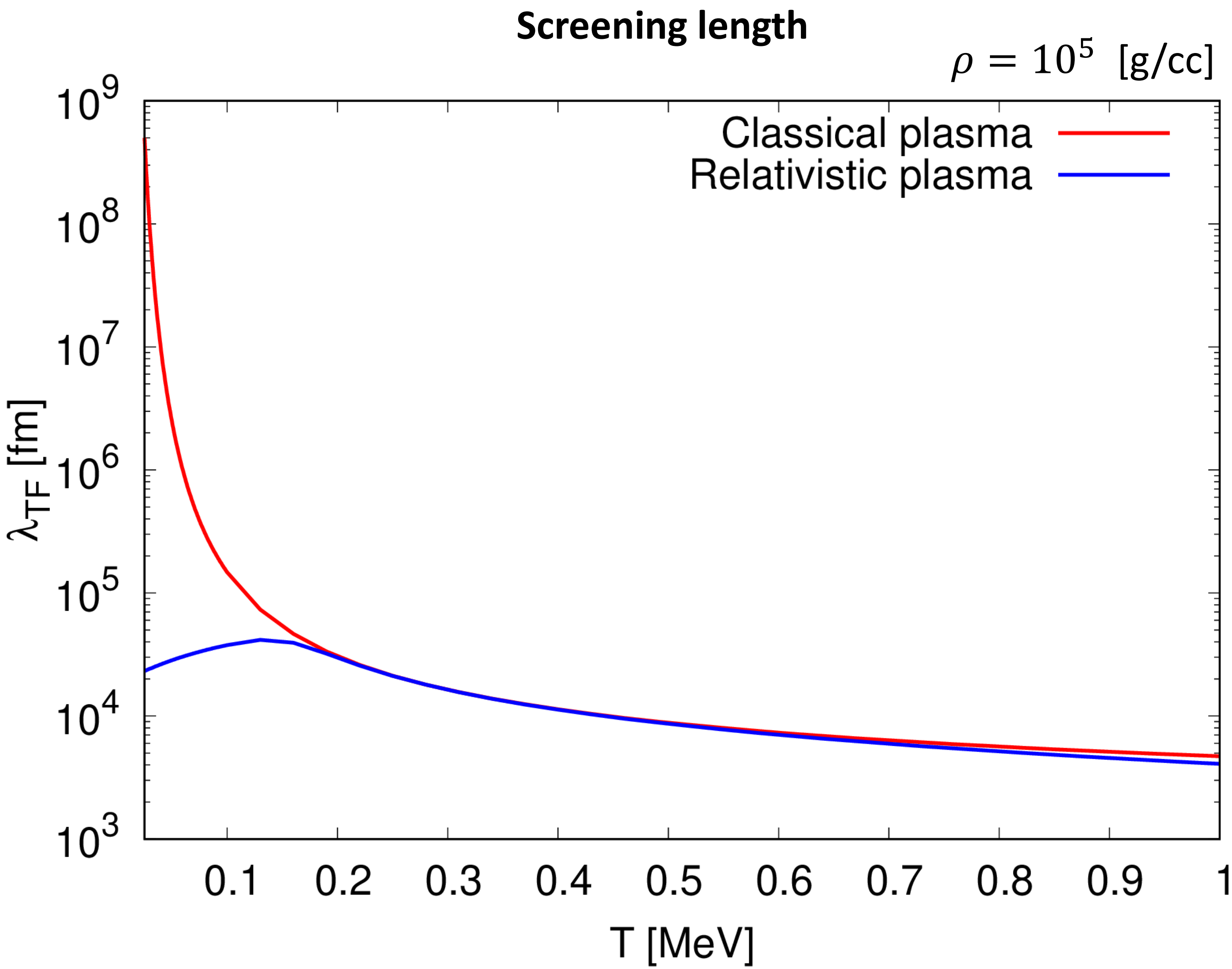
- **Charge neutrality**

$$\rho N_A \sum Y_i = \sum_{n=0}^{\infty} (2 - \delta_{n0}) \int_{-\infty}^{\infty} \frac{dp_{\parallel}}{2\pi} \frac{eB}{2\pi} f_{FD}(E_B, \mu, T)$$

Chemical potential

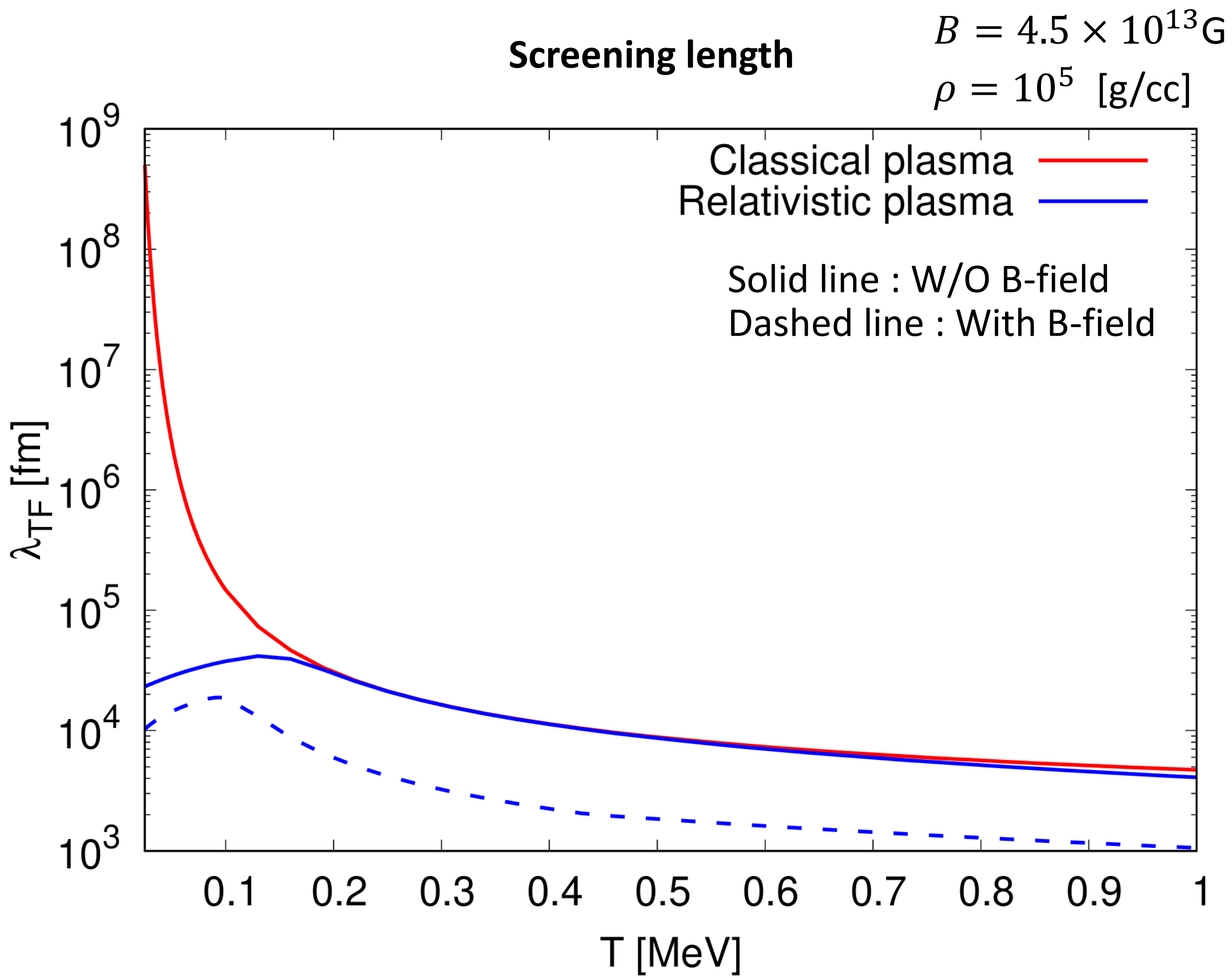


Result



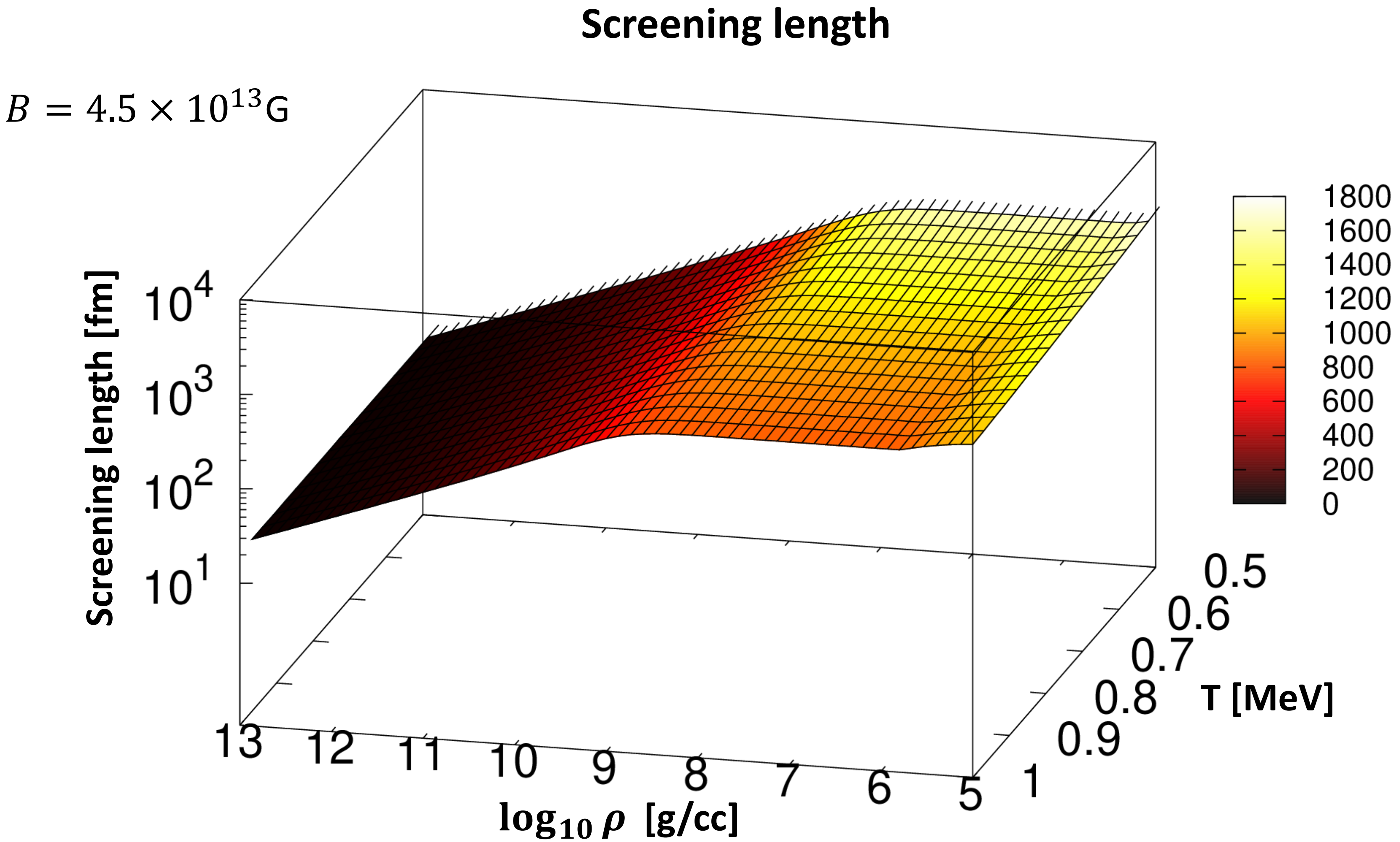
Screening length
$\rho = 10^5$ [g/cc]
Classical plasma
Relativistic plasma
10^9
10^8
10^7
10^6
10^5
10^4
10^3
λ_{TF} [fm]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
T [MeV]

Result



Screening length
$B = 4.5 \times 10^{13}$G
$\rho = 10^5$ [g/cc]
Classical plasma
Relativistic plasma
Solid line : W/O B-field
Dashed line : With B-field
λ_{TF} [fm]
T [MeV]

Result

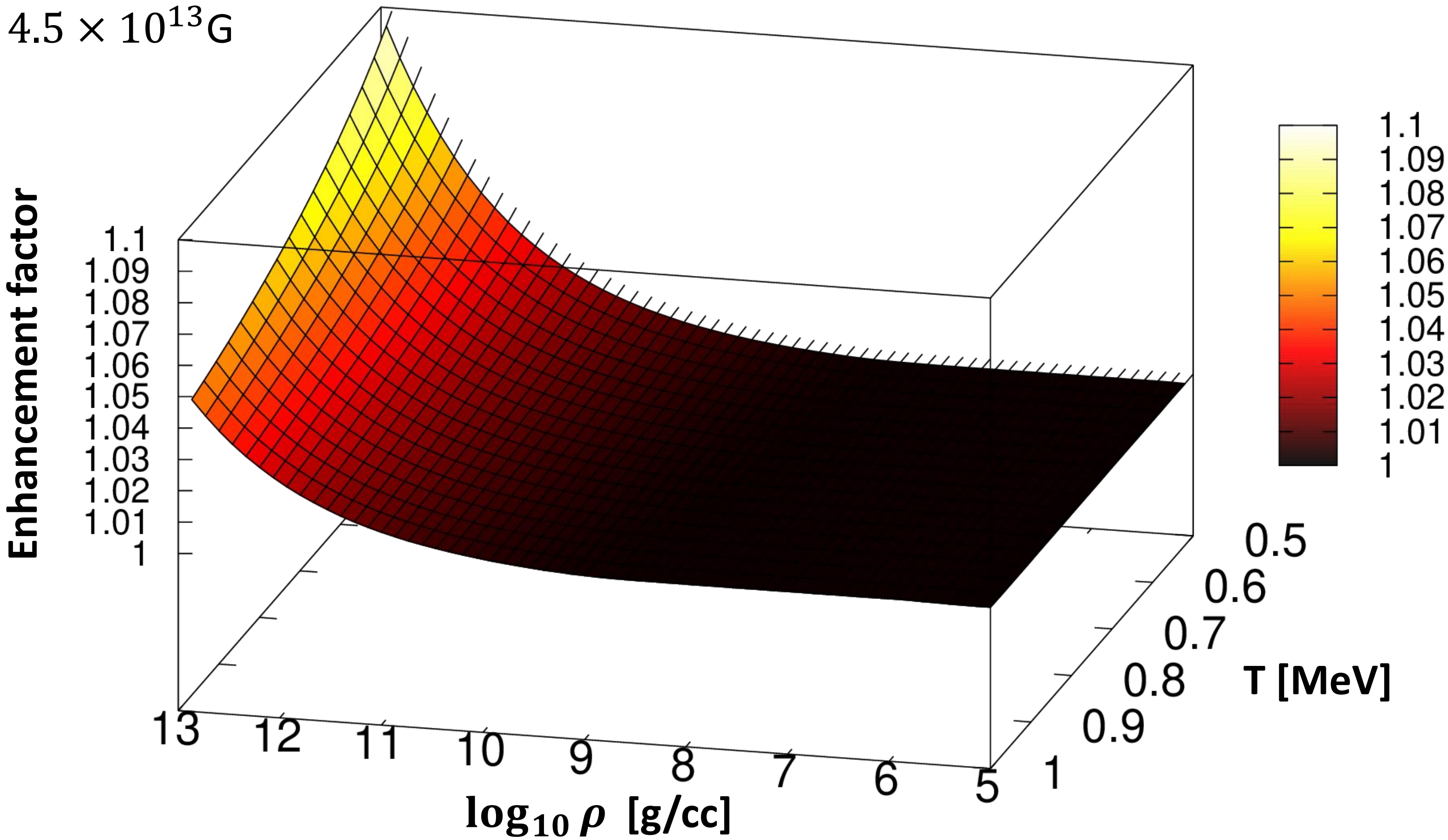

Screening length
$B = 4.5 \times 10^{13}$G
Screening length [fm]
10^4
10^3
10^2
10^1
13 12 11 10 9 8 7 6 5
$\log_{10} \rho$ [g/cc]
0.5 0.6 0.7 0.8 0.9 1
T [MeV]
1800 1600 1400 1200 1000 800 600 400 200 0

Result

Screening enhancement factor

$$f_s = e^{\frac{Z_1 Z_2 e^2}{T \lambda_{TF}}}$$

$B = 4.5 \times 10^{13}$G



Summary

- We try to modify the reaction rate using the electron screening effect.
- Considering only the effects of pair creation, there is little screening effect occurs in the electron positron plasma.
- Including magnetic field effect, the screening effect is increased.
- As a future work, we will investigate the specific stellar environment where screening effects, including magnetic field effect, may occur.

Thank you for your attention!