IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

17-06-2025

Study of the "Freeze-in" Scenario for Dark Matter Particle Production

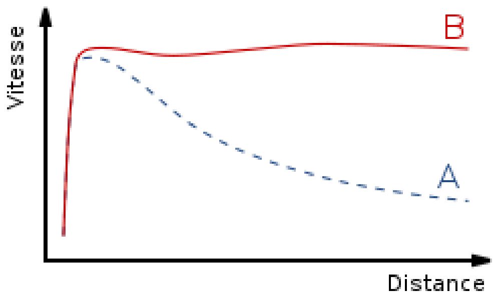
In connection with the DAMIC-M direct dark matter detection experiment
« **DA**rk **M**atter **I**n **C**CD at **M**odane »

Gabrielle Kruch

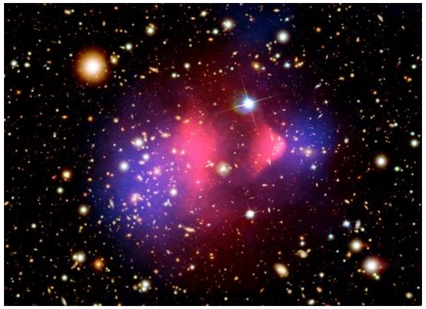
Supervisor : Olivier Deligny

Introduction

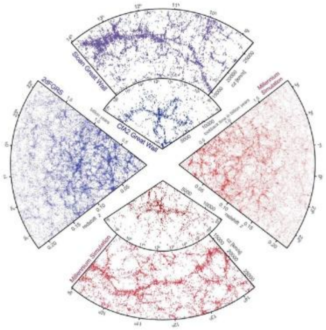
We know that dark matter exists :



Galaxy rotation curve



Bullet Clusters



Structure of the Universe

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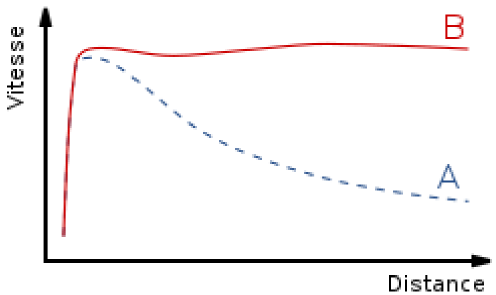

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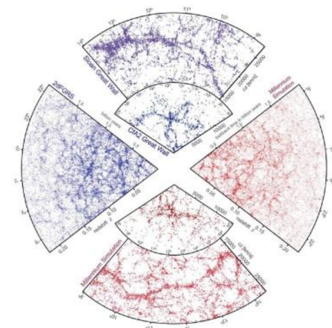

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We are trying to detect it :

Direct detection = interaction of dark matter particles with electrons in a detector

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DAMIC-M

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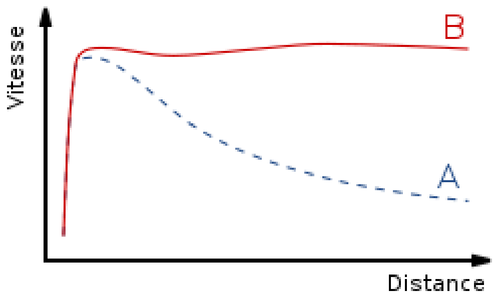

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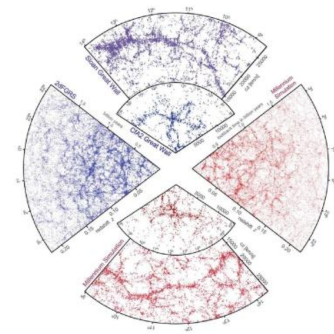

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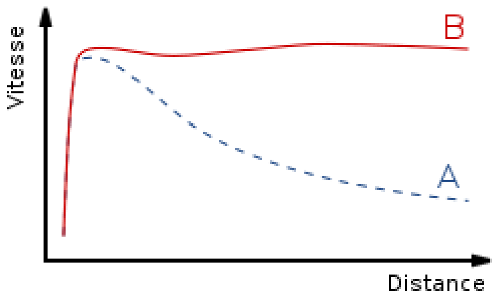

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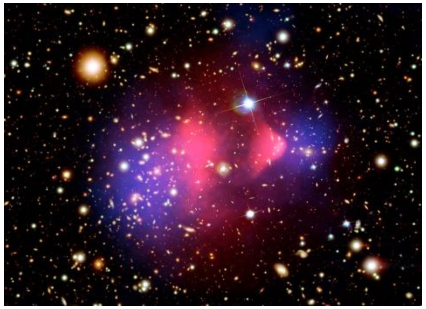

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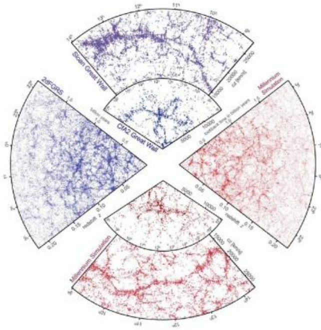

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DAMIC-M

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FREEZE-IN

←

Theoretical prediction: expected event rate

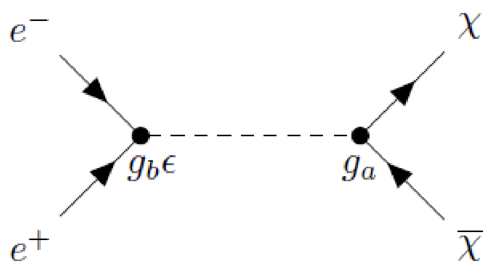
The Freeze-in :

→ Models the interaction between standard model particles and dark matter from a hidden sector through a photon and a "dark photon"

→ Dark matter is absent in the early moments of the universe, then its density gradually increases until it reaches the level we observe today through the energy density abundance rate : $\Omega = 25\%$

Internship objectives:

Study the freeze-in scenario to understand the interaction between standard matter and dark matter



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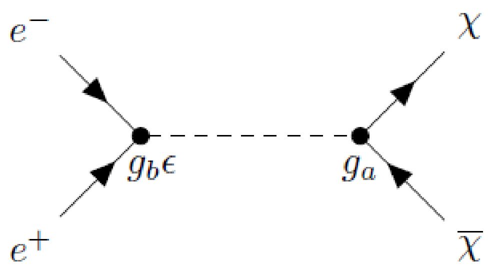

Establish the equations that model the evolution of dark matter density over time

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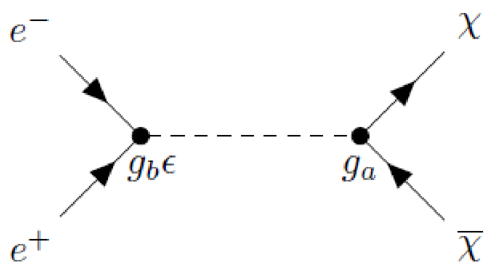
Reproduce the curve showing the evolution of the dark matter–electron interaction cross section as a function of the dark matter mass



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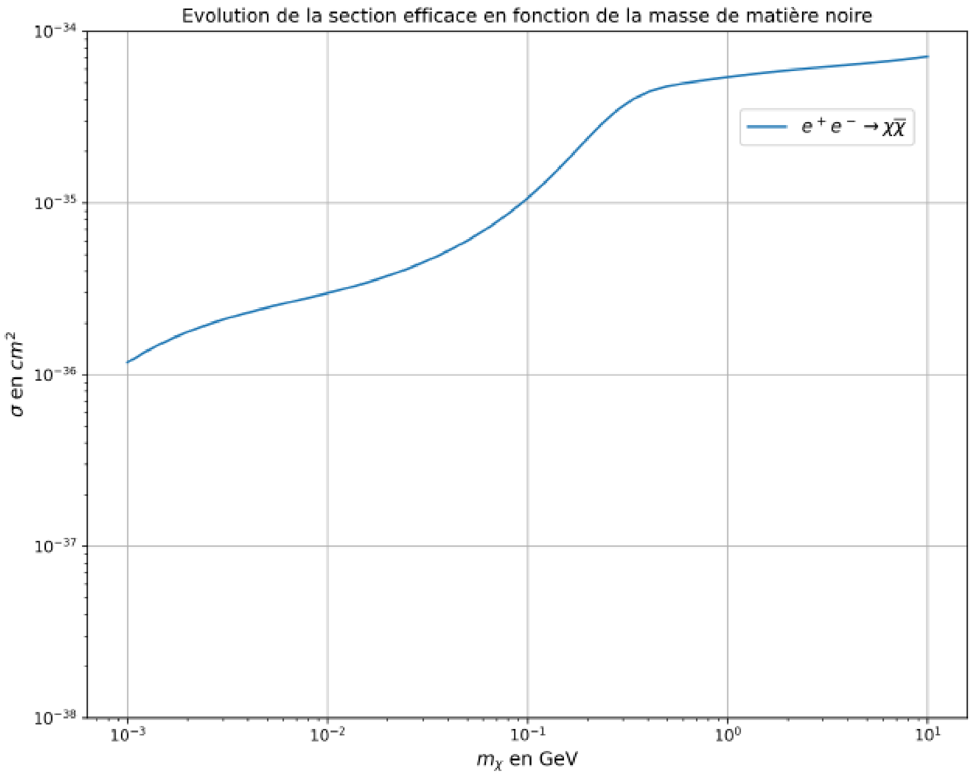
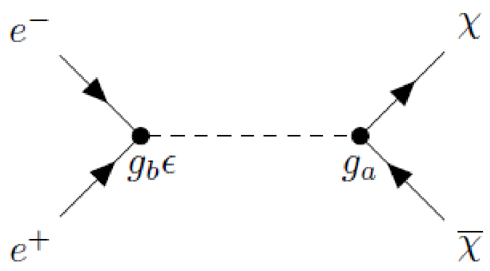


Internship objectives:

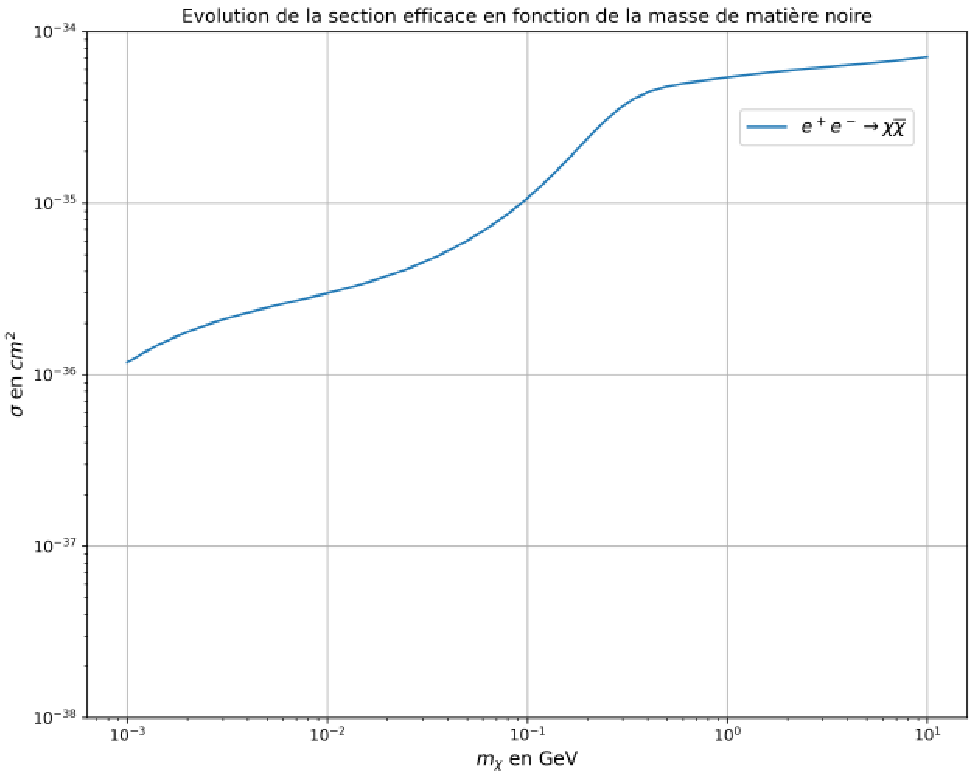
$\boldsymbol{g}$**:** Coupling constant that describes the interaction strength

$$\boldsymbol{\sigma_e(\mathbf{m}_\chi)}$$



$$\frac{dn_\chi}{dt} + 3\mathbf{H}(\mathbf{t})n_\chi = R(t, g)$$

Boltzmann equation



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Kinetic term :

$$L_k = -\frac{1}{4}F_a^{\mu\nu}F_{a\mu\nu} - \frac{1}{4}F_b^{\mu\nu}F_{b\mu\nu} - \frac{\epsilon}{2}F_{a\mu\nu}F_b^{\mu\nu}$$

Coupling between the photon and the dark photon

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Coupling between the photon and the dark photon

Interaction term : $$L_I = g_a J_a^{\mu} A_{\mu}^a + g_b J_b^{\mu} A_{\mu}^b$$

with :

- g_a coupling constant between two particles
- J_a^{μ} current associated with a particle
- A_{μ}^a vector field of the interaction boson

The free parameter g:

Change of basis :

$$L_I = \left(\frac{g_a}{\sqrt{1-\epsilon^2}} J^a_\mu - \frac{g_b \epsilon}{\sqrt{1-\epsilon^2}} J^b_\mu \right) B^\mu_a + g_b J^b_\mu B^\mu_b$$

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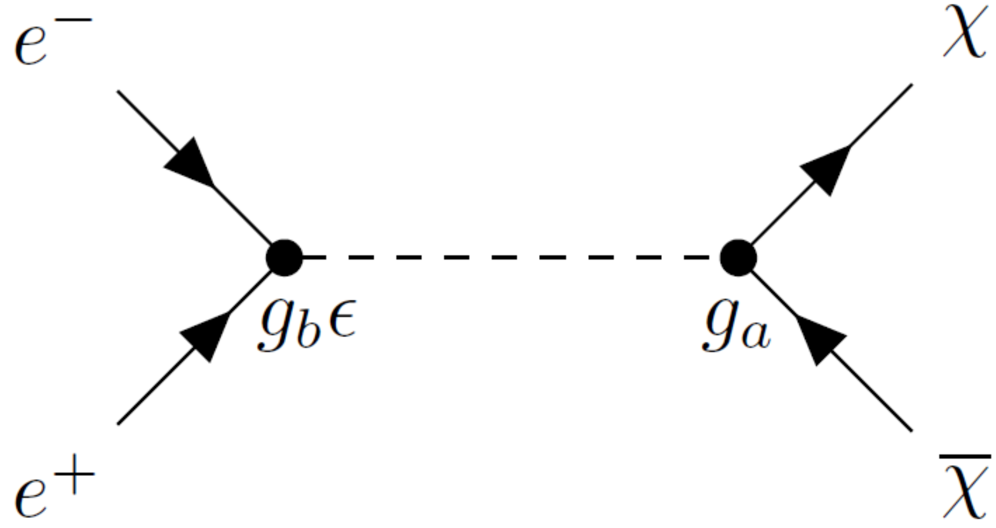

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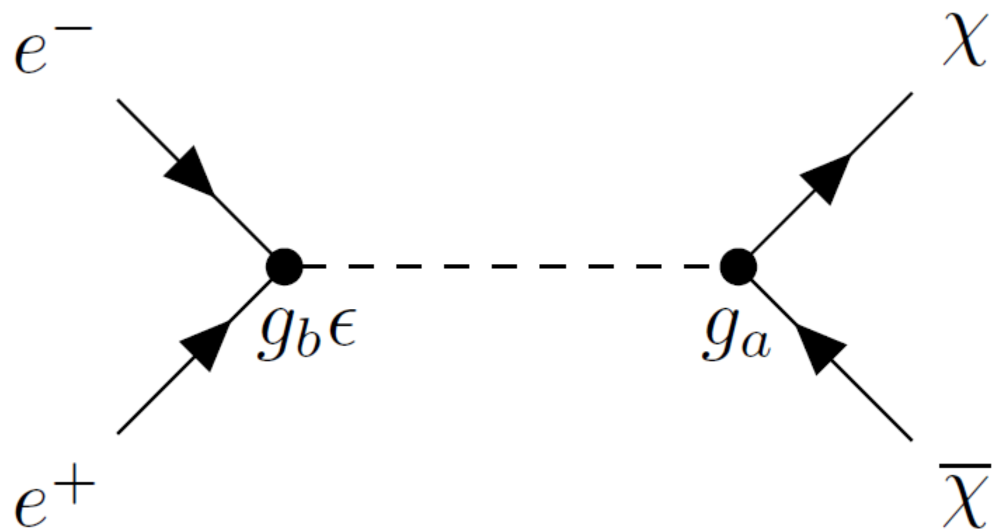

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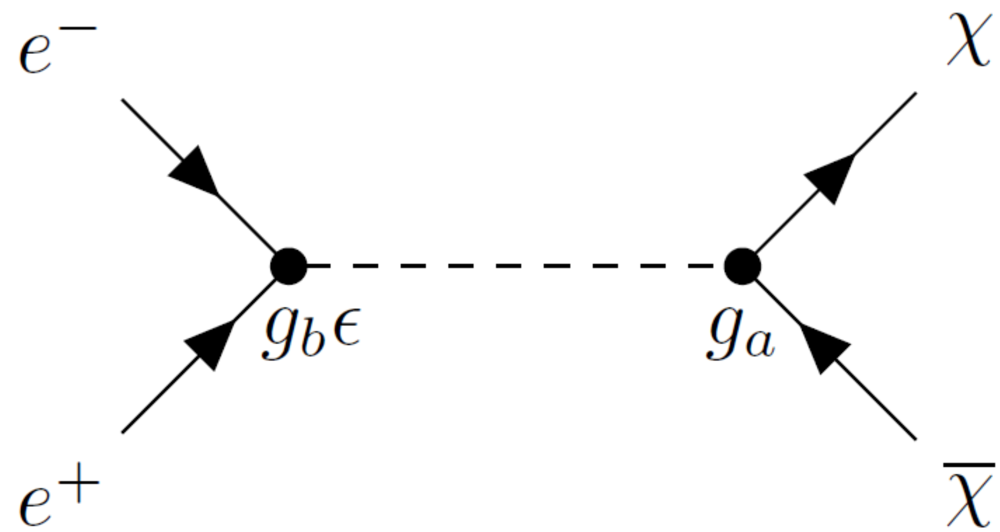
Parameter that we are looking for



The Boltzmann equation:

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Left-hand term: $H(t) = \frac{\dot{a}}{a}$ → Hubble constant, which measures the relative rate of expansion of the universe

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electron-dark matter interaction probability

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$$R(T) = \frac{T}{8(2\pi)^6} \int_{4m_\chi^2}^{\infty} \frac{ds}{\sqrt{s}} \sqrt{s - 4m_e^2} \sqrt{s - 4m_\chi^2}\, k_1 \left(\frac{\sqrt{s}}{T}\right) \frac{128\pi^2}{3}\, \alpha g^4 \left(1 + \frac{2m_e^2}{s}\right) \left(1 + \frac{2m_\chi^2}{s}\right)$$

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Solution of the equation and expression of $\sigma_e(m_\chi)$:

$$\frac{dn_\chi}{dt} + 3H(t)n_\chi = R(t) \xrightarrow[Y_\chi = \frac{n_\chi}{s}]{dt \approx -\frac{dT}{HT}} \frac{dY_\chi}{dT} = -\frac{\mathrm{R(T)}}{\mathrm{s(T)H(T)T}}$$

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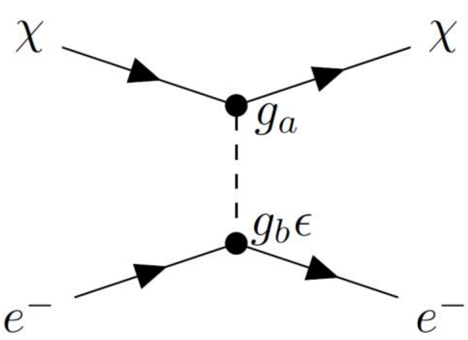
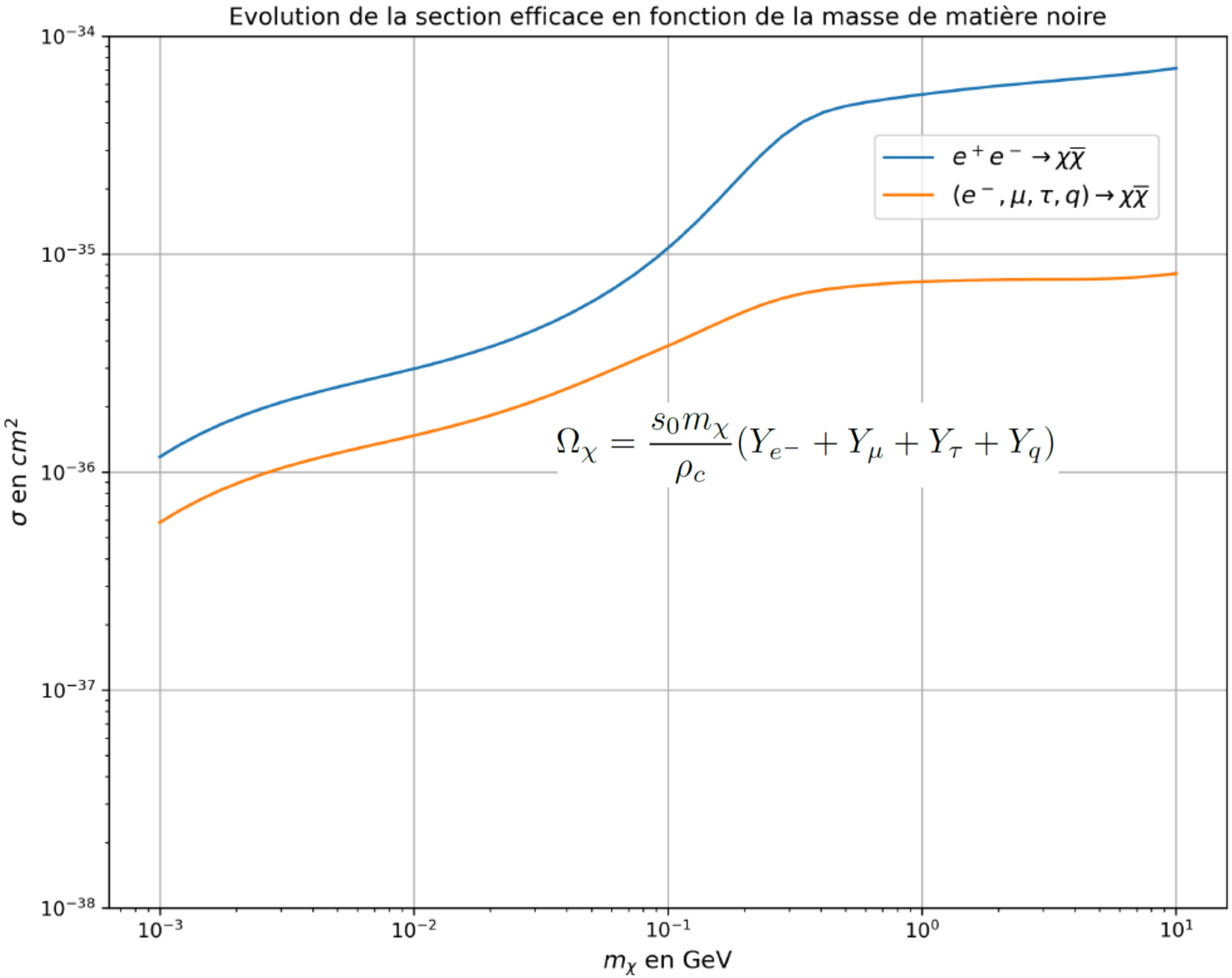
In DAMIC :



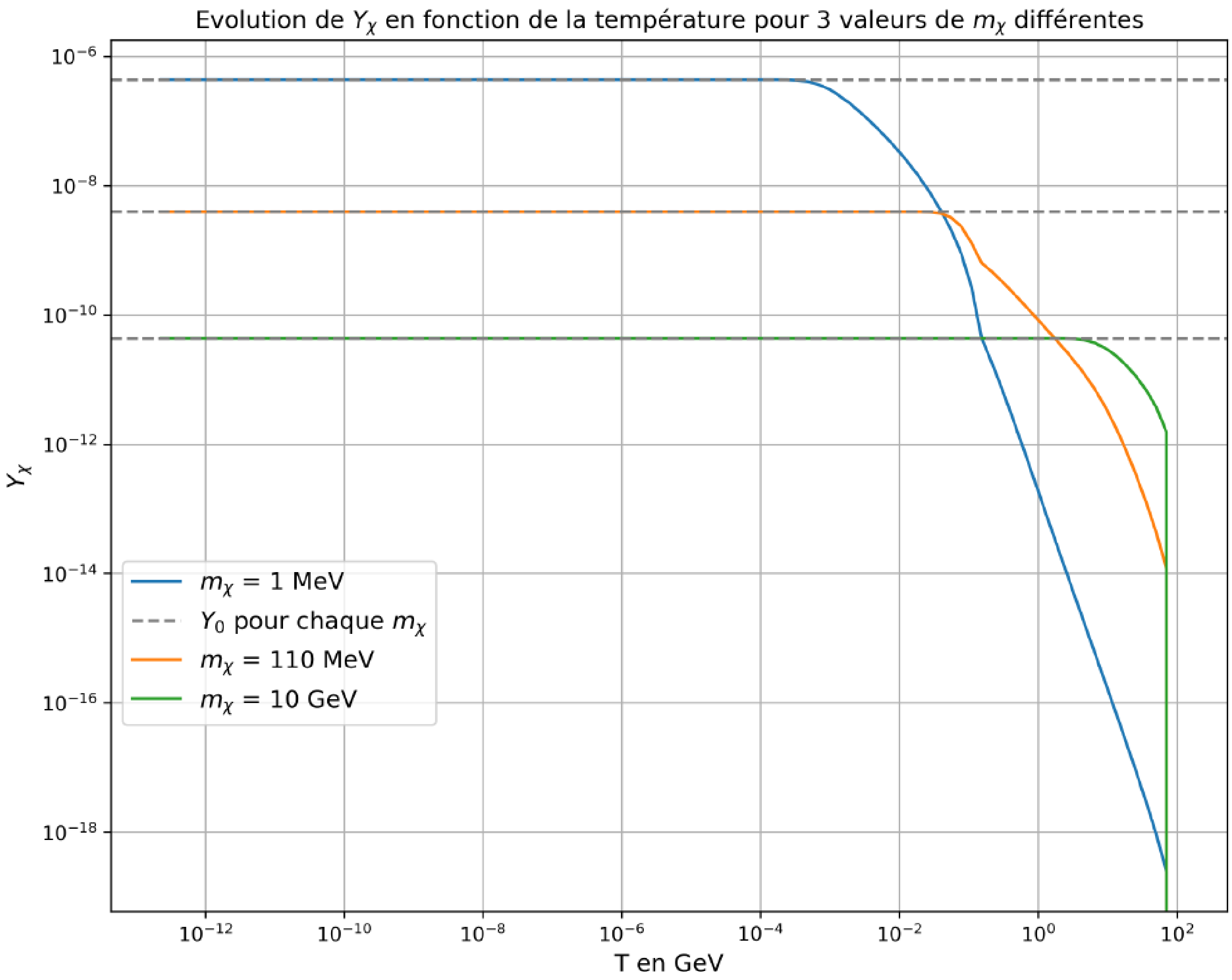
$$\rightarrow \boxed{\overline{\sigma_e} = \frac{4\alpha g^4 m_e^2 m_\chi^2}{(\alpha m_e)^4 (m_e + m_\chi)^2}}$$

Results: $\sigma_e(m_\chi)$



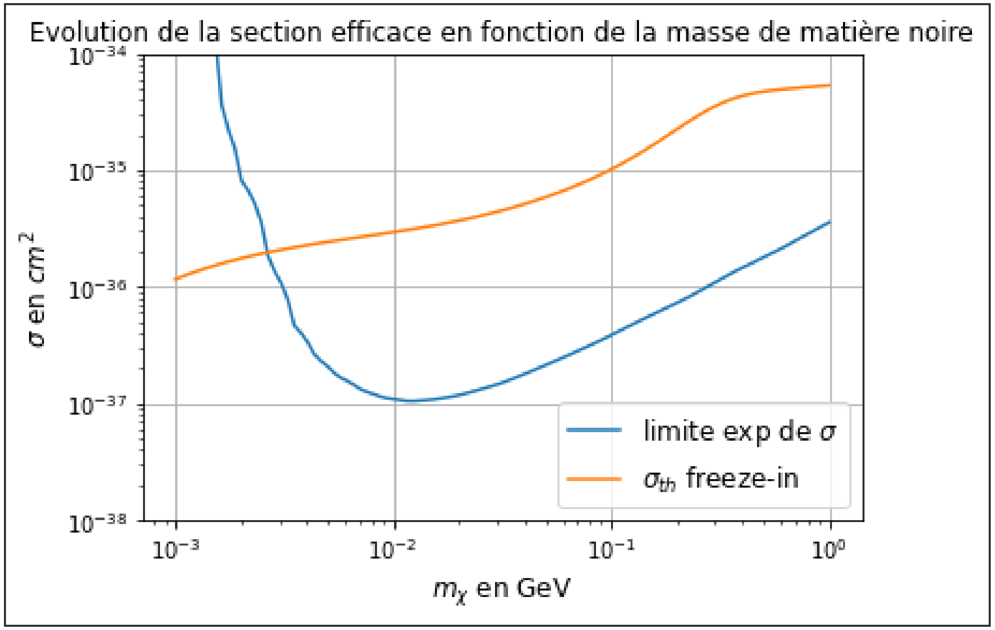
$$\Omega_\chi = \frac{s_0 m_\chi}{\rho_c}(Y_{e^-} + Y_\mu + Y_\tau + Y_q)$$

Results : $Y_\chi(T)$



Conclusion :

→ DAMIC-M's limits:



→ Inflaton can also give DM